CHAPTER 5: SHIELDING EVALUATION

5.0 INTRODUCTION

The shielding analysis of the HI-STAR 100 System is presented in this chapter. The HI-STAR 100 System is designed to accommodate different MPCs within one standard HI-STAR 100 overpack. The MPCs are designated as MPC-24, MPC-24E, and MPC-24EF (24 PWR fuel assemblies), MPC-32 (32 PWR fuel assemblies), and MPC-68 and MPC-68F (68 BWR fuel assemblies). The MPC-24E and MPC-24EF are essentially identical to the MPC-24 from a shielding perspective. Therefore, only the MPC-24 is analyzed in this chapter. Throughout this chapter, unless stated otherwise, MPC-24 refers to either the MPC-24, MPC-24E, or MPC-24EF and MPC-68 refers to the MPC-68 or MPC-68F.

In addition to housing intact PWR and BWR fuel assemblies, the HI-STAR 100 System is designed to transport damaged BWR fuel assemblies and BWR fuel debris. Damaged fuel assemblies and fuel debris are defined in Subsection 1.2.3. Both damaged BWR fuel assemblies and BWR fuel debris are required to be loaded into Damaged Fuel Containers (DFCs). DFCs containing BWR fuel debris must be stored in the MPC-68F. DFCs containing BWR damaged fuel assemblies may be stored in either the MPC-68 or the MPC-68F. Only the fuel assemblies in the Dresden 1 and Humboldt Bay fuel assembly classes identified in Table 1.2.9 are authorized as contents for transport in the HI-STAR 100 system as either BWR damaged fuel or fuel debris.

The MPC-68 and MPC-68F are also capable of transporting Dresden Unit 1 antimony-beryllium neutron sources and the single Thoria rod canister which contains 18 thoria rods that were irradiated in two separate fuel assemblies.

Slightly modified versions of the MPC-24E and MPC-24EF are being used for the transportation of Trojan nuclear power plant spent nuclear fuel, non-fuel hardware, neutron sources, and damaged fuel and fuel debris as described in Subsection 1.2.3. These MPCs are referred to as the Trojan MPC-24E and Trojan MPC-24EF. The Trojan MPC-24E/EF is explicitly analyzed in this chapter for the inclusion of the Trojan non-fuel hardware, damaged fuel, and Antimony-Beryllium and Californium neutron sources.

This chapter contains the following information:

- A description of the shielding features of the HI-STAR 100 System.
- A description of the bounding source terms.
- A general description of the shielding analysis methodology.
- A description of the analysis assumptions and results for the HI-STAR 100 System.

- Analyses for the HI-STAR 100 System's content conditions to show that the 10CFR71.47 radiation limits are met during normal conditions of transport and that the 10CFR71.51 dose rate limit is not exceeded following hypothetical accident conditions.
- Analyses which demonstrate that the storage of BWR damaged fuel in the HI-STAR 100 System is bounded by the BWR intact fuel analysis during normal and hypothetical accident conditions.
- Analyses for the Trojan Nuclear Power Plant spent fuel contents, including damaged fuel and fuel debris, and non-fuel hardware.

5.1 DISCUSSION AND RESULTS

The principal sources of radiation in the HI-STAR 100 System are:

- Gamma radiation originating from the following sources

    1. Decay of radioactive fission products
    2. Hardware activation products generated during core operations
    3. Secondary photons from neutron capture in fissile and non-fissile nuclides

- Neutron radiation originating from the following sources

    1. Spontaneous fission
    2. α,n reactions in fuel materials
    3. Secondary neutrons produced by fission from subcritical multiplication
    4. γ,n reactions (this source is negligible)
    5. Dresden Unit 1 and Trojan neutron sources

Shielding from gamma radiation is provided by the steel structure of the MPC and overpack. In order for the neutron shielding to be effective, the neutrons must be thermalized and then absorbed in a material of high neutron cross section. In the HI-STAR 100 System design, a neutron shielding material, Holtite-A, is used to thermalize the neutrons. Boron carbide, dispersed in the neutron shield, utilizes the high neutron absorption cross section of ^{10}B to absorb the thermalized neutrons.

The shielding analyses were performed with MCNP-4A [5.1.1] from Los Alamos National Laboratory. The source terms for the design basis fuels were calculated with the SAS2H and ORIGEN-S sequences from the SCALE 4.3 system [5.1.2, 5.1.3] from Oak Ridge National Laboratory. The source terms for the Trojan specific inventory were calculated with the SAS2H and ORIGEN-S sequences from the SCALE 4.4 system [5.1.4, 5.1.5] as described in the Trojan FSAR [5.1.6]. A detailed description of the MCNP models and the source term calculations are presented in Sections 5.3 and 5.2, respectively.

The design basis intact zircaloy clad fuels used in calculating the dose rates presented in this chapter are the B&W 15x15 (with zircaloy and non-zircaloy incore spacers) and the GE 7x7, for PWR and BWR fuel types, respectively. The design basis intact 6x6, damaged, and mixed oxide (MOX) fuel assemblies are the GE 6x6. Tables 1.2.22 through 1.2.27 specify the acceptable intact zircaloy clad fuel characteristics for transport. Tables 1.2.23 and 1.2.24 specify the acceptable damaged and MOX zircaloy clad fuel characteristics for transport.

The design bases intact stainless steel clad fuels are the WE 15x15 and the AC 10x10, for PWR and BWR fuel types, respectively. Tables 1.2.22, 1.2.23, 1.2.25, and 1.2.26 specify the acceptable fuel characteristics of stainless steel clad fuel for transport.

The Trojan spent fuel contents were analyzed separately, as discussed in later sections, and therefore are not covered by the design basis fuel assemblies mentioned above.

Tables 1.2.28 through 1.2.33 specify, in tabular form, the minimum enrichment, burnup and cooling time combinations for spent nuclear fuel that were analyzed for transport in the MPC-24, MPC-32, and MPC-68. Each combination provides a dose rate equal to or below the maximum values reported in this section. These tables represent the fuel assembly acceptance criteria.

The burnup, cooling time, and minimum enrichment combinations specified in Tables 1.2.28 through 1.2.33 were determined strictly based on the shielding analysis in this chapter. Each combination was specifically analyzed and it was verified that the calculated dose rates were less than the regulatory limits. Detailed results (e.g. dose from gammas, neutrons, co-60, etc.) are not presented in this chapter for each burnup, cooling time, and minimum enrichment combination analyzed. Rather, the detailed results for the combination that produced the highest dose rate for each of the three regulatory acceptance criteria and locations (i.e. surface normal condition, 2 meter normal condition, 1 meter accident condition) in a specific MPC are presented in this section. However, the total dose rates for all approved burnup and cooling time combinations are presented in Section 5.4. The choice of burnup and cooling time combinations for which detailed (i.e. individual dose components in addition to total) results are provided is discussed further in the following subsections.

Unless otherwise stated, all dose rates reported in this chapter are average surface dose rates. The effect of radiation peaking due to azimuthal variations in the fuel loading pattern and the steel radial channels is specifically addressed in Subsection 5.4.1.

5.1.1 Normal Operations

The 10CFR71.47 external radiation requirements during normal transport operations for an exclusive use shipment are:

1. 200 mrem/hr (2 mSv/hr) on the external surface of the package, unless the following conditions are met, in which case the limit is 1000 mrem/hr (10 mSv/hr).
   i. The shipment is made in a closed transport vehicle;
   ii. The package is secured within the vehicle so that its position remains fixed during transportation; and
   iii. There are no loading and unloading operations between the beginning and end of the transportation.

2. 200 mrem/hr (2 mSv/hr) at any point on the outer surface of the vehicle, including the top and underside of the vehicle; or in the case of a flat-bed style vehicle, at any point on the vertical planes projected from the outer edges of the vehicle, on the upper surface of the load or enclosure, if used, and on the lower external surface of the vehicle.

3. 10 mrem/hr (0.1 mSv/hr) at any point 2 meters (80 in) from the outer lateral surfaces of the vehicle (excluding the top and underside of the vehicle); or in the case of a flat-bed style vehicle, at any point 2 meters (6.6 feet) from the vertical planes projected by the outer edges of the vehicle (excluding the top and underside of the vehicle).

4. 2 mrem/h (0.02 mSv/hr) in any normally occupied space, except that this provision does not apply to private carriers, if exposed personnel under their control wear radiation dosimetry devices in conformance with 10CFR20.1502.

The Standard Review Plan for Transportation Packages of Spent Nuclear Fuel, NUREG-1617 [5.2.1] states that "Personnel barriers and similar devices that are attached to the conveyance, rather than the package, can, however, qualify the vehicle as a closed vehicle (NUREG/CR-5569A and NUREG/CR-5569B) as defined in 49 CFR 173.403."

When the HI-STAR is transported, a personnel barrier will be placed over the HI-STAR as depicted in Figure 1.2.8. This personnel barrier spans the distance between the impact limiters. The outer radial location of the personnel barrier is equal to the outer radial surface of the impact limiters and the personnel barrier is attached to the saddle on the rail car rather than the HI-STAR overpack. Therefore, the personnel barrier acts as an enclosure for the main body of the HI-STAR overpack. Consequently, the 1000 mrem/hr limit for the enclosed package is applicable for the outer radial surface of the overpack in the region between the impact limiters. Since the impact limiters are not enclosed, the surface of the impact limiters is required to meet the lower 200 mrem/hr limit for the package.

The HI-STAR 100 System will be transported on either a flat-bed rail car, heavy haul vehicle, or a barge. The smallest width of a transport vehicle is equivalent to the width of the impact limiters. Therefore, the vertical planes projected by the outer side edges of the transport vehicle are equivalent to the outer edge of the impact limiters. The minimum length of any transport vehicle will be 12 feet longer than the length of the overpack, with impact limiters attached. The bottom impact limiter of the HI-STAR 100 System will be conservatively positioned a minimum of 9 feet from the end of the transport vehicle. Therefore, the vertical planes projected from the outer edge of the ends of the vehicle will be taken as the end of the top impact limiter and 9 feet from the end of the bottom impact limiter.

Figure 5.1.1 shows the HI-STAR 100 System during normal transport conditions. The impact limiters and personnel barrier are outlined on the figure and various dose point locations are shown on the surface of the enclosure (personnel barrier) and the HI-STAR 100 System. The dose values reported at the locations shown on Figure 5.1.1 are averaged over a region that is approximately 1 foot in width. Each of the dose locations in Figure 5.1.1 (with the exception of 2a and 3a) has a corresponding location at 2 meters from the surface of the transport vehicle as defined above.

Dose locations 2a, 3a, and 2 shown in Figure 5.1.1 and Figure 5.1.2 (discussed below) do not correspond to single dose locations. Rather the dose rate for multiple axial segments of approximately 1 foot or less were calculated and the highest value was chosen for the corresponding dose location. Dose locations 2a and 2 encompass 14 axial segments that range from the pocket trunnion to the top of the Holtite. The highest dose rate of these 14 axial segments was chosen as the value for dose locations 2a and 2. Dose location 3a corresponds to two axial segments while dose locations 1, 3, and 4 correspond to a single axial segment. Dose locations 5 and 6 correspond to either the center radial segment of the overpack along the axis or the adjacent location radial segment.

Tables 5.1.1 through 5.1.3, 5.1.10, and 5.1.11 provide the maximum dose rates on the surface of the system during normal transport conditions for the MPC-24, MPC-32, and MPC-68 with design basis intact zircaloy clad fuel. Tables 5.1.4 through 5.1.6, 5.1.12, and 5.1.13 list the maximum dose rates two meters from the edge of the transport vehicle during normal conditions. Section 5.4 provides a detailed list of the total dose rates at several cask locations for all burnup and cooling times analyzed. The burnup and cooling time combinations chosen for the tables mentioned above was the combination that resulted in the absolute highest dose rate for the normal condition regulatory locations (i.e. surface and 2 meter). For example, Table 5.1.1 presents the burnup and cooling time combination that results in the highest dose rate from a review of the dose rates, in Table 5.4.8, for locations 2a, 3a, and 1-6 for all allowable burnup and cooling time combinations. This combination may not result in the highest dose rate at each individual dose location (e.q. 2a, 3a, 1-6) but it is the combination that results in the absolute highest dose rate for the surface or 2 meter locations.

Subsections 5.2.1 and 5.2.2 list the gamma and neutron sources for the design basis zircaloy clad intact, zircaloy clad damaged and MOX fuel assemblies. Since the source strengths of the damaged and MOX fuel are significantly smaller in all energy groups than the intact design basis fuel source strengths, the damaged and MOX fuel dose rates for normal conditions are bounded by the MPC-68 analysis with design basis intact fuel. Therefore, no explicit analysis of the MPC-68 with either damaged or MOX fuel for normal conditions is required to demonstrate that the MPC-68 with damaged fuel or MOX fuel will meet the normal condition regulatory requirements.

Subsection 5.2.6 lists the gamma and neutron sources from the Dresden Unit 1 Thoria rod canister and demonstrates that the Thoria rod canister is bounded by the design basis 6x6 intact fuel.

Subsection 5.4.5 demonstrates that the Dresden Unit 1 fuel assemblies containing antimony-beryllium neutron sources are bounded by the shielding analysis presented in this section.

Subsections 5.4.7 and 5.4.8 present the results for the Trojan contents in the MPC-24E/EF and demonstrate that these contents are acceptable for transportation.

Subsection 5.2.3 lists the gamma and neutron sources for the design basis intact stainless steel clad fuels. The dose rates from these fuels are provided in Subsection 5.4.4.

Tables 5.1.4 through 5.1.6, 5.1.12, and 5.1.13 show that the dose rate at Dose Location #5 (the top of the HI-STAR 100 System, see Figure 5.1.1) at 2 meters from the edge of the transport vehicle is less than 2 mrem/hr. It is, therefore, recommended that the HI-STAR 100 System be positioned such that the top impact limiter is facing the normally occupied space. If this is the orientation, radiation dosimetry will not be required as long as the normally occupied space is a minimum of 2 meters from the impact limiter on the top of the HI-STAR 100 System. If a different orientation is chosen for the HI-STAR 100 System, the dose rate in the normally occupied space will have to be evaluated against the dose requirement for the normally occupied space to determine if radiation dosimetry is required.

The analyses summarized in this section demonstrate the HI-STAR 100 System's compliance with the 10CFR71.47 limits.

5.1.2 Hypothetical Accident Conditions

The 10CFR71.51 external radiation dose limit for design basis accidents is:

- The external radiation dose rate shall not exceed 1 rem/hr (10 mSv/hr) at 1 m (40 in.) from the external surface of the package.

The hypothetical accident conditions of transport have two bounding consequences which affect the shielding materials. They are the damage to the neutron shield as a result of the design basis fire and damage of the impact limiters as a result of the 30 foot drop. In a conservative fashion, the dose analysis assumes that as a result of the fire, the neutron shield is completely destroyed and replaced by a void. Additionally, the impact limiters are assumed to have been lost. These are highly conservative assumptions since some portion of the neutron shield would be expected to remain after the fire as the neutron shield material is fire retardant, and the impact limiters have been shown by 1/4-scale testing to remain attached following impact.

Throughout the hypothetical accident condition the axial location of the fuel will remain fixed within the MPC because of the fuel spacers or by the MPC lid and baseplate if spacers are not used. Chapter 2 provides an analysis to show that the fuel spacers do not fail under all normal and hypothetical accident conditions. Chapter 2 also shows that the inner shell, intermediate shell, radial channels, and outer enclosure shell of the overpack remain unaltered throughout the hypothetical accident conditions. Localized damage of the overpack outer enclosure shell could be experienced during the pin puncture. However, the localized deformations will have only a negligible impact on the dose rate at 1 meter from the surface.

Figure 5.1.2 shows the HI-STAR 100 System after the postulated accident. The various dose point locations at 1 meter from the HI-STAR 100 System are shown on the figure. Tables 5.1.7

through 5.1.9, 5.1.14 and 5.1.15 provide the maximum dose rates at 1 meter for the accident conditions. The burnup and cooling time combinations chosen for the aforementioned tables were the combinations that resulted in the absolute highest dose rate for the accident condition regulatory location (i.e. 1 meter).

The consequences of the hypothetical accident conditions for the MPC-68F storing either damaged or MOX (which can also be considered damaged) fuel differ slightly from those with intact fuel. For this accident condition, it is conservatively assumed that during a drop accident the damaged fuel collapses and the pellets rest in the bottom of the damaged fuel container. The analysis presented in Subsections 5.4.2 and 5.4.3 demonstrate that the damaged fuel in the post-accident condition has lower source terms (both gamma and neutron) per inch than the intact BWR design basis fuel. Therefore, the damaged fuel post-accident dose rates are bounded by the BWR intact fuel post-accident dose rates.

Subsections 5.4.7 and 5.4.8 present the results for the Trojan contents in the MPC-24E/EF and demonstrate that these contents are acceptable for transportation.

Analyses summarized in this section demonstrate the HI-STAR 100 System's compliance with the 10CFR71.51 radiation dose limit.

Table 5.1.1

DOSE RATES ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-24 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
44,500 MWD/MTU AND 14-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)	10 CFR 71.47 Limit
2a	23.91	0.00	0.01	22.27	46.19	1000
3a	0.96	0.00	28.52	108.98	138.47	1000
1	1.92	0.00	13.98	18.95	34.85	200
2	15.33	0.00	0.09	12.82	28.24	200
3	1.11	0.00	10.45	18.63	30.19	200
4	0.62	0.00	9.21	18.22	28.05	200
5	0.49	0.00	0.02	3.82	4.33	200
6	4.60	0.00	53.31	31.63	89.54	200

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

Table 5.1.2

DOSE RATES ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-24 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
44,500 MWD/MTU AND 18-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)	10 CFR 71.47 Limit
2a	18.10	8.92	0.01	19.22	46.24	1000
3a	0.78	0.14	16.91	94.04	111.87	1000
1	1.48	0.63	8.29	16.35	26.75	200
2	11.56	5.93	0.05	11.07	28.62	200
3	0.85	0.35	6.19	16.08	23.47	200
4	0.49	0.19	5.46	15.72	21.85	200
5	0.42†††	-	0.01	3.30	3.73	200
6	4.69†††	-	31.60	27.29	63.58	200

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.1.3

DOSE RATES ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-68 WITH DESIGN BASIS ZIRCALOY CLAD FUEL AT
WORST CASE BURNUP AND COOLING TIME
34,500 MWD/MTU AND 11-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)	10 CFR 71.47 Limit
2a	27.04	4.53	0.01	18.53	50.12	1000
3a	0.43	0.08	94.78	36.91	132.20	1000
1	2.15	0.36	21.32	14.13	37.96	200
2	17.55	3.08	0.08	10.40	31.12	200
3	0.67	0.10	23.02	7.90	31.69	200
4	0.36	0.06	22.01	7.48	29.91	200
5	0.20†††	-	0.03	1.56	1.78	200
6	3.17†††	-	72.37	19.73	95.27	200

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.1.4

DOSE RATES AT TWO METERS FOR NORMAL CONDITIONS
MPC-24 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
24,500 MWD/MTU AND 6-YEAR COOLING

Dose Point† Location	**Fuel Gammas†† (mrem/hr)**	**Gammas from Incore Spacers (mrem/hr)**	**^{60}Co Gammas (mrem/hr)**	**Neutrons (mrem/hr)**	**Totals (mrem/hr)**
1	3.06	0.00	3.56	0.78	7.41
2	7.52	0.00	1.16	0.88	9.57
3	2.57	0.00	3.41	0.74	6.72
4	2.03	0.00	3.43	0.70	6.16
5	0.01	0.00	0.01	0.09	0.10
6	0.32	0.00	7.60	0.19	8.11
10CFR71.47 Limit					10.00

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

Table 5.1.5

DOSE RATES AT TWO METERS FOR NORMAL CONDITIONS
MPC-24 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
24,500 MWD/MTU AND 9-YEAR COOLING

Dose Point† Location	**Fuel Gammas†† (mrem/hr)**	**Gammas from Incore Spacers (mrem/hr)**	**^{60}Co Gammas (mrem/hr)**	**Neutrons (mrem/hr)**	**Totals (mrem/hr)**
1	1.42	1.90	2.40	0.70	6.42
2	3.38	4.56	0.80	0.77	9.51
3	1.18	1.54	2.30	0.66	5.68
4	0.94	1.21	2.31	0.63	5.08
5	0.01†††	-	0.01	0.08	0.09
6	0.38†††	-	5.12	0.17	5.67
10CFR71.47 Limit					10.00

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.1.6

DOSE RATES AT TWO METERS FOR NORMAL CONDITIONS
MPC-68 WITH DESIGN BASIS ZIRCALOY CLAD FUEL
AT WORST CASE BURNUP AND COOLING TIME
34,500 MWD/MTU AND 11-YEAR COOLING

Dose Point† Location	**Fuel Gammas†† (mrem/hr)**	**Gammas from Incore Spacers (mrem/hr)**	**^{60}Co Gammas (mrem/hr)**	**Neutrons (mrem/hr)**	**Totals (mrem/hr)**
1	2.38	0.43	2.33	2.45	7.59
2	5.19	0.95	0.65	2.83	9.62
3	1.56	0.28	3.14	1.64	6.62
4	1.21	0.21	3.33	1.57	6.32
5	0.02†††	-	0.01	0.18	0.20
6	0.15†††	-	4.31	0.48	4.94
10CFR71.47 Limit					10.00

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.1.7

DOSE RATES AT ONE METER FOR ACCIDENT CONDITIONS
MPC-24 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
29,500 MWD/MTU AND 7-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
1	7.11	34.28	56.17	97.55
2	37.07	1.19	185.96	224.23
3	4.67	19.87	39.87	64.41
4	2.70	15.08	29.35	47.12
5	0.03	0.24	6.32	6.59
6	20.66	618.44	47.99	687.08
10CFR71.51 Limit				1000.00

† Refer to Figure 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.1.8

DOSE RATES AT ONE METER FOR ACCIDENT CONDITIONS
MPC-24 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
24,500 MWD/MTU AND 9-YEAR COOLING

Dose Point† Location	**Fuel Gammas†† (mrem/hr)**	**^{60}Co Gammas (mrem/hr)**	**Neutrons (mrem/hr)**	**Totals (mrem/hr)**
1	8.40	23.69	30.24	62.33
2	44.07	0.82	100.11	145.00
3	5.51	13.73	21.46	40.70
4	3.17	10.42	15.80	29.39
5	0.02	0.17	3.40	3.59
6	25.07	427.37	25.84	478.28
10CFR71.51 Limit				1000.00

† Refer to Figure 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.1.9

DOSE RATES AT ONE METER FOR ACCIDENT CONDITIONS
MPC-68 WITH DESIGN BASIS ZIRCALOY CLAD FUEL
AT WORST CASE BURNUP AND COOLING TIME
44,500 MWD/MTU AND 19-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
1	4.47	10.20	183.86	198.52
2	21.94	0.22	600.71	622.86
3	1.81	6.93	93.91	102.65
4	1.02	6.18	67.17	74.36
5	0.04	0.07	10.93	11.04
6	5.76	171.42	123.53	300.71
10CFR71.51 Limit				1000.00

† Refer to Figure 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.1.10

DOSE RATES ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-32 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
44,500 MWD/MTU AND 19-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)	10 CFR 71.47 Limit
2a	2.77	0.00	17.29	30.84	50.90	1000
3a	2.01	0.00	27.39	234.56	263.95	1000
1	1.90	0.00	11.60	29.02	42.51	200
2	2.80	0.00	8.42	24.26	35.48	200
3	1.45	0.00	9.60	38.62	49.68	200
4	0.74	0.00	8.99	37.58	47.31	200
5	0.89	0.00	0.01	8.21	9.11	200
6	5.53	0.00	42.31	49.50	97.35	200

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

Table 5.1.11

DOSE RATES ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-32 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
42,500 MWD/MTU AND 20-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)	10 CFR 71.47 Limit
2a	18.92	9.15	0.01	16.46	44.54	1000
3a	1.65	0.29	22.98	188.28	213.21	1000
1	1.61	0.70	9.73	23.29	35.33	200
2	2.38	1.01	7.06	19.48	29.93	200
3	1.22	0.46	8.06	31.01	40.74	200
4	0.63	0.24	7.54	30.17	38.57	200
5	0.71†††	-	0.01	6.59	7.32	200
6	5.78†††	-	35.51	39.74	81.03	200

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.1.12

DOSE RATES AT TWO METERS FOR NORMAL CONDITIONS
MPC-32 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
39,500 MWD/MTU AND 14-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
1	2.29	0.00	2.59	3.56	8.43
2	5.25	0.00	0.82	3.58	9.65
3	1.92	0.00	2.66	4.52	9.10
4	1.57	0.00	2.67	4.56	8.79
5	0.05	0.00	0.01	0.64	0.70
6	0.23	0.00	4.41	0.96	5.60
10CFR71.47 Limit					10.00

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

Table 5.1.13

DOSE RATES AT TWO METERS FOR NORMAL CONDITIONS
MPC-32 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
42,500 MWD/MTU AND 20-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
1	1.68	0.80	1.22	3.43	7.13
2	3.81	1.96	0.38	3.46	9.61
3	1.43	0.67	1.25	4.36	7.71
4	1.16	0.54	1.26	4.40	7.36
5	0.05†††	-	0.00	0.62	0.67
6	0.24†††	-	2.08	0.92	3.24
10CFR71.47 Limit					10.00

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.1.14

DOSE RATES AT ONE METER FOR ACCIDENT CONDITIONS
MPC-32 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
29,500 MWD/MTU AND 9-YEAR COOLING

Dose Point† Location	**Fuel Gammas†† (mrem/hr)**	**^{60}Co Gammas (mrem/hr)**	**Neutrons (mrem/hr)**	**Totals (mrem/hr)**
1	6.51	43.30	68.18	117.99
2	32.65	1.42	196.89	230.95
3	4.37	25.54	60.00	89.91
4	2.64	20.54	43.37	66.55
5	0.06	0.27	14.76	15.09
6	18.89	720.63	77.64	817.16
10CFR71.51 Limit				1000.00

† Refer to Figure 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.1.15

DOSE RATES AT ONE METER FOR ACCIDENT CONDITIONS
MPC-32 WITH DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT WORST CASE BURNUP AND COOLING TIME
24,500 MWD/MTU AND 12-YEAR COOLING

Dose Point† Location	**Fuel Gammas†† (mrem/hr)**	**^{60}Co Gammas (mrem/hr)**	**Neutrons (mrem/hr)**	**Totals (mrem/hr)**
1	8.07	26.23	35.50	69.80
2	40.10	0.86	102.53	143.48
3	5.43	15.47	31.25	52.15
4	3.29	12.44	22.58	38.31
5	0.04	0.16	7.69	7.89
6	23.63	436.48	40.43	500.54
10CFR71.51 Limit				1000.00

† Refer to Figure 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

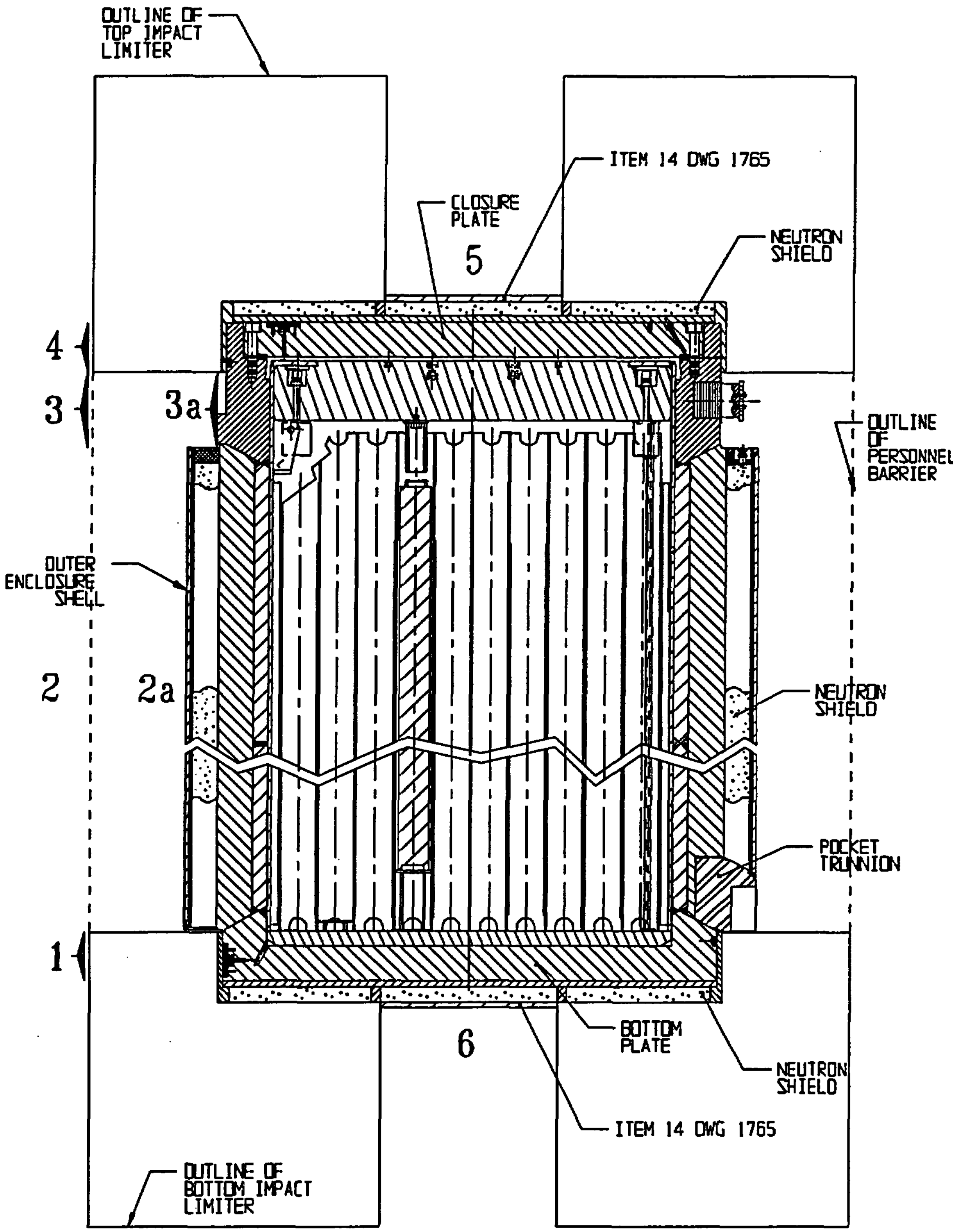


FIGURE 5.1.1; CROSS SECTION ELEVATION VIEW OF THE HI-STAR 100 SYSTEM WITH DOSE POINT LOCATIONS DURING NORMAL CONDITIONS

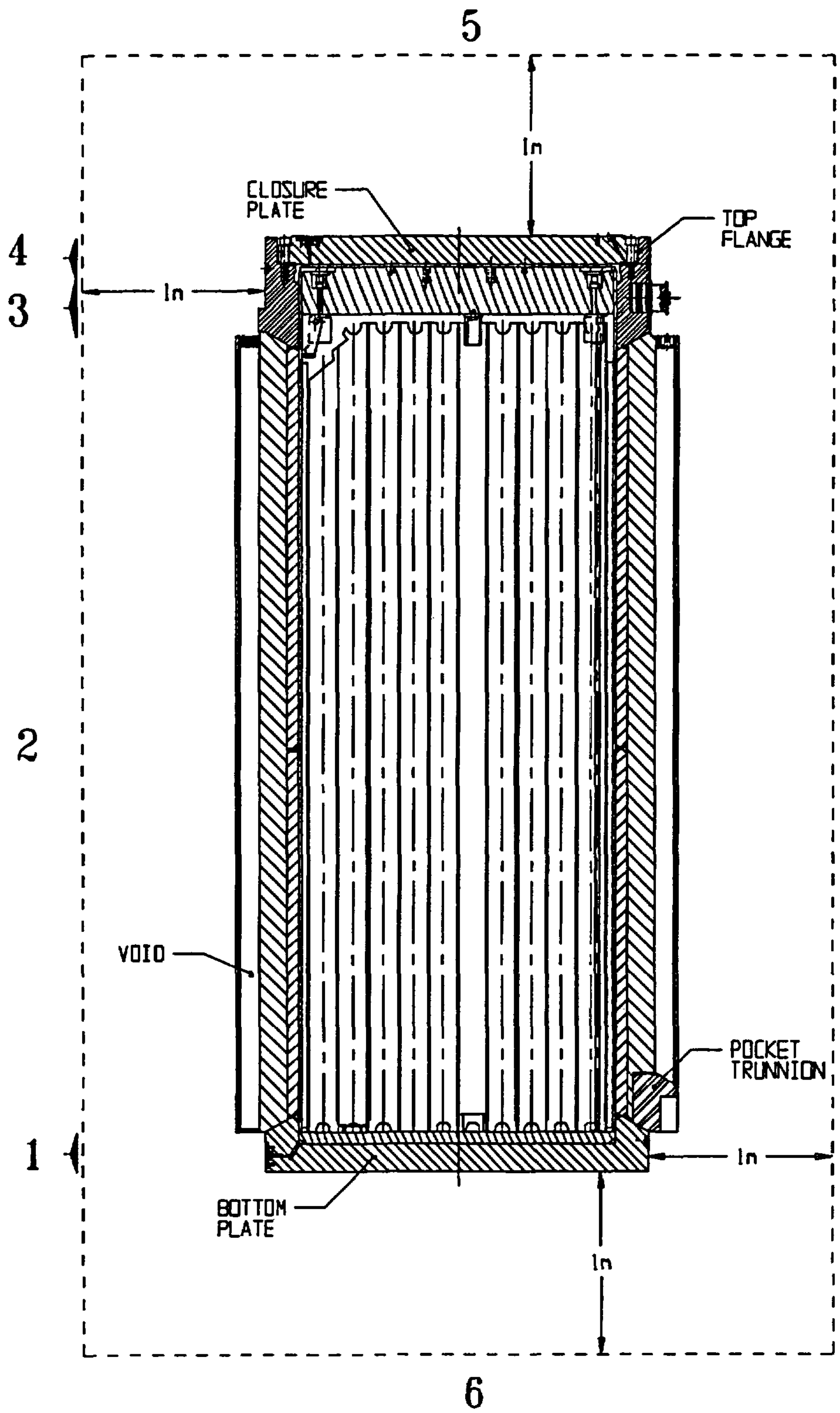


FIGURE 5.1.2; CROSS SECTION ELEVATION VIEW OF THE HI-STAR 100 SYSTEM WITH DOSE POINT LOCATIONS DURING ACCIDENT CONDITIONS

5.2 SOURCE SPECIFICATION

The neutron and gamma source terms, decay heat values, and quantities of radionuclides available for release were calculated with the SAS2H and ORIGEN-S modules of the SCALE 4.3 system [5.1.2, 5.1.3]. The source terms for the Trojan specific inventory were calculated with the SAS2H and ORIGEN-S sequences from the SCALE 4.4 system [5.1.4, 5.1.5] as described in the Trojan FSAR [5.1.6]. Sample input files for SAS2H and ORIGEN-S are provided in Appendices 5.A and 5.B, respectively. The gamma source term is actually comprised of three distinct sources. The first is a gamma source term from the active fuel region due to decay of fission products. The second source term is from ^{60}Co activity of the steel structural material in the fuel assembly above and below the active fuel region. The third source is from (n,γ) reactions described below.

A description of the design basis intact zircaloy clad fuel for the source term calculations is provided in Table 5.2.1. The PWR fuel assembly described is the assembly that produces the highest neutron and gamma sources and the highest decay heat load from the following fuel assembly classes listed in Table 1.2.8: B&W 15x15, B&W 17x17, CE 14x14, CE 16x16, WE 14x14, WE 15x15, WE 17x17, St. Lucie, and Ft. Calhoun. The BWR fuel assembly described is the assembly that produces the highest neutron and gamma sources and the highest decay heat load from the following fuel assembly classes listed in Table 1.2.9: GE BWR/2-3, GE BWR/4-6, Humboldt Bay 7x7, and Dresden 1 8x8. Multiple SAS2H and ORIGEN-S calculations were performed to confirm that the B&W 15x15 and the GE 7x7, which have the highest UO_2 mass, bound all other PWR and BWR fuel assemblies, respectively. Subsection 5.2.5 discusses, in detail, the determination of the design basis fuel assemblies.

The design basis Humboldt Bay and Dresden 1 6x6 fuel assembly, which is also the design basis damaged fuel assembly for the Humboldt Bay and Dresden 1 damaged fuel or fuel debris, is described in Table 5.2.2. The design basis damaged fuel assembly is also the design basis fuel assembly for fuel debris. The fuel assembly type listed produces the highest total neutron and gamma sources from the fuel assemblies at Dresden 1 and Humboldt Bay. Table 5.2.15 provides a description of the design basis Dresden 1 MOX fuel assembly used in this analysis. The design basis 6x6, damaged, and MOX fuel assemblies which are smaller than the GE 7x7, are assumed to have the same hardware characteristics as the GE 7x7. This is conservative because the larger hardware mass of the GE 7x7 results in a larger ^{60}Co activity.

The design basis stainless steel clad fuel assembly for the Indian Point 1, Haddam Neck and San Onofre 1 assembly classes is described in Table 5.2.18. This table also describes the design basis stainless steel clad LaCrosse fuel assembly.

Since the MPC-24E being used for Trojan fuel is slightly different than the standard MPC-24E, the Trojan contents were specifically analyzed and are not covered by the design basis PWR fuel assembly described above. The design basis Trojan WE 17x17 fuel assembly is described in Table 5.2.32 and was taken from the site specific Trojan FSAR analysis [5.1.6].

In performing the SAS2H and ORIGEN-S calculations, a single full power cycle was used to achieve the desired burnup. This assumption, in conjunction with the above-average specific powers listed in Tables 5.2.1, 5.2.2, 5.2.15, 5.2.18, and 5.2.32 resulted in conservative source term calculations.

Subsections 5.2.1 and 5.2.2 describe the calculation of the gamma and neutron source terms for zircaloy clad fuel while Subsection 5.2.3 discusses the calculation of the gamma and neutron source terms for the stainless steel clad fuel.

5.2.1 Gamma Source

Tables 5.2.3 through 5.2.6, 5.2.33, 5.2.40, and 5.2.41 provide the gamma source in MeV/s and photons/s as calculated with SAS2H and ORIGEN-S for the design bases intact fuels for the MPC-24, MPC-32, MPC-68, the design basis damaged fuel, and the Trojan fuel. Table 5.2.16 provides the gamma source in MeV/s and photons/s for the design basis MOX fuel. NUREG-1617 [5.2.1] states that "In general, only gammas from approximately 0.8 MeV-2.5 MeV will contribute significantly to the external radiation levels." However, specific analysis for the HI-STAR 100 system has revealed that, due to the magnitude of the gamma source in the energy range just below 0.8 MeV, gammas with energies as low as 0.45 MeV must be included in the shielding analysis. The effect of gammas with energies above 3.0 MeV, on the other hand, was found to be insignificant (less than 1% of the total gamma dose). This is due to the fact that the source of gammas in this range (i.e., above 3.0 MeV) is extremely low (less than 1% of the total source). Therefore, all gammas with energies in the range of 0.45 to 3.0 MeV are included in the shielding calculations. Photons with energies below 0.45 MeV are too weak to penetrate the steel of the overpack, and photons with energies above 3.0 MeV are too few to contribute significantly to the external dose. As discussed earlier, the MPC-24, MPC-32, and the MPC-68 are analyzed for transportation of spent nuclear fuel with varying minimum enrichments, burnup levels and cooling times. This section provides the radiation source for each of the burnup levels and cooling times evaluated.

The primary source of activity in the non-fuel regions of an assembly arise from the activation of ^{59}Co to ^{60}Co. The primary source of ^{59}Co in a fuel element is the steel and inconel structural material. The zircaloy in these regions is neglected since it does not have a significant ^{59}Co impurity level. Reference [5.2.3] indicates that the ^{59}Co impurity level in steel is 800 ppm or 0.8 gm/kg and in inconel is approximately 4700 ppm or 4.7 gm/kg. In the early to mid 1980s, the fuel vendors reduced the ^{59}Co impurity level in both inconel and steel to less than 500 ppm or 0.5 gm/kg. Prior to that, the impurity level in inconel in fuel assemblies was typically less than 1200 ppm or 1.2 gm/kg. Nevertheless, a conservative ^{59}Co impurity level of 1.0 gm/kg was used for the stainless steel end fittings and a highly conservative impurity level of 4.7 gm/kg was used for the inconel.

PWR fuel assemblies are currently manufactured with zircaloy incore grid spacers (the plenum spacer and the lower spacer are still inconel in some cases). However, earlier assemblies were

manufactured with inconel incore grid spacers. Since the mass of the spacers is significant and since the cobalt impurity level assumed for inconel is very conservative, the Cobalt-60 activity from the incore spacers contributes significantly to the external dose rate. As a result, separate burnup and cooling times were developed for PWR assemblies that utilize zircaloy and non-zircaloy incore spacers. Since steel has a lower cobalt impurity level than inconel, any zircaloy clad PWR assemblies with stainless steel grid spacers are bounded by the analysis performed in this chapter utilizing inconel grid spacers. The BWR assembly grid spacers are zircaloy, however, some assembly designs have inconel springs in conjunction with the grid spacers. The gamma source for the BWR fuel assembly includes the activation of these springs associated with the grid spacers.

The non-fuel data listed in Table 5.2.1 was taken from References [5.2.3], [5.2.4], and [5.2.5]while the non-fuel data listed in Table 5.2.32 was taken from References [5.2.5] and [5.2.8]. The BWR masses are for an 8x8 fuel assembly. These masses are also appropriate for the 7x7 assembly since the masses of the non-fuel hardware from a 7x7 and an 8x8 are approximately the same. The masses listed are those of the steel components. The zircaloy in these regions was not included because zircaloy does not produce significant activation. These masses are larger than most other fuel assemblies from other manufacturers. This, in combination with the conservative ^{59}Co impurity level, results in a conservative estimate of the ^{60}Co activity.

The masses in Table 5.2.1 and 5.2.32 were used to calculate a ^{59}Co impurity level in the fuel material. The grams of impurity were then used in ORIGEN-S to calculate a ^{60}Co activity level for the desired burnup and decay time. The methodology used to determine the activation level was developed from Reference [5.2.2] and is described here.

1. The activity of the ^{60}Co is calculated using ORIGEN-S. The flux used in the calculation was the in-core fuel region flux at full power.

2. The activity calculated in Step 1 for the region of interest was modified by the appropriate scaling factors listed in Table 5.2.7. These scaling factors were taken from Reference [5.2.2]. In the case of the Trojan fuel, the higher value of 0.2 was used for both the gas plenum springs and spacer consistent with the Trojan FSAR [5.1.6].

Tables 5.2.8 through 5.2.10, 5.2.34, 5.2.42, and 5.2.43 provide the ^{60}Co activity utilized in the shielding calculations in the non-fuel regions of the assemblies for the MPC-24, MPC-32, MPC-68, and Trojan fuel. The design basis damaged and MOX fuel assemblies are conservatively assumed to have the same ^{60}Co source strength as the BWR intact design basis fuel. This is a conservative assumption as the design basis damaged fuel and MOX fuel are limited to a significantly lower burnup and longer cooling time than the intact design basis zircaloy clad fuel.

In addition to the two sources already mentioned, a third source arises from (n,γ) reactions in the material of the MPC and the overpack. This source of photons is properly accounted for in MCNP when a neutron calculation is performed in a coupled neutron-gamma mode.

5.2.2 Neutron Source

It is well known that the neutron source strength increases as enrichment decreases, for a constant burnup and decay time. This is due to the increase in Pu content in the fuel which increases the inventory of other transuranium nuclides such as Cm. The gamma source also varies with enrichment, although only slightly. Because of this effect and in order to obtain conservative source terms, low initial fuel enrichments were chosen for the BWR and PWR design basis fuel assemblies as a function of burnup and cooling time. Conservatively, the minimum enrichments used to develop the source terms and dose rates presented in this chapter are specified in Tables 1.2.28 through 1.2.33 as fuel assembly acceptance criteria. The minimum enrichments for the design basis PWR and BWR assemblies are also listed in Table 5.2.23 for convenience.

The neutron source calculated for the design basis intact fuel assemblies for the MPC-24, MPC-32, MPC-68, Trojan fuel, and the design basis damaged fuel are listed in Tables 5.2.11 through 5.2.14, 5.2.35, 5.2.44, and 5.2.45 in neutrons/s. Table 5.2.17 provides the neutron source in neutrons/sec for the design basis MOX fuel assembly. ^{244}Cm accounts for approximately 96% of the total number of neutrons produced, with slightly over 2% originating from (α,n) reactions within the UO_2 fuel. The remaining 2% derive from spontaneous fission in various Pu and Cm radionuclides. In addition, any neutrons generated from subcritical multiplication, (n,2n) or similar reactions are properly accounted for in the MCNP calculation.

5.2.3 Stainless Steel Clad Fuel Source

Table 5.2.18 lists the characteristics of the design basis stainless steel clad fuel. The fuel characteristics listed in this table are the input parameters that were used in the shielding calculations described in this chapter. The active fuel length listed in the table is actually longer than the true active fuel length of 122 inches for the W15x15 and 83 inches for the A/C 10x10. Since the true active fuel length is shorter than the design basis zircaloy clad active fuel length, it would be incorrect to calculate source terms for the stainless steel fuel using the actual fuel length and compare them directly to the source terms from the zircaloy clad fuel with a longer active fuel length.

In order to eliminate the potential confusion when comparing source terms, the stainless steel clad fuel source terms were calculated with the same active fuel length as the design basis zircaloy clad fuel. Reference [5.2.3] indicates that the Cobalt-59 impurity level in steel is 800 ppm or 0.8 gm/kg and in inconel is approximately 4700 ppm or 4.7 gm/kg. In the early to mid 1980s, the fuel vendors reduced the Cobalt-59 impurity level in both inconel and steel to less than 500 ppm or 0.5 gm/kg. Prior to that, the impurity level in inconel in fuel assemblies was typically less than 1200 ppm or 1.2 gm/kg. Nevertheless, a conservative Cobalt-59 impurity level

of 0.8 gm/kg was used for the stainless steel cladding and a highly conservative impurity level of 4.7 gm/kg was used for the inconel incore spacers. It is assumed that the end fitting masses of the stainless steel clad fuel are the same as the end fittings masses of the zircaloy clad fuel. Therefore, separate source terms are not provided for the end fittings of the stainless steel fuel.

Tables 5.2.19 through 5.2.22 list the neutron and gamma source strengths for the design basis stainless steel clad fuel. The gamma source strengths include the contribution from the cobalt activation in the incore spacers. Subsection 5.4.4 presents the dose rates around the HI-STAR 100 for the normal and hypothetical accident conditions for the stainless steel fuel. In the calculation of these dose rates the length of the active fuel was conservatively assumed to be 144 inches. In addition, the fuel assembly configuration used in the MCNP calculations was identical to the configuration used for the design basis fuel assemblies as described in Table 5.3.1.

5.2.4 Non-fuel Hardware

Generic PWR non-fuel hardware is not permitted for transport in the HI-STAR 100 system. However, certain non-fuel hardware from the Trojan Nuclear plant has been analyzed and is approved for transportation. These components include rod cluster control assemblies (RCCAs), burnable poison rod assemblies (BPRAs) and thimble plug devices (TPDs). The methodology for analyzing the non-fuel hardware authorized for transportation is described below and has been previously approved in the HI-STORM 100 FSAR [5.2.9].

5.2.4.1 BPRAs and TPDs

Burnable poison rod assemblies (BPRA) and thimble plug devices (TPD) are an integral, yet removable, part of a large portion of PWR fuel. The TPDs are not used in all assemblies in a reactor core but are reused from cycle to cycle. Therefore, these devices can achieve very high burnups. In contrast, BPRAs are burned with a fuel assembly in core and are not reused. In fact, many BPRAs are removed after one or two cycles before the fuel assembly is discharged. Therefore, the achieved burnup for BPRAs is not significantly different than fuel assemblies.

TPDs are made of stainless steel and may contain a small amount of inconel. These devices extend down into the plenum region of the fuel assembly but do not extend into the active fuel region. Since these devices are made of stainless steel, there is a significant amount of cobalt-60 produced during irradiation. This is the only significant radiation source from the activation of steel and inconel.

BPRAs are made of stainless steel in the region above the active fuel zone and may contain a small amount of inconel in this region. Within the active fuel zone the BPRAs may contain 2-24 rodlets which are burnable absorbers clad in either zircaloy or stainless steel. The stainless steel clad BPRAs create a significant radiation source (Co-60) while the zircaloy clad BPRAs create a negligible radiation source. Therefore the stainless steel clad BPRAs are bounding.

SAS2H and ORIGEN-S were used to calculate a radiation source term for the Trojan TPDs and BPRAs. In the ORIGEN-S calculations the cobalt-59 impurity level was conservatively assumed to be 0.8 gm/kg for stainless steel and 4.7 gm/kg for inconel. These calculations were performed by irradiating the appropriate mass of steel and inconel using the flux calculated for the design basis Trojan 17x17 fuel assembly. The mass of material in the regions above the active fuel zone was scaled by the appropriate scaling factors listed in Table 5.2.7 in order to account for the reduced flux levels above the fuel assembly. The total curies of cobalt were calculated for the Trojan TPDs and BPRAs for the actual burnups and cooling times (the BPRAs were only used in the first cycle whereas the TPDs were used in all but the last cycle). The accumulated burnup and cooling time for the BPRAs and TPDs are 15,998 MWD/MTU and 24 years cooling and 118,674 MWD/MTU and 11 years cooling, respectively. Since the operating history of the shutdown Trojan reactor is well known the actual cycle lengths and conservatively short downtimes between cycles were used in the calculation of the source terms. In the ORIGEN-S calculations it was assumed that the burned fuel assembly was replaced with a fresh fuel assembly after every cycle. This was achieved in ORIGEN-S by resetting the flux levels and cross sections to the 0 MWD/MTU condition after every cycle.

Currently only the Trojan non-fuel hardware is permitted for transportation in the HI-STAR 100 System. The masses of the Trojan TPD and BPRA are listed in Table 5.2.36. This information was taken from references [5.2.5] and [5.2.7] and is the same information used in the Trojan FSAR [5.1.6].

Table 5.2.37 shows the curies of Co-60 that were calculated for BPRAs and TPDs in each region of the fuel assembly (e.g. incore, plenum, top). An allowable cooling time, separate from the fuel assemblies, of 24 years and 11 years is used for the Trojan BPRAs and TPDs, respectively.

Subsection 5.4.7 discusses the analysis of cask dose rates from Trojan fuel including the effect of the insertion of BPRAs or TPDs into Trojan fuel assemblies.

5.2.4.2 RCCAs

Rod cluster control assemblies (RCCAs) are an integral, yet reusable, portion of a PWR fuel assembly. These devices are utilized for many years (upwards of 20 years) prior to discharge into the spent fuel pool. The manner in which the RCCAs are utilized vary from plant to plant. Some utilities maintain the RCCAs fully withdrawn during normal operation while others may operate with a bank of rods partially inserted (approximately 10%) during normal operation. Even when fully withdrawn, the ends of the RCCAs are present in the upper portion of the fuel assembly since they are never fully removed from the fuel assembly during operation. The result of the different operating styles is a variation in the source term for the RCCAs. In all cases, however, only the lower portion of the RCCAs will be significantly activated. Therefore, when the RCCAs are stored with the PWR fuel assembly, the activated portion of the RCCAs will be in the lower portion of the cask. RCCAs are fabricated of various materials. The cladding is typically stainless steel, although inconel has been used. The absorber can be a single material or a combination of

materials. AgInCd is possibly the most common absorber although B_4C in aluminum is used, and hafnium has also been used. AgInCd produces a noticeable source term in the 0.3-1.0 MeV range due to the activation of Ag. The Trojan RCCAs, the only RCCAs currently authorized for transport, were made of AgInCd clad in stainless steel.

In order to determine the impact on the dose rates around the HI-STAR 100 System, source terms for the Trojan RCCAs were calculated using SAS2H and ORIGEN-S. In the ORIGEN-S calculations the cobalt-59 impurity level was conservatively assumed to be 0.8 gm/kg for stainless steel and 4.7 gm/kg for inconel. These calculations were performed by irradiating 1 kg of steel, inconel, and AgInCd using the flux calculated for the Trojan W 17x17 fuel assembly. The total curies of cobalt for the steel and inconel and the 0.3-1.0 MeV source for the AgInCd were calculated for a single burnup, 125,515 MWD/MTU, and cooling time, 9 years, corresponding to the lifetime operation of the Trojan reactor. Since the operating history of the shutdown Trojan reactor is well known the actual cycle lengths and conservatively short downtimes between cycles were used in the calculation of the source terms. In the ORIGEN-S calculations it was assumed that the burned fuel assembly was replaced with a fresh fuel assembly after every cycle. This was achieved in ORIGEN-S by resetting the flux levels and cross sections to the 0 MWD/MTU condition after every cycle. The sources were then scaled by the appropriate mass using the flux weighting factors for the different regions of the assembly to determine the final source term. Since the Trojan reactor normally operated with all RCCA rods fully withdrawn only one configuration was analyzed for the RCCAs. The configuration, which is summarized below, is described in Table 5.2.38 for the RCCAs. The masses of the materials listed in these tables were determined from reference [5.2.5]. The masses listed in Table 5.2.38 do not match exact values from [5.2.5] because the values in the reference were adjusted to the lengths shown in the tables.

RCCA Configuration
This configuration represents a fully removed RCCA during normal core operations. The activated portion corresponds to the upper portion of a fuel assembly above the active fuel length with the appropriate flux weighting factors used.

Table 5.2.38 presents the source terms that were calculated for the Trojan RCCAs. The only significant source from the activation of inconel or steel is Co-60 and the only significant source from the activation of AgInCd is from 0.3-1.0 MeV.

Subsection 5.4.7 discusses the analysis of cask dose rates from Trojan fuel including the effect of the insertion of RCCAs into Trojan fuel assemblies.

5.2.5 Choice of Design Basis Assembly

The analysis presented in this chapter was performed to bound the fuel assembly classes listed in Tables 1.2.8 and 1.2.9. In order to perform a bounding analysis, a design basis fuel assembly must be chosen. Therefore, a fuel assembly from each fuel class was analyzed and a comparison

of the neutrons/sec, photons/sec, and thermal power (watts) was performed. The fuel assembly which produced the highest source for a specified burnup, cooling time, and enrichment was chosen as the design basis fuel assembly. A separate design basis assembly was chosen for the PWR baskets (MPC-24 and MPC-32) and the BWR basket (MPC-68).

5.2.5.1 PWR Design Basis Assembly

Table 1.2.8 lists the PWR fuel assembly classes that were evaluated to determine the design basis PWR fuel assembly. Within each class, the fuel assembly with the highest UO_2 mass was analyzed. Since the variations of fuel assemblies within a class are very minor (pellet diameter, clad thickness, etc.), it is conservative to choose the assembly with the highest UO_2 mass. For a given class of assemblies, the one with the highest UO_2 mass will produce the highest radiation source because, for a given burnup (MWD/MTU) and enrichment, the highest UO_2 mass will have produced the most energy and therefore the most fission products.

Table 5.2.24 presents the characteristics of the fuel assemblies analyzed to determine the design basis zircaloy clad PWR fuel assembly. The fuel assembly listed for each class is the assembly with the highest UO_2 mass. The St. Lucie and Ft. Calhoun classes are not present in Table 5.2.24. These assemblies are shorter versions of the CE 16x16 and CE 14x14 assembly classes, respectively. Therefore, these assemblies are bounded by the CE 16x16 and CE 14x14 classes and were not explicitly analyzed. Since the Haddam Neck and San Onofre 1 classes are stainless steel clad fuel, these classes were analyzed separately and are discussed below. All fuel assemblies in Table 5.2.24 were analyzed at the same burnup and cooling time. The results of the comparison are provided in Table 5.2.26. These results indicate that the B&W 15x15 fuel assembly has the highest radiation source term of the zircaloy clad fuel assembly classes considered in Table 1.2.8. This fuel assembly also has the highest UO_2 mass (see Table 5.2.24) which confirms that, for a given initial enrichment, burnup, and cooling time, the assembly with the highest UO_2 mass produces the highest radiation source term.

The Haddam Neck and San Onofre 1 classes are shorter stainless steel clad versions of the WE 15x15 and WE 14x14 classes, respectively. Since these assemblies have stainless steel clad, they were analyzed separately as discussed in Subsection 5.2.3. Based on the results in Table 5.2.26, which show that the WE 15x15 assembly class has a higher source term than the WE 14x14 assembly class, the Haddam Neck, WE 15x15, fuel assembly was analyzed as the bounding PWR stainless steel clad fuel assembly.

5.2.5.2 BWR Design Basis Assembly

Table 1.2.9 lists the BWR fuel assembly classes that were evaluated to determine the design basis BWR fuel assembly. Since there are minor differences between the array types in the GE BWR/2-3 and GE BWR/4-6 assembly classes, these assembly classes were not considered individually but rather as a single class. Within that class, the array types, 7x7, 8x8, 9x9, and 10x10 were analyzed to determine the bounding BWR fuel assembly. Since the Humboldt Bay

7x7 and Dresden 1 8x8 are smaller versions of the 7x7 and 8x8 assemblies they are bounded by the 7x7 and 8x8 assemblies in the GE BWR/2-3 and GE BWR/4-6 classes. Within each array type, the fuel assembly with the highest UO_2 mass was analyzed. Since the variations of fuel assemblies within an array type are very minor, it is conservative to choose the assembly with the highest UO_2 mass. For a given array type of assemblies, the one with the highest UO_2 mass will produce the highest radiation source because, for a given burnup (MWD/MTU) and enrichment, it will have produced the most energy and therefore the most fission products. The Humboldt Bay 6x6, Dresden 1 6x6, and LaCrosse assembly classes were not considered in the determination of the bounding fuel assembly. However, these assemblies were analyzed explicitly as discussed below.

Table 5.2.25 presents the characteristics of the fuel assemblies analyzed to determine the design basis zircaloy clad BWR fuel assembly. The fuel assembly listed for each array type is the assembly that has the highest UO_2 mass. All fuel assemblies in Table 5.2.25 were analyzed at the same burnup and cooling time. The results of the comparison are provided in Table 5.2.27. These results indicate that the 7x7 fuel assembly has the highest radiation source term of the zircaloy clad fuel assembly classes considered in Table 1.2.9. This fuel assembly also has the highest UO_2 mass which confirms that, for a given initial enrichment, burnup, and cooling time, the assembly with the highest UO_2 mass produces the highest radiation source term. According to Reference [5.2.6], the last discharge of a 7x7 assembly was in 1985 and the maximum average burnup for a 7x7 during their operation was 29,000 MWD/MTU. This clearly indicates that the existing 7x7 assemblies have an average burnup and minimum cooling time that is well within the burnup and cooling time limits in Table 1.2.20. Therefore, the 7x7 assembly has never reached the burnup level analyzed in this chapter. However, in the interest of conservatism the 7x7 was chosen as the bounding fuel assembly array type.

Since the LaCrosse fuel assembly type is a stainless steel clad 10x10 assembly it was analyzed separately. The maximum burnup and minimum cooling times for this assembly are limited to 22,500 MWD/MTU and 15-year cooling as specified in Table 1.2.19. This assembly type is discussed further in Subsection 5.2.3.

The Humboldt Bay 6x6 and Dresden 1 6x6 fuel are older and shorter than the other array types analyzed and therefore are considered separately. The Dresden 1 6x6 was chosen as the design basis fuel assembly for the Humboldt Bay 6x6 and Dresden 1 6x6 fuel assembly classes because it has the higher UO_2 mass. Dresden 1 also contains a few 6x6 MOX fuel assemblies which were explicitly analyzed as well.

Reference [5.2.6] indicates that the Dresden 1 6x6 fuel assembly has a higher UO_2 mass than the Dresden 1 8x8 or the Humboldt Bay fuel (6x6 and 7x7). Therefore, the Dresden 1 6x6 fuel assembly was also chosen as the bounding assembly for damaged fuel and fuel debris for the Humboldt Bay and Dresden 1 fuel assembly classes.

Since the design basis damaged fuel assembly and the design basis intact 6x6 fuel assembly are identical, the analysis presented in Subsection 5.4.2 for the damaged fuel assembly also demonstrates the acceptability of transporting intact 6x6 fuel assemblies from the Dresden 1 and Humboldt Bay fuel assembly classes.

5.2.5.3 Decay Heat Loads

The decay heat values per assembly were calculated using the methodology described in Section 5.2. As demonstrated in Tables 5.2.26 and 5.2.27, the design basis fuel assembly produces a higher decay heat value than the other assembly types considered. This is due to the higher heavy metal mass in the design basis fuel assemblies. Conservatively, Tables 1.2.10 and 1.2.11 limit the heavy metal mass of the design basis fuel assembly classes to a value less than the design basis value utilized in this chapter. This provides additional assurance that the radiation source terms are bounding values.

As further demonstration that the decay heat values (calculated using the design basis fuel assemblies) are conservative, a comparison between these calculated decay heats and the decay heats reported in Reference [5.2.7] are presented in Table 5.2.28. This comparison is made for a burnup of 30,000 MWD/MTU and a cooling time of 5 years. The burnup was chosen based on the limited burnup data available in Reference [5.2.7].

The heavy metal mass of the non-design basis fuel assembly classes in Tables 1.2.10 and 1.2.11 are limited to the masses used in Tables 5.2.24 and 5.2.25. No margin is applied between the allowable mass and the analyzed mass of heavy metal for the non-design basis fuel assemblies. This is acceptable because additional assurance that the radiation source terms for the non-design basis fuel assemblies are bounding values is obtained by using the radiation source terms for the design basis fuel assemblies in determining the acceptable loading criteria for all fuel assemblies.

5.2.6 Thoria Rod Canister

Dresden Unit 1 has a single DFC containing 18 thoria rods which have obtained a relatively low burnup, 16,000 MWD/MTU. These rods were removed from two 8x8 fuel assemblies which contained 9 rods each. The irradiation of thorium produces an isotope which is not commonly found in depleted uranium fuel. Th-232 when irradiated produces U-233. The U-233 can undergo an (n,2n) reaction which produces U-232. The U-232 decays to produce Tl-208 which produces a 2.6 MeV gamma during Beta decay. This results in a significant source in the 2.5-3.0 MeV range which is not commonly present in depleted uranium fuel. Therefore, this single DFC container was analyzed to determine if it was bounded by the current shielding analysis.

A radiation source term was calculated for the 18 thoria rods using SAS2H and ORIGEN-S for a burnup of 16,000 MWD/MTU and a cooling time of 18 years. Table 5.2.29 describes the 8x8 fuel assembly that contains the thoria rods. Table 5.2.30 and 5.2.31 show the gamma and neutron source terms, respectively, that were calculated for the 18 thoria rods in the thoria rod canister.

Comparing these source terms to the design basis 6x6 source terms for Dresden Unit 1 fuel in Tables 5.2.6 and 5.2.14 clearly indicates that the design basis source terms bound the thoria rods source terms in all neutron groups and in all gamma groups except the 2.5-3.0 MeV group. As mentioned above, the thoria rods have a significant source in this energy range due to the decay of Tl-208.

Subsection 5.4.6 provides a further discussion of the thoria rod canister and its acceptability for transport in the HI-STAR 100 System.

5.2.7 Fuel Assembly Neutron Sources

Neutron sources are used in reactors during initial startup of reactor cores. There are different types of neutron sources (e.g. californium, americium-beryllium, plutonium-beryllium, antimony-beryllium). These neutron sources are typically inserted into the water rod of a fuel assembly and are usually removable.

Currently the only neutron source permitted for transport in the HI-STAR 100 System are from Dresden Unit 1 and Trojan Nuclear Plant as discussed below.

5.2.7.1 Dresden Unit 1 Neutron Source Assemblies

Dresden Unit 1 has a few antimony-beryllium neutron sources. These sources have been analyzed in Subsection 5.4.5 to demonstrate that they are acceptable for transport in the HI-STAR 100 System.

5.2.7.2 Trojan Nuclear Plant Neutron Source Assemblies

Trojan Nuclear Power has two primary (californium) neutron source assemblies and four secondary (antimony-beryllium) neutron source assemblies. The neutron source assemblies are basically BPRAs with the source material placed in a few of the rods instead of burnable absorber. In the case of the californium source, a single rod contained a nominally 1.5 inch long californium capsule while the remaining locations consisted of 19 burnable poison rods and 4 thimble plug rods. The initial source strength of the primary sources were approximately 6.0E+8 neutrons/sec. Since these devices were delivered prior to startup, they have realized more than 24 years of decay time. Based on the half-life of Cf-252 (2.65 years), the neutron source strength of these devices would be less than 1.2E+6 neutrons/sec after 24 years of decay time. Therefore, the neutron contribution from these devices is negligible and is not considered in the analysis in this chapter. Since these devices are clad in stainless steel, there is the potential for significant Co-60 activation from in-core activation of the cladding material. The primary sources were only operated during the first cycle of the Trojan nuclear plant and as a result achieved a burnup of 15,998 MWD/MTU and have a cooling time of more than 24 years. This burnup and cooling time is identical to the burnup and cooling time for the Trojan BPRAs as discussed in

Subsection 5.2.4.1. Therefore, the primary sources are not explicitly considered in this analysis but are bounded by the analysis of the BPRAs.

The Trojan Nuclear Plant secondary neutron source assemblies used 4 rods for the antimony-beryllium source and the remaining rods were either burnable poison rods or thimble plug rods. The 4 source rods in a secondary neutron source assembly each contained 88 inches of antimony-beryllium. Since the antimony-beryllium neutron sources are regenerative sources they will be producing a steady state level of neutrons while in the MPC. This production of neutrons has been explicitly analyzed in Subsection 5.4.8. In addition to the neutron source from the secondary sources, there will be a substantial Co-60 source from the activation of the stainless steel cladding. There are two different levels of activation since the first two source assemblies were used in-core for cycles 1-4 and the latter two source assemblies were used in-core for cycles 4-14. The operating history for these devices results in a burnup of 45,361 MWD/MTU and a cooling time of 19 years for the source assemblies that operated in the first four cycles. The burnup and cooling time for the other two source assemblies is 88,547 MWD/MTU and 9 years. In addition to the difference in the burnup and cooling times between the two sets of secondary source assemblies, the number of burnable poison rods and thimble plug rods is different. The two source assemblies used in Cycles 1-4 each contained 4 source rods, 16 burnable poison rods and 4 thimble plug rods. The two source assemblies used in Cycles 4-14 each contained 4 source rods and 20 thimble plug rods. Table 5.2.39 shows the physical description of these devices that was used in the source term calculation and the resultant Co-60 source term in each region. Subsection 5.4.8 discusses the effect of the secondary source assemblies on the calculated dose rates and demonstrates that these devices are acceptable for transport.

5.2.8 Trojan Non-Fuel Bearing Components, Damaged Fuel and Fuel Debris

Trojan Nuclear Power has failed fuel cans containing fuel process can capsules and fuel debris. The fuel process can capsules contain only a limited amount of fuel in the form of fuel debris (metal fragments). The source term from the fuel process can capsules is therefore bounded by the source from a fuel assembly.

The fuel assemblies classified as fuel debris consist of a few assemblies with each containing a maximum of 17 rods. There is also a single damaged fuel container that has 23 individual rods not bound in a fuel assembly configuration. If it is assumed that the 23 individual rods are from a design basis Trojan fuel assembly and have not collapsed, then the source strength per inch of active fuel is a small fraction (23 rods/264 rods in an intact assembly) of the source in an intact assembly. If it is assumed that the source strength per rod is "A" then the source per inch in an intact assembly is 264A/144=1.833A. The damaged fuel assembly with 23 rods would have to collapse from 144 inches in height to 12.5 inches (height = 23A/1.833A) in order for the source strength per unit inch in the collapsed assembly to be equivalent to the source strength per unit inch in an intact assembly. Further collapse would increase the source strength per inch beyond

that of a design basis assembly but it is not considered likely that this would occur. Therefore, even in a collapsed state which might exist after a transport accident, this fuel debris is bounded by an intact fuel assembly and therefore is not explicitly considered in the analysis in this chapter.

There are also a couple of fuel assemblies classified as damaged fuel because of missing rods. These assemblies are also bounded by an intact assembly and during the transport accident it is expected that these damaged assemblies would react the same as intact assemblies. Therefore, the Trojan damaged fuel assemblies were not explicitly considered in the analysis in this chapter.

Trojan fuel assembly hardware, non-fuel bearing components and one fuel skeleton will also be transported. These components are made of stainless steel, zircaloy and inconel. The source term from these additional components were not explicitly considered but are bounded by intact fuel assemblies. Therefore, the source term from these components were not explicitly considered.

Table 5.2.1

DESCRIPTION OF DESIGN BASIS INTACT ZIRCALOY CLAD FUEL

	PWR	BWR
Assembly type/class	B&W 15×15	GE 7×7
Active fuel length (in.)	144	144
No. of fuel rods	208	49
Rod pitch (in.)	0.568	0.738
Cladding material	zircaloy-4	zircaloy-2
Rod diameter (in.)	0.428	0.570
Cladding thickness (in.)	0.0230	0.0355
Pellet diameter (in.)	0.3742	0.488
Pellet material	UO_2	UO_2
Pellet density (gm/cc)	10.412 (95% of theoretical)	10.412 (95% of theoretical)
Enrichment (w/o ^{235}U)	See Tables 1.2.28, 1.2.29, 1.2.32, 1.2.33	See Table 1.2.31
Burnup (MWD/MTU)	See Table 1.2.28, 1.2.29, 1.2.32, 1.2.33	See Table 1.2.31
Cooling Time (years)	See Table 1.2.28, 1.2.29, 1.2.32, 1.2.33	See Table 1.2.31
Specific power (MW/MTU)	40	30
Weight of UO_2 (kg)†	562.029	225.177
Weight of U (kg)†	495.485	198.516

Notes:
1. The B&W 15x15 is the design basis assembly for the following fuel assembly classes listed in Table 1.2.8: B&W 15x15, B&W 17x17, CE 14x14, CE 16x16, WE 14x14, WE 15x15, WE 17x17, St. Lucie, and Ft. Calhoun.
2. The GE 7x7 is the design basis assembly for the following fuel assembly classes listed in Table 1.2.9: GE BWR/2-3, GE BWR/4-6, Humboldt Bay 7x7, and Dresden 1 8x8.

† Derived from parameters in this table.

Table 5.2.1 (continued)

DESCRIPTION OF DESIGN BASIS INTACT ZIRCALOY CLAD FUEL

	PWR	BWR
No. of Water Rods/Guide Tubes	17	0
Water Rod O.D. (in.)	0.53	N/A
Water Rod Thickness (in.)	0.0160	N/A
Lower End Fitting (kg)	8.16 (steel) 1.3 (inconel)	4.8 (steel)
Gas Plenum Springs (kg)	0.48428 (inconel) 0.23748 (steel)	1.1 (steel)
Gas Plenum Spacer (kg)	0.55572 (inconel) 0.27252 (steel)	N/A
Expansion Springs (kg)	N/A	0.4 (steel)
Upper End Fitting (kg)	9.28 (steel)	2.0 (steel)
Handle (kg)	N/A	0.5 (steel)
Incore Grid Spacers (kg)	4.9 (inconel)†	0.33 (inconel springs)

† This mass of inconel was used for fuel assemblies with non-zircaloy grid spacers. For fuel assemblies with zircaloy grid spacers the mass was 0.0. However, the mass of the inconel and steel in the other assembly components are identical for assemblies with zircaloy and non-zircaloy incore grid spacers.

Table 5.2.2

DESCRIPTION OF DESIGN BASIS DAMAGED ZIRCALOY CLAD FUEL

	BWR
Fuel type	GE 6x6
Active fuel length (in.)	110
No. of fuel rods	36
Rod pitch (in.)	0.694
Cladding material	zircaloy-2
Rod diameter (in.)	0.5645
Cladding thickness (in.)	0.035
Pellet diameter (in.)	0.494
Pellet material	UO_2
Pellet density (gm/cc)	10.412 (95% of theoretical)
Enrichment (w/o ^{235}U)	1.8
Burnup (MWD/MTU)	30,000
Cooling Time (years)	18
Specific power (MW/MTU)	16.5
Weight of UO_2 (kg)†	129.5
Weight of U (kg)†	114.2
Incore spacers (kg inconel)	1.07

Notes:
1. The 6x6 is the design basis damaged fuel assembly for the Humboldt Bay (all array types) and the Dresden 1 (all array types) damaged fuel assembly classes. It is also the design basis fuel assembly for the intact Humboldt Bay 6x6 and Dresden 1 6x6 fuel assembly classes.
2. This design basis damaged fuel assembly is also the design basis fuel assembly for fuel debris.

† Derived from parameters in this table.

Table 5.2.3

CALCULATED MPC-24 PWR FUEL GAMMA SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy	**Upper Energy**	**24,500 MWD/MTU 9 Year Cooling**		**29,500 MWD/MTU 11 Year Cooling**		**34,500 MWD/MTU 13 Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)
0.45	0.7	7.61E+14	1.32E+15	8.35E+14	1.45E+15	9.05E+14	1.57E+15
0.7	1.0	8.94E+13	1.05E+14	6.95E+13	8.18E+13	5.54E+13	6.52E+13
1.0	1.5	3.29E+13	2.63E+13	3.33E+13	2.67E+13	3.41E+13	2.73E+13
1.5	2.0	1.70E+12	9.74E+11	1.73E+12	9.91E+11	1.84E+12	1.05E+12
2.0	2.5	2.19E+11	9.71E+10	5.49E+10	2.44E+10	1.89E+10	8.40E+09
2.5	3.0	1.32E+10	4.81E+09	4.06E+09	1.47E+09	1.49E+09	5.42E+08
Totals		8.85E+14	1.46E+15	9.39E+14	1.56E+15	9.96E+14	1.67E+15
Lower Energy	**Upper Energy**	**39,500 MWD/MTU 15 Year Cooling**		**44,500 MWD/MTU 18 Year Cooling**			
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)		
0.45	0.7	9.70E+14	1.69E+15	1.00E+15	1.74E+15		
0.7	1.0	4.49E+13	5.28E+13	3.32E+13	3.90E+13		
1.0	1.5	3.39E+13	2.71E+13	3.07E+13	2.46E+13		
1.5	2.0	1.89E+12	1.08E+12	1.78E+12	1.02E+12		
2.0	2.5	1.11E+10	4.92E+09	9.00E+09	4.00E+09		
2.5	3.0	8.82E+08	3.21E+08	8.14E+08	2.96E+08		
Totals		1.05E+15	1.77E+15	1.07E+15	1.81E+15		

Table 5.2.4

CALCULATED MPC-24 PWR FUEL GAMMA SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy	Upper Energy	24,500 MWD/MTU 6 Year Cooling		29,500 MWD/MTU 7 Year Cooling		34,500 MWD/MTU 9 Year Cooling	
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)
0.45	0.7	9.60E+14	1.67E+15	1.06E+15	1.85E+15	1.08E+15	1.88E+15
0.7	1.0	2.17E+14	2.55E+14	2.09E+14	2.46E+14	1.48E+14	1.74E+14
1.0	1.5	5.67E+13	4.54E+13	5.96E+13	4.77E+13	5.44E+13	4.35E+13
1.5	2.0	3.71E+12	2.12E+12	3.24E+12	1.85E+12	2.70E+12	1.54E+12
2.0	2.5	2.48E+12	1.10E+12	1.19E+12	5.27E+11	2.57E+11	1.14E+11
2.5	3.0	1.02E+11	3.70E+10	5.83E+10	2.12E+10	1.67E+10	6.08E+09
Totals		1.24E+15	1.97E+15	1.33E+15	2.14E+15	1.29E+15	2.10E+15
Lower Energy	**Upper Energy**	**39,500 MWD/MTU11 Year Cooling**		**44,500 MWD/MTU14 Year Cooling**			
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)		
0.45	0.7	1.12E+15	1.94E+15	1.12E+15	1.95E+15		
0.7	1.0	1.05E+14	1.24E+14	6.36E+13	7.48E+13		
1.0	1.5	5.06E+13	4.05E+13	4.35E+13	3.48E+13		
1.5	2.0	2.58E+12	1.47E+12	2.37E+12	1.35E+12		
2.0	2.5	6.36E+10	2.83E+10	1.55E+10	6.89E+09		
2.5	3.0	5.07E+09	1.84E+09	1.41E+09	5.12E+08		
Totals		1.28E+15	2.11E+15	1.23E+15	2.06E+15		

Table 5.2.5

CALCULATED MPC-68 BWR FUEL GAMMA SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy	**Upper Energy**	**24,500 MWD/MTU 8 Year Cooling**		**29,500 MWD/MTU 9 Year Cooling**		**34,500 MWD/MTU 11 Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)
0.45	0.7	3.21E+14	5.57E+14	3.64E+14	6.34E+14	3.87E+14	6.73E+14
0.7	1.0	4.54E+13	5.34E+13	4.46E+13	5.25E+13	3.31E+13	3.89E+13
1.0	1.5	1.46E+13	1.17E+13	1.63E+13	1.30E+13	1.57E+13	1.26E+13
1.5	2.0	7.68E+11	4.39E+11	8.20E+11	4.69E+11	8.10E+11	4.63E+11
2.0	2.5	1.65E+11	7.34E+10	8.09E+10	3.60E+10	2.05E+10	9.10E+09
2.5	3.0	9.32E+09	3.39E+09	5.31E+09	1.93E+09	1.62E+09	5.91E+08
Total		3.82E+14	6.23E+14	4.26E+14	7.00E+14	4.36E+14	7.25E+14
Lower Energy	**Upper Energy**	**39,500 MWD/MTU14 Year Cooling**		**44,500 MWD/MTU 19 Year Cooling**			
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)		
0.45	0.7	3.96E+14	6.89E+14	3.87E+14	6.73E+14		
0.7	1.0	2.03E+13	2.39E+13	1.09E+13	1.28E+13		
1.0	1.5	1.38E+13	1.10E+13	1.05E+13	8.38E+12		
1.5	2.0	7.59E+11	4.34E+11	6.17E+11	3.53E+11		
2.0	2.5	5.27E+09	2.34E+09	3.33E+09	1.48E+09		
2.5	3.0	4.16E+08	1.51E+08	2.84E+08	1.03E+08		
Total		4.31E+14	7.24E+14	4.09E+14	6.95E+14		

Table 5.2.6

CALCULATED MPC-68 and MPC-68F BWR FUEL GAMMA SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD DAMAGED FUEL

Lower Energy	**Upper Energy**	**30,000 MWD/MTU 18 Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)
0.45	0.7	1.52E+14	2.65E+14
0.7	1.0	4.07E+12	4.79E+12
1.0	1.5	3.80E+12	3.04E+12
1.5	2.0	2.24E+11	1.28E+11
2.0	2.5	1.26E+9	5.58E+8
2.5	3.0	7.42E+7	2.70E+7
Totals		1.61E+14	2.73E+14

Table 5.2.7

SCALING FACTORS USED IN CALCULATING THE ^{60}Co SOURCE

Region	PWR	BWR
Handle	N/A	0.05
Top end fitting	0.1	0.1
Gas plenum spacer	0.1	N/A
Expansion springs	N/A	0.1
Gas plenum springs	0.2	0.2
Grid spacer spring	N/A	1.0
Bottom end fitting	0.2	0.15

Table 5.2.8

CALCULATED MPC-24 ^{60}Co SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS AT VARYING BURNUPS AND COOLING TIMES

Location	**24,500 MWD/MTU 9 Year Cooling (curies)**	**29,500 MWD/MTU 11 Year Cooling (curies)**	**34,500 MWD/MTU 13 Year Cooling (curies)**	**39,500 MWD/MTU 15 Year Cooling (curies)**	**44,500 MWD/MTU 18 Year Cooling (curies)**
Lower end fitting	95.83	81.89	68.71	56.79	41.33
Gas plenum springs	18.64	15.93	13.37	11.05	8.04
Gas plenum spacer	10.70	9.14	7.67	6.34	4.61
Expansion springs	N/A	N/A	N/A	N/A	N/A
Grid spacers	870.53	743.87	624.11	515.87	375.39
Upper end fitting	35.08	29.97	25.15	20.79	15.13
Handle	N/A	N/A	N/A	N/A	N/A

Table 5.2.9

CALCULATED MPC-24 ^{60}Co SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS AT VARYING BURNUPS AND COOLING TIMES

Location	24,500 MWD/MTU 6 Year Cooling (curies)	29,500 MWD/MTU 7 Year Cooling (curies)	34,500 MWD/MTU 9 Year Cooling (curies)	39,500 MWD/MTU 11 Year Cooling (curies)	44,500 MWD/MTU 14 Year Cooling (curies)
Lower end fitting	142.23	138.68	116.12	96.09	69.72
Gas plenum springs	27.67	26.98	22.59	18.69	13.56
Gas plenum spacer	15.88	15.48	12.96	10.73	7.78
Expansion springs	N/A	N/A	N/A	N/A	N/A
Grid spacers†	N/A	N/A	N/A	N/A	N/A
Upper end fitting	52.06	50.76	42.50	35.17	25.52
Handle	N/A	N/A	N/A	N/A	N/A

† These burnup and cooling times represent fuel with zircaloy grid spacers. Therefore, the cobalt activation is negligible.

Table 5.2.10

CALCULATED MPC-68 ^{60}CO SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL AT VARYING BURNUPS AND COOLING TIMES

Location	24,500 MWD/MTU 8 Year Cooling (curies)	29,500 MWD/MTU 9 Year Cooling (curies)	34,500 MWD/MTU 11 Year Cooling (curies)	39,500 MWD/MTU 14 Year Cooling (curies)	44,500 MWD/MTU 19 Year Cooling (curies)
Lower end fitting	34.04	30.55	27.49	19.64	11.08
Gas plenum springs	10.40	9.33	8.40	6.00	3.39
Gas plenum spacer	N/A	N/A	N/A	N/A	N/A
Expansion springs	1.89	1.70	1.53	1.09	0.62
Grid spacers	73.32	65.80	59.22	42.30	23.88
Upper end fitting	9.45	8.48	7.64	5.45	3.08
Handle	1.18	1.06	0.95	0.68	0.38

Table 5.2.11

CALCULATED MPC-24 PWR NEUTRON SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy (MeV)	Upper Energy (MeV)	24,500 MWD/MTU 9 Year Cooling (Neutrons/s)	29,500 MWD/MTU 11 Year Cooling (Neutrons/s)	34,500 MWD/MTU 13 Year Cooling (Neutrons/s)	39,500 MWD/MTU 15 Year Cooling (Neutrons/s)	44,500 MWD/MTU 18 Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	2.50E+06	4.04E+06	6.01E+06	8.09E+06	1.05E+07
4.0E-01	9.0E-01	1.28E+07	2.06E+07	3.07E+07	4.13E+07	5.35E+07
9.0E-01	1.4	1.18E+07	1.90E+07	2.82E+07	3.79E+07	4.91E+07
1.4	1.85	8.77E+06	1.41E+07	2.09E+07	2.81E+07	3.63E+07
1.85	3.0	1.58E+07	2.52E+07	3.73E+07	5.00E+07	6.47E+07
3.0	6.43	1.40E+07	2.25E+07	3.35E+07	4.50E+07	5.82E+07
6.43	20.0	1.23E+06	1.98E+06	2.94E+06	3.96E+06	5.13E+06
TOTALS		6.69E+07	1.07E+08	1.60E+08	2.14E+08	2.77E+08

Table 5.2.12

CALCULATED MPC-24 PWR NEUTRON SOURCE PER ASSEMBLY
FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY
INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy (MeV)	Upper Energy (MeV)	24,500 MWD/MTU 6 Year Cooling (Neutrons/s)	29,500 MWD/MTU 7 Year Cooling (Neutrons/s)	34,500 MWD/MTU 9 Year Cooling (Neutrons/s)	39,500 MWD/MTU 11 Year Cooling (Neutrons/s)	44,500 MWD/MTU 14 Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	2.80E+06	4.69E+06	6.98E+06	9.40E+06	1.22E+07
4.0E-01	9.0E-01	1.43E+07	2.40E+07	3.57E+07	4.80E+07	6.22E+07
9.0E-01	1.4	1.32E+07	2.20E+07	3.27E+07	4.40E+07	5.70E+07
1.4	1.85	9.76E+06	1.63E+07	2.42E+07	3.26E+07	4.21E+07
1.85	3.0	1.75E+07	2.90E+07	4.30E+07	5.78E+07	7.47E+07
3.0	6.43	1.56E+07	2.61E+07	3.88E+07	5.22E+07	6.75E+07
6.43	20.0	1.37E+06	2.29E+06	3.42E+06	4.60E+06	5.96E+06
TOTALS		7.45E+07	1.24E+08	1.85E+08	2.49E+08	3.22E+08

Table 5.2.13

CALCULATED MPC-68 BWR NEUTRON SOURCE PER ASSEMBLY
FOR DESIGN BASIS ZIRCALOY CLAD FUEL
FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy (MeV)	Upper Energy (MeV)	24,500 MWD/MTU 8 Year Cooling (Neutrons/s)	29,500 MWD/MTU 9 Year Cooling (Neutrons/s)	34,500 MWD/MTU 11 Year Cooling (Neutrons/s)	39,500 MWD/MTU 14 Year Cooling (Neutrons/s)	44,500 MWD/MTU 19 Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	1.08E+06	1.81E+06	2.80E+06	3.61E+06	4.57E+06
4.0E-01	9.0E-01	5.52E+06	9.23E+06	1.43E+07	1.84E+07	2.33E+07
9.0E-01	1.4	5.08E+06	8.47E+06	1.31E+07	1.69E+07	2.14E+07
1.4	1.85	3.77E+06	6.27E+06	9.71E+06	1.25E+07	1.58E+07
1.85	3.0	6.75E+06	1.12E+07	1.73E+07	2.22E+07	2.80E+07
3.0	6.43	6.04E+06	1.01E+07	1.56E+07	2.00E+07	2.53E+07
6.43	20.0	5.29E+05	8.84E+05	1.37E+06	1.77E+06	2.24E+06
TOTALS		2.88E+07	4.79E+07	7.42E+07	9.54E+07	1.21E+08

Table 5.2.14

CALCULATED MPC-68 and MPC-68F BWR NEUTRON SOURCE PER ASSEMBLY FOR DESIGN BASIS DAMAGED ZIRCALOY CLAD FUEL

Lower Energy (MeV)	Upper Energy (MeV)	30,000 MWD/MTU 18 Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	1.18E+6
4.0E-01	9.0E-01	6.05E+6
9.0E-01	1.4	5.55E+6
1.4	1.85	4.11E+6
1.85	3.0	7.34E+6
3.0	6.43	6.59E+6
6.43	20.0	5.79E+5
Totals		3.14E+7

Table 5.2.15

DESCRIPTION OF DESIGN BASIS ZIRCALOY CLAD MIXED OXIDE FUEL

	BWR
Fuel type	GE 6x6
Active fuel length (in.)	110
No. of fuel rods	36
Rod pitch (in.)	0.696
Cladding material	zircaloy-2
Rod diameter (in.)	0.5645
Cladding thickness (in.)	0.036
Pellet diameter (in.)	0.482
Pellet material	UO_2 and $PuUO_2$
No. of UO_2 Rods	27
No. of $PuUO_2$ Rods	9
Pellet density (gm/cc)	10.412 (95% of theoretical)
Enrichment (w/o ^{235}U)†	1.8 (UO_2 rods) 0.711 ($PuUO_2$ rods)
Burnup (MWD/MTU)	30,000
Cooling Time (years)	18
Specific power (MW/MTU)	16.5
Weight of UO_2, $PuUO_2$ (kg)††	123.3
Weight of U,Pu (kg)††	108.7
Incore spacers (kg inconel)	1.07

† See Table 5.3.3 for detailed composition of $PuUO_2$ rods.

†† Derived from parameters in this table.

Table 5.2.16

CALCULATED MPC-68 BWR FUEL GAMMA SOURCE PER ASSEMBLY
FOR DESIGN BASIS ZIRCALOY CLAD MIXED OXIDE FUEL

Lower Energy	**Upper Energy**	**30,000 MWD/MTU 18-Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)
0.45	0.7	1.45E+14	2.52E+14
0.7	1.0	3.95E+12	4.65E+12
1.0	1.5	3.82E+12	3.06E+12
1.5	2.0	2.22E+11	1.27E+11
2.0	2.5	1.11E+9	4.93E+8
2.5	3.0	9.31E+7	3.39E+7
Totals		1.53E+14	2.60E+14

Table 5.2.17

CALCULATED MPC-68 BWR NEUTRON SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD MIXED OXIDE FUEL

Lower Energy (MeV)	Upper Energy (MeV)	30,000 MWD/MTU 18-Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	1.50E+6
4.0E-01	9.0E-01	7.67E+6
9.0E-01	1.4	7.09E+6
1.4	1.85	5.31E+6
1.85	3.0	9.67E+6
3.0	6.43	8.47E+6
6.43	20.0	7.33E+5
Totals		4.04E+7

Table 5.2.18
DESCRIPTION OF DESIGN BASIS INTACT STAINLESS STEEL CLAD FUEL

	PWR	BWR
Fuel type	WE 15x15	A/C 10x10
Active fuel length (in.)	144	144
No. of fuel rods	204	100
Rod pitch (in.)	0.563	0.565
Cladding material	304 SS	348H SS
Rod diameter (in.)	0.422	0.396
Cladding thickness (in.)	0.0165	0.02
Pellet diameter (in.)	0.3825	0.35
Pellet material	UO_2	UO_2
Pellet density (gm/cc)	10.412 (95% of theoretical)	10.412 (95% of theoretical)
Enrichment (w/o ^{235}U)	3.1	3.5
Burnup (MWD/MTU)	30,000 @ 19 yr (MPC-24) 40,000 @ 24 yr (MPC-24)	22,500 (MPC-68)
Cooling Time (years)	19 (MPC-24) 24 (MPC-24)	16 (MPC-68)
Specific power (MW/MTU)	37.96	29.17
No. of Water Rods	21	0
Water Rod O.D. (in.)	0.546	N/A
Water Rod Thickness (in.)	0.017	N/A
Incore spacers (kg inconel)	5.1	0.83

Notes:

1. The WE 15x15 is the design basis assembly for the following fuel assembly classes listed in Table 1.2.8: Indian Point, Haddam Neck and San Onofre 1.
2. The A/C 10x10 is the design basis assembly for the following fuel assembly class listed in Table 1.2.9: LaCrosse.

Table 5.2.19

CALCULATED BWR FUEL GAMMA SOURCE PER ASSEMBLY
FOR STAINLESS STEEL CLAD FUEL

Lower Energy	Upper Energy	22,500 MWD/MTU 16-Year Cooling	
(MeV)	(MeV)	(MeV/s)	(Photons/s)
0.45	0.7	2.26E+14	3.94E+14
0.7	1.0	6.02E+12	7.08E+12
1.0	1.5	4.04E+13	3.23E+13
1.5	2.0	2.90E+11	1.66E+11
2.0	2.5	2.94E+9	1.31E+9
2.5	3.0	7.77E+7	2.83E+7
Totals		2.73E+14	4.33E+14

Note:

1. These source terms were calculated for a 144 inch active fuel length. The actual active fuel length is 83 inches.
2. The ^{60}Co activation from incore spacers is included in the 1.0-1.5 MeV energy group.

Table 5.2.20

CALCULATED PWR FUEL GAMMA SOURCE PER ASSEMBLY
FOR STAINLESS STEEL CLAD FUEL

Lower Energy	**Upper Energy**	**30,000 MWD/MTU 19-Year Cooling**		**40,000 MWD/MTU 24-Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)
0.45	0.7	6.81E+14	1.18E+15	7.97E+14	1.39E+15
0.7	1.0	1.83E+13	2.16E+13	1.70E+13	2.01E+13
1.0	1.5	1.13E+14	9.06E+13	8.24E+13	6.60E+13
1.5	2.0	1.06E+12	6.04E+11	1.12E+12	6.42E+11
2.0	2.5	7.25E+9	3.22E+9	7.42E+9	3.30E+9
2.5	3.0	3.52E+8	1.28E+8	6.43E+8	2.34E+8
Totals		8.14E+14	1.30E+15	8.98E+14	1.47E+15

Note:
1. These source terms were calculated for a 144 inch active fuel length. The actual active fuel length is 122 inches.
2. The ^{60}Co activation from incore spacers is included in the 1.0-1.5 MeV energy group.

Table 5.2.21

CALCULATED BWR NEUTRON SOURCE PER ASSEMBLY
FOR STAINLESS STEEL CLAD FUEL

Lower Energy (MeV)	Upper Energy (MeV)	22,500 MWD/MTU 16-Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	1.81E+5
4.0E-01	9.0E-01	9.26E+5
9.0E-01	1.4	8.75E+5
1.4	1.85	6.85E+5
1.85	3.0	1.34E+6
3.0	6.43	1.08E+6
6.43	20.0	8.77E+4
Total		5.18E+6

Note:
These source terms were calculated for a 144 inch active fuel length. The actual active fuel length is 83 inches.

Table 5.2.22

CALCULATED PWR NEUTRON SOURCE PER ASSEMBLY
FOR STAINLESS STEEL CLAD FUEL

Lower Energy (MeV)	**Upper Energy (MeV)**	**30,000 MWD/MTU 19-Year Cooling (Neutrons/s)**	**40,000 MWD/MTU 24-Year Cooling (Neutrons/s)**
1.0E-01	4.0E-01	2.68E+6	7.07E+6
4.0E-01	9.0E-01	1.37E+7	3.61E+7
9.0E-01	1.4	1.27E+7	3.32E+7
1.4	1.85	9.50E+6	2.47E+7
1.85	3.0	1.74E+7	4.43E+7
3.0	6.43	1.52E+7	3.95E+7
6.43	20.0	1.31E+6	3.46E+6
Totals		7.24E+7	1.88E+8

Note:
These source terms were calculated for a 144 inch active fuel length. The actual active fuel length is 122 inches.

Table 5.2.23

MINIMUM ENRICHMENTS AS A FUNCTION OF BURNUP FOR THE SHIELDING ANALYSIS

Minimum Enrichment (wt.% ^{235}U)	Maximum Burnup Analyzed (MWD/MTU)	
PWR assemblies with non-zircaloy incore spacers	MPC-24	MPC-32
2.3	24,500	24,500
2.6	29,500	29,500
2.9	34,500	34,500
3.2	39,500	39,500
3.4	44,500	42,500
PWR assemblies with zircaloy incore spacers	MPC-24	MPC-32
2.3	24,500	24,500
2.6	29,500	29,500
2.9	34,500	34,500
3.2	39,500	39,500
3.4	44,500	44,500
MPC-68		
2.1	24,500	
2.4	29,500	
2.6	34,500	
2.9	39,500	
3.0	44,500	

Table 5.2.24

DESCRIPTION OF EVALUATED INTACT ZIRCALOY CLAD PWR FUEL

Assembly class	WE 14×14	WE 15×15	WE 17×17	CE 14×14	CE 16×16	B&W 15×15	B&W 17×17
Active fuel length (in.)	144	144	144	144	150	144	144
No. of fuel rods	179	204	264	176	236	208	264
Rod pitch (in.)	0.556	0.563	0.496	0.580	0.5063	0.568	0.502
Cladding material	Zr-4	Zr-4	Zr-4	Zr-4	Zr-4	Zr-4	Zr-4
Rod diameter (in.)	0.422	0.422	0.374	0.440	0.382	0.428	0.377
Cladding thickness (in.)	0.0243	0.0245	0.0225	0.0280	0.0250	0.0230	0.0220
Pellet diameter (in.)	0.3659	0.366	0.3225	0.377	0.3255	0.3742	0.3252
Pellet material	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2
Pellet density (gm/cc) (95% of theoretical)	10.412	10.412	10.412	10.412	10.412	10.412	10.412
Enrichment (wt.% ^{235}U)	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Burnup (MWD/MTU)	40,000	40,000	40,000	40,000	40,000	40,000	40,000
Cooling time (years)	5	5	5	5	5	5	5
Specific power (MW/MTU)	40	40	40	40	40	40	40
Weight of UO_2 (kg)†	462.451	527.327	529.848	482.706	502.609	562.029	538.757
Weight of U (kg)†	407.697	464.891	467.114	425.554	443.100	495.485	474.968
No. of Guide Tubes	17	21	25	5	5	17	25
Guide Tube O.D. (in.)	0.539	0.546	0.474	1.115	0.98	0.53	0.564
Guide Tube Thickness (in.)	0.0170	0.0170	0.0160	0.0400	0.0400	0.0160	0.0175

† Derived from parameters in this table.

Table 5.2.25

DESCRIPTION OF EVALUATED INTACT ZIRCALOY CLAD BWR FUEL

Array Type	7×7	8×8	9×9	10×10
Active fuel length (in.)	144	144	144	144
No. of fuel rods	49	63	74	92
Rod pitch (in.)	0.738	0.640	0.566	0.510
Cladding material	Zr-2	Zr-2	Zr-2	Zr-2
Rod diameter (in.)	0.570	0.493	0.440	0.404
Cladding thickness (in.)	0.0355	0.0340	0.0280	0.0260
Pellet diameter (in.)	0.488	0.416	0.376	0.345
Pellet material	UO_2	UO_2	UO_2	UO_2
Pellet density (gm/cc) (95% of theoretical)	10.412	10.412	10.412	10.412
Enrichment (wt.% ^{235}U)	3.0	3.0	3.0	3.0
Burnup (MWD/MTU)	40,000	40,000	40,000	40,000
Cooling time (years)	5	5	5	5
Specific power (MW/MTU)	30	30	30	30
Weight of UO_2 (kg)†	225.177	210.385	201.881	211.307
Weight of U (kg)†	198.516	185.475	177.978	186.288
No. of Water Rods	0	1	2	2
Water Rod O.D. (in.)	n/a	0.493	0.980	0.980
Water Rod Thickness (in.)	n/a	0.0340	0.0300	0.0300

† Derived from parameters in this table.

Table 5.2.26

COMPARISON OF SOURCE TERMS FOR INTACT ZIRCALOY CLAD PWR FUEL
3.4 wt.% ^{235}U - 40,000 MWD/MTU - 5 years cooling

Assembly class	WE 14×14	WE 15×15	WE 17×17	CE 14×14	CE 16×16	B&W 15×15	B&W 17×17
Neutrons/sec	2.29E+8 / 2.31E+8	2.63E+8 / 2.65E+8	2.62E+8	2.31E+8	2.34E+8	2.94E+8	2.64E+8
Photons/sec (0.45-3.0 MeV)	3.28E+15/ 3.33E+15	3.74E+15/ 3.79E+15	3.76E+15	3.39E+15	3.54E+15	4.01E+15	3.82E+15
Thermal power (watts)	926.6 / 936.8	1056 / 1068	1062	956.6	995.7	1137	1077

Note:
The WE 14x14 and WE 15x15 have both zircaloy and stainless steel guide tubes. The first value presented is for the assembly with zircaloy guide tubes and the second value is for the assembly with stainless steel guide tubes.

Table 5.2.27

COMPARISON OF SOURCE TERMS FOR INTACT ZIRCALOY CLAD BWR FUEL
3.0 wt.% ^{235}U - 40,000 MWD/MTU - 5 years cooling

Assembly class	7×7	8×8	9×9	10×10
Neutrons/sec	1.33E+8	1.17E+8	1.11E+8	1.22E+8
Photons/sec (0.45-3.0 MeV)	1.55E+15	1.44E+15	1.38E+15	1.46E+15
Thermal power (watts)	435.5	402.3	385.3	407.4

Table 5.2.28

COMPARISON OF CALCULATED DECAY HEATS FOR DESIGN BASIS FUEL AND VALUES REPORTED IN THE DOE CHARACTERISTICS DATABASE † FOR 30,000 MWD/MTU AND 5-YEAR COOLING

Fuel Assembly Class	Decay Heat from the DOE Database (watts/assembly)	Decay Heat from Design Basis Fuel (watts/assembly)
PWR Fuel		
B&W 15x15	752.0	827.5
B&W 17x17	732.9	827.5
CE 16x16	653.7	827.5
CE 14x14	601.3	827.5
WE 17x17	742.5	827.5
WE 15x15	762.2	827.5
WE 14x14	649.6	827.5
BWR Fuel		
7x7	310.9	315.7
8x8	296.6	315.7
9x9	275.0	315.7

Notes:
1. The PWR and BWR design basis fuels are the B&W 15x15 and the GE 7x7, respectively.
2. The decay heat values from the database include contributions from in-core material (e.g. spacer grids).
3. Information on the 10x10 was not available in the DOE database. However, based on the results in Table 5.2.27, the actual decay heat values from the 10x10 would be very similar to the values shown above for the 8x8.

† Reference [5.2.7].

Table 5.2.29
DESCRIPTION OF FUEL ASSEMBLY USED TO ANNALYZE THORIA RODS IN THE THORIA ROD CANISTER

	BWR
Fuel type	8x8
Active fuel length (in.)	110.5
No. of UO_2 fuel rods	55
No. of UO_2/ThO_2 fuel rods	9
Rod pitch (in.)	0.523
Cladding material	zircaloy
Rod diameter (in.)	0.412
Cladding thickness (in.)	0.025
Pellet diameter (in.)	0.358
Pellet material	98.2% ThO_2 and 1.8% UO_2 for UO_2/ThO_2 rods
Pellet density (gm/cc)	10.412
Enrichment (w/o ^{235}U)	93.5 in UO_2 for UO_2/ThO_2 rods and 1.8 for UO_2 rods
Burnup (MWD/MTIHM)	16,000
Cooling Time (years)	18
Specific power (MW/MTIHM)	16.5
Weight of THO_2 and UO_2 (kg)†	121.46
Weight of U (kg)†	92.29
Weight of Th (kg)†	14.74

† Derived from parameters in this table.

Table 5.2.30

CALCULATED FUEL GAMMA SOURCE FOR THORIA ROD CANISTER CONTAINING EIGHTEEN THORIA RODS

Lower Energy	**Upper Energy**	**16,000 MWD/MTIHM 18-Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)
7.0E-01	1.0	5.79E+11	6.81E+11
1.0	1.5	3.79E+11	3.03E+11
1.5	2.0	4.25E+10	2.43E+10
2.0	2.5	4.16E+8	1.85E+8
2.5	3.0	2.31E+11	8.39E+10
Totals		1.23E+12	1.09E+12

Table 5.2.31

CALCULATED FUEL NEUTRON SOURCE FOR THORIA ROD CANISTER CONTAINING EIGHTEEN THORIA RODS

Lower Energy (MeV)	Upper Energy (MeV)	16,000 MWD/MTIHM 18-Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	5.65E+2
4.0E-01	9.0E-01	3.19E+3
9.0E-01	1.4	6.79E+3
1.4	1.85	1.05E+4
1.85	3.0	3.68E+4
3.0	6.43	1.41E+4
6.43	20.0	1.60E+2
Totals		7.21E+4

Table 5.2.32

DESCRIPTION OF DESIGN BASIS TROJAN FUEL

	PWR
Assembly type/class	WE 17×17
Active fuel length (in.)	144
No. of fuel rods	264
Rod pitch (in.)	0.496
Cladding material	zircaloy-4
Rod diameter (in.)	0.374
Cladding thickness (in.)	0.0225
Pellet diameter (in.)	0.3225
Pellet material	UO_2
Pellet density (gm/cc)	10.412 (95% of theoretical)
Enrichment (w/o ^{235}U)[††]	2.1, 2.6, 3.09
Burnup (MWD/MTU)	30,000, 37,500, 42,000
Cooling Time (years)	16
Specific power (MW/MTU)	40
Weight of UO_2 (kg)[†]	529.85
Weight of U (kg)[†]	467.11
No. of Water Rods/Guide Tubes	25
Water Rod O.D. (in.)	0.482
Water Rod Thickness (in.)	0.016
Lower End Fitting (kg)	5.9 (steel)
Gas Plenum Springs (kg)	1.15 (steel)
Gas Plenum Spacer (kg)	0.84 (steel) 0.79 (inconel)
Upper End Fitting (kg)	6.89 (steel) 0.96 (inconel)
Incore Grid Spacers (kg)	4.9 (inconel)

[††] The enrichments correspond directly to the burnups (e.g. 2.1 for 30,000 MWD/MTU)

[†] Derived from parameters in this table.

Table 5.2.33
CALCULATED TROJAN PWR FUEL GAMMA SOURCE PER ASSEMBLY

Lower Energy	**Upper Energy**	**30,000 MWD/MTU 16 Year Cooling**		**37,500 MWD/MTU 16 Year Cooling**		**42,000 MWD/MTU 16 Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)
0.45	0.7	6.80E+14	1.18E+15	8.46E+14	1.47E+15	9.44E+14	1.64E+15
0.7	1.0	2.52E+13	2.96E+13	3.35E+13	3.94E+13	3.82E+13	4.50E+13
1.0	1.5	2.04E+13	1.64E+13	2.71E+13	2.17E+13	3.09E+13	2.47E+13
1.5	2.0	1.16E+12	6.65E+11	1.53E+12	8.77E+11	1.75E+12	9.99E+11
2.0	2.5	6.72E+09	2.99E+09	8.28E+09	3.68E+09	9.33E+09	4.15E+09
2.5	3.0	4.10E+08	1.49E+08	6.13E+08	2.23E+08	7.47E+08	2.72E+08
Totals		7.26E+14	1.23E+15	9.08E+14	1.53E+15	1.01E+15	1.71E+15

Table 5.2.34
CALCULATED TROJAN FUEL ^{60}Co SOURCE PER ASSEMBLY

Location	**30,000 MWD/MTU 16 Year Cooling (curies)**	**37,500 MWD/MTU 16 Year Cooling (curies)**	**42,000 MWD/MTU 16 Year Cooling (curies)**
Lower End Fitting	21.48	23.72	24.19
Gas Plenum Springs	4.19	4.62	4.72
Gas Plenum Spacer	15.99	17.66	18.02
Grid Spacers	419.15	462.90	472.12
Upper End Fitting	18.29	20.20	20.60

Table 5.2.35
CALCULATED TROJAN FUEL NEUTRON SOURCE PER ASSEMBLY

Lower Energy (MeV)	**Upper Energy (MeV)**	**30,000 MWD/MTU 16 Year Cooling (Neutrons/s)**	**37,500 MWD/MTU 16 Year Cooling (Neutrons/s)**	**42,000 MWD/MTU 16 Year Cooling (Neutrons/s)**
1.0E-01	4.0E-01	4.71E+06	8.11E+06	9.55E+06
4.0E-01	9.0E-01	2.41E+07	4.15E+07	4.88E+07
9.0E-01	1.4	2.21E+07	3.80E+07	4.47E+07
1.4	1.85	1.64E+07	2.81E+07	3.31E+07
1.85	3.0	2.93E+07	5.00E+07	5.88E+07
3.0	6.43	2.63E+07	4.51E+07	5.30E+07
6.43	20.0	2.30E+06	3.97E+06	4.67E+06
Total		1.25E+08	2.15E+08	2.53E+08

Table 5.2.36

DESCRIPTION OF TROJAN BURNABLE POISON ROD ASSEMBLY AND THIMBLE PLUG DEVICE

Region	BPRA	TPD
Upper End Fitting (kg of steel)	2.62	2.31
Upper End Fitting (kg of inconel)	0.42	0.42
Gas Plenum Spacer (kg of steel)	0.72	1.6
Gas Plenum Springs (kg of steel)	0.73	1.6
In-core (kg of steel)	12.10	N/A

Table 5.2.37

COBALT-60 ACTIVITIES FOR TROJAN BURNABLE POISON ROD ASSEMBLIES AND THIMBLE PLUG DEVICES

Region	BPRA	TPD
Burnup (MWD/MTU)	15,998	118,674
Cooling Time (years)	24	11
Upper End Fitting (curies Co-60)	1.20	18.86
Gas Plenum Spacer (curies Co-60)	0.34	12.80
Gas Plenum Springs (curies Co-60)	0.34	12.80
In-core (curies Co-60)	28.68	N/A

Table 5.2.38

DESCRIPTION OF TROJAN ROD CLUSTER CONTROL ASSEMBLY
FOR SOURCE TERM CALCULATIONS

Physical Description

Axial Dimensions Relative to Bottom of Active Fuel			**Flux Weighting Factor**	**Mass of cladding (kg Steel)**	**Mass of absorber (kg AgInCd)**
Start (in)	**Finish (in)**	**Length (in)**			
Configuration - Fully Removed					
0.0	8.358	8.358	0.2	0.76	3.18
8.358	12.028	3.67	0.1	0.34	1.40

Radiological Description
125,515 MWD/MTU
9 Year Cooling

Axial Dimensions Relative to Bottom of Active Fuel			**Photons/sec from AgInCd**			**Curies Co-60 from Steel**
Start (in)	**Finish (in)**	**Length (in)**	**0.3-0.45 MeV**	**0.45-0.7 MeV**	**0.7-1.0 MeV**	
Configuration - Fully Removed						
0.0	8.358	8.358	7.66E+12	7.12E+12	5.66E+12	7.34
8.358	12.028	3.67	1.68E+12	1.56E+13	1.24E+12	1.61

Table 5.2.39

DESCRIPTION OF TROJAN SECONDARY SOURCE ASSEMBLIES

Physical Description

Region	Source in Cycles 1-4	Sources in Cycles 4-14
Upper End Fitting (kg of steel)	2.62	2.62
Upper End Fitting (kg of inconel)	0.42	0.42
Gas Plenum Spacer (kg of steel)	1.6	1.6
Gas Plenum Springs (kg of steel)	1.6	1.6
In-core (kg of steel)	10.08	2.02

Radiological Description

Region	Source in Cycles 1-4	Sources in Cycles 4-14
Burnup (MWD/MTU)	45,361	88,547
Cooling Time (years)	19	9
Upper End Fitting (curies Co-60)	10.08	45.09
Gas Plenum Spacer (curies Co-60)	3.18	14.30
Gas Plenum Springs (curies Co-60)	3.18	14.30
In-core (curies Co-60)	100.20	90.29

Table 5.2.40

CALCULATED MPC-32 PWR FUEL GAMMA SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy	**Upper Energy**	**24,500 MWD/MTU 12 Year Cooling**		**29,500 MWD/MTU 14 Year Cooling**		**34,500 MWD/MTU 16 Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)
0.45	0.7	6.67E+14	1.16E+15	7.51E+14	1.31E+15	8.26E+14	1.44E+15
0.7	1.0	4.19E+13	4.94E+13	3.59E+13	4.23E+13	3.18E+13	3.74E+13
1.0	1.5	2.29E+13	1.83E+13	2.45E+13	1.96E+13	2.59E+13	2.07E+13
1.5	2.0	1.23E+12	7.05E+11	1.36E+12	7.80E+11	1.48E+12	8.47E+11
2.0	2.5	2.57E+10	1.14E+10	1.14E+10	5.06E+09	8.42E+09	3.74E+09
2.5	3.0	1.87E+09	6.78E+08	7.75E+08	2.82E+08	5.66E+08	2.06E+08
Totals		7.33E+14	1.23E+15	8.13E+14	1.37E+15	8.85E+14	1.50E+15
Lower Energy	**Upper Energy**	**39,500 MWD/MTU 19 Year Cooling**		**42,500 MWD/MTU 20 Year Cooling**			
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)		
0.45	0.7	8.72E+14	1.52E+15	9.13E+14	1.59E+15		
0.7	1.0	2.51E+13	2.95E+13	2.46E+13	2.89E+13		
1.0	1.5	2.42E+13	1.94E+13	2.46E+13	1.97E+13		
1.5	2.0	1.43E+12	8.17E+11	1.46E+12	8.35E+11		
2.0	2.5	7.78E+09	3.46E+09	8.08E+09	3.59E+09		
2.5	3.0	5.98E+08	2.17E+08	6.89E+08	2.51E+08		
Totals		9.22E+14	1.57E+15	9.63E+14	1.64E+15		

Table 5.2.41
CALCULATED MPC-32 PWR FUEL GAMMA SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy	**Upper Energy**	**24,500 MWD/MTU 8 Year Cooling**		**29,500 MWD/MTU 9 Year Cooling**		**34,500 MWD/MTU 12 Year Cooling**	
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)
0.45	0.7	8.09E+14	1.41E+15	9.20E+14	1.60E+15	9.38E+14	1.63E+15
0.7	1.0	1.19E+14	1.40E+14	1.17E+14	1.38E+14	6.91E+13	8.13E+13
1.0	1.5	3.84E+13	3.07E+13	4.30E+13	3.44E+13	3.78E+13	3.02E+13
1.5	2.0	2.04E+12	1.17E+12	2.17E+12	1.24E+12	1.99E+12	1.14E+12
2.0	2.5	4.83E+11	2.15E+11	2.40E+11	1.07E+11	3.18E+10	1.41E+10
2.5	3.0	2.60E+10	9.46E+09	1.51E+10	5.48E+09	2.53E+09	9.20E+08
Totals		9.69E+14	1.58E+15	1.08E+15	1.77E+15	1.05E+15	1.74E+15
Lower Energy	**Upper Energy**	**39,500 MWD/MTU 14 Year Cooling**		**44,500 MWD/MTU 19 Year Cooling**			
(MeV)	(MeV)	(MeV/s)	(Photons/s)	(MeV/s)	(Photons/s)		
0.45	0.7	1.00E+15	1.74E+15	9.78E+14	1.70E+15		
0.7	1.0	5.41E+13	6.37E+13	2.92E+13	3.44E+13		
1.0	1.5	3.71E+13	2.97E+13	2.84E+13	2.27E+13		
1.5	2.0	2.03E+12	1.16E+12	1.66E+12	9.50E+11		
2.0	2.5	1.42E+10	6.32E+09	8.63E+09	3.84E+09		
2.5	3.0	1.17E+09	4.25E+08	7.88E+08	2.87E+08		
Totals		1.09E+15	1.83E+15	1.04E+15	1.76E+15		

Table 5.2.42

CALCULATED MPC-32 ^{60}Co SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS AT VARYING BURNUPS AND COOLING TIMES

Location	24,500 MWD/MTU 12 Year Cooling (curies)	29,500 MWD/MTU 14 Year Cooling (curies)	34,500 MWD/MTU 16 Year Cooling (curies)	39,500 MWD/MTU 19 Year Cooling (curies)	42,500 MWD/MTU 20 Year Cooling (curies)
Lower end fitting	64.65	55.27	46.40	33.47	30.42
Gas plenum springs	12.58	10.75	9.03	6.51	5.92
Gas plenum spacer	7.22	6.17	5.18	3.74	3.40
Expansion springs	N/A	N/A	N/A	N/A	N/A
Grid spacers	587.27	502.05	421.45	304.00	276.36
Upper end fitting	23.66	20.23	16.98	12.25	11.14
Handle	N/A	N/A	N/A	N/A	N/A

Table 5.2.43

CALCULATED MPC-32 ^{60}Co SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS AT VARYING BURNUPS AND COOLING TIMES

Location	24,500 MWD/MTU 8 Year Cooling (curies)	29,500 MWD/MTU 9 Year Cooling (curies)	34,500 MWD/MTU 12 Year Cooling (curies)	39,500 MWD/MTU 14 Year Cooling (curies)	44,500 MWD/MTU 19 Year Cooling (curies)
Lower end fitting	109.27	106.74	78.34	64.65	36.25
Gas plenum springs	21.26	20.77	15.24	12.58	7.05
Gas plenum spacer	12.20	11.91	8.74	7.22	4.05
Expansion springs	N/A	N/A	N/A	N/A	N/A
Grid spacers†	N/A	N/A	N/A	N/A	N/A
Upper end fitting	40.00	39.07	28.68	23.66	13.27
Handle	N/A	N/A	N/A	N/A	N/A

† These burnup and cooling times represent fuel with zircaloy grid spacers. Therefore, the cobalt activation is negligible.

Table 5.2.44

CALCULATED MPC-32 PWR NEUTRON SOURCE PER ASSEMBLY
FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY
INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy (MeV)	**Upper Energy (MeV)**	**24,500 MWD/MTU 12 Year Cooling (Neutrons/s)**	**29,500 MWD/MTU 14 Year Cooling (Neutrons/s)**	**34,500 MWD/MTU 16 Year Cooling (Neutrons/s)**	**39,500 MWD/MTU 19 Year Cooling (Neutrons/s)**	**42,500 MWD/MTU 20 Year Cooling (Neutrons/s)**
1.0E-01	4.0E-01	2.24E+06	3.61E+06	5.37E+06	6.97E+06	8.08E+06
4.0E-01	9.0E-01	1.15E+07	1.84E+07	2.74E+07	3.56E+07	4.13E+07
9.0E-01	1.4	1.06E+07	1.70E+07	2.52E+07	3.27E+07	3.79E+07
1.4	1.85	7.88E+06	1.26E+07	1.87E+07	2.43E+07	2.81E+07
1.85	3.0	1.43E+07	2.27E+07	3.35E+07	4.34E+07	5.02E+07
3.0	6.43	1.26E+07	2.02E+07	3.00E+07	3.89E+07	4.50E+07
6.43	20.0	1.10E+06	1.76E+06	2.63E+06	3.41E+06	3.95E+06
TOTALS		6.01E+07	9.63E+07	1.43E+08	1.85E+08	2.15E+08

Table 5.2.45

CALCULATED MPC-32 PWR NEUTRON SOURCE PER ASSEMBLY FOR DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS FOR VARYING BURNUPS AND COOLING TIMES

Lower Energy (MeV)	Upper Energy (MeV)	24,500 MWD/MTU 8 Year Cooling (Neutrons/s)	29,500 MWD/MTU 9 Year Cooling (Neutrons/s)	34,500 MWD/MTU 12 Year Cooling (Neutrons/s)	39,500 MWD/MTU 14 Year Cooling (Neutrons/s)	44,500 MWD/MTU 19 Year Cooling (Neutrons/s)
1.0E-01	4.0E-01	2.60E+06	4.35E+06	6.24E+06	8.40E+06	1.01E+07
4.0E-01	9.0E-01	1.33E+07	2.22E+07	3.19E+07	4.29E+07	5.16E+07
9.0E-01	1.4	1.22E+07	2.04E+07	2.92E+07	3.94E+07	4.73E+07
1.4	1.85	9.08E+06	1.51E+07	2.17E+07	2.91E+07	3.50E+07
1.85	3.0	1.63E+07	2.70E+07	3.86E+07	5.19E+07	6.24E+07
3.0	6.43	1.45E+07	2.42E+07	3.47E+07	4.67E+07	5.61E+07
6.43	20.0	1.27E+06	2.13E+06	3.05E+06	4.11E+06	4.94E+06
TOTALS		6.93E+07	1.16E+08	1.65E+08	2.23E+08	2.67E+08

5.3 MODEL SPECIFICATIONS

The shielding analysis of the HI-STAR 100 System was performed with MCNP-4A [5.1.1]. MCNP is a Monte Carlo transport code that offers a full three-dimensional combinatorial geometry modeling capability including such complex surfaces as cones and tori. This means that no gross approximations were required to represent the HI-STAR 100 System in the shielding analysis. A sample input file for MCNP is provided in Appendix 5.C.

Subsection 5.1.2 discussed the accident conditions and stated that the only accident that would impact the shielding analysis would be a loss of the neutron shield and impact limiters. Therefore, the MCNP models of the HI-STAR 100 System normal condition have the neutron shield and impact limiters in place while the hypothetical accident condition replaces the neutron shield with void and removes the impact limiters. The aluminum honeycomb in the impact limiters was conservatively neglected in the MCNP modeling. However, credit was taken for the outer dimensions of the impact limiters.

5.3.1 Description of the Radial and Axial Shielding Configuration

Section 1.4 provides the drawings that describe the HI-STAR 100 System. These drawings were used to create the MCNP models used in the radiation transport calculations. Figures 5.3.1 through 5.3.3 show cross sectional views of the HI-STAR 100 overpack and MPC as it was modeled in MCNP for each of the MPCs. These figures were created with the MCNP two-dimensional plotter and are drawn to scale. The figures clearly illustrate the radial steel fins and pocket trunnions in the neutron shield region. Since the fins and pocket trunnions were modeled explicitly, neutron streaming through these components is accounted for in the calculations of the dose adjacent to the overpack and 1 meter dose. In Subsection 5.4.1, the dose effect of localized streaming through these compartments is analyzed. Figures 5.3.4 through 5.3.6 show the MCNP models of the MPC-32, MPC-24, and MPC-68 fuel baskets including the as-modeled dimensions. Figure 5.3.9 shows a cross sectional view of the HI-STAR 100 overpack with the as-modeled thickness of the various materials. Figure 5.3.10 is an axial representation of the HI-STAR 100 overpack with the various as-modeled dimensions indicated. As Figure 5.3.10 indicates, the thickness of the MPC lid is 9.5 inches. Earlier versions of the MPC-68 used a 10 inch thick lid with a correspondingly smaller MPC-internal cavity height. The analysis in this chapter conservatively represents the 9.5 inch thick lid. Figures 5.3.11 and 5.3.12 provide the as-modeled dimensions of the impact limiters during normal conditions. The aluminum honeycomb material in the impact limiter is not shown in Figure 5.3.11 because it was conservatively not modeled in the MCNP calculations.

Calculations were performed to determine the acceptability of homogenizing the fuel assembly versus explicit modeling. Based on these calculations it was concluded that it was acceptable to homogenize the fuel assembly without loss of accuracy. The width of the PWR and BWR homogenized fuel assembly is equal to 15 times the pitch and 7 times the pitch, respectively.

Several conservative approximations were made in modeling the MPC and overpack. The conservative approximations are listed below.

1. The basket material in the top and bottom 0.9 inches where the MPC basket flow holes are located is not modeled. The length of the basket not modeled (0.9 inches) was determined by calculating the equivalent area removed by the flow holes. This method of approximation is conservative because no material for the basket shielding is provided in the 0.9 inch area at the top and bottom of the MPC basket.

2. The upper and lower fuel spacers are not modeled. The fuel spacers are not needed on all fuel assembly types. However, most PWR fuel assemblies will have upper and lower fuel spacers. The positioning of the fuel assembly for the shielding analysis is determined by the fuel spacer length for the design basis fuel assembly type, but the fuel spacer materials are not modeled. This is conservative since it removes steel which would provide a small amount of additional shielding.

3. For the MPC-24, MPC-32, and the MPC-68, the MPC basket supports are not modeled. This is conservative since it removes steel which would provide a small increase in shielding. The optional aluminum heat conduction elements were also conservatively not modeled.

4. Deleted.

5. In the modeling of the BWR fuel assemblies, the zircaloy flow channels were not represented. This was done because it cannot be guaranteed that all BWR fuel assemblies will have an associated flow channel when placed in the MPC. The flow channel does not contribute to the source, but does provide some small amount of shielding. However, no credit is taken for this additional shielding.

6. In the modeling of the impact limiters, only the neutron shield (Holtite-A) and the steel, shown in Figure 5.1.1, were represented. Conservatively, the aluminum honeycomb of the impact limiters was not modeled. However, credit was taken for the outer boundary of the impact limiter as the external surface of the HI-STAR 100 System.

7. Deleted

8. The Trojan MPC-24E was modeled explicitly with its shorter cavity length and larger cell sizes with shorter height on the four corner locations. The Trojan MPC was properly positioned in the bottom portion of the HI-STAR and the spacer device between the top of the MPC and the underside of the HI-STAR lid was conservatively not modeled.

During this project several design changes occurred that affected the drawings, but did not significantly affect the MCNP models of the HI-STAR 100 overpack or MPC. Therefore, in

some cases, these models do not exactly represent the drawings. The discrepancies between models and drawings are listed and discussed here.

MPC Modeling Discrepancies

1. In the newer MPCs, there is a sump in the baseplate to enhance draining of the MPC. This localized reduction in the thickness of the baseplate was not modeled. Since there is significant shielding and distance in the HI-STAR outside the MPC baseplate, this localized reduction in shielding will not affect the calculated dose rates outside the HI-STAR.
2. The MPC-24 has narrower boral (6.25 inches compared to 7.5 inches) on 16 of the 24 exterior panels. Conservatively, all 24 panels were modeled as 6.5 inches wide. This dimension is slightly larger than the actual 6.25 inch dimension but is considerably smaller than the 7.5 inch dimension and results in a net reduction in boral around the periphery of the basket.
3. An enhanced version of the MPC-24 design, the MPC-24E, has been created. The MPC-24E is superior to the MPC-24 from a criticality perspective. From a shielding perspective, the two designs are almost identical. The cell openings in the MPC-24E are slightly smaller than in the MPC-24 and the boral and sheathing are slightly thicker in the MPC-24E than in the MPC-24. As a result, the MPC-24E has slightly better shielding characteristics than the MPC-24 and the MPC-24 analysis bounds the MPC-24E.

5.3.1.1 Fuel Configuration

As described above, the active fuel region is modeled as a homogenous zone. The end fittings and the plenum regions are also modeled as homogenous regions of steel. The masses of steel used in these regions are shown in Tables 5.2.1 and 5.2.32. The axial description of the design basis fuel assemblies is provided in Table 5.3.1. The axial description of the Trojan fuel assembly is provided in Table 5.3.4. Figures 5.3.7 and 5.3.8 graphically depict the location of the PWR and BWR fuel assemblies within the HI-STAR 100 System. The impact limiters are not depicted in the figures for clarity. The axial locations of the Boral, basket, pocket trunnion, and transition areas are shown in these figures.

The axial position of the fuel assembly within the basket is maintained with the use of the upper and lower fuel spacers. These fuel spacers are used to position the active fuel region next to the Boral. Chapter 2 demonstrates that these fuel spacers do not fail under all normal and hypothetical accident conditions. Therefore, movement of the fuel assembly during transport is not considered.

5.3.1.2 Streaming Considerations

The streaming from the radial channels and pocket trunnions in the neutron shield is evaluated in Subsection 5.4.1. The MCNP model of the HI-STAR 100 completely describes the radial channels and pocket trunnions, thereby properly accounting for the streaming effect. In newer designs of the HI-STAR 100 overpack, the pocket trunnion has been removed. However, the analysis presented in this chapter using the pocket trunnion bounds the new configuration due to the reduction in streaming when the pocket trunnion is not present.

The design of the HI-STAR 100 System, as described in the drawings in Section 1.4, has eliminated all other possible streaming paths. Therefore, the MCNP model does not represent any additional streaming paths. A brief justification of this assumption is provided for each penetration.

- The lifting trunnions will remain installed in the overpack top flange. No credit is taken for any part of the trunnion that extends outside of the overpack.

- The pocket trunnions are modeled as solid blocks of steel. The pocket trunnion will be filled with a solid steel rotation trunnion attached to the transport frame during handling and shipping or a plug will be installed if rotation trunnions are not inserted into the pocket trunnion.

- The threaded holes in the MPC lid are plugged with solid plugs during shipping and, therefore, do not create a void in the MPC lid.

- The drain and vent ports in the MPC lid are designed to eliminate streaming paths. The steel lost in the MPC lid at the port location is replaced with a block of steel approximately 6 inches thick below the port opening and attached to the underside of the lid. This design feature is shown on the drawings in Section 1.4. The MCNP model did not explicitly represent this arrangement but, rather, modeled the MPC lid as a solid piece.

- The penetrations in the overpack are filled with bolts that extend into the penetration, thereby eliminating any potential direct streaming paths. Cover plates are also designed in such a way as to maintain the thickness of the overpack to the maximum extent practical. Therefore, the MCNP model does not represent any streaming paths due to penetrations in the overpack.

5.3.2 Regional Densities

Composition and densities of the various materials used in the HI-STAR 100 System shielding analyses are given in Tables 5.3.2 and 5.3.3. All of the materials and their actual geometries are

represented in the MCNP model. All steel in the MPC was modeled as stainless steel and all steel in the overpack was modeled as carbon steel.

Section 3.4 demonstrates that all materials used in the HI-STAR 100 System remain below their design temperatures as specified in Table 2.1.2 during all normal conditions. Therefore, the shielding analysis does not address changes in the material density or composition as a result of temperature changes.

During normal operations, the depletion of B-10 in the Boral and the Holtite-A neutron shield is negligible. The fraction of B-10 atoms that are depleted in 50 years is approximately 3.0E-9 and 4.0E-8 in the Boral and Holtite-A, respectively. Therefore, the shielding analysis does not address changes in the composition of the Boral or Holtite-A as a result of neutron absorption.

As discussed in Section 1.2.1.4.2, the density of the Holtite-A during normal condition was reduced by approximately 4% to account for any potential water loss. In addition, the Hydrogen weight percent was conservatively reduced from 6% to 5.92%.

Section 3.5 discusses the effect of the hypothetical accident condition (fire) on the temperatures of the shielding materials and the resultant impact on their shielding effectiveness. As stated in Subsection 5.1.2, the only consequence that has any significant impact on the shielding configuration is the loss of the neutron shield in the HI-STAR 100 System as a result of fire. The change in the neutron shield was conservatively analyzed by assuming that the entire volume of the neutron shield was replaced by void.

Table 5.3.1

DESCRIPTION OF THE AXIAL MCNP MODEL OF THE DESIGN BASIS FUEL ASSEMBLIES†

Region	Start (in.)	Finish (in.)	Length (in.)	Actual Material	Modeled Material
PWR					
Lower End Fitting	0.0	7.375	7.375	SS304	SS304
Space	7.375	8.375	1.0	zircaloy	void
Fuel	8.375	152.375	144	fuel & zircaloy	fuel
Gas Plenum Springs	152.375	156.1875	3.8125	SS304 & zircaloy	SS304
Gas Plenum Spacer	156.1875	160.5625	4.375	SS304 & zircaloy	SS304
Upper End Fitting	160.5625	165.625	5.0625	SS304	SS304
BWR					
Lower End Fitting	0.0	7.385	7.385	SS304	SS304
Fuel	7.385	151.385	144	fuel & zircaloy	fuel
Space	151.385	157.385	6	zircaloy	void
Gas Plenum Springs	157.385	166.865	9.48	SS304 & zircaloy	SS304
Expansion Springs	166.865	168.215	1.35	SS304	SS304
Upper End Fitting	168.215	171.555	3.34	SS304	SS304
Handle	171.555	176	4.445	SS304	SS304

† All dimensions start at the bottom of the fuel assembly. The length of the lower fuel spacer must be added to the distances to determine the distance from the top of the MPC baseplate.

Table 5.3.2

COMPOSITION OF THE MATERIALS IN THE HI-STAR 100 SYSTEM

Component	Density (g/cm^3)	Elements	Mass Fraction (%)
Uranium Oxide	10.412	^{235}U	2.9971(BWR) 3.2615(PWR)
		^{238}U	85.1529(BWR) 84.8885(PWR)
		O	11.85
Boral	2.644	^{10}B	4.4226 (MPC-68 & MPC-32) 4.367 (MPC-24)
		^{11}B	20.1474 (MPC-68 & MPC-32) 19.893 (MPC-24)
		Al	68.61 (MPC-68 & MPC-32) 69.01 (MPC-24)
		C	6.82 (MPC-68 & MPC-32) 6.73 (MPC-24)
SS304	7.92	Cr	19
		Mn	2
		Fe	69.5
		Ni	9.5
Carbon Steel	7.82	C	0.5
		Fe	99.5
Zircaloy	6.55	Zr	100

Table 5.3.2 (continued)

COMPOSITION OF THE MATERIALS IN THE HI-STAR 100 SYSTEM

Component	Density (g/cm^3)	Elements	Mass Fraction (%)
Neutron Shield Holtite-A	1.61	C	27.66039
		H	5.92
		Al	21.285
		N	1.98
		O	42.372
		^{10}B	0.14087
		^{11}B	0.64174
BWR Fuel Region Mixture	4.29251	^{235}U	2.4966
		^{238}U	70.9315
		O	9.8709
		Zr	16.701
PWR Fuel Region Mixture	3.853705	^{235}U	2.6944
		^{238}U	70.1276
		O	9.7895
		Zr	17.3885

Table 5.3.2 (continued)

COMPOSITION OF THE MATERIALS IN THE HI-STAR 100 SYSTEM

Component	Density (g/cm^3)	Elements	Mass Fraction (%)
Lower End Fitting (PWR)	1.0783	SS304	100
Gas Plenum Springs (PWR)	0.1591	SS304	100
Gas Plenum Spacer (PWR)	0.1591	SS304	100
Upper End Fitting (PWR)	1.5410	SS304	100
Lower End Fitting (BWR)	1.4862	SS304	100
Gas Plenum Springs (BWR)	0.2653	SS304	100
Expansion Springs (BWR)	0.6775	SS304	100
Upper End Fitting (BWR)	1.3692	SS304	100
Handle (BWR)	0.2572	SS304	100

Table 5.3.3

COMPOSITION OF THE FUEL IN THE MIXED OXIDE FUEL ASSEMBLIES IN THE MPC-68 OF THE HI-STAR 100 SYSTEM

Component	Density (g/cm^3)	Elements	Mass Fraction (%)
Mixed Oxide Pellets	10.412	^{238}U	85.498
		^{235}U	0.612
		^{238}Pu	0.421
		^{239}Pu	1.455
		^{240}Pu	0.034
		^{241}Pu	0.123
		^{242}Pu	0.007
		O	11.85
Uranium Oxide Pellets	10.412	^{238}U	86.175
		^{235}U	1.975
		O	11.85

Table 5.3.4

DESCRIPTION OF THE AXIAL MCNP MODEL OF THE TROJAN FUEL ASSEMBLY†

Region	**Start (in.)**	**Finish (in.)**	**Length (in.)**	**Actual Material**	**Modeled Material**
PWR					
Lower End Fitting	0.0	2.738	2.738	SS304	SS304
Space	2.738	3.738	1.0	zircaloy	Void
Fuel	3.738	147.738	144	fuel & zircaloy	Fuel
Gas Plenum Springs	147.738	151.916	4.178	SS304 & zircaloy	SS304
Gas Plenum Spacer	151.916	156.095	4.179	SS304 & zircaloy	SS304
Upper End Fitting	156.095	159.765	3.67	SS304	SS304

† All dimensions start at the bottom of the fuel assembly. The length of the lower fuel spacer must be added to the distances to determine the distance from the top of the MPC baseplate.

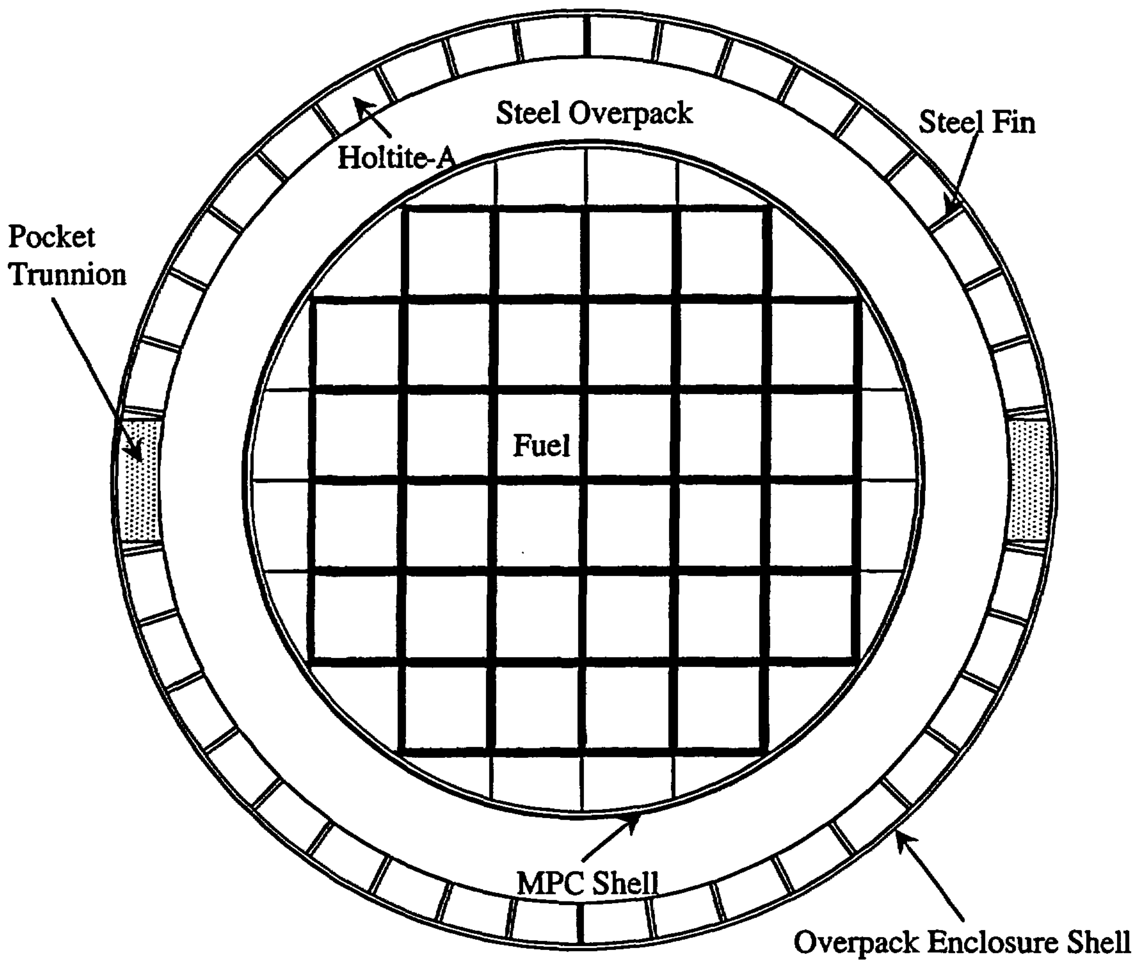


FIGURE 5.3.1; HI-STAR 100 OVERPACK WITH MPC-32 CROSS SECTIONAL VIEW AS MODELLED IN MCNP†

† This figure is drawn to scale using the MCNP plotter.

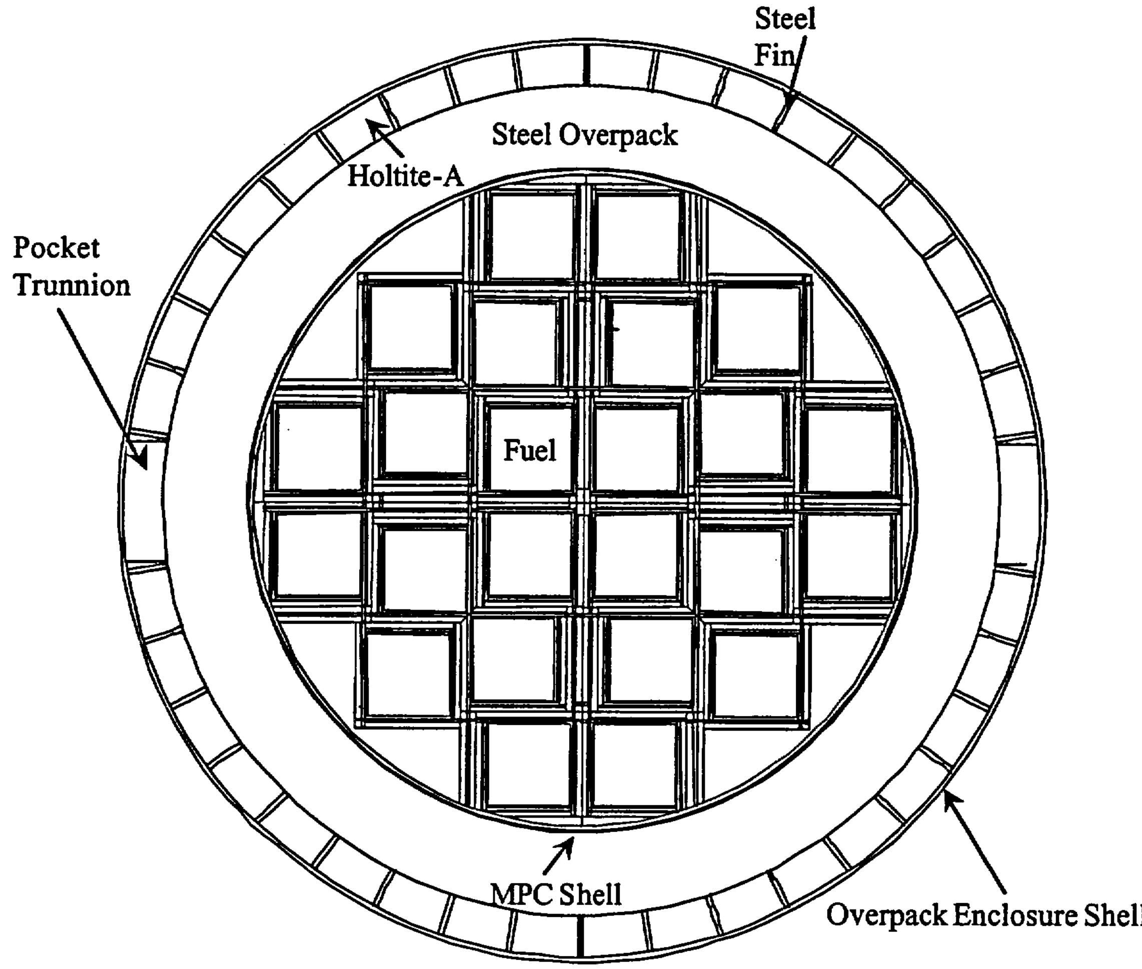


FIGURE 5.3.2; HI-STAR 100 OVERPACK WITH MPC-24 CROSS SECTIONAL VIEW AS MODELLED IN MCNP†

† This figure is drawn to scale using the MCNP plotter.

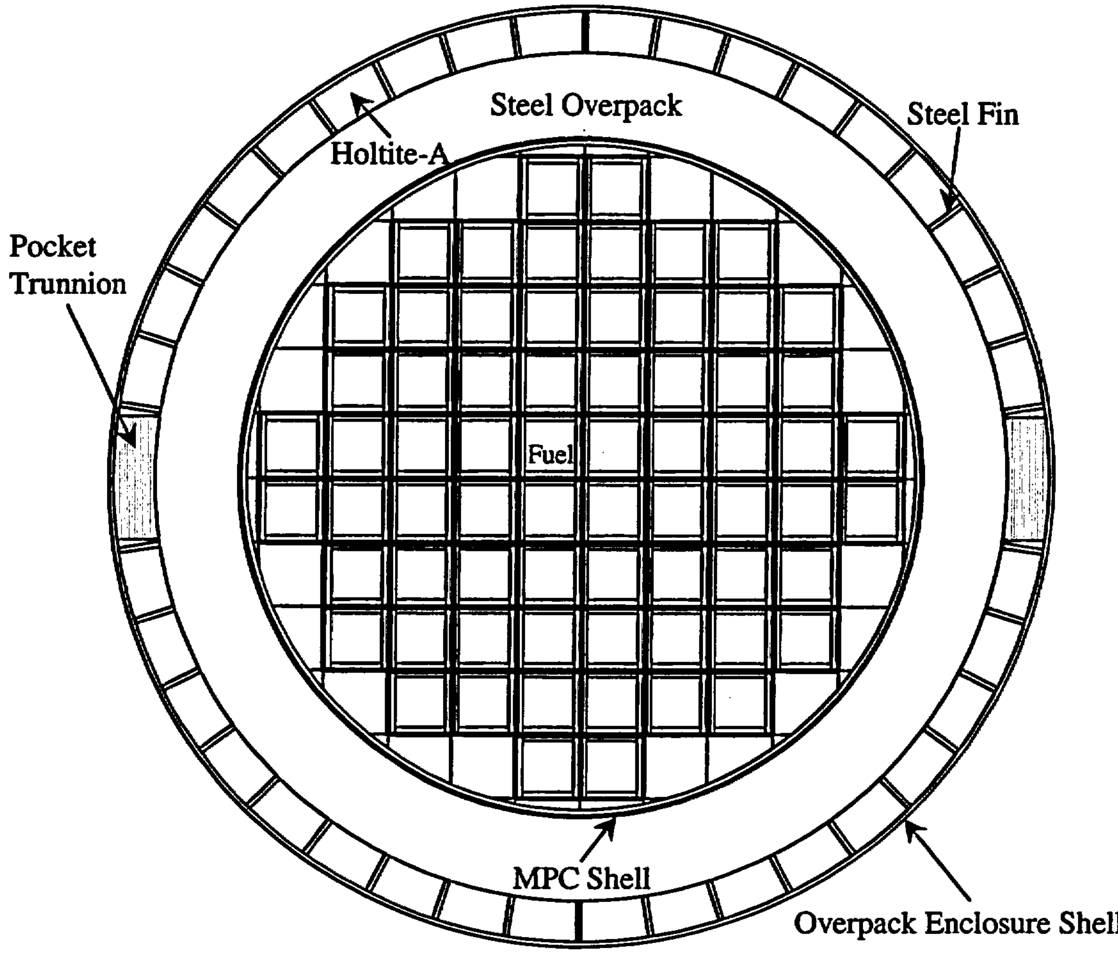


FIGURE 5.3.3; HI-STAR 100 OVERPACK WITH MPC-68 CROSS SECTIONAL VIEW AS MODELLED IN MCNP†

† This figure is drawn to scale using the MCNP plotter.

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

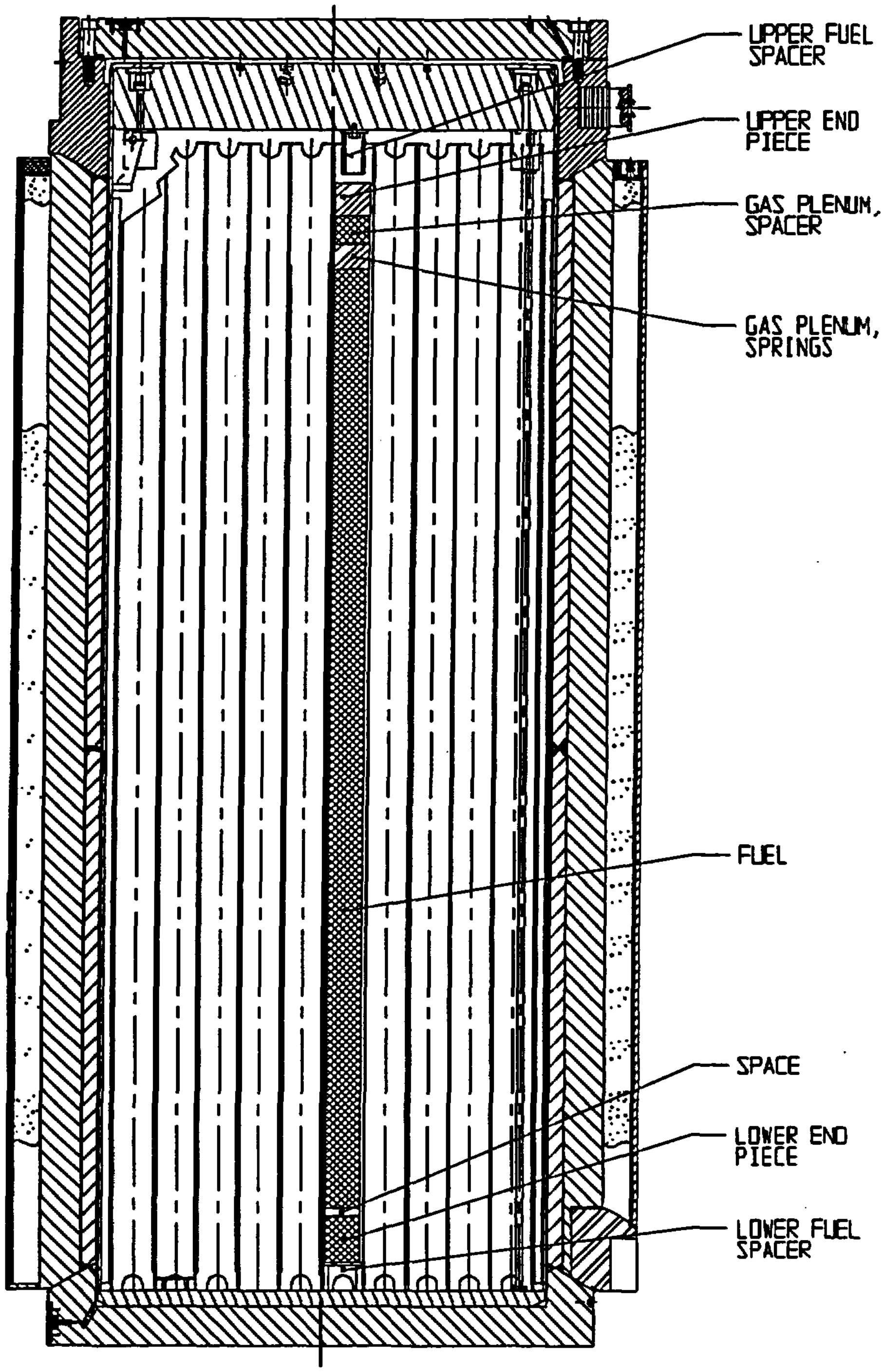


FIGURE 5.3.7; AXIAL LOCATION OF PWR DESIGN BASIS FUEL IN THE HI-STAR 100 SYSTEM

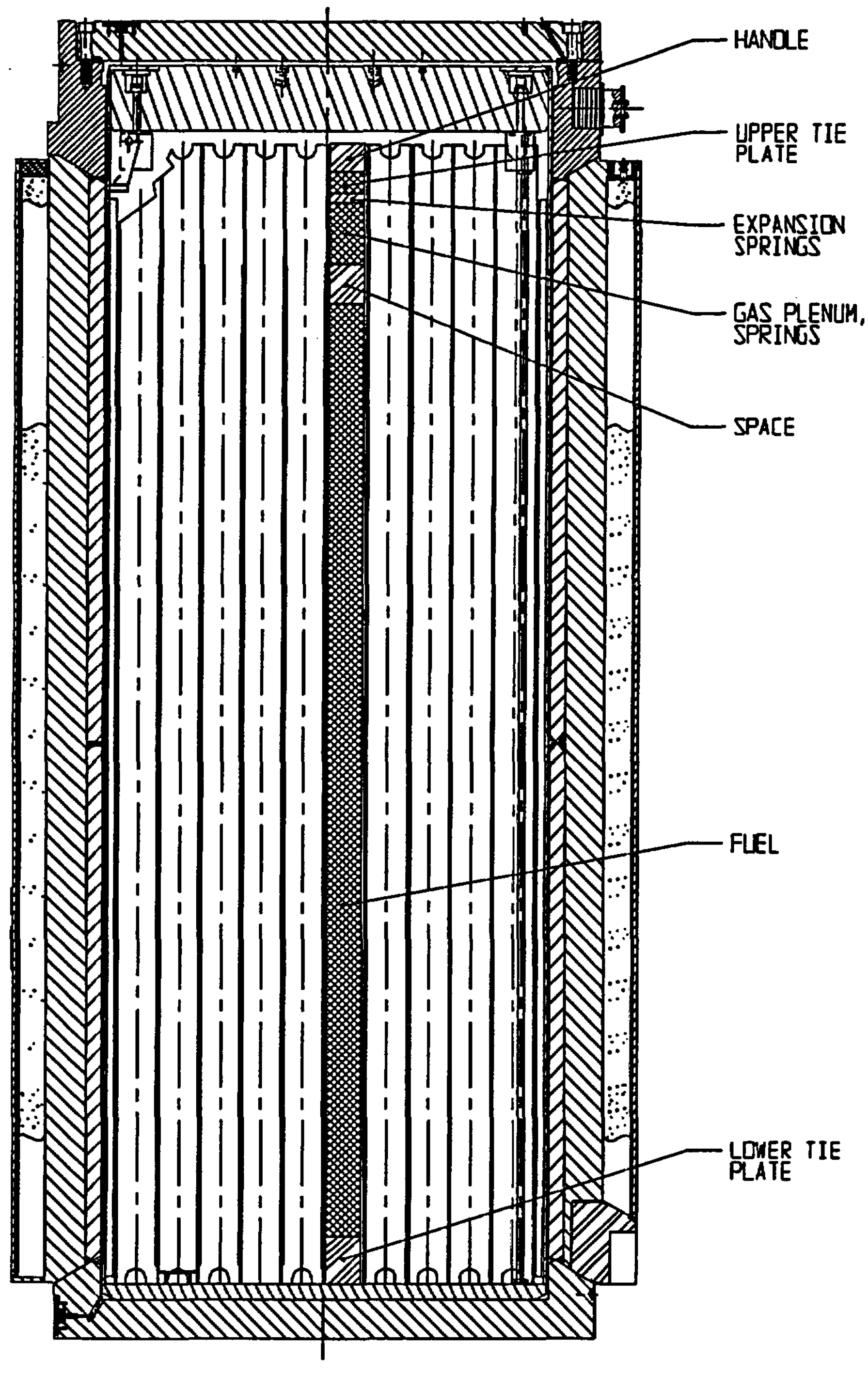
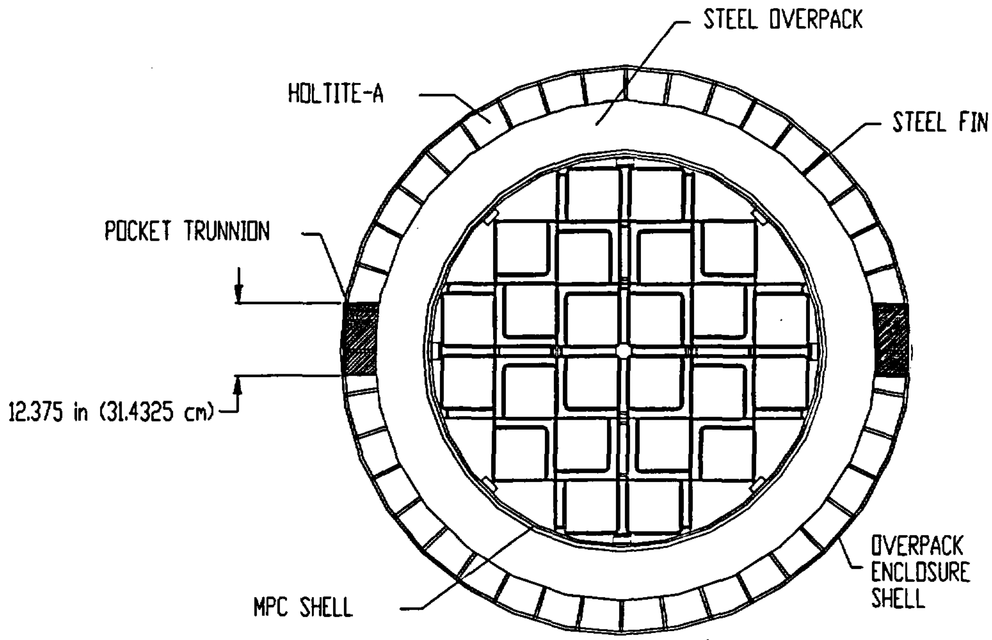


FIGURE 5.3.8; AXIAL LOCATION OF BWR DESIGN BASIS FUEL IN THE HI-STAR 100 SYSTEM



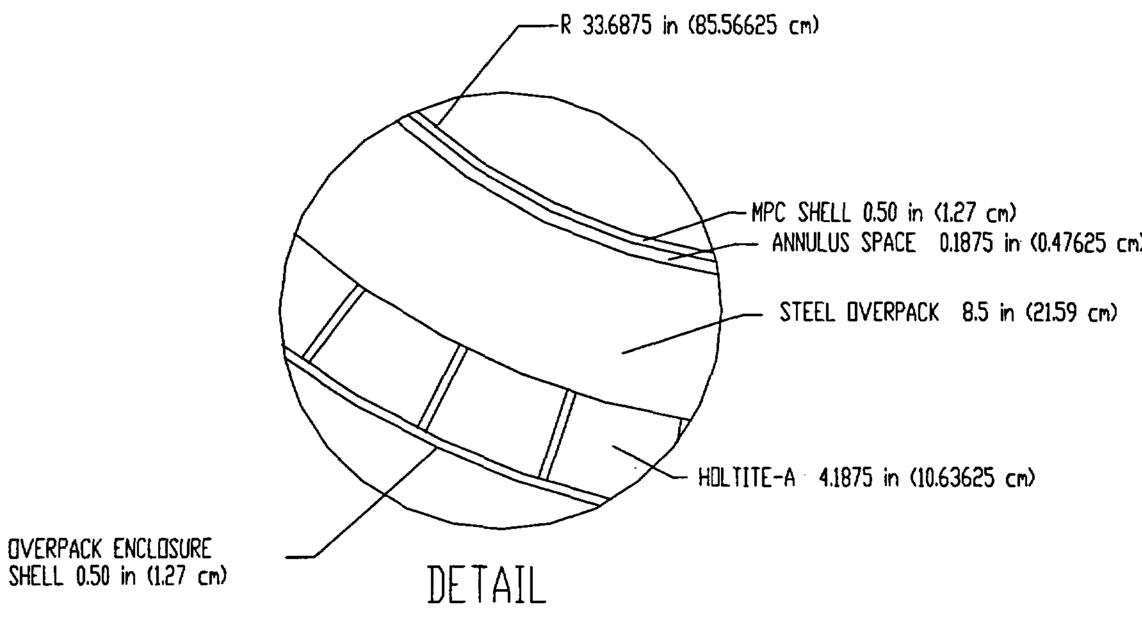


FIGURE 5.3.9; HI-STAR 100 OVERPACK WITH MPC-24 CROSS SECTIONAL VIEW SHOWING THE THICKNESS OF THE MPC SHELL AND OVERPACK AS MODELED IN MCNP

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

5.4 SHIELDING EVALUATION

The MCNP-4A code[5.1.1] was used for all of the shielding analyses. MCNP is a continuous energy, three-dimensional, coupled neutron-photon-electron Monte Carlo transport code. Continuous energy cross section data is represented with sufficient energy points to permit linear-linear interpolation between these points. The individual cross section libraries used for each nuclide are those recommended by the MCNP manual. All of these data are based on ENDF/B-V data. MCNP has been extensively benchmarked against experimental data by the large user community. References [5.4.2], [5.4.3], and [5.4.4] are three examples of the benchmarking that has been performed.

The energy distribution of the source term, as described earlier, is used explicitly in the MCNP model. A different MCNP calculation is performed for each of the three source terms (neutron, decay gamma, and ^{60}Co). The axial distribution of the fuel source term is described in Table 1.2.15 and Figures 1.2.13 and 1.2.14. The PWR and BWR axial burnup distributions were obtained from References [5.4.5] and [5.4.6] respectively. These axial distributions were obtained from operating plants and are representative of PWR and BWR fuel with burnups greater than 30,000 MWD/MTU. The ^{60}Co source in the hardware was assumed to be uniformly distributed over the appropriate regions. The axial distribution used for the Trojan Plant fuel was similar but not identical to the generic PWR distribution. Table 1.2.15 and Figure 1.2.13a present the axial burnup distribution used for the Trojan Plant fuel taken from the Trojan FSAR [5.1.6].

It has been shown that the neutron source strength varies as the burnup level raised by the power of 4.2. Since this relationship is non-linear and since the burnup in the axial center of a fuel assembly is greater than the average burnup, the neutron source strength in the axial center of the assembly is greater than the relative burnup times the average neutron source strength. In order to account for this effect, the neutron source strength in each of the 10 axial nodes listed in Table 1.2.15 was determined by multiplying the average source strength by the relative burnup level raised to the power of 4.2. The peak relative burnups listed in Table 1.2.15 for the generic PWR and BWR fuels are 1.105 and 1.195 respectively. Using the power of 4.2 relationship results in a 37.6% ($1.105^{4.2}/1.105$) and 76.8% ($1.195^{4.2}/1.195$) increase in the neutron source strength in the peak nodes for the PWR and BWR fuel respectively. The total neutron source strength increases by 15.6% for the PWR fuel assemblies and 36.9% for the BWR fuel assemblies.

MCNP was used to calculate dose at the various desired locations. MCNP calculates neutron or photon flux and these values can be converted into dose by the use of dose response functions. This is done internally in MCNP and the dose response functions are listed in the input file. The response functions used in these calculations are listed in Table 5.4.1 and were taken from ANSI/ANS 6.1.1, 1977 [5.4.1].

The dose rate at the various locations were calculated with MCNP using a two step process. The first step was to calculate the dose rate for each dose location per starting particle for each neutron and gamma group and each axial location in the end fittings. The second and last step was to multiply the dose rate per starting particle for each group by the source strength (i.e. particles/sec) in that group and sum the resulting dose rates for all groups in each dose location. The standard deviations of the various results were statistically combined to determine the standard deviation of the total dose in each dose location.

Figures 5.1.1 and 5.1.2 depict the dose point locations during normal and hypothetical accident conditions of transport. Dose point location 3a in Figure 5.1.1 covers two regions of different radii. The outermost region is 5.75 inches in height and the innermost region is 6.875 inches in height. The dose rate was calculated over both segments and the highest value was reported for dose location 3a. Dose point locations 1 through 4 in Figure 5.1.2 are conservatively located at a radial position that is approximately 1 meter from the outer radial surface of the bottom plate.

Tables 5.4.8, 5.4.9, 5.4.19, 5.4.29, and 5.4.32 provide the total dose rate on the surface of the HI-STAR 100 System for each burnup level and cooling time. Tables 5.4.10 through 5.4.13, 5.4.20, 5.4.21, 5.4.30, 5.4.31, 5.4.33, and 5.4.34 provide the total dose rate at 2 meters for normal conditions and at 1 meter for accident conditions for each burnup level and cooling time for the MPC-24, MPC-68 and the MPC-32. This information was used to determine the worst case burnup level and cooling time and corresponding maximum dose rates reported in Section 5.1.

Since MCNP is a statistical code, there is an uncertainty associated with the calculated values. In MCNP the uncertainty is expressed as the relative error which is defined as the standard deviation of the mean divided by the mean. Therefore, the standard deviation is represented as a percentage of the mean. The relative error for the total dose rates presented in this chapter were typically less than 2% and the relative error for the individual dose components was typically less than 5%.

5.4.1 Streaming Through Radial Steel Fins and Pocket Trunnions

The HI-STAR 100 overpack utilizes 0.5 inch thick radial channels for structural support and cooling. The attenuation of neutrons through steel is substantially less than the attenuation of neutrons through the neutron shield. Therefore, it is possible to have neutron streaming through the channels which could result in a localized dose peak. The reverse is true for photons which would result in a localized reduction in the photon dose. Analyses were performed to determine the magnitude of the dose peaks and depressions and the impact on localized dose as compared to average total dose. This effect was evaluated at the radial surface of the HI-STAR 100 System and a distance of two meters.

In addition to the radial channels, the pocket trunnions are essentially blocks of steel that are approximately 12 inches wide and 12 inches high. The effect of the pocket trunnion on neutron

streaming and photon transmission will be more substantial than the effect of a single fin. Therefore, analyses were performed to quantity this effect. Figures 5.3.7 and 5.3.8 illustrate the location of the pocket trunnion and its axial position relative to the active fuel.

The fuel loading pattern in the MPC-32, MPC-24 and the MPC-68, as depicted in Figures 5.3.1 through 5.3.3, is not cylindrical. Therefore, there is a potential to experience peaking as a result of azimuthal variations in the fuel loading. Since the MCNP models represent the fuel in the correct positions (i.e., cylindrical homogenization is not performed) the effect of azimuthal variations in the loading pattern is automatically accounted for in the calculations that are discussed below.

The effect of streaming through the pocket trunnion and the radial channels was analyzed using the full three-dimensional MCNP models of the MPC-24 and the MPC-68. The effect of peaking was calculated on the surface of the overpack adjacent to the pocket trunnion and dose locations 2a and 3a in Figures 5.1.1. The effect of peaking was also analyzed at 2 meters from the overpack at dose location 2 and at the axial height of the impact limiter. Dose location 3 was not analyzed at two meters because the dose at that point is less than the dose at location 2 as demonstrated in the tables at the end of this section. Figure 5.4.1 shows a quarter of the HI-STAR 100 overpack with 41 azimuthal bins drawn. There is one bin per steel fin and 3 bins in each neutron shield region. This azimuthal binning structure was used over the axial height of the overpack. The dose was calculated in each of these bins and then compared to the average dose calculated over the surface to determine a peak-to-average ratio for the dose in that bin. The azimuthal location of the pocket trunnion is shown in Figure 5.4.1. The pocket trunnion was modeled as solid steel. During shipping, a steel rotation trunnion or plug shall be placed in the pocket trunnion recess. To conservatively evaluate the peak to average ratio, the pocket trunnion is assumed to be solid steel.

Table 5.4.14 provides representative peak-to-average ratios that were calculated for the various dose components and locations. Table 5.4.15 presents the dose rates at the dose locations analyzed including the effect of peaking. These results can be compared with the surface average results in Tables 5.1.1, 5.1.3, 5.1.4, and 5.1.6. The peak dose on the surface of the overpack at dose location 2a occurs at a steel channel (fin). This is evident by the high neutron peaking at dose location 2a on the surface of the overpack. The dose rate at the pocket trunnion, in those overpacks containing pocket trunnions, is higher than the dose rate at dose location 2 on the surface of the overpack. However, these results clearly indicate that, at two meters, the peaking associated with the pocket trunnion is not present and that the peak dose location is #2.

The MPC-32 was not explicitly analyzed for azimuthal peaking. It is expected that the peaking in the MPC-32 will be similar if not smaller than in the MPC-24 due to the fact that the fuel assemblies in the MPC-24 are not as closely positioned to each other as in the MPC-32.

5.4.2 Damaged Fuel Post-Accident Shielding Evaluation

As discussed in Subsection 5.2.5.2, the analysis presented below, even though it is for damaged fuel, demonstrates the acceptability of transporting intact Humboldt Bay 6x6 and intact Dresden 1 6x6 fuel assemblies. As discussed in Subsection 5.2.8, the Trojan damaged fuel and fuel debris were not explicitly analyzed because they are bounded by the intact fuel assemblies.

For the damaged fuel and fuel debris accident condition, it is conservatively assumed the damaged fuel cladding ruptures and all the fuel pellets fall and collect at the bottom of the damaged fuel container. The inner dimension of the damaged fuel container, specified in the Design Drawings of Section 1.4, and the design basis damaged fuel and fuel debris assembly dimensions in Table 5.2.2 are used to calculate the axial height of the rubble in the damaged fuel container assuming 50% compaction. Neglecting the fuel pellet to cladding inner diameter gap, the volume of cladding and fuel pellets available for deposit is calculated assuming the fuel rods are solid. Using the volume in conjunction with the damaged fuel container, the axial height of rubble is calculated to be 80 inches.

Some of the 6x6 assemblies described in Table 5.2.2 were manufactured with Inconel grid spacers (the mass of inconel is listed in Table 5.2.2). The calculated ^{60}Co activity from these spacers was 66.7 curies for a burnup of 30,000 MWD/MTU and a cooling time of 18 years. Including this source with the total fuel gamma source for damaged fuel in Table 5.2.6 and dividing by the 80 inch rubble height provides a gamma source per inch of 3.47E+12 photon/s. Dividing the total neutron source for damaged fuel in Table 5.2.14 by 80 inches provides a neutron source per inch of 3.93E+5 neutron/s. These values are both bounded by the BWR design basis fuel gamma source per inch and neutron source per inch values of 5.03E+12 photon/s and 6.63E+5 neutron/s. These BWR design basis values were calculated by dividing the total source strengths as calculated from Tables 5.2.5 and 5.2.13 (39,500 MWD/MTU and 14 year cooling values) by the active fuel length of 144 inches. Therefore, the design basis damaged fuel assembly is bounded by the design basis intact BWR fuel assembly for accident conditions. No explicit analysis of the damaged fuel dose rates are provided as they are bounded by the intact fuel analysis.

5.4.3 Mixed Oxide Fuel Evaluation

The source terms calculated for the Dresden Unit 1 GE 6x6 MOX fuel assemblies can be compared to the design basis source terms for the BWR assemblies which demonstrates that the MOX fuel source terms are bounded by the design basis source terms and no additional shielding analysis is needed.

Since the active fuel length of the MOX fuel assemblies is shorter than the active fuel length of the design basis fuel, the source terms must be compared on a per inch basis. Including the ^{60}Co source from grid spacers as calculated in the previous subsection (66.7 curies) with the total fuel

gamma source for the MOX fuel in Table 5.2.16 and dividing by the 110 inch active fuel height provides a gamma source per inch of 2.41E+12 photons/s. Dividing the total neutron source for the MOX fuel assemblies in Table 5.2.17 by 110 inches provides a neutron source strength per inch of 3.67E+5 neutrons/s. These values are both bounded by the BWR design basis fuel gamma source per inch and neutron source per inch values of 5.03E+12 photons/s and 6.63E+5 neutrons/s. These BWR design basis values were calculated by dividing the total source strengths as calculated from Tables 5.2.5 and 5.2.13 (39,500 MWD/MTU and 14 year cooling values) by the active fuel length of 144 inches. This comparison shows that the MOX fuel source terms are bound by the design basis source terms. Therefore, no explicit analysis of dose rates is provided for MOX fuel.

Since the MOX fuel assemblies are Dresden Unit 1 6x6 assemblies, they can also be considered as damaged fuel. Using the same methodology as described in Subsection 5.4.2, the source term for the MOX fuel is calculated on a per inch basis assuming a post-accident rubble height of 80 inches. The resulting gamma and neutron source strengths are 3.31E+12 photons/s and 5.05E+5 neutrons/s. These values are also bounded by the design basis fuel gamma source per inch and neutron source per inch. Therefore, no explicit analysis of dose rates is provided for MOX fuel in a post-accident configuration.

5.4.4 Stainless Steel Clad Fuel Evaluation

Tables 5.4.22 through 5.4.24 present the dose rates from the stainless steel clad fuel at various dose locations around the HI-STAR 100 overpack for the MPC-24 and the MPC-68 for normal and hypothetical accident conditions. These dose rates are below the regulatory limits indicating that these fuel assemblies are acceptable for transport.

As described in Subsection 5.2.3, the source term for the stainless steel fuel was calculated conservatively with an artificial active fuel length of 144 inches. The end fitting masses of the stainless steel clad fuel are also assumed to be identical to the end fitting masses of the zircaloy clad fuel. In addition, the fuel assembly configuration used in the MCNP calculations was identical to the configuration used for the design basis fuel assemblies as described in Table 5.3.1.

5.4.5 Dresden Unit 1 Antimony-Beryllium Neutron Sources

Dresden Unit 1 has antimony-beryllium neutron sources which are placed in the water rod location of their fuel assemblies. These sources are steel rods which contain a cylindrical antimony-beryllium source which is 77.25 inches in length. The steel rod is approximately 95 inches in length. Information obtained from Dresden Unit 1 characterizes these sources in the following manner: "About one-quarter pound of beryllium will be employed as a special neutron source material. The beryllium produces neutrons upon gamma irradiation. The gamma rays for

the source at initial start-up will be provided by neutron-activated antimony (about 865 curies). The source strength is approximately 1E+8 neutrons/second."

As stated above, beryllium produces neutrons through gamma irradiation and in this particular case antimony is used as the gamma source. The threshold gamma energy for producing neutrons from beryllium is 1.666 MeV. The outgoing neutron energy increases as the incident gamma energy increases. Sb-124, which decays by Beta decay with a half life of 60.2 days, produces a gamma of energy 1.69 MeV which is just energetic enough to produce a neutron from beryllium. Approximately 54% of the Beta decays for Sb-124 produce gammas with energies greater than or equal to 1.69 MeV. Therefore, the neutron production rate in the neutron source can be specified as 5.8E-6 neutrons per gamma (1E+8/865/3.7E+10/0.54) with energy greater than 1.666 MeV or 1.16E+5 neutrons/curie (1E+8/865) of Sb-124.

With the short half life of 60.2 days all of the initial Sb-124 is decayed and any Sb-124 that was produced while the neutron source was in the reactor is also decayed since these neutron sources are assumed to have the same minimum cooling time as the Dresden 1 fuel assemblies (array classes 6x6A, 6x6B, 6x6C, and 8x8A) of 18 years. Therefore, there are only two possible gamma sources which can produce neutrons from this antimony-beryllium source. The first is the gammas from the decay of fission products in the fuel assemblies in the MPC. The second gamma source is from Sb-124 which is being produced in the MPC from neutron activation from neutrons from the decay of fission products.

MCNP calculations were performed to determine the gamma source as a result of decay gammas from fuel assemblies and Sb-124 activation. The calculations explicitly modeled the 6x6 fuel assembly described in Table 5.2.2. A single fuel rod was removed and replaced by a guide tube. In order to determine the amount of Sb-124 that is being activated from neutrons in the MPC it was necessary to estimate the amount of antimony in the neutron source. The O.D. of the source was assumed to be the I.D. of the steel rod encasing the source (0.345 in.). The length of the source is 77.25 inches. The beryllium is assumed to be annular in shape encompassing the antimony. Using the assumed O.D. of the beryllium and the mass and length, the I.D. of the beryllium was calculated to be 0.24 inches. The antimony is assumed to be a solid cylinder with an O.D. equal to the I.D. of the beryllium. These assumptions are conservative since the antimony and beryllium are probably encased in another material which would reduce the mass of antimony. A larger mass of antimony is conservative since the calculated activity of Sb-124 is directly proportional to the initial mass of antimony.

The number of gammas from fuel assemblies with energies greater than 1.666 MeV entering the 77.25 inch long neutron source was calculated to be 1.04E+8 gammas/sec which would produce a neutron source of 603.2 neutrons/sec (1.04E+8 * 5.8E-6). The steady state amount of Sb-124 activated in the antimony was calculated to be 39.9 curies. This activity level would produce a neutron source of 4.63E+6 neutrons/sec (39.9 * 1.16E+5) or 6.0E+4 neutrons/sec/inch (4.63E+6/77.25). These calculations conservatively neglect the reduction in antimony and

beryllium which would have occurred while the neutron sources were in the core and being irradiated at full reactor power.

Since this is a localized source (77.25 inches in length) it is appropriate to compare the neutron source per inch from the design basis Dresden Unit 1 fuel assembly, 6x6, containing an Sb-Be neutron source to the design basis fuel neutron source per inch. This comparison, presented in Table 5.4.25, demonstrates that a Dresden Unit 1 fuel assembly containing an Sb-Be neutron source is bounded by the design basis fuel.

As stated above, the Sb-Be source is encased in a steel rod. Therefore, the gamma source from the activation of the steel was considered assuming a burnup of 120,000 MWD/MTU which is the maximum burnup assuming the Sb-Be source was in the reactor for the entire 18 year life of Dresden Unit 1. The cooling time assumed was 18 years which is the minimum cooling time for Dresden Unit 1 fuel. The source from the steel was bounded by the design basis fuel assembly. In conclusion, transport of a Dresden Unit 1 Sb-Be neutron source in a Dresden Unit 1 fuel assembly is acceptable and bounded by the current analysis.

5.4.6 Thoria Rod Canister

Based on a comparison of the gamma spectra from Tables 5.2.30 and 5.2.6 for the thoria rod canister and design basis 6x6 fuel assembly, respectively, it is difficult to determine if the thoria rods will be bounded by the 6x6 fuel assemblies. However, it is obvious that the neutron spectra from the 6x6, Table 5.2.14, bounds the thoria rod neutron spectra, Table 5.2.31, with a significant margin. In order to demonstrate that the gamma spectrum from the single thoria rod canister is bounded by the gamma spectrum from the design basis 6x6 fuel assembly, the gamma dose rate on the outer radial surface of the overpack was estimated conservatively assuming an MPC full of thoria rod canisters. This gamma dose rate was compared to an estimate of the dose rate from an MPC full of design basis 6x6 fuel assemblies. The gamma dose rate from the 6x6 fuel was higher than the dose rate from an MPC full of thoria rod canisters. This in conjunction with the significant margin in neutron spectrum and the fact that there is only one thoria rod canister clearly demonstrates that the thoria rod canister is acceptable for transport in the MPC-68 or the MPC-68F.

5.4.7 Trojan Fuel Contents

Tables 5.4.26 through 5.4.28 present the results for the Trojan MPC-24E for normal surface and 2 meter as well as accident results. These results are presented for a single burnup and cooling time of 42,000 MWD/MTU and 16 year cooling. This burnup and cooling time combination is shown in Tables 5.2.33 through 5.2.35 to bound the other allowable burnup and cooling time combinations for Trojan fuel. Since the Trojan MPCs will contain BPRAs, RCCAs, and TPDs, the source from these devices was considered in the analysis. The source from BPRAs and TPDs were added to the fuel source in the appropriate location. The mass from these devices was

conservatively neglected. Separate calculations were performed for the BPRAs and the TPDs since both devices can not be present in the same fuel assembly. The results presented in Tables 5.4.26 through 5.4.28 represent the configuration (fuel plus non-fuel hardware: BPRA or TPD) that produces the highest dose rate at that location. Separate results for the different non-fuel hardware are not provided. Separate MCNP calculations were performed for the consideration of the RCCAs since this source is localized at the bottom of the MPC. The results for the RCCAs indicate that the presence of RCCAs will increase the dose rate on the surface of the overpack by a maximum of 1.3 mrem/hr and the dose rate at 2 meters will increase by a maximum of 0.08 mrem/hr for normal conditions. During accident conditions the dose rate will increase by a maximum of 6 mrem/hr with the presence of RCCAs.

These dose rates are less than the regulatory limits and therefore the Trojan contents are approved for transportation.

5.4.8 Trojan Antimony-Beryllium Neutron Sources

The analysis of the Trojan secondary antimony-beryllium neutron sources was performed in a manner very similar to that described above in Subsection 5.4.5. The secondary sources are basically BPRAs with four rods containing the antimony-beryllium with a length of 88 inches in each rod. As mentioned in Subsection 5.4.5, the antimony-beryllium source is a regenerative source in which the antimony is activated and the gammas released from the antimony induce a gamma,n reaction in the beryllium.

The steady state production of neutrons from this antimony-beryllium source was conservatively calculated in the MPC using an approach very similar to that described in Subsection 5.4.5. The depletion of antimony from the operation in the reactor core was conservatively neglected in the analysis. MCNP calculations were performed with explicitly modeled fuel assemblies in a Trojan MPC model to calculate the steady state activity of Sb-124 in the antimony-beryllium source due to the neutrons from the spent fuel. This activity level was used in a subsequent MCNP calculation to determine the gamma,n reaction rate in the beryllium. The gamma,n cross section for beryllium, which exhibits peaks at 1.5E-3 with lows at approximately 0.3E-3 barns, was used in MCNP as a reaction rate multiplier for the flux tallies. Additionally, the gamma,n reaction rate due to gammas from the spent fuel was determined. In the latter case, gammas from the spent fuel with energies up to 11 MeV were considered in the analysis compared to an upper limit of 3 MeV for the cask dose rate analysis. Finally, the gamma,n reaction rate was converted to neutrons/sec to yield the neutron source per secondary source assembly. In this conversion process the spectrum of neutrons emitted from the Sb-Be source was determined based on the energy spectrum of the gammas reacting in the beryllium [5.4.7]. The neutron source strength per secondary source assembly was calculated to be 9.9E+5 neutrons/sec with more than 99% of these having an upper energy of 0.03 MeV. The remaining 1% of the secondary source neutrons had energies up to 0.74 MeV. This is a conservative estimate of the neutrons/sec from the

secondary source because it neglects depletion of the antimony that has occurred during core operation and it assumes that all assemblies in the MPC are design basis Trojan fuel assemblies.

In order to determine the impact of the secondary neutron sources on the dose rates, MCNP calculations were performed. Since the dose rate that is closest to the regulatory limit is at 2 meters from the overpack, this was the only location considered in the analysis. Rather than calculate the average dose rate around the overpack at the 2 meter location, the dose rate was calculated for a specific location. Figure 5.4.2 shows the location where the dose rate was calculated. This location (an 8.2 inch diameter cylinder) is at 2 meters from the transport vehicle on a line drawn from the center of the MPC through the center of a corner assembly. The dose rate in this cylinder was calculated using the same axial segmentation as in the design basis calculations. In this analysis, the corner assembly was the only assembly considered to have the secondary source assembly. This choice of assembly position and dose location bounds all other possible locations for the single Trojan secondary source assembly permitted in any MPC.

The dose rates were calculated for the following combinations of fuel assemblies and non-fuel hardware inserts. In all dose rate calculations, both the neutron and gamma source from the secondary sources was considered.

1. One fuel assembly with secondary source assembly from cycles 1-4 and the remaining 23 fuel assemblies with BPRAs.
2. One fuel assembly with secondary source assembly from cycles 1-4 and the remaining 23 fuel assemblies with TPDs.
3. One fuel assembly with secondary source assembly from cycles 4-14 and the remaining 23 fuel assemblies with BPRAs.
4. One fuel assembly with secondary source assembly from cycles 4-14 and the remaining 23 fuel assemblies with TPDs.

The worst case dose rate from the configurations listed above was less than 9.8 mrem/hr from configuration 4. This value was conservatively calculated assuming all fuel assemblies were identical design basis Trojan fuel assemblies with design basis Trojan non-fuel hardware. This dose rate is slightly higher than the design basis dose rates for the Trojan fuel. However, this value is still below the regulatory limit of 10.0 mrem/hr. Therefore, the insertion of a single secondary source assembly into a Trojan MPC is acceptable for transport.

Table 5.4.1

FLUX-TO-DOSE CONVERSION FACTORS
(FROM [5.4.1])

Gamma Energy (MeV)	(rem/hr)/(photon/cm^2-s)
0.01	3.96E-06
0.03	5.82E-07
0.05	2.90E-07
0.07	2.58E-07
0.1	2.83E-07
0.15	3.79E-07
0.2	5.01E-07
0.25	6.31E-07
0.3	7.59E-07
0.35	8.78E-07
0.4	9.85E-07
0.45	1.08E-06
0.5	1.17E-06
0.55	1.27E-06
0.6	1.36E-06
0.65	1.44E-06
0.7	1.52E-06
0.8	1.68E-06
1.0	1.98E-06
1.4	2.51E-06
1.8	2.99E-06
2.2	3.42E-06

Table 5.4.1 (continued)

FLUX-TO-DOSE CONVERSION FACTORS
(FROM [5.4.1])

Gamma Energy (MeV)	(rem/hr)/(photon/cm^2-s)
2.6	3.82E-06
2.8	4.01E-06
3.25	4.41E-06
3.75	4.83E-06
4.25	5.23E-06
4.75	5.60E-06
5.0	5.80E-06
5.25	6.01E-06
5.75	6.37E-06
6.25	6.74E-06
6.75	7.11E-06
7.5	7.66E-06
9.0	8.77E-06
11.0	1.03E-05
13.0	1.18E-05
15.0	1.33E-05

Table 5.4.1 (continued)

FLUX-TO-DOSE CONVERSION FACTORS
(FROM [5.4.1])

Neutron Energy (MeV)	Quality Factor	(rem/hr)/(n/cm^2-s)†
2.5E-8	2.0	3.67E-6
1.0E-7	2.0	3.67E-6
1.0E-6	2.0	4.46E-6
1.0E-5	2.0	4.54E-6
1.0E-4	2.0	4.18E-6
1.0E-3	2.0	3.76E-6
1.0E-2	2.5	3.56E-6
0.1	7.5	2.17E-5
0.5	11.0	9.26E-5
1.0	11.0	1.32E-4
2.5	9.0	1.25E-4
5.0	8.0	1.56E-4
7.0	7.0	1.47E-4
10.0	6.5	1.47E-4
14.0	7.5	2.08E-4
20.0	8.0	2.27E-4

† Includes the Quality Factor.

Table 5.4.2

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Table 5.4.3

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Table 5.4.4

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Table 5.4.5

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Table 5.4.6

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Table 5.4.7

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Table 5.4.8

TOTAL DOSE RATES
DOSE LOCATION ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-24 DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	24,500 MWD/MTU 6 Year Cooling (mrem/hr)	29,500 MWD/MTU 7 Year Cooling (mrem/hr)	34,500 MWD/MTU 9 Year Cooling (mrem/hr)	39,500 MWD/MTU 11 Year Cooling (mrem/hr)	44,500 MWD/MTU 14 Year Cooling (mrem/hr)
2a	49.81	50.88	46.38	43.02	46.19
3a	95.80	108.16	113.72	124.43	138.47
1	35.33	37.42	36.18	35.89	34.85
2	29.01	28.87	26.11	26.57	28.24
3	27.02	29.30	29.26	29.94	30.19
4	23.73	26.05	26.43	27.40	28.05
5	1.04	1.70	2.51	3.36	4.33
6	120.60	122.66	111.08	102.27	89.54
10CFR71.47 Limit	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)

† Refer to Figure 5.1.1.

Table 5.4.9

TOTAL DOSE RATES
DOSE LOCATION ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-68 DESIGN BASIS ZIRCALOY CLAD FUEL AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 8 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 19 Year Cooling (mrem/hr)**
2a	44.53	44.60	50.12	52.65	55.25
3a	132.09	129.62	132.20	115.66	103.70
1	34.23	35.33	37.96	35.72	33.64
2	24.21	27.97	31.12	32.05	33.07
3	32.25	31.43	31.69	27.33	22.81
4	30.52	29.69	29.91	25.74	21.42
5	0.71	1.16	1.78	2.28	2.86
6	99.53	95.87	95.27	80.46	64.92
10CFR71.47 Limit	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)

† Refer to Figure 5.1.1.

Table 5.4.10

TOTAL DOSE RATES
DOSE LOCATION AT TWO METERS FOR NORMAL CONDITIONS
MPC-24 DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 6 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 7 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 14 Year Cooling (mrem/hr)**
1	7.41	7.61	7.26	7.31	7.27
2	9.57	9.45	8.77	8.95	9.10
3	6.72	6.93	6.61	6.64	6.59
4	6.16	6.39	6.13	6.16	6.11
5	0.10	0.17	0.24	0.32	0.41
6	8.11	8.01	6.91	5.99	4.75
10CFR71.47 Limit	10.00	10.00	10.00	10.00	10.00

† Refer to Figure 5.1.1.

Table 5.4.11

TOTAL DOSE RATES
DOSE LOCATION AT TWO METERS FOR NORMAL CONDITIONS
MPC-68 DESIGN BASIS ZIRCALOY CLAD FUEL AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 8 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 19 Year Cooling (mrem/hr)**
1	6.58	7.05	7.59	7.34	7.07
2	8.03	8.94	9.62	9.55	9.39
3	6.31	6.44	6.62	6.02	5.36
4	6.09	6.15	6.32	5.70	5.03
5	0.08	0.13	0.20	0.26	0.32
6	5.67	5.25	4.94	3.84	2.65
10CFR71.47 Limit	10.00	10.00	10.00	10.00	10.00

† Refer to Figure 5.1.1.

Table 5.4.12

TOTAL DOSE RATES
DOSE LOCATION AT ONE METER FOR ACCIDENT CONDITIONS
MPC-24 DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 6 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 7 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 14 Year Cooling (mrem/hr)**
1	76.55	97.55	117.95	141.21	166.93
2	153.26	224.23	307.31	399.33	504.35
3	49.37	64.41	79.67	96.85	116.00
4	35.97	47.12	58.44	71.10	85.20
5	4.06	6.59	9.62	12.83	16.51
6	685.36	687.08	605.96	539.45	447.78
10CFR71.51 Limit	1000.00	1000.00	1000.00	1000.00	1000.00

† Refer to Figure 5.1.2.

Table 5.4.13

TOTAL DOSE RATES
DOSE LOCATION AT ONE METER FOR ACCIDENT CONDITIONS
MPC-68 DESIGN BASIS ZIRCALOY CLAD FUEL AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 8 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 19 Year Cooling (mrem/hr)**
1	82.43	108.56	145.23	169.25	198.52
2	179.75	275.87	403.87	504.00	622.86
3	46.51	59.30	77.64	88.84	102.65
4	36.57	45.32	58.13	65.34	74.36
5	2.84	4.55	6.92	8.80	11.04
6	564.75	530.59	509.65	408.69	300.71
10CFR71.51 Limit	1000.00	1000.00	1000.00	1000.00	1000.00

† Refer to Figure 5.1.2.

Table 5.4.14

PEAK-TO-AVERAGE RATIOS FOR THE DOSE COMPONENTS AT VARIOUS LOCATIONS

Location	Fuel Gammas	Gammas from Neutrons	^{60}Co Gammas	Neutron
MPC-24				
Surface				
Pocket Trunnion	0.081	0.262	0.075	6.695
2a	0.713	0.955	0.407	2.362
3a	1.317	1.011	1.005	1.177
2 meter				
Pocket Trunnion	1.109	1.232	1.059	0.809
2	1.034	0.974	1.086	0.990
MPC-68				
Surface				
Pocket Trunnion	0.070	0.432	0.074	7.340
2a	0.737	0.977	1.123	2.284
3a	0.908	0.816	1.217	0.940
2 meter				
Pocket Trunnion	1.121	0.982	1.144	1.171
2	1.070	0.939	1.146	0.950

Table 5.4.15

DOSE RATES FOR NORMAL CONDITIONS SHOWING THE EFFECT OF PEAKING

Dose Point† Location	Fuel Gammas (mrem/hr)	Gammas from Neutrons (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Total (mrem/hr)
MPC-24					
Surface 44,500 MWD/MTU 14-Year Cooling					
Pocket Trunnion	0.15	0.37	1.98	97.92	100.42
2a	12.30	6.35	0.00	52.60	71.26
3a	0.40	0.67	28.67	128.27	158.01
2 meter 24,500 MWD/MTU 6-Year Cooling					
Pocket Trunnion	4.03	0.17	3.50	0.64	8.34
2	7.55	0.21	1.26	0.87	9.90
MPC-68					
Surface 34,500 MWD/MTU 11-Year Cooling					
Pocket Trunnion	0.25	0.45	1.97	77.42	80.09
2a	19.24	5.35	0.02	42.33	66.93
3a	0.33	0.12	115.34	34.69	150.49
2 meter 34,500 MWD/MTU 11-Year Cooling					
Pocket Trunnion	3.23	0.46	2.06	3.03	8.77
2	5.80	0.68	0.74	2.69	9.91

† Refer to Figure 5.1.1.

Table 5.4.16

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Table 5.4.17

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Table 5.4.18

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Table 5.4.19

TOTAL DOSE RATES
DOSE LOCATION ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-24 DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 13 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 15 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 18 Year Cooling (mrem/hr)**
2a	42.91	42.11	43.11	45.08	46.24
3a	69.70	74.06	83.00	96.79	111.87
1	25.77	25.19	25.54	26.31	26.75
2	26.97	26.54	27.34	28.35	28.62
3	19.70	19.86	20.87	22.23	23.47
4	17.23	17.64	18.84	20.37	21.85
5	0.92	1.46	2.16	2.89	3.73
6	84.38	77.61	72.77	69.20	63.58
10CFR71.47 Limit	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)

† Refer to Figure 5.1.1.

Table 5.4.20

TOTAL DOSE RATES
DOSE LOCATION AT TWO METERS FOR NORMAL CONDITIONS
MPC-24 DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 13 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 15 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 18 Year Cooling (mrem/hr)**
1	6.42	6.24	6.29	6.42	6.40
2	9.51	9.16	9.18	9.27	9.09
3	5.68	5.52	5.58	5.70	5.71
4	5.08	4.96	5.03	5.16	5.19
5	0.09	0.14	0.21	0.28	0.35
6	5.67	5.00	4.40	3.88	3.17
10CFR71.47 Limit	10.00	10.00	10.00	10.00	10.00

† Refer to Figure 5.1.1.

Table 5.4.21

TOTAL DOSE RATES
DOSE LOCATION AT ONE METER FOR ACCIDENT CONDITIONS
MPC-24 DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 11 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 13 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 15 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 18 Year Cooling (mrem/hr)**
1	62.33	76.36	95.99	117.23	140.85
2	145.00	201.06	275.44	354.15	442.83
3	40.70	51.15	65.54	81.04	98.36
4	29.39	37.13	47.76	59.20	72.01
5	3.59	5.63	8.26	11.03	14.21
6	478.28	429.22	388.56	354.69	306.90
10CFR71.51 Limit	1000.00	1000.00	1000.00	1000.00	1000.00

† Refer to Figure 5.1.2.

Table 5.4.22

DOSE RATES FOR
MPC-68 DESIGN BASIS STAINLESS STEEL CLAD FUEL
22,500 MWD/MTU AND 16-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
Dose Location at Surface for Normal Condition				
1	2.91	9.19	1.00	13.09
2a	39.68	0.00	1.20	40.88
3a	0.62	40.84	2.60	44.07
4	0.45	9.49	0.53	10.47
5	0.01	0.01	0.11	0.14
6	2.35	31.19	1.40	34.93
10CFR71.47 Limit				200.00
Dose Location at Two Meters for Normal Condition				
1	3.45	1.00	0.17	4.63
2	7.71	0.27	0.19	8.18
3	2.26	1.35	0.12	3.73
4	1.67	1.43	0.11	3.21
5	0.00	0.00	0.01	0.02
6	0.20	1.82	0.03	2.05
10CFR71.47 Limit				10.00
Dose Location at One Meter for Accident Condition				
1	9.43	10.90	7.95	28.29
2	46.22	0.23	25.97	72.42
3	3.58	7.41	4.06	15.05
4	2.00	6.60	2.91	11.51
5	0.01	0.07	0.48	0.57
6	11.14	183.23	5.34	199.71
10CFR71.51 Limit				1000.00

Note: The more conservative limit of 200 mrem/hr was applied for dose locations 2a and 3a while dose locations 2 and 3 were not analyzed.

† Refer to Figures 5.1.1 and 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.4.23

DOSE RATES FOR
MPC-24 DESIGN BASIS STAINLESS STEEL CLAD FUEL
30,000 MWD/MTU AND 19-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
Dose Location at Surface for Normal Condition				
1	2.40	5.54	4.27	12.22
2a	35.54	0.01	4.41	39.96
3a	0.66	11.31	24.60	36.57
4	0.73	3.65	4.11	8.49
5	0.11	0.01	0.86	0.98
6	4.19	21.13	7.14	32.46
10CFR71.47 Limit				200.00
Dose Location at Two Meters for Normal Condition				
1	3.05	0.69	0.76	4.50
2	7.23	0.23	0.83	8.29
3	2.47	0.66	0.72	3.85
4	1.95	0.67	0.69	3.30
5	0.01	0.00	0.08	0.09
6	0.36	1.48	0.18	2.02
10CFR71.47 Limit				10.00
Dose Location at One Meter for Accident Condition				
1	7.57	6.83	32.78	47.18
2	39.78	0.24	108.52	148.54
3	4.96	3.96	23.27	32.19
4	2.85	3.00	17.13	22.99
5	0.02	0.05	3.69	3.76
6	22.73	123.24	28.03	174.00
10CFR71.51 Limit				1000.00

Note: The more conservative limit of 200 mrem/hr was applied for dose locations 2a and 3a while dose locations 2 and 3 were not analyzed.

† Refer to Figures 5.1.1 and 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.4.24

DOSE RATES FOR
MPC-24 DESIGN BASIS STAINLESS STEEL CLAD FUEL
40,000 MWD/MTU AND 24-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
Dose Location at Surface for Normal Condition				
1	2.12	5.80	11.10	19.02
2a	28.04	0.00	13.06	41.10
3a	0.78	11.82	63.88	76.48
4	0.66	3.82	10.68	15.16
5	0.29	0.01	2.24	2.53
6	4.28	22.10	18.54	44.92
10CFR71.47 Limit				200.00
Dose Location at Two Meters for Normal Condition				
1	2.55	0.72	1.98	5.26
2	5.82	0.24	2.23	8.29
3	2.06	0.69	1.86	4.62
4	1.64	0.70	1.78	4.11
5	0.02	0.00	0.22	0.24
6	0.29	1.55	0.47	2.31
10CFR71.47 Limit				10.00
Dose Location at One Meter for Accident Condition				
1	5.88	7.14	85.12	98.14
2	30.69	0.25	281.83	312.76
3	3.85	4.14	60.42	68.41
4	2.24	3.14	44.48	49.86
5	0.04	0.05	9.57	9.66
6	17.44	128.89	72.74	219.07
10CFR71.51 Limit				1000.00

Note: The more conservative limit of 200 mrem/hr was applied for dose locations 2a and 3a while dose locations 2 and 3 were not analyzed.

† Refer to Figures 5.1.1 and 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.4.25

COMPARISON OF NEUTRON SOURCE PER INCH PER SECOND FOR DESIGN BASIS 7X7 FUEL AND DESIGN BASIS DRESDEN UNIT 1 FUEL

Assembly	**Active fuel length (inch)**	**Neutrons per sec per inch**	**Neutrons per sec per inch with Sb-Be source**	**Reference for neutrons per sec per inch**
7x7 design basis	144	6.63E+5	N/A	Table 5.2.13 39.5 GWD/MTU and 14 year cooling
6x6 design basis	110	2.85E+5	3.45E+5	Table 5.2.14
6x6 design basis MOX	110	3.67E+5	4.27E+5	Table 5.2.17

Table 5.4.26

DOSE RATES AT THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-24 WITH TROJAN ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
42,000 MWD/MTU AND 16-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)	10 CFR 71.47 Limit
2a	3.72	2.48	38.39	2.25	46.84	1000
3a	0.39	0.07	14.34	49.81	64.61	1000
1	1.62	1.09	4.54	14.43	21.68	200
2	10.94	7.72	0.05	9.69	28.40	200
3	0.62	0.32	10.66	8.00	19.60	200
4	0.36	0.16	5.01	7.80	13.34	200
5	0.34†††	-	0.06	3.17	3.58	200
6	6.99†††	-	21.45	23.26	51.70	200

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.4.27

DOSE RATES AT TWO METERS FROM THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-24 WITH TROJAN ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
42,000 MWD/MTU AND 16-YEAR COOLING

Dose Point† Location	Fuel Gammas†† (mrem/hr)	Gammas from Incore Spacers (mrem/hr)	^{60}Co Gammas (mrem/hr)	Neutrons (mrem/hr)	Totals (mrem/hr)
1	1.52	1.11	0.55	2.52	5.69
2	3.41	2.53	0.64	2.67	9.24
3	1.20	0.82	2.31	1.71	6.05
4	0.97	0.62	2.13	1.50	5.21
5	0.02†††	-	0.05	0.27	0.34
6	0.56†††	-	2.05	0.87	3.49
10CFR71.47 Limit					10.00

† Refer to Figure 5.1.1.

†† Gammas generated by neutron capture are included with fuel gammas.

††† Gammas from incore spacers are included with fuel gammas.

Table 5.4.28

DOSE RATES AT ONE METER FOR ACCIDENT CONDITIONS
MPC-24 WITH TROJAN ZIRCALOY CLAD FUEL WITH NON- ZIRCALOY INCORE SPACERS
42,000 MWD/MTU AND 16-YEAR COOLING

Dose Point† Location	**Fuel Gammas†† (mrem/hr)**	**^{60}Co Gammas (mrem/hr)**	**Neutrons (mrem/hr)**	**Totals (mrem/hr)**
1	7.01	5.69	106.18	118.88
2	31.31	0.30	356.39	387.99
3	3.27	15.94	69.43	88.64
4	1.86	8.65	49.17	59.68
5	0.11	0.25	12.42	12.78
6	34.74	128.20	82.48	245.42
10CFR71.51 Limit				1000.00

† Refer to Figure 5.1.2.

†† Gammas generated by neutron capture and gammas from incore spacers are included with fuel gammas.

Table 5.4.29

TOTAL DOSE RATES
DOSE LOCATION ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-32 DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 8 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 12 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 19 Year Cooling (mrem/hr)**
2a	62.31	66.79	58.99	59.34	50.90
3a	162.02	192.08	205.87	245.88	263.95
1	44.46	48.87	45.01	46.94	42.51
2	34.63	38.55	36.17	38.33	35.48
3	40.30	46.47	46.08	50.81	49.68
4	37.52	43.47	43.40	48.09	47.31
5	2.40	3.97	5.66	7.60	9.11
6	144.35	150.66	126.87	122.14	97.35
10CFR71.47 Limit	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)

† Refer to Figure 5.1.1.

Table 5.4.30

TOTAL DOSE RATES
DOSE LOCATION AT TWO METERS FOR NORMAL CONDITIONS
MPC-32 DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	24,500 MWD/MTU 8 Year Cooling (mrem/hr)	29,500 MWD/MTU 9 Year Cooling (mrem/hr)	34,500 MWD/MTU 12 Year Cooling (mrem/hr)	39,500 MWD/MTU 14 Year Cooling (mrem/hr)	44,500 MWD/MTU 19 Year Cooling (mrem/hr)
1	7.85	8.67	8.01	8.43	7.69
2	8.22	9.28	8.86	9.65	9.19
3	7.83	8.83	8.44	9.10	8.59
4	7.50	8.48	8.14	8.79	8.34
5	0.22	0.37	0.52	0.70	0.83
6	7.98	8.02	6.27	5.60	3.82
10CFR71.47 Limit	10.00	10.00	10.00	10.00	10.00

† Refer to Figure 5.1.1.

Table 5.4.31

TOTAL DOSE RATES
DOSE LOCATION AT ONE METER FOR ACCIDENT CONDITIONS
MPC-32 DESIGN BASIS ZIRCALOY CLAD FUEL WITH ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 8 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 9 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 12 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**44,500 MWD/MTU 19 Year Cooling (mrem/hr)**
1	91.38	117.99	134.85	162.88	176.78
2	150.55	230.95	310.10	406.55	477.18
3	66.27	89.91	108.35	134.66	150.49
4	49.53	66.55	79.40	98.17	109.14
5	9.17	15.09	21.41	28.69	34.38
6	802.16	817.16	656.05	601.72	437.06
10CFR71.51 Limit	1000.00	1000.00	1000.00	1000.00	1000.00

† Refer to Figure 5.1.2.

Table 5.4.32

TOTAL DOSE RATES
DOSE LOCATION ON THE SURFACE OF THE HI-STAR 100 SYSTEM FOR NORMAL CONDITIONS
MPC-32 DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 12 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 16 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 19 Year Cooling (mrem/hr)**	**42,500 MWD/MTU 20 Year Cooling (mrem/hr)**
2a	40.66	40.41	42.78	42.27	44.54
3a	110.58	127.81	162.16	189.57	213.21
1	29.82	30.69	32.88	33.09	35.33
2	24.88	25.46	27.44	27.93	29.93
3	27.57	30.30	34.70	37.26	40.74
4	25.39	28.15	32.50	35.17	38.57
5	2.07	3.30	4.88	6.32	7.32
6	91.55	87.51	86.14	78.83	81.03
10CFR71.47 Limit	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)	1000.00 (2a,3a) 200.00 (1-6)

† Refer to Figure 5.1.1.

Table 5.4.33

TOTAL DOSE RATES
DOSE LOCATION AT TWO METERS FOR NORMAL CONDITIONS
MPC-32 DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 12 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 16 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 19 Year Cooling (mrem/hr)**	**42,500 MWD/MTU 20 Year Cooling (mrem/hr)**
1	6.55	6.64	6.95	6.78	7.13
2	8.99	9.14	9.54	9.21	9.61
3	6.38	6.65	7.17	7.23	7.71
4	5.93	6.21	6.76	6.88	7.36
5	0.19	0.30	0.45	0.58	0.67
6	4.95	4.46	4.05	3.32	3.24
10CFR71.47 Limit	10.00	10.00	10.00	10.00	10.00

† Refer to Figure 5.1.1.

Table 5.4.34

TOTAL DOSE RATES
DOSE LOCATION AT ONE METER FOR ACCIDENT CONDITIONS
MPC-32 DESIGN BASIS ZIRCALOY CLAD FUEL WITH NON-ZIRCALOY INCORE SPACERS
AT VARYING BURNUPS AND COOLING TIMES

Dose Point† Location	**24,500 MWD/MTU 12 Year Cooling (mrem/hr)**	**29,500 MWD/MTU 14 Year Cooling (mrem/hr)**	**34,500 MWD/MTU 16 Year Cooling (mrem/hr)**	**39,500 MWD/MTU 19 Year Cooling (mrem/hr)**	**42,500 MWD/MTU 20 Year Cooling (mrem/hr)**
1	69.80	86.91	110.36	128.98	144.97
2	143.48	202.73	279.80	346.19	395.59
3	52.15	68.42	90.21	108.35	122.82
4	38.31	49.93	65.54	78.49	88.90
5	7.89	12.51	18.46	23.84	27.60
6	500.54	460.23	430.39	368.33	367.17
10CFR71.51 Limit	1000.00	1000.00	1000.00	1000.00	1000.00

† Refer to Figure 5.1.2.

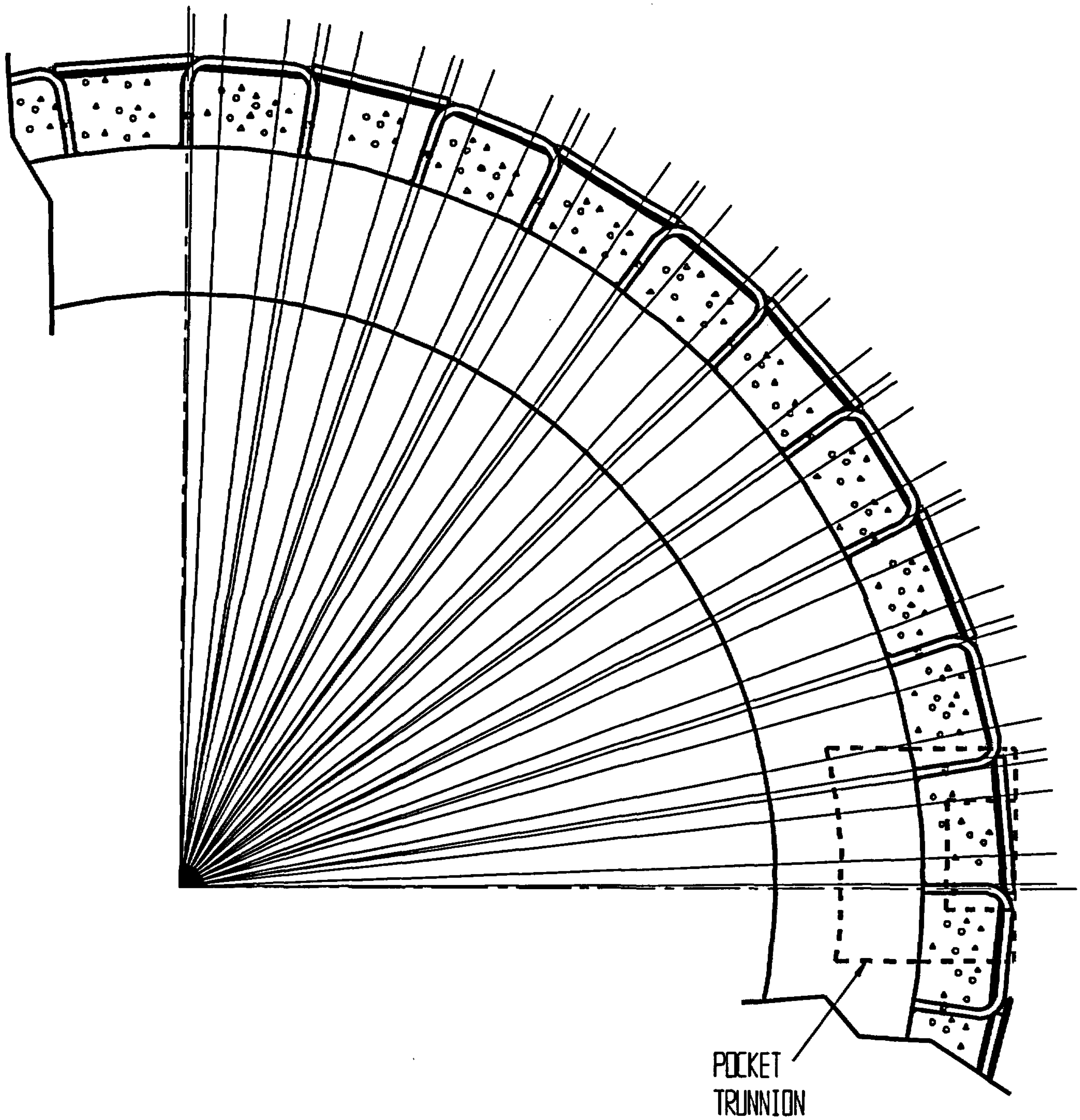

FIGURE 5.4.1; DEPICTION OF THE AZIMUTHAL SEGMENTATION OF THE OVERPACK USED IN ANALYZING NEUTRON AND PHOTON STREAMING

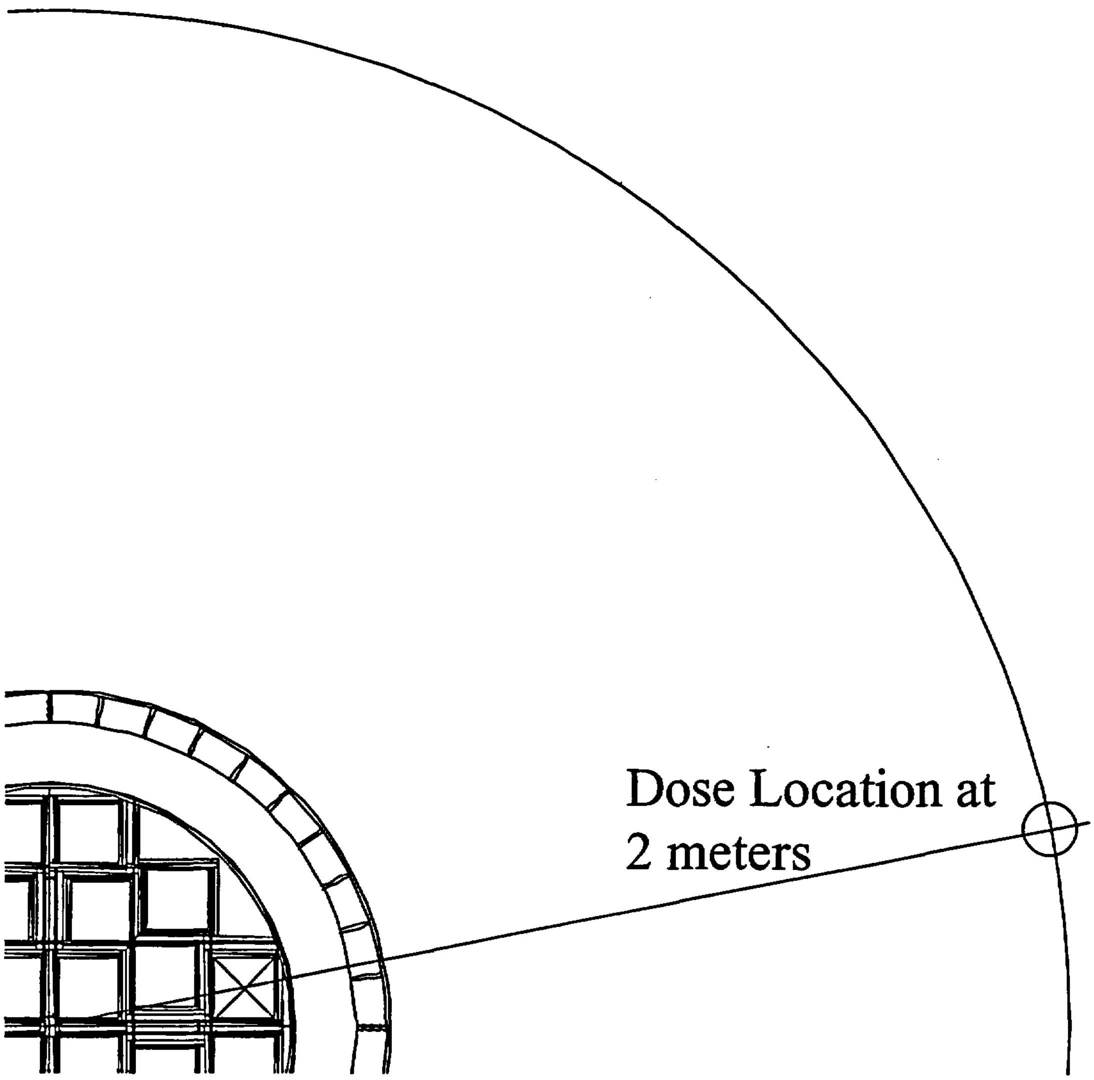

FIGURE 5.4.2: CROSS SECTIONAL VIEW OF THE TROJAN MPC-24E DESIGN SHOWING THE DOSE LOCATION USED FOR THE SECONDARY SOURCE CALCULATIONS.

5.5 REGULATORY COMPLIANCE

The analysis presented in this chapter has shown that the external radiation levels will not increase during normal conditions of transport consistent with the tests specified in 10CFR71.71. This chapter also confirms that the external dose rates from HI-STAR 100 System, when fully loaded with fuel assemblies that meet the acceptance criteria specified in Chapter 1, are less than the regulatory limits specified in 10CFR71.47.

This chapter also demonstrates that the maximum external radiation level at one meter from the external surface of the package does not exceed 1 Rem/hr (10 mSv/hr) during the hypothetical accident conditions consistent with the tests specified in 10CFR71.73.

Tables 5.5.1 through 5.5.3 summarize the maximum dose rates, including the effect of radiation peaking as discussed in Subsection 5.4.1, and demonstrate the HI-STAR 100 System's compliance with the regulatory requirements of 10CFR71.47 and 10CFR71.51. Since these dose rates include the effect of peaking, they may not be equivalent to values reported earlier in this chapter which were surface average dose rates. In these tables "Side" refers to the dose point location that has the maximum dose rate from locations 1-4 (including the pocket trunnion) on Figures 5.1.1 and 5.1.2; "Top" and "Bottom" refer to locations 5 and 6, respectively, on Figures 5.1.1 and 5.1.2. Dose location 2a and 3a from Figure 5.1.1 are not used in Tables 5.5.1 through 5.5.3. Since the maximum dose rate at each location is provided, the corresponding burnup and cooling time may be different between locations and therefore is not listed in the tables. Some of the dose rates in these tables are very close to the regulatory limit. These high dose rates are acceptable because the analysis has been demonstrated to be conservative. In addition, it is extremely unlikely that the casks would be loaded with all fuel assemblies containing the same identical burnup and cooling time analyzed. Finally, the ultimate demonstration of compliance with the 10 CFR 71 regulations will be the measurements that are taken before shipment of the fuel.

Table 5.5.1
MAXIMUM EXTERNAL DOSE RATES FOR THE
HI-STAR 100 SYSTEM CONTAINING THE MPC-24

Normal Conditions of Transport			
	External Surface of Package		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.51	1.35	110.43
Neutron	3.82	78.65	12.23
Total	4.33	80.00	122.66
10 CFR 71.47(b)(1) Limit	200	200	200
	2 Meters from Vehicle Outer Surface ††		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.04	9.04	7.92
Neutron	0.37	0.87	0.19
Total	0.41	9.91	8.11
10 CFR 71.47(b)(3) Limit	10	10	10
Hypothetical Accident Conditions			
	1 Meter from Surface of Package †††		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.18	23.43	639.09
Neutron	16.33	480.92	47.99
Total	16.51	504.35	687.08
10 CFR 71.51(a)(2) Limit	1000	1000	1000

† This includes fuel gammas, gammas from hardware activation including incore spacers, and gammas generated by neutron capture.

†† The vehicle outer surface is the outer radial surface of the impact limiters, the end of the top impact limiter, and 9 feet from the end of the bottom impact limiter.

††† The impact limiters are not present.

Table 5.5.2

MAXIMUM EXTERNAL DOSE RATES FOR THE
HI-STAR 100 SYSTEM CONTAINING THE MPC-32

Normal Conditions of Transport			
	External Surface of Package		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.90	1.19	129.27
Neutron	8.21	112.38	21.39
Total	9.11	113.57	150.66
10 CFR 71.47(b)(1) Limit	200	200	200
	2 Meters from Vehicle Outer Surface ††		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.06	5.89	7.52
Neutron	0.77	4.09	0.50
Total	0.83	9.98	8.02
10 CFR 71.47(b)(3) Limit	10	10	10
Hypothetical Accident Conditions			
	1 Meter from Surface of Package †††		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.22	21.45	739.52
Neutron	34.16	455.73	77.64
Total	34.38	477.18	817.16
10 CFR 71.51(a)(2) Limit	1000	1000	1000

† This includes fuel gammas, gammas from hardware activation including incore spacers, and gammas generated by neutron capture.

†† The vehicle outer surface is the outer radial surface of the impact limiters, the end of the top impact limiter, and 9 feet from the end of the bottom impact limiter.

††† The impact limiters are not present.

Table 5.5.3
MAXIMUM EXTERNAL DOSE RATES FOR THE
HI-STAR 100 SYSTEM CONTAINING THE MPC-68

Normal Conditions of Transport			
	External Surface of Package		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.33	1.15	91.87
Neutron	2.53	99.04	7.66
Total	2.86	100.19	99.53
10 CFR 71.47(b)(1) Limit	200	200	200
	2 Meters from Vehicle Outer Surface ††		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.03	5.92	5.48
Neutron	0.29	4.05	0.19
Total	0.32	9.97	5.67
10 CFR 71.47(b)(3) Limit	10	10	10
Hypothetical Accident Conditions			
	1 Meter from Surface of Package †††		
Radiation (mrem/hr)	**Top**	**Side**	**Bottom**
Gamma†	0.11	22.15	535.29
Neutron	10.93	600.71	29.46
Total	11.04	622.86	564.75
10 CFR 71.51(a)(2) Limit	1000	1000	1000

† This includes fuel gammas, gammas from hardware activation including incore spacers, and gammas generated by neutron capture.

†† The vehicle outer surface is the outer radial surface of the impact limiters, the end of the top impact limiter, and 9 feet from the end of the bottom impact limiter.

††† The impact limiters are not present.

5.6 REFERENCES

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APPENDIX 5.A

SAMPLE INPUT FILE FOR SAS2H

(Total number of pages in this appendix : 3)

```
=SAS2H    PARM='halt08,skipshipdata'
bw 15x15 PWR assembly
' fuel temp 923
44groupndf5    LATTICECELL
UO2 1 0.95 923 92234 0.03026 92235 3.4 92236 0.01564
    92238 96.5541 END
'
' Zirc 4 composition
ARBM-ZIRC4 6.55 4 1 0 0 50000 1.7 26000 0.24 24000 0.13 40000 97.93
           2 1.0 595 END
'
' water with 652.5 ppm boron
H2O       3 DEN=0.7135 1  579 END
ARBM-BORMOD  0.7135 1 1 0 0 5000 100 3 652.5E-6  579  END
'
co-59  3 0 1-20 579 end
kr-83  1 0 1-20 923 end
kr-84  1 0 1-20 923 end
kr-85  1 0 1-20 923 end
kr-86  1 0 1-20 923 end
sr-90  1 0 1-20 923 end
y-89   1 0 1-20 923 end
zr-94  1 0 1-20 923 end
zr-95  1 0 1-20 923 end
mo-94  1 0 1-20 923 end
mo-95  1 0 1-20 923 end
nb-94  1 0 1-20 923 end
nb-95  1 0 1-20 923 end
tc-99  1 0 1-20 923 end
ru-106  1 0 1-20 923 end
rh-103  1 0 1-20 923 end
rh-105  1 0 1-20 923 end
sb-124  1 0 1-20 923 end
sn-126  1 0 1-20 923 end
xe-131  1 0 1-20 923 end
xe-132  1 0 1-20 923 end
xe-134  1 0 1-20 923 end
'
xe-135  1 0 1-09 923 end
'
xe-136  1 0 1-20 923 end
cs-133  1 0 1-20 923 end
cs-134  1 0 1-20 923 end
cs-135  1 0 1-20 923 end
cs-137  1 0 1-20 923 end
ba-136  1 0 1-20 923 end
la-139  1 0 1-20 923 end
ce-144  1 0 1-20 923 end
pr-143  1 0 1-20 923 end
nd-143  1 0 1-20 923 end
nd-144  1 0 1-20 923 end
nd-145  1 0 1-20 923 end
nd-146  1 0 1-20 923 end
nd-147  1 0 1-20 923 end
nd-148  1 0 1-20 923 end
nd-150  1 0 1-20 923 end
pm-147  1 0 1-20 923 end
pm-148  1 0 1-20 923 end
pm-149  1 0 1-20 923 end
```

```
sm-147  1 0 1-20 923 end
sm-148  1 0 1-20 923 end
sm-149  1 0 1-20 923 end
sm-150  1 0 1-20 923 end
sm-151  1 0 1-20 923 end
sm-152  1 0 1-20 923 end
eu-151  1 0 1-20 923 end
eu-153  1 0 1-20 923 end
eu-154  1 0 1-20 923 end
eu-155  1 0 1-20 923 end
gd-154  1 0 1-20 923 end
gd-155  1 0 1-20 923 end
gd-157  1 0 1-20 923 end
gd-158  1 0 1-20 923 end
gd-160  1 0 1-20 923 end
'
END COMP
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'  FUEL-PIN-CELL GEOMETRY:
'
SQUAREPITCH  1.44272 0.950468 1 3 1.08712 2 0.97028 0 END
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'  MTU in this model is 0.495485 based on fuel dimensions provided
'
'  1 power cycle will be used and a library will be generated every
'  2500 MWD/MTU  power level is 40 MW/MTU
'  therefore 62.5 days per 2500 MWD/MTU
'  Below
'  BURN=62.5*NLIB/CYC
'  POWER=MTU*40
'
'  Number of libraries is 17 which is 42,500 MWD/MTU burnup (17*2500)
'
'  ASSEMBLY AND CYCLE PARAMETERS:
'
NPIN/ASSM=208 FUELNGTH=365.76 NCYCLES=1 NLIB/CYC=17
PRINTLEVEL=1
LIGHTEL=5  INPLEVEL=1   NUMHOLES=17
NUMINStr= 0  ORTUBE= 0.6731  SRTUBE=0.63246   END
POWER=19.81938 BURN=1062.5 END
'
 O  66.54421
 FE  0.24240868
 ZR 98.78151  CR  0.1311304   SN  1.714782
'
END
=SAS2H    PARM='restarts,halt17,skipshipdata'
bw 15x15 PWR assembly
END
```

APPENDIX 5.B

SAMPLE INPUT FILE FOR ORIGEN-S

(Total number of pages in this appendix : 6)

```
#ORIGENS
0$$  A4 33 A8 26 A11 71  E
1$$  1 T
bw 15x15 FUEL -- FT33F001 -
'
' SUBCASE  1 LIBRARY POSITION  1
'
'   lib    pos      grms   photon group
3$$ 33  A3  1  0  A16 2   E T
35$$ 0 T
56$$  5  5  A6 3  A10  0  A13 9  A15 3 A19 1 E
57** 0.0 A3 1.E-5 0.0625 E T
 FUEL 3.4
BW 15x15 0.495485 MTU
58** 19.81938  19.81938 19.81938 19.81938  19.81938
60**  1.0000   3.0000  15.0000  30.0000  62.5
66$$ A1 2 A5 2 A9 2  E
73$$  922350  922340  922360  922380  80000  500000
      260000  240000  400000
74** 16846.48 149.9336 77.49379 478410.7 66544.21 1714.782
     242.0868 131.1304 98781.51
75$$  2  2  2  2  4  4  4  4  4   T
'
' SUBCASE  2 LIBRARY POSITION  2
'
3$$ 33  A3   2  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   5  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE  3 LIBRARY POSITION  3
'
3$$ 33  A3   3  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE  4 LIBRARY POSITION  4
'
3$$ 33  A3   4  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
```

```
' SUBCASE  5 LIBRARY POSITION  5
'
3$$ 33  A3   5  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE  6 LIBRARY POSITION  6
'
3$$ 33  A3   6  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE  7 LIBRARY POSITION  7
'
3$$ 33  A3   7  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE  8 LIBRARY POSITION  8
'
3$$ 33  A3   8  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE  9 LIBRARY POSITION  9
'
3$$ 33  A3   9  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
```

```
'
' SUBCASE 10 LIBRARY POSITION 10
'
3$$ 33  A3  10  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE 11 LIBRARY POSITION 11
'
3$$ 33  A3  11  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE 12 LIBRARY POSITION 12
'
3$$ 33  A3  12  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE 13 LIBRARY POSITION 13
'
3$$ 33  A3  13  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE 14 LIBRARY POSITION 14
'
3$$ 33  A3  14  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
```

```
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE 15 LIBRARY POSITION 15
'
3$$ 33  A3  15  0  A16 2  A33 0  E T
35$$ 0 T
56$$  3  3  A6 3  A10   3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE 16 LIBRARY POSITION 16
'
3$$ 33  A3  16  A4 7 0  A16 2  A33 18  E T
35$$ 0 T
56$$  3  3  A6 1  A10  3  A15 3 A19 1 E
57** 0.0 A3 1.E-5  0.0625 E T
 fuel
BW 15X15
58** 19.81938 19.81938 19.81938
60** 18.5 37.0 62.5
66$$ A1 2 A5 2 A9 2  E T
'
' SUBCASE - decay
'
54$$ A8 1 E
56$$ 0 9 A6 1 A10 3 A14 3 A15 1 A19 1 E
57** 0.0 0 1.E-5  E T
 fuel enrichment above
60** 0.5 0.75 1.0 4.0 8.0 12.0 24.0 48.0 96.0
61** F0.1
65$$
'GRAM-ATOMS   GRAMS    CURIES     WATTS-ALL  WATTS-GAMMA
     3Z      0  1  0     0 0 0      1 0 0        3Z          6Z
     3Z      0  1  0     0 0 0      1 0 0        3Z          6Z
     3Z      0  1  0     0 0 0      1 0 0        3Z          6Z  T
'
' SUBCASE - decay
'
54$$ A8 1 E
56$$ 0 9 A6 1 A10 9 A14 4 A15 1 A19 1 E
57** 4.0 0 1.E-5  E T
 fuel enrichment above
60** 10.0 20.0 30.0 60.0 90.0 120.0 180.0 240.0 365.0
61** F0.1
65$$
'GRAM-ATOMS   GRAMS    CURIES     WATTS-ALL  WATTS-GAMMA
     3Z      0  1  0     0 0 0      1 0 0        3Z          6Z
     3Z      0  1  0     0 0 0      1 0 0        3Z          6Z
     3Z      0  1  0     0 0 0      1 0 0        3Z          6Z  T
'
' SUBCASE - decay
'
54$$ A8 0 E
56$$ 0 9 A6 1 A10 9 A14 5 A15 1 A19 1 E
57** 1.0 0 1.E-5  E T
```

```
 fuel enrichment above
60** 1.5 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0
61** F1.0e-5
65$$
'GRAM-ATOMS   GRAMS    CURIES     WATTS-ALL  WATTS-GAMMA
     3Z      0  1  0     1 0 0      1 0 0         3Z         6Z
     3Z      0  1  0     1 0 0      1 0 0         3Z         6Z
     3Z      0  1  0     1 0 0      1 0 0         3Z         6Z
81$$ 2 0 26 1 E
82$$ 0 2 2 2 2 2 2 2 2
83**  1.1E+7  8.0E+6 6.0E+6 4.0E+6 3.0E+6 2.5E+6 2.0E+6 1.5E+6
      1.0E+6  7.0E+5 4.5E+5 3.0E+5 1.5E+5 1.0E+5 7.0E+4 4.5E+4
      3.0E+4  2.0E+4 1.0E+4
84**  20.0E+6 6.43E+6 3.0E+6 1.85E+6 1.40E+6 9.00E+5 4.00E+5 1.0E+5 T
'
'
'
'
'
'
'
'
' SUBCASE - decay
'
54$$ A8 0 E
56$$ 0 10 A6 1 A10 9 A14 5 A15 1 A19 1 E
57** 10.0 0 1.E-5  E T
 fuel enrichment above
60** 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0
61** F1.0e-5
65$$
'GRAM-ATOMS   GRAMS    CURIES     WATTS-ALL  WATTS-GAMMA
     3Z      0  1  0     1 0 0      1 0 0         3Z         6Z
     3Z      0  1  0     1 0 0      1 0 0         3Z         6Z
     3Z      0  1  0     1 0 0      1 0 0         3Z         6Z
81$$ 2 0 26 1 E
82$$ 2 2 2 2 2 2 2 2 2 2
83**  1.1E+7  8.0E+6 6.0E+6 4.0E+6 3.0E+6 2.5E+6 2.0E+6 1.5E+6
      1.0E+6  7.0E+5 4.5E+5 3.0E+5 1.5E+5 1.0E+5 7.0E+4 4.5E+4
      3.0E+4  2.0E+4 1.0E+4
84**  20.0E+6 6.43E+6 3.0E+6 1.85E+6 1.40E+6 9.00E+5 4.00E+5 1.0E+5 T
'
'
'
'
'
'
'
'
'
'
' END
'
56$$ F0 T
END
```

APPENDIX 5.C

SAMPLE INPUT FILE FOR MCNP

(Total number of pages in this appendix : 33)

```
message:   outp=m8c7b08o  srctp=m8c7b08s  runtpe=m8c7b08r
           mctal=m8c7b08m  wssa=m8c7b08w  rssa=m8c7b08w

m8c7b08
c        HI STAR 100 MPC68
c
c
c      two pocket trunions modeled
c      holtite present
c      impact limiters present
c      radial model
c
c      origen is at the bottom of the overpack - as an example of the origen
c      item 1 on drawing 1397 is 6 inches thick and extends
c      from 0.0 to 6.0 inches in the axial direction
c
c      universe 1
c
c       egg crate
301     0            -30            -400 u=1
302     0             31            -400 u=1
303     0         30 -31 -32        -400 u=1
304     0         30 -31  33        -400 u=1
305     5 -7.92          28     400 -670 u=1
306     5 -7.92             -23 400 -670 u=1
307     5 -7.92      -15 23 -28 400 -670 u=1
308     5 -7.92  20      23 -28 400 -670 u=1
309     5 -7.92          28     670 -460 u=1
310     5 -7.92             -23 670 -460 u=1
311     5 -7.92      -15 23 -28 670 -460 u=1
312     5 -7.92  20      23 -28 670 -460 u=1
c       boral and inside of egg crate and outside of fuel
314     0         15 -30 23 -28 400 -410 u=-1
315     0         31 -20 23 -28 400 -410 u=-1
316     0         30 -31 33 -28 400 -410 u=-1
317     0         30 -31 23 -32 400 -410 u=-1
318     0         15 -18 26 -28 410 -435 u=-1
319     0         19 -20 26 -28 410 -435 u=-1
320     0         15 -17 23 -24 410 -435 u=-1
321     0         15 -17 25 -26 410 -435 u=-1
322     6 -2.644 18 -19 27 -28 410 -435 u=-1
323     5 -7.92  18 -19 26 -27 410 -435 u=-1
324     6 -2.644 15 -16 24 -25 410 -435 u=-1
325     5 -7.92  16 -17 24 -25 410 -435 u=-1
326     0         17 -30 23 -26 410 -435 u=-1
327     0         31 -20 23 -26 410 -435 u=-1
328     0         30 -31 23 -32 410 -435 u=-1
329     0         30 -31 33 -26 410 -435 u=-1
330     0         15 -30 23 -28 435 -460 u=-1
331     0         31 -20 23 -28 435 -460 u=-1
332     0         30 -31 33 -28 435 -460 u=-1
333     0         30 -31 23 -32 435 -460 u=-1
c       fuel element
338     5 -1.48621  30 -31 32 -33     -420 u=1
339     2 -4.29251 30 -31 32 -33 420 -425 u=-1
340     0             30 -31 32 -33 425 -430 u=-1
341     5 -0.265322 30 -31 32 -33 430 -440 u=-1
342     5 -0.677510 30 -31 32 -33 440 -445 u=-1
343     5 -1.369221 30 -31 32 -33 445 -450 u=-1
344     5 -0.257210 30 -31 32 -33 450 -670 u=-1
345     5 -0.257210 30 -31 32 -33 670 -455 u=-1
346     0             30 -31 32 -33 455  u=1
347     0            -30            460 u=1
348     0             31            460 u=1
349     0         30 -31 -32        460 u=1
350     0         30 -31  33        460 u=1
c
c      universe 2
c
```

```
c       egg crate
401     0             -30              -400 u=2
402     0              31              -400 u=2
403     0          30 -31 -32          -400 u=2
404     0          30 -31  33          -400 u=2
405     5 -7.92         28      400 -670 u=2
406     5 -7.92              -23 400 -670 u=2
407     5 -7.92       -15 23 -28 400 -670 u=2
408     5 -7.92  20       23 -28 400 -670 u=2
409     5 -7.92         28      670 -460 u=2
410     5 -7.92              -23 670 -460 u=2
411     5 -7.92       -15 23 -28 670 -460 u=2
412     5 -7.92  20       23 -28 670 -460 u=2
c       boral and inside of egg crate and outside of fuel
414     0          15 -30 23 -28 400 -460 u=-2
415     0          31 -20 23 -28 400 -460 u=-2
416     0          30 -31 33 -28 400 -460 u=-2
417     0          30 -31 23 -32 400 -460 u=-2
c       fuel element
438     5 -1.48621  30 -31 32 -33     -420 u=2
439     2 -4.29251 30 -31 32 -33 420 -425 u=-2
440     0             30 -31 32 -33 425 -430 u=-2
441     5 -0.265322 30 -31 32 -33 430 -440 u=-2
442     5 -0.677510 30 -31 32 -33 440 -445 u=-2
443     5 -1.369221 30 -31 32 -33 445 -450 u=-2
444     5 -0.257210 30 -31 32 -33 450 -670 u=-2
445     5 -0.257210 30 -31 32 -33 670 -455 u=-2
446     0             30 -31 32 -33 455 u=2
447     0             -30              460 u=2
448     0              31              460 u=2
449     0          30 -31 -32          460 u=2
450     0          30 -31  33          460 u=2
c
c     universe 3
c
c       egg crate
501     0             -30              -400 u=3
502     0              31              -400 u=3
503     0          30 -31 -32          -400 u=3
504     0          30 -31  33          -400 u=3
505     5 -7.92         28      400 -670 u=3
506     5 -7.92              -23 400 -670 u=3
507     5 -7.92       -15 23 -28 400 -670 u=3
508     5 -7.92  20       23 -28 400 -670 u=3
509     5 -7.92         28      670 -460 u=3
510     5 -7.92              -23 670 -460 u=3
511     5 -7.92       -15 23 -28 670 -460 u=3
512     5 -7.92  20       23 -28 670 -460 u=3
c       boral and inside of egg crate and outside of fuel
514     0          15 -30 23 -28 400 -410 u=-3
515     0          31 -20 23 -28 400 -410 u=-3
516     0          30 -31 33 -28 400 -410 u=-3
517     0          30 -31 23 -32 400 -410 u=-3
518     0          15 -18 26 -28 410 -435 u=-3
519     0          19 -20 26 -28 410 -435 u=-3
522     6 -2.644 18 -19 27 -28 410 -435 u=-3
523     5 -7.92  18 -19 26 -27 410 -435 u=-3
526     0          15 -30 23 -26 410 -435 u=-3
527     0          31 -20 23 -26 410 -435 u=-3
528     0          30 -31 23 -32 410 -435 u=-3
529     0          30 -31 33 -26 410 -435 u=-3
530     0          15 -30 23 -28 435 -460 u=-3
531     0          31 -20 23 -28 435 -460 u=-3
532     0          30 -31 33 -28 435 -460 u=-3
533     0          30 -31 23 -32 435 -460 u=-3
c       fuel element
538     5 -1.48621  30 -31 32 -33     -420 u=3
539     2 -4.29251 30 -31 32 -33 420 -425 u=-3
540     0             30 -31 32 -33 425 -430 u=-3
```

```
541     5 -0.265322 30 -31 32 -33 430 -440 u=-3
542     5 -0.677510 30 -31 32 -33 440 -445 u=-3
543     5 -1.369221 30 -31 32 -33 445 -450 u=-3
544     5 -0.257210 30 -31 32 -33 450 -670 u=-3
545     5 -0.257210 30 -31 32 -33 670 -455 u=-3
546     0           30 -31 32 -33 455 u=3
547     0           -30               460 u=3
548     0            31               460 u=3
549     0        30 -31 -32           460 u=3
550     0        30 -31  33           460 u=3
c
c      universe 4
c
c       egg crate
601     0           -30               -400 u=4
602     0            31               -400 u=4
603     0        30 -31 -32           -400 u=4
604     0        30 -31  33           -400 u=4
605     5 -7.92          28       400 -670 u=4
606     5 -7.92              -23 400 -670 u=4
607     5 -7.92      -15 23 -28 400 -670 u=4
608     5 -7.92  20      23 -28 400 -670 u=4
609     5 -7.92          28       670 -460 u=4
610     5 -7.92              -23 670 -460 u=4
611     5 -7.92      -15 23 -28 670 -460 u=4
612     5 -7.92  20      23 -28 670 -460 u=4
c       boral and inside of egg crate and outside of fuel
614     0        15 -30 23 -28 400 -410 u=-4
615     0        31 -20 23 -28 400 -410 u=-4
616     0        30 -31 33 -28 400 -410 u=-4
617     0        30 -31 23 -32 400 -410 u=-4
620     0        15 -17 23 -24 410 -435 u=-4
621     0        15 -17 25 -28 410 -435 u=-4
624     6 -2.644 15 -16 24 -25 410 -435 u=-4
625     5 -7.92  16 -17 24 -25 410 -435 u=-4
626     0        17 -30 23 -28 410 -435 u=-4
627     0        31 -20 23 -28 410 -435 u=-4
628     0        30 -31 23 -32 410 -435 u=-4
629     0        30 -31 33 -28 410 -435 u=-4
630     0        15 -30 23 -28 435 -460 u=-4
631     0        31 -20 23 -28 435 -460 u=-4
632     0        30 -31 33 -28 435 -460 u=-4
633     0        30 -31 23 -32 435 -460 u=-4
c       fuel element
638     5 -1.48621  30 -31 32 -33     -420 u=4
639     2 -4.29251 30 -31 32 -33 420 -425 u=-4
640     0           30 -31 32 -33 425 -430 u=-4
641     5 -0.265322 30 -31 32 -33 430 -440 u=-4
642     5 -0.677510 30 -31 32 -33 440 -445 u=-4
643     5 -1.369221 30 -31 32 -33 445 -450 u=-4
644     5 -0.257210 30 -31 32 -33 450 -670 u=-4
645     5 -0.257210 30 -31 32 -33 670 -455 u=-4
646     0           30 -31 32 -33 455  u=4
647     0           -30               460 u=4
648     0            31               460 u=4
649     0        30 -31 -32           460 u=4
650     0        30 -31  33           460 u=4
c
c      universe 5
c
701     0                -400 u=5
702     5 -7.92 20 400 -670 u=5
704     5 -7.92 20 670 -460 u=5
705     0       -20 400 -460 u=5
706     0           460      u=5
c
c      universe 6
c
710     0                   -400 u=6
```

```
711     5 -7.92  -23 400 -670 u=6
713     5 -7.92  -23 670 -460 u=6
714     0         23 400 -460 u=6
715     0            460      u=6
c
c     universe 7
c
720     0                    -400 u=7
721     5 -7.92 20      23 400 -670 u=7
722     5 -7.92    -23     400 -670 u=7
724     5 -7.92 20      23 670 -460 u=7
725     5 -7.92    -23     670 -460 u=7
726     0          -20  23 400 -460 u=7
727     0                  460      u=7
c
c     universe 8
c
730    0                          -400 u=8
731    0        15            400 -460 u=8
739    5 -7.92      -15       400 -670 u=8
740    5 -7.92      -15       670 -460 u=8
741    0                      460      u=8
c
c     universe 9
c
745    0        15     23     400 -460 u=9
753    0                          -400 u=9
754    5 -7.92      -15 23    400 -670 u=9
755    5 -7.92      -23       400 -670 u=9
756    5 -7.92      -15 23    670 -460 u=9
757    5 -7.92      -23       670 -460 u=9
758    0                      460      u=9
c
c     universe 10
c
760    0        15         -28 400 -460 u=10
772    0                           -400 u=10
773    5 -7.92      -15    -28 400 -670 u=10
774    5 -7.92          28     400 -670 u=10
775    5 -7.92      -15    -28 670 -460 u=10
776    5 -7.92          28     670 -460 u=10
777    0                       460      u=10
c
c     universe 11
c
780    0                   -28 400 -460 u=11
788    0                           -400 u=11
789    5 -7.92          28     400 -670 u=11
790    5 -7.92          28     670 -460 u=11
791    0                       460      u=11
c
c     universe 12
c
795    0            -20    -28 400 -460 u=12
803    0                           -400 u=12
804    5 -7.92      -20 28     400 -670 u=12
805    5 -7.92  20             400 -670 u=12
806    5 -7.92      -20 28     670 -460 u=12
807    5 -7.92  20             670 -460 u=12
808    0                       460      u=12
c
c     universe 13
c
c     810   0     -670   u=13
c     811   0      670   u=13
c     storage locations
c
201    0  -301   -106 212 620 -675
202    0  -301   106 -107 212 620 -675
```

```
        fill=6 (-8.2423 90.6653 0.0)
203   0  -301  107 -108 212 620 -675
        fill=6 ( 8.2423 90.6653 0.0)
204   0  -301  108 212 620 -675
c
205   0  -301 -104 211 620 -675
206   0  -301 104 -105 211 620 -675
        fill=6 (-41.2115 74.1807 0.0)
207   0  -301 105 -106 211 -212 620 -675
        fill=7 (-24.7269 74.1807 0.0)
c
101   0  106 -107 211 -212  620 -675
        fill=2 (-8.2423 74.1807 0.0)
102   0  107 -108 211 -212  620 -675
        fill=4 ( 8.2423 74.1807 0.0)
c
208   0  -301 108 -109 211 -212 620 -675
        fill=9 (24.7269 74.1807 0.0)
209   0  -301 109 -110 211 620 -675
        fill=6 (41.2115 74.1807 0.0)
210   0  -301 110 211 620 -675
c
211   0  -301 -103 210 620 -675
212   0  -301 103 -104 210 -211 620 -675
        fill=7 (-57.6961 57.6961 0.0)
c
103   0  104 -105 210 -211  620 -675
        fill=2 (-41.2115 57.6961 0.0)
104   0  105 -106 210 -211  620 -675
        fill=4 (-24.7269 57.6961 0.0)
105   0  106 -107 210 -211  620 -675
        fill=1 (-8.2423 57.6961 0.0)
106   0  107 -108 210 -211  620 -675
        fill=1 ( 8.2423 57.6961 0.0)
107   0  108 -109 210 -211  620 -675
        fill=4 ( 24.7269 57.6961 0.0)
108   0  109 -110 210 -211  620 -675
        fill=4 ( 41.2115 57.6961 0.0)
c
213   0  -301 110 -111 210 -211 620 -675
        fill=9 ( 57.6961 57.6961 0.0)
214   0  -301 111 210 620 -675
c
215   0  -301 -103 209 -210 620 -675
        fill=5 (-74.1807 41.2115 0.0)
c
109   0  103 -104 209 -210  620 -675
        fill=2 (-57.6961 41.2115 0.0)
110   0  104 -105 209 -210  620 -675
        fill=1 (-41.2115 41.2115 0.0)
111   0  105 -106 209 -210  620 -675
        fill=1 (-24.7269 41.2115 0.0)
112   0  106 -107 209 -210  620 -675
        fill=1 (-8.2423 41.2115 0.0)
113   0  107 -108 209 -210  620 -675
        fill=1 ( 8.2423 41.2115 0.0)
114   0  108 -109 209 -210  620 -675
        fill=1 ( 24.7269 41.2115 0.0)
115   0  109 -110 209 -210  620 -675
        fill=1 ( 41.2115 41.2115 0.0)
116   0  110 -111 209 -210  620 -675
        fill=4 ( 57.6961 41.2115 0.0)
c
216   0  -301 111 209 -210 620 -675
        fill=8 (74.1807 41.2115 0.0)
c
217   0  -301 -102 208 620 -675
218   0  -301 102 -103 208 -209 620 -675
        fill=7 (-74.1807 24.7269 0.0)
```

```
c
117    0  103 -104 208 -209  620 -675
          fill=3 (-57.6961 24.7269 0.0)
118    0  104 -105 208 -209  620 -675
          fill=1 (-41.2115 24.7269 0.0)
119    0  105 -106 208 -209  620 -675
          fill=1 (-24.7269 24.7269 0.0)
120    0  106 -107 208 -209  620 -675
          fill=1 (-8.2423 24.7269 0.0)
121    0  107 -108 208 -209  620 -675
          fill=1 ( 8.2423 24.7269 0.0)
122    0  108 -109 208 -209  620 -675
          fill=1 ( 24.7269 24.7269 0.0)
123    0  109 -110 208 -209  620 -675
          fill=1 ( 41.2115 24.7269 0.0)
124    0  110 -111 208 -209  620 -675
          fill=1 ( 57.6961 24.7269 0.0)
c
219    0  -301 111 -112 208 -209 620 -675
          fill=9 (74.1807 24.7269 0.0)
220    0  -301 112 208 620 -675
c
221    0  -301 -102 207 -208 620 -675
          fill=5 (-90.6653 8.2423 0.0)
c
125    0  102 -103 207 -208  620 -675
          fill=2 (-74.1807 8.2423 0.0)
126    0  103 -104 207 -208  620 -675
          fill=1 (-57.6961 8.2423 0.0)
127    0  104 -105 207 -208  620 -675
          fill=1 (-41.2115 8.2423 0.0)
128    0  105 -106 207 -208  620 -675
          fill=1 (-24.7269 8.2423 0.0)
129    0  106 -107 207 -208  620 -675
          fill=1 (-8.2423 8.2423 0.0)
130    0  107 -108 207 -208  620 -675
          fill=1 ( 8.2423 8.2423 0.0)
131    0  108 -109 207 -208  620 -675
          fill=1 ( 24.7269 8.2423 0.0)
132    0  109 -110 207 -208  620 -675
          fill=1 ( 41.2115 8.2423 0.0)
133    0  110 -111 207 -208  620 -675
          fill=1 ( 57.6961 8.2423 0.0)
134    0  111 -112 207 -208  620 -675
          fill=4 ( 74.1807 8.2423 0.0)
c
222    0  -301 112 207 -208 620 -675
          fill=8 (90.6653 8.2423 0.0)
c
223    0  -301 -102 206 -207 620 -675
          fill=5 (-90.6653 -8.2423 0.0)
c
135    0  102 -103 206 -207  620 -675
          fill=3 (-74.1807 -8.2423 0.0)
136    0  103 -104 206 -207  620 -675
          fill=1 (-57.6961 -8.2423 0.0)
137    0  104 -105 206 -207  620 -675
          fill=1 (-41.2115 -8.2423 0.0)
138    0  105 -106 206 -207  620 -675
          fill=1 (-24.7269 -8.2423 0.0)
139    0  106 -107 206 -207  620 -675
          fill=1 (-8.2423 -8.2423 0.0)
140    0  107 -108 206 -207  620 -675
          fill=1 ( 8.2423 -8.2423 0.0)
141    0  108 -109 206 -207  620 -675
          fill=1 ( 24.7269 -8.2423 0.0)
142    0  109 -110 206 -207  620 -675
          fill=1 ( 41.2115 -8.2423 0.0)
143    0  110 -111 206 -207  620 -675
```

```
        fill=1 ( 57.6961 -8.2423 0.0)
144  0  111 -112 206 -207  620 -675
        fill=1 ( 74.1807 -8.2423 0.0)
c
224  0  -301 112 206 -207 620 -675
        fill=8 (90.6653 -8.2423 0.0)
c
225  0  -301 -102 -206 620 -675
226  0  -301 102 -103 205 -206 620 -675
        fill=12 (-74.1807 -24.7269 0.0)
c
145  0  103 -104 205 -206  620 -675
        fill=3 (-57.6961 -24.7269 0.0)
146  0  104 -105 205 -206  620 -675
        fill=1 (-41.2115 -24.7269 0.0)
147  0  105 -106 205 -206  620 -675
        fill=1 (-24.7269 -24.7269 0.0)
148  0  106 -107 205 -206  620 -675
        fill=1 (-8.2423  -24.7269 0.0)
149  0  107 -108 205 -206  620 -675
        fill=1 ( 8.2423  -24.7269 0.0)
150  0  108 -109 205 -206  620 -675
        fill=1 ( 24.7269 -24.7269 0.0)
151  0  109 -110 205 -206  620 -675
        fill=1 ( 41.2115 -24.7269 0.0)
152  0  110 -111 205 -206  620 -675
        fill=1 ( 57.6961 -24.7269 0.0)
c
227  0  -301 111 -112 205 -206 620 -675
        fill=10 (74.1807 -24.7269 0.0)
228  0  -301 112 -206 620 -675
c
229  0  -301 -103 204 -205 620 -675
        fill=5 (-74.1807 -41.2115 0.0)
c
153  0  103 -104 204 -205  620 -675
        fill=3 (-57.6961 -41.2115 0.0)
154  0  104 -105 204 -205  620 -675
        fill=1 (-41.2115 -41.2115 0.0)
155  0  105 -106 204 -205  620 -675
        fill=1 (-24.7269 -41.2115 0.0)
156  0  106 -107 204 -205  620 -675
        fill=1 (-8.2423  -41.2115 0.0)
157  0  107 -108 204 -205  620 -675
        fill=1 ( 8.2423  -41.2115 0.0)
158  0  108 -109 204 -205  620 -675
        fill=1 ( 24.7269 -41.2115 0.0)
159  0  109 -110 204 -205  620 -675
        fill=1 ( 41.2115 -41.2115 0.0)
160  0  110 -111 204 -205  620 -675
        fill=1 ( 57.6961 -41.2115 0.0)
c
230  0  -301 111 204 -205 620 -675
        fill=8 (74.1807 -41.2115 0.0)
c
231  0  -301 -103 -204 620 -675
232  0  -301 103 -104 203 -204 620 -675
        fill=12 (-57.6961 -57.6961 0.0)
c
161  0  104 -105 203 -204  620 -675
        fill=3 (-41.2115 -57.6961 0.0)
162  0  105 -106 203 -204  620 -675
        fill=1 (-24.7269 -57.6961 0.0)
163  0  106 -107 203 -204  620 -675
        fill=1 (-8.2423 -57.6961 0.0)
164  0  107 -108 203 -204  620 -675
        fill=1 ( 8.2423 -57.6961 0.0)
165  0  108 -109 203 -204  620 -675
        fill=1 ( 24.7269 -57.6961 0.0)
```

```
166    0  109 -110 203 -204  620 -675
          fill=1 ( 41.2115 -57.6961 0.0)
c
233    0  -301 110 -111 203 -204 620 -675
          fill=10 ( 57.6961 -57.6961 0.0)
234    0  -301 111 -204 620 -675
c
235    0  -301 -104 -203 620 -675
236    0  -301 104 -105 -203 620 -675
          fill=11 (-41.2115 -74.1807 0.0)
237    0  -301 105 -106 202 -203 620 -675
          fill=12 (-24.7269 -74.1807 0.0)
c
167    0  106 -107 202 -203  620 -675
          fill=3 (-8.2423 -74.1807 0.0)
168    0  107 -108 202 -203  620 -675
          fill=1 ( 8.2423 -74.1807 0.0)
c
238    0  -301 108 -109 202 -203 620 -675
          fill=10 (24.7269 -74.1807 0.0)
239    0  -301 109 -110 -203 620 -675
          fill=11 (41.2115 -74.1807 0.0)
240    0  -301 110 -203 620 -675
c
241    0  -301  -106 -202 620 -675
242    0  -301  106 -107 -202 620 -675
          fill=11 (-8.2423 -90.6653 0.0)
243    0  -301  107 -108 -202 620 -675
          fill=11 ( 8.2423 -90.6653 0.0)
244    0  -301  108 -202 620 -675
c
821    5 -7.92 301 -302 610 -630  $ MPC shell
822    0       302 -501 610 -630  $ Air gap
823    5 -7.92 301 -302 630 -670  $ MPC shell
824    0       302 -501 630 -670  $ Air gap
825    5 -7.92 301 -302 670 -675  $ MPC shell
826    0       302 -501 670 -675  $ Air gap
827    5 -7.92 301 -302 675 -680  $ MPC shell
828    0       301 -302 680 -685  $ Air gap
829    0       302 -501 675 -685  $ Air gap
c
830    5 -7.92     -301 610 -620  $ MPC baseplate
840    5 -7.92     -301 675 -680  $ MPC lid (both)
850    0           -301 680 -685  $ Air gap
c      OVERPACK \/ \/ \/ \/ \/
c
1001   8 -7.82 501 -502 630 -670 $ steel shell
1002   8 -7.82 502 -503 630 -670 $ steel shell
1003   8 -7.82 503 -504 630 -670 $ steel shell
1004   8 -7.82 504 -505 630 -670 $ steel shell
1005   8 -7.82 505 -506 630 -670 $ steel shell
1006   8 -7.82 506 -507 630 -670 $ steel shell
1007   8 -7.82 507 -508 630 -670 $ steel shell
1008   0       508 -509 630 -670  fill=20
1009   0       509 -510 630 -670  fill=20
1010   0       510 -511 630 -670  fill=20
1011   0       511 -512 630 -670  fill=20
1012   8 -7.82 512 -513 630 -670 $ outer steel shell
c      1012  8 -7.82  512 -513 640 -670             $ outer steel shell
c      1013  0        512 -513 630 -640  1103 -1102 $ air in pocket trun.
c      1014  0        512 -513 630 -640  2103 -2102 $ air in pocket trun.
c      1015  8 -7.82  512 -513 630 -640  1102  2102 $ outer steel shell
c      1016  8 -7.82  512 -513 630 -640  1102 -2103 $ outer steel shell
c      1017  8 -7.82  512 -513 630 -640 -1103 -2103 $ outer steel shell
c      1018  8 -7.82  512 -513 630 -640 -1103  2102 $ outer steel shell
c
c       steel spines and holtite
10101   8 -7.82   2000 -2002  645 -660   1000  u=20 $ steel spine
10102   7 -1.61   2002 -2011  645 -660   2000  u=20 $ holtite
```

```
10103    8 -7.82   2011 -2012  645 -660   2000  u=20 $ steel spine
10104    7 -1.61   2012 -2021  645 -660   2000  u=20 $ holtite
10105    8 -7.82   2021 -2022  645 -660   2000  u=20 $ steel spine
10106    7 -1.61   2022 -2031  645 -660   2000  u=20 $ holtite
10107    8 -7.82   2031 -2032  645 -660   2000  u=20 $ steel spine
10108    7 -1.61   2032 -2041  645 -660   2000  u=20 $ holtite
10109    8 -7.82   2041 -2042  645 -660   2000  u=20 $ steel spine
10110    7 -1.61   2042 -2051  645 -660   2000  u=20 $ holtite
10111    8 -7.82   2051 -2052  645 -660   2000  u=20 $ steel spine
10112    7 -1.61   2052 -2061  645 -660   2000  u=20 $ holtite
10113    8 -7.82   2061 -2062  645 -660   2000  u=20 $ steel spine
10114    7 -1.61   2062 -2071  645 -660   2000  u=20 $ holtite
10115    8 -7.82   2071 -2072  645 -660   2000  u=20 $ steel spine
10116    7 -1.61   2072 -2081  645 -660   2000  u=20 $ holtite
10117    8 -7.82   2081 -2082  645 -660   2000  u=20 $ steel spine
10118    7 -1.61   2082 -2091  645 -660   2000  u=20 $ holtite
10119    8 -7.82   2091 -2092  645 -660   2000  u=20 $ steel spine
10120    7 -1.61   2092  1002  645 -660   2000  u=20 $ holtite
10121    8 -7.82   1000 -1002  645 -660   2000  u=20 $ steel spine
c
10122    8 -7.82   1001 -1000  645 -660   2000  u=20 $ steel spine
10123    7 -1.61   1012 -1001  645 -660   2000  u=20 $ holtite
10124    8 -7.82   1011 -1012  645 -660   2000  u=20 $ steel spine
10125    7 -1.61   1022 -1011  645 -660   2000  u=20 $ holtite
10126    8 -7.82   1021 -1022  645 -660   2000  u=20 $ steel spine
10127    7 -1.61   1032 -1021  645 -660   2000  u=20 $ holtite
10128    8 -7.82   1031 -1032  645 -660   2000  u=20 $ steel spine
10129    7 -1.61   1042 -1031  645 -660   2000  u=20 $ holtite
10130    8 -7.82   1041 -1042  645 -660   2000  u=20 $ steel spine
10131    7 -1.61   1052 -1041  645 -660   2000  u=20 $ holtite
10132    8 -7.82   1051 -1052  645 -660   2000  u=20 $ steel spine
10133    7 -1.61   1062 -1051  645 -660   2000  u=20 $ holtite
10134    8 -7.82   1061 -1062  645 -660   2000  u=20 $ steel spine
10135    7 -1.61   1072 -1061  645 -660   2000  u=20 $ holtite
10136    8 -7.82   1071 -1072  645 -660   2000  u=20 $ steel spine
10137    7 -1.61   1082 -1071  645 -660   2000  u=20 $ holtite
10138    8 -7.82   1081 -1082  645 -660   2000  u=20 $ steel spine
10139    7 -1.61   1092 -1081  645 -660   2000  u=20 $ holtite
10140    8 -7.82   1091 -1092  645 -660   2000  u=20 $ steel spine
10141    7 -1.61   2002 -1091  645 -660   2000  u=20 $ holtite
10142    8 -7.82   2000 -2002  645 -660  -1000  u=20 $ steel spine
c
10143    8 -7.82   2001 -2000  645 -660  -1000  u=20 $ steel spine
10144    7 -1.61   2012 -2001  645 -660  -2000  u=20 $ holtite
10145    8 -7.82   2011 -2012  645 -660  -2000  u=20 $ steel spine
10146    7 -1.61   2022 -2011  645 -660  -2000  u=20 $ holtite
10147    8 -7.82   2021 -2022  645 -660  -2000  u=20 $ steel spine
10148    7 -1.61   2032 -2021  645 -660  -2000  u=20 $ holtite
10149    8 -7.82   2031 -2032  645 -660  -2000  u=20 $ steel spine
10150    7 -1.61   2042 -2031  645 -660  -2000  u=20 $ holtite
10151    8 -7.82   2041 -2042  645 -660  -2000  u=20 $ steel spine
10152    7 -1.61   2052 -2041  645 -660  -2000  u=20 $ holtite
10153    8 -7.82   2051 -2052  645 -660  -2000  u=20 $ steel spine
10154    7 -1.61   2062 -2051  645 -660  -2000  u=20 $ holtite
10155    8 -7.82   2061 -2062  645 -660  -2000  u=20 $ steel spine
10156    7 -1.61   2072 -2061  645 -660  -2000  u=20 $ holtite
10157    8 -7.82   2071 -2072  645 -660  -2000  u=20 $ steel spine
10158    7 -1.61   2082 -2071  645 -660  -2000  u=20 $ holtite
10159    8 -7.82   2081 -2082  645 -660  -2000  u=20 $ steel spine
10160    7 -1.61   2092 -2081  645 -660  -2000  u=20 $ holtite
10161    8 -7.82   2091 -2092  645 -660  -2000  u=20 $ steel spine
10162    7 -1.61  -1001 -2091  645 -660  -2000  u=20 $ holtite
10163    8 -7.82   1001 -1000  645 -660  -2000  u=20 $ steel spine
c
10164    8 -7.82   1000 -1002  645 -660  -2000  u=20 $ steel spine
10165    7 -1.61   1002 -1011  645 -660  -2000  u=20 $ holtite
10166    8 -7.82   1011 -1012  645 -660  -2000  u=20 $ steel spine
10167    7 -1.61   1012 -1021  645 -660  -2000  u=20 $ holtite
10168    8 -7.82   1021 -1022  645 -660  -2000  u=20 $ steel spine
```

```
10169   7 -1.61   1022 -1031  645 -660  -2000  u=20 $ holtite
10170   8 -7.82   1031 -1032  645 -660  -2000  u=20 $ steel spine
10171   7 -1.61   1032 -1041  645 -660  -2000  u=20 $ holtite
10172   8 -7.82   1041 -1042  645 -660  -2000  u=20 $ steel spine
10173   7 -1.61   1042 -1051  645 -660  -2000  u=20 $ holtite
10174   8 -7.82   1051 -1052  645 -660  -2000  u=20 $ steel spine
10175   7 -1.61   1052 -1061  645 -660  -2000  u=20 $ holtite
10176   8 -7.82   1061 -1062  645 -660  -2000  u=20 $ steel spine
10177   7 -1.61   1062 -1071  645 -660  -2000  u=20 $ holtite
10178   8 -7.82   1071 -1072  645 -660  -2000  u=20 $ steel spine
10179   7 -1.61   1072 -1081  645 -660  -2000  u=20 $ holtite
10180   8 -7.82   1081 -1082  645 -660  -2000  u=20 $ steel spine
10181   7 -1.61   1082 -1091  645 -660  -2000  u=20 $ holtite
10182   8 -7.82   1091 -1092  645 -660  -2000  u=20 $ steel spine
10183   7 -1.61   1092 -2001  645 -660  -2000  u=20 $ holtite
10184   8 -7.82   2001 -2000  645 -660   1000  u=20 $ steel spine
c
c    10201   8 -7.82   2000 -2002  635 -645   1000  u=20 $ steel spine
c    10202   7 -1.61   2002 -2011  635 -645   2000  u=20 $ holtite
10202   7 -1.61   2101 -2011  635 -645   2000  u=20 $ holtite
10203   8 -7.82   2011 -2012  635 -645   2000  u=20 $ steel spine
10204   7 -1.61   2012 -2021  635 -645   2000  u=20 $ holtite
10205   8 -7.82   2021 -2022  635 -645   2000  u=20 $ steel spine
10206   7 -1.61   2022 -2031  635 -645   2000  u=20 $ holtite
10207   8 -7.82   2031 -2032  635 -645   2000  u=20 $ steel spine
10208   7 -1.61   2032 -2041  635 -645   2000  u=20 $ holtite
10209   8 -7.82   2041 -2042  635 -645   2000  u=20 $ steel spine
10210   7 -1.61   2042 -2051  635 -645   2000  u=20 $ holtite
10211   8 -7.82   2051 -2052  635 -645   2000  u=20 $ steel spine
10212   7 -1.61   2052 -2061  635 -645   2000  u=20 $ holtite
10213   8 -7.82   2061 -2062  635 -645   2000  u=20 $ steel spine
10214   7 -1.61   2062 -2071  635 -645   2000  u=20 $ holtite
10215   8 -7.82   2071 -2072  635 -645   2000  u=20 $ steel spine
10216   7 -1.61   2072 -2081  635 -645   2000  u=20 $ holtite
10217   8 -7.82   2081 -2082  635 -645   2000  u=20 $ steel spine
10218   7 -1.61   2082 -2091  635 -645   2000  u=20 $ holtite
10219   8 -7.82   2091 -2092  635 -645   2000  u=20 $ steel spine
c    10220   7 -1.61   2092  1101  635 -645   2000  u=20 $ holtite
10220   7 -1.61   2092  1002  635 -645   2000  u=20 $ holtite
10221   8 -7.82   1000 -1002  635 -645   2000  u=20 $ steel spine
c
10222   8 -7.82   1001 -1000  635 -645   2000  u=20 $ steel spine
10223   7 -1.61   1012 -1001  635 -645   2000  u=20 $ holtite
c    10223   7 -1.61   1012 -1104  635 -645   2000  u=20 $ holtite
10224   8 -7.82   1011 -1012  635 -645   2000  u=20 $ steel spine
10225   7 -1.61   1022 -1011  635 -645   2000  u=20 $ holtite
10226   8 -7.82   1021 -1022  635 -645   2000  u=20 $ steel spine
10227   7 -1.61   1032 -1021  635 -645   2000  u=20 $ holtite
10228   8 -7.82   1031 -1032  635 -645   2000  u=20 $ steel spine
10229   7 -1.61   1042 -1031  635 -645   2000  u=20 $ holtite
10230   8 -7.82   1041 -1042  635 -645   2000  u=20 $ steel spine
10231   7 -1.61   1052 -1041  635 -645   2000  u=20 $ holtite
10232   8 -7.82   1051 -1052  635 -645   2000  u=20 $ steel spine
10233   7 -1.61   1062 -1051  635 -645   2000  u=20 $ holtite
10234   8 -7.82   1061 -1062  635 -645   2000  u=20 $ steel spine
10235   7 -1.61   1072 -1061  635 -645   2000  u=20 $ holtite
10236   8 -7.82   1071 -1072  635 -645   2000  u=20 $ steel spine
10237   7 -1.61   1082 -1071  635 -645   2000  u=20 $ holtite
10238   8 -7.82   1081 -1082  635 -645   2000  u=20 $ steel spine
10239   7 -1.61   1092 -1081  635 -645   2000  u=20 $ holtite
10240   8 -7.82   1091 -1092  635 -645   2000  u=20 $ steel spine
10241   7 -1.61   2101 -1091  635 -645   2000  u=20 $ holtite
c    10241   7 -1.61   2002 -1091  635 -645   2000  u=20 $ holtite
c    10242   8 -7.82   2000 -2002  635 -645  -1000  u=20 $ steel spine
c
c    10243   8 -7.82   2001 -2000  635 -645  -1000  u=20 $ steel spine
c    10244   7 -1.61   2012 -2001  635 -645  -2000  u=20 $ holtite
10244   7 -1.61   2012 -2104  635 -645  -2000  u=20 $ holtite
10245   8 -7.82   2011 -2012  635 -645  -2000  u=20 $ steel spine
```

```
10246    7 -1.61    2022 -2011  635 -645   -2000  u=20 $ holtite
10247    8 -7.82    2021 -2022  635 -645   -2000  u=20 $ steel spine
10248    7 -1.61    2032 -2021  635 -645   -2000  u=20 $ holtite
10249    8 -7.82    2031 -2032  635 -645   -2000  u=20 $ steel spine
10250    7 -1.61    2042 -2031  635 -645   -2000  u=20 $ holtite
10251    8 -7.82    2041 -2042  635 -645   -2000  u=20 $ steel spine
10252    7 -1.61    2052 -2041  635 -645   -2000  u=20 $ holtite
10253    8 -7.82    2051 -2052  635 -645   -2000  u=20 $ steel spine
10254    7 -1.61    2062 -2051  635 -645   -2000  u=20 $ holtite
10255    8 -7.82    2061 -2062  635 -645   -2000  u=20 $ steel spine
10256    7 -1.61    2072 -2061  635 -645   -2000  u=20 $ holtite
10257    8 -7.82    2071 -2072  635 -645   -2000  u=20 $ steel spine
10258    7 -1.61    2082 -2071  635 -645   -2000  u=20 $ holtite
10259    8 -7.82    2081 -2082  635 -645   -2000  u=20 $ steel spine
10260    7 -1.61    2092 -2081  635 -645   -2000  u=20 $ holtite
10261    8 -7.82    2091 -2092  635 -645   -2000  u=20 $ steel spine
c    10262    7 -1.61   -1104 -2091  635 -645   -2000  u=20 $ holtite
10262    7 -1.61   -1001 -2091  635 -645   -2000  u=20 $ holtite
10263    8 -7.82    1001 -1000  635 -645   -2000  u=20 $ steel spine
c
10264    8 -7.82    1000 -1002  635 -645   -2000  u=20 $ steel spine
10265    7 -1.61    1002 -1011  635 -645   -2000  u=20 $ holtite
c    10265    7 -1.61    1101 -1011  635 -645   -2000  u=20 $ holtite
10266    8 -7.82    1011 -1012  635 -645   -2000  u=20 $ steel spine
10267    7 -1.61    1012 -1021  635 -645   -2000  u=20 $ holtite
10268    8 -7.82    1021 -1022  635 -645   -2000  u=20 $ steel spine
10269    7 -1.61    1022 -1031  635 -645   -2000  u=20 $ holtite
10270    8 -7.82    1031 -1032  635 -645   -2000  u=20 $ steel spine
10271    7 -1.61    1032 -1041  635 -645   -2000  u=20 $ holtite
10272    8 -7.82    1041 -1042  635 -645   -2000  u=20 $ steel spine
10273    7 -1.61    1042 -1051  635 -645   -2000  u=20 $ holtite
10274    8 -7.82    1051 -1052  635 -645   -2000  u=20 $ steel spine
10275    7 -1.61    1052 -1061  635 -645   -2000  u=20 $ holtite
10276    8 -7.82    1061 -1062  635 -645   -2000  u=20 $ steel spine
10277    7 -1.61    1062 -1071  635 -645   -2000  u=20 $ holtite
10278    8 -7.82    1071 -1072  635 -645   -2000  u=20 $ steel spine
10279    7 -1.61    1072 -1081  635 -645   -2000  u=20 $ holtite
10280    8 -7.82    1081 -1082  635 -645   -2000  u=20 $ steel spine
10281    7 -1.61    1082 -1091  635 -645   -2000  u=20 $ holtite
10282    8 -7.82    1091 -1092  635 -645   -2000  u=20 $ steel spine
10283    7 -1.61    1092 -2104  635 -645   -2000  u=20 $ holtite
c    10283    7 -1.61    1092 -2001  635 -645   -2000  u=20 $ holtite
c    10284    8 -7.82    2001 -2000  635 -645    1000  u=20 $ steel spine
c
11000    0          660 -665   u=20 $ foam
11001    8 -7.82    665        u=20 $ item 17 top
c    11002    8 -7.82    1101  2101   -635  u=20 $ item 17 bot
c    11003    8 -7.82   -2104  1101   -635  u=20 $ item 17 bot
c    11004    8 -7.82   -1104 -2104   -635  u=20 $ item 17 bot
c    11005    8 -7.82    2101 -1104   -635  u=20 $ item 17 bot
11002    8 -7.82          2101   -635  u=20 $ item 17 bot
11003    8 -7.82   -2104          -635  u=20 $ item 17 bot
c
c    pocket trunion
c
c    11101    8 -7.82   -514  1104 -1101 -640   u=20 $ pocket trunion before hole
c    11102    8 -7.82    514  1104 -1103 -640   u=20 $ steel on side of hole
c    11103    8 -7.82    514  1103 -1102 -640   u=20 $ hole
c    11104    8 -7.82    514  1102 -1101 -640   u=20 $ steel on side of hole
c    11105    8 -7.82         1104 -1101  640 -645  u=20 $ steel above hole
c
11111    8 -7.82   -514  2104 -2101 -640   u=20 $ pocket trunion before hole
11112    8 -7.82    514  2104 -2103 -640   u=20 $ steel on side of hole
11113    8 -7.82    514  2103 -2102 -640   u=20 $ hole
11114    8 -7.82    514  2102 -2101 -640   u=20 $ steel on side of hole
11115    8 -7.82         2104 -2101  640 -645   u=20 $ steel above hole
c
c     overpack base plate
c
```

```
2000  8 -7.82      -301 600 -610
2001  8 -7.82 301 -501 600 -610
2002  8 -7.82 501 -502 600 -630
2003  8 -7.82 502 -503 600 -630
2004  8 -7.82 503 -504 600 -630
2005  8 -7.82 504 -505 600 -630
2006  8 -7.82 505 -506 600 -630
2007  8 -7.82 506 -515 600 -630
2017  9 -1.17e-3    515 -507 600 -630 fill=27
2008  9 -1.17e-3    507 -508 600 -630 fill=27
2009  9 -1.17e-3    508 -509 600 -630
2010  9 -1.17e-3    509 -510 600 -630
2011  9 -1.17e-3    510 -511 600 -630
2012  9 -1.17e-3    511 -512 600 -630
2013  9 -1.17e-3    512 -513 600 -630
c
c     overpack lid
c
3000  8 -7.82      -301 685 -695
3001  8 -7.82 301 -501 685 -695
3002  8 -7.82 501 -502 685 -695
3003  8 -7.82 502 -503 685 -695
3004  8 -7.82 503 -504 685 -695
3005  8 -7.82 504 -505 685 -695
3006  8 -7.82 505 -518 685 -695
3007  9 -1.17e-3    518 -507 685 -695 fill=28
3008  9 -1.17e-3    507 -508 685 -695 fill=28
3009  9 -1.17e-3    508 -509 685 -695
3010  9 -1.17e-3    509 -510 685 -695
3011  9 -1.17e-3    510 -511 685 -695
3012  9 -1.17e-3    511 -512 685 -695
3013  9 -1.17e-3    512 -513 685 -695
c
3022  8 -7.82       501 -502 675 -685
3023  8 -7.82       502 -503 675 -685
3024  8 -7.82       503 -504 675 -685
3025  8 -7.82       504 -505 675 -685
3026  8 -7.82       505 -506 675 -677
3126  8 -7.82       505 -518 677 -685
3027  8 -7.82       506 -507 675 -676
3127  8 -7.82       506 -516 676 -677
3227  9 -1.17e-3    516 -507 676 -677
3327  9 -1.17e-3    518 -507 677 -685 fill=28
3028  8 -7.82       507 -508 675 -676
3128  9 -1.17e-3    507 -508 676 -677
3228  9 -1.17e-3    507 -508 677 -685 fill=28
3029  8 -7.82       508 -517 675 -676
3129  9 -1.17e-3    517 -509 675 -676
3229  9 -1.17e-3    508 -509 676 -685
3030  9 -1.17e-3    509 -510 675 -685
3031  9 -1.17e-3    510 -511 675 -685
3032  9 -1.17e-3    511 -512 675 -685
3033  9 -1.17e-3    512 -513 675 -685
c
3042  8 -7.82       501 -502 670 -675
3043  8 -7.82       502 -503 670 -675
3044  8 -7.82       503 -504 670 -675
3045  8 -7.82       504 -505 670 -675
3046  8 -7.82       505 -506 670 -675
3047  8 -7.82       506 -507 670 -675
3048  8 -7.82       507 -508 670 -675
3049  8 -7.82       508 -517 670 -675
3149  9 -1.17e-3    517 -509 670 -675
3050  9 -1.17e-3    509 -510 670 -675
3051  9 -1.17e-3    510 -511 670 -675
3052  9 -1.17e-3    511 -512 670 -675
3053  9 -1.17e-3    512 -513 670 -675
c
c     surrounding air regions
```

```
9000  9 -1.17e-3       -301 695 -723  fill=26
9001  9 -1.17e-3   301 -501 695 -723  fill=26
9002  9 -1.17e-3   501 -502 695 -723  fill=26
9003  9 -1.17e-3   502 -503 695 -723  fill=26
9004  9 -1.17e-3   503 -504 695 -723  fill=26
9005  9 -1.17e-3   504 -505 695 -723  fill=26
9006  9 -1.17e-3   505 -506 695 -723  fill=26
9007  9 -1.17e-3   506 -507 695 -723  fill=28
9008  9 -1.17e-3   507 -508 695 -723  fill=28
9009  9 -1.17e-3   508 -509 695 -723
9010  9 -1.17e-3   509 -510 695 -723
9011  9 -1.17e-3   510 -511 695 -723
9012  9 -1.17e-3   511 -512 695 -723
9013  9 -1.17e-3   512 -513 695 -723
c
9100  9 -1.17e-3       -301 701 -600  fill=25
9101  9 -1.17e-3   301 -501 701 -600  fill=25
9102  9 -1.17e-3   501 -502 701 -600  fill=25
9103  9 -1.17e-3   502 -503 701 -600  fill=25
9104  9 -1.17e-3   503 -504 701 -600  fill=25
9105  9 -1.17e-3   504 -505 701 -600  fill=25
9106  9 -1.17e-3   505 -506 701 -600  fill=25
9107  9 -1.17e-3   506 -507 701 -600  fill=27
9108  9 -1.17e-3   507 -508 701 -600  fill=27
9109  9 -1.17e-3   508 -509 701 -600
9110  9 -1.17e-3   509 -510 701 -600
9111  9 -1.17e-3   510 -511 701 -600
9112  9 -1.17e-3   511 -512 701 -600
9113  9 -1.17e-3   512 -513 701 -600
c
9200  9 -1.17e-3   513 -521 701 -630
9201  9 -1.17e-3   521 -522 701 -630
9202  9 -1.17e-3   522 -523 701 -630
9203  9 -1.17e-3   523 -524 701 -630
9204  9 -1.17e-3   524 -525 701 -630
9205  9 -1.17e-3   525 -526 701 -630
9206  9 -1.17e-3   526 -527 701 -630
c
9210  9 -1.17e-3   513 -521 630 -670
9211  9 -1.17e-3   521 -522 630 -670
9212  9 -1.17e-3   522 -523 630 -670
9213  9 -1.17e-3   523 -524 630 -670
9214  9 -1.17e-3   524 -525 630 -670
9215  9 -1.17e-3   525 -526 630 -670
9216  9 -1.17e-3   526 -527 630 -670
c
9220  9 -1.17e-3   513 -521 670 -675
9221  9 -1.17e-3   521 -522 670 -675
9222  9 -1.17e-3   522 -523 670 -675
9223  9 -1.17e-3   523 -524 670 -675
9224  9 -1.17e-3   524 -525 670 -675
9225  9 -1.17e-3   525 -526 670 -675
9226  9 -1.17e-3   526 -527 670 -675
c
9230  9 -1.17e-3   513 -521 675 -685
9231  9 -1.17e-3   521 -522 675 -685
9232  9 -1.17e-3   522 -523 675 -685
9233  9 -1.17e-3   523 -524 675 -685
9234  9 -1.17e-3   524 -525 675 -685
9235  9 -1.17e-3   525 -526 675 -685
9236  9 -1.17e-3   526 -527 675 -685
c
9240  9 -1.17e-3   513 -521 685 -723
9241  9 -1.17e-3   521 -522 685 -723
9242  9 -1.17e-3   522 -523 685 -723
9243  9 -1.17e-3   523 -524 685 -723
9244  9 -1.17e-3   524 -525 685 -723
9245  9 -1.17e-3   525 -526 685 -723
9246  9 -1.17e-3   526 -527 685 -723
```

```
c
c
c     impact limiters both top and bottom
c
9508  7 -1.61         -870 803 -801 u=25 $ holtite
9509  8 -7.82     870  -871  803 -801 u=25 $ steel support item 2
9510  8 -7.82     871   852 -851  803 -801 u=25
9511  8 -7.82     871   854 -853  803 -801 u=25
9512  8 -7.82     871   856 -855   803 -801 u=25
9513  8 -7.82     871   858 -857   803 -801 u=25
9514  8 -7.82     871   860 -859   803 -801 u=25
9515  8 -7.82     871   862 -861   803 -801 u=25
9516  8 -7.82     871   864 -863   803 -801 u=25
9517  8 -7.82     871   866 -865   803 -801 u=25
9518  7 -1.61     871   851 -854 2000  803 -801 u=25
9519  7 -1.61     871   853 -856 2000  803 -801 u=25
9520  7 -1.61     871   855 -858 2000  803 -801 u=25
9521  7 -1.61     871   857  859 2000  803 -801 u=25
9522  7 -1.61     871   861 -860 2000  803 -801 u=25
9523  7 -1.61     871   863 -862 2000  803 -801 u=25
9524  7 -1.61     871   865 -864 2000  803 -801 u=25
9525  7 -1.61     871   851 -866 2000  803 -801 u=25
9526  7 -1.61     871   853 -852 -2000  803 -801 u=25
9527  7 -1.61     871   855 -854 -2000  803 -801 u=25
9528  7 -1.61     871   857 -856 -2000  803 -801 u=25
9529  7 -1.61     871   -858 -860 -2000  803 -801 u=25
9530  7 -1.61     871   859 -862 -2000  803 -801 u=25
9531  7 -1.61     871   861 -864 -2000  803 -801 u=25
9532  7 -1.61     871   863 -866 -2000  803 -801 u=25
9533  7 -1.61     871   865 -852 -2000  803 -801 u=25
c
9534  8 -7.82                   801 u=25 $ steel plate
9535  9 -1.17e-3              -803  u=25 $ air below
c
9536  8 -7.82     -519  803 u=27
9537  9 -1.17e-3  519   803 u=27
9538  9 -1.17e-3       -803 u=27
c
9608  7 -1.61         -870 821 -823 u=26 $ holtite
9609  8 -7.82     870  -871  821 -823 u=26 $ steel support item 2
9610  8 -7.82     871   852 -851  821 -823 u=26
9611  8 -7.82     871   854 -853  821 -823 u=26
9612  8 -7.82     871   856 -855   821 -823 u=26
9613  8 -7.82     871   858 -857   821 -823 u=26
9614  8 -7.82     871   860 -859   821 -823 u=26
9615  8 -7.82     871   862 -861   821 -823 u=26
9616  8 -7.82     871   864 -863   821 -823 u=26
9617  8 -7.82     871   866 -865   821 -823 u=26
9618  7 -1.61     871   851 -854 2000  821 -823 u=26
9619  7 -1.61     871   853 -856 2000  821 -823 u=26
9620  7 -1.61     871   855 -858 2000  821 -823 u=26
9621  7 -1.61     871   857  859 2000  821 -823 u=26
9622  7 -1.61     871   861 -860 2000  821 -823 u=26
9623  7 -1.61     871   863 -862 2000  821 -823 u=26
9624  7 -1.61     871   865 -864 2000  821 -823 u=26
9625  7 -1.61     871   851 -866 2000  821 -823 u=26
9626  7 -1.61     871   853 -852 -2000  821 -823 u=26
9627  7 -1.61     871   855 -854 -2000  821 -823 u=26
9628  7 -1.61     871   857 -856 -2000  821 -823 u=26
9629  7 -1.61     871   -858 -860 -2000  821 -823 u=26
9630  7 -1.61     871   859 -862 -2000  821 -823 u=26
9631  7 -1.61     871   861 -864 -2000  821 -823 u=26
9632  7 -1.61     871   863 -866 -2000  821 -823 u=26
9633  7 -1.61     871   865 -852 -2000  821 -823 u=26
c
9634  8 -7.82                  -821 u=26 $ steel plate
9635  9 -1.17e-3                823  u=26 $ air above
9637  8 -7.82     -519        -823 u=28
9638  9 -1.17e-3               823 u=28
```

```
9639  9 -1.17e-3   519       -823 u=28
c
9999  0  527:-701:723
c
c     BLANK LINE

c     BLANK LINE
c
c     MPC surfaces\/ \/ \/ \/ \/
c
1     cz         0.52832
2     cz         0.53213
3     cz         0.61341
4     cz         0.67437
5     cz         0.75057
6     px         0.8128
7     px        -0.8128
8     py         0.8128
9     py        -0.8128
10    px        -4.445
11    px         4.445
12    py        -4.445
13    py         4.445
c     14    px        -8.2423
14    px        -8.242301
15    px        -7.9248
16    px        -7.66826
17    px        -7.47776
18    px        -6.0325
19    px         6.0325
20    px         7.9248
c     21    px         8.2423
c     22    py        -8.2423
21    px         8.242301
22    py        -8.242301
23    py        -7.9248
24    py        -6.0325
25    py         6.0325
26    py         7.47776
27    py         7.66826
28    py         7.9248
c     29    py         8.2423
29    py         8.242301
c
30    px   -6.56082
31    px    6.56082
32    py   -6.56082
33    py    6.56082
c
101   px  -98.9076
102   px  -82.423
103   px  -65.9384
104   px  -49.4538
105   px  -32.9692
106   px  -16.4846
107   px   0.0
108   px   16.4846
109   px   32.9692
110   px   49.4538
111   px   65.9384
112   px   82.423
113   px   98.9076
c
201   py  -98.9076
202   py  -82.423
203   py  -65.9384
204   py  -49.4538
205   py  -32.9692
206   py  -16.4846
```

```
207   py   0.0
208   py   16.4846
209   py   32.9692
210   py   49.4538
211   py   65.9384
212   py   82.423
213   py   98.9076
c
301   cz   85.4075
302   cz   86.6775
c
c     620   pz    21.59     $ MPC baseplate        - 2.5 inches
c     400   pz   24.765   $ start of egg crate
400   pz   23.876   $ start of egg crate
410   pz   33.9725   $ start of boral
420   pz   40.3479 $ beginning of fuel
425   pz   406.1079 $ end of fuel
430   pz   421.3479 $ space
435   pz   430.2125   $ end of boral
440   pz   445.4271 $ plenum
445   pz   448.8561 $ expansion springs
450   pz   457.3397 $ top end fitting
455   pz   468.63    $ top of element
460   pz   466.344   $ top of egg crate
c
c     MPC surfaces/\ /\ /\ /\ /\
c
c
c     OVERPACK survaces \/ \/ \/ \/ \/
c
501   cz    87.3125   $ IR for overpack
502   cz    90.4875   $ item 2   1.25 inch
503   cz    93.6625   $ item 2   1.25 inch
504   cz    96.8375     $ item 12   1.25 inch
505   cz    100.0125    $ item 13   1.25 inch
506   cz    103.1875    $ item 14   1.25 inch
507   cz    106.3625    $ item 15   1.25 inch
508   cz    108.9025    $ item 16   1 inch
509   cz    111.521875   $ holtite
510   cz    114.14125    $ holtite
511   cz    116.760625   $ holtite
512   cz    119.53875       $ holtite - total 4.1875 inches
513   cz    120.80875       $ outer steel shell - 0.5 inches
c     512   cz    119.38        $ holtite - total 4.125 inches
c     513   cz    120.65        $ outer steel shell - 0.5 inches
514   cz    111.54          $ hole in pocket trunion
515   cz    105.7275        $ flange bottom of overpack
516   cz    105.7275        $ flange top    of overpack
517   cz    109.5375        $ shear ring
518   cz    103.1875        $ item 14   1.25 inch
519   cz    108.2675        $ impact limiter - 2 inch steel
c
521   cz    162.56          $ surface of impact limiters
522   cz    203.1875        $ 1 meter from 506 - upper and lower part overpack
523   cz    220.80875       $ 1 meter from 513 - outer steel
524   cz    303.1875        $ 2 meter from 506 - upper and lower part overpack
525   cz    320.80875       $ 2 meter from 513 - outer steel
526   cz    362.56          $ 2 meter from 521 - edge of impact limiters
527   cz    400.00
c
600   pz    0.0         $ bottom of overpack
610   pz    15.24       $ overpack baseplate    - 6 inches
620   pz    21.59       $ MPC baseplate         - 2.5 inches
630   pz    22.225      $ beginning of item 17 - 0.25 inches
635   pz    23.495      $ item 17               - 0.5 inches
640   pz    41.75125    $ hole in pocket trun   - 7.6875 inches from 630
645   pz    54.61       $ top of pocket trun    - 12.75 inches from 630
660   pz    455.6125    $ top of holtite        - 170.125 inches from 635
665   pz    460.6925    $ top of foam           - 2 inches
```

```
670    pz     461.9625  $ top of item 17 on top- 0.5 inches
675    pz     474.98    $ bottom of MPC in lid - 178.5 inches from 620
676    pz     476.5675  $ top of shear ring
677    pz     494.03    $ top of add steel
680    pz     499.11    $ top of MPC outer lid - 7.5 inches from 675
685    pz     500.6975  $ bot of overpack lid  - 5/8 inch
695    pz     515.9375  $ top of overpack lid  - 6 inches
c
c      tally segment surfaces
c
701    pz     -121.92
702    pz     -91.44
703    pz     -60.96
704    pz     -30.48
c      600    pz     0.0        $ bottom of overpack
c      630    pz     22.225     $ beginning of item 17 - 0.25 inches
705    pz     51.5408
706    pz     80.8567
707    pz     110.1725
708    pz     139.4883
709    pz     168.8042
710    pz     198.1200
711    pz     227.4358
712    pz     256.7517
713    pz     286.0675
714    pz     315.3833
715    pz     344.6992
716    pz     374.0150
717    pz     403.3308
718    pz     432.6467
c      670    pz     461.9625  $ top of item 17 on top- 0.5 inches
719    pz     488.3150
c      695    pz     514.6675  $ top of overpack lid  - 6 inches
720    pz     545.1475
721    pz     575.6275
722    pz     606.1075
723    pz     636.5875
c
801    pz     -2.54     $ steel disk
802    pz     -5.715    $ holtite
803    pz     -8.89     $ holtite
804    pz     -9.2075   $ cover over holtite
805    pz     -53.34    $ item 2 on impact limiters
810    pz     -100.0    $ 1 meter from surface overpack
811    pz     -105.7275 $ edge of impact limiter
812    pz     -200.0    $ 2 meter from surface overpack
813    pz     -305.7275 $ 2 meter from surface impact limiter
814    pz     -427.6475 $ 2 meter + 4 feet
815    pz     -488.6075 $ 2 meter + 6 feet
816    pz     -671.4875 $ 2 meter + 12 feet
817    pz     -700.00
c
821    pz     517.2075    $ steel disk
822    pz     520.3825    $ holtite
823    pz     523.5575    $ holtite
824    pz     523.875     $ cover over holtite
825    pz     568.0075    $ item 2 on impact limiters
830    pz     614.6675    $ 1 meter from surface overpack
831    pz     620.3950    $ edge of impact limiter
832    pz     714.6675    $ 2 meter from surface overpack
833    pz     820.395     $ 2 meter from surface impact limiter
834    pz     942.3150    $ 2 meter + 4 feet
835    pz     1003.275    $ 2 meter + 6 feet
836    pz     1186.155    $ 2 meter + 12 feet
837    pz     1200.00
c
851       py    1.5875
852       py   -1.5875
853  11   py    1.5875
```

```
854  11  py   -1.5875
855  12  py    1.5875
856  12  py   -1.5875
857  13  py    1.5875
858  13  py   -1.5875
859      px    1.5875
860      px   -1.5875
861  11  px    1.5875
862  11  px   -1.5875
863  12  px    1.5875
864  12  px   -1.5875
865  13  px    1.5875
866  13  px   -1.5875
c
870      cz    38.1
871      cz    41.91
c         steel spine and holtite cells
c
1000      px    0.0
1001      px  -0.635
1002      px   0.635
1011   1  px  -0.635
1012   1  px   0.635
1021   2  px  -0.635
1022   2  px   0.635
1031   3  px  -0.635
1032   3  px   0.635
1041   4  px  -0.635
1042   4  px   0.635
1051   5  px  -0.635
1052   5  px   0.635
1061   6  px  -0.635
1062   6  px   0.635
1071   7  px  -0.635
1072   7  px   0.635
1081   8  px  -0.635
1082   8  px   0.635
1091   9  px  -0.635
1092   9  px   0.635
c
1101    px    15.71625   $ pocket trunion
1102    px    8.09625    $ pocket trunion opening
1103    px   -8.09625    $ pocket trunion opening 6 3/8 inches thick
1104    px   -15.71625   $ pocket trunion - 9 3/8 inches thick
c
2000      py   0.0
2001      py  -0.635
2002      py   0.635
2011   1  py  -0.635
2012   1  py   0.635
2021   2  py  -0.635
2022   2  py   0.635
2031   3  py  -0.635
2032   3  py   0.635
2041   4  py  -0.635
2042   4  py   0.635
2051   5  py  -0.635
2052   5  py   0.635
2061   6  py  -0.635
2062   6  py   0.635
2071   7  py  -0.635
2072   7  py   0.635
2081   8  py  -0.635
2082   8  py   0.635
2091   9  py  -0.635
2092   9  py   0.635
c
2101    py    15.71625   $ pocket trunion
2102    py    8.09625    $ pocket trunion opening
```

```
2103   py  -8.09625   $ pocket trunion opening 6 3/8 inches thick
2104   py  -15.71625  $ pocket trunion - 9 3/8 inches thick
c
c      OVERPACK surfaces /\ /\ /\ /\ /\
c
c      BLANK LINE

c      BLANK LINE
c
*tr1    0 0 0  9 279 90  99  9 90 90 90 0
*tr2    0 0 0 18 288 90 108 18 90 90 90 0
*tr3    0 0 0 27 297 90 117 27 90 90 90 0
*tr4    0 0 0 36 306 90 126 36 90 90 90 0
*tr5    0 0 0 45 315 90 135 45 90 90 90 0
*tr6    0 0 0 54 324 90 144 54 90 90 90 0
*tr7    0 0 0 63 333 90 153 63 90 90 90 0
*tr8    0 0 0 72 342 90 162 72 90 90 90 0
*tr9    0 0 0 81 351 90 171 81 90 90 90 0
*tr11   0 0 0 22.5 292.5 90 112.5 22.5 90 90 90 0
*tr12   0 0 0 45.0 315.0 90 135.0 45.0 90 90 90 0
*tr13   0 0 0 67.5 337.5 90 157.5 67.5 90 90 90 0
c
c          PHOTON MATERIALS
c
c      fuel 3.4 w/o U235  10.412 gm/cc
m1            92235.01p   -0.029971
              92238.01p   -0.851529
              8016.01p    -0.1185
c      homogenized fuel  density 4.29251 gm/cc
m2            92235.01p   -0.024966
              92238.01p   -0.709315
               8016.01p   -0.098709
              40000.01p   -0.16701
c      zirconium 6.55 gm/cc
m3            40000.01p   1.          $ Zr Clad
c      stainless steel 7.92 gm/cc
m5            24000.01p   -0.19
              25055.01p   -0.02
              26000.01p   -0.695
              28000.01p   -0.095
c      boral  2.644 gm/cc
m6            5010.01p    -0.044226
              5011.01p    -0.201474
              13027.01p   -0.6861
              6000.01p    -0.0682
c      holtite 1.61 gm/cc
m7            6000.01p  -0.2766039
             13027.01p  -0.21285
              1001.01p  -0.0592
              8016.01p  -0.42372
              7014.01p  -0.0198
              5010.01p  -0.0014087
              5011.01p  -0.0064174
c      carbon steel 7.82 gm/cc
m8      6000.01p -0.005 26000.01p -0.995
c      air density 1.17e-3 gm/cc
m9      7014.01p 0.78 8016.01p 0.22
c      c
c      c         NEUTRON MATERIALS
c
c      fuel 3.4 w/o U235  10.412 gm/cc
c      m1            92235.50c   -0.029971
c                    92238.50c   -0.851529
c                    8016.50c    -0.1185
c      c     homogenized fuel  density 4.29251 gm/cc
c      m2            92235.50c   -0.024966
c                    92238.50c   -0.709315
c                     8016.50c   -0.098709
c                    40000.35c   -0.16701
```

```
c     c     zirconium 6.55 gm/cc
c     m3           40000.35c   1.           $ Zr Clad
c     c     stainless steel 7.92 gm/cc
c     m5           24000.50c   -0.19
c                  25055.50c   -0.02
c                  26000.55c   -0.695
c                  28000.50c   -0.095
c     c     boral  2.644 gm/cc
c     m6           5010.50c    -0.044226
c                  5011.56c    -0.201474
c                  13027.50c   -0.6861
c                  6000.50c    -0.0682
c     c     holtite 1.61 gm/cc
c     m7           6000.50c  -0.2766039
c                 13027.50c  -0.21285
c                  1001.50c  -0.0592
c                  8016.50c  -0.42372
c                  7014.50c  -0.0198
c                  5010.50c  -0.0014087
c                  5011.56c  -0.0064174
c     mt7    lwtr.01t
c     c     carbon steel 7.82 gm/cc
c     m8      6000.50c -0.005 26000.55c -0.995
c     c     air density 1.17e-3 gm/cc
c     m9      7014.50c 0.78 8016.50c 0.22
c
phys:n   20 0.0
phys:p   100 0
c     imp:n    1 228r 0
c     imp:p    1 228r 0
nps     2000000
prdmp    j    -30   1   2
c     print    10 110 160 161 20 170
print
mode  p
c
sdef  par=2  erg=d1 axs=0 0 1 x=d4 y=fx d5 z=d3
c
c    energy dist for gammas in the fuel
c
c    si1  h  0.7 1.0 1.5 2.0 2.5 3.0
c    sp1     0  0.31 0.31 0.15 0.15 0.08
c
c    energy dist for neutrons in the fuel
c
c    si1  h  0.1 0.4 0.9 1.4 1.85 3.0 6.43 20.0
c    sp1     0   0.03787 0.1935 0.1773 0.1310 0.2320 0.2098 0.01853
c
c    energy dist for Co60 gammas
c
si1  l 1.3325 1.1732
sp1    0.5    0.5
c
c    axial dist for neut and phot in fuel
c
c    si3  h 40.3479 55.5879 70.8279 101.3079 162.2679 223.2279
c           284.1879 345.1479 375.6279 390.8679 406.1079
c    sp3    0 0.009167 0.031667 0.086250 0.194583 0.199167
c           0.193750 0.178750 0.072083 0.025833 0.009167
c
c    axial dist for Co60 - a zero prob is in the fuel
c
si3  h 21.59 40.3479 421.3479 445.4271 448.8561 457.3397 468.63
sp3    0     0.547   0.0      0.125    0.045    0.227    0.056
c
si4  s              15 16
              13 14 15 16 17 18
           12 13 14 15 16 17 18 19
           12 13 14 15 16 17 18 19
```

```
         11 12 13 14 15 16 17 18 19 20
         11 12 13 14 15 16 17 18 19 20
            12 13 14 15 16 17 18 19
            12 13 14 15 16 17 18 19
               13 14 15 16 17 18
                     15 16
sp4  1 67r
c
ds5  s               30 30
               29 29 29 29 29 29
            28 28 28 28 28 28 28 28
            27 27 27 27 27 27 27 27
         26 26 26 26 26 26 26 26 26 26
         25 25 25 25 25 25 25 25 25 25
            24 24 24 24 24 24 24 24
            23 23 23 23 23 23 23 23
               22 22 22 22 22 22
                     21 21
c
si11  -80.74152 -67.61988
si12  -64.25692 -51.13528
si13  -47.77232 -34.65068
si14  -31.28772 -18.16608
si15  -14.80312 -1.68148
si16   1.68148   14.80312
si17   18.16608  31.28772
si18   34.65068  47.77232
si19   51.13528  64.25692
si20   67.61988  80.74152
c
si21  -80.74152 -67.61988
si22  -64.25692 -51.13528
si23  -47.77232 -34.65068
si24  -31.28772 -18.16608
si25  -14.80312 -1.68148
si26   1.68148   14.80312
si27   18.16608  31.28772
si28   34.65068  47.77232
si29   51.13528  64.25692
si30   67.61988  80.74152
sp11  0 1
sp12  0 1
sp13  0 1
sp14  0 1
sp15  0 1
sp16  0 1
sp17  0 1
sp18  0 1
sp19  0 1
sp20  0 1
sp21  0 1
sp22  0 1
sp23  0 1
sp24  0 1
sp25  0 1
sp26  0 1
sp27  0 1
sp28  0 1
sp29  0 1
sp30  0 1
c
#           imp:p
   301        1
   302        1
   303        1
   304        1
   305        1
   306        1
   307        1
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10228	1
10229	1
10230	1
10231	1
10232	1
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10234	1
10235	1
10236	1
10237	1
10238	1
10239	1
10240	1
10241	1
10244	1
10245	1
10246	1
10247	1
10248	1
10249	1
10250	1
10251	1
10252	1
10253	1
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10255	1
10256	1
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10259	1
10260	1
10261	1
10262	1
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10264	1
10265	1
10266	1
10267	1
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10273	1
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10275	1
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10279	1
10280	1
10281	1
10282	1
10283	1
11000	1
11001	1
11002	1
11003	1
11111	1
11112	1
11113	1
11114	1
11115	1
2000	3
2001	9
2002	27
2003	81
2004	243
2005	729
2006	2187
2007	6561
2017	6561
2008	19683
2009	39366
2010	39366
2011	78732
2012	78732
2013	157464
3000	27
3001	81
3002	243
3003	729
3004	2187
3005	6561
3006	19683
3007	59049
3008	177147
3009	354294
3010	354294
3011	708588
3012	708588
3013	1417176
3022	81
3023	243
3024	729
3025	2181
3026	6561
3126	6561
3027	19683
3127	19683
3227	19683
3327	19683
3028	59049
3128	59049
3228	59049
3029	118098
3129	118098
3229	118098
3030	118098

3031	236196
3032	236196
3033	472392
3042	27
3043	81
3044	243
3045	729
3046	2187
3047	6561
3048	19683
3049	39366
3149	39366
3050	39366
3051	78732
3052	78732
3053	157464
9000	27
9001	81
9002	243
9003	729
9004	2187
9005	6561
9006	19683
9007	59049
9008	177147
9009	354294
9010	354294
9011	708588
9012	708588
9013	1417176
9100	3
9101	9
9102	27
9103	81
9104	243
9105	729
9106	2187
9107	6561
9108	19683
9109	39366
9110	39366
9111	78732
9112	78732
9113	157464
9200	157464
9201	157464
9202	157464
9203	157464
9204	157464
9205	157464
9206	157464
9210	52488
9211	52488
9212	52488
9213	52488
9214	52488
9215	52488
9216	52488
9220	157464
9221	157464
9222	157464
9223	157464
9224	157464
9225	157464
9226	157464
9230	472392
9231	472392
9232	472392
9233	472392

9234	472392
9235	472392
9236	472392
9240	1417176
9241	1417176
9242	1417176
9243	1417176
9244	1417176
9245	1417176
9246	1417176
9508	1
9509	1
9510	1
9511	1
9512	1
9513	1
9514	1
9515	1
9516	1
9517	1
9518	1
9519	1
9520	1
9521	1
9522	1
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9524	1
9525	1
9526	1
9527	1
9528	1
9529	1
9530	1
9531	1
9532	1
9533	1
9534	1
9535	1
9536	1
9537	1
9538	1
9608	1
9609	1
9610	1
9611	1
9612	1
9613	1
9614	1
9615	1
9616	1
9617	1
9618	1
9619	1
9620	1
9621	1
9622	1
9623	1
9624	1
9625	1
9626	1
9627	1
9628	1
9629	1
9630	1
9631	1
9632	1
9633	1
9634	1
9635	1

```
   9637        1
   9638        1
   9639        1
   9999        0
c
c      neutron dose factors
c
c    2.5e-8   1.0e-7   1.0e-6   1.0e-5   1.0e-4   1.0e-3   1.0e-2     0.1
c       0.5      1.0      2.5       5.0       7.0      10.0      14.0     20.0
c    3.67e-6  3.67e-6  4.46e-6  4.54e-6  4.18e-6  3.76e-6  3.56e-6 2.17e-5
c       9.26e-5  1.32e-4  1.25e-4  1.56e-4  1.47e-4  1.47e-4  2.08e-4 2.27e-4
c
c      photon dose factors
c
c    0.01  0.03  0.05  0.07  0.1  0.15  0.2  0.25  0.3  0.35  0.4  0.45
c         0.5  0.55  0.6  0.65  0.7  0.8  1.0  1.4  1.8  2.2  2.6  2.8  3.25
c         3.75  4.25  4.75  5.0  5.25  5.75  6.25  6.75  7.5  9.0  11.0
c         13.0  15.0
c   3.96e-06  5.82e-07  2.90e-07  2.58e-07  2.83e-07  3.79e-07  5.01e-07
c       6.31e-07  7.59e-07  8.78e-07  9.85e-07  1.08e-06  1.17e-06  1.27e-06
c       1.36e-06  1.44e-06  1.52e-06  1.68e-06  1.98e-06  2.51e-06  2.99e-06
c       3.42e-06  3.82e-06  4.01e-06  4.41e-06  4.83e-06  5.23e-06  5.60e-06
c       5.80e-06  6.01e-06  6.37e-06  6.74e-06  7.11e-06  7.66e-06  8.77e-06
c       1.03e-05  1.18e-05  1.33e-05
c
c     PHOTON TALLIES
c
f102:p    515 517 516 518
fc102     bot  shear top very-top
ft102     scx 3
de102     0.01  0.03  0.05  0.07  0.1  0.15  0.2  0.25  0.3  0.35  0.4  0.45
          0.5  0.55  0.6  0.65  0.7  0.8  1.0  1.4  1.8  2.2  2.6  2.8  3.25
          3.75  4.25  4.75  5.0  5.25  5.75  6.25  6.75  7.5  9.0  11.0
          13.0  15.0
df102    3.96e-06  5.82e-07  2.90e-07  2.58e-07  2.83e-07  3.79e-07  5.01e-07
         6.31e-07  7.59e-07  8.78e-07  9.85e-07  1.08e-06  1.17e-06  1.27e-06
         1.36e-06  1.44e-06  1.52e-06  1.68e-06  1.98e-06  2.51e-06  2.99e-06
         3.42e-06  3.82e-06  4.01e-06  4.41e-06  4.83e-06  5.23e-06  5.60e-06
         5.80e-06  6.01e-06  6.37e-06  6.74e-06  7.11e-06  7.66e-06  8.77e-06
         1.03e-05  1.18e-05  1.33e-05
fq102    u s
c
f112:p    513 521 522 523 524 525 526
fs112     -702 -703 -704 -600 -630 -705 -706 -707 -708 -709 -710
         -711 -712 -713 -714 -715 -716 -717 -718 -670 -719 -695
         -720 -721 -722 t
fc112     1ft     1ft     1ft     1ft     8.75in   11.54in  11.54in 11.54in
         11.54in 11.54in 11.54in 11.54in 11.54in  11.54in  11.54in 11.54in
         11.54in 11.54in 11.54in 11.54in 10.375in 10.375in 1ft     1ft
         1ft     1ft
ft112     scx 3
de112     0.01  0.03  0.05  0.07  0.1  0.15  0.2  0.25  0.3  0.35  0.4  0.45
          0.5  0.55  0.6  0.65  0.7  0.8  1.0  1.4  1.8  2.2  2.6  2.8  3.25
          3.75  4.25  4.75  5.0  5.25  5.75  6.25  6.75  7.5  9.0  11.0
          13.0  15.0
df112    3.96e-06  5.82e-07  2.90e-07  2.58e-07  2.83e-07  3.79e-07  5.01e-07
         6.31e-07  7.59e-07  8.78e-07  9.85e-07  1.08e-06  1.17e-06  1.27e-06
         1.36e-06  1.44e-06  1.52e-06  1.68e-06  1.98e-06  2.51e-06  2.99e-06
         3.42e-06  3.82e-06  4.01e-06  4.41e-06  4.83e-06  5.23e-06  5.60e-06
         5.80e-06  6.01e-06  6.37e-06  6.74e-06  7.11e-06  7.66e-06  8.77e-06
         1.03e-05  1.18e-05  1.33e-05
fq112    u s
c
```

CHAPTER 6: CRITICALITY EVALUATION

This chapter documents the criticality evaluation of the HI-STAR 100 System for the packaging and transportation of radioactive materials (spent nuclear fuel) in accordance with 10CFR71. The results of this evaluation demonstrate that, for the designated fuel assembly classes and basket configurations, an infinite number of HI-STAR 100 Systems with variations in internal and external moderation remain subcritical with a margin of subcriticality greater than $0.05\Delta k$. This corresponds to a transport index of zero (0) and demonstrates compliance with 10CFR71 criticality requirements for normal and hypothetical accident conditions of transport.

The criticality design is based on favorable geometry, fixed neutron poisons (Boral), an administrative limit on the maximum allowable enrichment, and an administrative limit on the minimum average assembly burnup for the MPC-32. Criticality safety of the HI-STAR 100 System does *not* rely on credit for: (1) fuel burnup except for the MPC-32; (2) fuel-related burnable absorbers; or (3) more than 75% of the manufacturer's minimum B-10 content for the Boral neutron absorber.

In addition to demonstrating that the criticality safety acceptance criteria are satisfied, this chapter describes the HI-STAR 100 System design structures and components important to criticality safety and limiting fuel characteristics in sufficient detail to identify the package accurately and provide a sufficient basis for the evaluation of the package.

Note:
The MPC-32 requires burnup credit. Methodology and results for burnup credit are not yet presented in this chapter, and will be added as Appendix 6.E in a later revision of this SAR. However, general discussions regarding the MPC-32, tables for burnup credit results and references to Appendix 6.E have already been added throughout this chapter.

6.1 DISCUSSION AND RESULTS

In conformance with the principles established in 10CFR71 [6.1.1], NUREG-1617 [6.1.2], and NUREG-0800 Section 9.1.2 [6.1.3], the results in this chapter demonstrate that the effective multiplication factor (k_{eff}) of the HI-STAR 100 System, including all biases and uncertainties evaluated with a 95% probability at the 95% confidence level, does not exceed 0.95 under all credible normal and hypothetical accident conditions of transport. This criterion provides a large subcritical margin, sufficient to assure the criticality safety of the HI-STAR 100 System when fully loaded with fuel of the highest permissible reactivity. In addition, the results of this evaluation demonstrate that the HI-STAR 100 System is in full compliance with the requirements outlined in the Standard Review Plan for Dry Cask Storage Systems, NUREG-1536.

Criticality safety of the HI-STAR 100 System depends on the following four principal design parameters:

1. The inherent geometry of the fuel basket designs within the MPC (and the flux-trap water gaps in the MPC-24),

2. The incorporation of permanent fixed neutron-absorbing panels (Boral) in the fuel basket structure, and

3. An administrative limit on the maximum average enrichment for PWR fuel and maximum planar-average enrichment for BWR fuel, and

4. An administrative limit on the minimum average assembly burnup for PWR fuel in the MPC-32.

The HI-STAR 100 System is designed such that the fixed neutron absorber (Boral) will remain effective for a period greater than 20 years, and there are no credible means to lose it. Therefore, there is no need to provide a surveillance or monitoring program to verify the continued efficacy of the neutron absorber.

Criticality safety of the HI-STAR 100 System does not rely on the use of any of the following credits:

- burnup of fuel, except for the MPC-32

- fuel-related burnable neutron absorbers

- more than 75 percent of the B-10 content for the fixed neutron absorber (Boral).

The following interchangeable basket designs are available for use in the HI-STAR 100 System:

- a 24-cell basket (MPC-24), designed for intact PWR fuel assemblies with a specified maximum enrichment.

- a 24-cell basket (MPC-24E/EF), designed for intact and damaged PWR fuel assemblies, and fuel debris (MPC-24EF only). This is a variation of the MPC-24, with increased ^{10}B content in the Boral and with four cells capable of accommodating either intact fuel or a damaged fuel container (DFC). The MPC-24E and MPC-24EF is designed for fuel assemblies with a specified maximum enrichment. Although the MPC-24E/EF is designed and analyzed for damaged fuel and fuel debris, it is only certified for intact fuel assemblies.

- a 24-cell basket (MPC-24E/EF Trojan), design for intact and damaged PWR fuel assemblies, and fuel debris (MPC-24EF Trojan only) from the Trojan Nuclear Plant (TNP). This is a variation of the MPC-24E/EF, with a slightly reduced height, and increased cell sizes for the cells designated for damaged fuel and fuel debris. This increased cell size is required to accommodate the Trojan specific Failed Fuel Cans and DFCs.

- a 32-cell basket (MPC-32), designed for intact PWR fuel assemblies of a specified minimum burnup, and

- a 68-cell basket (MPC-68), designed for both intact and damaged BWR fuel assemblies with a specified maximum planar-average enrichment. Additionally, a variation in the MPC-68, designated MPC-68F, is designed for damaged BWR fuel assemblies and BWR fuel debris with a specified maximum planar-average enrichment.

During the normal conditions of transport, the HI-STAR 100 System is dry (no moderator), and thus, the reactivity is very low (k_{eff} < 0.50). However, the HI-STAR 100 System for loading and unloading operations, as well as for the hypothetical accident conditions, is flooded, and thus, represents the limiting case in terms of reactivity. The calculational models for these conditions conservatively include: full flooding with ordinary water, corresponding to the highest reactivity, and the worst case (most conservative) combination of manufacturing and fabrication tolerances.

The MPC-24EF contains the same basket as the MPC-24E. More specifically, all dimensions relevant to the criticality analyses are identical between the MPC-24E and MPC-24EF. Therefore, all criticality results obtained for the MPC-24E are valid for the MPC-24EF and no separate analyses for the MPC-24EF are necessary.

Confirmation of the criticality safety of the HI-STAR 100 Systems under flooded conditions, when filled with fuel of the maximum permissible reactivity for which they are designed, was

accomplished with the three-dimensional Monte Carlo code MCNP4a [6.1.4]. Independent confirmatory calculations were made with NITAWL-KENO5a from the SCALE-4.3 package. KENO5a [6.1.5] calculations used the 238-group SCALE cross-section library in association with the NITAWL-II program [6.1.6], which adjusts the uranium-238 cross sections to compensate for resonance self-shielding effects. The Dancoff factors required by NITAWL-II were calculated with the CELLDAN code [6.1.13], which includes the SUPERDAN code [6.1.7] as a subroutine. K-factors for one-sided statistical tolerance limits with 95% probability at the 95% confidence level were obtained from the National Bureau of Standards (now NIST) Handbook 91 [6.1.8].

For the burnup credit calculations, CASMO-4, a two-dimensional transport theory code [6.1.10-6.1.12] for fuel assemblies, was used to calculate the isotopic composition of the spent fuel. The criticality evaluations for burnup credit were performed with MCNP4a [6.1.4].

To assess the incremental reactivity effects due to manufacturing tolerances, CASMO and MCNP4a [6.1.4] were used. The CASMO and MCNP4a calculations identify those tolerances that cause a positive reactivity effect, enabling the Monte Carlo code input to define the worst case (most conservative) conditions. CASMO was not used for quantitative criticality evaluations, but only to qualitatively indicate the direction and approximate magnitude of the reactivity effects of the manufacturing tolerances.

Benchmark calculations were made to compare the primary code packages (MCNP4a, CASMO and KENO5a) with experimental data, using experiments selected to encompass, insofar as practical, the design parameters of the HI-STAR 100 System. The most important parameters are (1) the enrichment, (2) the water-gap size (MPC-24) or cell spacing (MPC-32 and MPC-68), (3) the ^{10}B loading of the neutron absorber panels, and (4) the assembly burnup (MPC-32 only). Benchmark calculations are presented in Appendix 6.A and Appendix 6.E.

Applicable codes, standards, and regulations, or pertinent sections thereof, include the following:

- U.S. Code of Federal Regulations, "Packaging and Transportation of Radioactive Materials," Title 10, Part 71.

- NUREG-1617, "Standard Review Plan for Transportation Packages for Spent Nuclear Fuel" USNRC, Washington D.C., March 2000.

- U.S. Code of Federal Regulations, "Prevention of Criticality in Fuel Storage and Handling," Title 10, Part 50, Appendix A, General Design Criterion 62.

- USNRC Standard Review Plan, NUREG-0800, Section 9.1.2, Spent Fuel Storage, Rev. 3, July 1981.

- USNRC Interim Staff Guidance 8 (ISG-8), Revision 2, "Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks".

To assure the true reactivity will always be less than the calculated reactivity, the following conservative assumptions were made:

- The MPCs are assumed to contain the most reactive fuel authorized to be loaded into a specific basket design.

- No credit for fuel burnup is assumed, either in depleting the quantity of fissile nuclides or in producing fission product poisons, except for fuel in the MPC-32.

- The criticality analyses assume 75% of the manufacturer's minimum Boron-10 content for the Boral neutron absorber.

- The fuel stack density is assumed to be 96% of theoretical (10.522 g/cm^3) for all criticality analyses. The fuel stack density is approximately equal to 98% of the pellet density. Therefore, while the pellet density of some fuels might be slightly greater than 96% of theoretical, the actual stack density will still be less.

- For fresh fuel, no credit is taken for the ^{234}U and ^{236}U in the fuel.

- When flooded, the moderator is assumed to be water at a temperature corresponding to the highest reactivity within the expected operating range (i.e., water density of 1.000 g/cc).

- Neutron absorption in minor structural members and optional heat conduction elements is neglected, i.e., spacer grids, basket supports, and optional aluminum heat conduction elements are replaced by water.

- The worst hypothetical combination of tolerances (most conservative values within the range of acceptable values), as identified in Section 6.3, is assumed.

- When flooded, the fuel rod pellet-to-clad gap regions are assumed to be flooded.

- Planar-averaged enrichments are assumed for BWR fuel. (Analyses are presented in Appendix 6.B to demonstrate that the use of planar-average enrichments produces conservative results.)

- Fuel-related burnable neutron absorbers, such as the Gadolinia normally used in BWR fuel and IFBA normally used in PWR fuel, are neglected.

- For evaluation of the reactivity bias, all benchmark calculations that result in a k_{eff} greater than 1.0 are conservatively truncated to 1.0000.

- For fuel assemblies that contain low-enriched axial blankets, the governing enrichment is that of the highest planar average, and the blankets are not included in determining the average enrichment.

- Regarding the position of assemblies in the basket, configurations with centered and eccentric positioning of assemblies in the fuel storage locations are considered. For further discussions see Section 6.3.3.

- For intact fuel assemblies, as defined in Chapter 1, missing fuel rods must be replaced with dummy rods that displace a volume of water that is equal to, or larger than, that displaced by the original rods.

- The burnup credit methodology for the MPC-32 contains significant additional conservative assumption specific to burnup credit, as discussed in Appendix 6.E.

The principal calculational results, which address the following conditions:

- A single package, under the conditions of 10 CFR 71.55(b), (d), and (e);
- An array of undamaged packages, under the conditions of 10 CFR 71.59(a)(1); and
- An array of damaged packages, under the conditions of 10 CFR 71.59(a)(2)

are summarized in Table 6.1.4 for all MPCs and for the most reactive configuration and fuel condition in each MPC. These results demonstrate that the HI-STAR 100 System is in full compliance with 10CFR71 (71.55(b), (d), and (e) and 71.59(a)(1) and (a)(2)). The calculations for package arrays are performed for infinite arrays of HI-STAR 100 Systems under flooded conditions. Therefore, the transportation index based on criticality control is zero (0). It is noted that the results for the internally flooded single package and package arrays are statistically equivalent for each basket. This shows that the physical separation between overpacks and the steel radiation shielding are each adequate to preclude any significant neutronic coupling between casks in an array configuration. In addition, the table shows the result for an unreflected, internally flooded cask for each MPC. This configuration is used in many calculations and studies throughout this chapter, and is shown to yield results that are statistically equivalent to the results for the corresponding reflected package. Further analyses for the various conditions of flooding that support the conclusion that the fully flooded condition corresponds to the highest

reactivity, and thus is most limiting, are presented in Section 6.4. These analyses also include cases with various internal and external moderator densities and various cask-to-cask spacings.

Additional results of the design basis criticality safety calculations for single unreflected, internally flooded casks (limiting cases) are listed in Tables 6.1.1 through 6.1.3 and 6.1.5 through 6.1.7, conservatively evaluated for the worst combination of manufacturing tolerances (as identified in Section 6.3), and including the calculational bias, uncertainties, and calculational statistics. For each of the MPC designs and fuel assembly classes†, Tables 6.1.1 through 6.1.3 and 6.1.5 through 6.1.7 list the bounding maximum k_{eff} value, the associated maximum allowable enrichment, and the minimum required assembly average burnup (if applicable), as required by 10CFR71.33(b)(2). The maximum enrichment and minimum burnup acceptance criteria are defined in Chapter 1. Additional results for each of the candidate fuel assemblies, that are bounded by those listed in Tables 6.1.1 through 6.1.3, are given in Section 6.2 for the MPC-24, MPC-68 and MPC-68F. The tables in Section 6.2 list the maximum k_{eff} (including bias, uncertainties, and calculational statistics), calculated k_{eff}, standard deviation, and energy of the average lethargy causing fission (EALF) for each of the candidate fuel assemblies and basket configurations analyzed. The capability of the MPC-68F to safely accommodate Dresden-1 and Humboldt Bay damaged fuel (fuel assembly classes 6x6A, 6x6B, 6x6C, 7x7A, and 8x8A) is demonstrated in Subsection 6.4.4.

In Summary, these results confirm that the maximum k_{eff} values for the HI-STAR 100 System are below the limiting design criteria ($k_{eff} < 0.95$) when fully flooded and loaded with any of the candidate fuel assemblies and basket configurations. The transportation index based on criticality control is zero (0).

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† For each array size (e.g., 6x6, 7x7, 14x14, etc.), the fuel assemblies have been subdivided into a number of assembly classes, where an assembly class is defined in terms of the (1) number of fuel rods; (2) pitch; (3) number and location of guide tubes (PWR) or water rods (BWR); and (4) cladding material. The assembly classes for BWR and PWR fuel are defined in Section 6.2.

Table 6.1.1

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-24

Fuel Assembly Class	Maximum Allowable Enrichment (wt% ^{235}U)	Maximum† k_{eff}
14x14A	4.6	0.9296
14x14B	4.6	0.9228
14x14C	4.6	0.9307
14x14D	4.0	0.8507
14x14E	5.0	0.7627
15x15A	4.1	0.9227
15x15B	4.1	0.9388
15x15C	4.1	0.9361
15x15D	4.1	0.9367
15x15E	4.1	0.9392
15x15F	4.1	0.9410
15x15G	4.0	0.8907
15x15H	3.8	0.9337
16x16A	4.6	0.9287
17x17A	4.0	0.9368
17x17B	4.0	0.9355
17x17C	4.0	0.9349

Note: These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.1.2

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-68

Fuel Assembly Class	Maximum Allowable Planar-Average Enrichment (wt% ^{235}U)	Maximum† k_{eff}
6x6A	2.7††	0.7888†††
6x6B‡	2.7††	0.7824†††
6x6C	2.7††	0.8021†††
7x7A	2.7††	0.7974†††
7x7B	4.2	0.9386
8x8A	2.7††	0.7697†††
8x8B	4.2	0.9416
8x8C	4.2	0.9425
8x8D	4.2	0.9403
8x8E	4.2	0.9312
8x8F	4.0	0.9459

Note: These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† This calculation was performed for 3.0% planar-average enrichment, however, the authorized contents are limited to maximum planar-average enrichment of 2.7%. Therefore, the listed maximum k_{eff} value is conservative.

††† This calculation was performed for a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum ^{10}B loading of 0.0089 g/cm^2. The minimum ^{10}B loading in the MPC-68 is 0.0372 g/cm^2. Therefore, the listed maximum k_{eff} value is conservative.

‡ Assemblies in this class contain both MOX and UO_2 pins. The composition of the MOX fuel pins is given in Table 6.3.4. The maximum allowable planar-average enrichment for the MOX pins is given in the specification of authorized contents, Chapter 1.

Table 6.1.2 (continued)

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-68

Fuel Assembly Class	Maximum Allowable Planar-Average Enrichment (wt% ^{235}U)	Maximum† k_{eff}
9x9A	4.2	0.9417
9x9B	4.2	0.9436
9x9C	4.2	0.9395
9x9D	4.2	0.9394
9x9E	4.0	0.9486
9x9F	4.0	0.9486
9x9G	4.2	0.9383
10x10A	4.2	0.9457††
10x10B	4.2	0.9436
10x10C	4.2	0.9433
10x10D	4.0	0.9376
10x10E	4.0	0.9185

Note: These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† KENO5a verification calculation resulted in a maximum k_{eff} of 0.9453.

Table 6.1.3

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-68F

Fuel Assembly Class	Maximum Allowable Planar-Average Enrichment (wt% ^{235}U)	Maximum† k_{eff}
6x6A	2.7††	0.7888
6x6B†††	2.7	0.7824
6x6C	2.7	0.8021
7x7A	2.7	0.7974
8x8A	2.7	0.7697

Note:

1. These calculations are for single unreflected, fully flooded casks. However, comparable reactivities were obtained for fully reflected casks and for arrays of casks.

2. These calculations were performed for a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum ^{10}B loading of 0.0089 g/cm^2. The minimum ^{10}B loading in the MPC-68F is 0.010 g/cm^2. Therefore, the listed maximum k_{eff} values are conservative.

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† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† These calculations were performed for 3.0% planar-average enrichment, however, the authorized contents are limited to a maximum planar-average enrichment of 2.7%. Therefore, the listed maximum k_{eff} values are conservative.

††† Assemblies in this class contain both MOX and UO_2 pins. The composition of the MOX fuel pins is given in Table 6.3.4. The maximum allowable planar-average enrichment for the MOX pins is given in the specification of authorized contents, Chapter 1.

Table 6.1.4
SUMMARY OF THE CRITICALITY RESULTS FOR THE MOST REACTIVE ASSEMBLY FROM THE ASSEMBLY CLASSES IN EACH MPC
TO DEMONSTRATE COMPLIANCE WITH 10CFR71.55 AND 10CFR71.59

MPC-24, Assembly Class 15x15F, 4.1 wt% ^{235}U				
Configuration	% Internal Moderation	% External Moderation	Applicable Requirement	Maximum‡ k_{eff}
Single Package, unreflected	100%	0%	n/a	0.9410
Single Package, fully reflected	100%	100%	10CFR71.55 (b), (d), and (e)	0.9397
Containment, fully reflected	100%	100%		0.9397
Infinite Array of Damaged Packages	100%	100%	10CFR71.59 (a)(2)	0.9436
Infinite Array of Undamaged Packages	0%	0%	10CFR71.59 (a)(1)	0.3950
MPC-68, Assembly Class 9x9E/F, 4.0 wt% ^{235}U				
Configuration	% Internal Moderation	% External Moderation	Applicable Requirement	Maximum k_{eff}
Single Package, unreflected	100%	0%	n/a	0.9486
Single Package, fully reflected	100%	100%	10CFR71.55 (b), (d), and (e)	0.9470
Containment, fully reflected	100%	100%		0.9461
Infinite Array of Damaged Packages	100%	100%	10CFR71.59 (a)(2)	0.9468
Infinite Array of Undamaged Packages	0%	0%	10CFR71.59 (a)(1)	0.3808
MPC-68F, Assembly Class 6x6C, 2.7 wt% ^{235}U				
Configuration	% Internal Moderation	% External Moderation	Applicable Requirement	Maximum k_{eff}
Single Package, unreflected	100%	0%	n/a	0.8021
Single Package, fully reflected	100%	100%	10CFR71.55 (b), (d), and (e)	0.8033
Containment, fully reflected	100%	100%		0.8033
Infinite Array of Damaged Packages	100%	100%	10CFR71.59 (a)(2)	0.8026
Infinite Array of Undamaged Packages	0%	0%	10CFR71.59 (a)(1)	0.3034

‡ The maximum k_{eff} is equal to the sum of the calculated k_{eff}, two standard deviations, the code bias, and the uncertainty in the code bias. For cases with 100% internal moderation, the standard deviation is between 0.0007 and 0.0009, for cases with 0% internal moderation, the standard deviation is between 0.0002 and 0.0004.

Table 6.1.4 (continued)
SUMMARY OF THE CRITICALITY RESULTS FOR THE MOST REACTIVE ASSEMBLY FROM THE ASSEMBLY CLASSES IN EACH MPC
TO DEMONSTRATE COMPLIANCE WITH 10CFR71.55 AND 10CFR71.59

MPC-24E/EF, Assembly Class 15x15F, 4.5 wt% ^{235}U				
Configuration	% Internal Moderation	% External Moderation	Applicable Requirement	Maximum‡ k_{eff}
Single Package, unreflected	100%	0%	n/a	0.9495
Single Package, fully reflected	100%	100%	10CFR71.55 (b), (d), and (e)	0.9485
Containment, fully reflected	100%	100%		0.9486
Infinite Array of Damaged Packages	100%	100%	10CFR71.59 (a)(2)	0.9495
Infinite Array of Undamaged Packages	0%	0%	10CFR71.59 (a)(1)	0.4026
MPC-24E/EF TROJAN, Trojan Intact and Damaged Fuel, 3.7 wt% ^{235}U				
Configuration	% Internal Moderation	% External Moderation	Applicable Requirement	Maximum k_{eff}
Single Package, unreflected	100%	0%	n/a	0.9377
Single Package, fully reflected	100%	100%	10CFR71.55 (b), (d), and (e)	0.9366
Containment, fully reflected	100%	100%		0.9377
Infinite Array of Damaged Packages	100%	100%	10CFR71.59 (a)(2)	0.9383
Infinite Array of Undamaged Packages	0%	0%	10CFR71.59 (a)(1)	0.3518
MPC-32, Assembly Class 15x15F, 4.0 wt% ^{235}U				
Configuration	% Internal Moderation	% External Moderation	Applicable Requirement	Maximum k_{eff}
Single Package, unreflected	100%	0%	n/a	later
Single Package, fully reflected	100%	100%	10CFR71.55 (b), (d), and (e)	later
Containment, fully reflected	100%	100%		later
Infinite Array of Damaged Packages	100%	100%	10CFR71.59 (a)(2)	later
Infinite Array of Undamaged Packages	0%	0%	10CFR71.59 (a)(1)	later

‡ The maximum k_{eff} is equal to the sum of the calculated k_{eff}, two standard deviations, the code bias, and the uncertainty in the code bias. For cases with 100% internal moderation, the standard deviation is between 0.0007 and 0.0009, for cases with 0% internal moderation, the standard deviation is between 0.0002 and 0.0004.

Table 6.1.5

BOUNDING MAXIMUM k_{eff} VALUES FOR EACH ASSEMBLY CLASS IN THE MPC-24E/EF

Fuel Assembly Class	Maximum Allowable Enrichment (wt% ^{235}U)	Maximum† k_{eff}
14x14A	5.0	0.9380
14x14B	5.0	0.9312
14x14C	5.0	0.9365
14x14D	5.0	0.8875
14x14E	5.0	0.7651
15x15A	4.5	0.9336
15x15B	4.5	0.9487
15x15C	4.5	0.9462
15x15D	4.5	0.9445
15x15E	4.5	0.9471
15x15F	4.5	0.9495
15x15G	4.5	0.9062
15x15H	4.2	0.9455
16x16A	5.0	0.9358
17x17A	4.4	0.9447
17x17B	4.4	0.9438
17x17C	4.4	0.9433

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.1.6

BOUNDING MAXIMUM k_{eff} VALUES IN THE MPC-24E/EF TROJAN

Fuel Assembly Class	**Maximum Allowable Enrichment (wt% ^{235}U)**	**Content**	**Maximum† k_{eff}**
17x17B	3.7	Intact Fuel	0.9187
17x17B	3.7	Intact Fuel, Damaged Fuel and Fuel Debris	0.9377

† The term "maximum k_{eff} " as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.1.7

BOUNDING MAXIMUM k_{eff} VALUES IN THE MPC-32

Fuel Assembly Class	Maximum Allowable Enrichment†† (wt% ^{235}U)	Minimum Required Assembly Average Burnup†† (GWd/MTU)	Maximum† k_{eff}
15x15D, E, F, H	2.0	later	later
	3.0	later	later
	4.0	later	later
	5.0	later	later
17x17A, B, C	2.0	later	later
	3.0	later	later
	4.0	later	later
	5.0	later	later

†† Other combinations of maximum enrichment and minimum burnup have been evaluated which result in the same maximum k_{eff}. See Appendix 6.E for a bounding polynomial function.

† The term "maximum k_{eff} " as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

6.2 SPENT FUEL LOADING

Specifications for the BWR and PWR fuel assemblies that were analyzed in this criticality evaluation are given in Tables 6.2.1 and 6.2.2, respectively. For the BWR fuel characteristics, the number and dimensions for the water rods are the actual number and dimensions. For the PWR fuel characteristics, the actual number and dimensions of the control rod guide tubes and thimbles are used. Table 6.2.1 lists 72 unique BWR assemblies while Table 6.2.2 lists 46 unique PWR assemblies, all of which were explicitly analyzed for this evaluation. Examination of Tables 6.2.1 and 6.2.2 reveals that there are a large number of minor variations in fuel assembly dimensions.

Due to the large number of minor variations in fuel assembly dimensions, the use of explicit dimensions in defining the authorized contents could limit the applicability of the HI-STAR 100 System. To resolve this limitation, bounding criticality analyses are presented in this section for a number of defined fuel assembly classes for both fuel types (PWR and BWR). The results of the bounding criticality analyses justify using bounding fuel dimensions for defining the authorized contents.

6.2.1 Definition of Assembly Classes

For each array size (e.g., 6x6, 7x7, 15x15, etc.), the fuel assemblies have been subdivided into a number of defined classes, where a class is defined in terms of the (1) number of fuel rods; (2) pitch; (3) number and locations of guide tubes (PWR) or water rods (BWR); and (4) cladding material. The assembly classes for BWR and PWR fuel are defined in Tables 6.2.1 and 6.2.2, respectively. It should be noted that these assembly classes are unique to this evaluation and are not known to be consistent with any class designations in the open literature.

For each assembly class, calculations have been performed for all of the dimensional variations for which data is available (i.e., all data in Tables 6.2.1 and 6.2.2). These calculations demonstrate that the maximum reactivity corresponds to:

- maximum active fuel length,
- maximum fuel pellet diameter,
- minimum cladding outside diameter (OD),
- maximum cladding inside diameter (ID),
- minimum guide tube/water rod thickness, and
- maximum channel thickness (for BWR assemblies only).

Therefore, for each assembly class, a bounding assembly was defined based on the above characteristics and a calculation for the bounding assembly was performed to demonstrate compliance with the regulatory requirement of $k_{eff} < 0.95$. In some assembly classes this

bounding assembly corresponds directly to one of the actual (real) assemblies; while in most assembly classes, the bounding assembly is artificial (i.e., based on bounding dimensions from more than one of the actual assemblies). In classes where the bounding assembly is artificial, the reactivity of the actual (real) assemblies is typically much less than that of the bounding assembly; thereby providing additional conservatism. As a result of these analyses, the authorized contents (Chapter 1) are defined in terms of the bounding assembly parameters for each class.

To demonstrate that the aforementioned characteristics are bounding, a parametric study was performed for a reference BWR assembly, designated herein as 8x8C04 (identified generally as a GE8x8R). The results of this study are shown in Table 6.2.3, and verify the positive reactivity effect associated with (1) increasing the pellet diameter, (2) maximizing the cladding ID (while maintaining a constant cladding OD), (3) minimizing the cladding OD (while maintaining a constant cladding ID), (4) decreasing the water rod thickness, (5) artificially replacing the Zircaloy water rod tubes with water, (6) maximizing the channel thickness, and (7) increasing the active length. These results, and the many that follow, justify the approach for using bounding dimensions for defining the authorized contents. Where margins permit, the Zircaloy water rod tubes (BWR assemblies) are artificially replaced by water in the bounding cases to remove the requirement for water rod thickness from the specification of authorized contents.

As mentioned, the bounding approach used in these analyses often results in a maximum k_{eff} value for a given class of assemblies that is much greater than the reactivity of any of the actual (real) assemblies within the class, and yet, is still below the 0.95 regulatory limit.

6.2.2 PWR Fuel Assemblies in the MPC-24

For PWR fuel assemblies (specifications listed in Table 6.2.2) the 15x15F01 fuel assembly at 4.1% enrichment has the highest reactivity (see Table 6.2.13). The 17x17A01 assembly (otherwise known as a Westinghouse 17x17 OFA) has a similar reactivity (see Table 6.2.17) and was used throughout this criticality evaluation as a reference PWR assembly. The 17x17A01 assembly is a representative PWR fuel assembly in terms of design and reactivity and is useful for the reactivity studies presented in Sections 6.3 and 6.4. Calculations for the various PWR fuel assemblies in the MPC-24 are summarized in Tables 6.2.4 through 6.2.19 and 6.2.43 for the fully flooded condition with the fuel centered in each fuel storage location.

Tables 6.2.4 through 6.2.19 and 6.2.43 show the maximum k_{eff} values for the assembly classes that are acceptable for storage in the MPC-24. All maximum k_{eff} values include the bias, uncertainties, and calculational statistics, evaluated for the worst combination of manufacturing tolerances. All calculations for the MPC-24 were performed for a ^{10}B loading of 0.020 g/cm^2, which is 75% of the minimum loading, 0.0267 g/cm^2, specified for the MPC-24 in Section 1.4. The maximum allowable enrichment in the MPC-24 varies from 3.8 to 5.0 wt% ^{235}U, depending on the assembly class, and is defined in Tables 6.2.4 through 6.2.19 and 6.2.43. It should be

noted that the maximum allowable enrichment does not vary within an assembly class. Table 6.1.1 summarizes the maximum allowable enrichments for each of the assembly classes that are acceptable for storage in the MPC-24.

Tables 6.2.4 through 6.2.19 and 6.2.43 are formatted with the assembly class information in the top row, the unique assembly designations, dimensions, and k_{eff} values in the following rows above the bold double lines, and the bounding dimensions selected to define the authorized contents and corresponding bounding k_{eff} values in the final rows. Where the bounding assembly corresponds directly to one of the actual assemblies, the fuel assembly designation is listed in the bottom row in parentheses (e.g., Table 6.2.4). Otherwise, the bounding assembly is given a unique designation. For an assembly class that contains only a single assembly (e.g., 14x14D, see Table 6.2.7), the authorized contents dimensions are based on the assembly dimensions from that single assembly. Generally, the maximum k_{eff} values corresponding to the selected bounding dimensions are greater than or equal to those for the actual assembly dimensions, and all maximum k_{eff} values are below the 0.95 regulatory limit.

The results of the analyses for the MPC-24, which were performed for all assemblies in each class, further confirm the validity of the bounding dimensions established in Subsection 6.2.1. Thus, for all following calculations, namely analyses of the MPC-24E, only the bounding assembly in a class is analyzed. For the MPC-32 with burnup credit, the validity of the bounding dimensions is verified in Appendix 6.E.

6.2.3 BWR Fuel Assemblies in the MPC-68

For BWR fuel assemblies (specifications listed in Table 6.2.1) the artificial bounding assembly for the 10x10A assembly class at 4.2% enrichment has the highest reactivity (see Table 6.2.32). Calculations for the various BWR fuel assemblies in the MPC-68 are summarized in Tables 6.2.20 through 6.2.36 and 6.2.44 for the fully flooded condition. In all cases, the gadolinia (Gd_2O_3) normally incorporated in BWR fuel was conservatively neglected and the fuel assembly was assumed to be centered in the fuel storage location.

For calculations involving BWR assemblies, the use of a uniform (planar-average) enrichment, as opposed to the distributed enrichments normally used in BWR fuel, produces conservative results. Calculations confirming this statement are presented in Appendix 6.B for several representative BWR fuel assembly designs. These calculations justify the specification of planar-average enrichments to define acceptability of BWR fuel for loading into the MPC-68.

Tables 6.2.20 through 6.2.36 and 6.2.44 show the maximum k_{eff} values for assembly classes that are acceptable for storage in the MPC-68. All maximum k_{eff} values include the bias, uncertainties, and calculational statistics, evaluated for the worst combination of manufacturing tolerances. With the exception of assembly classes 6x6A, 6x6B, 6x6C, 7x7A, and 8x8A, which will be discussed in Section 6.2.4, all calculations for the MPC-68 were performed with a ^{10}B loading of 0.0279 g/cm^2, which is 75% of the minimum loading, 0.0372 g/cm^2, specified for the

MPC-68 in Section 1.4. Calculations for assembly classes 6x6A, 6x6B, 6x6C, 7x7A, and 8x8A were conservatively performed with a ^{10}B loading of 0.0067 g/cm^2. The maximum allowable enrichment in the MPC-68 varies from 2.7 to 4.2 wt% ^{235}U, depending on the assembly class. It should be noted that the maximum allowable enrichment does not vary within an assembly class. Table 6.1.2 summarizes the maximum allowable enrichments for all assembly classes that are acceptable for storage in the MPC-68.

Tables 6.2.20 through 6.2.36 and 6.2.44 are formatted with the assembly class information in the top row, the unique assembly designations, dimensions, and k_{eff} values in the following rows above the bold double lines, and the bounding dimensions selected to define the authorized contents and corresponding bounding k_{eff} values in the final rows. Where an assembly class contains only a single assembly (e.g., 8x8E, see Table 6.2.24), the authorized contents dimensions are based on the assembly dimensions from that single assembly. For assembly classes that are suspected to contain assemblies with thicker channels (e.g., 120 mils), bounding calculations are also performed to qualify the thicker channels (e.g. 7x7B, see Table 6.2.20). All of the maximum k_{eff} values corresponding to the selected bounding dimensions are shown to be greater than or equal to those for the actual assembly dimensions and are below the 0.95 regulatory limit.

For assembly classes that contain partial length rods (i.e., 9x9A, 10x10A, and 10x10B), calculations were performed for the actual (real) assembly configuration and for the axial segments (assumed to be full length) with and without the partial length rods. In all cases, the axial segment with only the full length rods present (where the partial length rods are absent) is bounding. Therefore, the bounding maximum k_{eff} values reported for assembly classes that contain partial length rods bound the reactivity regardless of the active fuel length of the partial length rods. As a result, the specification of authorized contents has no minimum requirement for the active fuel length of the partial length rods.

For BWR fuel assembly classes where margins permit, the Zircaloy water rod tubes are artificially replaced by water in the bounding cases to remove the requirement for water rod thickness from the specification of authorized contents. For these cases, the bounding water rod thickness is listed as zero.

As mentioned, the highest observed maximum k_{eff} value† corresponds to the artificial bounding assembly in the 10x10A assembly class. This assembly has the following bounding characteristics: (1) the partial length rods are assumed to be zero length (most reactive configuration); (2) the channel is assumed to be 120 mils thick; and (3) the active fuel length of the full length rods is 155 inches.

† Assuming assemblies are centered in their basket position. For cases with eccentric positioning see Section 6.3.3.

6.2.4 Damaged BWR Fuel Assemblies and BWR Fuel Debris

In addition to storing intact PWR and BWR fuel assemblies, the HI-STAR 100 System is designed to store damaged BWR fuel assemblies and BWR fuel debris. Damaged fuel assemblies and fuel debris are defined in Chapter 1. Both damaged BWR fuel assemblies and BWR fuel debris are required to be loaded into Damaged Fuel Containers (DFCs). Two different DFC types with slightly different cross sections are considered. DFCs containing fuel debris must be stored in the MPC-68F. DFCs containing damaged fuel assemblies may be stored in either the MPC-68 or MPC-68F. The criticality evaluation of various possible damaged conditions of the fuel is presented in Subsection 6.4.4 for both DFC types.

Tables 6.2.37 through 6.2.41 show the maximum k_{eff} values for the six assembly classes that may be stored as damaged fuel or fuel debris. All maximum k_{eff} values include the bias, uncertainties, and calculational statistics, evaluated for the worst combination of manufacturing tolerances. All calculations were performed for a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum loading, 0.0089 g/cm^2. However, because the practical manufacturing lower limit for minimum ^{10}B loading is 0.01 g/cm^2, the minimum ^{10}B loading of 0.01 g/cm^2 is specified in Section 1.4, for the MPC-68F. As an additional level of conservatism in the analyses, the calculations were performed for an enrichment of 3.0 wt% ^{235}U, while the maximum allowable enrichment for these assembly classes is limited to 2.7 wt% ^{235}U in the specification of authorized contents. Therefore, the maximum k_{eff} values for damaged BWR fuel assemblies and fuel debris are conservative. Calculations for the various BWR fuel assemblies in the MPC-68F are summarized in Tables 6.2.37 through 6.2.41 for the fully flooded condition.

For the assemblies that may be stored as damaged fuel or fuel debris, the 6x6C01 assembly at 3.0 wt% ^{235}U enrichment has the highest reactivity (see Table 6.2.39). Considering all of the conservatism built into this analysis (e.g., higher than allowed enrichment and lower than actual ^{10}B loading), the actual reactivity will be lower.

Because the analysis for the damaged BWR fuel assemblies and fuel debris was performed for a minimum ^{10}B loading of 0.0089 g/cm^2, which conservatively bounds damaged BWR fuel assemblies in a standard MPC-68 with a minimum ^{10}B loading of 0.0372 g/cm^2, damaged BWR fuel assemblies may also be stored in the standard MPC-68. However, fuel debris is limited to the MPC-68F by the specification of authorized contents in Chapter 1.

Tables 6.2.37 through 6.2.41 are formatted with the assembly class information in the top row, the unique assembly designations, dimensions, and k_{eff} values in the following rows above the bold double lines, and the bounding dimensions selected to define the authorized contents and corresponding bounding k_{eff} values in the final rows. Where an assembly class contains only a single assembly (e.g., 6x6C, see Table 6.2.39), the authorized contents dimensions are based on the assembly dimensions from that single assembly. All of the maximum k_{eff} values corresponding to the selected bounding dimensions are greater than or equal to those for the actual assembly dimensions and are well below the 0.95 regulatory limit.

6.2.5 Thoria Rod Canister

Additionally, the HI-STAR 100 System is designed to store a Thoria Rod Canister in the MPC68 or MPC68F. The canister is similar to a DFC and contains 18 intact Thoria Rods placed in a separator assembly. The reactivity of the canister in the MPC68 or MPC68F is very low compared to the reactivity of the approved fuel assemblies (The ^{235}U content of these rods corresponds to UO_2 rods with an initial enrichment of approximately 1.7 wt% ^{235}U). It is therefore permissible to store the Thoria Rod Canister together with any other approved content in a MPC68 or MPC68F. Specifications of the canister and the Thoria Rods that are used in the criticality evaluation are given in Table 6.2.42. The criticality evaluation is presented in Subsection 6.4.6.

6.2.6 PWR Assemblies in the MPC-24E and MPC-24EF

The MPC-24E and MPC-24EF are variations of the MPC-24, which provide for transportation of higher enriched fuel than the MPC-24 through an increased ^{10}B loading in the Boral neutron absorber. The maximum allowable fuel enrichment varies between 4.2 and 5.0 wt% ^{235}U, depending on the assembly class. The maximum allowable enrichment for each assembly class is listed in Table 6.1.5, together with the maximum k_{eff} for the bounding assembly in the assembly class. All maximum k_{eff} values are below the 0.95 regulatory limit. The 15x15F assembly class at 4.5% enrichment has the highest reactivity.

6.2.7 PWR Intact Fuel, Damaged Fuel and Fuel Debris in the Trojan MPC-24E/EF

The Trojan MPC-24E and MPC-24EF are variations of the MPC-24E/EF, designed to transport Trojan intact and damaged PWR fuel assemblies (MPC-24E and MPC-24EF) and fuel debris (MPC-24EF only). Damaged PWR fuel assemblies and fuel debris are required to be loaded into PWR Damaged Fuel Containers (DFCs) or Failed Fuel Cans. Up to four DFCs may be loaded in the MPC-24E or MPC-24EF. The maximum enrichment for intact fuel, damaged fuel and fuel debris is 3.7 wt% ^{235}U. Only the assembly class 17x17B is certified for the Trojan MPC-24E/EF. The maximum k_{eff} is listed in Table 6.1.6. The criticality evaluation of the damaged fuel is presented in Subsection 6.4.9.

6.2.8 PWR Assemblies in the MPC-32

Burnup credit is necessary to store PWR assemblies in the MPC-32, i.e. a required minimum average assembly burnup is specified as a function of the assembly initial enrichment. Only the assembly classes 15x15D, E, F, H and 17x17A, B, C are certified for transportation in the MPC-32. The maximum initial enrichment in 5.0 wt% ^{235}U. The criticality evaluations for burnup credit are presented in Appendix 6.E.

Table 6.2.1 (page 1 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
6x6A Assembly Class												
6x6A01	Zr	0.694	36	0.5645	0.0350	0.4940	110.0	0	n/a	n/a	0.060	4.290
6x6A02	Zr	0.694	36	0.5645	0.0360	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A03	Zr	0.694	36	0.5645	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A04	Zr	0.694	36	0.5550	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A05	Zr	0.696	36	0.5625	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6A06	Zr	0.696	35	0.5625	0.0350	0.4820	110.0	1	0.0	0.0	0.060	4.290
6x6A07	Zr	0.700	36	0.5555	0.03525	0.4780	110.0	0	n/a	n/a	0.060	4.290
6x6A08	Zr	0.710	36	0.5625	0.0260	0.4980	110.0	0	n/a	n/a	0.060	4.290
6x6B (MOX) Assembly Class												
6x6B01	Zr	0.694	36	0.5645	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6B02	Zr	0.694	36	0.5625	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6B03	Zr	0.696	36	0.5625	0.0350	0.4820	110.0	0	n/a	n/a	0.060	4.290
6x6B04	Zr	0.696	35	0.5625	0.0350	0.4820	110.0	1	0.0	0.0	0.060	4.290
6x6B05	Zr	0.710	35	0.5625	0.0350	0.4820	110.0	1	0.0	0.0	0.060	4.290
6x6C Assembly Class												
6x6C01	Zr	0.740	36	0.5630	0.0320	0.4880	77.5	0	n/a	n/a	0.060	4.542
7x7A Assembly Class												
7x7A01	Zr	0.631	49	0.4860	0.0328	0.4110	80	0	n/a	n/a	0.060	4.542

Table 6.2.1 (page 2 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
7x7B Assembly Class												
7x7B01	Zr	0.738	49	0.5630	0.0320	0.4870	150	0	n/a	n/a	0.080	5.278
7x7B02	Zr	0.738	49	0.5630	0.0370	0.4770	150	0	n/a	n/a	0.102	5.291
7x7B03	Zr	0.738	49	0.5630	0.0370	0.4770	150	0	n/a	n/a	0.080	5.278
7x7B04	Zr	0.738	49	0.5700	0.0355	0.4880	150	0	n/a	n/a	0.080	5.278
7x7B05	Zr	0.738	49	0.5630	0.0340	0.4775	150	0	n/a	n/a	0.080	5.278
7x7B06	Zr	0.738	49	0.5700	0.0355	0.4910	150	0	n/a	n/a	0.080	5.278
8x8A Assembly Class												
8x8A01	Zr	0.523	64	0.4120	0.0250	0.3580	110	0	n/a	n/a	0.100	4.290
8x8A02	Zr	0.523	63	0.4120	0.0250	0.3580	120	0	n/a	n/a	0.100	4.290

Table 6.2.1 (page 3 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
8x8B Assembly Class												
8x8B01	Zr	0.641	63	0.4840	0.0350	0.4050	150	1	0.484	0.414	0.100	5.278
8x8B02	Zr	0.636	63	0.4840	0.0350	0.4050	150	1	0.484	0.414	0.100	5.278
8x8B03	Zr	0.640	63	0.4930	0.0340	0.4160	150	1	0.493	0.425	0.100	5.278
8x8B04	Zr	0.642	64	0.5015	0.0360	0.4195	150	0	n/a	n/a	0.100	5.278
8x8C Assembly Class												
8x8C01	Zr	0.641	62	0.4840	0.0350	0.4050	150	2	0.484	0.414	0.100	5.278
8x8C02	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.000	no channel
8x8C03	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.080	5.278
8x8C04	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.100	5.278
8x8C05	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.591	0.531	0.120	5.278
8x8C06	Zr	0.640	62	0.4830	0.0320	0.4110	150	2	0.591	0.531	0.100	5.278
8x8C07	Zr	0.640	62	0.4830	0.0340	0.4100	150	2	0.591	0.531	0.100	5.278
8x8C08	Zr	0.640	62	0.4830	0.0320	0.4100	150	2	0.493	0.425	0.100	5.278
8x8C09	Zr	0.640	62	0.4930	0.0340	0.4160	150	2	0.493	0.425	0.100	5.278
8x8C10	Zr	0.640	62	0.4830	0.0340	0.4100	150	2	0.591	0.531	0.120	5.278
8x8C11	Zr	0.640	62	0.4830	0.0340	0.4100	150	2	0.591	0.531	0.120	5.215
8x8C12	Zr	0.636	62	0.4830	0.0320	0.4110	150	2	0.591	0.531	0.120	5.215

Table 6.2.1 (page 4 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
8x8D Assembly Class												
8x8D01	Zr	0.640	60	0.4830	0.0320	0.4110	150	2 large/ 2 small	0.591/ 0.483	0.531/ 0.433	0.100	5.278
8x8D02	Zr	0.640	60	0.4830	0.0320	0.4110	150	4	0.591	0.531	0.100	5.278
8x8D03	Zr	0.640	60	0.4830	0.0320	0.4110	150	4	0.483	0.433	0.100	5.278
8x8D04	Zr	0.640	60	0.4830	0.0320	0.4110	150	1	1.34	1.26	0.100	5.278
8x8D05	Zr	0.640	60	0.4830	0.0320	0.4100	150	1	1.34	1.26	0.100	5.278
8x8D06	Zr	0.640	60	0.4830	0.0320	0.4110	150	1	1.34	1.26	0.120	5.278
8x8D07	Zr	0.640	60	0.4830	0.0320	0.4110	150	1	1.34	1.26	0.080	5.278
8x8D08	Zr	0.640	61	0.4830	0.0300	0.4140	150	3	0.591	0.531	0.080	5.278
8x8E Assembly Class												
8x8E01	Zr	0.640	59	0.4930	0.0340	0.4160	150	5	0.493	0.425	0.100	5.278
8x8F Assembly Class												
8x8F01	Zr	0.609	64	0.4576	0.0290	0.3913	150	4†	0.291†	0.228†	0.055	5.390
9x9A Assembly Class												
9x9A01	Zr	0.566	74	0.4400	0.0280	0.3760	150	2	0.98	0.92	0.100	5.278
9x9A02	Zr	0.566	66	0.4400	0.0280	0.3760	150	2	0.98	0.92	0.100	5.278
9x9A03	Zr	0.566	74/66	0.4400	0.0280	0.3760	150/90	2	0.98	0.92	0.100	5.278
9x9A04	Zr	0.566	66	0.4400	0.0280	0.3760	150	2	0.98	0.92	0.120	5.278

† Four rectangular water cross segments dividing the assembly into four quadrants

Table 6.2.1 (page 5 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
9x9B Assembly Class												
9x9B01	Zr	0.569	72	0.4330	0.0262	0.3737	150	1	1.516	1.459	0.100	5.278
9x9B02	Zr	0.569	72	0.4330	0.0260	0.3737	150	1	1.516	1.459	0.100	5.278
9x9B03	Zr	0.572	72	0.4330	0.0260	0.3737	150	1	1.516	1.459	0.100	5.278
9x9C Assembly Class												
9x9C01	Zr	0.572	80	0.4230	0.0295	0.3565	150	1	0.512	0.472	0.100	5.278
9x9D Assembly Class												
9x9D01	Zr	0.572	79	0.4240	0.0300	0.3565	150	2	0.424	0.364	0.100	5.278
9x9E Assembly Class†												
9x9E01	Zr	0.572	76	0.4170	0.0265	0.3530	150	5	0.546	0.522	0.120	5.215
9x9E02	Zr	0.572	48 28	0.4170 0.4430	0.0265 0.0285	0.3530 0.3745	150	5	0.546	0.522	0.120	5.215
9x9F Assembly Class†												
9x9F01	Zr	0.572	76	0.4430	0.0285	0.3745	150	5	0.546	0.522	0.120	5.215
9x9F02	Zr	0.572	48 28	0.4170 0.4430	0.0265 0.0285	0.3530 0.3745	150	5	0.546	0.522	0.120	5.215
9x9G Assembly Class												
9x9G01	Zr	0.572	72	0.4240	0.0300	0.3565	150	1	1.668	1.604	0.120	5.278

† The 9x9E and 9x9F fuel assembly classes represent a single fuel type containing fuel rods with different dimensions (SPC 9x9-5). In addition to the actual configuration (9x9E02 and 9x9F02), the 9x9E class contains a hypothetical assembly with only small fuel rods (9x9E01), and the 9x9F class contains a hypothetical assembly with only large rods (9x9F01). This was done in order to simplify the specification of this assembly for the authorized contents.

Table 6.2.1 (page 6 of 6)
BWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Water Rods	Water Rod OD	Water Rod ID	Channel Thickness	Channel ID
10x10A Assembly Class												
10x10A01	Zr	0.510	92	0.4040	0.0260	0.3450	155	2	0.980	0.920	0.100	5.278
10x10A02	Zr	0.510	78	0.4040	0.0260	0.3450	155	2	0.980	0.920	0.100	5.278
10x10A03	Zr	0.510	92/78	0.4040	0.0260	0.3450	155/90	2	0.980	0.920	0.100	5.278
10x10B Assembly Class												
10x10B01	Zr	0.510	91	0.3957	0.0239	0.3413	155	1	1.378	1.321	0.100	5.278
10x10B02	Zr	0.510	83	0.3957	0.0239	0.3413	155	1	1.378	1.321	0.100	5.278
10x10B03	Zr	0.510	91/83	0.3957	0.0239	0.3413	155/90	1	1.378	1.321	0.100	5.278
10x10C Assembly Class												
10x10C01	Zr	0.488	96	0.3780	0.0243	0.3224	150	5	1.227	1.165	0.055	5.457
10x10D Assembly Class												
10x10D01	SS	0.565	100	0.3960	0.0200	0.3500	83	0	n/a	n/a	0.08	5.663
10x10E Assembly Class												
10x10E01	SS	0.557	96	0.3940	0.0220	0.3430	83	4	0.3940	0.3500	0.08	5.663

Table 6.2.2 (page 1 of 4)
PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Guide Tubes	Guide Tube OD	Guide Tube ID	Guide Tube Thickness
14x14A Assembly Class											
14x14A01	Zr	0.556	179	0.400	0.0243	0.3444	150	17	0.527	0.493	0.0170
14x14A02	Zr	0.556	179	0.400	0.0243	0.3444	150	17	0.528	0.490	0.0190
14x14A03	Zr	0.556	179	0.400	0.0243	0.3444	150	17	0.526	0.492	0.0170
14x14B Assembly Class											
14x14B01	Zr	0.556	179	0.422	0.0243	0.3659	150	17	0.539	0.505	0.0170
14x14B02	Zr	0.556	179	0.417	0.0295	0.3505	150	17	0.541	0.507	0.0170
14x14B03	Zr	0.556	179	0.424	0.0300	0.3565	150	17	0.541	0.507	0.0170
14x14B04	Zr	0.556	179	0.426	0.0310	0.3565	150	17	0.541	0.507	0.0170
14x14C Assembly Class											
14x14C01	Zr	0.580	176	0.440	0.0280	0.3765	150	5	1.115	1.035	0.0400
14x14C02	Zr	0.580	176	0.440	0.0280	0.3770	150	5	1.115	1.035	0.0400
14x14C03	Zr	0.580	176	0.440	0.0260	0.3805	150	5	1.111	1.035	0.0380
14x14D Assembly Class											
14x14D01	SS	0.556	180	0.422	0.0165	0.3835	144	16	0.543	0.514	0.0145

Table 6.2.2 (page 2 of 4)
PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Guide Tubes	Guide Tube OD	Guide Tube ID	Guide Tube Thickness
14x14E Assembly Class											
14x14E01†	SS	0.453 and 0.441	162 3 8	0.3415 0.3415 0.3415	0.0120 0.0285 0.0200	0.313 0.280 0.297	102	0	n/a	n/a	n/a
14x14E02†	SS	0.453 and 0.441	173	0.3415	0.0120	0.313	102	0	n/a	n/a	n/a
14x14E03†	SS	0.453 and 0.441	173	0.3415	0.0285	0.280	102	0	n/a	n/a	n/a
15x15A Assembly Class											
15x15A01	Zr	0.550	204	0.418	0.0260	0.3580	150	21	0.533	0.500	0.0165

† This is the fuel assembly used at Indian Point 1 (IP-1). This assembly is a 14x14 assembly with 23 fuel rods omitted to allow passage of control rods between assemblies. It has a different pitch in different sections of the assembly, and different fuel rod dimensions in some rods.

Table 6.2.2 (page 3 of 4)
PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Guide Tubes	Guide Tube OD	Guide Tube ID	Guide Tube Thickness
15x15B Assembly Class											
15x15B01	Zr	0.563	204	0.422	0.0245	0.3660	150	21	0.533	0.499	0.0170
15x15B02	Zr	0.563	204	0.422	0.0245	0.3660	150	21	0.546	0.512	0.0170
15x15B03	Zr	0.563	204	0.422	0.0243	0.3660	150	21	0.533	0.499	0.0170
15x15B04	Zr	0.563	204	0.422	0.0243	0.3659	150	21	0.545	0.515	0.0150
15x15B05	Zr	0.563	204	0.422	0.0242	0.3659	150	21	0.545	0.515	0.0150
15x15B06	Zr	0.563	204	0.420	0.0240	0.3671	150	21	0.544	0.514	0.0150
15x15C Assembly Class											
15x15C01	Zr	0.563	204	0.424	0.0300	0.3570	150	21	0.544	0.493	0.0255
15x15C02	Zr	0.563	204	0.424	0.0300	0.3570	150	21	0.544	0.511	0.0165
15x15C03	Zr	0.563	204	0.424	0.0300	0.3565	150	21	0.544	0.511	0.0165
15x15C04	Zr	0.563	204	0.417	0.0300	0.3565	150	21	0.544	0.511	0.0165
15x15D Assembly Class											
15x15D01	Zr	0.568	208	0.430	0.0265	0.3690	150	17	0.530	0.498	0.0160
15x15D02	Zr	0.568	208	0.430	0.0265	0.3686	150	17	0.530	0.498	0.0160
15x15D03	Zr	0.568	208	0.430	0.0265	0.3700	150	17	0.530	0.499	0.0155
15x15D04	Zr	0.568	208	0.430	0.0250	0.3735	150	17	0.530	0.500	0.0150
15x15E Assembly Class											
15x15E01	Zr	0.568	208	0.428	0.0245	0.3707	150	17	0.528	0.500	0.0140
15x15F Assembly Class											
15x15F01	Zr	0.568	208	0.428	0.0230	0.3742	150	17	0.528	0.500	0.0140

Table 6.2.2 (page 4 of 4)
PWR FUEL CHARACTERISTICS AND ASSEMBLY CLASS DEFINITIONS
(all dimensions are in inches)

Fuel Assembly Designation	Clad Material	Pitch	Number of Fuel Rods	Cladding OD	Cladding Thickness	Pellet Diameter	Active Fuel Length	Number of Guide Tubes	Guide Tube OD	Guide Tube ID	Guide Tube Thickness
15x15G Assembly Class											
15x15G01	SS	0.563	204	0.422	0.0165	0.3825	144	21	0.543	0.514	0.0145
15x15H Assembly Class											
15x15H01	Zr	0.568	208	0.414	0.0220	0.3622	150	17	0.528	0.500	0.0140
16x16A Assembly Class											
16x16A01	Zr	0.506	236	0.382	0.0250	0.3255	150	5	0.980	0.900	0.0400
16x16A02	Zr	0.506	236	0.382	0.0250	0.3250	150	5	0.980	0.900	0.0400
17x17A Assembly Class											
17x17A01	Zr	0.496	264	0.360	0.0225	0.3088	150	25	0.474	0.442	0.0160
17x17A02	Zr	0.496	264	0.360	0.0250	0.3030	150	25	0.480	0.448	0.0160
17x17B Assembly Class											
17x17B01	Zr	0.496	264	0.374	0.0225	0.3225	150	25	0.482	0.450	0.0160
17x17B02	Zr	0.496	264	0.374	0.0225	0.3225	150	25	0.474	0.442	0.0160
17x17B03	Zr	0.496	264	0.376	0.0240	0.3215	150	25	0.480	0.448	0.0160
17x17B04	Zr	0.496	264	0.372	0.0205	0.3232	150	25	0.427	0.399	0.0140
17x17B05	Zr	0.496	264	0.374	0.0240	0.3195	150	25	0.482	0.450	0.0160
17x17B06	Zr	0.496	264	0.372	0.0205	0.3232	150	25	0.480	0.452	0.0140
17x17C Assembly Class											
17x17C01	Zr	0.502	264	0.379	0.0240	0.3232	150	25	0.472	0.432	0.0200
17x17C02	Zr	0.502	264	0.377	0.0220	0.3252	150	25	0.472	0.432	0.0200

Table 6.2.3
REACTIVITY EFFECT OF ASSEMBLY PARAMETER VARIATIONS
(all dimensions are in inches)

Fuel Assembly/ Parameter Variation	reactivity effect	calculated k_{eff}	standard deviation	cladding OD	cladding ID	cladding thickness	pellet OD	water rod thickness	channel thickness
8x8C04 (GE8x8R)	reference	0.9307	0.0007	0.483	0.419	0.032	0.410	0.030	0.100
increase pellet OD (+0.001)	+0.0005	0.9312	0.0007	0.483	0.419	0.032	0.411	0.030	0.100
decrease pellet OD (-0.001)	-0.0008	0.9299	0.0009	0.483	0.419	0.032	0.409	0.030	0.100
increase clad ID (+0.004)	+0.0027	0.9334	0.0007	0.483	0.423	0.030	0.410	0.030	0.100
decrease clad ID (-0.004)	-0.0034	0.9273	0.0007	0.483	0.415	0.034	0.410	0.030	0.100
increase clad OD (+0.004)	-0.0041	0.9266	0.0008	0.487	0.419	0.034	0.410	0.030	0.100
decrease clad OD (-0.004)	+0.0023	0.9330	0.0007	0.479	0.419	0.030	0.410	0.030	0.100
increase water rod thickness (+0.015)	-0.0019	0.9288	0.0008	0.483	0.419	0.032	0.410	0.045	0.100
decrease water rod thickness (-0.015)	+0.0001	0.9308	0.0008	0.483	0.419	0.032	0.410	0.015	0.100
remove water rods (i.e., replace the water rod tubes with water)	+0.0021	0.9328	0.0008	0.483	0.419	0.032	0.410	0.000	0.100
remove channel	-0.0039	0.9268	0.0009	0.483	0.419	0.032	0.410	0.030	0.000
increase channel thickness (+0.020)	+0.0005	0.9312	0.0007	0.483	0.419	0.032	0.410	0.030	0.120
reduced active length (120 Inches)	-0.0007	0.9300	0.0007	0.483	0.419	0.032	0.410	0.030	0.100
reduced active length (90 Inches)	-0.0043	0.9264	0.0007	0.483	0.419	0.032	0.410	0.030	0.100

Table 6.2.4
MAXIMUM K_{EFF} VALUES FOR THE 14X14A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14A (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 179 fuel rods, 17 guide tubes, pitch=0.556, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14A01	0.9295	0.9252	0.0008	0.2084	0.400	0.3514	0.0243	0.3444	150	0.017
14x14A02	0.9286	0.9242	0.0008	0.2096	0.400	0.3514	0.0243	0.3444	150	0.019
14x14A03	0.9296	0.9253	0.0008	0.2093	0.400	0.3514	0.0243	0.3444	150	0.017
Dimensions Listed for Authorized Contents					0.400 (min.)	0.3514 (max.)		0.3444 (max.)	150 (max.)	0.017 (min.)
bounding dimensions (14x14A03)	0.9296	0.9253	0.0008	0.2093	0.400	0.3514	0.0243	0.3444	150	0.017

Table 6.2.5
MAXIMUM K_{EFF} VALUES FOR THE 14X14B ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14B (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 179 fuel rods, 17 guide tubes, pitch=0.556, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14B01	0.9159	0.9117	0.0007	0.2727	0.422	0.3734	0.0243	0.3659	150	0.017
14x14B02	0.9169	0.9126	0.0008	0.2345	0.417	0.3580	0.0295	0.3505	150	0.017
14x14B03	0.9110	0.9065	0.0009	0.2545	0.424	0.3640	0.0300	0.3565	150	0.017
14x14B04	0.9084	0.9039	0.0009	0.2563	0.426	0.3640	0.0310	0.3565	150	0.017
Dimensions Listed for Authorized Contents					0.417 (min.)	0.3734 (max.)		0.3659 (max.)	150 (max.)	0.017 (min.)
bounding dimensions (B14x14B01)	0.9228	0.9185	0.0008	0.2675	0.417	0.3734	0.0218	0.3659	150	0.017

Table 6.2.6
MAXIMUM K_{EFF} VALUES FOR THE 14X14C ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14C (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 176 fuel rods, 5 guide tubes, pitch=0.580, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14C01	0.9258	0.9215	0.0008	0.2729	0.440	0.3840	0.0280	0.3765	150	0.040
14x14C02	0.9265	0.9222	0.0008	0.2765	0.440	0.3840	0.0280	0.3770	150	0.040
14x14C03	0.9287	0.9242	0.0009	0.2825	0.440	0.3880	0.0260	0.3805	150	0.038
Dimensions Listed for Authorized Contents					0.440 (min.)	0.3880 (max.)		0.3805 (max.)	150 (max.)	0.038 (min.)
bounding dimensions (14x14C03)	0.9287	0.9242	0.0009	0.2825	0.440	0.3880	0.0260	0.3805	150	0.038

Table 6.2.7
MAXIMUM K_{EFF} VALUES FOR THE 14X14D ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14D (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 180 fuel rods, 16 guide tubes, pitch=0.556, SS clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
14x14D01	0.8507	0.8464	0.0008	0.3308	0.422	0.3890	0.0165	0.3835	144	0.0145
Dimensions Listed for Authorized Contents					0.422 (min.)	0.3890 (max.)		0.3835 (max.)	144 (max.)	0.0145 (min.)

Table 6.2.8
MAXIMUM K_{EFF} VALUES FOR THE 15X15A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15A (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, 21 guide tubes, pitch=0.550, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15A01	0.9204	0.9159	0.0009	0.2608	0.418	0.3660	0.0260	0.3580	150	0.0165
Dimensions Listed for Authorized Contents					0.418 (min.)	0.3660 (max.)		0.3580 (max.)	150 (max.)	0.0165 (min.)

Table 6.2.9
MAXIMUM K_{EFF} VALUES FOR THE 15X15B ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15B (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, 21 guide tubes, pitch=0.563, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15B01	0.9369	0.9326	0.0008	0.2632	0.422	0.3730	0.0245	0.3660	150	0.017
15x15B02	0.9338	0.9295	0.0008	0.2640	0.422	0.3730	0.0245	0.3660	150	0.017
15x15B03	0.9362	0.9318	0.0008	0.2632	0.422	0.3734	0.0243	0.3660	150	0.017
15x15B04	0.9370	0.9327	0.0008	0.2612	0.422	0.3734	0.0243	0.3659	150	0.015
15x15B05	0.9356	0.9313	0.0008	0.2606	0.422	0.3736	0.0242	0.3659	150	0.015
15x15B06	0.9366	0.9324	0.0007	0.2638	0.420	0.3720	0.0240	0.3671	150	0.015
Dimensions Listed for Authorized Contents					0.420 (min.)	0.3736 (max.)		0.3671 (max.)	150 (max.)	0.015 (min.)
bounding dimensions (B15x15B01)	0.9388	0.9343	0.0009	0.2626	0.420	0.3736	0.0232	0.3671	150	0.015

Table 6.2.10
MAXIMUM K_{EFF} VALUES FOR THE 15X15C ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15C (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, 21 guide tubes, pitch=0.563, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15C01	0.9255	0.9213	0.0007	0.2493	0.424	0.3640	0.0300	0.3570	150	0.0255
15x15C02	0.9297	0.9255	0.0007	0.2457	0.424	0.3640	0.0300	0.3570	150	0.0165
15x15C03	0.9297	0.9255	0.0007	0.2440	0.424	0.3640	0.0300	0.3565	150	0.0165
15x15C04	0.9311	0.9268	0.0008	0.2435	0.417	0.3570	0.0300	0.3565	150	0.0165
Dimensions Listed for Authorized Contents					0.417 (min.)	0.3640 (max.)		0.3570 (max.)	150 (max.)	0.0165 (min.)
bounding dimensions (B15x15C01)	0.9361	0.9316	0.0009	0.2385	0.417	0.3640	0.0265	0.3570	150	0.0165

Table 6.2.11
MAXIMUM K_{EFF} VALUES FOR THE 15X15D ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15D (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15D01	0.9341	0.9298	0.0008	0.2822	0.430	0.3770	0.0265	0.3690	150	0.0160
15x15D02	0.9367	0.9324	0.0008	0.2802	0.430	0.3770	0.0265	0.3686	150	0.0160
15x15D03	0.9354	0.9311	0.0008	0.2844	0.430	0.3770	0.0265	0.3700	150	0.0155
15x15D04	0.9339	0.9292	0.0010	0.2958	0.430	0.3800	0.0250	0.3735	150	0.0150
Dimensions Listed for Authorized Contents					0.430 (min.)	0.3800 (max.)		0.3735 (max.)	150 (max.)	0.0150 (min.)
bounding dimensions (15x15D04)	0.9339†	0.9292	0.0010	0.2958	0.430	0.3800	0.0250	0.3735	150	0.0150

† The k_{eff} value listed for the 15x15D02 case is slightly higher than that for the case with the bounding dimensions. However, calculations with significantly increased number of particles show that the two cases are statistically equivalent, with a maximum k_{eff} value of 0.9339. Nevertheless, the 15x15D02 case is used in Table 6.3.5 for the eccentric positioning analysis.

Table 6.2.12
MAXIMUM K_{EFF} VALUES FOR THE 15X15E ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15E (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15E01	0.9368	0.9325	0.0008	0.2826	0.428	0.3790	0.0245	0.3707	150	0.0140
Dimensions Listed for Authorized Contents					0.428 (min.)	0.3790 (max.)		0.3707 (max.)	150 (max.)	0.0140 (min.)

Table 6.2.13
MAXIMUM K_{EFF} VALUES FOR THE 15X15F ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15F (4.1% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15F01	0.9395†	0.9350	0.0009	0.2903	0.428	0.3820	0.0230	0.3742	150	0.0140
Dimensions Listed for Authorized Contents					0.428 (min.)	0.3820 (max.)		0.3742 (max.)	150 (max.)	0.0140 (min.)

† KENO5a verification calculation resulted in a maximum k_{eff} of 0.9378.

Table 6.2.14
MAXIMUM K_{EFF} VALUES FOR THE 15X15G ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15G (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 204 fuel rods, 21 guide tubes, pitch=0.563, SS clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel† length	guide tube thickness
15x15G01	0.8876	0.8833	0.0008	0.3357	0.422	0.3890	0.0165	0.3825	144	0.0145
Dimensions Listed for Authorized Contents					0.422 (min.)	0.3890 (max.)		0.3825 (max.)	144 (max.)	0.0145 (min.)

† Calculations were conservatively performed for a fuel length of 150 inches.

Table 6.2.15
MAXIMUM K_{EFF} VALUES FOR THE 15X15H ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

15x15H (3.8% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 208 fuel rods, 17 guide tubes, pitch=0.568, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
15x15H01	0.9337	0.9292	0.0009	0.2349	0.414	0.3700	0.0220	0.3622	150	0.0140
Dimensions Listed for Authorized Contents					0.414 (min.)	0.3700 (max.)		0.3622 (max.)	150 (max.)	0.0140 (min.)

Table 6.2.16
MAXIMUM K_{EFF} VALUES FOR THE 16X16A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

16x16A (4.6% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 236 fuel rods, 5 guide tubes, pitch=0.506, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
16x16A01	0.9287	0.9244	0.0008	0.2704	0.382	0.3320	0.0250	0.3255	150	0.0400
16x16A02	0.9263	0.9221	0.0007	0.2702	0.382	0.3320	0.0250	0.3250	150	0.0400
Dimensions Listed for Authorized Contents					0.382 (min.)	0.3320 (max.)		0.3255 (max.)	150 (max.)	0.0400 (min.)
bounding dimensions (16x16A01)	0.9287	0.9244	0.0008	0.2704	0.382	0.3320	0.0250	0.3255	150	0.0400

Table 6.2.17
MAXIMUM K_{EFF} VALUES FOR THE 17X17A ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

17x17A (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 264 fuel rods, 25 guide tubes, pitch=0.496, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
17x17A01	0.9368	0.9325	0.0008	0.2131	0.360	0.3150	0.0225	0.3088	150	0.016
17x17A02	0.9329	0.9286	0.0008	0.2018	0.360	0.3100	0.0250	0.3030	150	0.016
Dimensions Listed for Authorized Contents					0.360 (min.)	0.3150 (max.)		0.3088 (max.)	150 (max.)	0.016 (min.)
bounding dimensions (17x17A01)	0.9368	0.9325	0.0008	0.2131	0.360	0.3150	0.0225	0.3088	150	0.016

Table 6.2.18
MAXIMUM K_{EFF} VALUES FOR THE 17X17B ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

17x17B (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 264 fuel rods, 25 guide tubes, pitch=0.496, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
17x17B01	0.9288	0.9243	0.0009	0.2607	0.374	0.3290	0.0225	0.3225	150	0.016
17x17B02	0.9290	0.9247	0.0008	0.2596	0.374	0.3290	0.0225	0.3225	150	0.016
17x17B03	0.9243	0.9199	0.0008	0.2625	0.376	0.3280	0.0240	0.3215	150	0.016
17x17B04	0.9324	0.9279	0.0009	0.2576	0.372	0.3310	0.0205	0.3232	150	0.014
17x17B05	0.9266	0.9222	0.0008	0.2539	0.374	0.3260	0.0240	0.3195	150	0.016
17x17B06	0.9311	0.9268	0.0008	0.2593	0.372	0.3310	0.0205	0.3232	150	0.014
Dimensions Listed for Authorized Contents					0.372 (min.)	0.3310 (max.)		0.3232 (max.)	150 (max.)	0.014 (min.)
bounding dimensions (17x17B06)	0.9311†	0.9268	0.0008	0.2593	0.372	0.3310	0.0205	0.3232	150	0.014

† The k_{eff} value listed for the 17x17B04 case is slightly higher than that for the case with the bounding dimensions. However, the difference (0.0013) is well within the statistical uncertainties, and thus, the two values are statistically equivalent (within 2σ). Nevertheless, the17x17B04 case is used in Table 6.3.5 for the eccentric analysis.

Table 6.2.19
MAXIMUM K_{EFF} VALUES FOR THE 17X17C ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

17x17C (4.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 264 fuel rods, 25 guide tubes, pitch=0.502, Zr clad										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	guide tube thickness
17x17C01	0.9293	0.9250	0.0008	0.2595	0.379	0.3310	0.0240	0.3232	150	0.020
17x17C02	0.9336	0.9293	0.0008	0.2624	0.377	0.3330	0.0220	0.3252	150	0.020
Dimensions Listed for Authorized Contents					0.377 (min.)	0.3330 (max.)		0.3252 (max.)	150 (max.)	0.020 (min.)
bounding dimensions (17x17C02)	0.9336	0.9293	0.0008	0.2624	0.377	0.3330	0.0220	0.3252	150	0.020

Table 6.2.20
MAXIMUM K_{EFF} VALUES FOR THE 7X7B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

7x7B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 49 fuel rods, 0 water rods, pitch=0.738, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
7x7B01	0.9372	0.9330	0.0007	0.3658	0.5630	0.4990	0.0320	0.4870	150	n/a	0.080
7x7B02	0.9301	0.9260	0.0007	0.3524	0.5630	0.4890	0.0370	0.4770	150	n/a	0.102
7x7B03	0.9313	0.9271	0.0008	0.3438	0.5630	0.4890	0.0370	0.4770	150	n/a	0.080
7x7B04	0.9311	0.9270	0.0007	0.3816	0.5700	0.4990	0.0355	0.4880	150	n/a	0.080
7x7B05	0.9350	0.9306	0.0008	0.3382	0.5630	0.4950	0.0340	0.4775	150	n/a	0.080
7x7B06	0.9298	0.9260	0.0006	0.3957	0.5700	0.4990	0.0355	0.4910	150	n/a	0.080
Dimensions Listed for Authorized Contents					0.5630 (min.)	0.4990 (max.)		0.4910 (max.)	150 (max.)	n/a	0.120 (max.)
bounding dimensions (B7x7B01)	0.9375	0.9332	0.0008	0.3887	0.5630	0.4990	0.0320	0.4910	150	n/a	0.102
bounding dimensions with 120 mil channel (B7x7B02)	0.9386	0.9344	0.0007	0.3983	0.5630	0.4990	0.0320	0.4910	150	n/a	0.120

Table 6.2.21
MAXIMUM K_{EFF} VALUES FOR THE 8X8B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2)

63 or 64 fuel rods, 1 or 0 water rods, pitch† = 0.636-0.642, Zr clad

Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	Fuel rods	pitch	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8B01	0.9310	0.9265	0.0009	0.2935	63	0.641	0.4840	0.4140	0.0350	0.4050	150	0.035	0.100
8x8B02	0.9227	0.9185	0.0007	0.2993	63	0.636	0.4840	0.4140	0.0350	0.4050	150	0.035	0.100
8x8B03	0.9299	0.9257	0.0008	0.3319	63	0.640	0.4930	0.4250	0.0340	0.4160	150	0.034	0.100
8x8B04	0.9236	0.9194	0.0008	0.3700	64	0.642	0.5015	0.4295	0.0360	0.4195	150	n/a	0.100
Dimensions Listed for Authorized Contents					63 or 64	0.636-0.642	0.4840 (min.)	0.4295 (max.)		0.4195 (max.)	150 (max.)	0.034	0.120 (max.)
bounding (pitch=0.636) (B8x8B01)	0.9346	0.9301	0.0009	0.3389	63	0.636	0.4840	0.4295	0.02725	0.4195	150	0.034	0.120
bounding (pitch=0.640) (B8x8B02)	0.9385	0.9343	0.0008	0.3329	63	0.640	0.4840	0.4295	0.02725	0.4195	150	0.034	0.120
bounding (pitch=0.641) (B8x8B03)	0.9416	0.9375	0.0007	0.3293	63	0.642	0.4840	0.4295	0.02725	0.4195	150	0.034	0.120

† This assembly class was analyzed and qualified for a small variation in the pitch and a variation in the number of fuel and water rods.

Table 6.2.22
MAXIMUM K_{EFF} VALUES FOR THE 8X8C ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8C (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 62 fuel rods, 2 water rods, pitch† = 0.636-0.641, Zr clad												
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	pitch	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8C01	0.9315	0.9273	0.0007	0.2822	0.641	0.4840	0.4140	0.0350	0.4050	150	0.035	0.100
8x8C02	0.9313	0.9268	0.0009	0.2716	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.000
8x8C03	0.9329	0.9286	0.0008	0.2877	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.800
8x8C04	0.9348††	0.9307	0.0007	0.2915	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.100
8x8C05	0.9353	0.9312	0.0007	0.2971	0.640	0.4830	0.4190	0.0320	0.4100	150	0.030	0.120
8x8C06	0.9353	0.9312	0.0007	0.2944	0.640	0.4830	0.4190	0.0320	0.4110	150	0.030	0.100
8x8C07	0.9314	0.9273	0.0007	0.2972	0.640	0.4830	0.4150	0.0340	0.4100	150	0.030	0.100
8x8C08	0.9339	0.9298	0.0007	0.2915	0.640	0.4830	0.4190	0.0320	0.4100	150	0.034	0.100
8x8C09	0.9301	0.9260	0.0007	0.3183	0.640	0.4930	0.4250	0.0340	0.4160	150	0.034	0.100
8x8C10	0.9317	0.9275	0.0008	0.3018	0.640	0.4830	0.4150	0.0340	0.4100	150	0.030	0.120
8x8C11	0.9328	0.9287	0.0007	0.3001	0.640	0.4830	0.4150	0.0340	0.4100	150	0.030	0.120
8x8C12	0.9285	0.9242	0.0008	0.3062	0.636	0.4830	0.4190	0.0320	0.4110	150	0.030	0.120
Dimensions Listed for Authorized Contents					0.636-0.641	0.4830 (min.)	0.4250 (max.)		0.4160 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding (pitch=0.636) (B8x8C01)	0.9357	0.9313	0.0009	0.3141	0.636	0.4830	0.4250	0.0290	0.4160	150	0.000	0.120
bounding (pitch=0.640) (B8x8C02)	0.9425	0.9384	0.0007	0.3081	0.640	0.4830	0.4250	0.0290	0.4160	150	0.000	0.120
bounding (pitch=0.641) (B8x8C03)	0.9418	0.9375	0.0008	0.3056	0.641	0.4830	0.4250	0.0290	0.4160	150	0.000	0.120

† This assembly class was analyzed and qualified for a small variation in the pitch.

†† KENO5a verification calculation resulted in a maximum k_{eff} of 0.9343.

Table 6.2.23
MAXIMUM K_{EFF} VALUES FOR THE 8X8D ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8D (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 60 or 61 fuel rods, 1-4 water rods†, pitch=0.640, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8D01	0.9342	0.9302	0.0006	0.2733	0.4830	0.4190	0.0320	0.4110	150	0.03/0.025	0.100
8x8D02	0.9325	0.9284	0.0007	0.2750	0.4830	0.4190	0.0320	0.4110	150	0.030	0.100
8x8D03	0.9351	0.9309	0.0008	0.2731	0.4830	0.4190	0.0320	0.4110	150	0.025	0.100
8x8D04	0.9338	0.9296	0.0007	0.2727	0.4830	0.4190	0.0320	0.4110	150	0.040	0.100
8x8D05	0.9339	0.9294	0.0009	0.2700	0.4830	0.4190	0.0320	0.4100	150	0.040	0.100
8x8D06	0.9365	0.9324	0.0007	0.2777	0.4830	0.4190	0.0320	0.4110	150	0.040	0.120
8x8D07	0.9341	0.9297	0.0009	0.2694	0.4830	0.4190	0.0320	0.4110	150	0.040	0.080
8x8D08	0.9376	0.9332	0.0009	0.2841	0.4830	0.4230	0.0300	0.4140	150	0.030	0.080
Dimensions Listed for Authorized Contents					0.4830 (min.)	0.4230 (max.)		0.4140 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (B8x8D01)	0.9403	0.9363	0.0007	0.2778	0.4830	0.4230	0.0300	0.4140	150	0.000	0.120

† Fuel assemblies 8x8D01 through 8x8D03 have 4 water rods that are similar in size to the fuel rods, while assemblies 8x8D04 through 8x8D07 have 1 large water rod that takes the place of the 4 water rods. Fuel assembly 8x8D08 contains 3 water rods that are similar in size to the fuel rods.

Table 6.2.24
MAXIMUM K_{EFF} VALUES FOR THE 8X8E ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8E (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 59 fuel rods, 5 water rods, pitch=0.640, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8E01	0.9312	0.9270	0.0008	0.2831	0.4930	0.4250	0.0340	0.4160	150	0.034	0.100
Dimensions Listed for Authorized Contents					0.4930 (min.)	0.4250 (max.)		0.4160 (max.)	150 (max.)	0.034 (min.)	0.100 (max.)

Table 6.2.25
MAXIMUM K_{EFF} VALUES FOR THE 8X8F ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

8x8F (4.0% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 64 fuel rods, 4 rectangular water cross segments dividing the assembly into four quadrants, pitch=0.609, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8F01	0.9411	0.9366	0.0009	0.2264	0.4576	0.3996	0.0290	0.3913	150	0.0315	0.055
Dimensions Listed for Authorized Contents					0.4576 (min.)	0.3996 (max.)		0.3913 (max.)	150 (max.)	0.0315 (min.)	0.055 (max.)

Table 6.2.26
MAXIMUM K_{EFF} VALUES FOR THE 9X9A ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9A (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 74/66 fuel rods†, 2 water rods, pitch=0.566, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9A01 (axial segment with all rods)	0.9353	0.9310	0.0008	0.2875	0.4400	0.3840	0.0280	0.3760	150	0.030	0.100
9x9A02 (axial segment with only the full length rods)	0.9388	0.9345	0.0008	0.2228	0.4400	0.3840	0.0280	0.3760	150	0.030	0.100
9x9A03 (actual three-dimensional representation of all rods)	0.9351	0.9310	0.0007	0.2837	0.4400	0.3840	0.0280	0.3760	150/90	0.030	0.100
9x9A04 (axial segment with only the full length rods)	0.9396	0.9355	0.0007	0.2262	0.4400	0.3840	0.0280	0.3760	150	0.030	0.120
Dimensions Listed for Authorized Contents					0.4400 (min.)	0.3840 (max.)		0.3760 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (axial segment with only the full length rods) (B9x9A01)	0.9417	0.9374	0.0008	0.2236	0.4400	0.3840	0.0280	0.3760	150	0.000	0.120

† This assembly class contains 66 full length rods and 8 partial length rods. In order to eliminate a requirement on the length of the partial length rods, separate calculations were performed for the axial segments with and without the partial length rods.

Table 6.2.27
MAXIMUM K_{EFF} VALUES FOR THE 9X9B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 72 fuel rods, 1 water rod (square, replacing 9 fuel rods), pitch=0.569 to 0.572†, Zr clad												
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	pitch	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9B01	0.9380	0.9336	0.0008	0.2576	0.569	0.4330	0.3807	0.0262	0.3737	150	0.0285	0.100
9x9B02	0.9373	0.9329	0.0009	0.2578	0.569	0.4330	0.3810	0.0260	0.3737	150	0.0285	0.100
9x9B03	0.9417	0.9374	0.0008	0.2545	0.572	0.4330	0.3810	0.0260	0.3737	150	0.0285	0.100
Dimensions Listed for Authorized Contents					0.572	0.4330 (min.)	0.3810 (max.)		0.3740 (max.)	150 (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (B9x9B01)	0.9436	0.9394	0.0008	0.2506	0.572	0.4330	0.3810	0.0260	0.3740††	150	0.000	0.120

† This assembly class was analyzed and qualified for a small variation in the pitch.

†† This value was conservatively defined to be larger than any of the actual pellet diameters.

Table 6.2.28
MAXIMUM K_{EFF} VALUES FOR THE 9X9C ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9C (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 80 fuel rods, 1 water rods, pitch=0.572, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9C01	0.9395	0.9352	0.0008	0.2698	0.4230	0.3640	0.0295	0.3565	150	0.020	0.100
Dimensions Listed for Authorized Contents					0.4230 (min.)	0.3640 (max.)		0.3565 (max.)	150 (max.)	0.020 (min.)	0.100 (max.)

Table 6.2.29
MAXIMUM K_{EFF} VALUES FOR THE 9X9D ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9D (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 79 fuel rods, 2 water rods, pitch=0.572, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9D01	0.9394	0.9350	0.0009	0.2625	0.4240	0.3640	0.0300	0.3565	150	0.0300	0.100
Dimensions Listed for Authorized Contents					0.4240 (min.)	0.3640 (max.)		0.3565 (max.)	150 (max.)	0.0300 (min.)	0.100 (max.)

Table 6.2.30
MAXIMUM K_{EFF} VALUES FOR THE 9X9E ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9E (4.0% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 76 fuel rods, 5 water rods, pitch=0.572, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9E01	0.9334	0.9293	0.0007	0.2227	0.4170	0.3640	0.0265	0.3530	150	0.0120	0.120
9x9E02	0.9401	0.9359	0.0008	0.2065	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120
Dimensions Listed for Authorized Contents†					0.4170 (min.)	0.3640 (max.)		0.3530 (max.)	150 (max.)	0.0120 (min.)	0.120 (max.)
bounding dimensions (9x9E02)	0.9401	0.9359	0.0008	0.2065	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120

† This fuel assembly, also known as SPC 9x9-5, contains fuel rods with different cladding and pellet diameters which do not bound each other. To be consistent in the way fuel assemblies are listed for Authorized Contents, two assembly classes (9x9E and 9x9F) are required to specify this assembly. Each class contains the actual geometry (9x9E02 and 9x9F02), as well as a hypothetical geometry with either all small rods (9x9E01) or all large rods (9x9F01). The Authorized Content lists the small rod dimensions for class 9x9E and the large rod dimensions for class 9x9F, and a note that both classes are used to qualify the assembly. The analyses demonstrate that all configurations, including the actual geometry, are acceptable.

Table 6.2.31
MAXIMUM K_{EFF} VALUES FOR THE 9X9F ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

9x9F (4.0% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 76 fuel rods, 5 water rods, pitch=0.572, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9F01	0.9307	0.9265	0.0007	0.2899	0.4430	0.3860	0.0285	0.3745	150	0.0120	0.120
9x9F02	0.9401	0.9359	0.0008	0.2065	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120
Dimensions Listed for Authorized Contents†					0.4430 (min.)	0.3860 (max.)		0.3745 (max.)	150 (max.)	0.0120 (min.)	0.120 (max.)
bounding dimensions (9x9F02)	0.9401	0.9359	0.0008	0.2065	0.4170 0.4430	0.3640 0.3860	0.0265 0.0285	0.3530 0.3745	150	0.0120	0.120

† This fuel assembly, also known as SPC 9x9-5, contains fuel rods with different cladding and pellet diameters which do not bound each other. To be consistent in the way fuel assemblies are listed for Authorized Contents, two assembly classes (9x9E and 9x9F) are required to specify this assembly. Each class contains the actual geometry (9x9E02 and 9x9F02), as well as a hypothetical geometry with either all small rods (9x9E01) or all large rods (9x9F01). The Authorized Content lists the small rod dimensions for class 9x9E and the large rod dimensions for class 9x9F, and a note that both classes are used to qualify the assembly. The analyses demonstrate that all configurations, including the actual geometry, are acceptable.

Table 6.2.32
MAXIMUM K_{EFF} VALUES FOR THE 10X10A ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10A (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 92/78 fuel rods†, 2 water rods, pitch=0.510, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10A01 (axial segment with all rods)	0.9377	0.9335	0.0008	0.3170	0.4040	0.3520	0.0260	0.3450	155	0.030	0.100
10x10A02 (axial segment with only the full length rods)	0.9426	0.9386	0.0007	0.2159	0.4040	0.3520	0.0260	0.3450	155	0.030	0.100
10x10A03 (actual three-dimensional representation of all rods)	0.9396	0.9356	0.0007	0.3169	0.4040	0.3520	0.0260	0.3450	155/90	0.030	0.100
Dimensions Listed for Authorized Contents					0.4040 (min.)	0.3520 (max.)		0.3455 (max.)	150†† (max.)	0.030 (min.)	0.120 (max.)
bounding dimensions (axial segment with only the full length rods) (B10x10A01)	0.9457†††	0.9414	0.0008	0.2212	0.4040	0.3520	0.0260	0.3455‡	155	0.030	0.120

† This assembly class contains 78 full-length rods and 14 partial-length rods. In order to eliminate the requirement on the length of the partial length rods, separate calculations were performed for axial segments with and without the partial length rods.

†† Although the analysis qualifies this assembly for a maximum active fuel length of 155 inches, the specification for authorized contents limits the active fuel length to 150 inches. This is due to the fact that the Boral panels are 156 inches in length.

††† KENO5a verification calculation resulted in a maximum k_{eff} of 0.9453.

‡ This value was conservatively defined to be larger than any of the actual pellet diameters.

Table 6.2.33
MAXIMUM K_{EFF} VALUES FOR THE 10X10B ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10B (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2)

91/83 fuel rods†, 1 water rods (square, replacing 9 fuel rods), pitch=0.510, Zr clad

Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10B01 (axial segment with all rods)	0.9384	0.9341	0.0008	0.2881	0.3957	0.3480	0.0239	0.3413	155	0.0285	0.100
10x10B02 (axial segment with only the full length rods)	0.9416	0.9373	0.0008	0.2333	0.3957	0.3480	0.0239	0.3413	155	0.0285	0.100
10x10B03 (actual three-dimensional representation of all rods)	0.9375	0.9334	0.0007	0.2856	0.3957	0.3480	0.0239	0.3413	155/90	0.0285	0.100
Dimensions Listed for Authorized Contents					0.3957 (min.)	0.3480 (max.)		0.3420 (max.)	150†† (max.)	0.000 (min.)	0.120 (max.)
bounding dimensions (axial segment with only the full length rods) (B10x10B01)	0.9436	0.9395	0.0007	0.2366	0.3957	0.3480	0.0239	0.3420†††	155	0.000	0.120

† This assembly class contains 83 full length rods and 8 partial length rods. In order to eliminate a requirement on the length of the partial length rods, separate calculations were performed for the axial segments with and without the partial length rods.

†† Although the analysis qualifies this assembly for a maximum active fuel length of 155 inches, the specification for authorized contents limits the active fuel length to 150 inches. This is due to the fact that the Boral panels are 156 inches in length.

††† This value was conservatively defined to be larger than any of the actual pellet diameters.

Table 6.2.34
MAXIMUM K_{EFF} VALUES FOR THE 10X10C ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10C (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 96 fuel rods, 5 water rods (1 center diamond and 4 rectangular), pitch=0.488, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10C01	0.9433	0.9392	0.0007	0.2416	0.3780	0.3294	0.0243	0.3224	150	0.031	0.055
Dimensions Listed for Authorized Contents					0.3780 (min.)	0.3294 (max.)		0.3224 (max.)	150 (max.)	0.031 (min.)	0.055 (max.)

Table 6.2.35
MAXIMUM K_{EFF} VALUES FOR THE 10X10D ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10D (4.0% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 100 fuel rods, 0 water rods, pitch=0.565, SS clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10D01	0.9376	0.9333	0.0008	0.3355	0.3960	0.3560	0.0200	0.350	83	n/a	0.080
Dimensions Listed for Authorized Contents					0.3960 (min.)	0.3560 (max.)		0.350 (max.)	83 (max.)	n/a	0.080 (max.)

Table 6.2.36
MAXIMUM K_{EFF} VALUES FOR THE 10X10E ASSEMBLY CLASS IN THE MPC-68
(all dimensions are in inches)

10x10E (4.0% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 96 fuel rods, 4 water rods, pitch=0.557, SS clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
10x10E01	0.9185	0.9144	0.0007	0.2936	0.3940	0.3500	0.0220	0.3430	83	0.022	0.080
Dimensions Listed for Authorized Contents					0.3940 (min.)	0.3500 (max.)		0.3430 (max.)	83 (max.)	0.022 (min.)	0.080 (max.)

Table 6.2.37
MAXIMUM K_{EFF} VALUES FOR THE 6X6A ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

6x6A (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 35 or 36 fuel rods††, 1 or 0 water rods††, pitch=0.694 to 0.710††, Zr clad													
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	pitch	fuel rods	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
6x6A01	0.7539	0.7498	0.0007	0.2754	0.694	36	0.5645	0.4945	0.0350	0.4940	110	n/a	0.060
6x6A02	0.7517	0.7476	0.0007	0.2510	0.694	36	0.5645	0.4925	0.0360	0.4820	110	n/a	0.060
6x6A03	0.7545	0.7501	0.0008	0.2494	0.694	36	0.5645	0.4945	0.0350	0.4820	110	n/a	0.060
6x6A04	0.7537	0.7494	0.0008	0.2494	0.694	36	0.5550	0.4850	0.0350	0.4820	110	n/a	0.060
6x6A05	0.7555	0.7512	0.0008	0.2470	0.696	36	0.5625	0.4925	0.0350	0.4820	110	n/a	0.060
6x6A06	0.7618	0.7576	0.0008	0.2298	0.696	35	0.5625	0.4925	0.0350	0.4820	110	0.0	0.060
6x6A07	0.7588	0.7550	0.0007	0.2360	0.700	36	0.5555	0.4850	0.03525	0.4780	110	n/a	0.060
6x6A08	0.7808	0.7766	0.0007	0.2527	0.710	36	0.5625	0.5105	0.0260	0.4980	110	n/a	0.060
Dimensions Listed for Authorized Contents					0.710 (max.)	35 or 36	0.5550 (min.)	0.5105 (max.)	0.02225	0.4980 (max.)	120 (max.)	0.0	0.060 (max.)
bounding dimensions (B6x6A01)	0.7727	0.7685	0.0007	0.2460	0.694	35	0.5550	0.5105	0.02225	0.4980	120	0.0	0.060
bounding dimensions (B6x6A02)	0.7782	0.7738	0.0008	0.2408	0.700	35	0.5550	0.5105	0.02225	0.4980	120	0.0	0.060
bounding dimensions (B6x6A03)	0.7888	0.7846	0.0007	0.2310	0.710	35	0.5550	0.5105	0.02225	0.4980	120	0.0	0.060

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

†† This assembly class was analyzed and qualified for a small variation in the pitch and a variation in the number of fuel and water rods.

Table 6.2.38
MAXIMUM K_{EFF} VALUES FOR THE 6X6B ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

6x6B (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 35 or 36 fuel rods†† (up to 9 MOX rods), 1 or 0 water rods††, pitch=0.694 to 0.710††, Zr clad													
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	pitch	fuel rods	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
6x6B01	0.7604	0.7563	0.0007	0.2461	0.694	36	0.5645	0.4945	0.0350	0.4820	110	n/a	0.060
6x6B02	0.7618	0.7577	0.0007	0.2450	0.694	36	0.5625	0.4925	0.0350	0.4820	110	n/a	0.060
6x6B03	0.7619	0.7578	0.0007	0.2439	0.696	36	0.5625	0.4925	0.0350	0.4820	110	n/a	0.060
6x6B04	0.7686	0.7644	0.0008	0.2286	0.696	35	0.5625	0.4925	0.0350	0.4820	110	0.0	0.060
6x6B05	0.7824	0.7785	0.0006	0.2184	0.710	35	0.5625	0.4925	0.0350	0.4820	110	0.0	0.060
Dimensions Listed for Authorized Contents					0.710 (max.)	35 or 36	0.5625 (min.)	0.4945 (max.)		0.4820 (max.)	120 (max.)	0.0	0.060 (max.)
bounding dimensions (B6x6B01)	0.7822†††	0.7783	0.0007	0.2190	0.710	35	0.5625	0.4945	0.0340	0.4820	120	0.0	0.060

Note:

1. These assemblies contain up to 9 MOX pins. The composition of the MOX fuel pins is given in Table 6.3.4.

† The ^{235}U enrichment of the MOX and UO_2 pins is assumed to be 0.711% and 3.0%, respectively.

†† This assembly class was analyzed and qualified for a small variation in the pitch and a variation in the number of fuel and water rods.

††† The k_{eff} value listed for the 6x6B05 case is slightly higher than that for the case with the bounding dimensions. However, the difference (0.0002) is well within the statistical uncertainties, and thus, the two values are statistically equivalent (within 1σ). Therefore, the 0.7824 value is listed in Tables 6.1.2 and 6.1.3 as the maximum.

Table 6.2.39
MAXIMUM K_{EFF} VALUES FOR THE 6X6C ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

6x6C (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 36 fuel rods, 0 water rods, pitch=0.740, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
6x6C01	0.8021	0.7980	0.0007	0.2139	0.5630	0.4990	0.0320	0.4880	77.5	n/a	0.060
Dimensions Listed for Authorized Contents					0.5630 (min.)	0.4990 (max.)		0.4880 (max.)	77.5 (max.)	n/a	0.060 (max.)

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

Table 6.2.40
MAXIMUM K_{EFF} VALUES FOR THE 7X7A ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

7x7A (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 49 fuel rods, 0 water rods, pitch=0.631, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
7x7A01	0.7974	0.7932	0.0008	0.2015	0.4860	0.4204	0.0328	0.4110	80	n/a	0.060
Dimensions Listed for Authorized Contents					0.4860 (min.)	0.4204 (max.)		0.4110 (max.)	80 (max.)	n/a	0.060 (max.)

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

Table 6.2.41
MAXIMUM K_{EFF} VALUES FOR THE 8X8A ASSEMBLY CLASS IN THE MPC-68F
(all dimensions are in inches)

8x8A (3.0% Enrichment†, Boral ^{10}B minimum loading of 0.0067 g/cm^2) 63 or 64 fuel rods††, 0 water rods, pitch=0.523, Zr clad												
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	fuel rods	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
8x8A01	0.7685	0.7644	0.0007	0.2227	64	0.4120	0.3620	0.0250	0.3580	110	n/a	0.100
8x8A02	0.7697	0.7656	0.0007	0.2158	63	0.4120	0.3620	0.0250	0.3580	120	n/a	0.100
Dimensions Listed for Authorized Contents					63	0.4120 (min.)	0.3620 (max.)		0.3580 (max.)	110 (max.)	n/a	0.100 (max.)
bounding dimensions (8x8A02)	0.7697	0.7656	0.0007	0.2158	63	0.4120	0.3620	0.0250	0.3580	120	n/a	0.100

† Although the calculations were performed for 3.0%, the enrichment is limited in the specification for authorized contents to 2.7%.

†† This assembly class was analyzed and qualified for a variation in the number of fuel rods.

Table 6.2.42

SPECIFICATION OF THE THORIA ROD CANISTER AND THE THORIA RODS

Canister ID	4.81"
Canister Wall Thickness	0.11"
Separator Assembly Plates Thickness	0.11"
Cladding OD	0.412"
Cladding ID	0.362"
Pellet OD	0.358"
Active Length	110.5"
Fuel Composition	1.8% UO_2 and 98.2% ThO_2
Initial Enrichment	93.5 wt% ^{235}U for 1.8% of the fuel
Maximum k_{eff}	0.1813
Calculated k_{eff}	0.1779
Standard Deviation	0.0004

Table 6.2.43
MAXIMUM K_{EFF} VALUES FOR THE 14X14E ASSEMBLY CLASS IN THE MPC-24
(all dimensions are in inches)

14x14E (5.0% Enrichment, Boral ^{10}B minimum loading of 0.02 g/cm^2) 173 fuel rods, 0 guide tubes, pitch=0.453 and 0.441, SS clad†										
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length††	guide tube thickness
14x14E01	0.7598	0.7555	0.0008	0.3890	0.3415	0.3175 0.2845 0.3015	0.0120 0.0285 0.0200	0.3130 0.2800 0.2970	102	0.0000
14x14E02	0.7627	0.7586	0.0007	0.3607	0.3415	0.3175	0.0120	0.3130	102	0.0000
14x14E03	0.6952	0.6909	0.0008	0.2905	0.3415	0.2845	0.0285	0.2800	102	0.0000
Dimensions Listed for Authorized Contents					0.3415 (min.)	0.3175 (max.)		0.3130 (max.)	102 (max.)	0.0000 (min.)
Bounding dimensions (14x14E02)	0.7627	0.7586	0.0007	0.3607	0.3415	0.3175	0.0120	0.3130	102	0.0000

† This is the IP-1 fuel assembly at Indian Point. This assembly is a 14x14 assembly with 23 fuel rods omitted to allow passage of control rods between assemblies. Fuel rod dimensions are bounding for each of the three types of rods found in the IP-1 fuel assembly.

†† Calculations were conservatively performed for a fuel length of 150 inches.

Table 6.2.44
MAXIMUM K_{EFF} VALUES FOR THE 9X9G ASSEMBLY CLASS IN THE MPC-68 and MPC-68FF
(all dimensions are in inches)

9x9G (4.2% Enrichment, Boral ^{10}B minimum loading of 0.0279 g/cm^2) 72 fuel rods, 1 water rod (square, replacing 9 fuel rods), pitch=0.572, Zr clad											
Fuel Assembly Designation	maximum k_{eff}	calculated k_{eff}	standard deviation	EALF	cladding OD	cladding ID	cladding thickness	pellet OD	fuel length	water rod thickness	channel thickness
9x9G01	0.9309	0.9265	0.0008	0.2191	0.4240	0.3640	0.0300	0.3565	150	0.0320	0.120
Dimensions Listed for Authorized Contents					0.4240 (min.)	0.3640 (max.)		0.3565 (max.)	150 (max.)	0.0320 (min.)	0.120 (max.)

6.3 MODEL SPECIFICATION

In compliance with the requirements of 10CFR71.31(a)(1), 10CFR71.33(a)(5), and 10CFR71.33(b), this section provides a description of the HI-STAR 100 System in sufficient detail to identify the package accurately and provide a sufficient basis for the evaluation of the package.

6.3.1 Description of Calculational Model

Figures 6.3.1 through 6.3.3 show representative horizontal cross sections of the four types of cells used in the calculations, and Figures 6.3.4 through 6.3.6 illustrate the basket configurations used. Four different MPC fuel basket designs were evaluated as follows:

- a 24 PWR assembly basket,
- an optimized 24 PWR assembly basket (MPC-24E/EF and Trojan MPC-24E/EF),
- a 32 PWR assembly basket, and
- a 68 BWR assembly basket.

For all basket designs, the same techniques and the same level of detail are used in the calculational models.

Full three-dimensional calculations were used, assuming the axial configuration shown in Figure 6.3.7, and conservatively neglecting the absorption in the overpack neutron shielding material (Holtite-A). Although the Boral neutron absorber panels are 156 inches in length, which is much longer than the active fuel length (maximum of 150 inches), they are assumed equal to the active fuel length in the calculations, except for the Trojan MPC-24E/EF. Due to the reduced height of the Trojan MPCs, there is the potential of a misalignment of about 1 inch between the active length and the Boral at the bottom of the active region. Conservatively, a misalignment of 3 inches is assumed in the calculational model for the Trojan MPCs. As shown on the drawings in Section 1.4, 16 of the 24 periphery Boral panels on the MPC-24 have reduced width (i.e., 6.25 inches wide as opposed to 7.5 inches). However, the calculational models for the MPC-24 conservatively assume all of the periphery Boral panels are 6.25 inches in width.

The calculational model explicitly defines the fuel rods and cladding, the guide tubes (or water rods for BWR assemblies), the water-gaps and Boral absorber panels on the stainless steel walls of the basket cells. Under normal conditions of transport, when the MPC is dry, the resultant reactivity with the design basis fuel is very low ($k_{eff} < 0.5$). For the flooded condition (loading,

unloading, and hypothetical accident condition), water was assumed to be present in the fuel rod pellet-to-clad gap regions (see Subsection 6.4.2.3 for justification). Appendix 6.D provides sample input files for the MPC-24 and MPC-68 basket designs in the HI-STAR 100 System.

The water thickness above and below the fuel is intentionally maintained less than or equal to the actual water thickness. This assures that any positive reactivity effect of the steel in the MPC is conservatively included.

As indicated in Figures 6.3.1 through 6.3.3 and in Tables 6.3.1 and 6.3.2, calculations were made with dimensions assumed to be at their most conservative value with respect to criticality. CASMO and MCNP4a were used to determine the direction of the manufacturing tolerances which produced the most adverse effect on criticality. After the directional effect (positive effect with an increase in reactivity; or negative effect with a decrease in reactivity) of the manufacturing tolerances was determined, the criticality analyses were performed using the worst case tolerances in the direction which would increase reactivity.

CASMO-3 and -4 were used for one of each of the two principal basket designs, i.e. for the fluxtrap design MPC-24 and for the non-fluxtrap design MPC-68. The effects are shown in Table 6.3.1 which also identifies the approximate magnitude of the tolerances on reactivity. The conclusions in Table 6.3.1 are directly applicable to the MPC-24E/EF and the MPC-32, due to the similarity in the basket designs.

Additionaly, MCNP4a calculations are performed to evaluate the tolerances of the various basket dimensions of the MPC-68, MPC-24 and MPC-32 in further detail. The various basket dimensions are inter-dependent, and therefore cannot be individually varied (i.e., reduction in one parameter requires a corresponding reduction or increase in another parameter). Thus, it is not possible to determine the reactivity effect of each individual dimensional tolerance separately. However, it is possible to determine the reactivity effect of the dimensional tolerances by evaluating the various possible dimensional combinations. To this end, an evaluation of the various possible dimensional combinations was performed using MCNP4a, with fuel assemblies centered in the fuel storage locations. Calculated k_{eff} results (which do not include the bias, uncertainties, or calculational statistics), along with the actual dimensions, for a number of dimensional combinations are shown in Table 6.3.2 for the reference PWR and BWR fuel assemblies. Each of the basket dimensions are evaluated for their minimum, nominal and maximum values. Due to the close similarity between the MPC-24 and MPC-24E, the basket dimensions are only evaluated for the MPC-24, and the same dimensional assumptions are applied to both MPC designs.

Based on the MCNP4a and CASMO calculations, the conservative dimensional assumptions listed in Table 6.3.3 were determined for the MPC basket designs. Because the reactivity effect

(positive or negative) of the manufacturing tolerances are not assembly dependent, these dimensional assumptions were employed for the criticality analyses.

The design parameters important to criticality safety are: fuel enrichment, the inherent geometry of the fuel basket structure, and the fixed neutron absorbing panels (Boral). None of these parameters are affected by the hypothetical accident conditions of transport.

During the hypothetical accident conditions of transport, the HI-STAR 100 System is assumed to be flooded to such an extent as to cause the maximum reactivity and to have full water reflection to such an extent as to cause the maximum reactivity. Further, arrays of packages under the hypothetical accident conditions must be evaluated to determine the maximum number of packages that may be transported in a single shipment. Thus, the only differences between the normal and hypothetical accident condition calculational models are the internal/external moderator densities and the boundary conditions (to simulate an infinite array of HI-STAR 100 Systems).

6.3.2 Cask Regional Densities

Composition of the various components of the principal designs of the HI-STAR 100 Systems are listed in Table 6.3.4. In this table, only the composition of fresh fuel is listed. For a discussion on the composition of spent fuel for burnup credit in the MPC-32 see Appendix 6.E.

The HI-STAR 100 System is designed such that the fixed neutron absorber (Boral) will remain effective for a period greater than 20 years, and there are no credible means to lose it. A detailed physical description, historical applications, unique characteristics, service experience, and manufacturing quality assurance of Boral are provided in Subsection 1.2.1.4.1.

The continued efficacy of the Boral is assured by acceptance testing, documented in Subsection 8.1.5.3, to validate the ^{10}B (poison) concentration in the Boral. To demonstrate that the neutron flux from the irradiated fuel results in a negligible depletion of the poison material, an MCNP4a calculation of the number of neutrons absorbed in the ^{10}B was performed. The calculation conservatively assumed a constant neutron source for 50 years equal to the initial source for the design basis fuel, as determined in Section 5.2, and shows that the fraction of ^{10}B atoms destroyed is only 2.6E-09 in 50 years. Thus, the reduction in ^{10}B concentration in the Boral by neutron absorption is negligible. In addition, the structural analysis demonstrates that the sheathing, which affixes the Boral panel, remains in place during all hypothetical accident conditions, and thus, the Boral panel remains permanently fixed. Therefore, there is no need to provide a surveillance or monitoring program to verify the continued efficacy of the neutron absorber.

6.3.3 Eccentric Positioning of Assemblies in Fuel Storage Cells

Up to and including Revision 9 of this SAR, all criticality calculations were performed with fuel assemblies centered in the fuel storage locations since the effect of credible eccentric fuel positioning was judged to be not significant. Starting in Revision 10 of this SAR, the potential reactivity effect of eccentric positioning of assemblies in the fuel storage locations is accounted for in a conservatively bounding fashion, as described further in this subsection, for all new or changed MPC designs or assembly classes. The calculations in this subsection serve to determine the highest maximum k_{eff} value for each of these assembly class and basket combinations, that is then reported in the summary tables in Section 6.1 and the results tables in Section 6.4. Further, the calculations in this subsection are used to determine the assembly class in each basket with the highest maximum k_{eff} that is then used to demonstrate compliance with the requirements of 10CFR71.55 and 10CFR71.59. All other calculations throughout this chapter, such as studies to determine bounding fuel dimension, bounding basket dimensions, or bounding moderation conditions, are performed with assemblies centered in the fuel storage locations.

To conservatively account for eccentric fuel positioning in the fuel storage cells, three different configurations are analyzed, and the results are compared to determine the bounding configuration:

- Cell Center Configuration: All assemblies centered in their fuel storage cell; same configuration that is used in Section 6.2 and Section 6.3.1;
- Basket Center Configuration: All assemblies in the basket are moved as closely to the center of the basket as permitted by the basket geometry; and
- Basket Periphery Configuration: All assemblies in the basket are moved furthest away from the basket center, and as closely to the periphery of the basket as possible.

It needs to be noted that the two eccentric configurations are hypothetical, since there is no known physical effect that could move all assemblies within a basket consistently to the center or periphery. Instead, the most likely configuration would be that all assemblies are moved in the same direction when the cask is in a horizontal position, and that assemblies are positioned randomly when the cask is in a vertical position. Further, it is not credible to assume that any such configuration could exist by chance. Even if the probability for a single assembly placed in the corner towards the basket center would be 1/5 (i.e. assuming only the center and four corner positions in each cell, all with equal probability), then the probability that all assemblies would be located towards the center would be $(1/5)^{24}$ or approximately 10^{-17} for the MPC-24, $(1/5)^{32}$ or approximately 10^{-23} for the MPC-32, and $(1/5)^{68}$ or approximately 10^{-48} for the MPC-68. However, since the configurations listed above bound all credible configurations, they are conservatively used in the analyses.

The results are presented in Table 6.3.5 for the MPC-24, Table 6.3.6 for the MPC-24E/EF, Table 6.3.7 for the Trojan MPC-24E/EF, and Table 6.3.8 for the MPC-68. For evaluations of eccentric fuel positions in the MPC-32 with burnup credit see Appendix 6.E. Each table shows the maximum k_{eff} value for centered and the two eccentric configurations for each of the assembly classes, and indicates the bounding configuration. The results are summarized as follows:

- In all cases, moving the assemblies to the periphery of the basket results in a reduction in reactivity, compared to the cell centered position.
- Most cases show the maximum reactivity for the basket center configuration, however, in some cases the reactivity is higher for the cell center configuration.

For each of the assembly class and basket combinations listed in Tables 6.3.5 through Table 6.3.8, the configuration showing the highest reactivity is used as the bounding configuration, and listed in the respective tables in Section 6.1. and 6.4. For evaluations of eccentric fuel positions in the MPC-32 with burnup credit see Appendix 6.E.

Table 6.3.1

CASMO-4 CALCULATIONS FOR EFFECT OF TOLERANCES AND TEMPERATURE

Change in Nominal Parameter[†]	Δk for Maximum Tolerance		Action/Modeling Assumption
	MPC-24	MPC-68[‡]	
Reduce Boral Width to Minimum	N/A[†††] min. = nom. = 7.5" and 6.25"	N/A[†††] min. = nom. = 4.75"	Assume minimum Boral width
Increase UO_2 Density to Maximum	+0.0017 max. = 10.522 g/cc nom. = 10.412 g/cc	+0.0014 max. = 10.522 g/cc nom. = 10.412 g/cc	Assume maximum UO_2 density
Reduce Box Inside Dimension (I.D.) to Minimum	-0.0005 min.= 8.86" nom. = 8.92"	See Table 6.3.2	Assume maximum box I.D. for the MPC-24
Increase Box Inside Dimension (I.D.) to Maximum	+0.0007 max. = 8.98" nom. = 8.92"	-0.0030 max. = 6.113" nom. = 6.053"	Assume minimum box I.D. for the MPC-68
Decrease Water Gap to Minimum	+0.0069 min. = 1.09" nom. = 1.15"	N/A	Assume minimum water gap in the MPC-24

† Reduction (or increase) in a parameter indicates that the parameter is changed to its minimum (or maximum) value.

‡ Calculations for the MPC-68 were performed with CASMO-3 [6.3.1 – 6.3.4].

††

††† The Boral width for the MPC-68 is 4.75" +0.125", -0" , the Boral widths for the MPC-24 are 7.5" +0.125", -0" and 6.25" +0.125" –0" (i.e., the nominal and minimum values are the same).

Table 6.3.1 (continued)

CASMO-4 CALCULATIONS FOR EFFECT OF TOLERANCES AND TEMPERATURE

Change in Nominal Parameter	Δk Maximum Tolerance		Action/Modeling Assumption
	MPC-24	MPC-68‡	
Increase in Temperature 20°C 40°C 70°C 100°C	 Ref. -0.0030 -0.0089 -0.0162	 Ref. -0.0039 -0.0136 -0.0193	Assume 20°C
10% Void in Moderator 20°C with no void 20°C 100°C	 Ref. -0.0251 -0.0412	 Ref. -0.0241 -0.0432	Assume no void
Removal of Flow Channel (BWR)	N/A	-0.0073	Assume flow channel present for MPC-68

‡ Calculations for the MPC-68 were performed with CASMO-3 [6.3.1 – 6.3.4].

Table 6.3.2

MCNP4a EVALUATION OF BASKET MANUFACTURING TOLERANCES†

Pitch		Box I.D.		Box Wall Thickness		MCNP4a Calculated k_{eff}
MPC-24†† (17x17A01 @ 4.0% Enrichment)						
nominal	(10.906")	maximum	(8.98")	nominal	(5/16")	0.9325±0.0008†††
minimum	(10.846")	nominal	(8.92")	nominal	(5/16")	0.9300±0.0008
nominal	(10.906")	nom. –0.04"	(8.88")	nom. + 0.05"	(0.3625")	0.9305±0.0007
MPC-68 (8x8C04 @ 4.2% Enrichment)						
minimum	(6.43")	minimum	(5.993")	nominal	(1/4")	0.9307±0.0007
nominal	(6.49")	nominal	(6.053")	nominal	(1/4")	0.9274±0.0007
maximum	(6.55")	maximum	(6.113")	nominal	(1/4")	0.9272±0.0008
nom. + 0.05"	(6.54")	nominal	(6.053")	nom. + 0.05"	(0.30")	0.9267±0.0007

Note: Values in parentheses are the actual value used.

† Tolerance for pitch and box I.D. are ± 0.06".
Tolerance for box wall thickness is +0.05", -0.00".

†† All calculations for the MPC-24 assume minimum water gap thickness (1.09").

††† Numbers are 1σ statistical uncertainties.

Table 6.3.2 (cont.)

MCNP4a EVALUATION OF BASKET MANUFACTURING TOLERANCES†

Pitch	Box I.D.	Box Wall Thickness	MCNP4a Calculated k_{eff}
MPC-32 (17x17A @ 4.0% Enrichment)			
minimum (9.158")	minimum (8.73")	nominal (9/32")	later
nominal (9.218")	nominal (8.79")	nominal (9/32")	later
maximum (9.278")	maximum (8.85")	nominal (9/32")	later
nominal+0.05" (9.268")	nominal (8.79")	nominal+0.05" (0.331")	later
minimum+0.05"(9.208")	minimum (8.73")	nominal+0.05" (0.331")	later
maximum (9.278")	Maximum-0.05" (8.80")	nominal+0.05" (0.331")	later

Notes:

1. Values in parentheses are the actual value used.

† Tolerance for pitch and box I.D. are ± 0.06".
Tolerance for box wall thickness is +0.05", -0.00".

Table 6.3.3

BASKET DIMENSIONAL ASSUMPTIONS

Basket Type	Pitch	Box I.D.	Box Wall Thickness	Water-Gap Flux Trap
MPC-24	nominal (10.906")	maximum (8.98")	nominal (5/16")	minimum (1.09")
MPC-24E	nominal (10.847")	maximum (8.81", 9.11" for DFC Positions, 9.36" for DFC Positions in Trojan MPC)	nominal (5/16")	minimum (1.076", 0.776" for DFC Positions, 0.526" for DFC Positions in Trojan MPC)
MPC-32	minimum (9.158")	minimum (8.73")	nominal (9/32")	N/A
MPC-68	minimum (6.43")	minimum (5.993")	nominal (1/4")	N/A

Table 6.3.4

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

MPC-24		
UO_2 4.0% ENRICHMENT, DENSITY (g/cc) = 10.522		
Nuclide	**Atom-Density**	**Wgt. Fraction**
8016	4.693E-02	1.185E-01
92235	9.505E-04	3.526E-02
92238	2.252E-02	8.462E-01
BORAL (0.02 g ^{10}B/cm sq), DENSITY (g/cc) = 2.660		
Nuclide	**Atom-Density**	**Wgt. Fraction**
5010	8.707E-03	5.443E-02
5011	3.512E-02	2.414E-01
6012	1.095E-02	8.210E-02
13027	3.694E-02	6.222E-01
MPC-32		
BORAL (0.0279 g ^{10}B/cm sq), DENSITY (g/cc) = 2.660		
Nuclide	**Atom-Density**	**Wgt. Fraction**
5010	8.071E-03	5.089E-02
5011	3.255E-02	2.257E-01
6012	1.015E-02	7.675E-02
13027	3.805E-02	6.467E-01

Table 6.3.4 (continued)

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

MPC-68		
UO_2 4.2% ENRICHMENT, DENSITY (g/cc) = 10.522		
Nuclide	Atom-Density	Wgt. Fraction
8016	4.697E-02	1.185E-01
92235	9.983E-04	3.702E-02
92238	2.248E-02	8.445E-01
UO_2 3.0% ENRICHMENT, DENSITY (g/cc) = 10.522		
Nuclide	Atom-Density	Wgt. Fraction
8016	4.695E-02	1.185E-01
92235	7.127E-04	2.644E-02
92238	2.276E-02	8.550E-01
MOX FUEL†, DENSITY (g/cc) = 10.522		
Nuclide	Atom-Density	Wgt. Fraction
8016	4.714E-02	1.190E-01
92235	1.719E-04	6.380E-03
92238	2.285E-02	8.584E-01
94239	3.876E-04	1.461E-02
94240	9.177E-06	3.400E-04
94241	3.247E-05	1.240E-03
94242	2.118E-06	7.000E-05

† The Pu-238, which is an absorber, was conservatively neglected in the MOX description for analysis purposes.

Table 6.3.4 (continued)

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

BORAL (0.0279 g ^{10}B/cm sq), DENSITY (g/cc) = 2.660		
Nuclide	**Atom-Density**	**Wgt. Fraction**
5010	8.071E-03	5.089E-02
5011	3.255E-02	2.257E-01
6012	1.015E-02	7.675E-02
13027	3.805E-02	6.467E-01
FUEL IN THORIA RODS, DENSITY (g/cc) = 10.522		
Nuclide	**Atom-Density**	**Wgt. Fraction**
8016	4.798E-02	1.212E-01
92235	4.001E-04	1.484E-02
92238	2.742E-05	1.030E-03
90232	2.357E-02	8.630E-01

Table 6.3.4 (continued)

COMPOSITION OF THE MAJOR COMPONENTS OF THE HI-STAR 100 SYSTEM

COMMON MATERIALS		
ZR CLAD, DENSITY (g/cc) = 6.550		
Nuclide	**Atom-Density**	**Wgt. Fraction**
40000	4.323E-02	1.000E+00
MODERATOR (H_2O), DENSITY (g/cc) = 1.000		
Nuclide	**Atom-Density**	**Wgt. Fraction**
1001	6.688E-02	1.119E-01
8016	3.344E-02	8.881E-01
STAINLESS STEEL, DENSITY (g/cc) = 7.840		
Nuclide	**Atom-Density**	**Wgt. Fraction**
24000	1.761E-02	1.894E-01
25055	1.761E-03	2.001E-02
26000	5.977E-02	6.905E-01
28000	8.239E-03	1.000E-01
ALUMINUM, DENSITY (g/cc) = 2.700		
Nuclide	**Atom-Density**	**Wgt. Fraction**
13027	6.026E-02	1.000E+00

Table 6.3.5

EFFECT OF ECCENTRIC FUEL POSITIONING IN THE MPC-24

Fuel Assembly Class	Maximum k_{eff}			Bounding Configuration	Bounding Maximum k_{eff}
	Cell Center Configuration	Basket Center Configuration	Basket Periphery Configuration		
14x14A	0.9296	0.9271	0.8951	Cell Center	0.9296
14x14B	0.9228	0.9207	0.8904	Cell Center	0.9228
14x14C	0.9287	0.9307	0.9068	Basket Center	0.9307
14x14D	0.8507	0.8498	0.8225	Cell Center	0.8507
14x14E	0.7627	0.7608	0.7003	Cell Center	0.7627
15x15A	0.9204	0.9227	0.9037	Basket Center	0.9227
15x15B	0.9388	0.9388	0.9240	Basket Center	0.9388
15x15C	0.9361	0.9351	0.9218	Cell Center	0.9361
15x15D	0.9367	0.9364	0.9248	Cell Center	0.9367
15x15E	0.9368	0.9392	0.9264	Basket Center	0.9392
15x15F	0.9395	0.9410	0.9271	Basket Center	0.9410
15x15G	0.8876	0.8907	0.8761	Basket Center	0.8907
15x15H	0.9337	0.9335	0.9214	Cell Center	0.9337
16x16A	0.9287	0.9284	0.9051	Cell Center	0.9287
17x17A	0.9368	0.9362	0.9221	Cell Center	0.9368
17x17B	0.9324	0.9355	0.9204	Basket Center	0.9355
17x17C	0.9336	0.9349	0.9225	Basket Center	0.9349

Table 6.3.6

EFFECT OF ECCENTRIC FUEL POSITIONING IN THE MPC-24E/EF

Fuel Assembly Class	Maximum k_{eff}			Bounding Configuration	Bounding Maximum k_{eff}
	Cell Center Configuration	Basket Center Configuration	Basket Periphery Configuration		
14x14A	0.9380	0.9327	0.9080	Cell Center	0.9380
14x14B	0.9312	0.9288	0.9029	Cell Center	0.9312
14x14C	0.9356	0.9365	0.9189	Basket Center	0.9365
14x14D	0.8875	0.8857	0.8621	Cell Center	0.8875
14x14E	0.7651	0.7536	0.7001	Cell Center	0.7651
15x15A	0.9336	0.9304	0.9188	Cell Center	0.9336
15x15B	0.9465	0.9487	0.9367	Basket Center	0.9487
15x15C	0.9462	0.9452	0.9348	Cell Center	0.9462
15x15D	0.9440	0.9445	0.9343	Basket Center	0.9445
15x15E	0.9455	0.9471	0.9372	Basket Center	0.9471
15x15F	0.9468	0.9495	0.9406	Basket Center	0.9495
15x15G	0.9054	0.9062	0.8970	Basket Center	0.9062
15x15H	0.9423	0.9455	0.9365	Basket Center	0.9455
16x16A	0.9341	0.9358	0.9183	Basket Center	0.9358
17x17A	0.9447	0.9443	0.9355	Cell Center	0.9447
17x17B	0.9421	0.9438	0.9303	Basket Center	0.9438
17x17C	0.9433	0.9431	0.9347	Cell Center	0.9433

Table 6.3.7

EFFECT OF ECCENTRIC FUEL POSITIONING IN THE TROJAN MPC-24E/EF

Fuel Assembly Class	Maximum k_{eff}			Bounding Configuration	Bounding Maximum k_{eff}
	Cell Center Configuration	Basket Center Configuration	Basket Periphery Configuration		
17x17B (Intact Fuel)	0.9161	0.9187	0.9059	Basket Center	0.9187
17x17B (Intact Fuel and Damaged Fuel/Fuel Debris)	0.9377	0.9353	0.9338	Cell Center	0.9377

Table 6.3.8

EFFECT OF ECCENTRIC FUEL POSITIONING IN THE MPC-68

Fuel Assembly Class	Maximum k_{eff}			Bounding Configuration	Bounding Maximum k_{eff}
	Cell Center Configuration	Basket Center Configuration	Basket Periphery Configuration		
8x8F	0.9411	0.9459	0.9193	Basket Center	0.9459
9x9E/F	0.9401	0.9486	0.9166	Basket Center	0.9486
9x9G	0.9309	0.9383	0.9124	Basket Center	0.9383

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

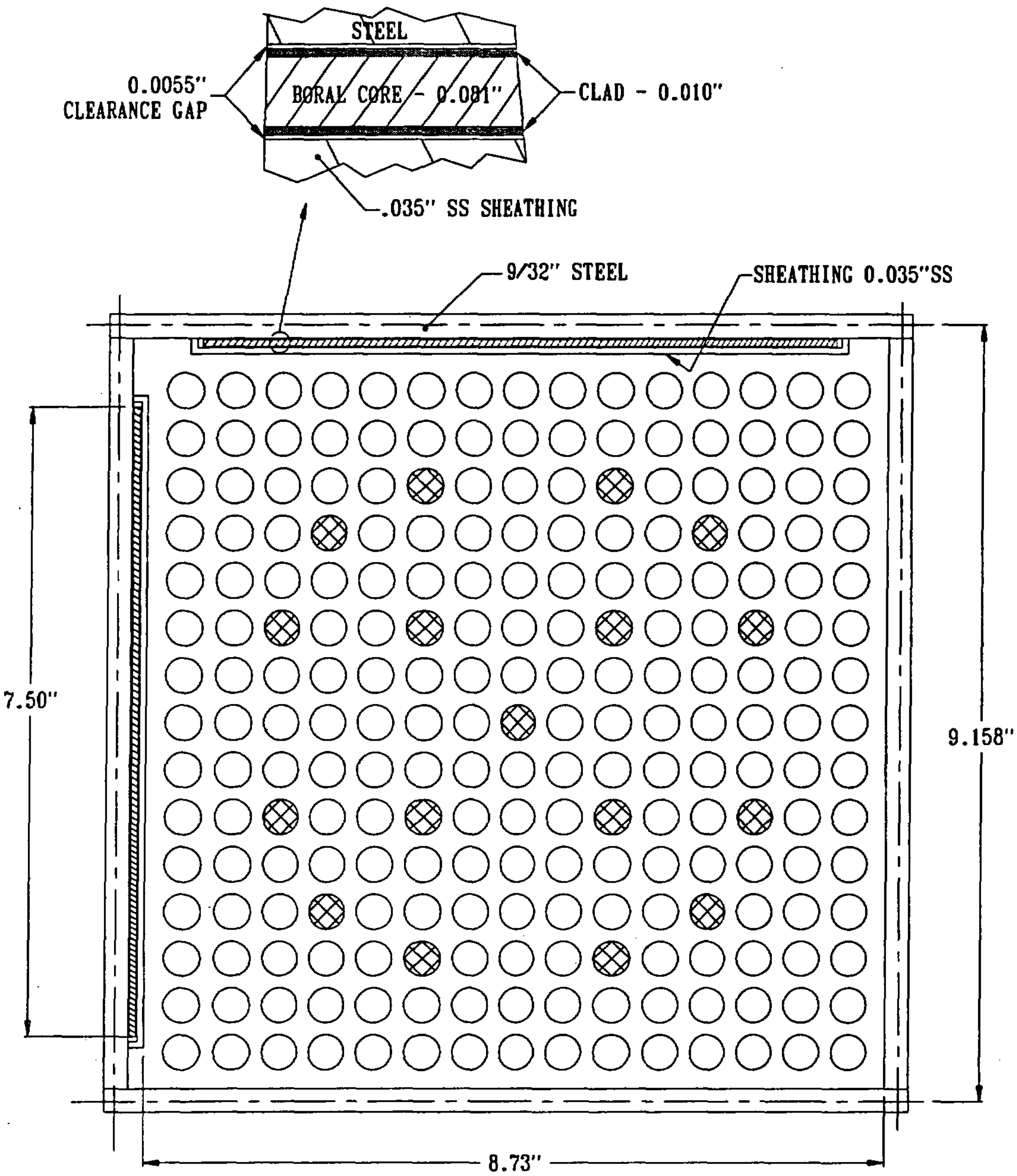

FIGURE 6.3.2; TYPICAL CELL IN THE CALCULATION MODEL (PLANAR CROSS-SECTION) WITH REPRESENTATIVE FUEL IN THE MPC-32 BASKET (SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

NOTE: THESE DIMENSIONS WERE CONSERVATIVELY USED FOR CRITICALITY ANALYSES.

FIGURE WITHHELD UNDER 10 CFR 2.390

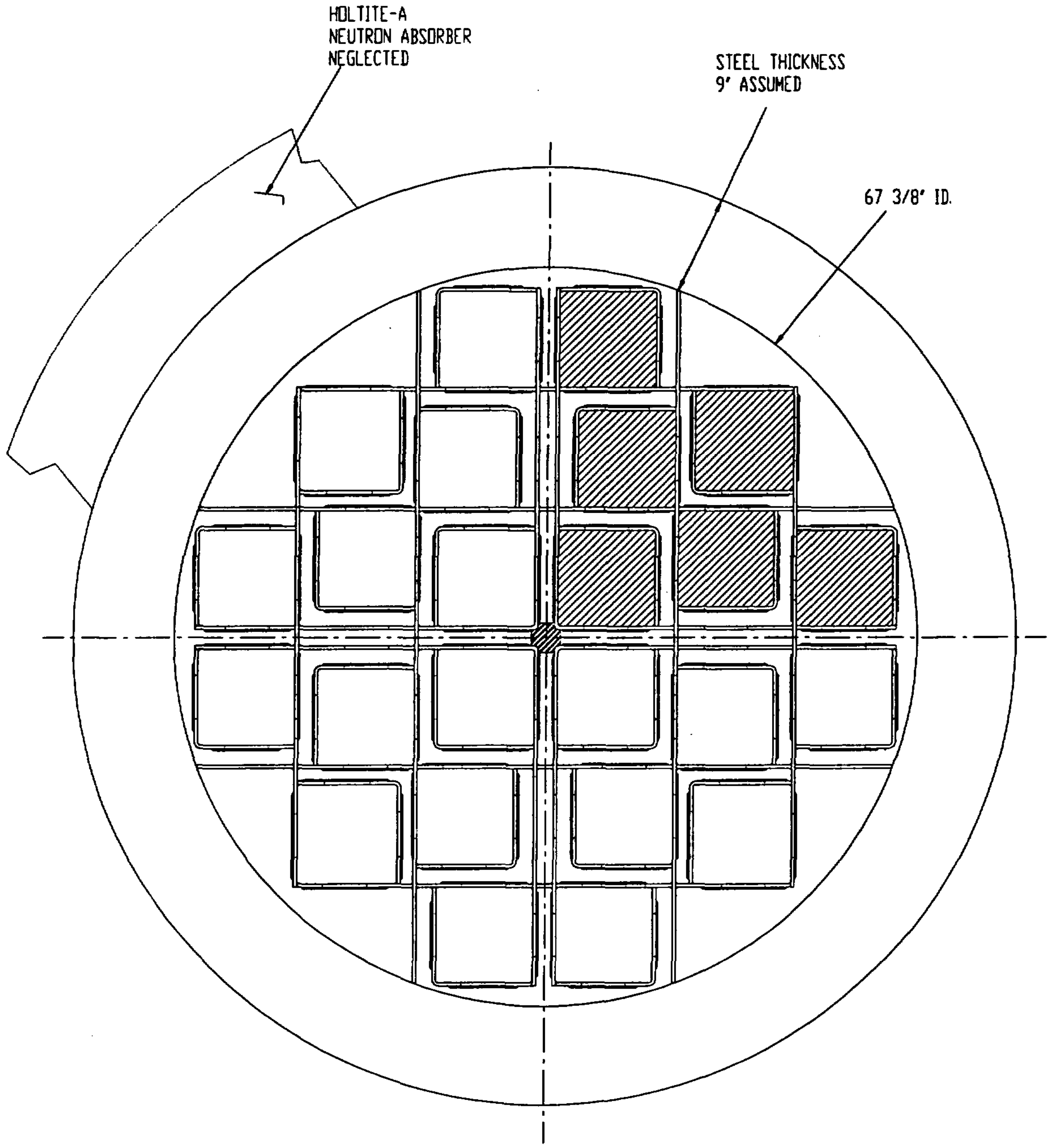

FIGURE 6.3.4; CALCULATION MODEL (PLANAR CROSS-SECTION) WITH FUEL ILLUSTRATED IN ONE QUADRANT OF THE MPC-24, MPC-24E AND MPC-24E/EF TROJAN.

(SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

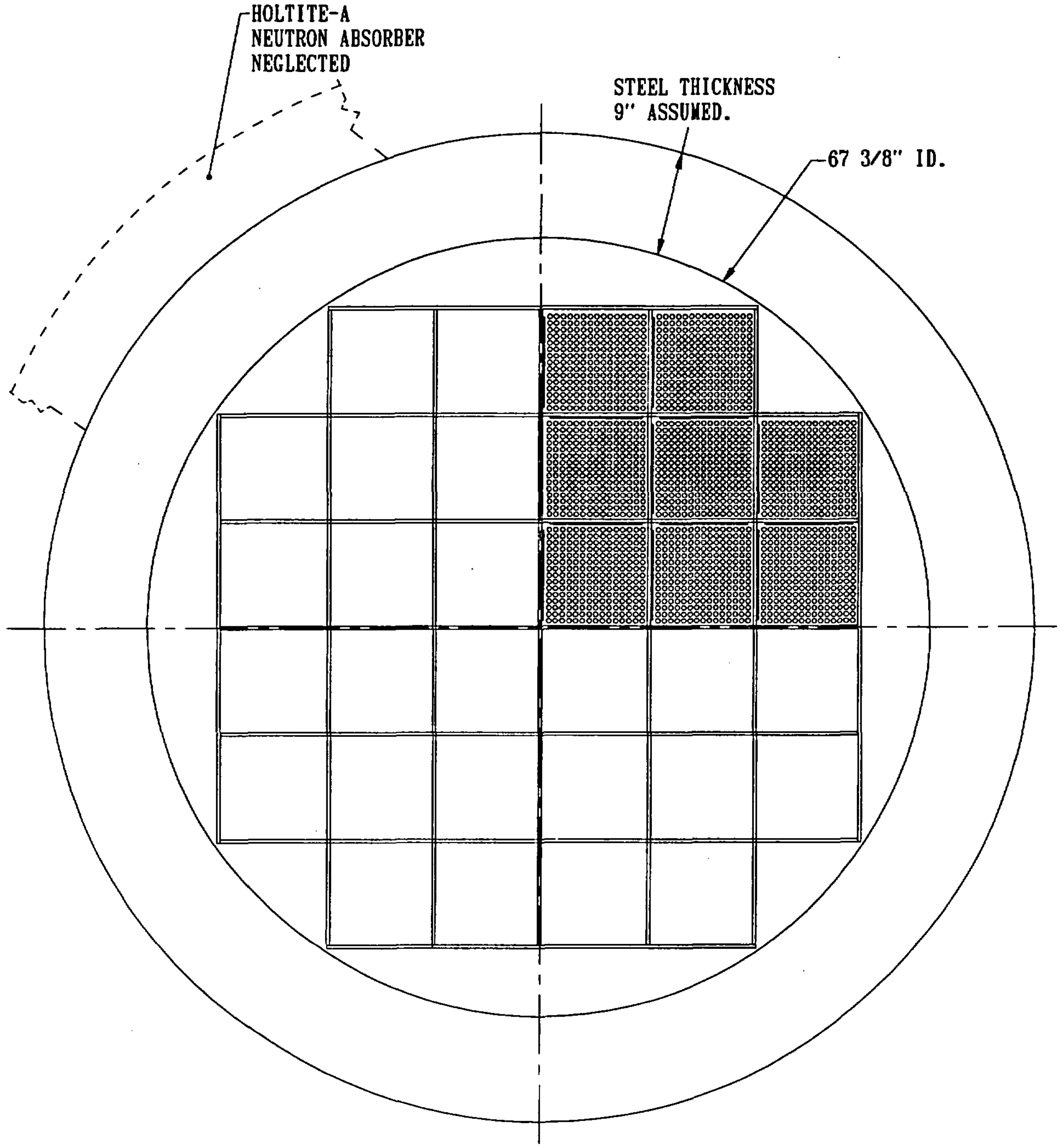

FIGURE 6.3.5; CALCULATION MODEL (PLANAR CROSS-SECTION) WITH FUEL ILLUSTRATED IN ONE QUADRANT OF THE MPC-32.
(SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

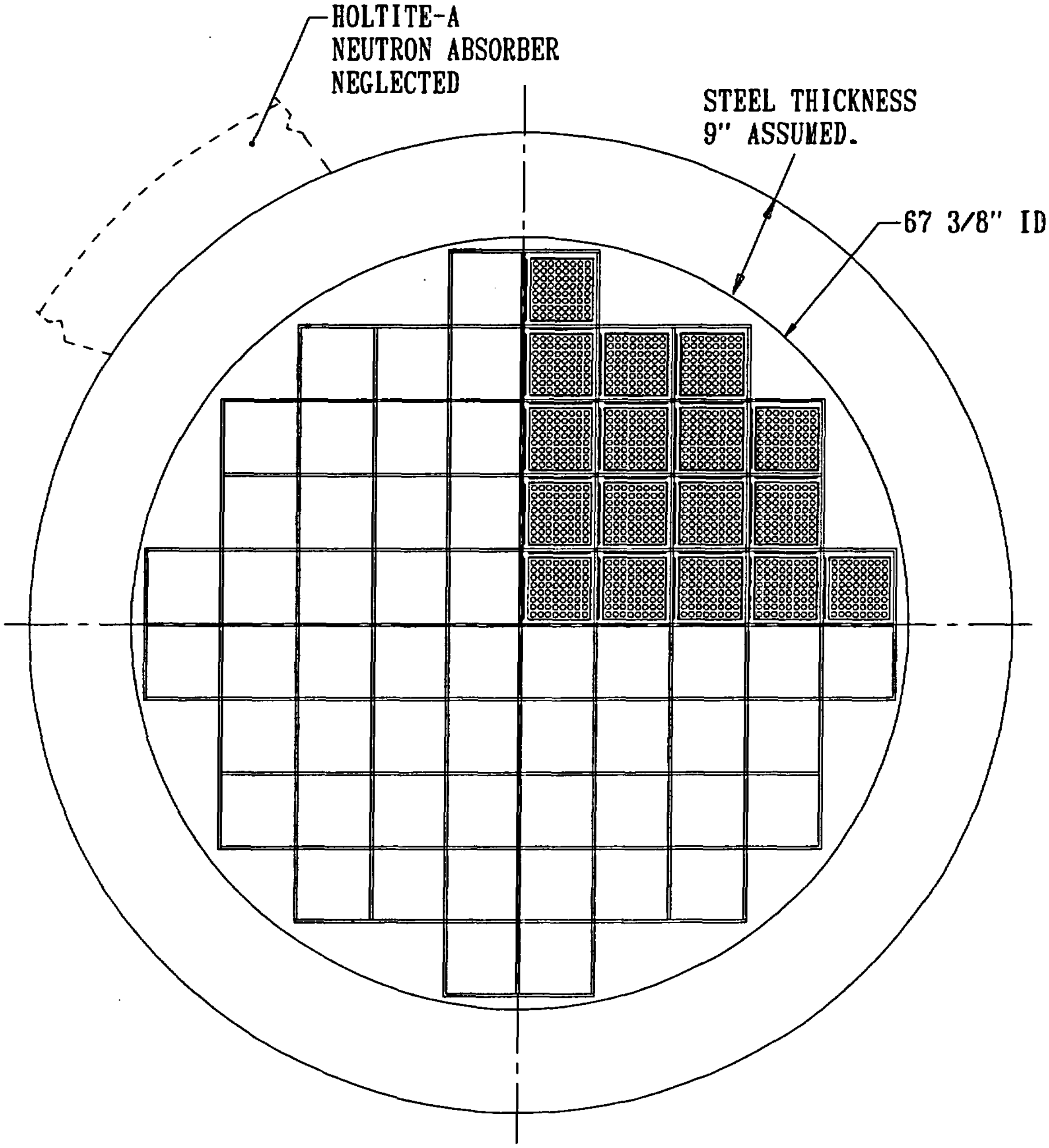

FIGURE 6.3.6; CALCULATION MODEL (PLANAR CROSS-SECTION) WITH FUEL ILLUSTRATED IN ONE QUADRANT OF THE MPC-68
(SEE CHAPTER 1 FOR TRUE BASKET DIMENSIONS)

FIGURE WITHHELD UNDER 10 CFR 2.390

6.4 CRITICALITY CALCULATIONS

6.4.1 Calculational or Experimental Method

The principal method for the criticality analysis is the general three-dimensional continuous energy Monte Carlo N-Particle code MCNP4a [6.1.4] developed at the Los Alamos National Laboratory. MCNP4a was selected because it has been extensively used and verified and has all of the necessary features for this analysis. MCNP4a calculations used continuous energy cross-section data based on ENDF/B-V†, as distributed with the code [6.1.4]. Independent verification calculations were performed with NITAWL-KENO5a [6.1.5], which is a three-dimensional multigroup Monte Carlo code developed at the Oak Ridge National Laboratory. The KENO5a calculations used the 238-group cross-section library, which is based on ENDF/B-V data and is distributed as part of the SCALE-4.3 package [6.4.1], in association with the NITAWL-II program [6.1.6], which adjusts the uranium-238 cross sections to compensate for resonance self-shielding effects. The Dancoff factors required by NITAWL-II were calculated with the CELLDAN code [6.1.13], which includes the SUPERDAN code [6.1.7] as a subroutine.

The convergence of a Monte Carlo criticality problem is sensitive to the following parameters: (1) number of histories per cycle, (2) the number of cycles skipped before averaging, (3) the total number of cycles and (4) the initial source distribution. The MCNP4a criticality output contains a great deal of useful information that may be used to determine the acceptability of the problem convergence. This information was used in parametric studies to develop appropriate values for the aforementioned criticality parameters to be used in the criticality calculations for this submittal. Based on these studies, calculations assuming fresh fuel used a minimum of 5,000 simulated histories per cycle, a minimum of 20 cycles were skipped before averaging, a minimum of 100 cycles were accumulated, and the initial source was specified as uniform over the fueled regions (assemblies). For parameters used in the burnup credit calculations see Appendix 6.E. Further, the output was examined to ensure that each calculation achieved acceptable convergence. These parameters represent an acceptable compromise between calculational precision and computational time. Appendix 6.D provides sample input files for the MPC-24 and MPC-68 basket in the HI-STAR 100 System.

CASMO-4 [6.1.10-6.1.12] was used for determining the small incremental reactivity effects of manufacturing tolerances. Although CASMO has been extensively benchmarked, these calculations are used only to establish direction of reactivity uncertainties due to manufacturing tolerances (and their magnitude). This allows the MCNP4a calculational model to use the worst combination of manufacturing tolerances. Table 6.3.1 shows results of the CASMO calculations.

† For burnup credit calculations in the MPC-32, ENDF/B-VI cross sections are used for nuclides where ENDF/B-V cross sections are not available.

Additionally, CASMO-4 was used to determine the isotopic composition of spent fuel for burnup credit in the MPC-32 (see Appendix 6.E).

6.4.2 Fuel Loading or Other Contents Loading Optimization

The basket designs are intended to safely accommodate the candidate fuel assemblies with enrichments indicated in Tables 6.1.1 through 6.1.3 and 6.1.5 through 6.1.7. The calculations were based on the assumption that the HI-STAR 100 System was fully flooded with water. In all cases, the calculations include bias and calculational uncertainties, as well as the reactivity effects of manufacturing tolerances, determined by assuming the worst case geometry.

6.4.2.1 Internal and External Moderation

The regulations in 10CFR71.55 include the requirement that the system remains subcritical when assuming moderation to the most reactive credible extent. The regulations in 10CFR71.59 require subcriticality for package arrays under different moderation conditions. The calculations in this section demonstrate that the HI-STAR 100 System remains subcritical for all credible conditions of moderation, and that the system fulfills all requirements of 10CFR71.55 and 10CFR71.59. The following subsections 6.4.2.1.1 through 6.4.2.4 present various studies to confirm or identify the most reactive configuration or moderation condition. Specifically, the following conditions are analyzed:

- Reduced internal and external water density for single packages (6.4.2.1.1) and package arrays (6.4.2.1.2);
- Variation in package to package distance in package arrays (6.4.2.1.2);
- Partial internal flooding of package (6.4.2.2);
- Flooding of pellet to cladding gap of the fuel rods (6.4.2.3); and
- Preferential flooding, i.e. uneven flooding inside the package (6.4.2.4).

The calculations that specifically demonstrate compliance with the individual requirements of 10CFR71.55 and 10CFR71.59 are presented in Section 6.4.3. These calculations are performed for all MPCs.

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† PNL critical experiments have shown a small positive reactivity effect of thick steel reflectors, with the maximum effect at 1 cm distance from the fuel. In the cask designs, the fuel is mechanically prohibited from being positioned at a 1 cm spacing from the overpack steel.

The studies in subsections 6.4.2.1.1 through 6.4.2.4 have been performed for both principal basket designs (flux-trap and non-flux-trap) and for both fuel designs (BWR and PWR). Specifically, the studies are performed with the MPC-24 (flux-trap design / PWR fuel) and the MPC-68 (non-flux-trap design / BWR fuel). The results of the studies show a consistent behavior of the different basket designs and fuel types for different moderation conditions. Consequently, the conclusions drawn from these studies are directly applicable to the remaining baskets, namely the MPC-24E/EF (flux-trap design, PWR), MPC-32 (non-flux-trap design, PWR) and MPC-68F (non-flux-trap design, BWR), and no further studies are required for these baskets.

The studies in subsection 6.4.2.1.1 through 6.4.2.4 have been performed with the fuel assemblies centered in each storage location in the basket, which is not necessarily the most reactive position. However, this assumption is acceptable since the objective of these studies is to determine the most reactive moderation condition, not the highest reactivity. The calculations in Section 6.4.3 that demonstrate compliance with 10CFR71.55 and 19CFR71.59 are performed with the most reactive assembly position as discussed in Section 6.3.3.

Regarding the effect of low moderator density it is noted that with a neutron absorber present (i.e., the Boral sheets on the steel walls of the storage compartments), the phenomenon of a peak in reactivity at a hypothetical low moderator density (sometimes called "optimum" moderation) does not occur to any significant extent. In a definitive study, Cano, et al. [6.4.2] has demonstrated that the phenomenon of a peak in reactivity at low moderator densities does not occur when strong neutron absorbing material is present or in the absence of large water spaces between fuel assemblies in storage. Nevertheless, calculations for a single reflected cask and for infinite arrays of casks were made to confirm that the phenomenon does not occur with low density water inside or outside the HI-STAR 100 Systems.

6.4.2.1.1 Single Package Evaluation

Calculations for a single package are performed for the MPC-24 and MPC-68. The Calculational model consists of the HI-STAR System surrounded by a rectangular box filled with water. The neutron absorber on the outside of the HI-STAR is neglected, since it might be damaged under accident conditions, and since it is conservative to replace the neutron absorber (Holtite-A) with a neutron reflector (water). The minimum water thickness on each side of the cask is 30 cm, which effectively represents full water reflection. The outer surfaces of the surrounding box are conservatively set to be fully reflective, which effectively models a three dimensional array of cask systems with an minimum surface to surface distance of 60 cm. The calculations with internal and external moderators of various densities are shown in Table 6.4.1. For comparison purposes, a calculation for a single unreflected cask (Case 1) is also included in Table 6.4.1. At 100% external moderator density, Case 2 corresponds to a single fully-flooded cask, fully reflected by water. Figure 6.4.9 plots calculated k_{eff} values ($\pm 2\sigma$) as a function of internal

moderator density for both MPC designs with 100% external moderator density (i.e., full water reflection).

Results listed in Table 6.4.1 and plotted in Figure 6.4.9 support the following conclusions:

- The calculated k_{eff} for a fully-flooded cask is independent of the external moderator (the small variations in the listed values are due to statistical uncertainties which are inherent to the calculational method (Monte Carlo)), and

- Reducing the internal moderation results in a monotonic reduction in reactivity, with no evidence of any optimum moderation. Thus, the fully flooded condition corresponds to the highest reactivity, and the phenomenon of optimum low-density moderation does not occur and is not applicable to the HI-STAR 100 System.

6.4.2.1.2 Evaluation of Package Arrays

In terms of reactivity, the normal conditions of transport (i.e., no internal or external moderation) are bounded by the hypothetical accident conditions of transport. Therefore, the calculations in this section evaluate arrays of HI-STAR 100 Systems under hypothetical accident conditions (i.e, internal and external moderation by water to the most reactive credible extent and no neutron shield present).

In accordance with 10CFR71.59 requirements, calculations were performed to simulate an infinite three-dimensional square array of internally fully-flooded (highest reactivity) casks with varying cask spacing and external moderation density. The MPC-24 was used for this analysis. The maximum k_{eff} results of these calculations are listed in Table 6.4.2 and confirm that the individual casks in a square-pitched array are independent of external moderation and cask spacing. The maximum value listed in Table 6.4.2 is statistically equivalent (within three standard deviations) to the reference value (Case 1 shown in Table 6.4.1) for a single unreflected fully flooded cask.

To further investigate the reactivity effects of array configurations, calculations were also performed to simulate an infinite three-dimensional hexagonal (triangular-pitched) array of internally fully-flooded (highest reactivity) MPC-24 casks with varying cask spacing and external moderation density. The maximum k_{eff} results of these calculations are listed in Table 6.4.3 and confirm that the individual casks in a hexagonal (triangular pitched) array are effectively independent of external moderation and cask spacing. The maximum value listed in Table 6.4.3 is statistically equivalent (within two standard deviations) to the reference value (Case 1 shown in Table 6.4.1) for a single unreflected fully flooded cask.

To assure that internal moderation does not result in increased reactivity, hexagonal array calculations were also performed for 10% internal moderator with 10% and 100% external moderation for varying cask spacing. Maximum k_{eff} results are summarized in Table 6.4.4 and confirm the very low values of k_{eff} for low values of internal moderation.

The results presented thus far indicate that neutronic interaction between casks is not enhanced by the neighboring casks or the water between the neighboring casks, and thus, the most reactive arrangement of casks corresponds to a tightly packed array with the cask surfaces touching. Therefore, calculations were performed for an infinite hexagonal (triangular pitched) array of touching casks (neglecting the Holtite-A neutron shield). These calculations were performed for the MPC-24 and the MPC-68 designs, in the internally flooded (highest reactivity) and internally dry conditions, with and without external flooding. The results of these calculations are listed in Table 6.4.5. For both the MPC-24 and MPC-68, the maximum k_{eff} values are shown to be statistically equivalent (within one standard deviation) to that of a single internally flooded unreflected cask and are below the regulatory limit of 0.95.

The calculations demonstrate that the thick steel wall of the overpack is more than sufficient to preclude neutron coupling between casks, consistent with the findings of Cano, et al. Neglecting the Holtite-A neutron shielding in the calculational model provides further assurance of conservatism in the calculations.

6.4.2.2 Partial Flooding

To demonstrate that the HI-STAR 100 System would remain subcritical if water were to leak into the containment system, as required by 10CFR71.55, calculations in this section address partial flooding in the HI-STAR 100 System and demonstrate that the fully flooded condition is the most reactive.

The reactivity changes during the flooding process were evaluated in both the vertical and horizontal positions for the MPC-24 and MPC-68 designs. For these calculations, the cask is partially filled (at various levels) with full density (1.0 g/cc) water and the remainder of the cask is filled with steam consisting of ordinary water at partial density (0.002 g/cc). Results of these calculations are shown in Table 6.4.6. In all cases, the reactivity increases monotonically as the water level rises, confirming that the most reactive condition is fully flooded. This conclusion is also true for the other baskets that were not analyzed under partial flooding conditions, since increasing the water level always improves the moderation condition of the fuel and therefore

results in an increase in reactivity†. The fully flooded case therefore represents the bounding condition for all MPC basket types.

6.4.2.3 Clad Gap Flooding

The reactivity effect of flooding the fuel rod pellet-to-clad gap regions, in the fully flooded condition, has been investigated. Table 6.4.7 presents maximum k_{eff} values that demonstrate the positive reactivity effect associated with flooding the pellet-to-clad gap regions. These results confirm that it is conservative to assume that the pellet-to-clad gap regions are flooded. For all cases that involve flooding, the pellet-to-clad gap regions are assumed to be flooded.

6.4.2.4 Preferential Flooding

Two different potential conditions of preferential flooding are considered: preferential flooding of the MPC basket itself (i.e. different water levels in different basket cells), and preferential flooding involving Damaged Fuel Containers.

Preferential flooding of the MPC basket itself for any of the MPC fuel basket designs is not possible because flow holes are present on all four walls of each basket cell and on the two flux trap walls at both the top and bottom of the MPC basket. The flow holes are sized to ensure that they cannot be blocked by crud deposits. Because the fuel cladding temperatures remain below their design limits (as demonstrated in Chapter 3) and the inertial loading remains below 63g's (Section 2.9), the cladding remains intact. For damaged BWR fuel assemblies and BWR fuel debris, the assemblies or debris are pre-loaded into stainless steel Damaged Fuel Containers fitted with 250x250 fine mesh screens (20x20 for Trojan FFC) which prevent damaged fuel assemblies or fuel debris from blocking the basket flow holes. Therefore, the flow holes cannot be blocked and the MPC fuel baskets cannot be preferentially flooded.

However, when DFCs are present in the MPC, a condition could exist during the draining of the MPC, where the DFCs are still partly filled with water while the remainder of the MPC is dry. This condition would be the result of the water tension across the mesh screens. The maximum water level inside the DFCs for this condition is calculated from the dimensions of the mesh screen and the surface tension of water. The wetted perimeter of the screen openings is up to 50 ft per square inch of screen. With a surface tension of water of 0.005 lbf/ft, this results in a maximum pressure across the screen of 0.25 psi, corresponding to a maximum water height in the DFC of 7 inches. For added conservativism, a value of 12 inches is used. Assuming this condition, calculations are performed for the two possible DFC configurations:

† The rate of increase in reactivity along the fuel length, though, could be different between different MPC designs. An example would be the MPC-32 with burnup credit where the reactivity is strongly affected by the lower burned ends of the fuel.

- MPC-68 or MPC-68F with 68 DFCs (Assembly Classes 6x6A/B/C, 7x7A and 8x8A, see Subsection 6.4.4)
- MPC-24E or MPC-24EF with 4 DFCs and 20 intact assemblies (Bounding all PWR assembly classes, see Subsection 6.4.9)

For each configuration, the case resulting in the highest maximum k_{eff} for the fully flooded condition (see Subsections 6.4.4 and 6.4.9) is re-analyzed assuming the preferential flooding condition. For these analyses, the lower 12 inches of the active fuel in the DFCs and the water region below the active fuel (see Figure 6.3.7) are filled with full density water (1.0 g/cc). The remainder of the cask is filled with steam consisting of ordinary water at partial density (0.002 g/cc). All calculations are performed for a single unreflected cask. Table 6.4.10 lists the maximum k_{eff} for the configurations in comparison with the maximum k_{eff} for the fully flooded condition. For all configurations, the preferential flooding condition results in a lower maximum k_{eff} than the fully flooded condition. Thus, the preferential flooding condition is bounded by the fully flooded condition.

In summary, it is concluded that the MPC fuel baskets cannot be preferentially flooded, and that the potential preferential flooding conditions involving DFCs are bounded by the result for the fully flooded condition listed in Subsections 6.4.4 and 6.4.9.

6.4.2.5 Hypothetical Accidents Conditions of Transport

The analyses presented in Section 2.7 of Chapter 2 and Section 3.5 of Chapter 3 demonstrate that the damage resulting from the hypothetical accident conditions of transport are limited to a loss of the neutron shield material as a result of the hypothetical fire accident. Because the criticality analyses do not take credit for the neutron shield material (Holtite-A), this condition has no effect on the criticality analyses.

As reported in Table 2.7.1, the minimum factor of safety for all MPCs as a result of the hypothetical accident conditions of transport is larger than 1.0 against the Level D allowables for Subsection NG, Section III of the ASME Code. Therefore, because the maximum box wall stresses are well within the ASME Level D allowables, the flux-trap gap change in the MPC-24 and MPC-24E/EF will be insignificant compared to the characteristic dimension of the flux trap.

Regarding the fuel assembly integrity, SAR Section 2.9 contains an evaluation of the fuel under accident conditions that concludes that the fuel rod cladding remains intact under the design basis deceleration levels set for the HI-STAR 100.

In summary, the hypothetical transport accidents have no adverse effect on the geometric form of the package contents important to criticality safety, and thus, are limited to the effects on internal and external moderation evaluated in Subsection 6.4.2.1.

6.4.3 Criticality Results

In calculating the maximum reactivity, the analysis used the following equation:

$$k_{eff}^{max} = k_c + K_c\sigma_c + Bias + \sigma_B$$

where:

- ⇒ k_c is the calculated k_{eff} under the worst combination of tolerances;
- ⇒ K_c is the K multiplier for a one-sided statistical tolerance limit with 95% probability at the 95% confidence level [6.1.8]. Each final k_{eff} value calculated by MCNP4a (or KENO5a) is the result of averaging 100 (or more) cycle k_{eff} values, and thus, is based on a sample size of 100. The K multiplier corresponding to a sample size of 100 is 1.93. However, for this analysis a value of 2.00 was assumed for the K multiplier, which is larger (more conservative) than the value corresponding to a sample size of 100;
- ⇒ σ_c is the standard deviation of the calculated k_{eff}, as determined by the computer code (MCNP4a or KENO5a);
- ⇒ *Bias* is the systematic error in the calculations (code dependent) determined by comparison with critical experiments in Appendix 6.A; and
- ⇒ σ_B is the standard error of the bias (which includes the K multiplier for 95% probability at the 95% confidence level; see Appendix 6.A).

Appendix 6.A presents the critical experiment benchmarking and the derivation of the bias and standard error of the bias (95% probability at the 95% confidence level).

The studies in sections 6.4.2.1 through 6.4.2.4 demonstrate that the moderation by water to the most reactive credible extent corresponds to the internally fully flooded condition of the MPC, with the pellet-to-clad gap in the fuel rods also flooded with water. The external moderation and/or the presence of other surrounding packages, however, has a statistically negligible effect. To demonstrate compliance with 10CFR71.55 and 10CFR71.59, the following set of four calculations is performed for each of the MPC designs:

- Single containment with full internal and external water moderation. The full external water moderation is modeled through an infinite array of containments with a 60cm surface to surface distance. The containment system corresponds to the 2.5 inch inner shell of the overpack. This case addresses the requirement of 10CFR71.55 (b).

- Single cask with full internal and external water moderation. As for the single containment, the full external water moderation is modeled through an infinite array. The external neutron moderator is conservatively neglected in the model. This case also addresses the requirement of 10CFR71.55 (b).
- Hexagonal array of touching casks with full internal and external water reflection. This addresses the requirement of 10CFR71.59 (a)(2) and the determination of the transport index based on criticality control according to 10CFR71.59 (b).
- Hexagonal array of touching casks, internally and externally dry. This addresses the requirement of 10CFR71.59 (a) (1) and the determination of the transport index based on criticality control according to 10CFR71.59 (b). This also addresses the requirement of 10CFR71.55 (d)(1).

To satisfy the requirements of 10CFR71.55 (b)(1), the calculations are performed

- with the assembly type that results in the highest reactivity in the MPC. This is the assembly class 15x15F for the MPC-24, MPC-24E/EF and MPC-32, the assembly class 17x17B with intact and damaged assemblies in the Trojan MPC-24E/EF, the assembly class 9x9E/F in the MPC-68, and the assembly class 6x6C for the MPC-68F; and
- with the bounding basket dimensions as determined in Section 6.3.1 for each basket; and
- with eccentric fuel positioning as necessary, as discussed in Section 6.3.3.

The maximum k_{eff} values for all these cases, calculated with 95% probability at the 95% confidence level, are listed in Table 6.4.12. Results of the criticality safety calculations for other assembly classes under the condition of full internal flooding with water are summarized in Section 6.1. Corresponding detailed results including the maximum k_{eff}, standard deviation and energy of the average lethargy causing fission (EALF) are listed for all MPCs except the MPC-32 in Tables 6.4.13 through 6.4.17. Results for the MPC-32 are presented in Appendix 6.E. Overall, these results confirm that for each of the candidate fuel assemblies and basket configurations the effective multiplication factor (k_{eff}), including all biases and uncertainties at a 95-percent confidence level, do not exceed 0.95 under all credible normal and hypothetical accident conditions of transport. Therefore, compliance with 10CFR71.55 for single packages and 10CFR71.59 for package arrays in both normal and hypothetical accident conditions of transport is demonstrated for all of the fuel assembly classes and basket configurations listed in Tables 6.1.1 through 6.1.3 and 6.1.5 through 6.1.7. It further demonstrates that the transportation index for criticality control is zero because an infinite number of HI-STAR 100 casks will remain subcritical (k_{eff}<0.95) under both normal and hypothetical accident conditions of transport.

Additional calculations (CASMO-4) at elevated temperatures confirm that the temperature coefficients of reactivity are negative as shown in Table 6.3.1. This confirms that the calculations for the storage baskets are conservative.

Tables listing the maximum k_{eff}, calculated k_{eff}, standard deviation, and energy of the average lethargy causing fission (EALF) for each of the candidate fuel assemblies in each assembly class for the MPC-24, MPC-68 and MPC-68F basket configurations, and with assemblies centered in the fuel storage locations, are provided in Section 6.2.

6.4.4 Damaged Fuel Container for BWR Fuel

Both damaged BWR fuel assemblies and BWR fuel debris are required to be loaded into Damaged Fuel Containers (DFCs). Two different DFC types with slightly different cross sections are analyzed. DFCs containing fuel debris must be stored in the MPC-68F. DFCs containing damaged fuel assemblies may be stored in either the MPC-68 or MPC-68F. Evaluation of the capability of storing damaged fuel and fuel debris (loaded in DFCs) is limited to very low reactivity fuel in the MPC-68F. Because the MPC-68 has a higher specified ^{10}B loading, the evaluation of the MPC-68F conservatively bounds the storage of damaged BWR fuel assemblies in a standard MPC-68 Although the maximum planar-average enrichment of the damaged fuel is limited to 2.7% ^{235}U as specified in Chapter 1, analyses have been made for three possible scenarios, conservatively assuming fuel[††] of 3.0% enrichment. The scenarios considered included the following:

1. Lost or missing fuel rods, calculated for various numbers of missing rods in order to determine the maximum reactivity. The configurations assumed for analysis are illustrated in Figures 6.4.1 through 6.4.7.
2. Broken fuel assembly with the upper segments falling into the lower segment creating a close-packed array (described as a 8x8 array). For conservatism, the array analytically retained the same length as the original fuel assemblies in this analysis. This configuration is illustrated in Figure 6.4.8.
3. Fuel pellets lost from the assembly and forming powdered fuel dispersed through a volume equivalent to the height of the original fuel. (Flow channel and clad material assumed to disappear).

Results of the analyses, shown in Table 6.4.8, confirm that, in all cases, the maximum reactivity is well below the regulatory limit. There is no significant difference in reactivity between the two DFC types. Collapsed fuel reactivity (simulating fuel debris) is low because of the reduced moderation. Dispersed powdered fuel results in low reactivity because of the increase in ^{238}U neutron capture (higher effective resonance integral for ^{238}U absorption).

†† 6x6A01 and 7x7A01 fuel assemblies were used as representative assemblies.

The loss of fuel rods results in a small increase in reactivity (i.e., rods assumed to collapse, leaving a smaller number of rods still intact). The peak reactivity occurs for 8 missing rods, and a smaller (or larger) number of intact rods will have a lower reactivity, as indicated in Table 6.4.8.

The analyses performed and summarized in Table 6.4.8 provides the relative magnitude of the effects on the reactivity. This information in combination with the maximum k_{eff} values listed in Table 6.1.3 and the conservatism in the analyses, demonstrate that the maximum k_{eff} of the damaged fuel in the most adverse post-accident condition will remain well below the regulatory requirement of $k_{eff} < 0.95$.

Appendix 6.D provides sample input files for the damaged fuel analysis.

6.4.5 Fuel Assemblies with Missing Rods

For fuel assemblies that are qualified for damaged fuel storage, missing and/or damaged fuel rods are acceptable. However, for fuel assemblies to meet the limitations of intact fuel assembly storage, missing fuel rods must be replaced with dummy rods that displace a volume of water that is equal to, or larger than, that displaced by the original rods.

6.4.6 Thoria Rod Canister

The Thoria Rod Canister is similar to a DFC with an internal separator assembly containing 18 intact fuel rods. The configuration is illustrated in Figure 6.4.10. The k_{eff} value for an MPC-68F filled with Thoria Rod Canisters is calculated to be 0.1813. This low reactivity is attributed to the relatively low content in ^{235}U (equivalent to UO_2 fuel with an enrichment of approximately 1.7 wt% ^{235}U), the large spacing between the rods (the pitch is approximately 1", the cladding OD is 0.412") and the absorption in the separator assembly. Together with the maximum k_{eff} values listed in Tables 6.1.2 and 6.1.3 this result demonstrates, that the k_{eff} for a Thoria Rod Canister loaded into the MPC68 or the MPC68F together with other approved fuel assemblies or DFCs will remain well below the regulatory requirement of $k_{eff} < 0.95$.

6.4.7 Sealed Rods Replacing BWR Water Rods

Some BWR fuel assemblies contain sealed rods filled with a non-fissile instead of water rods. Compared to the configuration with water rods, the configuration with sealed rods has a reduced amount of moderator, while the amount of fissile material is maintained. Thus, the reactivity of the configuration with sealed rods will be lower compared to the configuration with water rods. Any configuration containing sealed rods instead of water rods is therefore bounded by the analysis for the configuration with water rods and no further analysis is required to demonstrate the acceptability. Therefore, for all BWR fuel assemblies analyzed, it is permissible that water rods are replaced by sealed rods filled with a non-fissile material.

6.4.8 Neutron Sources in Fuel Assemblies

Fuel assemblies containing start-up neutron sources are permitted for storage in the HI-STAR 100 System. The reactivity of a fuel assembly is not affected by the presence of a neutron source (other than by the presence of the material of the source, which is discussed later). This is true because in a system with a keff less than 1.0, any given neutron population at any time, regardless of its origin or size, will decrease over time. Therefore, a neutron source of any strength will not increase reactivity, but only the neutron flux in a system, and no additional criticality analyses are required. Sources are inserted as rods into fuel assemblies, i.e. they replace either a fuel rod or water rod (moderator). Therefore, the insertion of the material of the source into a fuel assembly will not lead to an increase of reactivity either.

6.4.9 PWR Damaged Fuel and Fuel Debris

The MPC-24E, MPC-24EF, and Trojan MPC-24E and MPC-24EF are designed to contain damaged fuel and fuel debris, loaded into Damaged Fuel Containers (DFCs) or Failed Fuel Cans (FFCs). There is one generic DFC for the MPC-24E/EF, and two containers, a Holtec DFC and a Trojan FFC for the Trojan MPC-24E/EF. In this section, the term "DFC" is used to specify either of these components. In any case, the number of DFCs is limited to 4, and the permissible locations of the DFCs are shown in Figure 6.4.11.

Only the Trojan MPC-24E/EF is certified for damaged fuel and fuel debris. However, the generic MPC-24E/EF is also designed to accommodate damaged fuel debris, and the majority of criticality evaluations for damaged fuel and fuel debris are performed for the generic MPC-24E/EF, with only a smaller number of calculations performed for the Trojan MPCs. Therefore, criticality evaluations for both the generic MPC-24E/EF and the Trojan MPC-24E/EF are presented in this subsection, even though the Trojan MPC-24E/EF are the only MPCs authorized to transport damaged fuel and fuel debris.

Damaged fuel assemblies are assemblies with known or suspected cladding defects greater than pinholes or hairlines, or with missing rods, but excluding fuel assemblies with gross defects (for a full definition see Chapter 1). Therefore, apart from possible missing fuel rods, damaged fuel assemblies have the same geometric configuration as intact fuel assemblies and consequently the same reactivity. Missing fuel rods can result in a slight increase of reactivity. After a drop accident, however, it can not be assumed that the initial geometric integrity is still maintained. For a drop on either the top or bottom of the cask, the damaged fuel assemblies could collapse. This would result in a configuration with a reduced length, but increased amount of fuel per unit length. For a side drop, fuel rods could be compacted to one side of the DFC. In either case, a significant relocation of fuel within the DFC is possible, which creates a greater amount of fuel in some areas of the DFC, whereas the amount of fuel in other areas is reduced. Fuel debris can

include a large variety of configurations ranging from whole fuel assemblies with severe damage down to individual fuel pellets.

In the cases of fuel debris or relocated damaged fuel, there is the potential that fuel could be present in axial sections of the DFCs that are outside the basket height covered with Boral. However, in these sections, the DFCs are not surrounded by any intact fuel, only by basket cell walls, non-fuel hardware and water. Studies have shown that this condition does not result in any significant effect on reactivity, compared to a condition where the damaged fuel and fuel debris is restricted to the axial section of the basket covered by Boral. All calculations for damaged fuel and fuel debris are therefore performed assuming that fuel is present only in the axial sections covered by Boral, and the results are directly applicable to any situation where damaged fuel and fuel debris is located outside these sections in the DFCs.

To address all the situations listed above and identify the configuration or configurations leading to the highest reactivity, it is impractical to analyze a large number of different geometrical configurations for each of the fuel classes. Instead, a bounding approach is taken which is based on the analysis of regular arrays of bare fuel rods without cladding. Details and results of the analyses are discussed in the following sections.

All calculations for generic damaged fuel and fuel debris are performed using a full cask model with the maximum permissible number of Damaged Fuel Containers. For the MPC-24E and MPC-24EF, the model consists of 20 intact assemblies, and 4 DFCs in the locations shown in Figure 6.4.11. The bounding assumptions regarding the intact assemblies and the modeling of the damaged fuel and fuel debris in the DFCs are discussed in the following sections.

6.4.9.1 Bounding Intact Assemblies

Intact PWR assemblies stored together with DFCs in the MPC-24E/EF are limited to a maximum enrichment of 4.0 wt% ^{235}U, regardless of the fuel class. Results presented in Table 6.1.5 for the MPC-24E/EF loaded with intact assemblies only are for different enrichments for each class, ranging between 4.2 and 5.0 wt% ^{235}U, making it difficult to directly identify the bounding assembly. However, the assembly class 15x15H is among the classes with the highest reactivity, but has the lowest initial enrichment. Therefore, the 15x15H assembly is used as the intact PWR assembly for all calculations with DFCs.

The Trojan MPC-24E/EF is only certified for the assembly class 17x17B, which bounds the fuel types used at the Trojan plant. Consequently, the assembly class 17x17B is used as the intact assembly in all calculations for the Trojan MPC-24E/EF.

6.4.9.2 Bare Fuel Rod Arrays

A conservative approach is used to model both damaged fuel and fuel debris in the DFCs, using arrays of bare fuel rods:

- Fuel in the DFCs is arranged in regular, rectangular arrays of bare fuel rods, i.e. all cladding and other structural material in the DFC is replaced by water.
- The active length of these rods is chosen to be the maximum active fuel length of all fuel assemblies listed in Section 6.2, which is 150 inch for PWR fuel.
- To ensure the configuration with optimum moderation and highest reactivity is analyzed, the amount of fuel per unit length of the DFC is varied over a large range. This is achieved by changing the number of rods in the array and the rod pitch. The number of rods are varied between 64 (8x8) and 729 (27x27) for PWR fuel.
- Analyses are performed for the minimum, maximum and typical pellet diameter of the fuel.

This is a very conservative approach to model damaged fuel, and to model fuel debris configurations such as severely damaged assemblies and bundles of individual fuel rods, as the absorption in the cladding and structural material is neglected.

This is also a conservative approach to model fuel debris configurations such as bare fuel pellets due to the assumption of an active length of 150 inch. For some of the analyzed cases, this assumption results in more uranium mass being modeled in the DFCs than is permitted by the uranium mass loading restrictions listed in Chapter 1.

To demonstrate the level of conservatism, additional analyses are performed with the DFC containing various realistic assembly configurations such as intact assemblies, assemblies with missing fuel rods and collapsed assemblies, i.e. assemblies with increased number of rods and decreased rod pitch.

As discussed in Subsection 6.4.9, all calculations are performed for full cask models, containing the maximum permissible number of DFCs together with intact assemblies.

Graphical presentations of the calculated maximum k_{eff} for each case as a function of the fuel mass per unit length of the DFC are shown in Figure 6.4.12. The results for the bare fuel rods show a distinct peak in the maximum k_{eff} at about 3.5 $kgUO_2$/inch.

The realistic assembly configurations are typically about 0.01 (delta-k) or more below the peak results for the bare fuel rods, demonstrating the conservatism of this approach to model damaged fuel and fuel debris configurations such as severely damaged assemblies and bundles of fuel rods.

For fuel debris configurations consisting of bare fuel pellets only, the fuel mass per unit length would be beyond the value corresponding to the peak reactivity. For example, for DFCs filled with a mixture of 60 vol% fuel and 40 vol% water the fuel mass per unit length is 7.92 $kgUO_2$/inch for the PWR DFC. The corresponding reactivities are significantly below the peak reactivies. The difference is about 0.01 (delta-k) or more for PWR fuel. Furthermore, the filling height of the DFC would be less than 70 inches in these examples due to the limitation of the fuel mass per basket position, whereas the calculation is conservatively performed for a height of 150 inch. These results demonstrate that even for the fuel debris configuration of bare fuel pellets, the model using bare fuel rods is a conservative approach.

To demonstrate that the bare fuel rod approach also bounds the potential presence of fuel fragments in the DFCs, additional calculations were performed with fuel fragments in the DFCs instead of bare fuel rods. The fuel fragments are modeled as regular 3-dimensional arrays of fuel cubes positioned inside water cubes. Both the dimension of the fuel cubes and the fuel-to-water-volume ratio are varied over a wide range. Calculations are performed for the MPC-24E/EF Trojan, and the results are presented in Table 6.4.18. The highest maximum k_{eff} is 0.9320 for a fragment outer dimension of 0.2 inches and a fuel to water volume ratio of 0.4. This maximum k_{eff} value is lower than the corresponding value for the bare fuel rod model, which is 0.9377 as shown in Table 6.4.17. The damaged fuel and fuel debris model based on bare fuel rods therefore bounds any condition involving fuel fragments in the DFCs.

6.4.9.3 Results for MPC-24E and MPC-24EF

The MPC-24E is designed for the storage of up to four DFCs with damaged fuel in the four outer fuel baskets cells shaded in Figure 6.4.11. The MPC-24EF allows storage of up to four DFCs with damaged fuel or fuel debris in these locations. These locations are designed with a larger box ID to accommodate the DFCs. For an enrichment of 4.0 wt% ^{235}U for the intact fuel, damaged fuel and fuel debris, the results for the various configurations outlined in Subsection 6.4.9.2 are summarized in Figure 6.4.12 and in Table 6.4.11. Figure 6.4.12 shows the maximum k_{eff}, including bias and calculational uncertainties, for various actual and hypothetical damaged fuel and fuel debris configurations as a function of the fuel mass per unit length of the DFC. For the intact assemblies, the 15x15H assembly class was chosen (see Subsection 6.4.9.1). Table 6.4.11 lists the highest maximum k_{eff} for the various configurations. All maximum k_{eff} values are below the 0.95 regulatory limit.

6.4.9.4 Results for Trojan MPC-24E and MPC-24EF

For the Trojan MPC-24E/EF, bare fuel rod arrays with arrays sizes between 11x11 and 23x23 were analyzed as damaged fuel/fuel debris, with a pellet diameter corresponding to the 17x17B assembly class. The highest maximum k_{eff} value is shown in Table 6.1.6, and is below the 0.95 regulatory limit. The realistic damaged fuel assembly configurations in the DFC, such as assemblies with missing rods, were not analyzed in the Trojan MPC-24E/EF since the evaluations for the generic MPC-24E/EF demonstrate that these conditions are bounded by the fuel debris model using bare fuel pellets.

6.4.10 Non-fuel Hardware in PWR Fuel Assemblies

Non-fuel hardware such as Thimble Plugs (TPs), Burnable Poison Rod Assemblies (BPRAs), Rod Cluster Control Assemblies (RCCAs) and similar devices are permitted for storage with the PWR fuel assemblies in the Trojan MC-24E/EF. Non-fuel hardware is inserted in the guide tubes of the assemblies. For pure water, the reactivity of any PWR assembly with inserts is bounded by (i.e. lower than) the reactivity of the same assembly without the insert. This is due to the fact that the insert reduces the amount of moderator in the assembly, while the amount of fissile material remains unchanged.

Therefore, from a criticality safety perspective, non-fuel hardware inserted into PWR assemblies are acceptable for all allowable PWR types, and, depending on the assembly class, can increase the safety margin.

6.4.11 Reactivity Effect of Potential Boral Damage

During the manufacturing process of the fuel baskets, it is possible that minor damage to Boral panels occurs during welding operations. Criticality calculations have been performed for all basket types to determine whether this condition could have an effect on the reactivity of the system. Since the potential Boral damage is typically the result of welding operations, the damage would occur in a narrow area along the edge of the panel, and would only be present in a few panels within each basket. However, in order to maximize the potential reactivity effect of the damage in the calculations, it is assumed that the damage occurs in an area with a diameter of 1 inch at the center of the Boral panel, and that this condition exists in every panel in the basket. It is further assumed that the Boral in this area is completely replaced by water, while in reality only a relocation of the Boral would occur, since the Boral is completely covered by the sheathing. Calculations performed under these assumption demonstrate that the conservatively modeled Boral damage has a negligible effect on the reactivity, i.e. the difference to the condition without the damage is less than 2 standard deviations. For example, for the MPC-24 and MPC-24E, the change in reactivity is +0.0006 and -0.0004, respectively, for a standard deviation between 0.0004 and 0.0005. In the MPC-24E for Trojan, a specific potential damage was

identified that is not bounded by the generic approach described above. To demonstrate that this condition is acceptable, a specific calculation was performed assuming a damage of 5 square-inches in a specific location in up to 8 Boral panels in the basket, and was found to have again a negligible effect on reactivity. In summary, these calculations demonstrate that Boral damage bounded by the configurations assumed in the analyses is acceptable and does not affect the reactivity of the HI-STAR System.

Table 6.4.1

MAXIMUM REACTIVITIES WITH REDUCED WATER DENSITIES FOR CASK ARRAYS† WITH MPC-24 AND MPC-68

	Water Density		MCNP4a Results					
Case Number	Internal	External	MPC-24 (17x17A01 @ 4.0%)			MPC-68 (8x8C04 @ 4.2%)		
			Max. k_{eff} ††	1 σ	EALF (eV)	Max. k_{eff}	1 σ	EALF (eV)
1	100%	single cask	0.9368	0.0008	0.2131	0.9348	0.0007	0.2915
2	100%	100%	0.9354	0.0009	0.2136	0.9339	0.0005	0.2922
3	100%	70%	0.9362	0.0008	0.2139	0.9339	0.0006	0.2921
4	100%	50%	0.9352	0.0008	0.2144	0.9347	0.0004	0.2924
5	100%	20%	0.9372	0.0008	0.2138	0.9338	0.0005	0.2921
6	100%	10%	0.9380	0.0009	0.2140	0.9336	0.0005	0.2920
7	100%	5%	0.9351	0.0008	0.2142	0.9333	0.0006	0.2936
8	100%	0%	0.9342	0.0008	0.2136	0.9338	0.0005	0.2922
9	70%	0%	0.8337	0.0007	0.4115	0.8488	0.0004	0.6064
10	50%	0%	0.7426	0.0008	0.8958	0.7631	0.0004	1.4515
11	20%	0%	0.5606	0.0007	15.444	0.5797	0.0006	26.5
12	10%	0%	0.4834	0.0005	160.28	0.5139	0.0003	241
13	5%	0%	0.4432	0.0004	1133.9	0.4763	0.0003	1770
14	10%	100%	0.4793	0.0005	171.79	0.4946	0.0003	342

† For an infinite square array of casks with 60 cm spacing between cask surfaces.

†† Maximum k_{eff} includes the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.2

REACTIVITY EFFECTS OF SPACING AND WATER MODERATOR DENSITY FOR SQUARE ARRAYS OF MPC-24 CASKS
(17x17A01 @ 4.0% E)

	Cask-to-Cask External Spacing (cm)				
External Moderator Density (%)	2	10	20	40	60
5	0.9352	0.9389	0.9356	0.9345	0.9351
10	0.9366	0.9353	0.9338	0.9357	0.9380
20	0.9368	0.9371	0.9359	0.9366	0.9372
50	0.9363	0.9363	0.9371	0.9352	0.9352
100	0.9355	0.9369	0.9354	0.9354	0.9354

Note:

1. All values are maximum k_{eff} which include the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.
2. The standard deviation (σ) of the calculations ranges between 0.0007 and 0.0010.

Table 6.4.3

REACTIVITY EFFECTS OF SPACING AND WATER MODERATOR DENSITY FOR HEXAGONAL (TRIANGULAR-PITCHED) ARRAYS OF MPC-24 CASKS (17x17A01 @ 4.0% E)

	Cask-to-Cask External Spacing (cm)				
External Moderator Density (%)	2	10	20	40	60
5	0.9358	0.9365	0.9369	0.9354	0.9354
10	0.9363	0.9372	0.9351	0.9368	0.9372
20	0.9354	0.9357	0.9345	0.9358	0.9381
50	0.9347	0.9361	0.9371	0.9365	0.9370
100	0.9373	0.9381	0.9354	0.9354	0.9354

Note:

1. All values are maximum k_{eff} which include the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.
2. The standard deviation (σ) of the calculations ranges between 0.0007 and 0.0009.

Table 6.4.4

REACTIVITY EFFECTS OF SPACING AND EXTERNAL MODERATOR DENSITY FOR HEXAGONAL (TRIANGULAR-PITCHED) ARRAYS OF MPC-24 CASKS (17x17A01 @ 4.0% E) INTERNALLY FLOODED WITH WATER OF 10% FULL DENSITY

	Cask-to-Cask External Spacing (cm)				
External Moderator Density (%)	2	10	20	40	60
10	0.4818	0.4808	0.4798	0.4795	0.4789
100	0.4798	0.4788	0.4781	0.4793	0.4793

Note:

1. All values are maximum k_{eff} which include the bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.
2. The standard deviation (σ) of the calculations ranges between 0.0004 and 0.0005.

Table 6.4.5

CALCULATIONS FOR HEXAGONAL (TRIANGULAR-PITCHED) ARRAYS OF TOUCHING CASKS WITH MPC-24 AND MPC-68

MPC-24 (17x17A01 @ 4.0% ENRICHMENT)		
Internal Moderation (%)	External Moderation (%)	Maximum k_{eff}
0	0	0.3910
0	100	0.3767
100	0	0.9366
100	100	0.9341
MPC-68 (8x8C04 @ 4.2% ENRICHMENT)		
Internal Moderation (%)	External Moderation (%)	Maximum k_{eff}
0	0	0.4036
0	100	0.3716
100	0	0.9351
100	100	0.9340

Note:

1. All values are maximum k_{eff} which include bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.
2. The standard deviation (σ) of the calculations ranges between 0.0007 and 0.0008 for 100% internal moderation, and between 0.0002 and 0.0003 for 0% internal moderation.

Table 6.4.6

REACTIVITY EFFECTS OF PARTIAL CASK FLOODING FOR MPC-24 AND MPC-68

MPC-24 (17x17A01 @ 4.0% ENRICHMENT)			
Flooded Condition (% Full)	Vertical Orientation	Flooded Condition (% Full)	Horizontal Orientation
25	0.9157	25	0.8766
50	0.9305	50	0.9240
75	0.9330	75	0.9329
100	0.9368	100	0.9368
MPC-68 (8x8C04 @ 4.2% ENRICHMENT)			
Flooded Condition (% Full)	Vertical Orientation	Flooded Condition (% Full)	Horizontal Orientation
25	0.9132	23.5	0.8586
50	0.9307	50	0.9088
75	0.9312	76.5	0.9275
100	0.9348	100	0.9348

Notes:

1. All values are maximum k_{eff} which include bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.
2. The standard deviation (σ) of the calculations ranges between 0.0007 and 0.0010.

Table 6.4.7

REACTIVITY EFFECT OF FLOODING THE PELLET-TO-CLAD GAP FOR MPC-24 AND MPC-68

Pellet-to-Clad Condition	MPC-24 17x17A01 4.0% Enrichment	MPC-68 8x8C04 4.2% Enrichment
dry	0.9295	0.9279
flooded	0.9368	0.9348

Notes:

1. All values are maximum k_{eff} which includes bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.
2. The standard deviation (σ) of the calculations ranges between 0.0007 and 0.0010.

Table 6.4.8

MAXIMUM k_{eff} VALUES† IN THE DAMAGED FUEL CONTAINER

Condition	MCNP4a Results					
	DFC Dimensions: ID 4.93" THK. 0.12"			DFC Dimensions: ID 4.81" THK. 0.11"		
	Max.†† k_{eff}	1 σ	EALF (eV)	Max.†† k_{eff}	1 σ	EALF (eV)
<u>6x6 Fuel Assembly</u>						
6x6 Intact Fuel	0.7086	0.0007	0.3474	0.7016	0.0006	0.3521
w/32 Rods Standing	0.7183	0.0008	0.2570	0.7117	0.0007	0.2593
w/28 Rods Standing	0.7315	0.0007	0.1887	0.7241	0.0006	0.1909
w/24 Rods Standing	0.7086	0.0007	0.1568	0.7010	0.0008	0.1601
w/18 Rods Standing	0.6524	0.0006	0.1277	0.6453	0.0007	0.1288
Collapsed to 8x8 array	0.7845	0.0007	1.1550	0.7857	0.0007	1.1162
Dispersed Powder	0.7628	0.0007	0.0926	0.7440	0.0007	0.0902
<u>7x7 Fuel Assembly</u>						
7x7 Intact Fuel	0.7463	0.0007	0.2492	0.7393	0.0006	0.2504
w/41 Rods Standing	0.7529	0.0007	0.1733	0.7481	0.0007	0.1735
w/36 Rods Standing	0.7487	0.0007	0.1389	0.7444	0.0006	0.1406
w/25 Rods Standing	0.6718	0.0007	0.1070	0.6644	0.0007	0.1082

† These calculations were performed with a planar-average enrichment of 3.0% and a ^{10}B loading of 0.0067 g/cm^2, which is 75% of a minimum ^{10}B loading of 0.0089 g/cm^2. The minimum ^{10}B loading in the MPC-68F is 0.010 g/cm^2. Therefore, the listed maximum k_{eff} values are conservative.

†† Maximum k_{eff} includes bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.9

DELETED

Table 6.4.10

REACTIVITY EFFECT OF PREFERENTIAL FLOODING OF THE DFCs

DFC Configuration	Preferential Flooding	Fully Flooded
MPC-68 or MPC-68F with 68 DFCs (Assembly Classes 6x6A/B/C, 7x7A and 8x8A)	0.6560	0.7857
MPC-24E or MPC-24EF with 4 DFCs (Bounding All PWR Assembly Classes)	0.7895	0.9480

Notes:

1. All values are maximum k_{eff} which includes bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.11

MAXIMUM k_{eff} VALUES IN THE GENERIC PWR DAMAGED FUEL CONTAINER FOR A MAXIMUM INITIAL ENRICHMENT OF 4.0 wt% ^{235}U.

Model Configuration inside the DFC	Maximum k_{eff}
Intact Assemblies (2 assemblies analyzed)	0.9340
Assemblies with missing rods (4 configurations analyzed)	0.9350
Collapsed Assemblies (6 configurations analyzed)	0.9360
Regular Arrays of Bare Fuel Rods (36 configurations analyzed)	0.9480

Notes:

1. All values are maximum k_{eff} which includes bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.
2. The standard deviation (σ) of the calculations ranges between 0.0007 and 0.0010.

Table 6.4.12
SUMMARY OF THE CRITICALITY RESULTS FOR THE MOST REACTIVE ASSEMBLY FROM THE MOST REACTIVE ASSEMBLY CLASS IN EACH MPC-24 TO DEMONSTRATE COMPLIANCE WITH 10CFR71.55 AND 10CFR71.59

MPC-24, Assembly Class 15x15F, 4.1 wt% ^{235}U					
Configuration	% Internal Moderation	% External Moderation	Max.‡ k_{eff}	1 σ	EALF (eV)
Single Package, unreflected	100%	0%	0.9410	0.0007	0.2998
Single Package, fully reflected	100%	100%	0.9397	0.0008	0.3016
Containment, fully reflected	100%	100%	0.9397	0.0008	0.3006
Infinite Array of Damaged Packages	100%	100%	0.9436	0.0009	0.2998
Infinite Array of Undamaged Packages	0%	0%	0.3950	0.0004	82612.0
MPC-68, Assembly Class 9x9E/F, 4.0 wt% ^{235}U					
Configuration	% Internal Moderation	% External Moderation	Max. k_{eff}	1 σ	EALF (eV)
Single Package, unreflected	100%	0%	0.9486	0.0008	0.2095
Single Package, fully reflected	100%	100%	0.9470	0.0008	0.2079
Containment, fully reflected	100%	100%	0.9461	0.0007	0.2092
Infinite Array of Damaged Packages	100%	100%	0.9468	0.0008	0.2106
Infinite Array of Undamaged Packages	0%	0%	0.3808	0.0003	85218.0
MPC-68F, Assembly Class 6x6C, 2.7 wt% ^{235}U					
Configuration	% Internal Moderation	% External Moderation	Max. k_{eff}	1 σ	EALF (eV)
Single Package, unreflected	100%	0%	0.8021	0.0007	0.2139
Single Package, fully reflected	100%	100%	0.8033	0.0008	0.2142
Containment, fully reflected	100%	100%	0.8033	0.0008	0.2138
Infinite Array of Damaged Packages	100%	100%	0.8026	0.0008	0.2142
Infinite Array of Undamaged Packages	0%	0%	0.3034	0.0002	99463.0

‡ The maximum k_{eff} is equal to the sum of the calculated k_{eff}, two standard deviations, the code bias, and the uncertainty in the code bias.

Table 6.4.12 (continued)
SUMMARY OF THE CRITICALITY RESULTS FOR THE MOST REACTIVE ASSEMBLY FROM THE MOST REACTIVE ASSEMBLY CLASS IN EACH MPC-24
TO DEMONSTRATE COMPLIANCE WITH 10CFR71.55 AND 10CFR71.59

MPC-24E/EF, Assembly Class 15x15F, 4.5 wt% ^{235}U					
Configuration	% Internal Moderation	% External Moderation	Max.‡ k_{eff}	1 σ	EALF (eV)
Single Package, unreflected	100%	0%	0.9495	0.0008	0.3351
Single Package, fully reflected	100%	100%	0.9485	0.0008	0.3313
Containment, fully reflected	100%	100%	0.9486	0.0008	0.3362
Infinite Array of Damaged Packages	100%	100%	0.9495	0.0008	0.3335
Infinite Array of Undamaged Packages	0%	0%	0.4026	0.0004	87546.0
MPC-24E/EF TROJAN, Trojan Intact and Damaged Fuel, 3.7 wt% ^{235}U					
Configuration	% Internal Moderation	% External Moderation	Max. k_{eff}	1 σ	EALF (eV)
Single Package, unreflected	100%	0%	0.9377	0.0008	n/c†
Single Package, fully reflected	100%	100%	0.9366	0.0008	n/c
Containment, fully reflected	100%	100%	0.9377	0.0008	n/c
Infinite Array of Damaged Packages	100%	100%	0.9383	0.0007	n/c
Infinite Array of Undamaged Packages	0%	0%	0.3518	0.0003	n/c
MPC-32, Assembly Class 15x15F, 4.0 wt% ^{235}U					
Configuration	% Internal Moderation	% External Moderation	Max. k_{eff}	1 σ	EALF (eV)
Single Package, unreflected	100%	0%	later	later	later
Single Package, fully reflected	100%	100%	later	later	later
Containment, fully reflected	100%	100%	later	later	later
Infinite Array of Damaged Packages	100%	100%	later	later	later
Infinite Array of Undamaged Packages	0%	0%	later	later	later

‡ The maximum k_{eff} is equal to the sum of the calculated k_{eff}, two standard deviations, the code bias, and the uncertainty in the code bias.
† n/c = not calculated

Table 6.4.13

RESULTS FOR EACH ASSEMBLY CLASS IN THE MPC-24

Fuel Assembly Class	Maximum Allowable Enrichment (wt% ^{235}U)	Max.† k_{eff}	1 σ	EALF (eV)
14x14A	4.6	0.9296	0.0008	0.2093
14x14B	4.6	0.9228	0.0008	0.2675
14x14C	4.6	0.9307	0.0008	0.3001
14x14D	4.0	0.8507	0.0008	0.3308
14x14E	5.0	0.7627	0.0007	0.3607
15x15A	4.1	0.9227	0.0007	0.2708
15x15B	4.1	0.9388	0.0009	0.2626
15x15C	4.1	0.9361	0.0009	0.2385
15x15D	4.1	0.9367	0.0008	0.2802
15x15E	4.1	0.9392	0.0008	0.2908
15x15F	4.1	0.9410	0.0007	0.2998
15x15G	4.0	0.8907	0.0008	0.3456
15x15H	3.8	0.9337	0.0009	0.2349
16x16A	4.6	0.9287	0.0008	0.2704
17x17A	4.0	0.9368	0.0008	0.2131
17x17B	4.0	0.9355	0.0008	0.2659
17x17C	4.0	0.9349	0.0009	0.2677

† The term "maximum k_{eff} " as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.14

RESULTS FOR EACH ASSEMBLY CLASS IN THE MPC-68

Fuel Assembly Class	Maximum Allowable Enrichment (wt% ^{235}U)	Max.† k_{eff}	1 σ	EALF (eV)
7x7B	4.2	0.9386	0.0007	0.3983
8x8B	4.2	0.9416	0.0007	0.3293
8x8C	4.2	0.9425	0.0007	0.3081
8x8D	4.2	0.9403	0.0006	0.2778
8x8E	4.2	0.9312	0.0008	0.2831
8x8F	4.0	0.9459	0.0007	0.2361
9x9A	4.2	0.9417	0.0008	0.2236
9x9B	4.2	0.9436	0.0008	0.2506
9x9C	4.2	0.9395	0.0008	0.2698
9x9D	4.2	0.9394	0.0009	0.2625
9x9E	4.0	0.9486	0.0008	0.2095
9x9F	4.0	0.9486	0.0008	0.2095
9x9G	4.2	0.9383	0.0008	0.2292
10x10A	4.2	0.9457	0.0008	0.2212
10x10B	4.2	0.9436	0.0007	0.2366
10x10C	4.2	0.9433	0.0007	0.2416
10x10D	4.0	0.9376	0.0008	0.3355
10x10E	4.0	0.9185	0.0007	0.2936

† The term "maximum k_{eff} " as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.15

RESULTS FOR EACH ASSEMBLY CLASS IN THE MPC-68F

Fuel Assembly Class	Maximum Allowable Enrichment (wt% ^{235}U)	Max.† k_{eff}	1 σ	EALF (eV)
6x6A	2.7††	0.7888	0.0007	0.2310
6x6B†††	2.7	0.7824	0.0006	0.2184
6x6C	2.7	0.8021	0.0007	0.2139
7x7A	2.7	0.7974	0.0008	0.2015
8x8A	2.7	0.7697	0.0007	0.2158

† The term "maximum k_{eff} " as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

†† These calculations were performed for 3.0% planar-average enrichment, however, the authorized contents are limited to a maximum planar-average enrichment of 2.7%. Therefore, the listed maximum k_{eff} values are conservative.

††† Assemblies in this class contain both MOX and UO_2 pins. The composition of the MOX fuel pins is given in Table 6.3.4. The maximum allowable planar-average enrichment for the MOX pins is given in the specification of authorized contents, Chapter 1.

Table 6.4.16

RESULTS FOR EACH ASSEMBLY CLASS IN THE MPC-24E/EF

Fuel Assembly Class	Maximum Allowable Enrichment (wt% ^{235}U)	Max.† k_{eff}	1 σ	EALF (eV)
14x14A	5.0	0.9380	0.0008	0.2277
14x14B	5.0	0.9312	0.0008	0.2927
14x14C	5.0	0.9365	0.0008	0.3318
14x14D	5.0	0.8875	0.0009	0.4026
14x14E	5.0	0.7651	0.0007	0.3644
15x15A	4.5	0.9336	0.0008	0.2879
15x15B	4.5	0.9487	0.0009	0.3002
15x15C	4.5	0.9462	0.0008	0.2631
15x15D	4.5	0.9445	0.0008	0.3375
15x15E	4.5	0.9471	0.0008	0.3242
15x15F	4.5	0.9495	0.0008	0.3351
15x15G	4.5	0.9062	0.0008	0.3883
15x15H	4.2	0.9455	0.0009	0.2663
16x16A	5.0	0.9358	0.0008	0.3150
17x17A	4.4	0.9447	0.0007	0.2374
17x17B	4.4	0.9438	0.0008	0.2951
17x17C	4.4	0.9433	0.0008	0.2932

Table 6.4.17

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

RESULTS FOR THE MPC-24E/EF TROJAN

Fuel Assembly Class	Maximum Allowable Enrichment (wt% ^{235}U)	Content	Max.† k_{eff}	1 σ	EALF (eV)
17x17B	3.7	Intact Fuel	0.9187	0.0009	not calculated
17x17B	3.7	Intact Fuel, Damaged Fuel and Fuel Debris	0.9377	0.0008	not calculated

† The term "maximum k_{eff}" as used here, and elsewhere in this document, means the highest possible k-effective, including bias, uncertainties, and calculational statistics, evaluated for the worst case combination of manufacturing tolerances.

Table 6.4.18

RESULTS FOR THE MPC-24E/EF TROJAN USING A FUEL FRAGMENT MODEL FOR DAMAGED FUEL AND FUEL DEBRIS

Fuel Cube OD (Inches)	Maximum k_{eff}			
	Fuel Volume / Water Volume			
	0.2	0.4	0.6	0.8
1	0.9098	0.9223	0.9260	0.9204
0.5	0.9156	0.9310	0.9273	0.9168
0.2	0.9254	0.9320	0.9216	0.9137
0.1	0.9253	0.9274	0.9183	0.9135
0.05	0.9224	0.9228	0.9168	0.9126
0.02	0.9183	0.9213	0.9140	0.9122

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

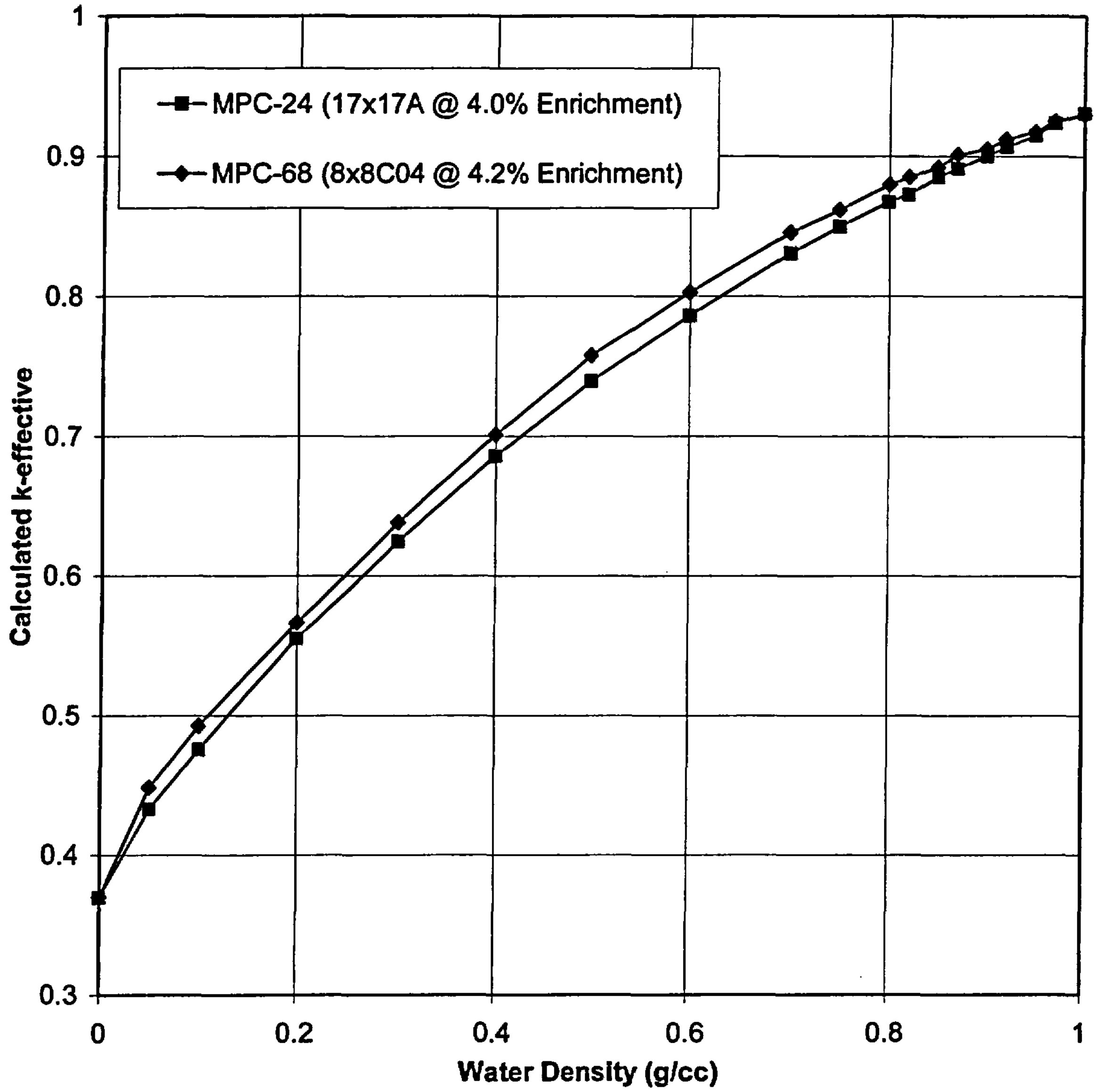

FIGURE 6.4.9; CALCULATED K-EFFECTIVE AS A FUNCTION OF INTERNAL MODERATOR DENSITY

FIGURE WITHHELD UNDER 10 CFR 2.390

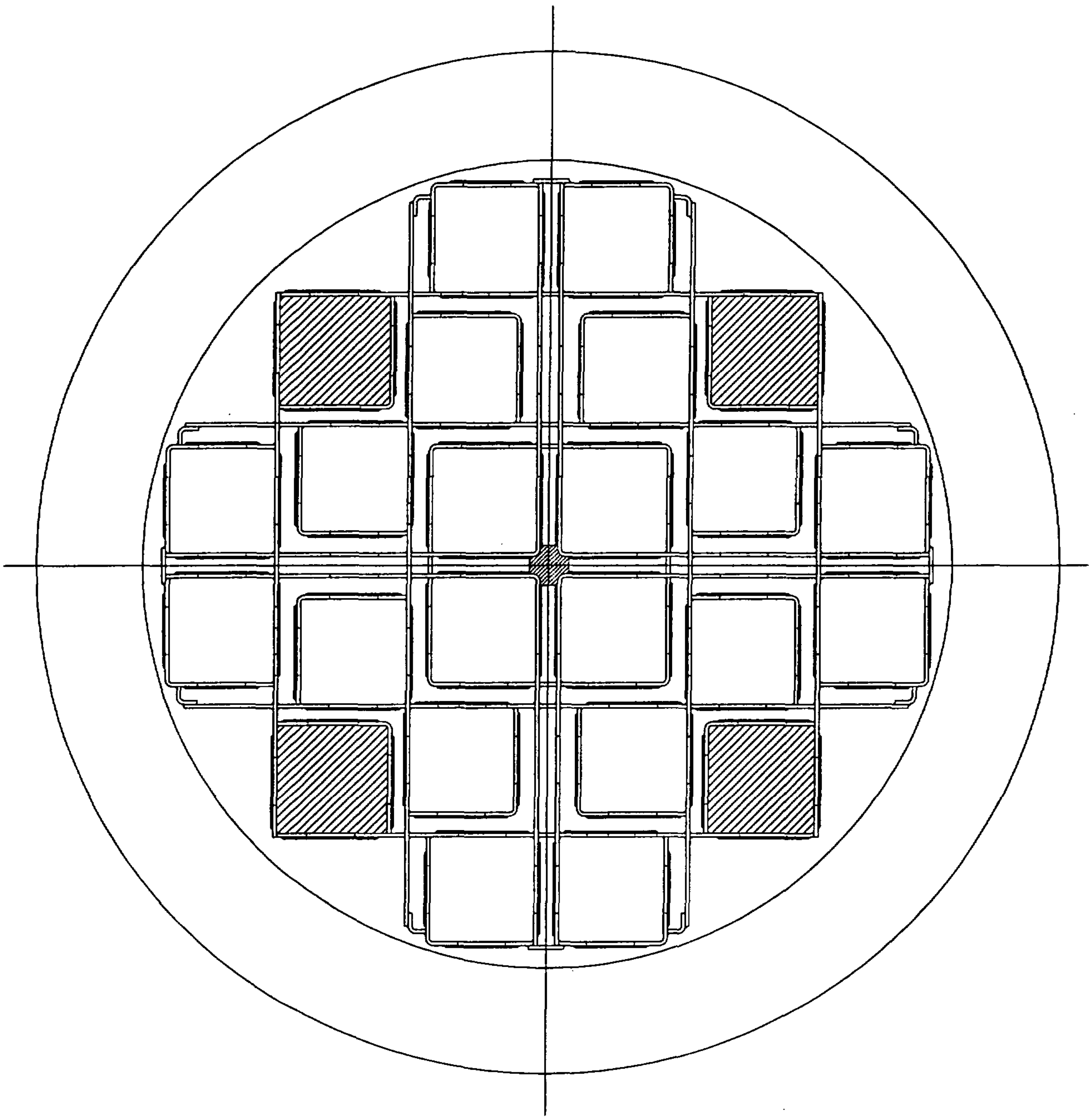

FIGURE 6.4.11: LOCATIONS OF THE DAMAGED FUEL CONTAINERS IN THE MPC-24E/EF

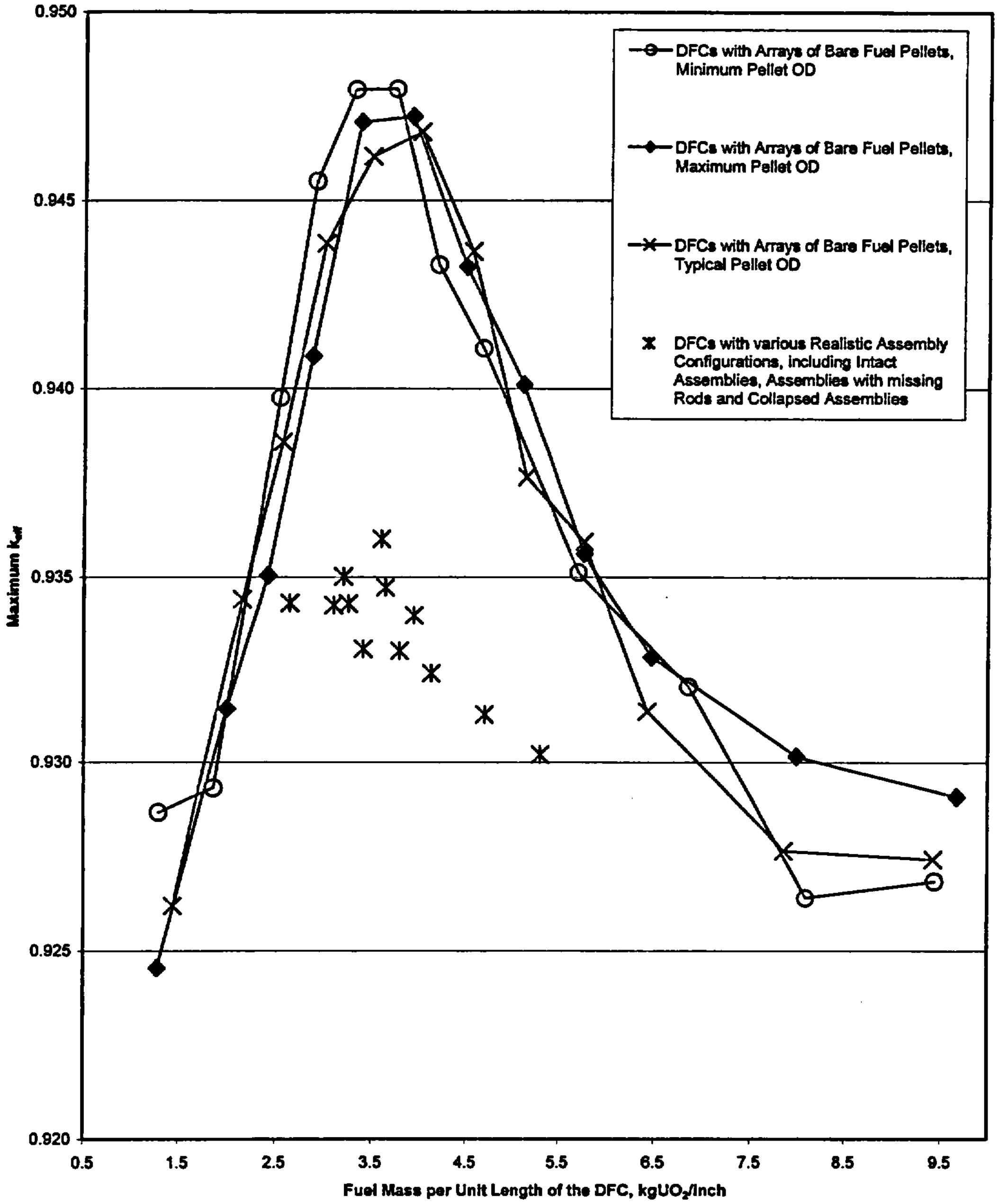

FIGURE 6.4.12: MAXIMUM K_{EFF} FOR THE MPC-24E/EF WITH GENERIC PWR DAMAGED FUEL CONTAINER, INITIAL ENRICHMENT OF 4.0 WT% FOR DAMAGED AND INTACT FUEL.

6.5 CRITICALITY BENCHMARK EXPERIMENTS

Benchmark calculations have been made on selected critical experiments, chosen, insofar as possible, to bound the range of variables in the cask designs. The most important parameters are (1) the enrichment, (2) the water-gap size (MPC-24) or cell spacing (MPC-68), and (3) the ^{10}B loading of the neutron absorber panels. Other parameters, within the normal range of cask and fuel designs, have a smaller effect, but are also included. No significant trends were evident in the benchmark calculations or the derived bias. Detailed benchmark calculations are presented in Appendix 6.A.

The benchmark calculations were performed with the same computer codes and cross-section data, described in Section 6.4, that were used to calculate the k_{eff} values for the cask. Further, all calculations were performed on the same computer hardware, specifically, personal computers using the pentium processor.

Additional benchmark calculations performed for the burnup methodology for the MPC-32 are presented in Appendix 6.E.

6.6 REGULATORY COMPLIANCE

This chapter documents the criticality evaluation of the HI-STAR 100 System for the packaging and transportation of radioactive materials (spent nuclear fuel). This evaluation demonstrates that the HI-STAR 100 System is in full compliance with the criticality safety requirements of 10CFR71.

The criticality design is based on favorable geometry, fixed neutron poisons (Boral), and an administrative limit on the maximum allowable enrichment and the minimum allowable burnup in the MPC-32. The HI-STAR 100 System design structures and components important to criticality safety are described in sufficient detail in this chapter to identify the package accurately and provide a sufficient basis for the evaluation of the package, including the maximum allowable enrichments and minimum allowable burnups.

The HI-STAR 100 System is designed to be subcritical under both normal and hypothetical accident conditions of transport. The evaluations presented in the chapter address the criticality safety requirements of 10CFR71 and demonstrate that a single HI-STAR 100 System remains subcritical under the most reactive normal and hypothetical accident conditions of transport and that the most reactive infinite array of HI-STAR 100 Systems is subcritical under both normal and hypothetical accident conditions of transport. This corresponds to a transport index of zero (0) and demonstrates compliance with 10CFR71 criticality requirements.

Therefore, it is concluded that the criticality design features for the HI-STAR 100 System are in compliance with 10CFR71 and that the applicable design and acceptance criteria have been satisfied. This criticality evaluation provides reasonable assurance that the HI-STAR 100 System will allow safe transport of spent fuel.

6.7 REFERENCES

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APPENDIX 6.A: BENCHMARK CALCULATIONS

6.A.1 INTRODUCTION AND SUMMARY

Benchmark calculations have been made on selected critical experiments, chosen, in so far as possible, to bound the range of variables in the cask designs. Two independent methods of analysis were used, differing in cross section libraries and in the treatment of the cross sections. MCNP4a [6.A.1] is a continuous energy Monte Carlo code and KENO5a [6.A.2] uses group-dependent cross sections. For the KENO5a analyses reported here, the 238-group library was chosen, processed through the NITAWL-II [6.A.2] program to create a working library and to account for resonance self-shielding in uranium-238 (Nordheim integral treatment). The 238 group library was chosen to avoid or minimize the errors† (trends) that have been reported (e.g., [6.A.3 through 6.A.5]) for calculations with collapsed cross section sets.

The results of the benchmark calculations presented herein are separated into two parts. The first part (Sections 6.A.1 through 6.A.5) presents the calculational bias for fresh fuel calculations and encompasses the benchmark critical experiments numbered 1 through 62 in Table 6.A.1. The second part (Section 6.A.6) presents the calculational bias for burnup credit and encompasses all of the benchmark critical experiments presented in Table 6.A.1.

In cask designs, the three most significant parameters affecting criticality are (1) the fuel enrichment, (2) the ^{10}B loading in the neutron absorber, and (3) the lattice spacing (or water-gap thickness if a flux-trap design is used). Other parameters, within the normal range of cask and fuel designs, have a smaller effect, but are also included in the analyses.

Table 6.A.1 summarizes results of the benchmark calculations for all cases selected and analyzed, as referenced in the table. The effect of the major variables are discussed in subsequent sections below. It is important to note that there is obviously considerable overlap in parameters since it is not possible to vary a single parameter and maintain criticality; some other parameter or parameters must be concurrently varied to maintain criticality.

One possible way of representing the data is through a spectrum index that incorporates all of the variations in parameters. KENO5a computes and prints the "energy of the average lethargy causing fission". In MCNP4a, by utilizing the tally option with the identical 238-group energy structure as in KENO5a, the number of fissions in each group may be collected and the energy of the average lethargy causing fission determined (post-processing).

Figures 6.A.1 and 6.A.2 show the calculated k_{eff} for the benchmark critical experiments as a function of the "energy of the average lethargy causing fission" for MCNP4a and KENO5a, respectively (UO_2 fuel only). The scatter in the data (even for comparatively minor variation in

† Small but observable trends (errors) have been reported for calculations with the 27-group and 44-group collapsed libraries. These errors are probably due to the use of a single collapsing spectrum when the spectrum should be different for the various cases analyzed, as evidenced by the spectrum indices.

critical parameters) represents experimental error[††] in performing the critical experiments within each laboratory, as well as between the various testing laboratories. The B&W critical experiments show a larger experimental error than the PNL criticals. This would be expected since the B&W criticals encompass a greater range of critical parameters than the PNL criticals.

Linear regression analysis of the data in Figures 6.A.1 and 6.A.2 show that there are no trends, as evidenced by very low values of the correlation coefficient (0.13 for MCNP4a and 0.21 for KENO5a). The total bias (systematic error, or mean of the deviation from a k_{eff} of exactly 1.000) for the two methods of analysis are shown in the table below.

Calculational Bias of MCNP4a and KENO5a		
	Total	Truncated
MCNP4a	0.0009 ± 0.0011	0.0021 ± 0.0007
KENO5a	0.0030 ± 0.0012	0.0036 ± 0.0009

The values of bias shown in this table include both the bias derived directly from the calculated k_{eff} values in Table 6.A.1, and a more conservative value derived by arbitrarily truncating to 1.000 any calculated value that exceeds 1.000. The bias and standard error of the bias were calculated by the following equations[†], with the standard error multiplied by the one-sided K-factor for 95% probability at the 95% confidence level from NBS Handbook 91 [6.A.18] (for the number of cases analyzed, the K-factor is ~2.05 or slightly more than 2).

$$\bar{k} = \frac{1}{n}\sum_{i=1}^{n} k_i \qquad (6.A.1)$$

$$\sigma_{\bar{k}}^2 = \frac{\sum_{i=1}^{n} k_i^2 - (\sum_{i=1}^{n} k_i)^2 / n}{n(n-1)} \qquad (6.A.2)$$

$$\text{Bias} = (1 - \bar{k}) \pm K\sigma_{\bar{k}} \qquad (6.A.3)$$

where k_i are the calculated reactivities for n critical experiments; $\sigma_{\bar{k}}$ is the unbiased estimator of the standard deviation of the mean (also called the standard error of the bias (mean)); and K is the one-sided multiplier for 95% probability at the 95% confidence level (NBS Handbook 91 [6.A.18]).

[††] A classical example of experimental error is the corrected enrichment in the PNL experiments, first as an addendum to the initial report and, secondly, by revised values in subsequent reports for the same fuel rods.

[†]These equations may be found in any standard text on statistics, for example, reference [6.A.6] (or the MCNP4a manual) and is the same methodology used in MCNP4a and in KENO5a.

Formula 6.A.3 is based on the methodology of the National Bureau of Standards (now NIST) and is used to calculate the values presented on page 6.A-2. The first portion of the equation, (1-$\bar{k}$), is the actual bias which is added to the MCNP4a and KENO5a results. The second term, $K\sigma_{\bar{k}}$, which corresponds to σ_B in Section 6.4.3, is the uncertainty or standard error associated with the bias. The K values used were obtained from the National Bureau of Standards Handbook 91 and are for one-sided statistical tolerance limits for 95% probability at the 95% confidence level. The actual K values for the 56 critical experiments evaluated with MCNP4a and the 53 critical experiments evaluated with KENO5a are 2.04 and 2.05, respectively.

The larger of the calculational biases (truncated bias) was used to evaluate the maximum k_{eff} values for the cask designs.

6.A.2 Effect of Enrichment

The benchmark critical experiments include those with enrichments ranging from 2.46% to 5.74% and therefore span the enrichment range for the MPC designs. Figures 6.A.3 and 6.A.4 show the calculated k_{eff} values (Table 6.A.1) as a function of the fuel enrichment reported for the critical experiments. Linear regression analyses for these data confirms that there are no trends, as indicated by low values of the correlation coefficients (0.08 for MCNP4a and 0.37 for KENO5a). Thus, there are no corrections to the bias for the various enrichments.

As further confirmation of the absence of any trends with enrichment, the MPC-68 configuration was calculated with both MCNP4a and KENO5a for various enrichments. The cross-comparison of calculations with codes of comparable sophistication is suggested in Reg. Guide 3.41. Results of this comparison, shown in Table 6.A.2 and Figure 6.A.5, confirm no significant difference in the calculated values of k_{eff} for the two independent codes as evidenced by the 45° slope of the curve. Since it is very unlikely that two independent methods of analysis would be subject to the same error, this comparison is considered confirmation of the absence of an enrichment effect (trend) in the bias.

6.A.3 Effect of ^{10}B Loading

Several laboratories have performed critical experiments with a variety of thin absorber panels similar to the Boral panels in the cask designs. Of these critical experiments, those performed by B&W are the most representative of the cask designs. PNL has also made some measurements with absorber plates, but, with one exception (a flux-trap experiment), the reactivity worth of the absorbers in the PNL tests is very low and any significant errors that might exist in the treatment of strong thin absorbers could not be revealed.

Table 6.A.3 lists the subset of experiments using thin neutron absorbers (from Table 6.A.1) and shows the reactivity worth (Δk) of the absorber.†

†The reactivity worth of the absorber panels was determined by repeating the calculation with the absorber analytically removed and calculating the incremental (Δk) change in reactivity due to the absorber.

No trends with reactivity worth of the absorber are evident, although based on the calculations shown in Table 6.A.3, some of the B&W critical experiments seem to have unusually large experimental errors. B&W made an effort to report some of their experimental errors. Other laboratories did not evaluate their experimental errors.

To further confirm the absence of a significant trend with ^{10}B concentration in the absorber, a cross-comparison was made with MCNP4a and KENO5a (as suggested in Reg. Guide 3.41). Results are shown in Figure 6.A.6 and Table 6.A.4 for the MPC-68 cask[††] geometry. These data substantiate the absence of any error (trend) in either of the two codes for the conditions analyzed (data points fall on a 45° line, within an expected 95% probability limit).

6.A.4 Miscellaneous and Minor Parameters

6.A.4.1 Reflector Material and Spacings

PNL has performed a number of critical experiments with thick steel and lead reflectors.[†] Analysis of these critical experiments are listed in Table 6.A.5 (subset of data in Table 6.A.1). There appears to be a small tendency toward overprediction of k_{eff} at the lower spacing, although there are an insufficient number of data points in each series to allow a quantitative determination of any trends. The tendency toward overprediction at close spacing means that the cask calculations may be slightly more conservative than otherwise.

6.A.4.2 Fuel Pellet Diameter and Lattice Pitch

The critical experiments selected for analysis cover a range of fuel pellet diameters from 0.311 to 0.444 inches, and lattice spacings from 0.476 to 1.00 inches. In the cask designs, the fuel pellet diameters range from 0.303 to 0.3835 inches O.D. (0.496 to 0.580 inch lattice spacing) for PWR fuel and from 0.3224 to 0.498 inches O.D. (0.488 to 0.740 inch lattice spacing) for BWR fuel. Thus, the critical experiments analyzed provide a reasonable representation of the fuel in the MPC designs. Based on the data in Table 6.A.1, there does not appear to be any observable trend with either fuel pellet diameter or lattice pitch, at least over the range of the critical experiments or the cask designs.

6.A.4.3 Soluble Boron Concentration Effects

Various soluble boron concentrations were used in the B&W series of critical experiments and in one PNL experiment, with boron concentrations ranging up to 2550 ppm. Results of MCNP4a (and one KENO5a) calculations are shown in Table 6.A.6. Analyses of the very high boron

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[††]The MPC-68 geometry was chosen for this comparison since it contains the greater number of Boral panels and would therefore be expected to be the most sensitive to trends (errors) in calculations.

[†]Parallel experiments with a depleted uranium reflector were also performed but not included in the present analysis since they are not pertinent to the Holtec cask design. A lead reflector is also not directly pertinent, but might be used in future designs.

concentration experiments (>1300 ppm) show a tendency to slightly overpredict reactivity for the three experiments exceeding 1300 ppm.

6.A.5 MOX Fuel Critical Experiments

The number of critical experiments with PuO_2 bearing fuel (MOX) is more limited than for UO_2 fuel. However, a number of MOX critical experiments have been analyzed and the results are shown in Table 6.A.7. Results of these analyses are generally above a k_{eff} of 1.00, indicating that when Pu is present, MCNP4a and KENO5a overpredict the reactivity.

This may indicate that calculation of k_{eff} for MOX fuel will be expected to be conservative, especially with MCNP4a. It may be noted that for the larger lattice spacings, the KENO5a calculated reactivities are below 1.00, suggested that a small trend may exist with KENO5a. It is also possible that the overprediction in k_{eff} in both codes may be due to a small inadequacy in the determination of the Pu-241 decay and Am-241 growth. This possibility is supported by the consistency in calculated k_{eff} over a wide range of the spectral index (energy of the average lethargy causing fission).

6.A.6 Burnup Credit Benchmark Experiments

The use of burnup credit in a spent fuel transportation cask license requires benchmarking of the appropriate codes to spent fuel critical experiments. However, spent fuel critical experiments are not available, therefore benchmarking with an extended set of mixed oxide fuel critical experiments is performed. Thirty-nine MOX fuel critical experiments (31 from reference [6.A.21] and eight additional MOX critical experiments from Section 6.A.5) have been selected for validating MCNP4a for burnup credit. The total bias (systematic error, or mean of the deviation from a k_{eff} of exactly 1.000) for MCNP4a for the entire set of 87 critical experiments identified in Table 6.A.1 is shown in the table below.

Calculational Bias of MCNP4a and KENO5a		
	Total	Truncated
MCNP4a	-0.0006 ± 0.0009	0.0015 ± 0.0005

The values of bias shown in this table include both the bias derived directly from the calculated k_{eff} values in Table 6.A.1, and a more conservative value derived by arbitrarily truncating to 1.000 any calculated value that exceeds 1.000. The bias and standard error of the bias were calculated with the equations in Section 6.A.1, with the standard error multiplied by the one-sided K-factor for 95% probability at the 95% confidence level from NBS Handbook 91 [6.A.18] (for the number of cases analyzed, the K-factor is ~1.95 or slightly less than 2).

6.A.6.1 Effect of EALF

Figure 6.A.7 shows the MOX fuel calculated k_{eff} values as a function of the calculated EALF from MCNP4a during post-processing as described in Section 6.A.1. Linear regression analysis for this data confirms that the MCNP4a results do not exhibit any trends with respect to the

EALF as evidenced by the low value of the correlation coefficient (-0.34). Thus there is no correction to the bias as a function of the EALF.

6.A.6.2 Effect of Cladding OD

The MOX critical experiments selected for analysis cover a range of cladding outside diameters from 0.230 to 0.565 inches. In the Holtec cask designs, the allowable cladding outside diameters range from 0.342 to 0.440 inches O.D. for PWR fuel and from 0.378 to 0.563 inches O.D. for BWR and PWR fuel. Thus, the critical experiments analyzed provide a reasonable representation of the fuel in the MPC designs. Linear regression analysis for this data confirms that the MCNP4a results do not exhibit any trends with respect to the Cladding O.D. as evidenced by the low value of the correlation coefficient (-0.14). Thus there is no correction to the bias as a function of the Cladding O.D.

6.A.7 References

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Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
1	B&W-1484 (6.A.7)	Core I	2.46	0.9964 ± 0.0010	0.9898 ± 0.0006	0.1759	0.1753
2	B&W-1484 (6.A.7)	Core II	2.46	1.0008 ± 0.0011	1.0015 ± 0.0005	0.2553	0.2446
3	B&W-1484 (6.A.7)	Core III	2.46	1.0010 ± 0.0012	1.0005 ± 0.0005	0.1999	0.1939
4	B&W-1484 (6.A.7)	Core IX	2.46	0.9956 ± 0.0012	0.9901 ± 0.0006	0.1422	0.1426
5	B&W-1484 (6.A.7)	Core X	2.46	0.9980 ± 0.0014	0.9922 ± 0.0006	0.1513	0.1499
6	B&W-1484 (6.A.7)	Core XI	2.46	0.9978 ± 0.0012	1.0005 ± 0.0005	0.2031	0.1947
7	B&W-1484 (6.A.7)	Core XII	2.46	0.9988 ± 0.0011	0.9978 ± 0.0006	0.1718	0.1662
8	B&W-1484 (6.A.7)	Core XIII	2.46	1.0020 ± 0.0010	0.9952 ± 0.0006	0.1988	0.1965
9	B&W-1484 (6.A.7)	Core XIV	2.46	0.9953 ± 0.0011	0.9928 ± 0.0006	0.2022	0.1986
10	B&W-1484 (6.A.7)	Core XV[††]	2.46	0.9910 ± 0.0011	0.9909 ± 0.0006	0.2092	0.2014
11	B&W-1484 (6.A.7)	Core XVI[††]	2.46	0.9935 ± 0.0010	0.9889 ± 0.0006	0.1757	0.1713
12	B&W-1484 (6.A.7)	Core XVII	2.46	0.9962 ± 0.0012	0.9942 ± 0.0005	0.2083	0.2021

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
13	B&W-1484 (6.A.7)	Core XVIII	2.46	1.0036 ± 0.0012	0.9931 ± 0.0006	0.1705	0.1708
14	B&W-1484 (6.A.7)	Core XIX	2.46	0.9961 ± 0.0012	0.9971 ± 0.0005	0.2103	0.2011
15	B&W-1484 (6.A.7)	Core XX	2.46	1.0008 ± 0.0011	0.9932 ± 0.0006	0.1724	0.1701
16	B&W-1484 (6.A.7)	Core XXI	2.46	0.9994 ± 0.0010	0.9918 ± 0.0006	0.1544	0.1536
17	B&W-1645 (6.A.8)	S-type Fuel, w/886 ppm B	2.46	0.9970 ± 0.0010	0.9924 ± 0.0006	1.4475	1.4680
18	B&W-1645 (6.A.8)	S-type Fuel, w/746 ppm B	2.46	0.9990 ± 0.0010	0.9913 ± 0.0006	1.5463	1.5660
19	B&W-1645 (6.A.8)	SO-type Fuel, w/1156 ppm B	2.46	0.9972 ± 0.0009	0.9949 ± 0.0005	0.4241	0.4331
20	B&W-1810 (6.A.9)	Case 1 1337 ppm B	2.46	1.0023 ± 0.0010	NC	0.1531	NC
21	B&W-1810 (6.A.9)	Case 12 1899 ppm B	2.46/4.02	1.0060 ± 0.0009	NC	0.4493	NC
22	French (6.A.10)	Water Moderator 0 gap	4.75	0.9966 ± 0.0013	NC	0.2172	NC
23	French (6.A.10)	Water Moderator 2.5 cm gap	4.75	0.9952 ± 0.0012	NC	0.1778	NC
24	French (6.A.10)	Water Moderator 5 cm gap	4.75	0.9943 ± 0.0010	NC	0.1677	NC

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
25	French (6.A.10)	Water Moderator 10 cm gap	4.75	0.9979 ± 0.0010	NC	0.1736	NC
26	PNL-3602 (6.A.11)	Steel Reflector, 0 cm separation	2.35	NC	1.0004 ± 0.0006	NC	0.1018
27	PNL-3602 (6.A.11)	Steel Reflector, 1.321 cm separation	2.35	0.9980 ± 0.0009	0.9992 ± 0.0006	0.1000	0.0909
28	PNL-3602 (6.A.11)	Steel Reflector, 2.616 cm separation	2.35	0.9968 ± 0.0009	0.9964 ± 0.0006	0.0981	0.0975
29	PNL-3602 (6.A.11)	Steel Reflector, 3.912 cm separation	2.35	0.9974 ± 0.0010	0.9980 ± 0.0006	0.0976	0.0970
30	PNL-3602 (6.A.11)	Steel Reflector, Infinite separation	2.35	0.9962 ± 0.0008	0.9939 ± 0.0006	0.0973	0.0968
31	PNL-3602 (6.A.11)	Steel Reflector, 0 cm separation	4.306	NC	1.0003 ± 0.0007	NC	0.3282
32	PNL-3602 (6.A.11)	Steel Reflector, 1.321 cm separation	4.306	0.9997 ± 0.0010	1.0012 ± 0.0007	0.3016	0.3039
33	PNL-3602 (6.A.11)	Steel Reflector, 2.616 cm separation	4.306	0.9994 ± 0.0012	0.9974 ± 0.0007	0.2911	0.2927
34	PNL-3602 (6.A.11)	Steel Reflector, 5.405 cm separation	4.306	0.9969 ± 0.0011	0.9951 ± 0.0007	0.2828	0.2860
35	PNL-3602 (6.A.11)	Steel Reflector, Infinite separation	4.306	0.9910 ± 0.0020	0.9947 ± 0.0007	0.2851	0.2864
36	PNL-3602 (6.A.11)	Steel Reflector, with Boral Sheets	4.306	0.9941 ± 0.0011	0.9970 ± 0.0007	0.3135	0.3150

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
37	PNL-3626 (6.A.12)	Lead Reflector, 0 cm sepn.	4.306	NC	1.0003 ± 0.0007	NC	0.3159
38	PNL-3626 (6.A.12)	Lead Reflector, 0.55 cm sepn.	4.306	1.0025 ± 0.0011	0.9997 ± 0.0007	0.3030	0.3044
39	PNL-3626 (6.A.12)	Lead Reflector, 1.956 cm sepn.	4.306	1.0000 ± 0.0012	0.9985 ± 0.0007	0.2883	0.2930
40	PNL-3626 (6.A.12)	Lead Reflector, 5.405 cm sepn.	4.306	0.9971 ± 0.0012	0.9946 ± 0.0007	0.2831	0.2854
41	PNL-2615 (6.A.13)	Experiment 004/032 – no absorber	4.306	0.9925 ± 0.0012	0.9950 ± 0.0007	0.1155	0.1159
42	PNL-2615 (6.A.13)	Experiment 030 – Zr plates	4.306	NC	0.9971 ± 0.0007	NC	0.1154
43	PNL-2615 (6.A.13)	Experiment 013 – Steel plates	4.306	NC	0.9965 ± 0.0007	NC	0.1164
44	PNL-2615 (6.A.13)	Experiment 014 – Steel plates	4.306	NC	0.9972 ± 0.0007	NC	0.1164
45	PNL-2615 (6.A.13)	Exp. 009 1.05% Boron Steel plates	4.306	0.9982 ± 0.0010	0.9981 ± 0.0007	0.1172	0.1162
46	PNL-2615 (6.A.13)	Exp. 009 1.62% Boron Steel plates	4.306	0.9996 ± 0.0012	0.9982 ± 0.0007	0.1161	0.1173
47	PNL-2615 (6.A.13)	Exp. 031 – Boral plates	4.306	0.9994 ± 0.0012	0.9969 ± 0.0007	0.1165	0.1171
48	PNL-7167 (6.A.14)	Experiment 214R – with flux traps	4.306	0.9991 ± 0.0011	0.9956 ± 0.0007	0.3722	0.3812

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
49	PNL-7167 (6.A.14)	Experiment 214V3 –with flux trap	4.306	0.9969 ± 0.0011	0.9963 ± 0.0007	0.3742	0.3826
50	PNL-4267 (6.A.15)	Case 173 – 0 ppm B	4.306	0.9974 ± 0.0012	NC	0.2893	NC
51	PNL-4267 (6.A.15)	Case 177 – 2550 ppm B	4.306	1.0057 ± 0.0010	NC	0.5509	NC
52	PNL-5803 (6.A.16)	MOX Fuel – Type 3.2 Exp. 21	20% Pu	1.0041 ± 0.0011	1.0046 ± 0.0006	0.9171	0.8868
53	PNL-5803 (6.A.16)	MOX Fuel – Type 3.2 Exp. 43	20% Pu	1.0058 ± 0.0012	1.0036 ± 0.0006	0.2968	0.2944
54	PNL-5803 (6.A.16)	MOX Fuel – Type 3.2 Exp. 13	20% Pu	1.0083 ± 0.0011	0.9989 ± 0.0006	0.1665	0.1706
55	PNL-5803 (6.A.16)	MOX Fuel – Type 3.2 Exp. 32	20% Pu	1.0079 ± 0.0011	0.9966 ± 0.0006	0.1339	0.1165
56	WCAP-3385 (6.A.17)	Saxton Case 52 PuO_2 0.52" pitch	6.6% Pu	0.9996 ± 0.0011	1.0005 ± 0.0006	0.8665	0.8417
57	WCAP-3385 (6.A.17)	Saxton Case 52 U 0.52" pitch	5.74	1.0000 ± 0.0010	0.9956 ± 0.0007	0.4476	0.4580
58	WCAP-3385 (6.A.17)	Saxton Case 56 PuO_2 0.56" pitch	6.6% Pu	1.0036 ± 0.0011	1.0047 ± 0.0006	0.5289	0.5197
59	WCAP-3385 (6.A.17)	Saxton Case 56 borated PuO_2	6.6% Pu	1.0008 ± 0.0010	NC	0.6389	NC
60	WCAP-3385 (6.A.17)	Saxton Case 56 U 0.56" pitch	5.74	0.9994 ± 0.0011	0.9967 ± 0.0007	0.2923	0.2954

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
61	WCAP-3385 (6.A.17)	Saxton Case 79 PuO_2 0.79" pitch	6.6% Pu	1.0063 ± 0.0011	1.0133 ± 0.0006	0.1520	0.1555
62	WCAP-3385 (6.A.17)	Saxton Case 79 U 0.79" pitch	5.74	1.0039 ± 0.0011	1.0008 ± 0.0006	0.1036	0.1047
		Additional MOX					
63	EPRI Exp22 (6.A.19)	0.700-in. pitch 0 ppm B	2% Pu	1.0065 ± 0.0011	NC	0.5458	NC
64	EPRI Exp23 (6.A.19)	0.700-in. pitch 688 ppm B	2% Pu	1.0069 ± 0.0010	NC	0.7256	NC
65	EPRI Exp24 (6.A.19)	0.870-in. pitch 0 ppm B	2% Pu	1.0037 ± 0.0011	NC	0.1963	NC
66	EPRI Exp25 (6.A.19)	0.870-in. pitch 1090 ppm B	2% Pu	1.0073 ± 0.0011	NC	0.2880	NC
67	EPRI Exp26 (6.A.19)	0.990-in. pitch 0 ppm B	2% Pu	1.0057 ± 0.0010	NC	0.1386	NC
68	EPRI Exp27 (6.A.19)	0.990-in. pitch 767 ppm B	2% Pu	1.0079 ± 0.0010	NC	0.1849	NC
69	WCAP-3385 (6.A.17)	Saxton Case PuO_2 0.735" pitch	6.6% Pu	1.0081 ± 0.0012	NC	0.1843	NC
70	WCAP-3385 (6.A.17)	Saxton Case PuO_2 1.04" pitch	6.6% Pu	1.0085 ± 0.0011	NC	0.0999	NC
71	PUP Exp35 (6.A.20)	8 wt% ^{240}Pu 0.80" pitch	2% Pu	0.9971 ± 0.0010	NC	0.3582	NC
72	PUP Exp36 (6.A.20)	8 wt% ^{240}Pu 0.93" pitch	2% Pu	1.0018 ± 0.0011	NC	0.1883	NC

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	Calculated k_{eff} KENO5a	EALF (eV) MCNP4a	EALF (eV) KENO5a
73	PUP Exp37 (6.A.20)	8 wt% ^{240}Pu 1.05" pitch	2% Pu	0.9959 ± 0.0011	NC	0.1377	NC
74	PUP Exp38 (6.A.20)	8 wt% ^{240}Pu 1.143" pitch	2% Pu	1.0017 ± 0.0010	NC	0.1170	NC
75	PUP Exp39 (6.A.20)	8 wt% ^{240}Pu 1.32" pitch	2% Pu	1.0000 ± 0.0010	NC	0.0956	NC
76	PUP Exp40 (6.A.20)	8 wt% ^{240}Pu 1.386" pitch	2% Pu	0.9994 ± 0.0009	NC	0.0908	NC
77	PUP Exp41 (6.A.20)	16 wt% ^{240}Pu 0.93" pitch	2% Pu	1.0042 ± 0.0010	NC	0.1981	NC
78	PUP Exp42 (6.A.20)	16 wt% ^{240}Pu 1.05" pitch	2% Pu	1.0018 ± 0.0010	NC	0.1408	NC
79	PUP Exp43 (6.A.20)	16 wt% ^{240}Pu 1.143" pitch	2% Pu	1.0029 ± 0.0009	NC	0.1200	NC
80	PUP Exp44 (6.A.20)	16 wt% ^{240}Pu 1.32" pitch	2% Pu	1.0019 ± 0.0008	NC	0.0970	NC
81	PUP Exp45 (6.A.20)	24 wt% ^{240}Pu 0.80" pitch	2% Pu	0.9947 ± 0.0010	NC	0.3988	NC
82	PUP Exp46 (6.A.20)	24 wt% ^{240}Pu 0.93" pitch	2% Pu	0.9993 ± 0.0008	NC	0.2006	NC
83	PUP Exp47 (6.A.20)	24 wt% ^{240}Pu 1.05" pitch	2% Pu	1.0014 ± 0.0008	NC	0.1414	NC
84	PUP Exp48 (6.A.20)	24 wt% ^{240}Pu 1.143" pitch	2% Pu	1.0019 ± 0.0009	NC	0.1196	NC

Table 6.A.1
Summary of Criticality Benchmark Calculations

	Reference	Identification	Enrich.	Calculated k_{eff} MCNP4a	KENO5a	EALF (eV) MCNP4a	KENO5a
85	PUP Exp49 (6.A.20)	24 wt% ^{240}Pu 1.32" pitch	2% Pu	1.0049 ± 0.0008	NC	0.0973	NC
86	PUP Exp50 (6.A.20)	24 wt% ^{240}Pu 1.386" pitch	2% Pu	1.0040 ± 0.0008	NC	0.0917	NC
87	PUP Exp51 (6.A.20)	18 wt% ^{240}Pu 0.85" pitch	4% Pu	0.9993 ± 0.0011	NC	0.3918	NC
88	PUP Exp52 (6.A.20)	18 wt% ^{240}Pu 0.93" pitch	4% Pu	0.9991 ± 0.0010	NC	0.2565	NC
89	PUP Exp53 (6.A.20)	18 wt% ^{240}Pu 1.05" pitch	4% Pu	1.0073 ± 0.0011	NC	0.1757	NC
90	PUP Exp54 (6.A.20)	18 wt% ^{240}Pu 1.143" pitch	4% Pu	1.0065 ± 0.0010	NC	0.1454	NC
91	PUP Exp55 (6.A.20)	18 wt% ^{240}Pu 1.386" pitch	4% Pu	1.0093 ± 0.0009	NC	0.1068	NC
92	PUP Exp56 (6.A.20)	18 wt% ^{240}Pu 1.60" pitch	4% Pu	1.0086 ± 0.0010	NC	0.0932	NC
93	PUP Exp57 (6.A.20)	18 wt% ^{240}Pu 1.70" pitch	4% Pu	1.0106 ± 0.0009	NC	0.0884	NC

Notes: NC stands for not calculated.

† EALF is the energy of the average lethargy causing fission

†† The experimental results appear to be statistical outliers (>3σ) suggesting the possibility of unusually large experimental error. Although they could be justifiably excluded, for conservatism, they were retained in determining the calculational basis.

Table 6.A.2

COMPARISON OF MCNP4a AND KENO5a CALCULATED REACTIVITIES†
FOR VARIOUS ENRICHMENTS (UO_2)

Enrichment	Calculated $k_{eff} \pm 1\sigma$	
	MCNP4a	KENO5a
3.0	0.8465 ± 0.0011	0.8478 ± 0.0004
3.5	0.8820 ± 0.0011	0.8841 ±0.0004
3.75	0.9019 ± 0.0011	0.8987 ± 0.0004
4.0	0.9132 ± 0.0010	0.9140 ± 0.0004
4.2	0.9276 ± 0.0011	0.9237 ± 0.0004
4.5	0.9400 ± 0.0011	0.9388 ± 0.0004

† Based on the MPC-68 with the GE 8x8R

Table 6.A.3

MCNP4a CALCULATED REACTIVITIES FOR
CRITICAL EXPERIMENTS WITH NEUTRON ABSORBERS (UO_2)

Ref.	Experiment		Δk Worth of Absorber	MCNP4a Calculated k_{eff}	EALF† (eV)
6.A.13	PNL-2615	Boral Sheet	0.0139	0.9994 ± 0.0012	0.1165
6.A.7	BAW-1484	Core XX	0.0165	1.0008 ± 0.0011	0.1724
6.A.13	PNL-2615	1.62% Boron-steel	0.0165	0.9996 ± 0.0012	0.1161
6.A.7	BAW-1484	Core XIX	0.0202	0.9961 ± 0.0012	0.2103
6.A.7	BAW-1484	Core XXI	0.0243	0.9994 ± 0.0010	0.1544
6.A.7	BAW-1484	Core XVII	0.0519	0.9962 ± 0.0012	0.2083
6.A.11	PNL-3602	Boral Sheet	0.0708	0.9941 ± 0.0011	0.3135
6.A.7	BAW-1484	Core XV	0.0786	0.9910 ± 0.0011	0.2092
6.A.7	BAW-1484	Core XVI	0.0845	0.9935 ± 0.0010	0.1757
6.A.7	BAW-1484	Core XIV	0.1575	0.9953 ± 0.0011	0.2022
6.A.7	BAW-1484	Core XIII	0.1738	1.0020 ± 0.0011	0.1988
6.A.14	PNL-7167	Expt 214R flux trap	0.1931	0.9991 ± 0.0011	0.3722

† EALF is the energy of the average lethargy causing fission

Table 6.A.4
COMPARISON OF MCNP4a AND KENO5a
CALCULATED REACTIVITIES† FOR VARIOUS BORON LOADINGS (UO_2)

^{10}B, g/cm^2	Calcualted $k_{eff} \pm 1\sigma$	
	MCNP4a	KENO5a
0.005	1.0381 ± 0.0012	1.0340 ± 0.0004
0.010	0.9960 ±0.0010	0.9941 ± 0.0004
0.015	0.9727 ± 0.0009	0.9713 ± 0.0004
0.020	0.9541 ± 0.0012	0.9560 ± 0.0004
0.025	0.9433 ± 0.0011	0.9428 ± 0.0004
0.030	0.9325 ± 0.0011	0.9338 ± 0.0004
0.035	0.9234 ± 0.0011	0.9251 ± 0.0004
0.040	0.9173 ± 0.0011	0.9179 ± 0.0004

† based on 4.5% enrichment GE 8x8R in the MPC-68 cask.

Table 6.A.5

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH THICK LEAD AND STEEL REFLECTORS† (UO_2)

Ref.	Case	Enrichment, wt%	Separation, cm	MCNP4a k_{eff}	KENO5a k_{eff}
6.A.11	Steel Reflector	2.35	1.321	0.9980 ± 0.0009	0.9992 ± 0.0006
		2.35	2.616	0.9968 ± 0.0009	0.9964 ± 0.0006
		2.35	3.912	0.9974 ± 0.0010	0.9980 ± 0.0006
		2.35	∞	0.9962 ± 0.0008	0.9939 ± 0.0006
6.A.11	Steel Reflector	4.306	1.321	0.9997 ± 0.0010	1.0012 ± 0.0007
		4.306	2.616	0.9994 ± 0.0012	0.9974 ± 0.0007
		4.306	3.405	0.9969 ± 0.0011	0.9951 ± 0.0007
		4.306	∞	0.9910 ± 0.0020	0.9947 ± 0.0007
6.A.11	Lead Reflector	4.306	0.55	1.0025 ± 0.0011	0.9997 ± 0.0007
		4.306	1.956	1.0000 ± 0.0012	0.9985 ± 0.0007
		4.306	5.405	0.9971 ± 0.0012	0.9946 ± 0.0007

† Arranged in order of increasing reflector fuel spacing.

Table 6.A.6

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH VARIOUS SOLUBLE BORON CONCENTRATIONS (UO_2)

Reference	Experiment	Boron Concentration ppm	Calculated k_{eff}	
			MCNP4a	KENO5a
6.A.15	PNL-4267	0	0.9974 ± 0.0012	-
6.A.8	BAW-1645-4	886	0.9970 ± 0.0010	0.9924 ± 0.0006
6.A.9	BAW-1810	1337	1.0023 ± 0.0010	-
6.A.9	BAW-1810	1899	1.0060 ± 0.0009	-
6.A.15	PNL-4267	2550	1.0057 ± 0.0010	-

Table 6.A.7

CALCULATIONS FOR CRITICAL EXPERIMENTS WITH MOX FUEL

Reference	Case[†]	MCNP4a		KENO 5a	
		k_{eff}	EALF[††] (eV)	k_{eff}	EALF[††] (eV)
PNL-5803 [6.A.16]	MOX Fuel – Exp No 21	1.0041±0.0011	0.9171	1.0046±0.0006	0.8868
	MOX Fuel – Exp No 43	1.0058±0.0012	0.2968	1.0036±0.0006	0.2944
	MOX Fuel – Exp No 13	1.0083±0.0011	0.1665	0.9989±0.0006	0.1706
	MOX Fuel – Exp No 32	1.0079±0.0011	0.1139	0.9966±0.0006	0.1165
WCAP- 3385-54 [6.A.17]	Saxton @ 0.52" pitch	0.9996±0.0011	0.8665	1.0005±0.0006	0.8417
	Saxton @ 0.56" pitch	1.0036±0.0011	0.5289	1.0047±0.0006	0.5197
	Saxton @ 0.56" pitch borated	1.0008±0.0010	0.6389	NC	NC
	Saxton @ 0.79" pitch	1.0063±0.0011	0.1520	1.0133±0.0006	0.1555

† Arranged in order of increasing lattice spacing.

†† EALF is the energy of the average lethargy causing fission.

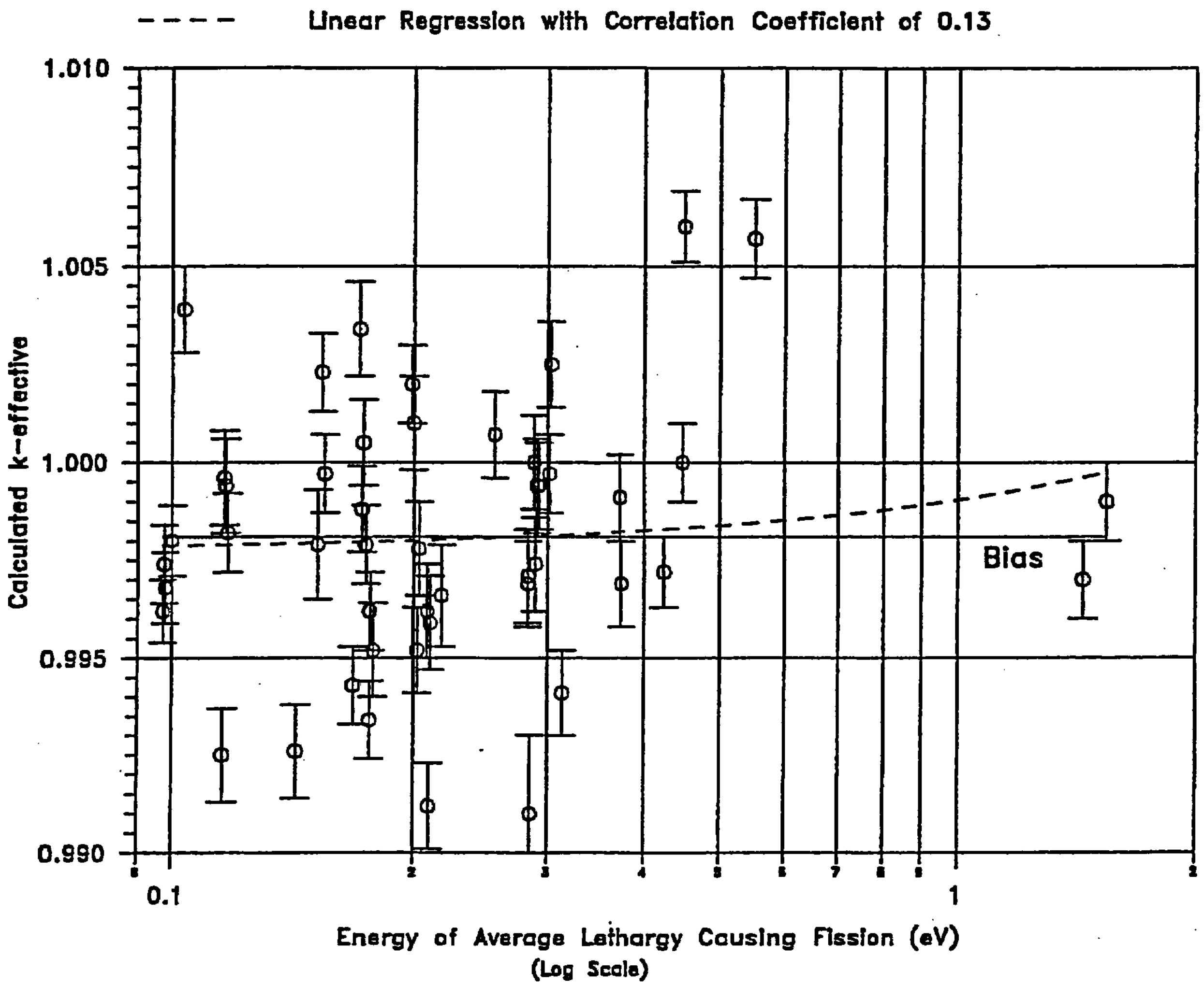

FIGURE 6.A.1 MCNP4a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

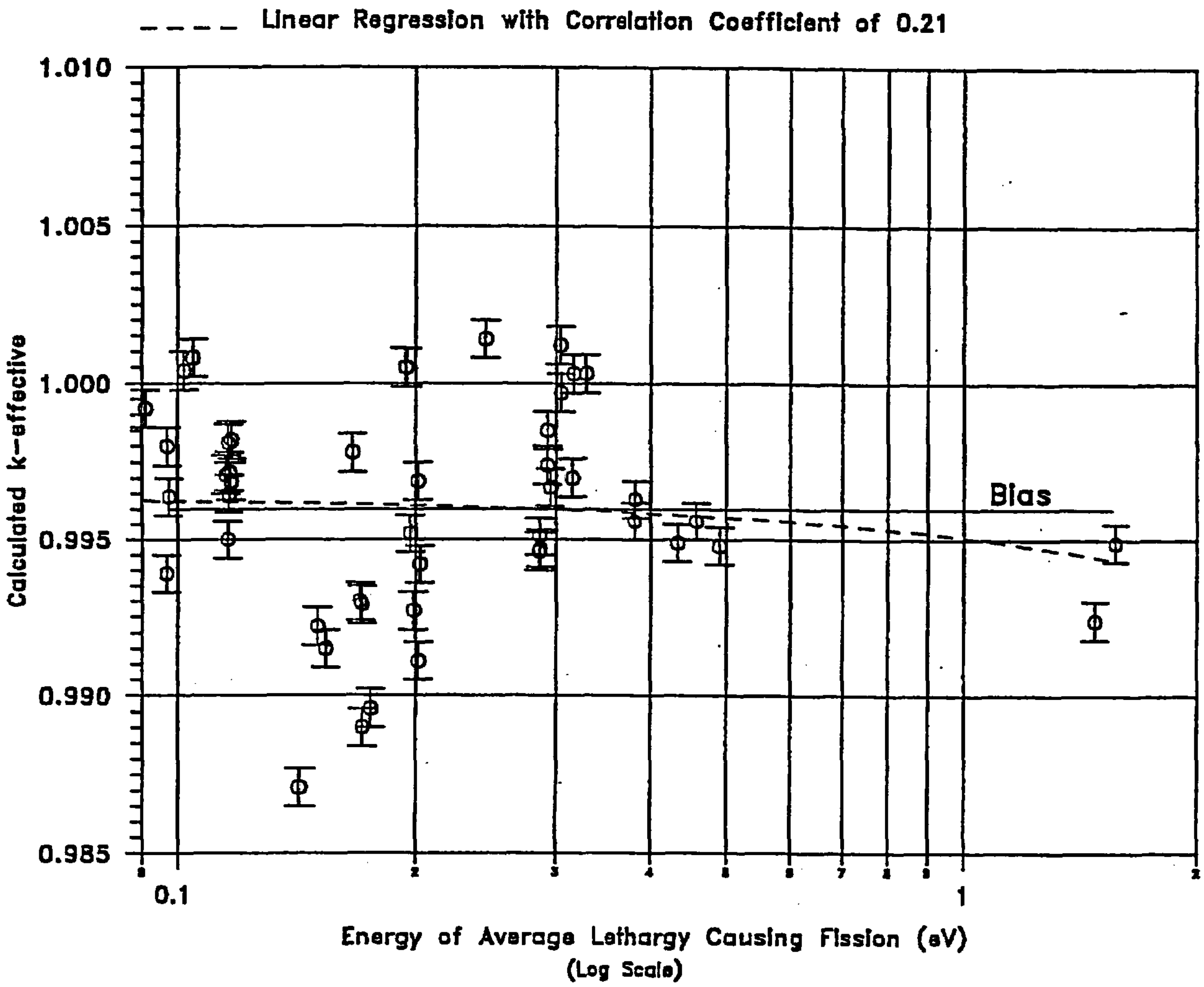

FIGURE 6.A.2 KENO5a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

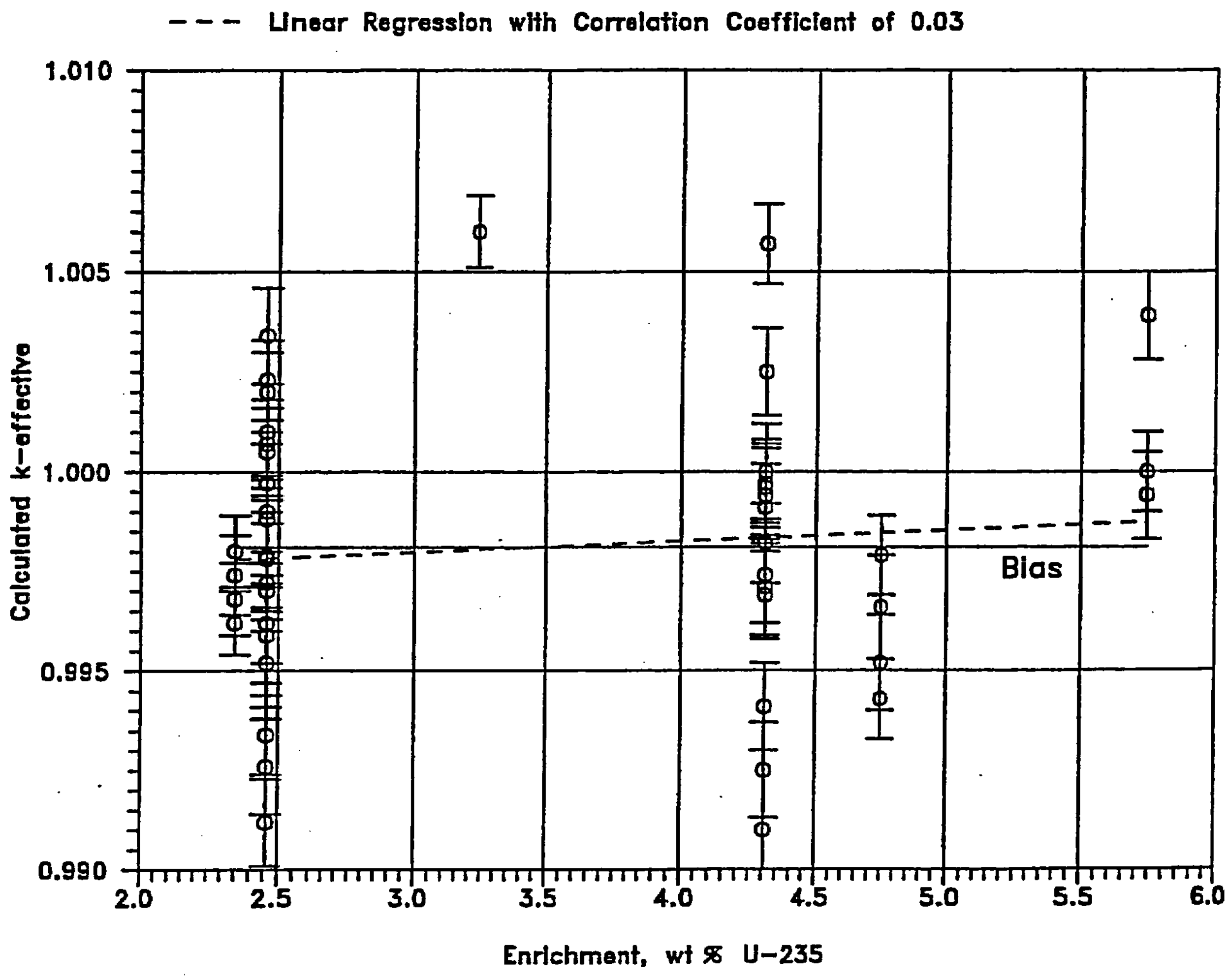

FIGURE 6.A.3 MCNP4a CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

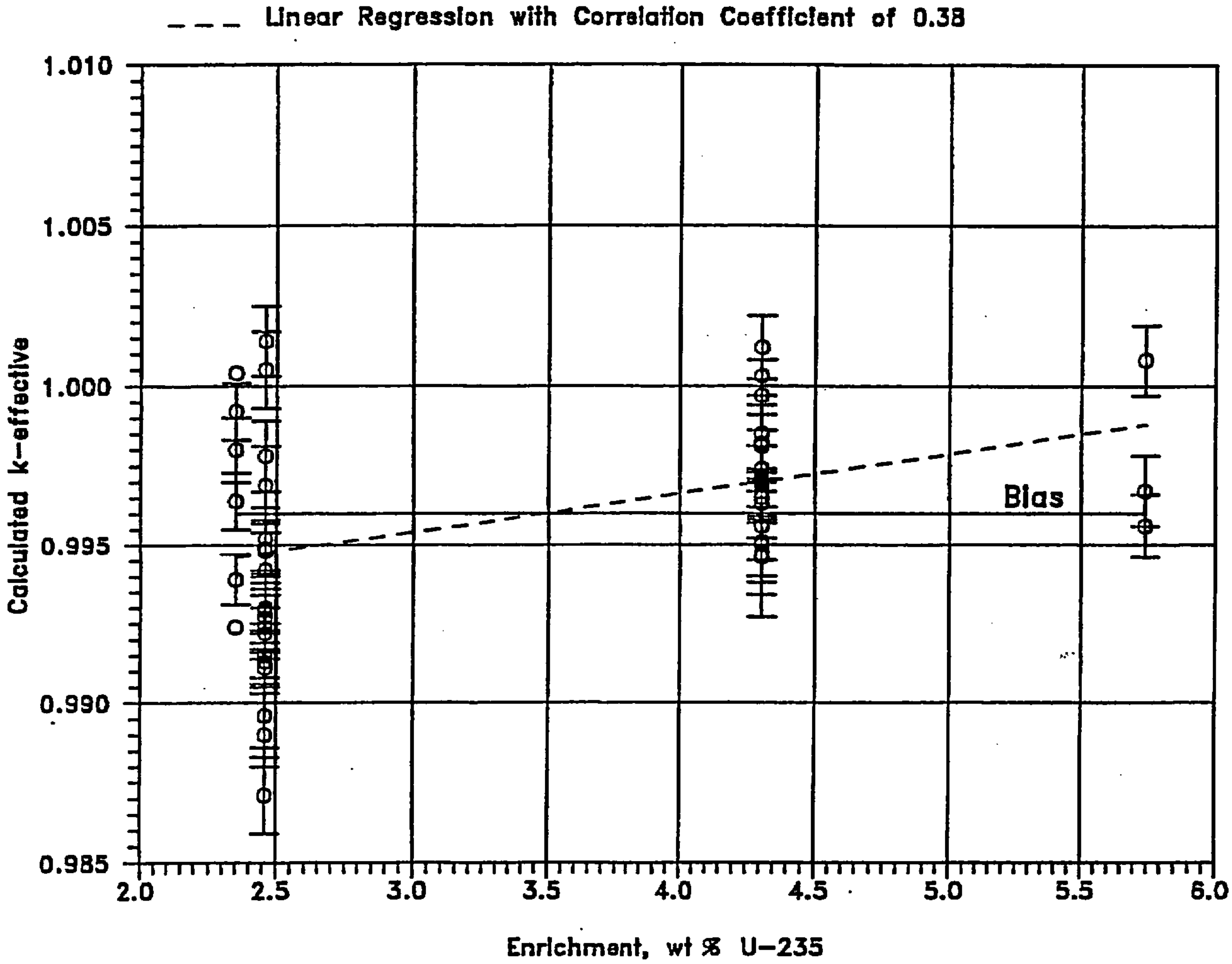

FIGURE 6.A.4 KENO5a CALCULATED k-eff VALUES AT VARIOUS U-235 ENRICHMENTS

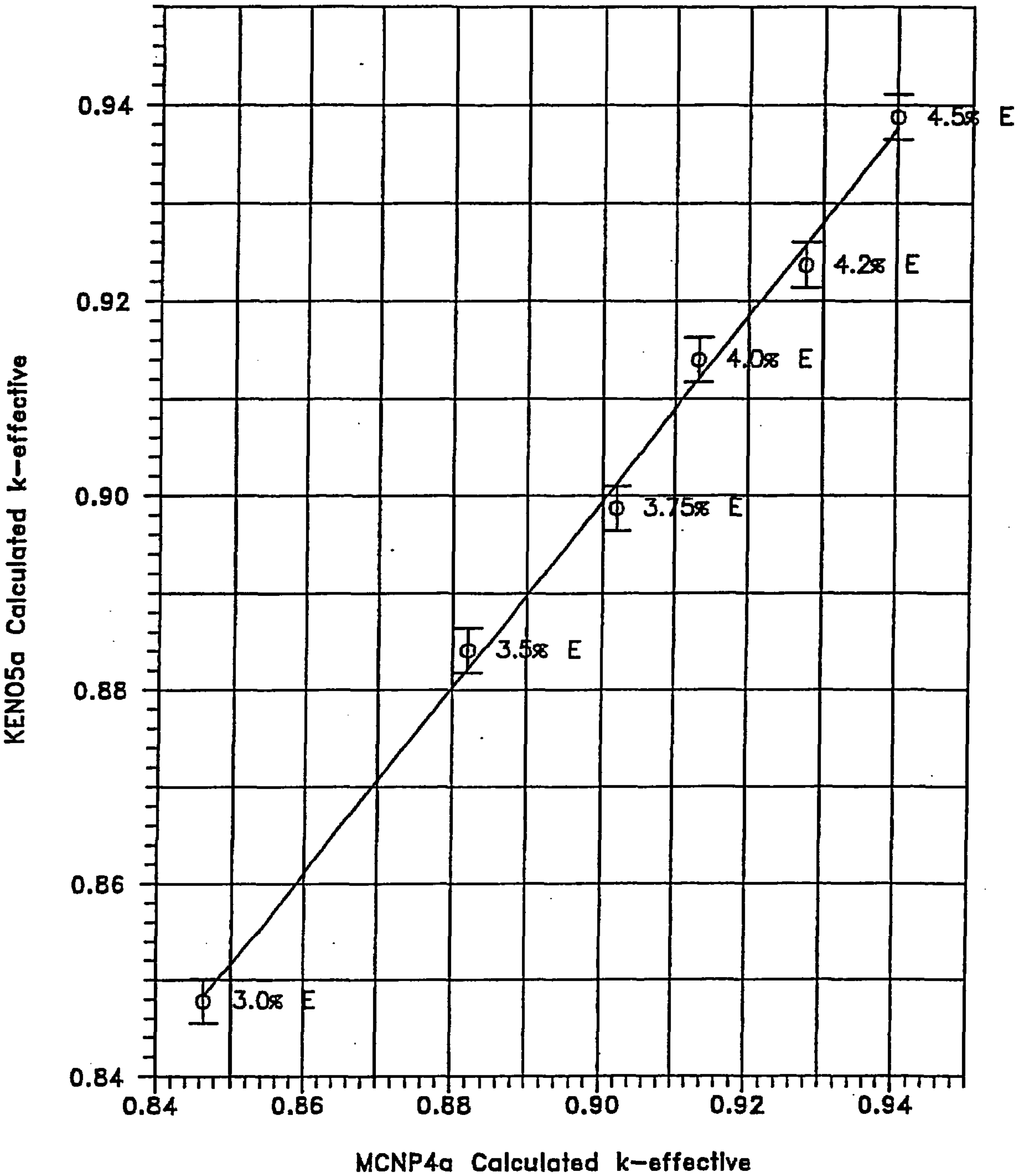

FIGURE 6.A.5 COMPARISON OF MCNP4a AND KENO5a CALCULATIONS FOR VARIOUS FUEL ENRICHMENTS

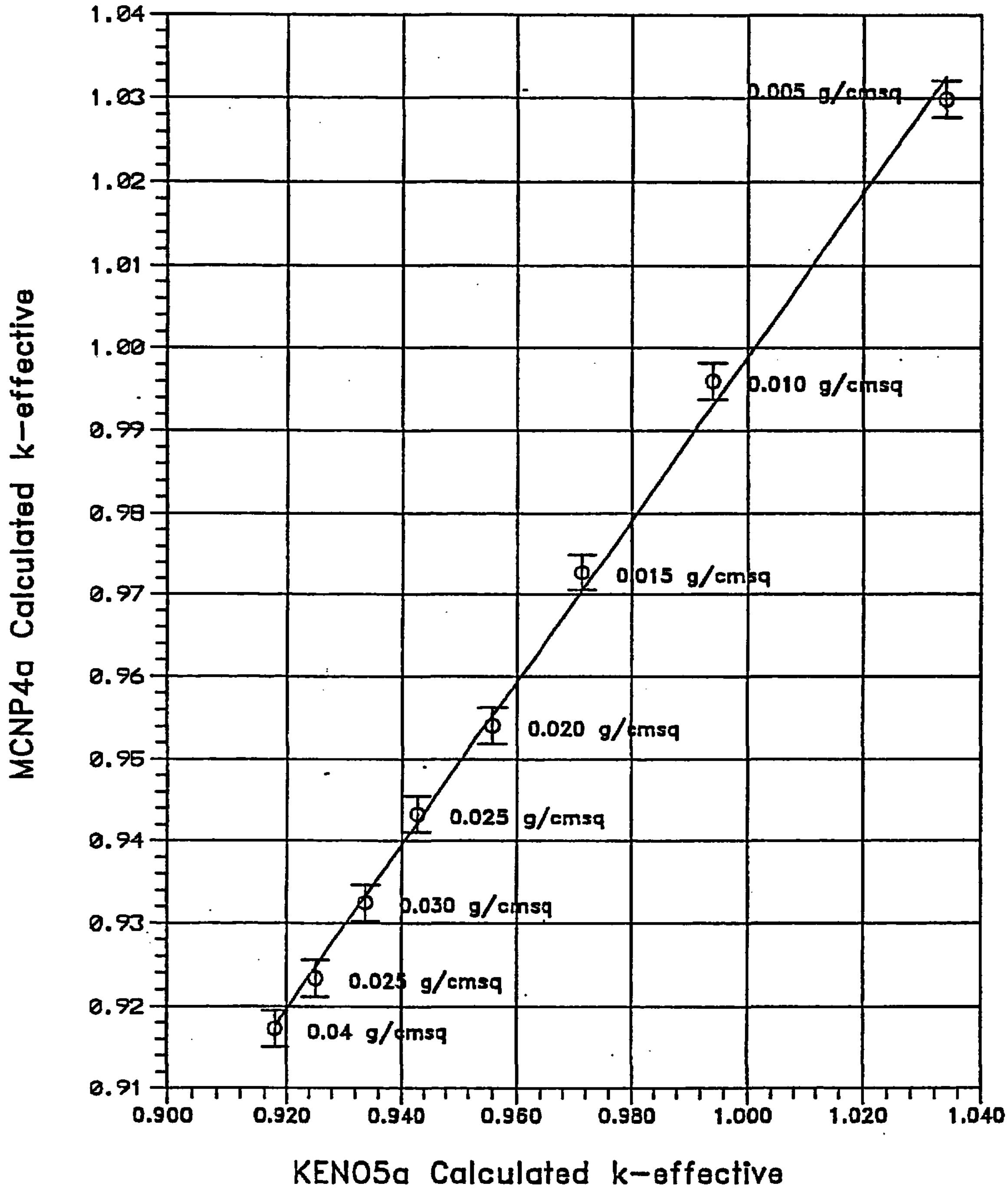

FIGURE 6.A.6 COMPARISON OF MCNP4a AND KENO5a CALCULATIONS FOR VARIOUS BORON-10 AREAL DENSITIES

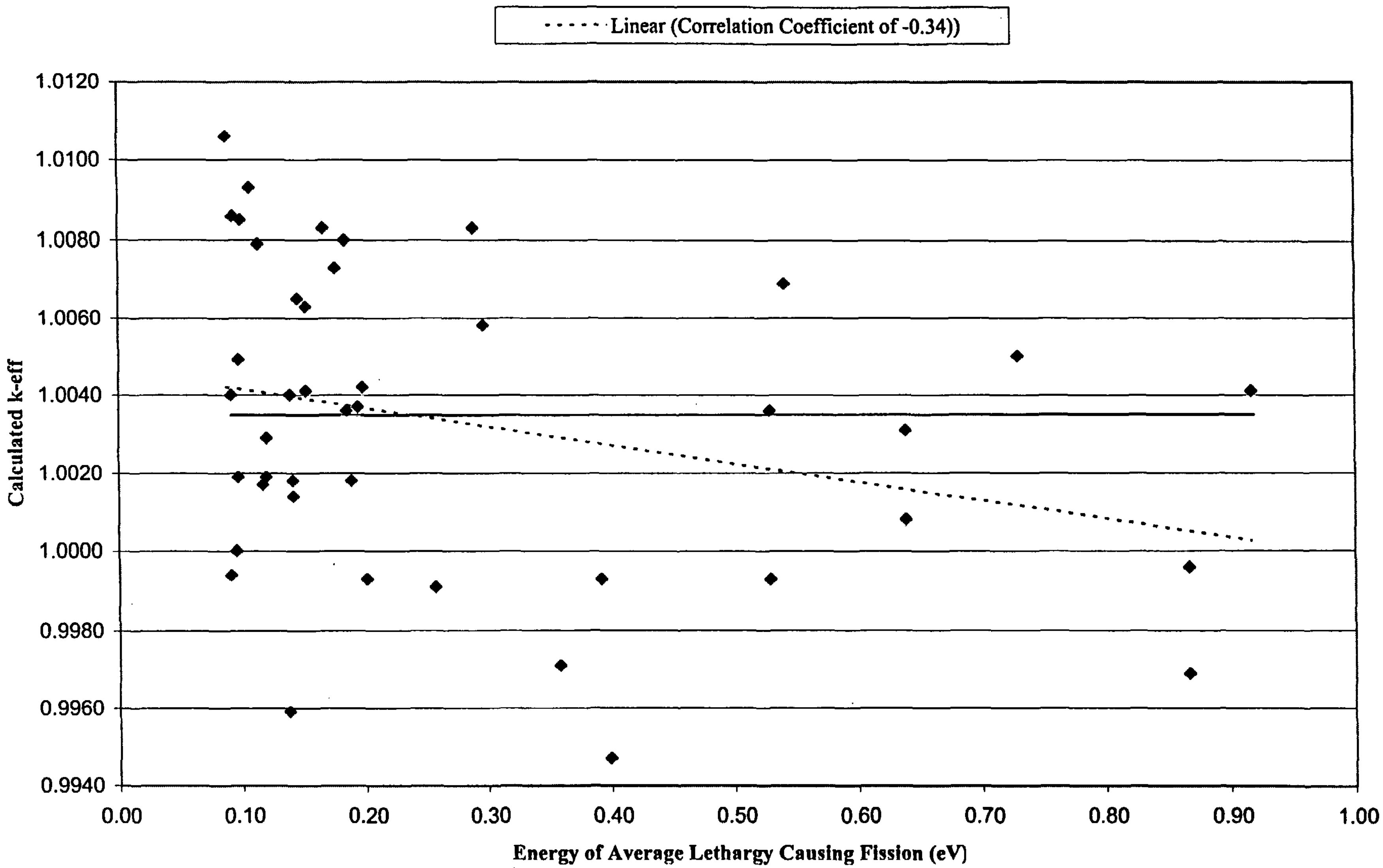

Figure 6.A.7: MCNP4a CALCULATED k-eff VALUES FOR VARIOUS VALUES OF THE SPECTRAL INDEX

APPENDIX 6.B: DISTRIBUTED ENRICHMENTS IN BWR FUEL

Fuel assemblies used in BWRs utilize fuel rods of varying enrichments as a means of controlling power peaking during in-core operation. For calculations involving BWR assemblies, the use of a uniform (planar-average) enrichment, as opposed to the distributed enrichments normally used in BWR fuel, produces conservative results. Calculations have been performed to confirm that this statement remains valid in the geometry of the MPC-68. These calculations are based on fuel assembly designs currently in use and two hypothetical distributions, all intended to illustrate that calculations with uniform average enrichments are conservative.

The average enrichment is calculated as the linear average of the various fuel rod enrichments, i.e.,

$$\overline{E} = \frac{1}{n} \sum_{i=1}^{n} E_i ,$$

where E_i is the enrichment in each of the n rods, and E is the assembly average enrichment. This parameter conservatively characterizes the fuel assembly and is readily available for specific fuel assemblies in determining the acceptability of the assembly for placement in the MPC-68 cask.

The criticality calculations for average and distributed enrichment cases are compared in Table 6.B.1 to illustrate and confirm the conservatism inherent in using average enrichments. With two exceptions, the cases analyzed represent realistic designs currently in use and encompass fuel with different ratios of maximum pin enrichment to average assembly enrichment. The two exceptions are hypothetical cases intended to extend the models to higher enrichments and to demonstrate that using the average enrichment remains conservative.

Table 6.B.1 shows that, in all cases, the averaged enrichment yields conservative values of reactivity relative to distributed enrichments for both the actual fuel designs and the hypothetical higher enrichment cases. Thus, it is concluded that uniform average enrichments will always yield higher (more conservative) values for reactivity than the corresponding distributed enrichments.[†]

† This conclusion implicitly assumes the higher enrichment fuel rods are located internal to the assembly (as in BWR fuel), and the lower enriched rods are on the outside.

Table 6.B.1

COMPARISON CALCULATIONS FOR BWR FUEL WITH AVERAGE AND DISTRIBUTED ENRICHMENTS

Case	Average %E	Peak Rod E%	Calculated k_{eff}	
			Average E	Distributed E
8x8C04	3.01	3.80	0.8549	0.8429
8x8C04	3.934	4.9	0.9128	0.9029
8x8D05	3.42	3.95	0.8790	0.8708
8x8D05	3.78	4.40	0.9030	0.8974
8x8D05	3.90	4.90	0.9062	0.9042
9x9B01	4.34	4.71	0.9347	0.9285
9x9D01	3.35	4.34	0.8793	0.8583
Hypothetical #1 (48 outer rods of 3.967%E,14 inner rods of 5.0%)	4.20	5.00	0.9289	0.9151
Hypothetical #2 (48 outer rods of 4.354%E,14 inner rods of 5.0%)	4.50	5.00	0.9422	0.9384

APPENDIX 6.C: CALCULATIONAL SUMMARY

DELETED

APPENDIX 6.D: SAMPLE INPUT FILES

(Total number of pages in this appendix : 46)

```
 message:   outp=4rf5f45o  srctp=4rf5f45s  runtpe=4rf5f45r

4rf5f45
c
c
c Bounding Assembly in Class 15x15F
c
c MPC-24/24E cell configuration
c
c HI-STAR with active length 150 inch
c
c Cask Input Preprocessor
c cskinp 15f 15f mpc24n mpc24n histar star150 4.1 4rf5f45 pure
c ------      10580 30-Jul-101 09:38 cpp\15f.bat
c   added 15f.co
c   added 15f.ce
c   added 15f.su
c   added 15f.sp
c ------      37966 21-Aug-101 10:10 cpp\mpc24n.bat
c   added mpc24n.co
c   added mpc24n.ce
c   added mpc24n.su
c   added mpc24n.sp
c ------       5620 22-Aug-101 14:05 cpp\histar.bat
c   added histar.co
c   added histar.ce
c   added histar.su
c   added histar.sp
c end of comments
c
c start of cells
c
c 15x15f
c
c number of cells: 6
c cell numbers:      1 to 7 and 201 to 299
c univers numbers:   1 to 3 and 201 to 299
c surface numbers:   1 to 9 and 201 to 299
c
c number of cells: 1
1     1 -10.522     -1  u=2       $ fuel
2     4 -1.0     1  -2  u=2       $ gap
3     3 -6.55    2  -3  u=2       $ Zr Clad
4     4 -1.0        3  u=2       $ water in fuel region
5     4 -1.0  -4:5     u=3       $ water in guide tubes
6     3 -6.55   4 -5    u=3       $ guide tubes
7     4 -1.0  -6   +7   -8   +9   u=1  lat=1
      fill= -8:8    -8:8   0:0
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
      1 2 2 2 2 2 3 2 2 2 3 2 2 2 2 2 1
      1 2 2 2 3 2 2 2 2 2 2 2 3 2 2 2 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
      1 2 2 3 2 2 3 2 2 2 3 2 2 3 2 2 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
      1 2 2 2 2 2 2 2 3 2 2 2 2 2 2 2 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
      1 2 2 3 2 2 3 2 2 2 3 2 2 3 2 2 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
```

```
      1 2 2 2 3 2 2 2 2 2 2 2 3 2 2 2 1
      1 2 2 2 2 2 3 2 2 2 3 2 2 2 2 2 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
      1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
c
c      MPC-24
c
c number of cells: 102
c cell numbers :       400   to  699
c universe numbers :     4   to    9
c surface numbers :   400   to  699
c
c      Right Side
c
408      0          -410   411   -412   413    u=4 fill=1 (1)
409      5  -7.84    410  -424   413   -426    u=4
410     4 -1.0     424   -428   448   -445    u=4
411     7  -2.7     428   -528  448   -445    u=4
412     6  -2.66   528   -532   448   -445    u=4
413     7  -2.7    532   -432   448   -445    u=4
414     4 -1.0     432   -436   448   -445    u=4
415     5  -7.84    436   -440   448   -445    u=4
416     4 -1.0     440          413           u=4
417     4 -1.0     424   -440   413   -447    u=4
418     4 -1.0     424   -440   446           u=4
419     5  -7.84    424   -440   447   -448    u=4
420     5  -7.84    424   -440   445   -446    u=4
c
c     Left Side
c
421     5  -7.84    425   -411   413           u=4
422     4 -1.0     429   -425   448   -445    u=4
423     7  -2.7    529   -429   448   -445    u=4
424     6  -2.66   533 -529    448   -445    u=4
425     7  -2.7     433 -533    448   -445    u=4
426     4 -1.0     437   -433   448   -445    u=4
427     5  -7.84    441   -437   448   -445    u=4
428     4 -1.0         -441    413           u=4
429     4 -1.0     441   -425   413   -447    u=4
430     4 -1.0     441   -425   446           u=4
431     5  -7.84    441   -425   447   -448    u=4
432     5  -7.84    441   -425   445   -446    u=4
c
c      Top
c
433     5  -7.84    411   -410   412   -426    u=4
434     4 -1.0     451   -452   426   -430    u=4
435     7  -2.7     451   -452   430 -530    u=4
436     6  -2.66    451   -452   530 -534    u=4
437     7  -2.7     451   -452   534   -434    u=4
438     4 -1.0     451   -452   434   -438    u=4
439     5  -7.84    451   -452   438   -442    u=4
440     4 -1.0     411   -424   442           u=4
441     4 -1.0     411   -450   426   -442    u=4
442     4 -1.0     453   -424   426   -442    u=4
443     5  -7.84    450   -451   426   -442    u=4
444     5  -7.84    452   -453   426   -442    u=4
c
c      Bottom
```

```
c
445    5  -7.84    427               -413    u=4
446    4 -1.0     451  -452   431  -427    u=4
447    7  -2.7     451  -452  531  -431    u=4
448    6  -2.66    451  -452  535 -531    u=4
449    7  -2.7     451  -452   435 -535    u=4
450    4 -1.0     451  -452   439  -435    u=4
451    5  -7.84    451  -452   443  -439    u=4
452    4 -1.0     411               -443    u=4
453    4 -1.0     411  -450   443  -427    u=4
454    4 -1.0     453         443  -427    u=4
455    5  -7.84    450  -451   443  -427    u=4
456    5  -7.84    452  -453   443  -427    u=4
457    5  -7.84    425  -411        -427    u=4
458    4 -1.0         -425        -427    u=4
c
c     TYPE B CELL  -  Short Boral on top and right
c
c     Right Side
c
459    0          -410   411  -412   413    u=5 fill=1 (1)
460    5  -7.84    410  -424   413  -426    u=5
470    4 -1.0     424  -428  548 -545    u=5
471    7  -2.7     428  -528 548 -545    u=5
472    6  -2.66    528  -532 548 -545    u=5
473    7  -2.7     532  -432  548 -545    u=5
474    4 -1.0     432  -436  548 -545    u=5
475    5  -7.84    436  -440  548 -545    u=5
476    4 -1.0     440        413          u=5
477    4 -1.0     424  -440   413 -547    u=5
478    4 -1.0     424  -440  546          u=5
479    5  -7.84    424  -440  547 -548    u=5
480    5  -7.84    424  -440  545 -546    u=5
c
c    Left Side
c
481    5  -7.84    425  -411   413          u=5
482    4 -1.0     429  -425   448  -445    u=5
483    7  -2.7     529  -429   448  -445    u=5
484    6  -2.66    533 -529   448  -445    u=5
485    7  -2.7     433 -533   448  -445    u=5
486    4 -1.0     437  -433   448  -445    u=5
487    5  -7.84    441  -437   448  -445    u=5
488    4 -1.0        -441   413          u=5
489    4 -1.0     441  -425   413  -447    u=5
490    4 -1.0     441  -425   446          u=5
491    5  -7.84    441  -425   447  -448    u=5
492    5  -7.84    441  -425   445  -446    u=5
c
c     Top
c
493    5  -7.84    411  -410   412  -426    u=5
494    4 -1.0    551 -552   426  -430    u=5
495    7  -2.7    551 -552   430  -530    u=5
496    6  -2.66   551 -552  530 -534    u=5
497    7  -2.7    551 -552  534  -434    u=5
498    4 -1.0    551 -552  434  -438    u=5
499    5  -7.84   551 -552  438  -442    u=5
500   4 -1.0     411  -424   442          u=5
501   4 -1.0     411 -550   426  -442    u=5
```

```
502    4 -1.0     553  -424    426  -442     u=5
503    5  -7.84    550 -551    426  -442     u=5
504    5  -7.84    552 -553    426  -442     u=5
c
c      Bottom
c
505    5  -7.84    427              -413     u=5
506    4 -1.0     451   -452   431   -427     u=5
507    7  -2.7     451   -452  531   -431     u=5
508    6  -2.66    451   -452  535 -531     u=5
509    7  -2.7     451   -452   435 -535     u=5
510    4 -1.0     451   -452   439   -435     u=5
511    5  -7.84    451   -452   443   -439     u=5
512    4 -1.0     411              -443     u=5
513    4 -1.0     411   -450   443   -427     u=5
514    4 -1.0     453          443  -427     u=5
515    5  -7.84    450   -451   443   -427     u=5
516    5  -7.84    452   -453   443   -427     u=5
517    5  -7.84    425   -411         -427     u=5
518    4 -1.0          -425         -427     u=5
c
c
c
c      TYPE D CELL  -  Short Boral on left and bottom, different cell ID
c
c number of cells: 51
c
c      Right Side
c
1570    0          -1410   1411  -1412   1413    u=17 fill=1 (1)
1571    5  -7.84    1410  -1424   1413  -1426    u=17
1572    4 -1.0     1424  -1428   1448  -1445    u=17
1573    7  -2.7     1428  -1528  1448  -1445    u=17
1574    6  -2.66   1528  -1532  1448  -1445    u=17
1575    7  -2.7     1532  -1432   1448  -1445    u=17
1576    4 -1.0     1432  -1436   1448  -1445    u=17
1577    5  -7.84    1436  -1440   1448  -1445    u=17
1578    4 -1.0     1440          1413          u=17
1579    4 -1.0     1424  -1440   1413  -1447    u=17
1580    4 -1.0     1424  -1440   1446          u=17
1581    5  -7.84    1424  -1440   1447  -1448    u=17
1582    5  -7.84    1424  -1440   1445  -1446    u=17
c
c    Left Side
c
1583    5  -7.84    1425  -1411   1413          u=17
1584    4 -1.0     1429  -1425  1548 -1545    u=17
1585    7  -2.7     1529  -1429  1548 -1545    u=17
1586    6  -2.66   1533 -1529  1548 -1545    u=17
1587    7  -2.7     1433 -1533  1548 -1545    u=17
1588    4 -1.0     1437  -1433  1548 -1545    u=17
1589    5  -7.84    1441  -1437  1548 -1545    u=17
1590    4 -1.0          -1441   1413          u=17
1591    4 -1.0     1441  -1425   1413 -1547    u=17
1592    4 -1.0     1441  -1425  1546          u=17
1593    5  -7.84    1441  -1425  1547 -1548    u=17
1594    5  -7.84    1441  -1425  1545 -1546    u=17
c
c      Top
c
```

```
1595   5  -7.84    1411  -1410   1412  -1426    u=17
1596   4 -1.0     1451  -1452   1426  -1430    u=17
1597   7  -2.7     1451  -1452   1430 -1530    u=17
1598   6  -2.66    1451  -1452  1530 -1534    u=17
1599   7  -2.7     1451  -1452  1534  -1434    u=17
1600   4 -1.0     1451  -1452  1434  -1438    u=17
1601   5  -7.84    1451  -1452   1438  -1442    u=17
1602   4 -1.0     1411  -1424   1442          u=17
1603   4 -1.0     1411  -1450   1426  -1442    u=17
1604   4 -1.0     1453  -1424   1426  -1442    u=17
1605   5  -7.84    1450  -1451   1426  -1442    u=17
1606   5  -7.84    1452  -1453   1426  -1442    u=17
c
c     Bottom
c
1607   5  -7.84    1427            -1413    u=17
1608   4 -1.0    1551 -1552   1431  -1427    u=17
1609   7  -2.7    1551 -1552   1531  -1431    u=17
1610   6  -2.66   1551 -1552   1535 -1531    u=17
1611   7  -2.7    1551 -1552   1435 -1535    u=17
1612   4 -1.0    1551 -1552   1439  -1435    u=17
1613   5  -7.84   1551 -1552   1443  -1439    u=17
1614   4 -1.0     1411             -1443    u=17
1615   4 -1.0     1411 -1550   1443  -1427    u=17
1616   4 -1.0    1553          1443  -1427    u=17
1617   5  -7.84   1550 -1551   1443  -1427    u=17
1618   5  -7.84   1552 -1553   1443  -1427    u=17
1619   5  -7.84    1425  -1411        -1427    u=17
1620   4 -1.0        -1425        -1427    u=17
c
c number of cells: 29
c
c empty cell no boral, no top
c
c
751     4 -1.0   -410   411  -412   413    u=14
752     5  -7.84    410  -424   413  -426    u=14
753    5  -7.84    425  -411   413          u=14
754    4 -1.0     411  -410   412  -426    u=14
755    5  -7.84    427            -413    u=14
756    5  -7.84    425  -411       -427    u=14
757    4 -1.0     411   426                u=14
758    4 -1.0     411  -427                u=14
759    4 -1.0    -425   413                u=14
760    4 -1.0     424   413   -426         u=14
761    4 -1.0    -425  -427                u=14
c
c
701    5    -7.84    701 -702 711 -713     u=9   $ steel post
702    5    -7.84    702 -703 711 -712     u=9   $ steel post
c
711    0             701 -705 711 -715 (702:713) (703:712)
                     fill=4 (13.8506 13.8506 0) u=9
712    0             704 (-706:-716) (705:715) -717 -710
                     fill=4 (17.9489 41.5518 0  0 1 0  -1 0 0   0 0 1) u=9
713    0             (705:715) -707 714 (-706:-716)  710
                     fill=4 (41.5518 17.9489 0  0 -1 0  1 0 0   0 0 1) u=9
714    0             701 -705 717 -719
                     fill=5 (13.8506 69.253 0) u=9
715    0             707 -709 711 -715
```

```
                     fill=5 (69.253 13.8506 0) u=9
716    0             706 -708 716 -718
                     fill=17 (45.6501 45.6501 0  -1 0 0  0 -1 0  0 0 1) u=9
717    0             705 -706 717 -719
                     fill=14 (41.5518 69.253 0) u=9
718    0             707 -709 715 -716
                     fill=14 (69.253 41.5518 0 0 1 0   1 0 0   0 0 1) u=9
719    0             701 -704 715 -717
                     fill=14 (-9.75233 41.5518 0  -1 0 0  0 1 0   0 0 1) u=9
720    0             705 -707 711 -714
                     fill=14 (41.5518 -9.75233 0   0 -1 0  1 0 0   0 0 1) u=9
721    4 -1.0       (706:719) (708:718) (709:716) u=9
c
c
c q-offset  0 inch
c
731    4 -1.0       720  721   fill=9 (0 0 0) u=19
732    4 -1.0      -720  721   fill=9 (0 0 0
                                -1 0 0  0  1 0  0 0 1) u=19
733    4 -1.0       720 -721   fill=9 (0 0 0
                                 1 0 0  0 -1 0  0 0 1) u=19
734    4 -1.0      -720 -721   fill=9 (0 0 0
                                -1 0 0  0 -1 0  0 0 1) u=19
c
673    0            -41               39  -40  fill=19
c
c number of cells: 6
102   4  -1.0    -41        40  -44             $ 6.0" Water above Fuel
103   5  -7.84   -41        44  -45             $ 15.5" Steel above Fuel
104   4  -1.0    -41       -39   43             $ 7.3" Water below Fuel
105   5  -7.84   -41       -43   46             $ 8.5" Steel below Fuel
106   5  -7.84   46  -45 41 -42                 $ 6.0" Radial Steel Shield
107   0            -46:45:42                    $ Outside world
c end of cells
c --- empty line

c --- empty line
c start of surfaces
1      cz          0.4752    $ fuel
2      cz          0.4851    $ clad ID
3      cz          0.5436    $ clad OD
4      cz          0.6350    $ guide ID
5      cz          0.6706    $ guide OD
6      px          0.7214    $ pin pitch
7      px         -0.7214
8      py          0.7214
9      py         -0.7214
c
c
c cell-id       8.98
c cell-pitch    10.906
c wall-thkns    5/16
c angle-thkns   5/16
c boral-gap     0.0035
c boral-gap-o   0.0035
c boral-thkns   0.075
c boral-clad    0.01
c sheathing     0.0235
c boral-wide    7.5
c boral-narrow  6.25
```

```
c
c gap size      1.09
c basket-od     67.335
c
410     px        11.40460 $x 8.98/2
411     px       -11.40460 $x {410} *-1
412     py        11.40460 $x {410}
413     py       -11.40460 $x {411}
416     px        13.85062 $x (10.906 + 5/16 - 5/16) /2
417     px       -13.85062 $x -10.906 + {416}
418     py        13.85062 $x {416}
419     py       -13.85062 $x {417}
424     px        12.19835 $x {410} + 5/16     $ angle
425     px       -12.19835 $x {411} - 5/16     $ box wall
426     py        12.19835 $x {412} + 5/16
427     py       -12.19835 $x {413} - 5/16
428     px        12.20724 $x {424} + 0.0035   $ wall to boral gap
429     px       -12.20724 $x {425} - 0.0035
430     py        12.20724 $x {426} + 0.0035
431     py       -12.20724 $x {427} - 0.0035
432     px        12.39774 $x {428} + 0.075    $ boral
433     px       -12.39774 $x {429} - 0.075
434     py        12.39774 $x {430} + 0.075
435     py       -12.39774 $x {431} - 0.075
436     px        12.40663 $x {432} + 0.0035   $ boral to sheathing gap
437     px       -12.40663 $x {433} - 0.0035
438     py        12.40663 $x {434} + 0.0035
439     py       -12.40663 $x {435} - 0.0035
440     px        12.46632 $x {436} + 0.0235   $ sheathing
441     px       -12.46632 $x {437} - 0.0235
442     py        12.46632 $x {438} + 0.0235
443     py       -12.46632 $x {439} - 0.0235
445     py         9.52500 $x 7.5/2
446     py         9.58469 $x {445} + 0.0235   $ sheathing
447     py        -9.58469 $x {446} *-1
448     py        -9.52500 $x {445} *-1
450     px        -9.58469 $x {447}
451     px        -9.52500 $x {448}
452     px         9.52500 $x {445}
453     px         9.58469 $x {446}
528    px        12.23264 $x {428} + 0.01  $ Aluminum on the outside of boral
529    px       -12.23264 $x {429} - 0.01
530    py        12.23264 $x {430} + 0.01
531    py       -12.23264 $x {431} - 0.01
532    px        12.37234 $x {432} - 0.01
533    px       -12.37234 $x {433} + 0.01
534    py        12.37234 $x {434} - 0.01
535    py       -12.37234 $x {435} + 0.01
545    py         7.93750 $x 6.25/2
546    py         7.99719 $x {545} + 0.0235   $ sheathing
547    py        -7.99719 $x {546} *-1
548    py        -7.93750 $x {545} *-1
550    px        -7.99719 $x {547}
551    px        -7.93750 $x {548}
552    px         7.93750 $x {545}
553    px         7.99719 $x {546}
c
c cell-id-2 8.98
c gap-o     1.09
c
```

```
701    px        -5.0
702    px        1.90627 $x (10.906 - 8.98)/2 - 5/16 + 0.1
703    px        3.45694 $x 2.722/2
704    px        4.09829 $x 10.906 - 8.98 - 5/16
705    px        27.70124 $x 10.906
706    px        31.79953 $x 2 * 10.906 - (8.98+8.98)/2 - 5/16
707    px        55.40248 $x 2 * 10.906
708    px        59.50077 $x {707} + {704}
709    px        83.10372 $x 3 * 10.906
710    p     1  -1  0  0.1 $ diagonal x=y, offset by 0.1 to avoid intersecting corners
711    py        -4.99999 $x {701}
712    py        1.90627 $x {702}
713    py        3.45694 $x {703}
714    py        4.09829 $x {704}
715    py        27.70124 $x {705}
716    py        31.79953 $x {706}
717    py        55.40248 $x {707}
718    py        59.50077 $x {708}
719    py        83.10372 $x {709}
720    px        0.0
721    py        0.0
1410     px         11.40460 $x 8.98/2
1411     px        -11.40460 $x {1410} *-1
1412     py         11.40460 $x {1410}
1413     py        -11.40460 $x {1411}
1424     px         12.19835 $x {1410} + 5/16     $ angle
1425     px        -12.19835 $x {1411} - 5/16     $ box wall
1426     py         12.19835 $x {1412} + 5/16
1427     py        -12.19835 $x {1413} - 5/16
1428     px         12.20724 $x {1424} + 0.0035   $ wall to boral gap
1429     px        -12.20724 $x {1425} - 0.0035
1430     py         12.20724 $x {1426} + 0.0035
1431     py        -12.20724 $x {1427} - 0.0035
1432     px         12.39774 $x {1428} + 0.075    $ boral
1433     px        -12.39774 $x {1429} - 0.075
1434     py         12.39774 $x {1430} + 0.075
1435     py        -12.39774 $x {1431} - 0.075
1436     px         12.40663 $x {1432} + 0.0035   $ boral to sheathing gap
1437     px        -12.40663 $x {1433} - 0.0035
1438     py         12.40663 $x {1434} + 0.0035
1439     py        -12.40663 $x {1435} - 0.0035
1440     px         12.46632 $x {1436} + 0.0235   $ sheathing
1441     px        -12.46632 $x {1437} - 0.0235
1442     py         12.46632 $x {1438} + 0.0235
1443     py        -12.46632 $x {1439} - 0.0235
1445     py          9.52500 $x 7.5/2
1446     py          9.58469 $x {1445} + 0.0235   $ sheathing
1447     py         -9.58469 $x {1446} *-1
1448     py         -9.52500 $x {1445} *-1
1450     px         -9.58469 $x {1447}
1451     px         -9.52500 $x {1448}
1452     px          9.52500 $x {1445}
1453     px          9.58469 $x {1446}
1528   px         12.23264 $x {1428} + 0.01  $ Aluminum on the outside of boral
1529   px        -12.23264 $x {1429} - 0.01
1530   py         12.23264 $x {1430} + 0.01
1531   py        -12.23264 $x {1431} - 0.01
1532   px         12.37234 $x {1432} - 0.01
1533   px        -12.37234 $x {1433} + 0.01
1534   py         12.37234 $x {1434} - 0.01
```

```
1535    py        -12.37234 $x {1435} + 0.01
1545    py          7.93750 $x 6.25/2
1546    py          7.99719 $x {1545} + 0.0235    $ sheathing
1547    py         -7.99719 $x {1546} *-1
1548    py         -7.93750 $x {1545} *-1
1550    px         -7.99719 $x {1547}
1551    px         -7.93750 $x {1548}
1552    px          7.93750 $x {1545}
1553    px          7.99719 $x {1546}
46     pz         -31.75        $ 8.5"  lower steel thickness
43     pz         -10.16        $ lower water thickness
39     pz           0.0         $ bottom of active fuel assembly
40     pz         381.0         $ top of active fuel assembly
44     pz         396.24        $ upper water thickness
45     pz         435.61        $ 15.5" upper steel thickness
41     cz          85.57        $ mpc steel ID
42     cz         108.43        $ mpc water
c end of surfaces
c --- empty line

c --- empty line
tr1 0 0 0
kcode     10000  .94  20  120
sdef  par=1  erg=d1 axs=0 0 1 x=d4 y=fx d5 z=d3
c
sp1  -2 1.2895
c
sp3  0 1
c
si4  s          13 14
             12 13 14 15
          11 12 13 14 15 16
          11 12 13 14 15 16
             12 13 14 15
                13 14
sp4  1 23r
c
ds5  s                26 26
                   25 25 25 25
                24 24 24 24 24 24
                23 23 23 23 23 23
                   22 22 22 22
                      21 21
c
si11  -79.25435 -57.61355
si12  -51.88077 -30.23997
si13  -24.50719 -2.86639
si14    2.86639   24.50719
si15   30.23997   51.88077
si16   57.61355   79.25435
c
si21  -79.25435 -57.61355
si22  -51.88077 -30.23997
si23  -24.50719 -2.86639
si24    2.86639   24.50719
si25   30.23997   51.88077
si26   57.61355   79.25435
c
sp11  0 1
sp12  0 1
```

```
sp13   0 1
sp14   0 1
sp15   0 1
sp16   0 1
sp21   0 1
sp22   0 1
sp23   0 1
sp24   0 1
sp25   0 1
sp26   0 1
c
m3           40000.56c   1.           $ Zr Clad
m4           1001.50c    0.6667       $ Water
             8016.50c    0.3333
m5           24000.50c   0.01761      $ Steel
             25055.50c   0.001761
             26000.55c   0.05977
             28000.50c   0.008239
m6           5010.50c   -0.054427     $ Boral Central Section @ 0.02 g/cmsq
             5011.50c   -0.241373
             13027.50c  -0.6222
             6000.50c   -0.0821
m7           13027.50c   1.0
mt4        lwtr.01t
prdmp    j   -120   j   2
fm4      1000   1   -6
f4:n   1
sd4      1000
e4     1.000E-11   1.000E-10   5.000E-10   7.500E-10   1.000E-09   1.200E-09
       1.500E-09   2.000E-09   2.500E-09   3.000E-09
       4.700E-09   5.000E-09   7.500E-09   1.000E-08   2.530E-08
       3.000E-08   4.000E-08   5.000E-08   6.000E-08   7.000E-08
       8.000E-08   9.000E-08   1.000E-07   1.250E-07   1.500E-07
       1.750E-07   2.000E-07   2.250E-07   2.500E-07   2.750E-07
       3.000E-07   3.250E-07   3.500E-07   3.750E-07   4.000E-07
       4.500E-07   5.000E-07   5.500E-07   6.000E-07   6.250E-07
       6.500E-07   7.000E-07   7.500E-07   8.000E-07   8.500E-07
       9.000E-07   9.250E-07   9.500E-07   9.750E-07   1.000E-06
       1.010E-06   1.020E-06   1.030E-06   1.040E-06   1.050E-06
       1.060E-06   1.070E-06   1.080E-06   1.090E-06   1.100E-06
       1.110E-06   1.120E-06   1.130E-06   1.140E-06   1.150E-06
       1.175E-06   1.200E-06   1.225E-06   1.250E-06   1.300E-06
       1.350E-06   1.400E-06   1.450E-06   1.500E-06   1.590E-06
       1.680E-06   1.770E-06   1.860E-06   1.940E-06   2.000E-06
       2.120E-06   2.210E-06   2.300E-06   2.380E-06   2.470E-06
       2.570E-06   2.670E-06   2.770E-06   2.870E-06   2.970E-06
       3.000E-06   3.050E-06   3.150E-06   3.500E-06   3.730E-06
       4.000E-06   4.750E-06   5.000E-06   5.400E-06   6.000E-06
       6.250E-06   6.500E-06   6.750E-06   7.000E-06   7.150E-06
       8.100E-06   9.100E-06   1.000E-05   1.150E-05   1.190E-05
       1.290E-05   1.375E-05   1.440E-05   1.510E-05   1.600E-05
       1.700E-05   1.850E-05   1.900E-05   2.000E-05   2.100E-05
       2.250E-05   2.500E-05   2.750E-05   3.000E-05   3.125E-05
       3.175E-05   3.325E-05   3.375E-05   3.460E-05   3.550E-05
       3.700E-05   3.800E-05   3.910E-05   3.960E-05   4.100E-05
       4.240E-05   4.400E-05   4.520E-05   4.700E-05   4.830E-05
       4.920E-05   5.060E-05   5.200E-05   5.340E-05   5.900E-05
       6.100E-05   6.500E-05   6.750E-05   7.200E-05   7.600E-05
       8.000E-05   8.200E-05   9.000E-05   1.000E-04   1.080E-04
       1.150E-04   1.190E-04   1.220E-04   1.860E-04   1.925E-04
```

```
        2.075E-04   2.100E-04   2.400E-04   2.850E-04   3.050E-04
        5.500E-04   6.700E-04   6.830E-04   9.500E-04   1.150E-03
        1.500E-03   1.550E-03   1.800E-03   2.200E-03   2.290E-03
        2.580E-03   3.000E-03   3.740E-03   3.900E-03   6.000E-03
        8.030E-03   9.500E-03   1.300E-02   1.700E-02   2.500E-02
        3.000E-02   4.500E-02   5.000E-02   5.200E-02   6.000E-02
        7.300E-02   7.500E-02   8.200E-02   8.500E-02   1.000E-01
        1.283E-01   1.500E-01   2.000E-01   2.700E-01   3.300E-01
        4.000E-01   4.200E-01   4.400E-01   4.700E-01   4.995E-01
        5.500E-01   5.730E-01   6.000E-01   6.700E-01   6.790E-01
        7.500E-01   8.200E-01   8.611E-01   8.750E-01   9.000E-01
        9.200E-01   1.010E+00   1.100E+00   1.200E+00   1.250E+00
        1.317E+00   1.356E+00   1.400E+00   1.500E+00   1.850E+00
        2.354E+00   2.479E+00   3.000E+00   4.304E+00   4.800E+00
        6.434E+00   8.187E+00   1.000E+01   1.284E+01   1.384E+01
        1.455E+01   1.568E+01   1.733E+01   2.000E+01
si3  h 0 381.00
imp:n 1 193r 0
c fuel enrichment 4.1 %
m1       92235.50c      -0.03614
         92238.50c      -0.84536
          8016.50c      -0.11850
c end of file
c
```

```
HI-STAR containing MPC68, 08x08 @ 4.2 wt% Enrich.
c     4.20 % uniform enrichment,  unreflected cask, 0.0279 g/cmsq B-10 in Boral
c
c
1     1 -10.522      -1  u=2        $ fuel
2     4 -1.0     1   -2  u=2        $ gap
3     3 -6.55    2   -3  u=2        $ Zr Clad
4     4 -1.0         3   u=2        $ water in fuel region
5     4 -1.0    -4:5     u=3        $ water in guide tubes
6     3 -6.55    4 -5    u=3        $ guide tubes
7     4 -1.0    -6   +7   -8   +9   u=1  lat=1
      fill= -5:4    -5:4    0:0
      1  1 1 1 1 1 1 1 1  1
      1  2 2 2 2 2 2 2 2  1
      1  2 2 2 2 2 2 2 2  1
      1  2 2 2 2 2 2 2 2  1
      1  2 2 2 3 2 2 2 2  1
      1  2 2 2 2 3 2 2 2  1
      1  2 2 2 2 2 2 2 2  1
      1  2 2 2 2 2 2 2 2  1
      1  2 2 2 2 2 2 2 2  1
      1  1 1 1 1 1 1 1 1  1
c
C  BOX TYPE R
c
8     0  -10   11  -12   13          u=4 fill=1 (0.8128  0.8128  0)
9     3  -6.55    60   -61    62    -63  #8      u=4     $ Zr flow channel
10    4  -1.      64   -65    66    -67  #8 #9   u=4     $ water
11    5  -7.84    20   -23    67    -14          u=4     $ 0.075" STEEL
12    4  -1.      20   -23    14    -15          u=4     $ WATER POCKET
13    7  -2.7     20   -23    15    -16          u=4     $ Al CLAD
14    6  -2.66    20   -23    16    -17          u=4     $ BORAL Absorber
15    7  -2.7     20   -23    17    -18          u=4     $ Al Clad
16    4  -1.      20   -23    18   -118          u=4     $ Water
17    5  -7.84    118:-129:65:-66                u=4     $ Steel
18    4  -1.      64   -21    67   -118          u=4     $ Water
19    4  -1.      24   -65    67   -118          u=4     $ water
20    5  -7.84    21   -20    67   -118          u=4     $ Steel
21    5  -7.84    23   -24    67   -118          u=4     $ Steel
22    4  -1.     129   -64    33   -118          u=4     $ Water
c
23    5  -7.84    25   -64    30    -31          u=4     $ Steel
24    4  -1.      26   -25    30    -31          u=4     $ Water
25    7  -2.7     27   -26    30    -31          u=4     $ Al clad
26    6  -2.66    28   -27    30    -31          u=4     $ Boral
27    7  -2.7     29   -28    30    -31          u=4     $ Al clad
28    4  -1.     129   -29    30    -31          u=4     $ water
29    5  -7.84   129   -64    32    -30          u=4     $ Steel ends
30    5  -7.84   129   -64    31    -33          u=4     $ Steel ends
31    4  -1.     129   -64    66    -32          u=4     $ Water
c
c    Type A box - Boral only on left side
c
32    0  -10   11  -12   13          u=6 fill=1 (0.8128  0.8128  0)
33    3  -6.55    60   -61    62    -63  #8      u=6     $ Zr flow channel
34    4  -1.      64   -65    66   -118  #8 #9   u=6     $ water
35    5  -7.84    118:-129:65:-66                u=6     $ Steel
36    4  -1.     129   -64    67   -118          u=6     $ Water
c
37    5  -7.84    25   -64    30    -31          u=6     $ Steel
```

```
38    4  -1.        26    -25     30    -31             u=6        $ Water
39    7  -2.7       27    -26     30    -31             u=6        $ Al clad
40    6  -2.66      28    -27     30    -31             u=6        $ Boral
41    7  -2.7       29    -28     30    -31             u=6        $ Al clad
42    4  -1.       129    -29     30    -31             u=6        $ water
43    4  -1.       129    -64     33    -67             u=6        $ Water
44    5  -7.84     129    -64     32    -30             u=6        $ Steel ends
45    5  -7.84     129    -64     31    -33             u=6        $ Steel ends
46    4  -1.       129    -64     66    -32             u=6        $ Water
c
c     Type B box -  Boral on Top only
c
47    0  -10     11   -12    13            u=7 fill=1 (0.8128    0.8128  0)
48    3  -6.55      60    -61     62    -63   #8        u=7        $ Zr flow channel
49    4  -1.        64    -65     66    -67   #8 #9     u=7        $ water
50    5  -7.84      20    -23     67    -14             u=7        $ 0.075" STEEL
51    4  -1.        20    -23     14    -15             u=7        $ WATER POCKET
52    7  -2.7       20    -23     15    -16             u=7        $ Al CLAD
53    6  -2.66      20    -23     16    -17             u=7        $ BORAL Absorber
54    7  -2.7       20    -23     17    -18             u=7        $ water
55    4  -1.        20    -23     18   -118             u=7        $ Water
56    5  -7.84      118:-129:65:-66                     u=7        $ Steel
57    4  -1.        64    -21     67   -118             u=7        $ Water
58    4  -1.        24    -65     67   -118             u=7        $ water
59    5  -7.84      21    -20     67   -118             u=7        $ Steel
60    5  -7.84      23    -24     67   -118             u=7        $ Steel
61    4  -1.       129    -64     66   -118             u=7        $ Water
c
c     Type E box  - No Boral Panels
c
62    0  -10     11   -12    13            u=8 fill=1 (0.8128    0.8128  0)
63    3  -6.55      60    -61     62    -63   #8        u=8        $ Zr flow channel
64    4  -1.       129    -65     66   -118   #8 #9     u=8        $ water
65    5  -7.84      118:-129:65:-66                     u=8        $ Steel
c
c     Type F box  - No Boral Panels or fuel
c
66    4  -1.       129    -65     66   -118             u=9        $ water
67    5  -7.84      118:-129:65:-66                     u=9        $ Steel
c
68    4  -1.0      -34   35   -36   37   u=5   lat=1   fill=-7:6   -7:6   0:0
                 5 5 5 5 5 5 5 5 5 5 5 5 5 5
                 5 9 9 9 9 9 9 9 9 9 9 9 9 5
                 5 9 9 9 9 9 7 4 9 9 9 9 9 5
                 5 9 9 9 7 4 4 4 4 4 9 9 9 5
                 5 9 9 7 4 4 4 4 4 4 4 9 9 5
                 5 9 9 7 4 4 4 4 4 4 4 9 9 5
                 5 9 7 4 4 4 4 4 4 4 4 4 9 5
                 5 9 8 4 4 4 4 4 4 4 4 6 9 5
                 5 9 9 7 4 4 4 4 4 4 4 9 9 5
                 5 9 9 8 4 4 4 4 4 4 6 9 9 5
                 5 9 9 9 8 4 4 4 6 6 9 9 9 5
                 5 9 9 9 9 9 8 6 9 9 9 9 9 5
                 5 9 9 9 9 9 9 9 9 9 9 9 9 5
                 5 5 5 5 5 5 5 5 5 5 5 5 5 5
69    0            -41                      50   -49   fill=5 (8.1661   8.1661   0)
70    4  -1.0      -41          43   -50             $ Water below Fuel
71    4  -1.0      -41          49   -44             $ Water above Fuel
72    5  -7.84     -42          68   -43             $ Steel below Fuel
73    5  -7.84     -42          44   -69             $ Steel above Fuel
```

```
74     5   -7.84     41   -42   43   -44            $ Radial Steel
75     0              42 :-68:   69                 $ outside world

1      cz          0.5207       $ Fuel OD
2      cz          0.5321       $ Clad ID
3      cz          0.6134       $ Clad OD
4      cz          0.6744       $ Thimble ID
5      cz          0.7506       $ Thimble OD
6      px          0.8128       $ Pin Pitch
7      px         -0.8128
8      py          0.8128
9      py         -0.8128
10     px          6.7031       $ Channel ID
11     px         -6.7031
12     py          6.7031
13     py         -6.7031
14     py          7.8016
15     py          7.8155
16     py          7.8410
17     py          8.0467
18     py          8.0721
118    py          8.0861
20     px         -6.0325
21     px         -6.2230
23     px          6.0325
24     px          6.2230
25     px         -7.8016
26     px         -7.8155
27     px         -7.8410
28     px         -8.0467
29     px         -8.0721
129    px         -8.0861
30     py         -6.0325
31     py          6.0325
32     py         -6.2230
33     py          6.2230
34     px          7.6111
35     px         -8.7211
36     py          8.7211
37     py         -7.6111
41     cz          85.57
42     cz          108.43
43     pz         -18.54
44     pz          402.5
49     pz          381.         $ Top of Active Fuel
50     pz            0          $ Start of Active Fuel
60     px          -6.9571      $ Channel OD
61     px           6.9571
62     py          -6.9571
63     py           6.9571
64     px          -7.6111      $ Cell Box ID
65     px           7.6111
66     py          -7.6111
67     py           7.6111
68     pz         -40.13
69     pz           441.9

imp:n      1 73r 0
kcode    10000  0.94    20   120
c
```

```
sdef  par=1  erg=d1 axs=0 0 1 x=d4 y=fx d5 z=d3
c
sp1 -2 1.2895
c
c
si3  h 0 365.76
sp3  0 1
c
c
si4  s             15 16
              13 14 15 16 17 18
           12 13 14 15 16 17 18 19
           12 13 14 15 16 17 18 19
        11 12 13 14 15 16 17 18 19 20
        11 12 13 14 15 16 17 18 19 20
           12 13 14 15 16 17 18 19
           12 13 14 15 16 17 18 19
              13 14 15 16 17 18
                    15 16
sp4  1 67r
c
ds5  s             30 30
              29 29 29 29 29 29
           28 28 28 28 28 28 28 28
           27 27 27 27 27 27 27 27
        26 26 26 26 26 26 26 26 26 26
        25 25 25 25 25 25 25 25 25 25
           24 24 24 24 24 24 24 24
           23 23 23 23 23 23 23 23
              22 22 22 22 22 22
                    21 21
c
si11  -80.6831 -67.6783
si12  -64.1985 -51.1937
si13  -47.7139 -34.7091
si14  -31.2293 -18.2245
si15  -14.7447 -1.7399
si16   1.7399   14.7447
si17   18.2245  31.2293
si18   34.7091  47.7139
si19   51.1937  64.1985
si20   67.6783  80.6831
c
si21  -80.6831 -67.6783
si22  -64.1985 -51.1937
si23  -47.7139 -34.7091
si24  -31.2293 -18.2245
si25  -14.7447 -1.7399
si26   1.7399   14.7447
si27   18.2245  31.2293
si28   34.7091  47.7139
si29   51.1937  64.1985
si30   67.6783  80.6831
sp11  0 1
sp12  0 1
sp13  0 1
sp14  0 1
sp15  0 1
sp16  0 1
sp17  0 1
```

```
sp18   0 1
sp19   0 1
sp20   0 1
sp21   0 1
sp22   0 1
sp23   0 1
sp24   0 1
sp25   0 1
sp26   0 1
sp27   0 1
sp28   0 1
sp29   0 1
sp30   0 1
c
m1          92235.50c   9.98343E-04  $ 4.20% E Fuel
            92238.50c   0.022484
            8016.50c    0.046965
m2          8016.50c    1.           $ Void
m3          40000.56c   1.           $ Zr Clad
m4          1001.50c    0.6667       $ Water
            8016.50c    0.3333
m5          24000.50c   0.01761      $ Steel
            25055.50c   0.001761
            26000.55c   0.05977
            28000.50c   0.008239
m6          5010.50c    8.0707E-03   $ Boral
            5011.50c    3.2553E-02
            6000.50c    1.0146E-02
            13027.50c   3.8054E-02
m7          13027.50c    1.           $ Al Clad
mt4        lwtr.01t
prdmp    j   -30   1   2
fm4      1000   1   -6
f4:n   1
sd4      1000
e4     1.000E-11  1.000E-10  5.000E-10  7.500E-10  1.000E-09  1.200E-09
       1.500E-09  2.000E-09  2.500E-09  3.000E-09
       4.700E-09  5.000E-09  7.500E-09  1.000E-08  2.530E-08
       3.000E-08  4.000E-08  5.000E-08  6.000E-08  7.000E-08
       8.000E-08  9.000E-08  1.000E-07  1.250E-07  1.500E-07
       1.750E-07  2.000E-07  2.250E-07  2.500E-07  2.750E-07
       3.000E-07  3.250E-07  3.500E-07  3.750E-07  4.000E-07
       4.500E-07  5.000E-07  5.500E-07  6.000E-07  6.250E-07
       6.500E-07  7.000E-07  7.500E-07  8.000E-07  8.500E-07
       9.000E-07  9.250E-07  9.500E-07  9.750E-07  1.000E-06
       1.010E-06  1.020E-06  1.030E-06  1.040E-06  1.050E-06
       1.060E-06  1.070E-06  1.080E-06  1.090E-06  1.100E-06
       1.110E-06  1.120E-06  1.130E-06  1.140E-06  1.150E-06
       1.175E-06  1.200E-06  1.225E-06  1.250E-06  1.300E-06
       1.350E-06  1.400E-06  1.450E-06  1.500E-06  1.590E-06
       1.680E-06  1.770E-06  1.860E-06  1.940E-06  2.000E-06
       2.120E-06  2.210E-06  2.300E-06  2.380E-06  2.470E-06
       2.570E-06  2.670E-06  2.770E-06  2.870E-06  2.970E-06
       3.000E-06  3.050E-06  3.150E-06  3.500E-06  3.730E-06
       4.000E-06  4.750E-06  5.000E-06  5.400E-06  6.000E-06
       6.250E-06  6.500E-06  6.750E-06  7.000E-06  7.150E-06
       8.100E-06  9.100E-06  1.000E-05  1.150E-05  1.190E-05
       1.290E-05  1.375E-05  1.440E-05  1.510E-05  1.600E-05
       1.700E-05  1.850E-05  1.900E-05  2.000E-05  2.100E-05
       2.250E-05  2.500E-05  2.750E-05  3.000E-05  3.125E-05
```

3.175E-05	3.325E-05	3.375E-05	3.460E-05	3.550E-05
3.700E-05	3.800E-05	3.910E-05	3.960E-05	4.100E-05
4.240E-05	4.400E-05	4.520E-05	4.700E-05	4.830E-05
4.920E-05	5.060E-05	5.200E-05	5.340E-05	5.900E-05
6.100E-05	6.500E-05	6.750E-05	7.200E-05	7.600E-05
8.000E-05	8.200E-05	9.000E-05	1.000E-04	1.080E-04
1.150E-04	1.190E-04	1.220E-04	1.860E-04	1.925E-04
2.075E-04	2.100E-04	2.400E-04	2.850E-04	3.050E-04
5.500E-04	6.700E-04	6.830E-04	9.500E-04	1.150E-03
1.500E-03	1.550E-03	1.800E-03	2.200E-03	2.290E-03
2.580E-03	3.000E-03	3.740E-03	3.900E-03	6.000E-03
8.030E-03	9.500E-03	1.300E-02	1.700E-02	2.500E-02
3.000E-02	4.500E-02	5.000E-02	5.200E-02	6.000E-02
7.300E-02	7.500E-02	8.200E-02	8.500E-02	1.000E-01
1.283E-01	1.500E-01	2.000E-01	2.700E-01	3.300E-01
4.000E-01	4.200E-01	4.400E-01	4.700E-01	4.995E-01
5.500E-01	5.730E-01	6.000E-01	6.700E-01	6.790E-01
7.500E-01	8.200E-01	8.611E-01	8.750E-01	9.000E-01
9.200E-01	1.010E+00	1.100E+00	1.200E+00	1.250E+00
1.317E+00	1.356E+00	1.400E+00	1.500E+00	1.850E+00
2.354E+00	2.479E+00	3.000E+00	4.304E+00	4.800E+00
6.434E+00	8.187E+00	1.000E+01	1.284E+01	1.384E+01
1.455E+01	1.568E+01	1.733E+01	2.000E+01	

```
HI-STAR containing MPC68F, 06x06 @ 3.0 wt% Enrich.
c     3.00 % uniform enrichment, unreflected cask, 0.0067 g/cmsq B-10 in Boral
c     Dresden-1 6x6
c
c
1     1 -10.522      -1  u=2        $ fuel
2     4 -1.0      1  -2  u=2        $ gap
3     3 -6.55     2  -3  u=2        $ Zr Clad
4     4 -1.0         3   u=2        $ water in fuel region
5     4 -1.0    -4:5     u=3        $ water in guide tubes
6     3 -6.55    4 -5    u=3        $ guide tubes
7     4 -1.0    -6    +7   -8    +9   u=1  lat=1
      fill= -4:3    -4:3    0:0
      1  1 1 1 1 1 1  1
      1  2 2 2 2 2 2  1
      1  2 2 2 2 2 2  1
      1  2 2 2 2 2 2  1
      1  2 2 2 2 2 2  1
      1  2 2 2 2 2 2  1
      1  2 2 2 2 2 2  1
      1  1 1 1 1 1 1  1
c
C  BOX TYPE R
c
8     0  -10    11  -12    13          u=4 fill=1 (0.8814  0.8814  0)
9     3  -6.55     60    -61     62    -63  #8       u=4     $ Zr flow channel
10    4  -1.       64    -65     66    -67  #8 #9    u=4     $ water
11    5  -7.84     20    -23     67    -14           u=4     $ 0.075" STEEL
12    4  -1.       20    -23     14    -15           u=4     $ WATER POCKET
13    7  -2.7      20    -23     15    -16           u=4     $ Al CLAD
14    6  -2.66     20    -23     16    -17           u=4     $ BORAL Absorber
15    7  -2.7      20    -23     17    -18           u=4     $ Al Clad
16    4  -1.       20    -23     18   -118           u=4     $ Water
17    5  -7.84     118:-129:65:-66                   u=4     $ Steel
18    4  -1.       64    -21     67   -118           u=4     $ Water
19    4  -1.       24    -65     67   -118           u=4     $ water
20    5  -7.84     21    -20     67   -118           u=4     $ Steel
21    5  -7.84     23    -24     67   -118           u=4     $ Steel
22    4  -1.      129    -64     33   -118           u=4     $ Water
c
23    5  -7.84     25    -64     30    -31           u=4     $ Steel
24    4  -1.       26    -25     30    -31           u=4     $ Water
25    7  -2.7      27    -26     30    -31           u=4     $ Al clad
26    6  -2.66     28    -27     30    -31           u=4     $ Boral
27    7  -2.7      29    -28     30    -31           u=4     $ Al clad
28    4  -1.      129    -29     30    -31           u=4     $ water
29    5  -7.84    129    -64     32    -30           u=4     $ Steel ends
30    5  -7.84    129    -64     31    -33           u=4     $ Steel ends
31    4  -1.      129    -64     66    -32           u=4     $ Water
c
c   Type A box - Boral only on left side
c
32    0  -10    11  -12    13          u=6 fill=1 (0.8814  0.8814  0)
33    3  -6.55     60    -61     62    -63  #8       u=6     $ Zr flow channel
34    4  -1.       64    -65     66   -118  #8 #9    u=6     $ water
35    5  -7.84     118:-129:65:-66                   u=6     $ Steel
36    4  -1.      129    -64     67   -118           u=6     $ Water
c
37    5  -7.84     25    -64     30    -31           u=6     $ Steel
38    4  -1.       26    -25     30    -31           u=6     $ Water
```

```
39    7  -2.7      27    -26     30    -31           u=6     $ Al clad
40    6  -2.66     28    -27     30    -31           u=6     $ Boral
41    7  -2.7      29    -28     30    -31           u=6     $ Al clad
42    4  -1.      129    -29     30    -31           u=6     $ water
43    4  -1.      129    -64     33    -67           u=6     $ Water
44    5  -7.84    129    -64     32    -30           u=6     $ Steel ends
45    5  -7.84    129    -64     31    -33           u=6     $ Steel ends
46    4  -1.      129    -64     66    -32           u=6     $ Water
c
c    Type B box -  Boral on Top only
c
47    0  -10   11  -12   13         u=7 fill=1 (0.8814  0.8814  0)
48    3  -6.55    60    -61     62    -63  #8      u=7     $ Zr flow channel
49    4  -1.      64    -65     66    -67  #8 #9   u=7     $ water
50    5  -7.84    20    -23     67    -14          u=7     $ 0.075" STEEL
51    4  -1.      20    -23     14    -15          u=7     $ WATER POCKET
52    7  -2.7     20    -23     15    -16          u=7     $ Al CLAD
53    6  -2.66    20    -23     16    -17          u=7     $ BORAL Absorber
54    7  -2.7     20    -23     17    -18          u=7     $ water
55    4  -1.      20    -23     18   -118          u=7     $ Water
56    5  -7.84    118:-129:65:-66                  u=7     $ Steel
57    4  -1.      64    -21     67   -118          u=7     $ Water
58    4  -1.      24    -65     67   -118          u=7     $ water
59    5  -7.84    21    -20     67   -118          u=7     $ Steel
60    5  -7.84    23    -24     67   -118          u=7     $ Steel
61    4  -1.     129    -64     66   -118          u=7     $ Water
c
c    Type E box  - No Boral Panels
c
62    0  -10   11  -12   13         u=8 fill=1 (0.8814  0.8814  0)
63    3  -6.55    60    -61     62    -63  #8      u=8     $ Zr flow channel
64    4  -1.     129    -65     66   -118  #8 #9   u=8     $ water
65    5  -7.84    118:-129:65:-66                  u=8     $ Steel
c
c    Type F box  - No Boral Panels or fuel
c
66    4  -1.     129    -65     66   -118          u=9     $ water
67    5  -7.84    118:-129:65:-66                  u=9     $ Steel
c
68    4  -1.0    -34  35  -36  37  u=5  lat=1  fill=-7:6  -7:6  0:0
               5 5 5 5 5 5 5 5 5 5 5 5 5 5
               5 9 9 9 9 9 9 9 9 9 9 9 9 5
               5 9 9 9 9 9 7 4 9 9 9 9 9 5
               5 9 9 9 7 4 4 4 4 4 9 9 9 5
               5 9 9 7 4 4 4 4 4 4 4 9 9 5
               5 9 9 7 4 4 4 4 4 4 4 9 9 5
               5 9 7 4 4 4 4 4 4 4 4 4 9 5
               5 9 8 4 4 4 4 4 4 4 4 6 9 5
               5 9 9 7 4 4 4 4 4 4 4 9 9 5
               5 9 9 8 4 4 4 4 4 4 6 9 9 5
               5 9 9 9 8 4 4 4 6 6 9 9 9 5
               5 9 9 9 9 9 8 6 9 9 9 9 9 5
               5 9 9 9 9 9 9 9 9 9 9 9 9 5
               5 5 5 5 5 5 5 5 5 5 5 5 5 5
69    0          -41               50  -49  fill=5 (8.1661  8.1661  0)
70    4  -1.0    -41        43  -50          $ Water below Fuel
71    4  -1.0    -41        49  -44          $ Water above Fuel
72    5  -7.84   -42        68  -43          $ Steel below Fuel
73    5  -7.84   -42        44  -69          $ Steel above Fuel
74    5  -7.84    41   -42  43  -44          $ Radial Steel
```

```
75     0          42 :-68:  69             $ outside world

1      cz        0.6274      $ Fuel OD
2      cz        0.6280      $ Clad ID
3      cz        0.7169      $ Clad OD
4      cz        0.6280      $ Thimble ID
5      cz        0.7169      $ Thimble OD
6      px        0.8814      $ Pin Pitch
7      px       -0.8814
8      py        0.8814
9      py       -0.8814
10     px        5.4483      $ Channel ID
11     px       -5.4483
12     py        5.4483
13     py       -5.4483
14     py        7.8016
15     py        7.8155
16     py        7.8410
17     py        8.0467
18     py        8.0721
118    py        8.0861
20     px       -6.0325
21     px       -6.2230
23     px        6.0325
24     px        6.2230
25     px       -7.8016
26     px       -7.8155
27     px       -7.8410
28     px       -8.0467
29     px       -8.0721
129    px       -8.0861
30     py       -6.0325
31     py        6.0325
32     py       -6.2230
33     py        6.2230
34     px        7.6111
35     px       -8.7211
36     py        8.7211
37     py       -7.6111
41     cz        85.57
42     cz        108.43
43     pz        11.46
44     pz        331.0
49     pz        309.4        $ Top of Active F
50     pz         30.         $ Start of Active
60     px        -5.6007      $ Channel OD
61     px         5.6007
62     py        -5.6007
63     py         5.6007
64     px        -7.6111      $ Cell Box ID
65     px         7.6111
66     py        -7.6111
67     py         7.6111
68     pz        -10.13
69     pz         370.36

imp:n     1 73r 0
kcode    10000  0.94   20  120
c
sdef  par=1  erg=d1 axs=0 0 1 x=d4 y=fx d5 z=d3
```

```
c
sp1 -2 1.2895
c
si3  h 30. 309.
sp3  0 1
c
c
si4  s             15 16
              13 14 15 16 17 18
           12 13 14 15 16 17 18 19
           12 13 14 15 16 17 18 19
        11 12 13 14 15 16 17 18 19 20
        11 12 13 14 15 16 17 18 19 20
           12 13 14 15 16 17 18 19
           12 13 14 15 16 17 18 19
              13 14 15 16 17 18
                    15 16
sp4  1 67r
c
ds5  s             30 30
              29 29 29 29 29 29
           28 28 28 28 28 28 28 28
           27 27 27 27 27 27 27 27
        26 26 26 26 26 26 26 26 26 26
        25 25 25 25 25 25 25 25 25 25
           24 24 24 24 24 24 24 24
           23 23 23 23 23 23 23 23
              22 22 22 22 22 22
                    21 21
c
si11  -80.6831 -67.6783
si12  -64.1985 -51.1937
si13  -47.7139 -34.7091
si14  -31.2293 -18.2245
si15  -14.7447 -1.7399
si16   1.7399   14.7447
si17   18.2245  31.2293
si18   34.7091  47.7139
si19   51.1937  64.1985
si20   67.6783  80.6831
c
si21  -80.6831 -67.6783
si22  -64.1985 -51.1937
si23  -47.7139 -34.7091
si24  -31.2293 -18.2245
si25  -14.7447 -1.7399
si26   1.7399   14.7447
si27   18.2245  31.2293
si28   34.7091  47.7139
si29   51.1937  64.1985
si30   67.6783  80.6831
sp11  0 1
sp12  0 1
sp13  0 1
sp14  0 1
sp15  0 1
sp16  0 1
sp17  0 1
sp18  0 1
sp19  0 1
```

```
sp20   0 1
sp21   0 1
sp22   0 1
sp23   0 1
sp24   0 1
sp25   0 1
sp26   0 1
sp27   0 1
sp28   0 1
sp29   0 1
sp30   0 1
c
m1          92235.50c   -0.02644      $ 3.00% E Fuel
            92238.50c   -0.85504
            8016.50c    -0.11852
m3          40000.56c   1.            $ Zr Clad
m4          1001.50c    0.6667        $ Water
            8016.50c    0.3333
m5          24000.50c   0.01761       $ Steel
            25055.50c   0.001761
            26000.55c   0.05977
            28000.50c   0.008239
m6          5010.50c  1.9592E-03      $ Boral 0.0067 gm/cm2
            5011.50c  8.1175E-03
            6000.50c  2.5176E-03
            13027.50c 5.4933E-02
m7          13027.50c    1.           $ Al Clad
mt4         lwtr.01t
prdmp     j   -120    j    2
fm4       1000    1    -6
f4:n    1
sd4       1000
e4    1.000E-11   1.000E-10   5.000E-10   7.500E-10   1.000E-09   1.200E-09
      1.500E-09   2.000E-09   2.500E-09   3.000E-09
      4.700E-09   5.000E-09   7.500E-09   1.000E-08   2.530E-08
      3.000E-08   4.000E-08   5.000E-08   6.000E-08   7.000E-08
      8.000E-08   9.000E-08   1.000E-07   1.250E-07   1.500E-07
      1.750E-07   2.000E-07   2.250E-07   2.500E-07   2.750E-07
      3.000E-07   3.250E-07   3.500E-07   3.750E-07   4.000E-07
      4.500E-07   5.000E-07   5.500E-07   6.000E-07   6.250E-07
      6.500E-07   7.000E-07   7.500E-07   8.000E-07   8.500E-07
      9.000E-07   9.250E-07   9.500E-07   9.750E-07   1.000E-06
      1.010E-06   1.020E-06   1.030E-06   1.040E-06   1.050E-06
      1.060E-06   1.070E-06   1.080E-06   1.090E-06   1.100E-06
      1.110E-06   1.120E-06   1.130E-06   1.140E-06   1.150E-06
      1.175E-06   1.200E-06   1.225E-06   1.250E-06   1.300E-06
      1.350E-06   1.400E-06   1.450E-06   1.500E-06   1.590E-06
      1.680E-06   1.770E-06   1.860E-06   1.940E-06   2.000E-06
      2.120E-06   2.210E-06   2.300E-06   2.380E-06   2.470E-06
      2.570E-06   2.670E-06   2.770E-06   2.870E-06   2.970E-06
      3.000E-06   3.050E-06   3.150E-06   3.500E-06   3.730E-06
      4.000E-06   4.750E-06   5.000E-06   5.400E-06   6.000E-06
      6.250E-06   6.500E-06   6.750E-06   7.000E-06   7.150E-06
      8.100E-06   9.100E-06   1.000E-05   1.150E-05   1.190E-05
      1.290E-05   1.375E-05   1.440E-05   1.510E-05   1.600E-05
      1.700E-05   1.850E-05   1.900E-05   2.000E-05   2.100E-05
      2.250E-05   2.500E-05   2.750E-05   3.000E-05   3.125E-05
      3.175E-05   3.325E-05   3.375E-05   3.460E-05   3.550E-05
      3.700E-05   3.800E-05   3.910E-05   3.960E-05   4.100E-05
      4.240E-05   4.400E-05   4.520E-05   4.700E-05   4.830E-05
```

4.920E-05	5.060E-05	5.200E-05	5.340E-05	5.900E-05
6.100E-05	6.500E-05	6.750E-05	7.200E-05	7.600E-05
8.000E-05	8.200E-05	9.000E-05	1.000E-04	1.080E-04
1.150E-04	1.190E-04	1.220E-04	1.860E-04	1.925E-04
2.075E-04	2.100E-04	2.400E-04	2.850E-04	3.050E-04
5.500E-04	6.700E-04	6.830E-04	9.500E-04	1.150E-03
1.500E-03	1.550E-03	1.800E-03	2.200E-03	2.290E-03
2.580E-03	3.000E-03	3.740E-03	3.900E-03	6.000E-03
8.030E-03	9.500E-03	1.300E-02	1.700E-02	2.500E-02
3.000E-02	4.500E-02	5.000E-02	5.200E-02	6.000E-02
7.300E-02	7.500E-02	8.200E-02	8.500E-02	1.000E-01
1.283E-01	1.500E-01	2.000E-01	2.700E-01	3.300E-01
4.000E-01	4.200E-01	4.400E-01	4.700E-01	4.995E-01
5.500E-01	5.730E-01	6.000E-01	6.700E-01	6.790E-01
7.500E-01	8.200E-01	8.611E-01	8.750E-01	9.000E-01
9.200E-01	1.010E+00	1.100E+00	1.200E+00	1.250E+00
1.317E+00	1.356E+00	1.400E+00	1.500E+00	1.850E+00
2.354E+00	2.479E+00	3.000E+00	4.304E+00	4.800E+00
6.434E+00	8.187E+00	1.000E+01	1.284E+01	1.384E+01
1.455E+01	1.568E+01	1.733E+01	2.000E+01	

```
HI-STAR containing MPC68F, 06x06 in DFC with 08 missing rods
c     3.00 % uniform enrichment, unreflected cask, 0.0067 g/cmsq B-10 in Boral
c
c
1     1 -10.522     -1   u=2        $ fuel
2     4 -1.0      1  -2   u=2        $ gap
3     3 -6.55     2  -3   u=2        $ Zr Clad
4     4 -1.0          3   u=2        $ water in fuel region
5     4 -1.0    -4:5      u=3        $ water in guide tubes
6     3 -6.55    4 -5     u=3        $ guide tubes
7     4 -1.0    -6   +7    -8    +9    u=1  lat=1
      fill= -4:3     -4:3    0:0
      1  1 1 1 1 1 1  1
      1  2 2 2 2 2 2  1
      1  2 1 2 1 2 2  1
      1  2 2 1 2 1 2  1
      1  2 1 2 1 2 2  1
      1  2 2 1 2 1 2  1
      1  2 2 2 2 2 2  1
      1  1 1 1 1 1 1  1
c
C  BOX TYPE R
c
8     0  -10    11   -12    13          u=4 fill=1 (0.8814  0.8814  0)
9     3  -6.55    60    -61     62    -63  #8       u=4      $ Zr flow channel
100   5  -7.84    74 -75 76 -77 (-70:71:-72:73)  u=4      $ DFC
10    4  -1.      64    -65     66    -67  #8 #9 #100  u=4 $ water
11    5  -7.84    20    -23     67    -14           u=4      $ 0.075" STEEL
12    4  -1.      20    -23     14    -15           u=4      $ WATER POCKET
13    7  -2.7     20    -23     15    -16           u=4      $ Al CLAD
14    6  -2.66    20    -23     16    -17           u=4      $ BORAL Absorber
15    7  -2.7     20    -23     17    -18           u=4      $ Al Clad
16    4  -1.      20    -23     18   -118           u=4      $ Water
17    5  -7.84    118:-129:65:-66                   u=4      $ Steel
18    4  -1.      64    -21     67    -118          u=4      $ Water
19    4  -1.      24    -65     67    -118          u=4      $ water
20    5  -7.84    21    -20     67    -118          u=4      $ Steel
21    5  -7.84    23    -24     67    -118          u=4      $ Steel
22    4  -1.     129    -64     33    -118          u=4      $ Water
c
23    5  -7.84    25    -64     30    -31           u=4      $ Steel
24    4  -1.      26    -25     30    -31           u=4      $ Water
25    7  -2.7     27    -26     30    -31           u=4      $ Al clad
26    6  -2.66    28    -27     30    -31           u=4      $ Boral
27    7  -2.7     29    -28     30    -31           u=4      $ Al clad
28    4  -1.     129    -29     30    -31           u=4      $ water
29    5  -7.84   129    -64     32    -30           u=4      $ Steel ends
30    5  -7.84   129    -64     31    -33           u=4      $ Steel ends
31    4  -1.     129    -64     66    -32           u=4      $ Water
c
c    Type A box - Boral only on left side
c
32    0  -10    1i   -12    13          u=6 fill=1 (0.8814  0.8814  0)
33    3  -6.55    60    -61     62    -63  #8       u=6      $ Zr flow channel
101   5  -7.84    74 -75 76 -77 (-70:71:-72:73)  u=6      $ DFC
34    4  -1.      64    -65     66   -118  #8 #9 #101 u=6  $ water
35    5  -7.84    118:-129:65:-66                   u=6      $ Steel
36    4  -1.     129    -64     67    -118          u=6      $ Water
c
37    5  -7.84    25    -64     30    -31           u=6      $ Steel
```

```
38    4  -1.      26   -25    30   -31          u=6     $ Water
39    7  -2.7     27   -26    30   -31          u=6     $ Al clad
40    6  -2.66    28   -27    30   -31          u=6     $ Boral
41    7  -2.7     29   -28    30   -31          u=6     $ Al clad
42    4  -1.     129   -29    30   -31          u=6     $ water
43    4  -1.     129   -64    33   -67          u=6     $ Water
44    5  -7.84   129   -64    32   -30          u=6     $ Steel ends
45    5  -7.84   129   -64    31   -33          u=6     $ Steel ends
46    4  -1.     129   -64    66   -32          u=6     $ Water
c
c     Type B box -  Boral on Top only
c
47    0  -10   11  -12   13          u=7 fill=1 (0.8814  0.8814  0)
48    3  -6.55    60   -61    62   -63  #8      u=7     $ Zr flow channel
102   5  -7.84   74 -75 76 -77 (-70:71:-72:73)  u=7     $ DFC
49    4  -1.      64   -65    66   -67  #8 #9 #102 u=7  $ water
50    5  -7.84    20   -23    67   -14          u=7     $ 0.075" STEEL
51    4  -1.      20   -23    14   -15          u=7     $ WATER POCKET
52    7  -2.7     20   -23    15   -16          u=7     $ Al CLAD
53    6  -2.66    20   -23    16   -17          u=7     $ BORAL Absorber
54    7  -2.7     20   -23    17   -18          u=7     $ water
55    4  -1.      20   -23    18  -118          u=7     $ Water
56    5  -7.84    118:-129:65:-66               u=7     $ Steel
57    4  -1.      64   -21    67  -118          u=7     $ Water
58    4  -1.      24   -65    67  -118          u=7     $ water
59    5  -7.84    21   -20    67  -118          u=7     $ Steel
60    5  -7.84    23   -24    67  -118          u=7     $ Steel
61    4  -1.     129   -64    66  -118          u=7     $ Water
c
c     Type E box  - No Boral Panels
c
62    0  -10   11  -12   13          u=8 fill=1 (0.8814  0.8814  0)
63    3  -6.55    60   -61    62   -63  #8      u=8     $ Zr flow channel
103   5  -7.84   74 -75 76 -77 (-70:71:-72:73)  u=8     $ DFC
64    4  -1.     129   -65    66  -118  #8 #9 #103 u=8  $ water
65    5  -7.84    118:-129:65:-66               u=8     $ Steel
c
c     Type F box  - No Boral Panels or fuel
c
66    4  -1.     129   -65    66  -118          u=9     $ water
67    5  -7.84    118:-129:65:-66               u=9     $ Steel
c
68    4  -1.0    -34  35  -36  37  u=5  lat=1  fill=-7:6  -7:6  0:0
                5 5 5 5 5 5 5 5 5 5 5 5 5 5
                5 9 9 9 9 9 9 9 9 9 9 9 9 5
                5 9 9 9 9 9 7 4 9 9 9 9 9 5
                5 9 9 9 7 4 4 4 4 4 9 9 9 5
                5 9 9 7 4 4 4 4 4 4 4 9 9 5
                5 9 9 7 4 4 4 4 4 4 4 9 9 5
                5 9 7 4 4 4 4 4 4 4 4 4 9 5
                5 9 8 4 4 4 4 4 4 4 4 6 9 5
                5 9 9 7 4 4 4 4 4 4 4 9 9 5
                5 9 9 8 4 4 4 4 4 4 6 9 9 5
                5 9 9 9 8 4 4 4 6 6 9 9 9 5
                5 9 9 9 9 9 8 6 9 9 9 9 9 5
                5 9 9 9 9 9 9 9 9 9 9 9 9 5
                5 5 5 5 5 5 5 5 5 5 5 5 5 5
69    0          -41                50  -49  fill=5 (8.1661  8.1661  0)
70    4  -1.0    -41         43  -50            $ Water below Fuel
71    4  -1.0    -41         49  -44            $ Water above Fuel
```

```
72      5   -7.84    -42         68   -43            $ Steel below Fuel
73      5   -7.84    -42         44   -69            $ Steel above Fuel
74      5   -7.84     41   -42   43   -44            $ Radial Steel
75      0              42 :-68:   69                 $ outside world

1       cz            0.6274      $ Fuel OD
2       cz            0.6280      $ Clad ID
3       cz            0.7169      $ Clad OD
4       cz            0.6280      $ Thimble ID
5       cz            0.7169      $ Thimble OD
6       px            0.8814      $ Pin Pitch
7       px           -0.8814
8       py            0.8814
9       py           -0.8814
10      px            5.4483      $ Channel ID
11      px           -5.4483
12      py            5.4483
13      py           -5.4483
14      py            7.8016
15      py            7.8155
16      py            7.8410
17      py            8.0467
18      py            8.0721
118     py            8.0861
20      px           -6.0325
21      px           -6.2230
23      px            6.0325
24      px            6.2230
25      px           -7.8016
26      px           -7.8155
27      px           -7.8410
28      px           -8.0467
29      px           -8.0721
129     px           -8.0861
30      py           -6.0325
31      py            6.0325
32      py           -6.2230
33      py            6.2230
34      px            7.6111
35      px           -8.7211
36      py            8.7211
37      py           -7.6111
41      cz            85.57
42      cz            108.43
43      pz            11.46
44      pz            331.0
49      pz            309.4       $ Top of Active F
50      pz             30.        $ Start of Active
60      px           -5.6007      $ Channel OD
61      px            5.6007
62      py           -5.6007
63      py            5.6007
64      px           -7.6111      $ Cell Box ID
65      px            7.6111
66      py           -7.6111
67      py            7.6111
68      pz           -10.13
69      pz            370.36
70      px           -6.2611      $ DFC ID
71      px            6.2611
```

```
72    py          -6.2611
73    py           6.2611
74    px          -6.5659       $ DFC OD
75    px           6.5659
76    py          -6.5659
77    py           6.5659

imp:n     1 77r 0
kcode    10000  0.94   20  120
c
sdef  par=1  erg=d1 axs=0 0 1 x=d4 y=fx d5 z=d3
c
sp1 -2 1.2895
c
si3  h 30. 309.
sp3  0 1
c
c
si4  s                 15 16
                 13 14 15 16 17 18
              12 13 14 15 16 17 18 19
              12 13 14 15 16 17 18 19
           11 12 13 14 15 16 17 18 19 20
           11 12 13 14 15 16 17 18 19 20
              12 13 14 15 16 17 18 19
              12 13 14 15 16 17 18 19
                 13 14 15 16 17 18
                       15 16
sp4  1 67r
c
ds5  s                 30 30
                 29 29 29 29 29 29
              28 28 28 28 28 28 28 28
              27 27 27 27 27 27 27 27
           26 26 26 26 26 26 26 26 26 26
           25 25 25 25 25 25 25 25 25 25
              24 24 24 24 24 24 24 24
              23 23 23 23 23 23 23 23
                 22 22 22 22 22 22
                       21 21
c
si11  -80.6831 -67.6783
si12  -64.1985 -51.1937
si13  -47.7139 -34.7091
si14  -31.2293 -18.2245
si15  -14.7447 -1.7399
si16   1.7399   14.7447
si17   18.2245  31.2293
si18   34.7091  47.7139
si19   51.1937  64.1985
si20   67.6783  80.6831
c
si21  -80.6831 -67.6783
si22  -64.1985 -51.1937
si23  -47.7139 -34.7091
si24  -31.2293 -18.2245
si25  -14.7447 -1.7399
si26   1.7399   14.7447
si27   18.2245  31.2293
si28   34.7091  47.7139
```

```
si29    51.1937  64.1985
si30    67.6783  80.6831
sp11   0 1
sp12   0 1
sp13   0 1
sp14   0 1
sp15   0 1
sp16   0 1
sp17   0 1
sp18   0 1
sp19   0 1
sp20   0 1
sp21   0 1
sp22   0 1
sp23   0 1
sp24   0 1
sp25   0 1
sp26   0 1
sp27   0 1
sp28   0 1
sp29   0 1
sp30   0 1
c
m1             92235.50c   -0.02644       $ 3.00% E Fuel
               92238.50c   -0.85504
               8016.50c    -0.11852
m3             40000.56c   1.            $ Zr Clad
m4             1001.50c    0.6667        $ Water
               8016.50c    0.3333
m5             24000.50c   0.01761       $ Steel
               25055.50c   0.001761
               26000.55c   0.05977
               28000.50c   0.008239
m6             5010.50c  1.9592E-03       $ Boral 0.0067 gm/cm2
               5011.50c  8.1175E-03
               6000.50c  2.5176E-03
               13027.50c 5.4933E-02
m7             13027.50c    1.            $ Al Clad
mt4          lwtr.01t
prdmp     j    -120    j    2
fm4       1000    1    -6
f4:n    1
sd4       1000
e4     1.000E-11   1.000E-10   5.000E-10   7.500E-10   1.000E-09   1.200E-09
       1.500E-09   2.000E-09   2.500E-09   3.000E-09
       4.700E-09   5.000E-09   7.500E-09   1.000E-08   2.530E-08
       3.000E-08   4.000E-08   5.000E-08   6.000E-08   7.000E-08
       8.000E-08   9.000E-08   1.000E-07   1.250E-07   1.500E-07
       1.750E-07   2.000E-07   2.250E-07   2.500E-07   2.750E-07
       3.000E-07   3.250E-07   3.500E-07   3.750E-07   4.000E-07
       4.500E-07   5.000E-07   5.500E-07   6.000E-07   6.250E-07
       6.500E-07   7.000E-07   7.500E-07   8.000E-07   8.500E-07
       9.000E-07   9.250E-07   9.500E-07   9.750E-07   1.000E-06
       1.010E-06   1.020E-06   1.030E-06   1.040E-06   1.050E-06
       1.060E-06   1.070E-06   1.080E-06   1.090E-06   1.100E-06
       1.110E-06   1.120E-06   1.130E-06   1.140E-06   1.150E-06
       1.175E-06   1.200E-06   1.225E-06   1.250E-06   1.300E-06
       1.350E-06   1.400E-06   1.450E-06   1.500E-06   1.590E-06
       1.680E-06   1.770E-06   1.860E-06   1.940E-06   2.000E-06
       2.120E-06   2.210E-06   2.300E-06   2.380E-06   2.470E-06
```

2.570E-06	2.670E-06	2.770E-06	2.870E-06	2.970E-06
3.000E-06	3.050E-06	3.150E-06	3.500E-06	3.730E-06
4.000E-06	4.750E-06	5.000E-06	5.400E-06	6.000E-06
6.250E-06	6.500E-06	6.750E-06	7.000E-06	7.150E-06
8.100E-06	9.100E-06	1.000E-05	1.150E-05	1.190E-05
1.290E-05	1.375E-05	1.440E-05	1.510E-05	1.600E-05
1.700E-05	1.850E-05	1.900E-05	2.000E-05	2.100E-05
2.250E-05	2.500E-05	2.750E-05	3.000E-05	3.125E-05
3.175E-05	3.325E-05	3.375E-05	3.460E-05	3.550E-05
3.700E-05	3.800E-05	3.910E-05	3.960E-05	4.100E-05
4.240E-05	4.400E-05	4.520E-05	4.700E-05	4.830E-05
4.920E-05	5.060E-05	5.200E-05	5.340E-05	5.900E-05
6.100E-05	6.500E-05	6.750E-05	7.200E-05	7.600E-05
8.000E-05	8.200E-05	9.000E-05	1.000E-04	1.080E-04
1.150E-04	1.190E-04	1.220E-04	1.860E-04	1.925E-04
2.075E-04	2.100E-04	2.400E-04	2.850E-04	3.050E-04
5.500E-04	6.700E-04	6.830E-04	9.500E-04	1.150E-03
1.500E-03	1.550E-03	1.800E-03	2.200E-03	2.290E-03
2.580E-03	3.000E-03	3.740E-03	3.900E-03	6.000E-03
8.030E-03	9.500E-03	1.300E-02	1.700E-02	2.500E-02
3.000E-02	4.500E-02	5.000E-02	5.200E-02	6.000E-02
7.300E-02	7.500E-02	8.200E-02	8.500E-02	1.000E-01
1.283E-01	1.500E-01	2.000E-01	2.700E-01	3.300E-01
4.000E-01	4.200E-01	4.400E-01	4.700E-01	4.995E-01
5.500E-01	5.730E-01	6.000E-01	6.700E-01	6.790E-01
7.500E-01	8.200E-01	8.611E-01	8.750E-01	9.000E-01
9.200E-01	1.010E+00	1.100E+00	1.200E+00	1.250E+00
1.317E+00	1.356E+00	1.400E+00	1.500E+00	1.850E+00
2.354E+00	2.479E+00	3.000E+00	4.304E+00	4.800E+00
6.434E+00	8.187E+00	1.000E+01	1.284E+01	1.384E+01
1.455E+01	1.568E+01	1.733E+01	2.000E+01	

```
HI-STAR containing MPC68F, 07x07 in DFC with 13 missing rods
c     3.00 % uniform enrichment, unreflected cask, 0.0067 g/cmsq B-10 in Boral
c
c
1     1 -10.522      -1  u=2        $ fuel
2     4 -1.0      1  -2  u=2        $ gap
3     3 -6.55     2  -3  u=2        $ Zr Clad
4     4 -1.0         3   u=2        $ water in fuel region
5     4 -1.0    -4:5     u=3        $ water in guide tubes
6     3 -6.55    4 -5    u=3        $ guide tubes
7     4 -1.0    -6   +7   -8   +9    u=1  lat=1
      fill= -4:4    -4:4    0:0
      1  1 1 1 1 1 1 1  1
      1  2 2 2 2 2 2 2  1
      1  2 1 2 1 2 1 2  1
      1  2 2 1 2 1 2 2  1
      1  2 1 2 1 2 1 2  1
      1  2 2 1 2 1 2 2  1
      1  2 1 2 1 2 1 2  1
      1  2 2 2 2 2 2 2  1
      1  1 1 1 1 1 1 1  1
c
C  BOX TYPE R
c
8     0  -10   11  -12   13          u=4 fill=1
9     3  -6.55    60   -61    62   -63  #8        u=4      $ Zr flow channel
100   5  -7.84   74 -75 76 -77 (-70:71:-72:73)  u=4      $ DFC
10    4  -1.      64   -65    66   -67  #8 #9 #100 u=4   $ water
11    5  -7.84    20   -23    67   -14            u=4      $ 0.075" STEEL
12    4  -1.      20   -23    14   -15            u=4      $ WATER POCKET
13    7  -2.7     20   -23    15   -16            u=4      $ Al CLAD
14    6  -2.66    20   -23    16   -17            u=4      $ BORAL Absorber
15    7  -2.7     20   -23    17   -18            u=4      $ Al Clad
16    4  -1.      20   -23    18  -118            u=4      $ Water
17    5  -7.84    118:-129:65:-66                 u=4      $ Steel
18    4  -1.      64   -21    67   -118           u=4      $ Water
19    4  -1.      24   -65    67   -118           u=4      $ water
20    5  -7.84    21   -20    67   -118           u=4      $ Steel
21    5  -7.84    23   -24    67   -118           u=4      $ Steel
22    4  -1.     129   -64    33   -118           u=4      $ Water
c
23    5  -7.84    25   -64    30   -31            u=4      $ Steel
24    4  -1.      26   -25    30   -31            u=4      $ Water
25    7  -2.7     27   -26    30   -31            u=4      $ Al clad
26    6  -2.66    28   -27    30   -31            u=4      $ Boral
27    7  -2.7     29   -28    30   -31            u=4      $ Al clad
28    4  -1.     129   -29    30   -31            u=4      $ water
29    5  -7.84   129   -64    32   -30            u=4      $ Steel ends
30    5  -7.84   129   -64    31   -33            u=4      $ Steel ends
31    4  -1.     129   -64    66   -32            u=4      $ Water
c
c    Type A box - Boral only on left side
c
32    0  -10   11  -12   13          u=6 fill=1
33    3  -6.55    60   -61    62   -63  #8        u=6      $ Zr flow channel
101   5  -7.84   74 -75 76 -77 (-70:71:-72:73)  u=6      $ DFC
34    4  -1.      64   -65    66   -118 #8 #9 #101 u=6   $ water
35    5  -7.84    118:-129:65:-66                 u=6      $ Steel
36    4  -1.     129   -64    67   -118           u=6      $ Water
c
```

```
37     5  -7.84     25    -64     30    -31            u=6      $ Steel
38     4  -1.       26    -25     30    -31            u=6      $ Water
39     7  -2.7      27    -26     30    -31            u=6      $ Al clad
40     6  -2.66     28    -27     30    -31            u=6      $ Boral
41     7  -2.7      29    -28     30    -31            u=6      $ Al clad
42     4  -1.      129    -29     30    -31            u=6      $ water
43     4  -1.      129    -64     33    -67            u=6      $ Water
44     5  -7.84    129    -64     32    -30            u=6      $ Steel ends
45     5  -7.84    129    -64     31    -33            u=6      $ Steel ends
46     4  -1.      129    -64     66    -32            u=6      $ Water
c
c    Type B box -  Boral on Top only
c
47     0  -10    11  -12    13          u=7 fill=1
48     3  -6.55     60    -61     62    -63  #8        u=7      $ Zr flow channel
102    5  -7.84    74 -75 76 -77 (-70:71:-72:73)  u=7      $ DFC
49     4  -1.       64    -65     66    -67  #8 #9 #102 u=7   $ water
50     5  -7.84     20    -23     67    -14            u=7      $ 0.075" STEEL
51     4  -1.       20    -23     14    -15            u=7      $ WATER POCKET
52     7  -2.7      20    -23     15    -16            u=7      $ Al CLAD
53     6  -2.66     20    -23     16    -17            u=7      $ BORAL Absorber
54     7  -2.7      20    -23     17    -18            u=7      $ water
55     4  -1.       20    -23     18  -118             u=7      $ Water
56     5  -7.84     118:-129:65:-66                    u=7      $ Steel
57     4  -1.       64    -21     67    -118           u=7      $ Water
58     4  -1.       24    -65     67    -118           u=7      $ water
59     5  -7.84     21    -20     67    -118           u=7      $ Steel
60     5  -7.84     23    -24     67    -118           u=7      $ Steel
61     4  -1.      129    -64     66    -118           u=7      $ Water
c
c    Type E box  - No Boral Panels
c
62     0  -10    11  -12    13          u=8 fill=1
63     3  -6.55     60    -61     62    -63  #8        u=8      $ Zr flow channel
103    5  -7.84    74 -75 76 -77 (-70:71:-72:73)  u=8      $ DFC
64     4  -1.      129    -65     66  -118  #8 #9 #103 u=8   $ water
65     5  -7.84     118:-129:65:-66                    u=8      $ Steel
c
c    Type F box  - No Boral Panels or fuel
c
66     4  -1.      129    -65     66  -118             u=9      $ water
67     5  -7.84     118:-129:65:-66                    u=9      $ Steel
c
68     4  -1.0     -34   35   -36   37   u=5   lat=1   fill=-7:6   -7:6   0:0
                 5 5 5 5 5 5 5 5 5 5 5 5 5 5
                 5 9 9 9 9 9 9 9 9 9 9 9 9 5
                 5 9 9 9 9 9 7 4 9 9 9 9 9 5
                 5 9 9 9 7 4 4 4 4 4 9 9 9 5
                 5 9 9 7 4 4 4 4 4 4 4 9 9 5
                 5 9 9 7 4 4 4 4 4 4 4 9 9 5
                 5 9 7 4 4 4 4 4 4 4 4 4 9 5
                 5 9 8 4 4 4 4 4 4 4 4 6 9 5
                 5 9 9 7 4 4 4 4 4 4 4 9 9 5
                 5 9 9 8 4 4 4 4 4 4 6 9 9 5
                 5 9 9 9 8 4 4 4 6 6 9 9 9 5
                 5 9 9 9 9 9 8 6 9 9 9 9 9 5
                 5 9 9 9 9 9 9 9 9 9 9 9 9 5
                 5 5 5 5 5 5 5 5 5 5 5 5 5 5
69     0            -41              50   -49   fill=5 (8.1661   8.1661   0)
70     4  -1.0     -41         43   -50           $ Water below Fuel
```

```
71     4  -1.0    -41        49  -44              $ Water above Fuel
72     5  -7.84   -42        68  -43              $ Steel below Fuel
73     5  -7.84   -42        44  -69              $ Steel above Fuel
74     5  -7.84    41  -42  43  -44               $ Radial Steel
75     0            42 :-68:  69                  $ outside world

1      cz          0.5220    $ Fuel OD
2      cz          0.5334    $ Clad ID
3      cz          0.6172    $ Clad OD
4      cz          0.5398    $ Thimble ID
5      cz          0.6261    $ Thimble OD
6      px          0.8014    $ Pin Pitch
7      px         -0.8014
8      py          0.8014
9      py         -0.8014
10     px          5.7684    $ Channel ID
11     px         -5.7684
12     py          5.7684
13     py         -5.7684
14     py          7.8016
15     py          7.8155
16     py          7.8410
17     py          8.0467
18     py          8.0721
118    py          8.0861
20     px         -6.0325
21     px         -6.2230
23     px          6.0325
24     px          6.2230
25     px         -7.8016
26     px         -7.8155
27     px         -7.8410
28     px         -8.0467
29     px         -8.0721
129    px         -8.0861
30     py         -6.0325
31     py          6.0325
32     py         -6.2230
33     py          6.2230
34     px          7.6111
35     px         -8.7211
36     py          8.7211
37     py         -7.6111
41     cz          85.57
42     cz          108.43
43     pz          11.46
44     pz          252.15
49     pz          230.66     $ Top of Active Fuel
50     pz          30.        $ Start of Active Fuel
60     px         -5.9207     $ Channel OD
61     px          5.9207
62     py         -5.9207
63     py          5.9207
64     px         -7.6111     $ Cell Box ID
65     px          7.6111
66     py         -7.6111
67     py          7.6111
68     pz         -10.13
69     pz          291.52
70     px         -6.2611       $ DFC ID
```

```
71     px          6.2611
72     py         -6.2611
73     py          6.2611
74     px         -6.5659       $ DFC OD
75     px          6.5659
76     py         -6.5659
77     py          6.5659

imp:n     1 77r 0
kcode   10000  0.94   20  120
c
sdef  par=1  erg=d1 axs=0 0 1 x=d4 y=fx d5 z=d3
c
sp1 -2 1.2895
c
si3  h 30. 230.66
sp3  0 1
c
c
si4  s              15 16
              13 14 15 16 17 18
           12 13 14 15 16 17 18 19
           12 13 14 15 16 17 18 19
        11 12 13 14 15 16 17 18 19 20
        11 12 13 14 15 16 17 18 19 20
           12 13 14 15 16 17 18 19
           12 13 14 15 16 17 18 19
              13 14 15 16 17 18
                    15 16
sp4  1 67r
c
ds5  s              30 30
              29 29 29 29 29 29
           28 28 28 28 28 28 28 28
           27 27 27 27 27 27 27 27
        26 26 26 26 26 26 26 26 26 26
        25 25 25 25 25 25 25 25 25 25
           24 24 24 24 24 24 24 24
           23 23 23 23 23 23 23 23
              22 22 22 22 22 22
                    21 21
c
si11  -80.6831 -67.6783
si12  -64.1985 -51.1937
si13  -47.7139 -34.7091
si14  -31.2293 -18.2245
si15  -14.7447 -1.7399
si16   1.7399   14.7447
si17   18.2245  31.2293
si18   34.7091  47.7139
si19   51.1937  64.1985
si20   67.6783  80.6831
c
si21  -80.6831 -67.6783
si22  -64.1985 -51.1937
si23  -47.7139 -34.7091
si24  -31.2293 -18.2245
si25  -14.7447 -1.7399
si26   1.7399   14.7447
si27   18.2245  31.2293
```

```
si28    34.7091  47.7139
si29    51.1937  64.1985
si30    67.6783  80.6831
sp11   0 1
sp12   0 1
sp13   0 1
sp14   0 1
sp15   0 1
sp16   0 1
sp17   0 1
sp18   0 1
sp19   0 1
sp20   0 1
sp21   0 1
sp22   0 1
sp23   0 1
sp24   0 1
sp25   0 1
sp26   0 1
sp27   0 1
sp28   0 1
sp29   0 1
sp30   0 1
c
m1          92235.50c   -0.02644      $ 3.00% E Fuel
            92238.50c   -0.85504
            8016.50c    -0.11852
m3          40000.56c   1.           $ Zr Clad
m4          1001.50c    0.6667       $ Water
            8016.50c    0.3333
m5          24000.50c   0.01761      $ Steel
            25055.50c   0.001761
            26000.55c   0.05977
            28000.50c   0.008239
m6          5010.50c  1.9592E-03      $ Boral 0.0067 gm/cm2
            5011.50c  8.1175E-03
            6000.50c  2.5176E-03
            13027.50c 5.4933E-02
m7          13027.50c   1.            $ Al Clad
mt4        lwtr.01t
prdmp    j   -120    j   2
fm4      1000   1   -6
f4:n    1
sd4      1000
e4    1.000E-11  1.000E-10  5.000E-10  7.500E-10  1.000E-09  1.200E-09
      1.500E-09  2.000E-09  2.500E-09  3.000E-09
      4.700E-09  5.000E-09  7.500E-09  1.000E-08  2.530E-08
      3.000E-08  4.000E-08  5.000E-08  6.000E-08  7.000E-08
      8.000E-08  9.000E-08  1.000E-07  1.250E-07  1.500E-07
      1.750E-07  2.000E-07  2.250E-07  2.500E-07  2.750E-07
      3.000E-07  3.250E-07  3.500E-07  3.750E-07  4.000E-07
      4.500E-07  5.000E-07  5.500E-07  6.000E-07  6.250E-07
      6.500E-07  7.000E-07  7.500E-07  8.000E-07  8.500E-07
      9.000E-07  9.250E-07  9.500E-07  9.750E-07  1.000E-06
      1.010E-06  1.020E-06  1.030E-06  1.040E-06  1.050E-06
      1.060E-06  1.070E-06  1.080E-06  1.090E-06  1.100E-06
      1.110E-06  1.120E-06  1.130E-06  1.140E-06  1.150E-06
      1.175E-06  1.200E-06  1.225E-06  1.250E-06  1.300E-06
      1.350E-06  1.400E-06  1.450E-06  1.500E-06  1.590E-06
      1.680E-06  1.770E-06  1.860E-06  1.940E-06  2.000E-06
```

2.120E-06	2.210E-06	2.300E-06	2.380E-06	2.470E-06
2.570E-06	2.670E-06	2.770E-06	2.870E-06	2.970E-06
3.000E-06	3.050E-06	3.150E-06	3.500E-06	3.730E-06
4.000E-06	4.750E-06	5.000E-06	5.400E-06	6.000E-06
6.250E-06	6.500E-06	6.750E-06	7.000E-06	7.150E-06
8.100E-06	9.100E-06	1.000E-05	1.150E-05	1.190E-05
1.290E-05	1.375E-05	1.440E-05	1.510E-05	1.600E-05
1.700E-05	1.850E-05	1.900E-05	2.000E-05	2.100E-05
2.250E-05	2.500E-05	2.750E-05	3.000E-05	3.125E-05
3.175E-05	3.325E-05	3.375E-05	3.460E-05	3.550E-05
3.700E-05	3.800E-05	3.910E-05	3.960E-05	4.100E-05
4.240E-05	4.400E-05	4.520E-05	4.700E-05	4.830E-05
4.920E-05	5.060E-05	5.200E-05	5.340E-05	5.900E-05
6.100E-05	6.500E-05	6.750E-05	7.200E-05	7.600E-05
8.000E-05	8.200E-05	9.000E-05	1.000E-04	1.080E-04
1.150E-04	1.190E-04	1.220E-04	1.860E-04	1.925E-04
2.075E-04	2.100E-04	2.400E-04	2.850E-04	3.050E-04
5.500E-04	6.700E-04	6.830E-04	9.500E-04	1.150E-03
1.500E-03	1.550E-03	1.800E-03	2.200E-03	2.290E-03
2.580E-03	3.000E-03	3.740E-03	3.900E-03	6.000E-03
8.030E-03	9.500E-03	1.300E-02	1.700E-02	2.500E-02
3.000E-02	4.500E-02	5.000E-02	5.200E-02	6.000E-02
7.300E-02	7.500E-02	8.200E-02	8.500E-02	1.000E-01
1.283E-01	1.500E-01	2.000E-01	2.700E-01	3.300E-01
4.000E-01	4.200E-01	4.400E-01	4.700E-01	4.995E-01
5.500E-01	5.730E-01	6.000E-01	6.700E-01	6.790E-01
7.500E-01	8.200E-01	8.611E-01	8.750E-01	9.000E-01
9.200E-01	1.010E+00	1.100E+00	1.200E+00	1.250E+00
1.317E+00	1.356E+00	1.400E+00	1.500E+00	1.850E+00
2.354E+00	2.479E+00	3.000E+00	4.304E+00	4.800E+00
6.434E+00	8.187E+00	1.000E+01	1.284E+01	1.384E+01
1.455E+01	1.568E+01	1.733E+01	2.000E+01	

```
=NITAWL
' k4rf5f45, HI-STAR containing MPC24, 15x15 assembly a17 @ 4.1% E
0$$ 84 E
1$$ 0 13  0  4R0  1  E T
2$$ 92235    92238
    40000    1001     8016     5010      5011      6012
    13027    24000    25055     26000     28000
3** 92238 294.6    2    .4752    .1928     0.       0.02251      1
   16.0   7.8209   1    235.04  0.5154    1       1.0            T
END
=KENO5A
k4rf5f45, HI-STAR containing MPC24, 15x15 assembly a17 @ 4.1% E
READ PARAM TME=10000 GEN=300 NPG=10000 NSK=50 LIB=4 TBA=5
END PARAM
READ MIXT SCT=2  EPS=1.0
MIX=1    92235  9.7463E-04
         92238  0.02251
         8016   0.04694
MIX=2    40000  0.04323
MIX=3    1001   0.06688
         8016   0.03344
MIX=4    24000  0.01761
         25055  0.001761
         26000  0.05977
         28000  0.008239
MIX=5    5010   8.7066E-03
         5011   3.5116E-02
         6012   1.0948E-02
         13027  3.6936E-02
MIX=6    1001   0.06688
         8016   0.03344
MIX=7    13027  0.06026
END MIXT
'
' cell-id       8.98
' cell-pitch    10.906
' wall-thkns    5/16
' angle-thkns   5/16
' boral-gap     0.0035
' boral-pocket  0.082
' boral-thkns   0.075
' boral-clad    0.01
' boral-core    0.055
' sheathing     0.0235
' boral-wide    7.500
' boral-narrow  6.250
'
' gap size      1.09
'
READ GEOM
UNIT           1
COM="FUEL ROD"
CYLINDER        1  1  0.4752                                        381.0   0.
CYLINDER        3  1  0.4851                                        381.0   0.
CYLINDER        2  1  0.5436                                        381.0   0.
CUBOID          3  1  0.7214   -0.7214    0.7214    -0.7214         381.0   0.
UNIT           2
COM="GUIDE  TUBE CELL"
CYLINDER        3  1  0.6350                                        381.0   0.
CYLINDER        2  1  0.6706                                        381.0   0.
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CUBOID          3  1  0.7214   -0.7214    0.7214    -0.7214     381.0   0.
UNIT            4
COM="LONG HORIZONTAL BORAL PANEL - NORTH"
CUBOID          5  1  9.525  -9.525   0.06985    -0.06985     381.0   0.
CUBOID          7  1  9.525  -9.525   0.09525    -0.09525     381.0   0.
CUBOID          3  1  9.525  -9.525   0.10414    -0.10414     381.0   0.
CUBOID          4  1  9.58469  -9.58469   0.16383      -0.10414     381.0   0.
UNIT            5
COM="LONG VERTICAL BORAL PANEL - EAST"
CUBOID          5  1  0.06985     -0.06985    9.525  -9.525     381.0   0.
CUBOID          7  1  0.09525     -0.09525    9.525  -9.525     381.0   0.
CUBOID          3  1  0.10414     -0.10414    9.525  -9.525     381.0   0.
CUBOID          4  1  0.16383       -0.10414    9.58469  -9.58469    381.0   0.
UNIT            6
COM="LONG HORIZONTAL BORAL PANEL - SOUTH"
CUBOID          5  1  9.525  -9.525    0.06985    -0.06985     381.0   0.
CUBOID          7  1  9.525  -9.525    0.09525    -0.09525     381.0   0.
CUBOID          3  1  9.525  -9.525    0.10414    -0.10414     381.0   0.
CUBOID          4  1  9.58469  -9.58469    0.10414    -0.16383       381.0   0.
UNIT            7
COM="LONG VERTICAL BORAL PANEL - WEST"
CUBOID          5  1  0.06985     -0.06985    9.525  -9.525     381.0   0.
CUBOID          7  1  0.09525     -0.09525    9.525  -9.525     381.0   0.
CUBOID          3  1  0.10414     -0.10414    9.525  -9.525     381.0   0.
CUBOID          4  1  0.10414     -0.16383    9.58469  -9.58469    381.0   0.
UNIT            8  ARRAY 1  -10.8204     -10.8204        0.
COM="CENTRAL FUEL ASSEMBLIES - 4 BORAL PANELS"
CUBOID          3  1  11.4046  -11.4046   11.4046  -11.4046     381.0   0.
CUBOID          4  1  12.1984  -12.1984   12.1984  -12.1984     381.0   0.
CUBOID          3  1  12.4673  -12.4673   12.4673  -12.4673     381.0   0.
HOLE            4    0.          12.3026     0.
HOLE            5   12.3026         0.       0.
HOLE            6  0.           -12.3026    0.
HOLE            7  -12.3026        0.       0.
' HOLE           17    -11.9802     11.9805     0.
' HOLE           17    -11.9802    -13.59       0.
' HOLE           18    -13.59      -11.90       0.
UNIT           21  ARRAY 1  -10.8204     -10.8204        0.
COM="CENTRAL FUEL ASSEMBLIES - 4 BORAL PANELS, W/O EAST WALL"
CUBOID          3  1  11.4046  -11.4046   11.4046  -11.4046     381.0   0.
CUBOID          4  1  11.4046  -12.1984   12.1984  -12.1984     381.0   0.
CUBOID          3  1  11.4046  -12.4673   12.4673  -12.4673     381.0   0.
HOLE            4    0.          12.3026     0.
HOLE            6  0.           -12.3026    0.
HOLE            7  -12.3026        0.       0.
UNIT           22  ARRAY 1  -10.8204     -10.8204        0.
COM="CENTRAL FUEL ASSEMBLIES - 4 BORAL PANELS, W/O WEST WALL"
CUBOID          3  1  11.4046  -11.4046   11.4046  -11.4046     381.0   0.
CUBOID          4  1  12.1984  -11.4046   12.1984  -12.1984     381.0   0.
CUBOID          3  1  12.4673  -11.4046   12.4673  -12.4673     381.0   0.
HOLE            4    0.          12.3026     0.
HOLE            5   12.3026         0.       0.
HOLE            6  0.           -12.3026    0.
UNIT           23
COM="CELL WALL BETWEEN UNITS 21 AND 22"
CUBOID          4  1  0.396775  -0.396775   23.9998  -23.9998     381.0   0.
UNIT            9
COM="SHORT HORIZONTAL BORAL PANEL - NORTH"
CUBOID          5  1  7.9375  -7.9375   0.06985    -0.06985     381.0   0.
CUBOID          7  1  7.9375  -7.9375   0.09525    -0.09525     381.0   0.
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CUBOID          3  1  7.9375  -7.9375   0.10414    -0.10414     381.0   0.
CUBOID          4  1  7.99719  -7.99719   0.16383      -0.10414     381.0   0.
UNIT         10
COM="SHORT VERTICAL BORAL PANEL - EAST"
CUBOID          5  1  0.06985    -0.06985    7.9375  -7.9375    381.0   0.
CUBOID          7  1  0.09525    -0.09525    7.9375  -7.9375    381.0   0.
CUBOID          3  1  0.10414    -0.10414    7.9375  -7.9375    381.0   0.
CUBOID          4  1  0.16383      -0.10414    7.99719  -7.99719    381.0   0.
UNIT         11
COM="SHORT HORIZONTAL BORAL PANEL - SOUTH"
CUBOID          5  1  7.9375  -7.9375   0.06985   -0.06985    381.0   0.
CUBOID          7  1  7.9375  -7.9375   0.09525   -0.09525    381.0   0.
CUBOID          3  1  7.9375  -7.9375   0.10414   -0.10414    381.0   0.
CUBOID          4  1  7.99719  -7.99719   0.10414   -0.16383      381.0   0.
UNIT         12
COM="SHORT VERTICAL BORAL PANEL - WEST"
CUBOID          5  1  0.06985    -0.06985    7.9375  -7.9375    381.0   0.
CUBOID          7  1  0.09525    -0.09525    7.9375  -7.9375    381.0   0.
CUBOID          3  1  0.10414    -0.10414    7.9375  -7.9375    381.0   0.
CUBOID          4  1  0.10414    -0.16383    7.99719  -7.99719    381.0   0.
UNIT         13  ARRAY 1  -10.8204    -10.8204       0.
COM="Array B short Boral N & E "
CUBOID          3  1  11.4046  -11.4046   11.4046  -11.4046    381.0   0.
CUBOID          4  1  12.1984  -12.1984   12.1984  -12.1984    381.0   0.
CUBOID          3  1  12.4673  -12.4673   12.4673  -12.4673    381.0   0.
HOLE            9    0.           12.3026     0.
HOLE           10   12.3026         0.        0.
HOLE            6  0.            -12.3026    0.
HOLE            7  -12.3026       0.        0.
' HOLE          17   -11.9802     11.9805     0.
' HOLE          17   -11.9802    -13.59      0.
' HOLE          18   -13.59      -11.90      0.
UNIT         14  ARRAY 1  -10.8204    -10.8204       0.
COM="Array C short Boral E & S "
CUBOID          3  1  11.4046  -11.4046   11.4046  -11.4046    381.0   0.
CUBOID          4  1  12.1984  -12.1984   12.1984  -12.1984    381.0   0.
CUBOID          3  1  12.4673  -12.4673   12.4673  -12.4673    381.0   0.
HOLE            4    0.           12.3026     0.
HOLE           10   12.3026         0.        0.
HOLE           11  0.            -12.3026    0.
HOLE            7  -12.3026       0.        0.
' HOLE          17   -11.9802     11.9805     0.
' HOLE          17   -11.9802    -13.59      0.
' HOLE          18   -13.59      -11.90      0.
UNIT         15  ARRAY 1  -10.8204    -10.8204       0.
COM="Array D short Boral S & W "
CUBOID          3  1  11.4046  -11.4046   11.4046  -11.4046    381.0   0.
CUBOID          4  1  12.1984  -12.1984   12.1984  -12.1984    381.0   0.
CUBOID          3  1  12.4673  -12.4673   12.4673  -12.4673    381.0   0.
HOLE            4    0.           12.3026     0.
HOLE            5   12.3026         0.        0.
HOLE           11  0.            -12.3026    0.
HOLE           12  -12.3026       0.        0.
' HOLE          17   -11.9802     11.9805     0.
' HOLE          17   -11.9802    -13.59      0.
' HOLE          18   -13.59      -11.90      0.
UNIT         16  ARRAY 1  -10.8204    -10.8204       0.
COM="Array E short Boral N & W "
CUBOID          3  1  11.4046  -11.4046   11.4046  -11.4046    381.0   0.
CUBOID          4  1  12.1984  -12.1984   12.1984  -12.1984    381.0   0.
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CUBOID          3  1  12.4673   -12.4673    12.4673   -12.4673     381.0    0.
HOLE            9    0.            12.3026      0.
HOLE            5    12.3026        0.           0.
HOLE            6  0.            -12.3026     0.
HOLE           12  -12.3026        0.          0.
' HOLE           17    -11.9802    11.9805      0.
' HOLE           17    -11.9802    -13.59       0.
' HOLE           18    -13.59      -11.90       0.
UNIT           17
CUBOID          4  1  0.7938    -0.         1.60       -0.         381.0   0.
UNIT           18
CUBOID          4  1  1.60      -0.         0.7938     -0.         381.0   0.
UNIT           30
CUBOID          4  1  1.37332   -1.37332    3.4925   -3.4925     381.0   0.
UNIT           31
CUBOID          4  1  1.05959   -1.05959    1.37332   -1.37332    381.0   0.
UNIT           41
CUBOID          3  1  14.6768   -14.6768    1.65227   -1.65227    381.0   0.
CUBOID          4  1  14.6768   -14.6768    2.44602   -2.44602    381.0   0.
UNIT           42
CUBOID          3  1  1.65227   -1.65227    14.6768   -14.6768    381.0   0.
CUBOID          4  1  2.44602   -2.44602    14.6768   -14.6768    381.0   0.
GLOBAL
UNIT           19
COM="ASSEMBLY ARRAY + X DIRECTION"
CYLINDER        3  1  86.57                                     396.24  -10.16
HOLE            8   13.8506     13.8506     0.
HOLE            8   13.8506    -13.8506     0.
HOLE           21   17.949      41.5519    0.
HOLE           21   17.949     -41.5519    0.
HOLE           13   13.8506     69.2531     0.
HOLE           14   13.8506    -69.2531     0.
HOLE           22   41.5519     17.949     0.
HOLE           22   41.5519    -17.949     0.
HOLE           13   45.6502     45.6502     0.
HOLE           14   45.6502    -45.6502     0.
HOLE           13   69.2531     13.8506     0.
HOLE           14   69.2531    -13.8506     0.
HOLE            8  -13.8506     13.8506     0.
HOLE            8  -13.8506    -13.8506     0.
HOLE           22  -17.949      41.5519    0.
HOLE           22  -17.949     -41.5519    0.
HOLE           16  -13.8506     69.2531     0.
HOLE           15  -13.8506    -69.2531     0.
HOLE           21  -41.5519     17.949     0.
HOLE           21  -41.5519    -17.949     0.
HOLE           16  -45.6502     45.6502     0.
HOLE           15  -45.6502    -45.6502     0.
HOLE           16  -69.2531     13.8506     0.
HOLE           15  -69.2531    -13.8506     0.
HOLE           23   29.7505     29.7505     0.
HOLE           23  -29.7505     29.7505     0.
HOLE           23   29.7505    -29.7505     0.
HOLE           23  -29.7505    -29.7505     0.
HOLE            5   30.2516     41.5519     0.
HOLE            5   30.2516    -41.5519     0.
HOLE            7  -30.2516     41.5519     0.
HOLE            7  -30.2516    -41.5519     0.
HOLE            7   29.2494     17.949     0.
HOLE            7   29.2494    -17.949     0.
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HOLE            5  -29.2494    17.949    0.
HOLE            5  -29.2494   -17.949    0.
HOLE           30      0.         0.   0.
HOLE           31    2.43291        0.    0.
HOLE           31   -2.43291        0.    0.
HOLE           41   41.5519         0.    0.
HOLE           41  -41.5519         0.    0.
HOLE           42      0.    41.5519    0.
HOLE           42      0.   -41.5519    0.
CYLINDER        4  1  108.43                                    435.61  -31.75
CUBOID          3  1  139   -139    139   -139    435.61   -31.75
END GEOM
READ ARRAY
ARA=1  NUX=15  NUY=15  NUZ=1
COM="15 X 15 FUEL ASSEMBLY"
FILL
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 2 1 1 1 2 1 1 1 1 1
      1 1 1 2 1 1 1 1 1 1 1 2 1 1 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 1 2 1 1 2 1 1 1 2 1 1 2 1 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 2 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 1 2 1 1 2 1 1 1 2 1 1 2 1 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 1 1 2 1 1 1 1 1 1 1 2 1 1 1
      1 1 1 1 1 2 1 1 1 2 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
END FILL
END ARRAY
END DATA
END
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=NITAWL
' HI-STAR containing MPC68, 08x08 @ 4.2% E
0$$ 84 E
1$$ 0 13  0  4R0  1  E T
2$$ 92235   92238
    40000   1001     8016     5010     5011     6012
    13027   24000    25055    26000    28000
3** 92238 294.6   2   .5207   .1623    0.     0.02248    1
   16.0   7.8330  1   235.04  0.5662   1      1.0        T
END
=KENO5A
HI-STAR containing MPC68, 08x08 @ 4.2% E
'  GE 8X8R FUEL 2 WATER HOLES
READ PARAM TME=10000 GEN=1100 NPG=5000 NSK=100
     LIB=4 TBA=5  LNG=400000   NB8=900
END PARAM
READ MIXT SCT=2  EPS=1.
MIX=1    92235  9.983E-04
         92238  0.02248
         8016   0.04697
MIX=2    40000  0.04323
MIX=3    1001   0.06688
         8016   0.03344
MIX=4    24000  0.01761
         25055  0.001761
         26000  0.05977
         28000  0.008239
MIX=5    5010   8.071E-03
         5011   3.255E-02
         6012   1.015E-02
         13027  3.805E-02
MIX=6    13027  0.06026
END MIXT
READ GEOM
UNIT            1
COM=            "FUEL ROD"
CYLINDER         1  1  0.5207                                     381.0   0.
CYLINDER         3  1  0.5321                                     381.0   0.
CYLINDER         2  1  0.6134                                     381.0   0.
CUBOID           3  1  0.8128   -0.8128   0.8128   -0.8128        381.0   0.
UNIT            2
COM=            "GUIDE  TUBE CELL"
CYLINDER         3  1  0.6744                                     381.0   0.
CYLINDER         2  1  0.7506                                     381.0   0.
CUBOID           3  1  0.8128   -0.8128   0.8128   -0.8128        381.0   0.
UNIT            4
COM=            "HORIZONTAL BORAL PANEL"
CUBOID           5  1  6.0325   -6.0325   0.1027   -0.1027        381.0   0.
CUBOID           6  1  6.0325   -6.0325   0.1283   -0.1283        381.0   0.
CUBOID           3  1  6.0325   -6.0325   0.1422   -0.1422        381.0   0.
CUBOID           4  1  6.4611   -6.4611   0.1422   -0.3327        381.0   0.
UNIT            5
COM=            "VERTICAL BORAL PANEL"
CUBOID           5  1  0.1027   -0.1027   6.0325   -6.0325      381.0   0.
CUBOID           6  1  0.1283   -0.1283   6.0325   -6.0325      381.0   0.
CUBOID           3  1  0.1422   -0.1422   6.0325   -6.0325      381.0   0.
CUBOID           4  1  0.3327   -0.1422   6.4611   -6.4611      381.0   0.
UNIT            8  ARRAY 1  -6.5024     -6.5024      0.
COM=            "FUEL ASSEMBLIES - 2 BORAL PANELS"
CUBOID           3  1  6.7031   -6.7031   6.7031   -6.7031        381.0   0.
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CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         4    0.         7.9438    0.
HOLE         5  -7.9438     0.         0.
CUBOID       4  1  7.6111   -8.7211    8.7211   -7.6111        381.0   0.
UNIT        9  ARRAY 1  -6.5024     -6.5024        0.
COM=         "FUEL ASSEMBLIES - Type A"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         5  -7.9438     0.         0.
CUBOID       4  1  8.2461   -8.7211    8.7211   -7.6111        381.0   0.
UNIT        10  ARRAY 1  -6.5024     -6.5024       0.
COM=         "FUEL ASSEMBLIES - Type B"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         5  -7.9438     0.         0.
CUBOID       4  1  7.6111   -8.7211    8.7211   -7.6111        381.0   0.
UNIT        11  ARRAY 1  -6.5024     -6.5024       0.
COM=         "FUEL ASSEMBLIES - Type C"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         4    0.         7.9438    0.
HOLE         5  -7.9438     0.         0.
CUBOID       4  1  8.2461   -8.7211    8.7211   -7.6111        381.0   0.
UNIT        12  ARRAY 1  -6.5024     -6.5024       0.
COM=         "FUEL ASSEMBLIES - Type D"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         4    0.         7.9438    0.
HOLE         5  -7.9438     0.         0.
CUBOID       4  1  8.2461   -8.7211    8.7211   -8.2461        381.0   0.
UNIT        13  ARRAY 1  -6.5024     -6.5024       0.
COM=         "FUEL ASSEMBLIES - Type E"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         4    0.         7.9438    0.
HOLE         5  -7.9438     0.         0.
CUBOID       4  1  7.6111   -8.7211    8.7211   -8.2461        381.0   0.
UNIT        14  ARRAY 1  -6.5024     -6.5024       0.
COM=         "FUEL ASSEMBLIES - Type F"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         4    0.         7.9438    0.
CUBOID       4  1  7.6111   -8.7211    8.7211   -8.2461        381.0   0.
UNIT        15  ARRAY 1  -6.5024     -6.5024       0.
COM=         "FUEL ASSEMBLIES - TYPE G"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
CUBOID       2  1  6.9571   -6.9571    6.9571   -6.9571        381.0   0.
CUBOID       3  1  7.6111   -8.0861    8.0861   -7.6111        381.0   0.
HOLE         4    0.         7.9438    0.
CUBOID       4  1  7.6111   -8.7211    8.7211   -7.6111        381.0   0.
UNIT        16  ARRAY 1  -6.5024     -6.5024       0.
COM=         "FUEL ASSEMBLIES - TYPE H"
CUBOID       3  1  6.7031   -6.7031    6.7031   -6.7031        381.0   0.
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CUBOID          2  1  6.9571   -6.9571    6.9571   -6.9571          381.0   0.
CUBOID          3  1  7.6111   -8.0861    8.0861   -7.6111          381.0   0.
CUBOID          4  1  7.6111   -8.7211    8.7211   -7.6111          381.0   0.
UNIT           17  ARRAY 2     -48.9966  -48.9966          0
UNIT           18  ARRAY 3     -16.3322  -7.6111           0.
UNIT           19  ARRAY 4     -48.9966  -7.6111           0.
UNIT           20  ARRAY 5     -8.7211   -16.3322          0.
UNIT           21  ARRAY 6     -8.7211   -50.1068          0.
UNIT           22  ARRAY 7     -8.7211   -16.3322          0.
UNIT           23  ARRAY 8     -8.7211   -16.3322          0.
UNIT           24  ARRAY 9     -8.7211   -16.3322          0.
UNIT           25  ARRAY 10    -8.7211   -16.3322          0.
UNIT           26  ARRAY 11    -16.3322  -8.7213           0.
UNIT           27  ARRAY 12    -16.3322  -7.6111           0.
UNIT           28  ARRAY 13    -16.3322  -8.7213           0.
UNIT           29  ARRAY 14    -16.3322  -8.7213           0.
GLOBAL
UNIT           30
CYLINDER        3  1    85.57                                    402.5   -18.54.
HOLE           17       0.0        0.0       0.
HOLE           18       0.0       73.4949    0.
HOLE           19       0.0       57.1627    0.
HOLE           20     -73.4949     0.0       0.
HOLE           21     -56.6077     0.0       0.
HOLE           22      57.7177    32.6644    0.
HOLE           23      57.7177     0.0       0.
HOLE           24      74.052      0.0       0.
HOLE           25      57.7177   -32.6644    0.
HOLE           26      32.6644   -57.7177    0.
HOLE           27       0.0      -57.7177    0.
HOLE           28     -32.6644   -57.7177    0.
HOLE           29       0.0      -74.052     0.
CYLINDER        4   1   108.43                               441.85  -40.13
CUBOID          3   1   109.      -109.      109.     -109.     442     -40.2
END GEOM
READ ARRAY
ARA=1  NUX=8   NUY=8   NUZ=1
COM=   "8 X 8 FUEL ASSEMBLY"
FILL
 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1
 1 1 1 2 1 1 1 1
 1 1 1 1 2 1 1 1
 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1
END FILL
ARA=2  NUX=6   NUY=6   NUZ=1
COM=   "6 X 6 CENTRAL ARRAY OF FUEL ASSEMBLIES"
FILL
  8 8 8 8 8 8
  8 8 8 8 8 8
  8 8 8 8 8 8
  8 8 8 8 8 8
  8 8 8 8 8 8
  8 8 8 8 8 8
END FILL
ARA=3  NUX=2   NUY=1   NUZ=1
COM=   "2 X 1  ARRAY OF FUEL ASSEMBLIES - TOP ROW"
```

```
FILL
 16  9
END FILL
ARA=4  NUX=6   NUY=1   NUZ=1
COM=   "6 X 1  ARRAY OF FUEL ASSEMBLIES - 2ND ROW"
FILL
  16  10  8  8  10  9
END FILL
ARA=5  NUX=1   NUY=2   NUZ=1
COM=   "2 X 1  ARRAY OF FUEL ASSEMBLIES - OUTER LEFT"
FILL
  14
  16
END FILL
ARA=6  NUX=1   NUY=6   NUZ=1
COM=   "1 X 6  ARRAY OF FUEL ASSEMBLIES - 2ND ROW LEFT"
FILL
  14  15  8  8  15  16
END FILL
ARA=7  NUX=1   NUY=2   NUZ=1
COM=   "1 X 2  ARRAY OF FUEL ASSEMBLIES - UPPER RIGHT"
FILL
  11
   9
END FILL
ARA=8  NUX=1   NUY=2   NUZ=1
COM=   "1 X 2  ARRAY OF FUEL ASSEMBLIES - MIDDLE RIGHT"
FILL
   8
   8
END FILL
ARA=9  NUX=1   NUY=2   NUZ=1
COM=   "1 X 2  ARRAY OF FUEL ASSEMBLIES - MIDDLE RIGHT"
FILL
   11
    9
END FILL
ARA=10  NUX=1   NUY=2   NUZ=1
COM=   "1 X 2  ARRAY OF FUEL ASSEMBLIES - LOWER RIGHT"
FILL
  11
  11
END FILL
ARA=11  NUX=2   NUY=1   NUZ=1
COM=   "2 X 1  ARRAY OF FUEL ASSEMBLIES - 2ND BOTTOM ROW"
FILL
  13  13
END FILL
ARA=12  NUX=2   NUY=1   NUZ=1
COM=   "2 X 1  ARRAY OF FUEL ASSEMBLIES - BOTTOM ROW"
FILL
  8  8
END FILL
ARA=13  NUX=2   NUY=1   NUZ=1
COM=   "2 X 1  ARRAY OF FUEL ASSEMBLIES - BOTTOM ROW"
FILL
  14  13
END FILL
ARA=14  NUX=2   NUY=1   NUZ=1
COM=   "2 X 1  ARRAY OF FUEL ASSEMBLIES - BOTTOM ROW"
```

```
FILL
  14 13
END FILL
END ARRAY
END DATA
END
```

APPENDIX 6.E: BURNUP CREDIT FOR THE MPC-32

This Appendix will be added in a future revision of this report.

CHAPTER 7: OPERATING PROCEDURES

7.0 INTRODUCTION

The HI-STAR 100 System is a dual-purpose system certified for use as a dry storage cask under 10 CFR 72 and a transportation package under 10 CFR 71. In addition, the MPC is certified for use under 10 CFR 72 in the storage-only HI-STORM 100 System (a ventilated concrete cask system). Therefore, it is possible that the HI-STAR 100 overpack and/or the MPC may be loaded, prepared, and sealed under the operating procedures for storage delineated in the HI-STAR storage FSAR (Docket 72-1008) or the HI-STORM 100 storage FSAR (Docket 72-1014). In those cases, the operating procedures governing MPC and overpack preparation for storage would apply. The MPC and overpack, as applicable, would have to be confirmed to meet all requirements of the Part 71 certificate of compliance before being released for shipment.

For those instances where the MPC is being loaded and shipped off-site in a HI-STAR 100 overpack under 10 CFR 71 without first being deployed at an ISFSI (known as "load-and-go" operations), the operating procedures in Chapter 7 (and summarized below) apply for preparation of the MPC and HI-STAR overpack. For those cases where the MPC is transferred from storage in a HI-STORM overpack to a HI-STAR overpack for shipment, the operating procedures in Chapter 7 (and summarized below) govern the preparation activities for the HI-STAR overpack.

This chapter outlines the procedures for loading, preparation for shipment, unloading, and preparation for empty cask shipment of the HI-STAR 100 System in accordance with 10CFR71 [7.0.1]. The procedures provided in this chapter are prescriptive in that they provide the basis and general guidance for plant personnel in preparing detailed written site-specific loading, handling, and unloading procedures. Users may add or delete steps in their site-specific implementation procedures provided the intent of these guidelines is met. Section 7.1 provides the guidance for loading the HI-STAR 100 System in the spent fuel pool. Section 7.2 provides the guidance for unloading the HI-STAR 100 System in the spent fuel pool. Section 7.3 provides the guidance for the preparation of the empty HI-STAR 100 for transport. Section 7.4 provides guidance for preparing the HI-STAR 100 Overpack for transport following a period of storage. Equipment specific operating details such as valve manipulation and onsite transporter operation will be provided to users based on the specific equipment selected by the users and the configuration of the site.

Licensees (users) will utilize the procedures provided in this chapter, the conditions of the Certificate of Compliance (CoC), equipment-specific operating instructions, and plant working procedures and apply them to develop the site-specific written loading, unloading, and handling procedures. The procedures contained herein describe acceptable methods for performing HI-STAR 100 loading and unloading operations and preparation for shipment. Users may alter these procedures to allow operations to be performed in parallel or out of sequence as long as the general intent of the procedure is met. In the figures following each section, acceptable configurations of rigging, piping, equipment and instrumentation are shown. These figures are not intended to restrict users, but to provide examples for users to develop their own site specific procedures. Users may select alternate equipment, configurations and methodology to accommodate their specific needs. Any deviations to the rigging should be approved by the user's load handling authority.

The loading and unloading procedures in Section 7.1 and 7.2 can also be appropriately revised into written site-specific procedures to allow dry loading and unloading of the system in a hot cell or other remote handling facility. The Dry Transfer Facility (DTF) loading and unloading procedures are essentially the same with respect to loading and drying, inerting, and leakage testing of the MPC. Section 7.4 provides a synopsis of the regulatory requirements for the HI-STAR 100 package. The dry transfer facility shall develop the appropriate site-specific procedures as part of the DTF facility license.

Tables 7.1.1 and 7.1.2, respectively, provide estimates of the handling weights for each of the HI-STAR 100 System major components and the loads to be lifted during the operation of the HI-STAR 100 System. Table 7.1.3 provides the HI-STAR 100 System bolt torque and sequencing requirements. Table 7.1.4 provides an operational description of the HI-STAR 100 System ancillary equipment and its safety designation. Licensee's may make alterations or substitutions to this equipment to accommodate their specific needs. Fuel assembly selection and verification shall be performed by the licensee in accordance with written, approved procedures that ensure that only SNF assemblies authorized in the Certificate of Compliance are loaded into the HI-STAR 100 System.

Users will be required to develop or modify existing programs and procedures to account for the transport operation of the HI-STAR 100 system. Written procedures will be required to be developed or modified to account for such things as nondestructive examination (NDE) of the MPC welds, handling and storage of items and components identified as important to safety, heavy load handling, specialized instrument calibration, special nuclear material accountability, fuel handling procedures, training, equipment and process qualifications. Users shall implement controls to ensure that the lifted weights do not exceed the HI-STAR 100 lifting trunnion design limit. Users shall implement controls to monitor the time limit from the removal of the HI-STAR 100 from the spent fuel pool to the commencement of MPC draining to prevent boiling. Chapter 3 of this SAR provides examples of time limits based on representative spent fuel pool temperatures and design basis heat loads. Users shall also implement controls to ensure that the HI-STAR 100 overpack cannot be subjected to a fire in excess of design limits during loading operations.

Table 7.1.5 summarizes the instrumentation necessary to load and unload the HI-STAR 100 System. Tables 7.1.6 and 7.1.7 provide sample receipt inspection checklists for the HI-STAR 100 overpack and the MPC, respectively. Users shall develop site-specific receipt inspection checklists, as required. Fuel handling, including the handling of fuel assemblies in the Damaged Fuel Container (DFC) shall be performed in accordance with written site-specific procedures. Damaged fuel and fuel debris, as defined in the CoC, shall be loaded in DFCs.

7.0.1 Technical and Safety Basis for Loading and Unloading Procedures

The procedural guidelines herein (7.1 through 7.3) are developed for the loading, unloading, and empty (after initial transport) transport of the HI-STAR 100 System. The activities involved in loading of spent fuel in a canister system, if not carefully performed, may present personnel hazards and radiological impact. The design of the HI-STAR 100 System, including these guidelines and the ancillary equipment was performed to minimize risks and mitigate consequences of potential events. The primary objective is to reduce the risk of occurrence and/or to mitigate the consequences of the event. The procedures contain notes, warnings, and cautions to notify the operators to upcoming situations and provide additional information as needed. The notes, warnings and cautions are purposely bolded and boxed, and immediately precede the applicable steps.

In the event of an extreme abnormal condition (e.g., cask drop or tip-over event) the user shall have appropriate procedural guidance to respond to the situation. As a minimum, the procedures shall address establishing emergency action levels, implementation of emergency action program, establishment of personnel exclusion zones, monitoring of radiological conditions, actions to mitigate or prevent the release of radioactive materials, and recovery planning and execution.

7.1 PROCEDURE FOR LOADING THE HI-STAR 100 SYSTEM IN THE SPENT FUEL POOL AND PREPARATION FOR SHIPMENT

7.1.1 Overview of Loading Operations

Note:
The MPC loading operations described herein are for HI-STAR 100 systems prepared for "load-and-go" directly into transportation under 10CFR71. HI-STAR 100 systems that are loaded and stored on an ISFSI site must be prepared in accordance with the procedures detailed in the applicable Part 72 HI-STAR or HI-STORM FSAR and CoC. Any HI-STAR 100 overpack and/or MPC deployed at an ISFSI must be confirmed to meet all conditions of the 10CFR71 CoC prior to shipment.

The HI-STAR 100 System is used to load and transport spent fuel. Specific steps are performed to prepare the HI-STAR 100 System for fuel loading, to load the fuel, to prepare the system for transport and to ship the HI-STAR 100 System. The HI-STAR 100 overpack may be transported off-site using a rail car or a specially designed heavy haul trailer, or any other load handling equipment designed for such applications. Users shall develop detailed written procedures to control on-site transport operations. Section 7.1.2 provides the general procedures for handling of the HI-STAR 100 overpack and MPC both with and without fuel loaded inside.

Figure 7.1.1 shows a flow diagram of the HI-STAR 100 System loading operations. Figure 7.1.2 illustrates some of the major HI-STAR 100 System loading operations. The HI-STAR 100 overpack and empty MPC may arrive together or separately. The procedures provided assume that these components arrive separately. If the HI-STAR 100 overpack and MPC arrive together, certain steps of the procedure may be omitted.

Note:
The procedures describe plant facilities, functions, and processes in general terms. Each site is different with regard to layout, organization and nomenclature. Users shall interpret the nomenclature used herein to suit their particular site, organization, and methods of operation.

Refer to the boxes of Figure 7.1.2 for the following description. The HI-STAR 100 overpack is received and the personnel barrier is removed. Receipt inspection and radiological surveys are performed. The impact limiters are removed and the HI-STAR 100 overpack is upended. At the start of loading operations, an empty MPC is upended (Box 1). The empty MPC is raised and inserted into the HI-STAR 100 overpack (Box 2). The annulus is filled with clean (uncontaminated) water and an inflatable seal is installed in the annulus between the MPC and the HI-STAR 100 overpack to prevent spent fuel pool water from contaminating the exterior surface of the MPC. The MPC is filled with either spent fuel pool water or clean water (Box 3). The HI-STAR 100 overpack and the MPC are then raised and lowered into the spent fuel pool for fuel loading using the lift yoke (Box 4). Pre-selected assemblies are loaded into the MPC and a visual verification of the assembly identification is performed (Box 5).

While still underwater, a thick shielded lid (the MPC lid) is installed using either slings attached to the lift yoke or the lid retention system (Box 6). The lift yoke remotely engages to the HI-STAR 100 overpack lifting trunnions to lift the HI-STAR 100 overpack and loaded MPC close to the spent fuel pool surface (Box 7). The cask is removed from the spent fuel pool. If the lid retention system is being used, the bolts are installed to the lid retention system to secure the MPC lid for the transfer to the cask preparation area. The lift yoke and HI-STAR 100 overpack are sprayed with clean water to help remove contamination as they are removed from the spent fuel pool.

The HI-STAR 100 overpack is placed in the designated preparation area and the lift yoke and lid retention system retention disk are removed. The next phase of decontamination is then performed. The top surfaces of the MPC lid and the upper flange of the HI-STAR 100 overpack are decontaminated. The temporary shield ring (if used) is installed and filled with water. The inflatable annulus seal is removed, and the annulus shield is installed. The temporary shield ring provides additional personnel shielding around the top of the HI-STAR 100 overpack during MPC closure operations. The annulus shield provides additional personnel shielding at the top of the annulus and also prevents small items from being dropped into the annulus. Dose rates are measured at the MPC lid and around the mid-height circumference of the HI-STAR 100 overpack to establish appropriate radiological control.

The MPC water level is lowered slightly, the MPC is vented or purged and checked for combustible gas concentrations, and the MPC lid is seal welded using the Automated Welding System (AWS) (Box 8), by manual welding, or a combination of the two. Visual examinations are performed on the tack welds. Liquid penetrant examinations are performed on the root and final passes. A volumetric examination is performed on the MPC welds to ensure that the completed weld is satisfactory. As an alternative to volumetric examination of the MPC lid-to-shell weld, a multi-layer PT may be performed including intermediate examinations after approximately every three-eighth inch of weld depth. At the appropriate time in the sequence of activities, based on the type of test performed (hydrostatic or pneumatic), a pressure test of the MPC enclosure vessel is performed. The area below the MPC lid is filled with helium gas for leakage testing. A leakage rate test is performed on the MPC lid-to-shell weld to verify weld integrity and to ensure that leakage rates are within acceptance criteria.

The MPC water is displaced from the MPC by blowdown of the water using pressurized helium or nitrogen gas introduced into the vent port of the MPC thus displacing the water through the drain line. The Forced Helium Dehydration (FHD) is connected to the MPC and is used to remove all liquid water from the MPC (Box 9). After the bulk water has been removed, the helium exiting the FHD demoisturizer is cooled to a temperature of less than or equal to 21 °F and circulated through the MPC for greater than or equal to 30 minutes to ensure that the MPC cavity is suitably dry.

Following the drying operations, the MPC is backfilled with a predetermined pressure of helium gas. The helium backfill ensures adequate heat transfer during transport. Cover plates are installed and seal welded over the MPC vent and drain ports and liquid penetrant examinations are performed on the root (for multi-pass welds) and final passes (Box 10). The cover plates are

leakage tested to confirm that they meet the established leakage rate criteria.

The MPC closure ring is then placed on the MPC and dose rates are measured. The closure ring is aligned, tacked in place and seal welded providing redundant closure of the MPC confinement boundary closure welds. Tack welds are visually examined, and the root (for multi-pass welds) and final welds are inspected using the liquid penetrant examination technique to ensure weld integrity.

The annulus shield is removed and the remaining water in the annulus is drained. The temporary shield ring is drained and removed. The MPC lid and accessible areas at the top of the MPC shell are smeared for removable contamination. The HI-STAR 100 overpack closure plate is installed (Box 11) and the bolts are torqued. The HI-STAR 100 overpack annulus is dried. If the package contains an MPC-68F or MPC-24EF, a secondary leakage verification test is performed. The overpack is then backfilled with helium gas. The HI-STAR 100 overpack mechanical seals and the vent and drain plug seals are leakage tested to assure they will provide long-term retention of the annulus helium. The HI-STAR 100 overpack vent and drain port cover plates are installed. The HI-STAR 100 overpack is surveyed for removable contamination.

The HI-STAR 100 overpack is moved to the transport location. An inspection for signs of impaired condition is performed. Contamination surveys are performed. The AL-STAR impact limiters are installed and the HI-STAR 100 system is placed on the transport vehicle, the tie-down system is installed and a shielding effectiveness test is performed to ensure that the HI-STAR 100 shielding has been manufactured and is functioning as designed. Radiation levels are verified to be within acceptable limits. The assembled package is given a final inspection to verify that all conditions for transport have been met (e.g., all mechanical seals have been installed and tested, relief devicesare intact, installed and not covered. The carrier is provided with the appropriate paperwork and the receiver is notified of the impending shipment) and the personnel barrier is installed (Box 12). The package is then labeled, placarded and released for transport.

7.1.2 HI-STAR 100 System Receiving and Handling Operations

Note:
The HI-STAR 100 overpack may be received and handled in several different configurations and may be transported on-site in a horizontal or vertical orientation. This section provides general guidance for the HI-STAR 100 overpack and MPC rigging and handling. Site-specific procedures shall specify the required operational sequences based on the design of the overpack (i.e., with or without pocket trunnions) and site capabilities.

Note:
Steps 1 through 4 describe the handling operations using a lift yoke. Specialty rigging may be substituted if the lift complies with NUREG-0612 [7.1.1].

1. Vertical Handling of the HI-STAR 100 overpack:

Note:
Prior to performing any lifting operation, the removable shear ring segments under the two lifting trunnions must be removed.

Caution:
Users shall maintain controls to ensure that heights to which the loaded HI-STAR 100 is lifted outside the fuel building are limited to ensure that the structural integrity of the MPC and overpack is not compromised should the overpack be dropped.

a. Verify that the lift yoke load test certifications are current.

b. Visually inspect the lift yoke and the lifting trunnions for gouges, cracks, deformation or other indications of damage.

c. Engage the lift yoke to the lifting trunnions. See Figure 7.1.3.

d. Apply lifting tension to the lift yoke and verify proper engagement of the lift yoke.

Note:
Refer to the site's heavy load handling procedures for lift height, load path, floor loading and other applicable load handling requirements.

e. Raise the HI-STAR 100 overpack and position it accordingly.

2. Upending of the HI-STAR 100 overpack

Warning:
Personnel shall remain clear of the unshielded bottom of the loaded overpack. Users shall coordinate operations to keep the bottom cover installed to the maximum extent practicable whenever when the loaded overpack is downended.

a. Position the HI-STAR 100 overpack under the lifting device.

b. Verify that the lift yoke load test certifications are current.

c. Visually inspect the lift yoke and the lifting trunnions for gouges, cracks, deformation or other indications of damage.

d. Place a light layer of Fel-Pro Chemical Products, N-5000, Nuclear Grade Lubricant (or equivalent) on the cask lifting trunnions and the palms of the lift yoke.

e. Engage the lift yoke to the lifting trunnions. See Figure 7.1.3.

f. Apply lifting tension to the lift yoke and verify proper engagement of the lift yoke.

g. Slowly rotate the HI-STAR 100 overpack to the vertical position keeping all rigging as close to vertical as practicable. See Figure 7.1.4.

h. Lift the overpack clear of the transport vehicle.

i. Position the HI-STAR 100 overpack per site direction.

3. Downending of the HI-STAR 100 overpack.

a. Position the transport vehicle under the lifting device.

b. Verify that the lift yoke load test certifications are current.

c. Visually inspect the lift yoke and the lifting trunnions for gouges, cracks, deformation or other indications of damage.

d. Place a light layer of Fel-Pro Chemical Products, N-5000, Nuclear Grade Lubricant (or equivalent) on the cask trunnions and the palms of the lift yoke.

e. Deleted.

f. Engage the lift yoke to the lifting trunnions. See Figure 7.1.3.

g. Apply lifting tension to the lift yoke and verify proper lift yoke engagement.

h. Deleted.

i. Slowly rotate the HI-STAR 100 overpack to the horizontal position keeping all rigging as close to vertical as practicable.

j. Disengage the lift yoke.

Warning:
Personnel shall remain clear of the unshielded bottom of the loaded overpack. Users shall coordinate operations to keep the bottom cover installed to the maximum extent practicable whenever when the loaded overpack is downended.

k. If necessary for radiation shielding, install the overpack bottom cover. Rigging points are provided.

4. Horizontal handling of the HI-STAR 100 overpack.

a. Deleted..

b. Downend the HI-STAR 100 overpack per Step 3, if necessary.

c. Rig the overpack as shown in Figure 7.1.5.

d. Position the overpack accordingly.

5. Empty MPC Installation in the HI-STAR 100 overpack:

Note:
To avoid side loading the MPC lift lugs, the MPC must be upended in the MPC Upending Frame (or equivalent). See Figure 7.1.6.

a. If necessary, remove any MPC shipping covers and rinse off any road dirt with water. Be sure to remove any foreign objects from the MPC internals.

b. Upend the MPC as follows:

1. Visually inspect the MPC upending frame for gouges, cracks, deformation or other indications of damage.
2. Install the MPC on the upending frame. Make sure that the banding straps are secure around the MPC shell. See Figure 7.1.6.
3. Inspect the upending frame slings in accordance with the site's lifting equipment inspection procedures. Rig the slings to the bar. See Figure 7.1.6.
4. Attach the MPC upper end slings of the upending frame to the main overhead lifting device. Attach the bottom-end slings to a secondary lifting device (or a chain fall attached to the primary lifting device).
5. Raise the MPC in the upending frame.

Warning:
The upending frame corner should be kept close to the ground during the upending process.

6. Slowly lift the upper end of the upending frame while lowering the bottom end of the Upending Frame.
7. When the MPC approaches the vertical orientation, release the tension on the lower slings.
8. Place the MPC in a vertical orientation on a level surface.
9. Disconnect the MPC straps and disconnect the rigging.

c. Install the MPC in the HI-STAR 100 overpack as follows:

1. Install the four point lift sling to the lift lugs inside the MPC. See Figure 7.1.7.

Caution:
Be careful not to damage the overpack seal seating surface during MPC installation.

2. Raise and place the MPC inside the HI-STAR 100 overpack.

Note:
An alignment punch mark is provided on the HI-STAR 100 overpack and the top edge of the MPC. Similar marks are provided on the MPC lid and closure ring. See Figure 7.1.8.

3. Rotate the MPC so the alignment marks agree and seat the MPC inside the HI-STAR 100 overpack. Disconnect the MPC rigging or the MPC lift rig.

7.1.3 HI-STAR 100 Overpack and MPC Receipt Inspection and Loading Preparation

1. Recover the shipping documentation from the carrier.

   a. If necessary, recover the keys to the personnel barrier locks from the carrier.

   b. Record the impact limiter security seal serial numbers and verify that they match the corresponding shipping documentation, as applicable.

   c. Perform a receipt radiation and contamination survey in accordance with 49CFR173.443 [7.1.3] and 10CFR20.1906 [7.1.4].

2. If necessary, remove the personnel barrier as follows:

Note:
The personnel barrier is a ventilated enclosure cage that fits over the main body of the HI-STAR 100 overpack. The personnel barrier is designed to restrict personnel accessibility to the surfaces of the HI-STAR 100 overpack. The personnel barrier in conjunction with the impact limiters restrict accessibility to all surfaces of the HI-STAR 100 overpack during transport. The personnel barrier is equipped with locks to prevent unauthorized access.

a. Remove the locks securing the personnel barrier and remove the personnel barrier.

b. Remove any fasteners securing the personnel barrier to the transport frame.

c. Rig the personnel barrier to the lifting device.

d. Remove the personnel barrier as shown on Figure 7.1.9.

e. Perform a partial visual inspection of the overpack surfaces to verify that there is no outward indication that would suggest impaired condition of the overpack in accordance with 10CFR71.87(b) [7.0.1]. Identify any significant indications to the cognizant individual for evaluation and resolution and record on the receiving documentation.

3. If necessary, remove the impact limiters as follows:

Note:
To prevent damage to the impact limiters, the impact limiter handling frame must be used to remove, install, handle and store the impact limiters.

a. Clip the security seal wires and remove the security seals and wires.

b. Attach the impact limiter handling frame as shown on Figure 7.1.10. The rigging arms secure the impact limiter and maintain it at the proper orientation during rigging.

c. Using a load measuring device, apply the correct lift load. See Table 7.1.1 for approximate weights.

d. Remove the bolts securing the impact limiter to the overpack. See Figure 7.1.11.

e. Remove the impact limiter and store the impact limiter and bolts in a site-approved location.

f. Repeat Steps 3.c. through 3.e. for the other impact limiter

g. Remove the alignment pins from the bottom of the HI-STAR 100 overpack. See Figure 7.1.11.

h. Complete the visual inspection to verify that there is no outward indication that would suggest impaired condition of the overpack. (10CFR71.87(b)) [7.0.1]. Identify any significant indications to the cognizant individual for evaluation and resolution.

i. Verify that the HI-STAR 100 overpack neutron shield relief devices are installed, intact and not covered by tape or other covering.

ALARA Note:
A bottom protective cover may be attached to the HI-STAR 100 overpack bottom or placed in the designated preparation area or spent fuel pool. This will help prevent embedding contaminated particles in the HI-STAR 100 overpack bottom surface and ease the decontamination effort.

4. Upend the HI-STAR 100 and place the overpack in the cask receiving area in accordance with Section 7.1.2.

5. If necessary, remove the buttress plate bolts and remove the buttress plate. See Figure 7.1.11. See Figure 7.1.12 for rigging. Store these components in a site-approved storage location.

6. If necessary, remove the HI-STAR 100 overpack closure plate by removing the closure plate bolts and using the dedicated lift sling. See Figure 7.1.12 for rigging.

    a. Place the closure plate on cribbing that protects the seal seating surfaces and allows access for seal replacement.

    b. Store the closure plate and bolts in a site-approved location.

    c. Install the seal surface protector on the HI-STAR 100 overpack seal seating surface. See Figure 7.1.13.

7. Install the MPC inside the HI-STAR 100 overpack as follows:

    a. Rinse off any MPC road dirt with water. Inspect all cavity locations for foreign objects. Remove any foreign objects.

    b. At the site's discretion, perform an MPC receipt inspection and cleanliness inspection in accordance with a site-specific inspection checklist.

    c. Install the MPC in the HI-STAR 100 taking care not to damage the overpack seal surface. See Figure 7.1.7 for rigging requirements.

    d. Place the HI-STAR 100 overpack in the designated preparation area.

Note:
Upper fuel spacers are fuel-type specific. Not all fuel types require fuel spacers. See Figure 7.1.14. Upper fuel spacers may be loaded any time prior to placement of the MPC lid in the spent fuel pool for installation in the MPC.

8. Install the upper fuel spacers in the MPC lid as follows:

Warning:
Never work under a suspended load.

    a. Position the MPC lid on supports to allow access to the underside of the MPC lid.

b. Thread the fuel spacers into the holes provided on the underside of the MPC lid. See Figure 7.1.14 and Table 7.1.3 for torque requirements.

c. Install threaded plugs in the MPC lid where and when spacers will not be installed, if necessary. See Table 7.1.3 for torque requirements.

9. At the user's discretion, perform an MPC lid and closure ring fit test:

Note:
It will be necessary to perform the MPC installation and inspection in a location that has sufficient crane clearance to perform the operation.

a. Visually inspect the MPC lid rigging (See Figure 7.1.12).

b. Raise the MPC lid such that the drain line can be installed. Install the drain line to the underside of the MPC lid. See Figure 7.1.15.

c. Align the MPC lid and lift yoke so the drain line will be positioned in the MPC drain location. See Figure 7.1.16. Install the MPC lid. Verify that the MPC lid fit and weld prep are in accordance with the approved design drawings.

ALARA Note:
The closure ring is installed by hand. No tools are required.

d. Install the closure ring.

e. Verify that closure ring fit and weld prep are in accordance with the approved design drawings.

f. Remove the closure ring and the MPC lid. Disconnect the drain line. Store these components in an approved plant storage location.

Note:
Fuel spacers are fuel-type specific. Not all fuel types require fuel spacers. Lower fuel spacers are set in the MPC cells manually. No restraining devices are used. Fuel spacers may be loaded any time prior to insertion of the fuel assemblies in the MPC.

10. Install lower fuel spacers in the MPC (if required for the fuel type). See Figure 7.1.14.

11. Fill the MPC and annulus as follows:

Caution:
Do not use any sharp tools or instruments to install the inflatable seal. Some air in the inflatable seal helps in the installation.

a. Remove the HI-STAR 100 overpack drain port cover and port plug and install the drain connector. Store the drain port cover plate and port plug in an approved storage location.

b. Fill the annulus with clean water to just below the inflatable seal seating surface.

c. Manually insert the inflatable annulus seal around the MPC. See Figure 7.1.13.

d. Ensure that the seal is uniformly positioned in the annulus area.

e. Inflate the seal to between 30 and 35 psig or as directed by the manufacturer.

f. Visually inspect the seal to ensure that it is properly seated in the annulus. Deflate, adjust and inflate the seal as necessary. Replace the seal as necessary.

ALARA Note:
Waterproof tape placed over empty bolt holes, and bolt plugs may reduce the time required for decontamination.

12. At the user's discretion, install the HI-STAR 100 overpack closure plate bolt plugs and/or apply waterproof tape over any empty bolt holes.

ALARA Note:
Keeping the water level below the top of the MPC prevents splashing during handling.

13. Fill the MPC with either clean water or spent fuel pool water to approximately 12 inches below the top of the MPC shell.

14. Place the HI-STAR 100 overpack in the spent fuel pool as follows:

ALARA Note:
The Annulus Overpressure System is used to provide further protection against MPC external shell contamination during in-pool operations. The Annulus Overpressure System is equipped with design features to prevent inadvertent draining. The reservoir valve must be closed to ensure that the annulus is not inadvertently drained through the Annulus Overpressure System when the cask is raised above the level of the annulus reservoir.

a. If used, fill the Annulus Overpressure System lines and reservoir with clean water and close the reservoir valve. Attach the Annulus Overpressure System to the HI-STAR 100 overpack. See Figure 7.1.17.

b. Engage the lift yoke to the HI-STAR 100 overpack lifting trunnions and position the HI-STAR 100 overpack over the cask loading area.

ALARA Note:
Wetting the components that enter the spent fuel pool may reduce the amount of decontamination work to be performed later.

c. Wet the surfaces of the HI-STAR 100 overpack and lift yoke with clean water while slowly lowering the HI-STAR 100 overpack into the spent fuel pool.

d. When the top of the HI-STAR 100 overpack reaches the elevation of the reservoir, start the Annulus Overpressure System water flow. Maintain the reservoir water level at approximately 3/4 full the entire time the cask is in the spent fuel pool.

e. Place the HI-STAR 100 overpack on the floor of the cask loading area and disengage the lift yoke. Visually verify that the lift yoke is fully disengaged. Remove the lift yoke from the spent fuel pool while spraying the crane cables and yoke with clean water.

7.1.4 MPC Fuel Loading

Note:
An underwater camera or other suitable viewing device may be used for monitoring underwater operations.

1. Perform a fuel assembly selection verification using plant fuel records to ensure that only fuel assemblies that meet all the conditions for loading as specified in the Certificate of Compliance have been selected for loading into the MPC.

2. Load the pre-selected fuel assemblies into the MPC in accordance with the approved fuel loading pattern.

3. Perform a post-loading visual verification of the assembly identification to confirm that the serial numbers match the approved fuel loading pattern.

7.1.5 MPC Closure

Note:
The user may elect to use the optional Lid Retention System (See Figure 7.1.18) to assist in the installation of the MPC lid and attachment of the lift yoke, and to provide the means to secure the MPC lid in the event of a drop or tip-over accident during loaded cask handling operations outside of the spent fuel pool. The user is responsible for evaluating the additional weight imposed on the cask, lift yoke, crane and floor prior to use to ensure that its use does not exceed the crane capacity, heavy loads handling restrictions, or 250,000 pounds. See Tables 7.1.1 and 7.1.2.

1. Visually inspect the MPC lid rigging or Lid Retention System in accordance with site-approved rigging procedures. Attach the MPC lid to the lift yoke so that MPC lid, drain line and trunnions will be in relative alignment. Raise the MPC lid and adjust the rigging so the MPC lid hangs level as necessary.

2. Install the drain line to the underside of the MPC lid. See Figure 7.1.15.

3. Align the MPC lid and lift yoke so the drain line will be positioned in the MPC drain location and the cask trunnions will also engage. See Figure 7.1.16 and 7.1.19.

ALARA Note:
Wetting the components that enter the spent fuel pool may reduce the amount of decontamination work to be performed later.

4. Slowly lower the MPC lid into the pool and insert the drain line into the drain access location and visually verify that the drain line is correctly oriented. See Figure 7.1.16.

5. Lower the MPC lid while monitoring for any hang-up of the drain line. If the drain line becomes kinked or disfigured for any reason, remove the MPC lid and inspect and replace the drain line as necessary.

Note:
The upper surface of the MPC lid will seat approximately flush with the top edge of the MPC shell when properly installed.

6. Seat the MPC lid in the MPC and visually verify that the lid is properly installed.

7. Engage the lift yoke to the HI-STAR 100 overpack lifting trunnions.

8. Apply a slight tension to the lift yoke and visually verify proper engagement of the lift yoke to the lifting trunnions.

ALARA Note:
Activated debris may have settled on the top face of the HI-STAR 100 overpack and MPC during fuel loading. The cask top surface should be kept under water until a preliminary dose rate scan clears the cask for removal.

9. Raise the HI-STAR 100 overpack until the MPC lid is just below the surface of the spent fuel pool. Survey the area above the cask lid to check for hot particles. Raise and flush the upper surface of the HI-STAR 100 overpack and MPC as necessary to remove any activated particles from the HI-STAR 100 overpack or the MPC lid.

10. Visually verify that the MPC lid is properly seated. Lower the HI-STAR 100 overpack, reinstall the MPC lid, and repeat Step 9, as necessary.

11. If the Lid Retention System is used, inspect the closure plate bolts for general condition. Replace worn or damaged bolts with new bolts.

12. Install the Lid Retention System bolts if the Lid Retention System is used.

Warning:
Cask removal from the spent fuel pool is typically the heaviest lift that occurs during HI-STAR 100 loading operations. The HI-STAR 100 trunnions must not be subjected to lifted loads in excess of 250,000 lbs. . Users must ensure that plant-specific lifting equipment is qualified to lift the expected load. Users may elect to pump a measured quantity of water from the MPC prior to removing the HI-STAR 100 from the spent fuel pool. See Tables 7.1.1 and 7.1.2 for weight information.

13. If necessary for lifted weight conditions, pump a measured amount of water from the MPC. See Figure 7.1.22 and Tables 7.1.1 and 7.1.2.

14. Continue to raise the HI-STAR 100 overpack under the direction of the plant's radiological control personnel. Continue rinsing the surfaces with clean water. When the top of the HI-STAR 100 overpack reaches the approximate elevation of the reservoir, stop the Annulus Overpressure System water flow. See Figure 7.1.17.

Caution:
Users are required to take necessary actions to prevent boiling of the water in the MPC. This may be accomplished by performing a site-specific analysis to identify a time limitation to ensure that water boiling will not occur in the MPC prior to the initiation of draining operations. Chapter 3 of this SAR provides some sample time limits for the time to initiation of draining for various spent fuel pool water temperatures using design basis heat loads. These time limits may be adopted if the user chooses not to perform a site-specific analysis. If time limitations are imposed, users shall have appropriate procedures and equipment to take action if time limits are approached or exceeded. One course of action involves initiating an MPC water flush for a certain duration and flow rate. Any site-specific analysis shall identify the methods to respond should it become likely that the imposed time limit could be exceeded.

ALARA Note:
To reduce decontamination time, the surfaces of the HI-STAR 100 overpack and lift yoke should be kept wet until decontamination begins.

15. Remove the HI-STAR 100 overpack from the spent fuel pool while spraying the surfaces with clean water. Record the time.

ALARA Note:
Decontamination of the HI-STAR 100 overpack bottom should be performed using pole-mounted cleaning devices.

16. Decontaminate the HI-STAR 100 overpack bottom and perform a contamination survey of the HI-STAR 100 overpack bottom. Remove the bottom protective cover, if used.

17. If used, disconnect the Annulus Overpressure System from the HI-STAR 100 overpack. See Figure 7.1.17.

18. Set the HI-STAR 100 overpack in the designated cask preparation area.

19. Disconnect the lifting slings or Lid Retention System (if used) from the MPC lid and disengage the lift yoke. Decontaminate and store these items in an approved storage location.

Warning:
MPC lid dose rates are measured to provide assurance that the dose rates at the lid are reasonable to allow worker access.

    a. Measure the dose rates at the MPC lid..

20. Perform decontamination of the HI-STAR 100 overpack.

21. Prepare the MPC for MPC lid welding as follows:

    a. Decontaminate the area around the HI-STAR 100 overpack top flange and install the Temporary Shield Ring, (if used). See Figure 7.1.20.

    b. Fill the Temporary Shield Ring with water (if used).

    c. Carefully decontaminate the MPC lid top surface and the shell area above the inflatable annulus seal.

    d. Deflate and remove the annulus seal.

ALARA Note:
The water in the HI-STAR 100 overpack-to-MPC annulus provides personnel shielding. The level should be checked periodically and refilled accordingly.

22. Attach the drain line to the HI-STAR 100 overpack drain port connector and lower the annulus water level approximately 6 inches.

ALARA Note:
The MPC exterior shell survey is performed to evaluate the performance of the inflatable annulus seal. Indications of contamination could require the MPC to be unloaded.

    a. Survey the MPC lid top surfaces and the accessible areas of the top two inches of the MPC shell.

ALARA Note:
The annulus shield is used to prevent objects from being dropped into the annulus and helps reduce dose rates directly above the annulus region. The annulus shield is hand installed and requires no tools.

23. Install the annulus shield. See Figure 7.1.13.

24. Prepare for MPC lid welding as follows:

Note:
The following steps use two identical Remote Valve Operating Assemblies (RVOAs) (See Figure 7.1.21) to engage the MPC vent and drain ports. The MPC vent and drain ports are equipped with metal-to-metal seals to minimize leakage during vacuum drying, and to withstand the long-term effects of temperature and radiation. The RVOAs allow the vent and drain ports to be operated like valves and prevent the need to hot tap into the penetrations during unloading operations. The RVOAs are purposely not installed until the cask is removed from the spent fuel pool to reduce the amount of decontamination.

Note:

The vent and drain ports are opened by pushing the RVOA handle down to engage the square nut on the cap and turning the handle fully in the counter-clockwise direction. The handle will not turn once the port is fully open. Similarly, the vent and drain ports are closed by turning the handle fully in the clockwise direction. The ports are closed when the handle cannot be turned further.

a. Clean the vent and drain ports to remove any dirt. Install the RVOAs (See Figure 7.1.21) to the vent and drain ports leaving caps open.

ALARA Warning:

Personnel should remain clear of the drain lines any time water is being pumped or purged from the MPC. Assembly crud, suspended in the water, may create a radiation hazard to workers. Controlling the amount of water pumped from the MPC prior to welding keeps the fuel assembly cladding covered with water yet still allows room for thermal expansion.

b. Connect the water pump to the drain port (See Figure 7.1.22) and pump between 50 and 120 gallons to the spent fuel pool or liquid radwaste system. The water level is lowered to keep moisture away from the weld region.

c. Disconnect the water pump.

25. Weld the MPC lid as follows:

ALARA Warning:

Grinding of MPC welds may create the potential for contamination. All grinding activities shall be performed under the direction of radiation protection personnel.

Caution:

Oxidation of Boral panels contained in the MPC may create hydrogen gas while the MPC is filled with water. Appropriate monitoring for combustible gas concentrations shall be performed prior to, and during MPC lid welding operations. The space below the MPC lid shall be exhausted or purged with inert gas prior to, and during MPC lid welding operations to provide additional assurance that flammable gas concentrations will not develop in this space.

Note:

Exhausting or purging may help improve the weld quality by keeping moist air from condensing on the MPC lid weld area. The vacuum source can be supplied from a wet/dry vacuum cleaner or small vacuum pump.

a. Attach a vacuum source to the vent port or inert the gas space under the MPC lid and begin monitoring for combustible gas concentrations.

ALARA Warning:
It may be necessary to rotate or reposition the MPC lid slightly to achieve uniform weld gap and lid alignment. A punch mark is located on the outer edge of the MPC lid and shell. These marks are aligned with the alignment mark on the top edge of the HI-STAR 100 overpack (See Figure 7.1.8). If necessary, the MPC lid lift should be performed using a hand operated chain fall to closely control the lift to allow rotation and repositioning by hand. If the chain fall is hung from the crane hook, the crane should be secured to prevent inadvertent use during this operation. Continuous radiation monitoring is recommended.

b. If necessary center the lid in the MPC shell using a hand-operated chain fall.

Note:
The MPC is equipped with lid shims that serve to close the gap in the joint for MPC lid closure weld.

c. As necessary, install the MPC lid shims around the MPC lid to make the weld gap uniform.

ALARA Note:
The optional AWS Baseplate shield is used to further reduce the dose rates to the operators working around the top cask surfaces.

d. Install the Automated Welding System baseplate shield (if used). See Figure 7.1.12 for rigging.

e. Install the Automated Welding System Robot (if used). See Figure 7.1.12 for rigging.

f. Tack weld the MPC lid.

g. Visually inspect the tack welds.

h. Lay the root weld.

Note:

The Lid-to-Shell weld may be examined by either volumetric examination (UT) or multi-layer liquid penetrant examination. If volumetric examination is used, it shall be the ultrasonic method and shall include a liquid penetrant (PT) of the root and final weld layers. If PT alone is used, at a minimum, it must include the root and final weld layers and one intermediate PT after approximately every 3/8 inch weld depth.

The methods and acceptance criteria for MPC welding examinations are specified in Section 8.1.1.

i. Disconnect the vacuum /purge source from the MPC and terminate combustible gas monitoring.

j. Perform a liquid penetrant examination of the weld root.

k. Complete the MPC lid welding, performing at least one intermediate layer liquid penetrant examination after approximately every 3/8 inch weld depth if the multi-layer liquid penetrant method is used.

l. Perform a liquid penetrant examination on the MPC lid final pass and UT (if required).

> **Note:**
> The timing of the ASME Code pressure test may depend on the type of test used (hydraulic or pneumatic). The test shall be performed at any time after welding is complete and prior to installation of the MPC closure rings.

26. Perform an ASME Code pressure test and MPC leakage rate testing as follows:

> **ALARA Note:**
> The leakage rates may be determined before the MPC is drained for ALARA reasons. A weld repair is a lower dose activity if water remains inside the MPC.

a. Attach the drain line to the vent port and route the drain line to the spent fuel pool or the plant liquid radwaste system. See Figure 7.1.23 for an example of a pressure test arrangement.

> **ALARA Warning:**
> Water and gas flowing from the MPC may carry activated particles and fuel particles. Apply appropriate ALARA practices around the drain line.

b. Fill the MPC with the pressure test fluid.

c. Perform a pressure test of the MPC as follows:

1. Close the outlet valve and pressurize the MPC to the appropriate pressure as dictated by the requirements contained in Section 8.1.2. .

2. Close the inlet valve and monitor the pressure for a minimum of 10 minutes. The pressure shall not drop during the performance of the test.

3. Following the 10-minute hold period, visually examine the MPC lid-to-shell weld for leakage. The acceptance criteria is no observable leakage.

d. Release the MPC internal pressure, disconnect the fill line and drain line from the vent and drain port RVOAs leaving the vent and drain port caps open.

e. Perform required NDE inspections on the MPC lid-to-shell weld.

f. Attach a regulated helium supply to the vent port and attach the drain line to the drain port as shown in Figure 7.1.24

g. Verify the correct pressure on the helium supply and open the helium supply valve. Drain approximately 5 to 10 gallons.

h. Close the drain port valve and pressurize the MPC to a mininum of 85 psig with helium.

i. Close the vent port.

Note:
The leakage test is performed to provide the user with an indication of the integrity of the weld for all MPC types. The CoC required secondary containment helium leakage test for the MPC-68F and MPC-24EF is performed after MPC closure operations are completed. (See Step 7.1.6.5) The leakage detector may detect residual helium in the atmosphere. If the leakage tests detects a leak, the area should be flushed with nitrogen or compressed air and the location should be retested.

j. Perform a helium leakage rate test of the MPC lid-to shell weld using the tracer gas-sniffer method in accordance with the Mass Spectrometer Leak Detector (MSLD) manufacturer's instructions and ANSI N14.5 [7.1.5]. The sum of the MPC Helium Leak Rates shall meet the requirements of Section 8.1.3..

k. Repair any weld defects in accordance with the site's approved weld repair procedures. Re-perform the Ultrasonic, Liquid Penetrant, Hydrostatic and Helium Leakage tests if weld repair is performed.

27. Drain the MPC as follows:

ALARA Warning:
Dose rates will rise as water is drained from the MPC. Continuous dose rate monitoring is recommended.

a. Attach a regulated helium or nitrogen supply to the vent port.

b. Attach a drain line to the drain port shown on Figure 7.1.24.

c. Deleted.

d. Open the gas supply valve and record the time at the start of MPC draindown.

e. Deleted.

f. Blow the water out of the MPC until water ceases to flow out of the drain line. Shut the gas supply valve.

g. Disconnect the gas supply line from the MPC.

h. Disconnect the drain line from the MPC.

28. Dry the MPC as follows:

> **Note:**
> When the MPC is dried under the "load and go" operations, The Forced Helium Dehydrator (FHD) will be used to remove water to the levels required in the CoC. The FHD operates in two distinct phases. In Phase 1, liquid water is removed through a forced evaporation process. In Phase 2, heated, dry helium is circulated through the MPC to reduce the remaining water vapor to below required limits.

a. Connect the FHD to the MPC vent and drain port RVOAs. See Figure 7.1.25.

b. Purge the FHD and connecting piping to remove oxygen from the lines.

c. Operate the FHD through Phase 1 to remove liquid water.

d. Operate the FHD through Phase 2 to remove the water vapor. Helium shall be circulated though the MPC for greater than or equal to 30 minutes with the temperature at the demoisturizer outlet held less than or equal to 21 °F.

29. Backfill the MPC as follows:

> **Note:**
> Backfill requires use of 99.995% (minimum) purity helium.

a. Continue operation of the FHD system with the demoisturizer on.

b. While monitoring the temperatures into and out of the MPC, adjust the helium pressure in the MPC to provide a fill pressure as required in Table 1.2.3.

c. Open the FHD bypass line and Close the vent and drain port RVOAs.

d. Disconnect the FHD from the MPC.

30. Weld the vent and drain port cover plates as follows:

a. Wipe the inside area of the vent and drain port recesses to dry and clean the surfaces.

b. Place the cover plate over the vent port recess.

c. Deleted..

> **Note:**
> The vent and drain port cover plates are provided with two small threaded holes with set screws for the injection of helium. The set screws may be installed or removed during welding.

d. Deleted.

e. Tack weld the cover plate.

f. Visually inspect the tack welds.

g. Weld the root pass on the vent port cover plate.

h. Perform a liquid penetrant examination on the vent port cover plate root weld.

i. If required, complete the vent port cover plate welding and perform a liquid penetrant examination on the final weld pass.

j. Repeat Steps 30.a through 30.i for the drain port cover plate.

31. Perform a leakage test of the MPC vent and drain port cover plates as follows:

Note:
The leakage test is performed to provide the user with an indication of the integrity of the weld for all MPC types. The CoC required secondary containment helium leakage test for the MPC-68F and MPC-24EF is performed after MPC closure operations are completed. (See Step 7.1.6.5) The leakage detector may detect residual helium in the atmosphere from the helium injection process. If the leakage tests detects a leak, the area should be blown clear with compressed air or nitrogen and the location should be retested. The following process provides a high concentration of helium gas into the cavity. Other methods that ensure a high concentration of helium gas are also acceptable.

a. If necessary, remove the cover plate set screws.

b. Flush the cavity with helium to remove the air and immediately install the set screws recessed ¼-inch below the top of the cover plate.

c. Plug weld the recess above each set screw to complete the penetration closure welding.

d. Perform a liquid penetrant examination on the plug weld.

e. Flush the area around the vent and drain cover plates with compressed air or nitrogen to remove any residual helium gas.

f. Perform a helium leakage rate test of vent and drain cover plate welds using the evacuated envelope-gas detector method in accordance with the Mass Spectrometer Leak Detector (MSLD) manufacturer's instructions and ANSI N14.5 [7.1.5]. The sum of the MPC Helium Leak Rates shall meet the requirements of Section 8.1.3.

g. Repair any weld defects in accordance with the site's approved code weld repair procedures. Re-perform the leakage test as required.

32. Weld the MPC closure ring as follows:

> **ALARA Note:**
> The closure ring is installed by hand. No tools are required. The closure ring may be provided as a complete ring or in multiple sections. In the case of the single ring, no radial connecting welds are needed. Portions of the closure ring may be installed while the MPC is filled with water and after the lid-to-shell weld is complete to reduce dose.

a. Install and align the closure ring. See Figure 7.1.8.

b. Tack weld the closure ring to the MPC shell and the MPC lid.

c. Visually inspect the tack welds.

d. Lay the root weld between the closure ring and the MPC.

e. Perform a liquid penetrant examination on the closure ring root welds.

f. If necessary, complete the closure ring welding and perform a liquid penetrant examination on the closure ring final welds.

g. Remove the Automated Welding System.

h. If used, remove the AWS baseplate shield. See Figure 7.1.12 for rigging.

7.1.6 Preparation for Transport

1. Remove the annulus shield and seal surface protector and store it in an approved plant storage location

> **ALARA Warning:**
> Dose rates will rise around the top of the annulus as water is drained from the annulus. Apply appropriate ALARA practices.

2. Attach a drain line to the HI-STAR 100 overpack drain connector and drain the remaining water from the annulus to the spent fuel pool or the plant liquid radwaste system (See Figure 7.1.17).

3. Install the overpack closure plate as follows:

a. Remove any waterproof tape or bolt plugs used for contamination mitigation and ensure that the threaded holes in the MPC lid are plugged to prevent radiation streaming.

b. Clean the closure plate seal seating surface and the HI-STAR 100 overpack seal seating surface and install new overpack closure plate mechanical seals.

c. Remove the test port plug and store it in a site-approved location. Discard any used metallic seals.

Note:
Care should be taken to protect the overpack seal seating surface from scratches, nicks or dents.

d. Install the closure plate (see Figure 7.1.12). Disconnect the closure plate lifting eyes and install the bolt hole plugs in the empty bolt holes.

e. Install and torque the closure plate bolts. See Table 7.1.3 for torque requirements.

f. Remove the vent port cover plate and remove the port plug and seal. Discard any used mechanical seals.

4. Dry the overpack annulus as follows:

a. Disconnect the drain connector from the overpack.

b. Install the drain port plug with a new seal and torque the plug. See Table 7.1.3 for torque requirements. Discard any used metallic seals.

Note:
Preliminary annulus vacuum drying may be performed using the test cover to improve flow rates and reduce vacuum drying time. Dryness testing and helium backfill shall use the backfill tool.

c. Load the backfill tool with the HI-STAR 100 overpack vent port plug and the vent port with a new plug seal. Attach the backfill tool to the HI-STAR 100 overpack vent port with the plug in the open position. See Figure 7.1.28. See Table 7.1.3 for torque requirements.

d. Connect the vacuum pump and evacuate the HI-STAR 100 overpack pressure to below 3 torr.

Note:
The annulus pressure may rise due to the presence of water in the HI-STAR 100 overpack. The dryness test may need to be repeated several times until all the water has been removed. Leaks in the Vacuum Drying System, damage to the vacuum pump, and improper vacuum gauge calibration may cause repeated failure of the dryness verification test. These conditions should be checked as part of the corrective actions if repeated failure of the dryness verification test is occurring.

e. Perform a HI-STAR 100 overpack Annulus Dryness Verification. The overpack annulus shall hold stable vacuum drying pressure of $\leq$ 3 torr for $\geq$ 30 minutes.

5. Perform a leakage test of the MPC-68F/24EF as follows:

    a. Evacuate the annulus per the MSLD manufacturer's instructions and isolate the vacuum pump from the backfill tool.

    b. Connect the MSLD to the backfill tool and perform a leakage rate test of MPC-68F/24EF using the evacuated envelope-gas detector method in accordance with the MSLD manufacturer's instructions and ANSI N14.5 [7.1.5]. The total MPC Helium Leak Rate shall meet the requirements of Section 8.1.3.

> **Note:**
> The sum of the helium leak rates from the overpack penetrations (i.e. the overpack closure plate inner mechanical seal and vent and drain port plugs) shall meet the limit established in Section 8.1.3.

6. Backfill, and leakage test the overpack as follows:

    a. Attach the helium supply to the backfill tool.

    b. Verify the correct pressure on the helium supply and open the helium supply valve.

    c. Backfill the HI-STAR 100 overpack annulus to the pressure required by Table 1.2.3.

    d. Install the overpack vent port plug and torque. See Table 7.1.3 for torque requirements.

    e. Disconnect the overpack backfill tool from the vent port.

    f. Flush the overpack vent port recess with compressed air to remove any standing helium gas.

    g. Install the overpack test cover to the overpack vent port as shown on Figure 7.1.27. See Table 7.1.3 for torque requirements.

    h. Evacuate the test cavity per the MSLD manufacturer's instructions and isolate the vacuum pump from the overpack test cover.

    i. Perform a leakage rate test of overpack vent port plug using the evacuated envelope-gas detector method in accordance with the MSLD manufacturer's instructions and ANSI N14.5 [7.1.5].

    j. Remove the overpack test cover and install a new metallic seal on the overpack vent port cover plate. Discard any used metallic seals.

    k. Install the vent port cover plate and torque the bolts. See Table 7.1.3 for torque requirements.

l. Repeat Steps 6.f through 6.k for the overpack drain port.

7. Leak test the overpack closure plate inner mechanical seal as follows:

a. Attach the closure plate test tool to the closure plate test port with the MSLD attached. See Figure 7.1.29. See Table 7.1.3 for torque requirements.

b. Evacuate the closure plate test port tool and closure plate inter-seal area per the MSLD manufacturer's instructions.

c. Perform a leakage rate test of overpack closure plate inner mechanical seal using the evacuated envelope-gas detector method in accordance with the MSLD manufacturer's instructions and ANSI N14.5 [7.1.5].

d. Remove the closure plate test tool from the test port and install the test port plug with a new mechanical seal. See Table 7.1.3 for torque requirements. Discard any used metallic seals.

8. Sum the individual leak rates for the closure plate inner mechanical seal and the vent and drain port plugs and ensure that they meet the requirements of Section 8.1.3.

9. Drain the temporary shield ring (Figure 7.1.20), if used. Remove and store in an approved plant storage location.

ALARA Warning:
For ALARA reasons, decontamination of the overpack bottom shall be performed using pole-mounted cleaning tools or other remote cleaning devices.

ALARA Warning:
If the overpack is to be downended on the transport frame, the bottom shield should be installed quickly. Personnel should remain clear of the bottom of the unshielded overpack.

7.1.7 Placement of the HI-STAR 100 Overpack on the Transport Vehicle

1. Position the transport vehicle under the overhead lifting device.

2. Install the HI-STAR 100 overpack buttress plate on the HI-STAR 100 overpack. See Figure 7.1.11 and 7.1.12 for rigging. See Table 7.1.3 for torque requirements.

3. Downend the HI-STAR 100 overpack . See Section 7.1.2.

4. Install the removable shear ring segments. See Table 7.1.3 for torque requirements.

5. Ensure that pocket trunnions are plugged if present and not in use on the transport vehicle.

Note:
To prevent damage to the impact limiters, the impact limiter handling frame must be used to remove, install, handle and store the impact limiters.

6. Install the impact limiters as follows:

    a. Install the alignment pins in the bottom of the HI-STAR 100 overpack. See Figure 7.1.11. See Table 7.1.3 for torque requirements.

    b. Using the impact limiter handling frame, raise and position the impact limiter over the end of HI-STAR 100. See Figure 7.1.10.

    c. Install the impact limiter bolts. See Table 7.1.3 for torque requirements.

    d. Repeat for the other impact limiter.

Note:
The impact limiters cover all the HI-STAR 100 penetrations. The security seals are used to provide tamper detection.

    e. Install a security seal (one per impact limiter) through the threaded hole in the top and bottom impact limiter bolts. Record the security seal number on the shipping documentation.

    f. Perform final radiation surveys of the package surfaces per 10CFR71.47 [7.0.1] and SAR Section 8.1.5.2 and 49CFR173.443 [7.1.3]. Record the results on the shipping documentation.

Note:
The HI-STAR shall be secured and positioned in the transport vehicle in accordance with the drawing in Section 1.4.

7. Place the overpack in the transport vehicle. See Figure 7.1.5

8. Perform a final inspection of the HI-STAR 100 overpack as follows:

ALARA Warning:
Dose rates around the unshielded bottom end of the HI-STAR 100 overpack may be higher that other locations around the overpack. Workers should exercise appropriate ALARA controls when working around the bottom end of the HI-STAR 100 overpack.

Note:
Prior to shipment of the HI-STAR 100 package, the accessible external surfaces of the HI-STAR 100 packaging (HI-STAR 100 overpack, impact limiters, personnel barrier, and transport vehicle) shall be surveyed for removable radiological contamination in accordance with 49CFR173.428 [7.1.3].

a. Perform a final decontamination of the HI-STAR 100 overpack, and survey for removable contamination.

b. Perform a visual inspection of the HI-STAR 100 overpack to verify that there are no outward visual indications of impaired physical condition. Identify any significant indications to the cognizant individual for evaluation and resolution and record on the shipping documentation.

c. Verify that the HI-STAR 100 overpack neutron shield relief devicesare installed, intact and not covered by tape or other covering.

9. Secure the HI-STAR 100 to the transport vehicle using the tie-downs. I

10. Install the personnel barrier as follows:

a. Rig the personnel barrier as shown in Figure 7.1.9 and position the personnel barrier over the frame.

b. Remove the personnel barrier rigging and install the personnel barrier locks.

c. Transfer the personnel barrier keys to the carrier.

11. Perform a final check to ensure that the package is ready for release as follows:

a. Verify that required radiation survey results are properly documented on the shipping documentation.

b. Perform a HI-STAR 100 overpack surface temperature check. The accessible surfaces of the HI-STAR 100 Package (impact limiters and personnel barrier) shall not exceed the Exclusive Use temperature limits of 49CFR173.442 [7.1.3].

c. Verify that all required leakage testing has been performed and the acceptance criteria has been met and document the results on the shipping documentation.

d. Verify that the receiver has been notified of the impending shipment and that the receiver has the appropriate procedures and equipment available to safely receive and handle the HI-STAR 100 System (10CFR20.1906(e)) [7.1.4].

e. Verify that the carrier has the written instructions and a list of appropriate contacts for notification of accidents or delays.

f. Verify that the carrier has written instructions that the shipment is to be Exclusive Use in accordance with 49CFR173.441 [7.1.3].

g. Verify that route approvals and notification to appropriate agencies have been completed.

h. Verify that the appropriate labels have been applied in accordance with 49CFR172.403.

i. Verify that the appropriate placards have been applied in accordance with 49CFR172.500.

j. Verify that all required information is recorded on the shipping documentation.

12. Release the HI-STAR 100 System for transport.

Table 7.1.1

ESTIMATED HI-STAR 100 SYSTEM COMPONENT AND HANDLING WEIGHTS

Component	Weight (lbs)			Case Applicability †			
	MPC-24/24E/24EF	MPC-32	MPC-68/68F	1	2	3	4
Empty HI-STAR Overpack (without Closure Plate)	145,726	145,726	145,726	1	1	1	1
HI-STAR Closure Plate (without rigging)	7,984	7,984	7,984		1	1	1
Empty MPC (without Lid or Closure Ring)	31,000	24,700	27,300	1	1	1	1
MPC Lid (without Fuel Spacers or Drain Line)	9,677	9,677	10,113	1	1	1	1
MPC Closure Ring	145	145	145		1	1	1
MPC Fuel Spacers††	1,256	1,440	1,904	1	1	1	1
MPC Drain Line	50	50	50	1	1	1	1
Fuel and non-fuel components (Design Basis)	40,320	53,760	47,600	1	1	1	1
Damaged Fuel Container (Dresden 1)	N/A	N/A	150				
Damaged Fuel Container (Humboldt Bay)	N/A	N/A	120				
Damaged Fuel Container (Trojan)	276	N/A	N/A				
MPC Water ††† (with Fuel in MPC)	17,630	17,630	16,957	1			
Annulus Water	280	280	280	1			
HI-STAR Lift Yoke (with slings)	3600	3600	3600	1	1		
Annulus Seal	50	50	50	1			
Lid Retention System	2300	2300	2300				
Transport Frame	9000	9000	9000			1	
Temporary Shield Ring	2500	2500	2500				
Automated Welding System Baseplate Shield	2000	2000	2000				
Automated Welding System Robot	1900	1900	1900				
Top Impact Limiter (without Buttress Plate)	19,187	19,187	19,187			1	1
Bottom Impact Limiter	17,231	17,231	17,231			1	1
Impact Limiter Handling Frame	1980	1980	1980				
Buttress Plate	2520	2520	2520			1	1
Tie-Down	995	995	995			1	
Personnel Barrier	1500	1500	1500			1	

Note: These weights are estimated from the design drawings and assuming maximum design weight in each fuel cell location. Actual weights will vary based on component as-built conditions and actual contents of each fuel cell location (i.e., fuel assembly, non-fuel hardware, DFC, etc.). Licensees shall confirm weights for lifting and handling operations. MPC-24/24E/24EF weights are bounding for Trojan design MPC-24E/EF.

† See Table 7.1.2.

†† The fuel spacers referenced in this table are for the heaviest fuel assembly for each MPC. This yields the maximum weight of fuel assemblies and spacers.

††† Varies by fuel type and loading configuration. Users may opt to pump some water from the MPC prior to removal from the spent fuel pool to reduce the overall lifted weight.

TABLE 7.1.2
ESTIMATED MAXIMUM HANDLING WEIGHTS
HI-STAR 100 SYSTEM

Caution:
The maximum weight supported by the HI-STAR 100 overpack lifting trunnions (not including the lift yoke) cannot exceed 250,000 lbs. Users should determine their specific handling weights based on the MPC contents and the expected handling modes.

Note:
The weight of the fuel spacers and the damaged fuel container are less than the weight of the design basis fuel assembly for each MPC and are therefore not included in the maximum handling weight calculations.

Case No.	Load Handling Evolution	Weight (lbs)		
		MPC-24/24E/24EF	MPC-32	MPC-68/68F
1	Loaded HI-STAR Removal from Spent Fuel Pool	249,589	256,913	253,580
2	Loaded HI-STAR During Movement through Hatchway	239,758	247,082	244,422
3	Weight on Transport Vehicle	286,591	293,915	291,255
4	Gross HI-STAR 100 Package Weight	275,096	282,420	279,760

Note: These weights are estimated from the design drawings. Actual weights may vary based on as-built conditions. Licensee shall confirm weights based on actual equipment received. MPC-24/24E/24EF weights are bounding for Trojan design MPC-24E/EF.

Table 7.1.3

HI-STAR 100 SYSTEM TORQUE REQUIREMENTS

Fastener	Torque (ft-lbs)	Pattern
Overpack Closure Plate Bolts†, ††	First Pass – Hand Tight Second Pass – Wrench Tight Third Pass – 700 +50/-50 Fourth Pass –1400 +100/-100 Final Pass 2000 +250/-0	Figure 7.1.30
Overpack Vent and Drain Port Cover Plate Bolts††	12+2/-0	X-pattern
Overpack Vent and Drain Port Plugs	45+5/-2	None
Closure Plate Test Port Plug	45+5/-2	None
Backfill Tool Test Cover Bolts††	16+2/-0	X-pattern
Shear Ring Segments	22+2/-0	None
Overpack Bottom Cover Bolts	200+20/-0	None
Pocket Trunnion Plugs	Hand Tight	None
Threaded Fuel Spacers	Hand Tight	None
MPC Lid Threaded Plugs	Hand Tight	None
Impact Limiter Alignment Pin	Hand Tight	None
Top Impact Limiter Attachment Bolt	256+10/-0	None
Bottom Impact Limiter Attachment Bolt	1500+45/-0	None
Buttress Plate Bolts	150 +10-0	None

† Detorquing shall be performed by turning the bolts counter-clockwise in 1/3 turn +/- 30 degrees increments per pass according to Figure 7.1.30 for three passes. The bolts may then be removed.

†† Bolts shall be cleaned and inspected for damage or excessive wear (replaced if necessary) and coated with a light layer of Fel-Pro Chemical Products, N-5000, Nuclear Grade Lubricant (or equivalent).

Table 7.1.4
HI-STAR 100 SYSTEM ANCILLARY EQUIPMENT OPERATIONAL DESCRIPTION

Equipment	Important To Safety Classification	Reference Figure	Description
Annulus Overpressure System (optional)	Not Important To Safety	7.1.17	The Annulus Overpressure System is used for supplemental protection against spent fuel pool water contamination of the external MPC shell and baseplate surfaces by providing a slight annulus overpressure. The Annulus Overpressure System consists of the quick disconnects water reservoir, reservoir valve and annulus connector hoses. User is responsible for supplying clean water to the location of the Annulus Overpressure System.
Annulus Shield (optional)	Not Important To Safety	7.1.13	A shield that is placed at the top of the annulus to provide supplemental shielding to the operators performing cask loading and closure operations.
Automated Welding System (optional)	Not Important To Safety	7.1.2b	Used for remote welding of the MPC lid, vent and drain port cover plates and the MPC closure ring. The AWS consists of the robot, wire feed system, torch system, weld power supply and gas lines.
AWS Baseplate Shield (optional)	Not Important To Safety	7.1.2b	The AWS baseplate shield provides supplemental shielding to the operators during the cask closure operations.
Backfill Tool	Not Important to Safety	7.1.28	Used to dry, backfill the HI-STAR 100 annulus and install the HI-STAR 100 overpack vent and drain port plugs. The backfill tool uses the same bolts as the HI-STAR 100 overpack vent and drain cover plates.
Closure Plate Test Tool	Not Important to Safety	7.1.29	Used to helium leakage test the HI-STAR 100 overpack Closure Plate inner mechanical seal.
Cool-Down System	Not Important To Safety	7.2.5	The Cool-Down System is a closed-loop forced ventilation cooling system used to gas-cool the MPC fuel assemblies down to a temperature water can be introduced without the risk of thermally shocking the fuel assemblies or flashing the water, causing uncontrolled pressure transients. The Cool-Down System is attached between the MPC drain and vent ports The CDS consists of the piping, blower, heat exchanger, valves, instrumentation, and connectors. The CDS is used only for unloading operations.
Forced Helium Dehydration System	Not Important To Safety	7.1.25	Used for drying the MPC cavity. Consists of a circulating blower, heat exchangers, heater and associated piping and controls.

Table 7.1.4 (Continued)
HI-STAR 100 SYSTEM ANCILLARY EQUIPMENT OPERATIONAL DESCRIPTION

Equipment	Important To Safety Classification	Reference Figure	Description
Four Legged Sling and Lifting Rings	Not Important To Safety (controlled under the user's rigging equipment program)	7.1.12	Used for rigging the HI-STAR 100 overpack upper shield lid, MPC lid, Automated Welding System Baseplate shield, Automated Welding System Baseplate Shield and other ancillary equipment. Consists of a four legged sling, lifting rings, shackles and a main lift link.
Helium Backfill System	Not Important To Safety	7.1.26	Used for helium backfilling of the MPC. System consists of the gas lines regulator and measurement equipment used to backfill the MPC with helium.
Code Pressure Test System	Not Important to Safety	7.1.23	Used to perform a Code pressure test on the MPC primary welds. The test system consists of the gauges, piping, pressure protection system piping and connectors.
Impact Limiter Handling Frame	Not Important to Safety	7.1.10	The impact limiter handling frame is used for installing, removing, handling and storing the impact limiters. The impact limiter handling frame consists of the handling frame and rigging.
Impact Limiters	Important to Safety	7.1.11	The impact limiters are used to limit the HI-STAR 100 decelerations to less than 60 g during postulated transportation accidents. The impact limiters consist of the top and bottom impact limiter and the connecting fasteners.
Inflatable Annulus Seal	Not Important To Safety	7.1.13	Used to prevent spent fuel pool water from contaminating the external MPC shell and baseplate surfaces during in-pool operations.
Lid Retention System (optional)	User designated	7.1.18	The Lid Retention System provides three functions; it guides the MPC lid into place during underwater installation, establishes lift yoke alignment with the HI-STAR 100 overpack trunnions, and locks the MPC lid in place during cask handling operations between the pool and decontamination pad. The device consists of the retention disk, alignment pins, lift yoke connector links and lift yoke attachment bolts.
Lift Yoke	User designated	7.1.3	Used for HI-STAR 100 overpack cask handling when used in conjunction with the overhead crane. The lift yoke consists of the lift yoke assembly and crane hook engagement pin(s). The lift yoke is a modular design that allows inspection, disassembly, maintenance and replacement of components.
MPC Upending Frame	Not Important to Safety	7.1.6	A welded steel frame used to evenly support the MPC during upending operations. The frame consists of the main frame, MPC support saddles, two rigging bars, wrap around-straps, and strap attachment lugs.

Table 7.1.4 (Continued)
HI-STAR 100 SYSTEM ANCILLARY EQUIPMENT OPERATIONAL DESCRIPTION

Equipment	Important To Safety Classification	Reference Figure	Description
MSLD (Helium Leakage Detector)	Not Important To Safety	Not shown	Used for helium leakage testing of the MPC closure welds.
Overpack Bottom Cover (optional)	Not Important to Safety	Not shown	A cup-shaped shield used to reduce dose rates around the HI-STAR 100 overpack bottom end when operated in the horizontal orientation.
Overpack Test Cover	Not Important to Safety	7.1.27	Used to helium leakage test the HI-STAR 100 overpack vent and drain port plug seals.
Personnel Barrier	Not Important to Safety	7.1.9	The personnel barrier is a ventilated enclosure cage that fits over the main body of the HI-STAR 100 overpack. The personnel barrier is designed to restrict personnel accessibility to the potentially hot surfaces of the HI-STAR 100 overpack. The personnel barrier in conjunction with the impact limiters restrict accessibility to all surfaces of the HI-STAR 100 overpack during transport. The personnel barrier is equipped with locks to prevent unauthorized access. The personnel barrier is equipped with a four-legged bridle sling used for installation and removal.
Seal Surface Protector (optional)	Not Important to Safety	7.1.13	Used to protect the HI-STAR 100 overpack mechanical seal seating surface during loading and MPC closure operations.
Temporary Shield Ring (optional)	Not Important To Safety	7.1.20	A water-filled tank that fits on the cask neutron shield around the upper forging and provides supplemental shielding to personnel performing cask loading and closure operations.
Threaded Inserts	Not Important To Safety	Not shown	Used to fill the empty threaded holes in the HI-STAR 100 overpack and MPC.
Tie-Down	Not Important to Safety	Not shown	The tie-down is a horse-shoe shaped collar that secures the HI-STAR 100 top end to the transport frame. The tie-down is secured by multiple bolts.
Transport Frame	Not Important To Safety	Not shown	A welded steel frame used to support the HI-STAR 100 overpack during on-site movement.

Table 7.1.4 (Continued)
HI-STAR 100 SYSTEM ANCILLARY EQUIPMENT OPERATIONAL DESCRIPTION

Equipment	Important To Safety Classification	Reference Figure	Description
Transport Vehicle	Not Important to Safety	Not Shown	Any flatbed rail car, heavy haul trailer or other device used to transport the loaded HI-STAR 100 overpack.
Vacuum Drying System	Not Important To Safety	Not shown	Used for removal of residual moisture from the HI-STAR 100 Overpack annulus following water draining. May be used for evacuation of the MPC to support backfilling operations. Used to support test volume samples for MPC unloading operations. The VDS consists of the vacuum pump, piping, skid, gauges, valves, inlet filter, flexible hoses, connectors, control system.
Vent and Drain RVOAs (optional)	Not Important To Safety	7.1.21	Used to drain, dry, inert and fill the MPC through the vent and drain ports. The vent and drain RVOAs allow the vent and drain ports to be operated like valves and prevent the need to hot tap into the penetrations during unloading operation.
Weld Removal System (optional)	Not Important To Safety	7.2.2b	Semi-automated weld removal system used for removal of the MPC to shell weld, MPC to closure ring weld and closure ring to MPC shell weld. The WRS mechanically removes the welds using a high-speed cutter.

Table 7.1.5
HI-STAR 100 SYSTEM INSTRUMENTATION SUMMARY FOR LOADING AND UNLOADING OPERATIONS†

Note:
The following list summarizes the instruments identified in the procedures for cask loading and unloading operations. Alternate instruments are acceptable as long as they can perform appropriate measurements.

Instrument	Function
Dose Rate Monitors/Survey Equipment	Monitors dose rate and contamination levels and ensures proper function of shielding. Ensures assembly debris is not inadvertently removed from the spent fuel pool during overpack removal.
Flow Rate Monitor (Optional)	Monitors the gas flow rate during assembly cool-down.
Helium Mass Flow Monitor (Optional)	Determines the amount of helium introduced into the MPC during backfilling operations. Includes integrator.
Helium Mass Spectrometer Leak Detector (MSLD)	Ensures leakage rates of welds are within acceptance criteria.
Helium Pressure Gauges	Ensures correct helium backfill pressure during backfilling operation.
Moisture Monitoring Instrument	Used to measure the moisture out of the MPC to determine the end of Phase 1 operation of the FHD.
Volumetric Testing Rig (Optional)	Used to assess the integrity of the MPC lid-to-shell weld.
Pressure Gauge	Ensures correct helium pressure during fuel cool-down operations.
Test Pressure Gauges	Used for during the Code pressure testing of MPC lid-to-shell weld and back filling operations.
Temperature Gauge	Monitors the MPC temperature during FHD operations and th state of fuel cool-down prior to MPC flooding.
Temperature Probe	For fuel cool-down operations
Vacuum Gauges	Used for vacuum drying operations and to prepare an MPC evacuated sample bottle for MPC gas sampling for unloading operations.

† All instruments require calibration. See figures at the end of this section for additional instruments, controllers and piping diagrams.

Table 7.1.6
HI-STAR 100 OVERPACK SAMPLE INSPECTION CHECKLIST

Note:
This checklist provides the basis for establishing a site-specific inspection checklist for the HI-STAR 100 overpack. Specific findings shall be brought to the attention of the appropriate site organizations for assessment, evaluation and potential corrective action prior to use.

HI-STAR 100 Overpack Closure Plate:

1. Lifting rings shall be inspected for general condition and date of required load test certification.
2. The test port shall be inspected for dirt and debris, hole blockage, thread condition, presence or availability of the port plug and replacement mechanical seals.
3. The mechanical seal grooves shall be inspected for cleanliness, dents, scratches and gouges and the presence or availability of replacement mechanical seals.
4. The painted surfaces shall be inspected for corrosion and chipped, cracked or blistered paint.
5. All closure plate surfaces shall be relatively free of dents, scratches, gouges or other damage.
6. The vent port plug shall be inspected for thread condition, and sealing surface condition (scratches, gouges).
7. Overpack vent port shall be inspected for presence or availability of port plugs, hole blockage, and plug seal seating surface condition.
8. Overpack vent port cover plate shall be inspected for cleanliness, scratches, dents, and gouges, availability of retention bolts, availability of replacement mechanical seals.

HI-STAR 100 Overpack Main Body:

1. The impact limiter attachment bolt holes shall be inspected for dirt and debris and thread condition.
2. The mechanical seal seating surface shall be inspected for cleanliness, scratches, and dents or gouges.
3. The drain port plug shall be inspected for thread condition, and sealing surface condition (scratches, gouges).
4. The closure plate bolt holes shall be inspected for dirt, debris and thread damage.
5. Painted surfaces shall be inspected for corrosion and chipped, cracked or blistered paint.
6. Trunnions shall be inspected for deformation, cracks, thread damage, end plate damage, corrosion, excessive galling, damage to the locking plate, presence or availability of locking plate and end plate retention bolts.

Table 7.1.6
HI-STAR 100 OVERPACK SAMPLE INSPECTION CHECKLIST
(continued)

7. Deleted.
8. Overpack drain port cover plate shall be inspected for cleanliness, scratches, dents, and gouges, availability of retention bolts, and availability of replacement mechanical seals.
9. Overpack drain port shall be inspected for presence or availability of port plug, availability of replacement mechanical seals, hole blockage, plug seal seating surface condition.
10. Annulus inflatable seal groove shall be inspected for cleanliness, scratches, dents, gouges, sharp corners, burrs or any other condition that may damage the inflatable seal.
11. The overpack relief devicesshall be inspected for presence or availability and the general condition.
12. The nameplate shall be inspected for presence and general condition.
13. The removable shear ring shall be inspected for fit and thread condition.

Table 7.1.7
MPC SAMPLE INSPECTION CHECKLIST

Note:
This checklist provides the basis for establishing a site-specific inspection checklist for MPC. Specific findings shall be brought to the attention of the appropriate site organizations for assessment, evaluation and potential corrective action prior to use.

MPC Lid and Closure Ring:

1. The MPC lid and closure ring surfaces shall be relatively free of dents, gouges or other shipping damage.
2. The drain line shall be inspected for straightness, thread condition, and blockage.
3. Upper fuel spacers (if used) shall be inspected for availability and general condition. Plugs shall be available for non-used spacer locations.
4. Lower fuel spacers (if used) shall be inspected for availability and general condition.
5. Drain and vent port cover plates shall be inspected for availability and general condition.
6. Serial numbers shall be inspected for readability.

MPC Main Body:

1. All visible MPC body surfaces shall be inspected for dents, gouges or other shipping damage.
2. Fuel cell openings shall be inspected for debris, dents and general condition.
3. Lift lugs shall be inspected for general condition.
4. Verify proper MPC basket type for contents.
5. Inspect drain guide tube for debris, dents, and general condition.

LOCATION: CASK RECEIVING AREA

- REMOVE PERSONNEL BARRIER
- PERFORM RECEIPT INSPECTION
- SURVEY HI-STAR 100 OVERPACK
- REMOVE IMPACT LIMITERS
- REMOVE TIE-DOWN
- UPEND HI-STAR 100 OVERPACK
- REMOVE HI-STAR CLOSURE PLATE
- INSTALL MPC
- INSTALL UPPER FUEL SPACERS
- INSTALL LOWER FUEL SPACERS
- FILL ANNULUS
- INSTALL ANNULUS SEAL
- FILL MPC
- PLACE HI-STAR IN SPENT FUEL POOL

LOCATION: SPENT FUEL POOL

- LOAD FUEL ASSEMBLIES INTO MPC
- PERFORM ASSEMBLY IDENTIFICATION VERIFICATION
- INSTALL DRAIN LINE TO MPC LID
- ALIGN MPC LID AND LIFT YOKE
- INSTALL MPC LID
- REMOVE HI-STAR FROM SPENT FUEL POOL AND PLACE IN PREPARATION AREA

LOCATION: CASK PREPARATION AREA

- DECONTAMINATE HI-STAR 100 BOTTOM
- SET HISTAR 100 IN CASK PREPARATION AREA
- MEASURE DOSE RATES AT MPC LID
- DECONTAMINATE HI-STAR 100 AND LIFT YOKE
- INSTALL TEMPORARY SHIELD RING, IF USED
- REMOVE INFLATABLE ANNULUS SEAL
- LOWER ANNULUS WATER LEVEL SLIGHTLY
- SMEAR MPC LID TOP SURFACES
- INSTALL ANNULUS SHIELD
- LOWER MPC WATER LEVEL
- WELD MPC LID
- PERFORM NDE ON MPC LID WELD
- PERFORM CODE PRESSURE TEST ON MPC
- PERFORM LEAKAGE TESTING
- DRAIN MPC
- DRY MPC
- BACKFILL MPC
- WELD VENT AND DRAIN PORT COVER PLATES
- PERFORM NDE ON COVER PLATE WELDS
- PERFORM LEAKAGE TEST ON COVER PLATES
- WELD MPC CLOSURE RING
- PERFORM NDE ON CLOSURE RING WELDS
- DRAIN ANNULUS
- PERFORM SURVEYS ON HI-STAR
- INSTALL HI-STAR CLOSURE PLATE
- REMOVE TEMPORARY SHIELD RING
- PERFORM FINAL SURVEYS ON HI-STAR

LOCATION: SHIPPING FACILITY

- PERFORM SHIELDING EFFECTIVENESS TEST
- DOWNEND HI-STAR 100 OVERPACK
- INSTALL IMPACT LIMITERS
- SURVEY HI-STAR 100 OVERPACK
- INSTALL TIE-DOWN
- PERFORM FINAL INSPECTION
- INSTALL PERSONNEL BARRIER.

FIGURE 7.1.1; Loading Operations Flow Diagram

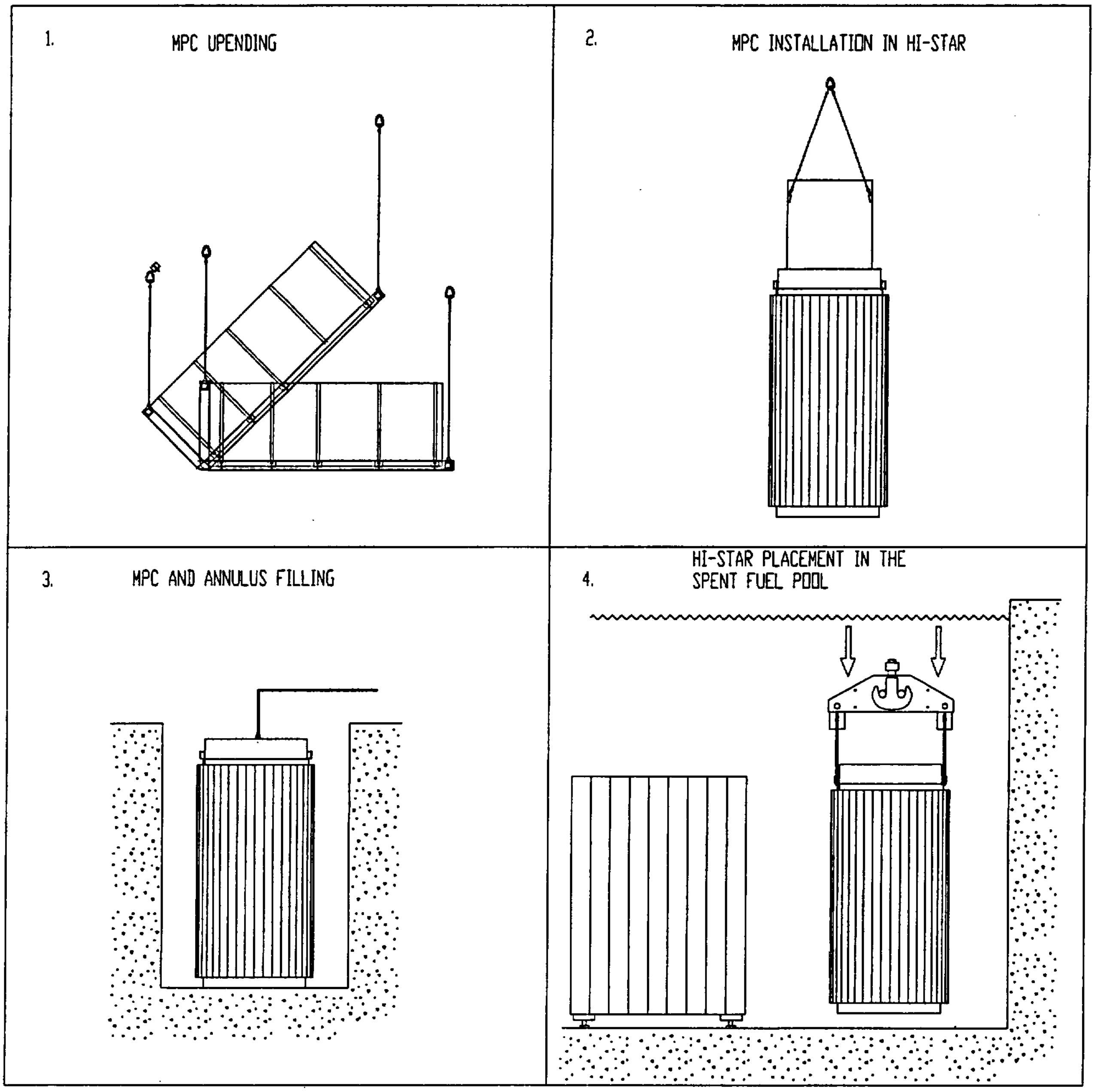


Figure 7.1.2a; Major HI-STAR 100 Loading Operations (Sheet 1 of 3)

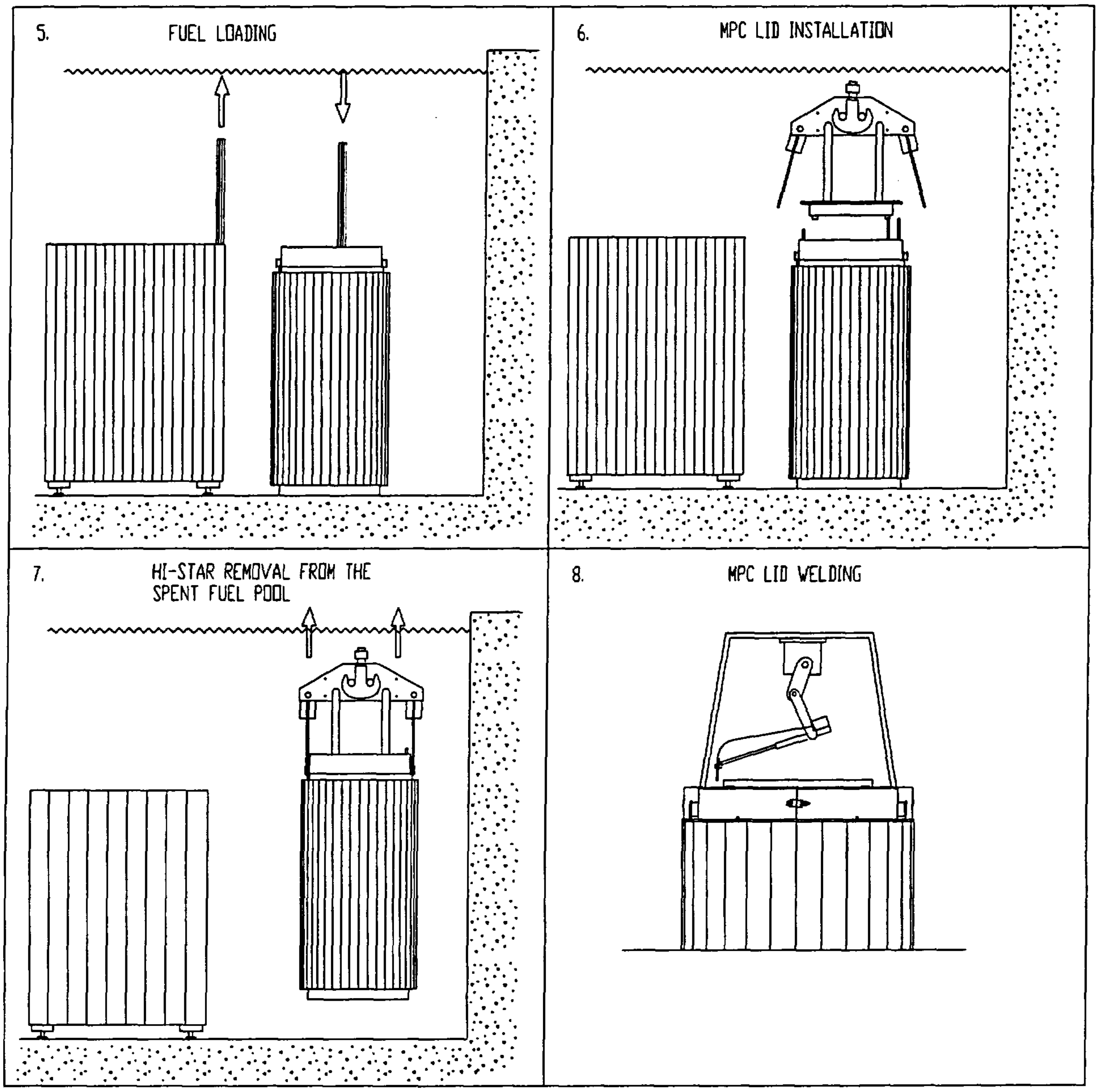


Figure 7.1.2b; Major HI-STAR 100 Loading Operations (Sheet 2 of 3)

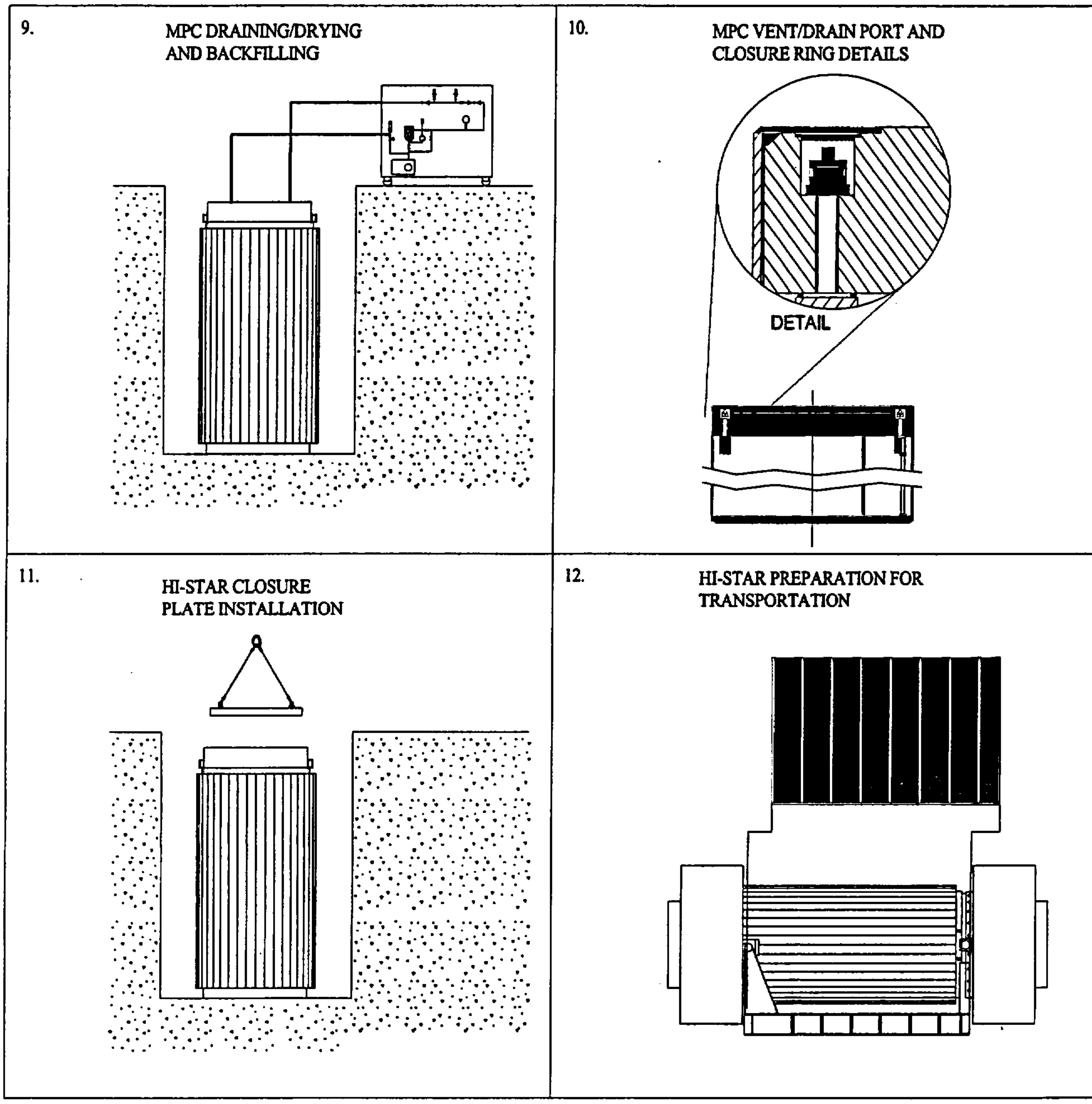


Figure 7.1.2c; Major HI-STAR 100 Loading Operations (Sheet 3 of 3)

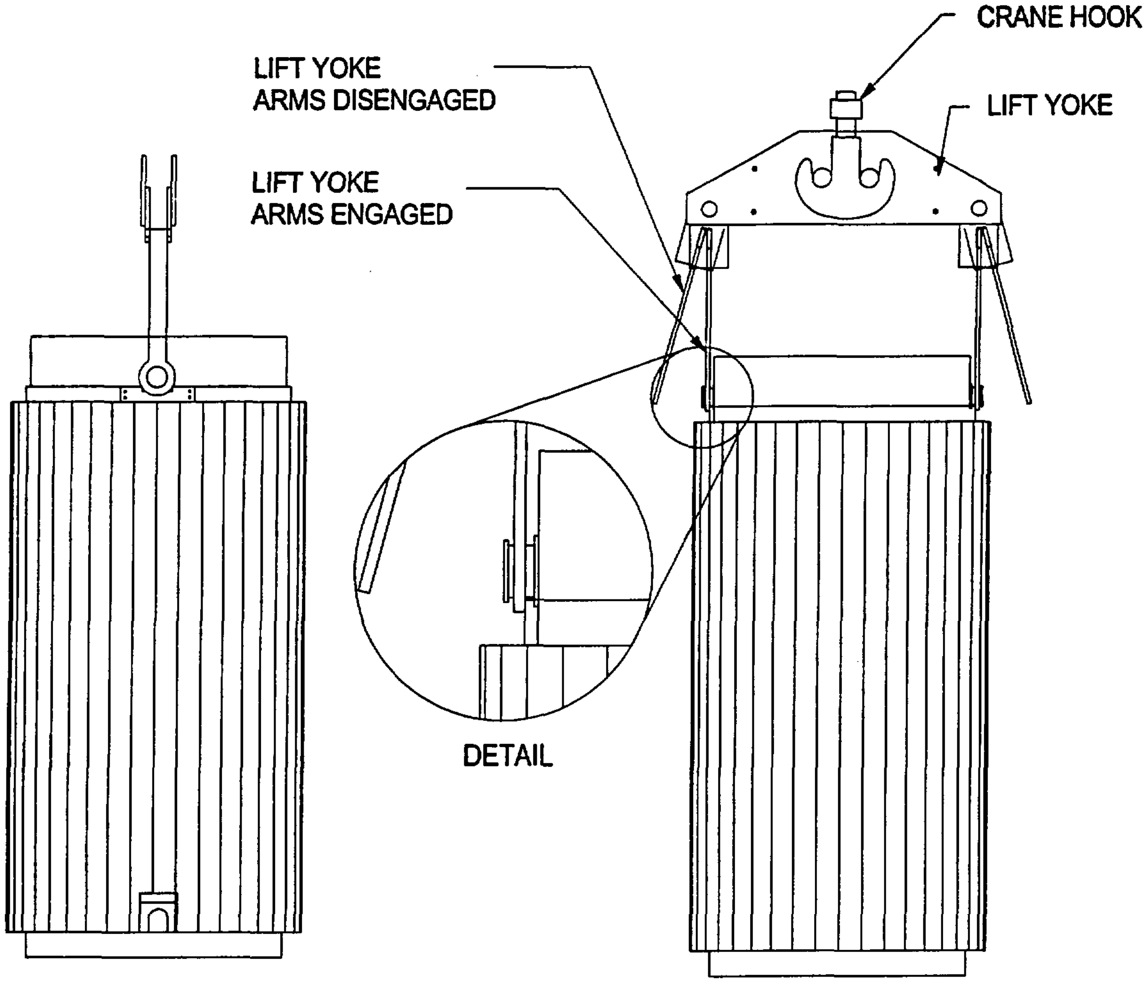


Figure 7.1.3; Lift Yoke Engagement and Vertical HI-STAR Handling

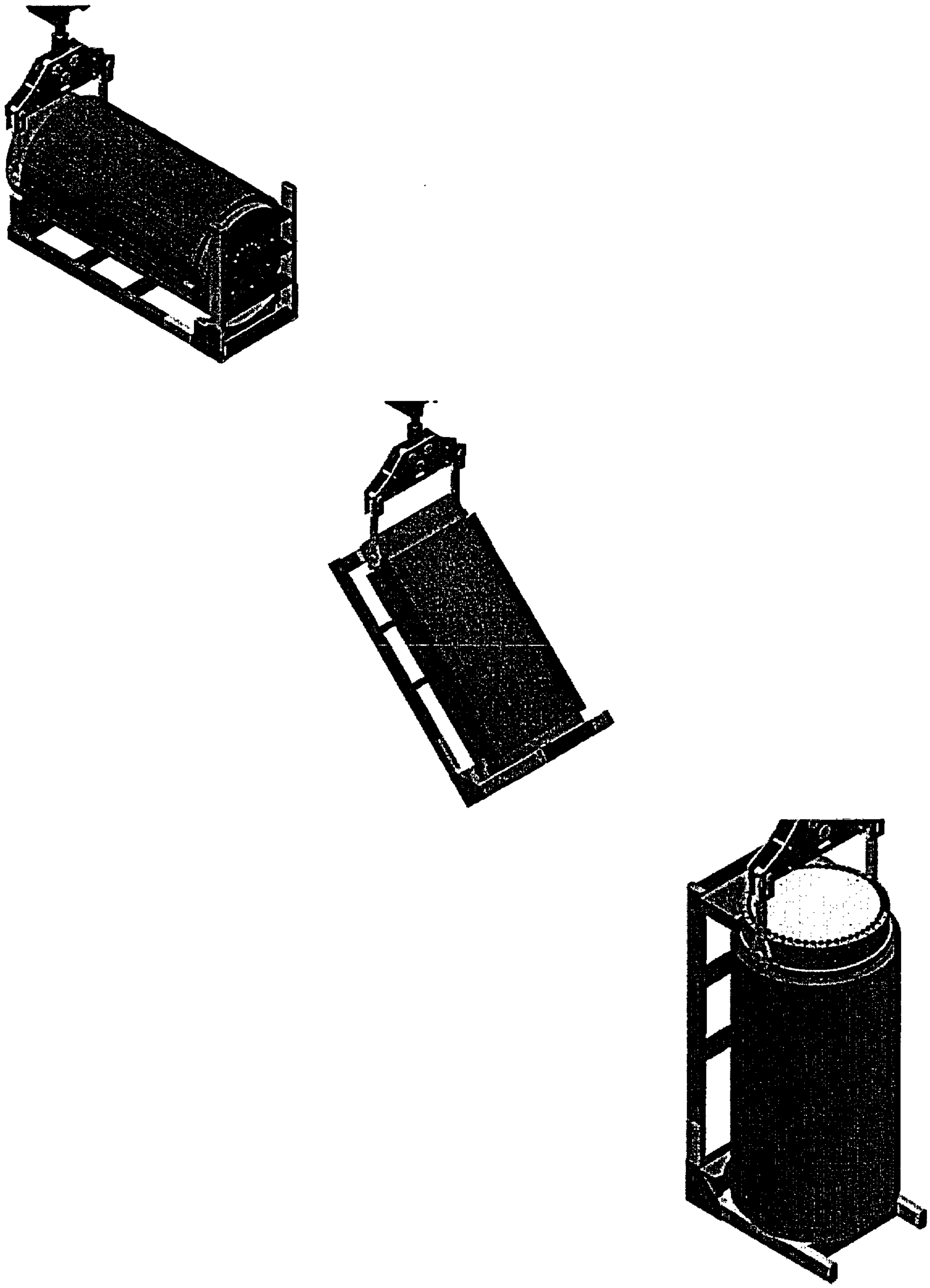


Figure 7.1.4; HI-STAR Upending/Downending

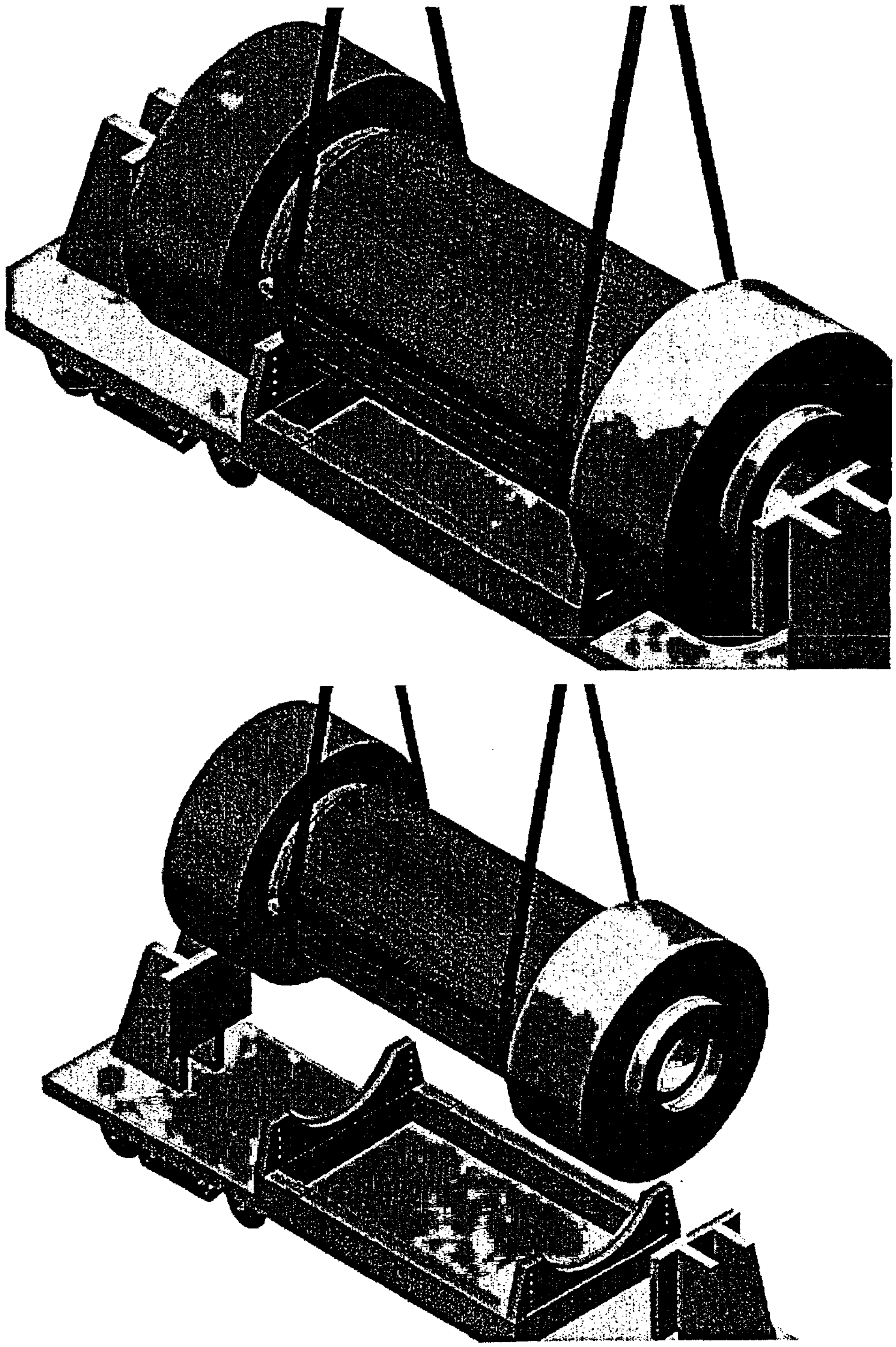


Figure 7.1.5: HI-STAR 100 Overpack Rigging for Horizontal Handling

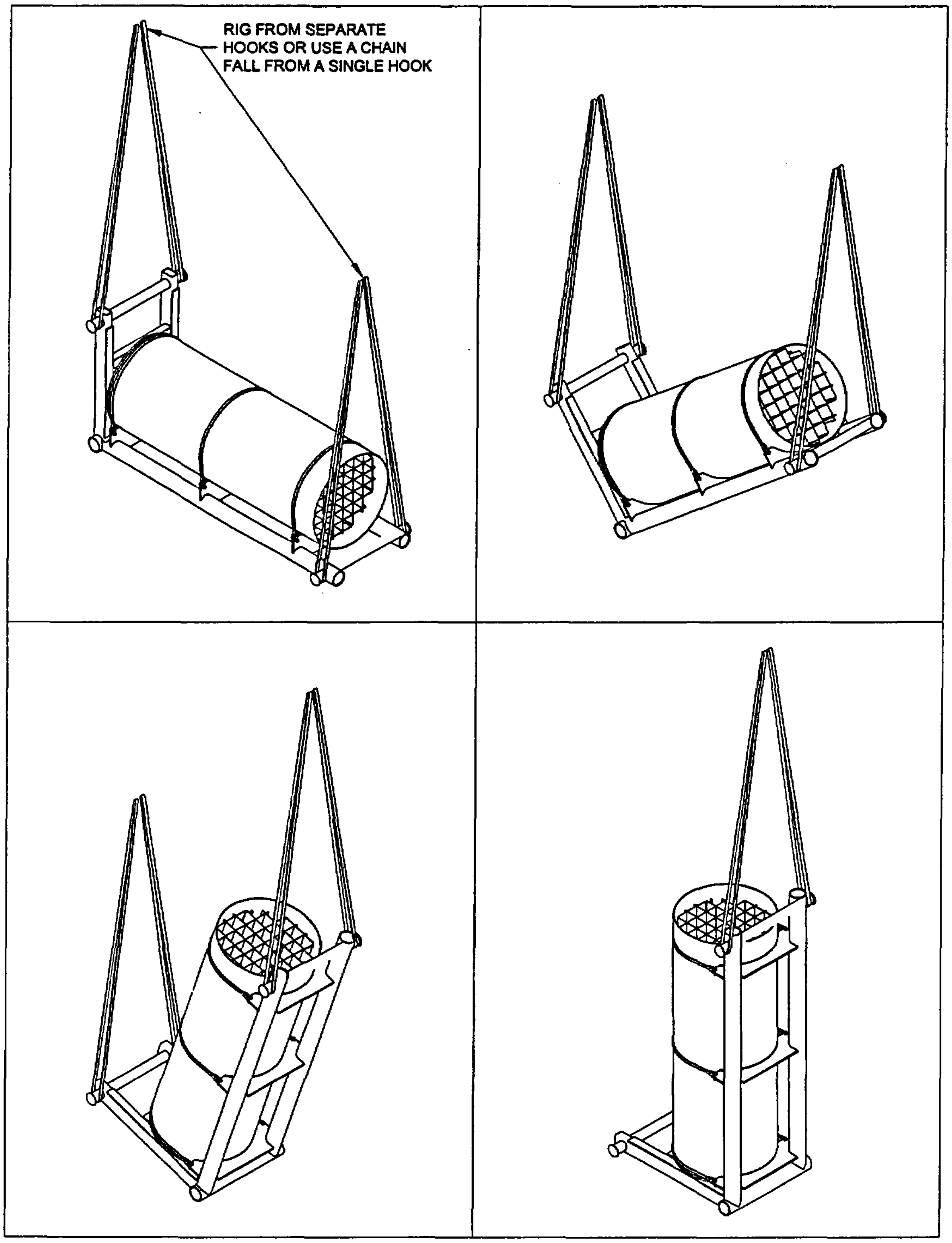


Figure 7.1.6; MPC Upending In The MPC Upending Frame

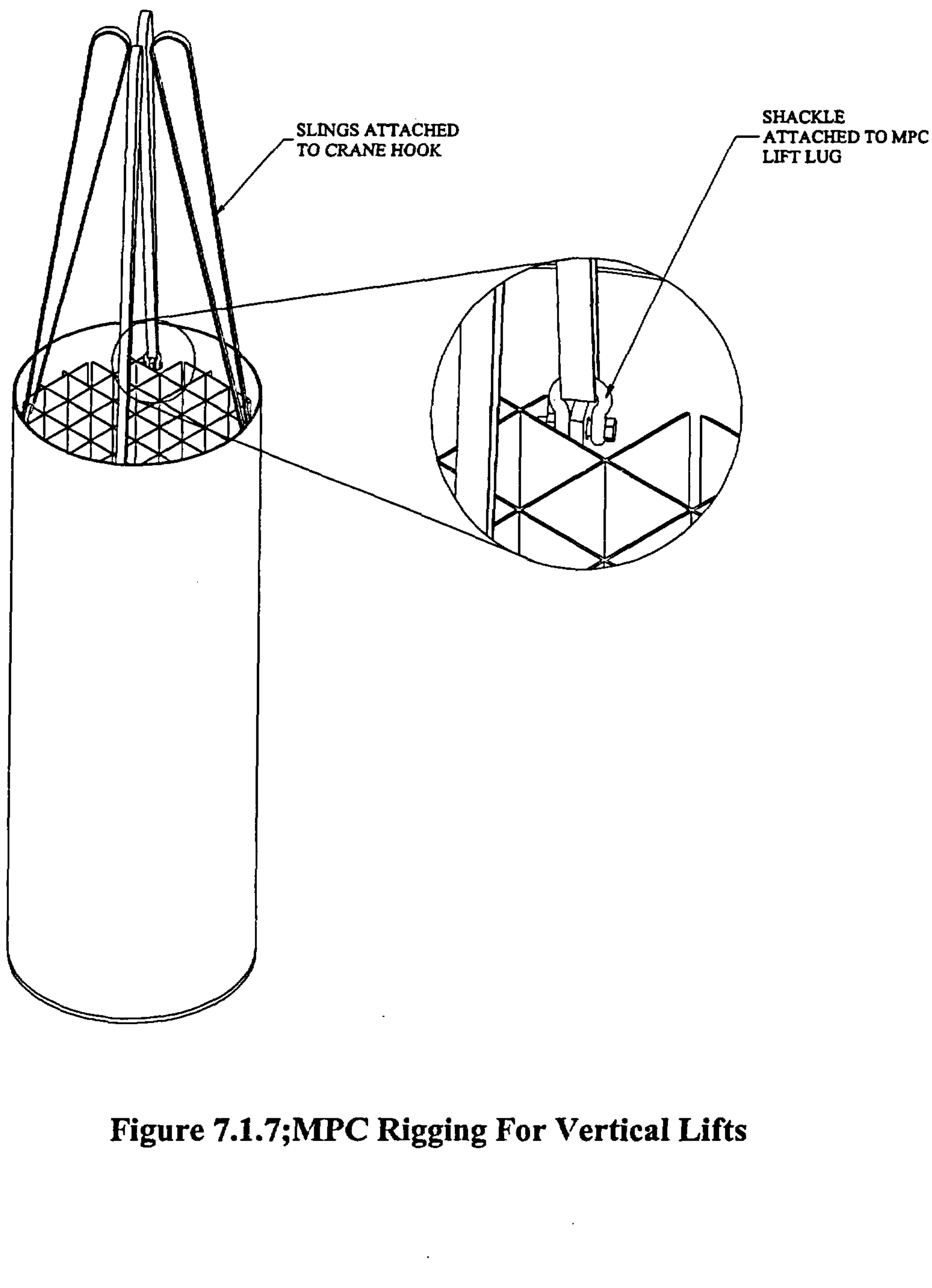


Figure 7.1.7;MPC Rigging For Vertical Lifts

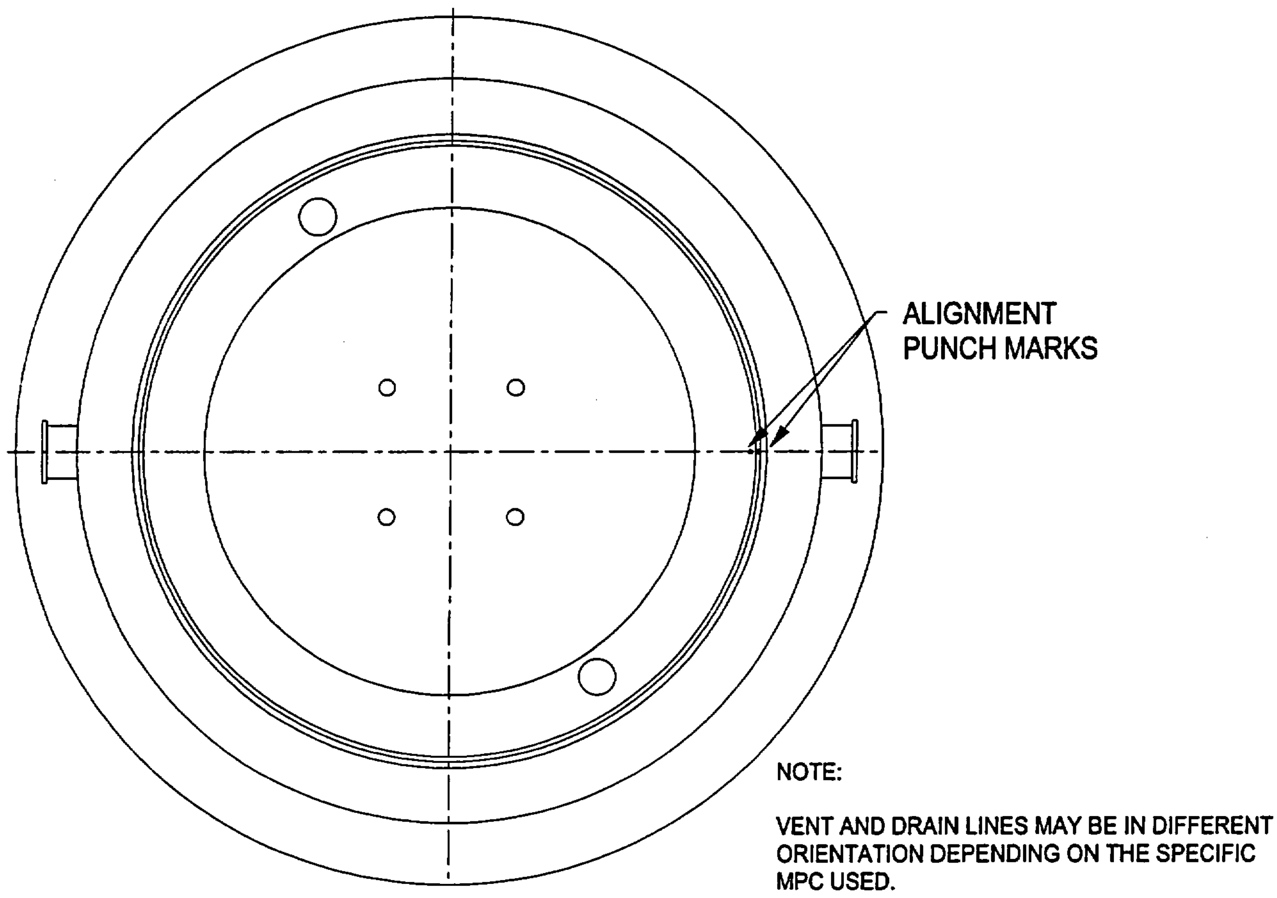


Figure 7.1.8; MPC Alignment in HI-STAR

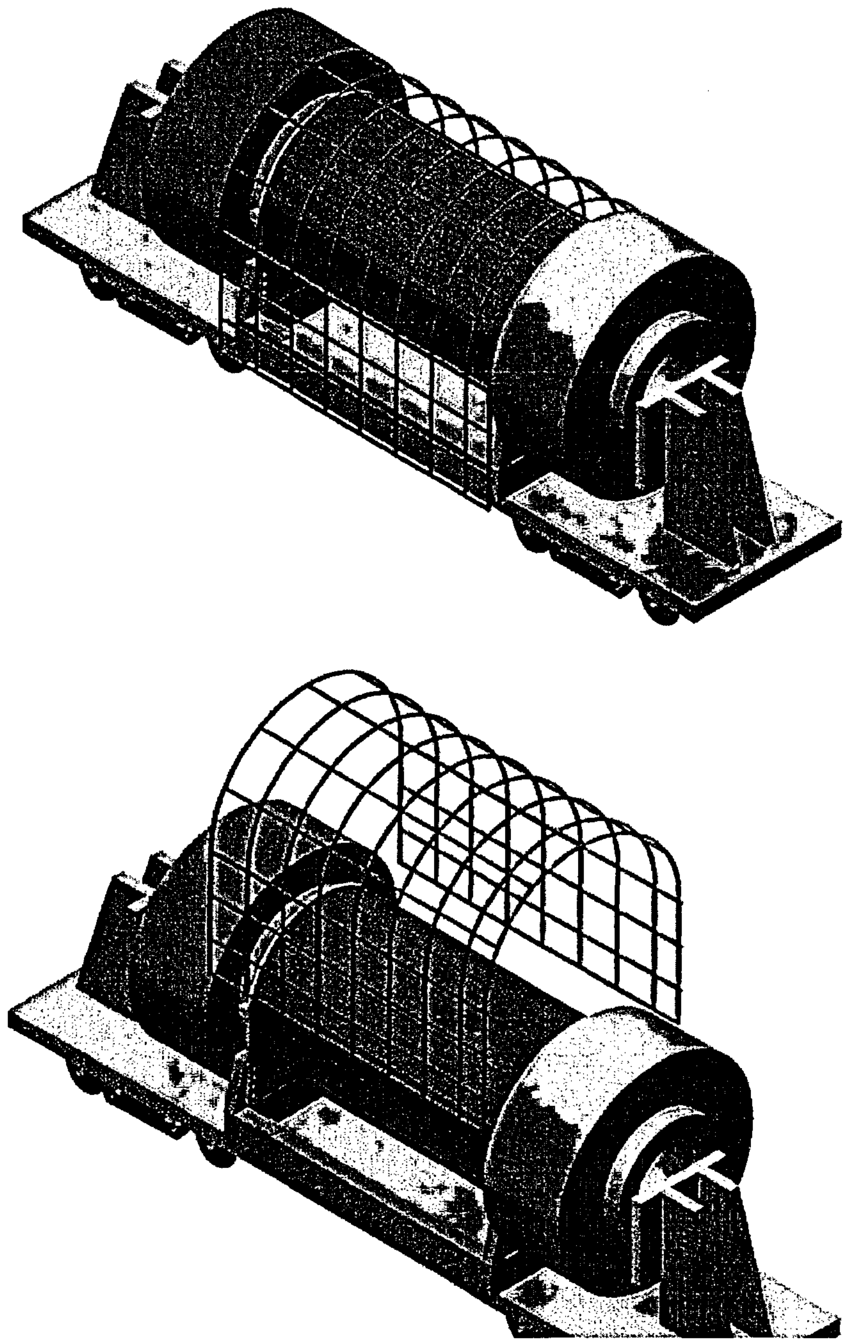


Figure 7.1.9; Personnel Barrier Removal and Installation

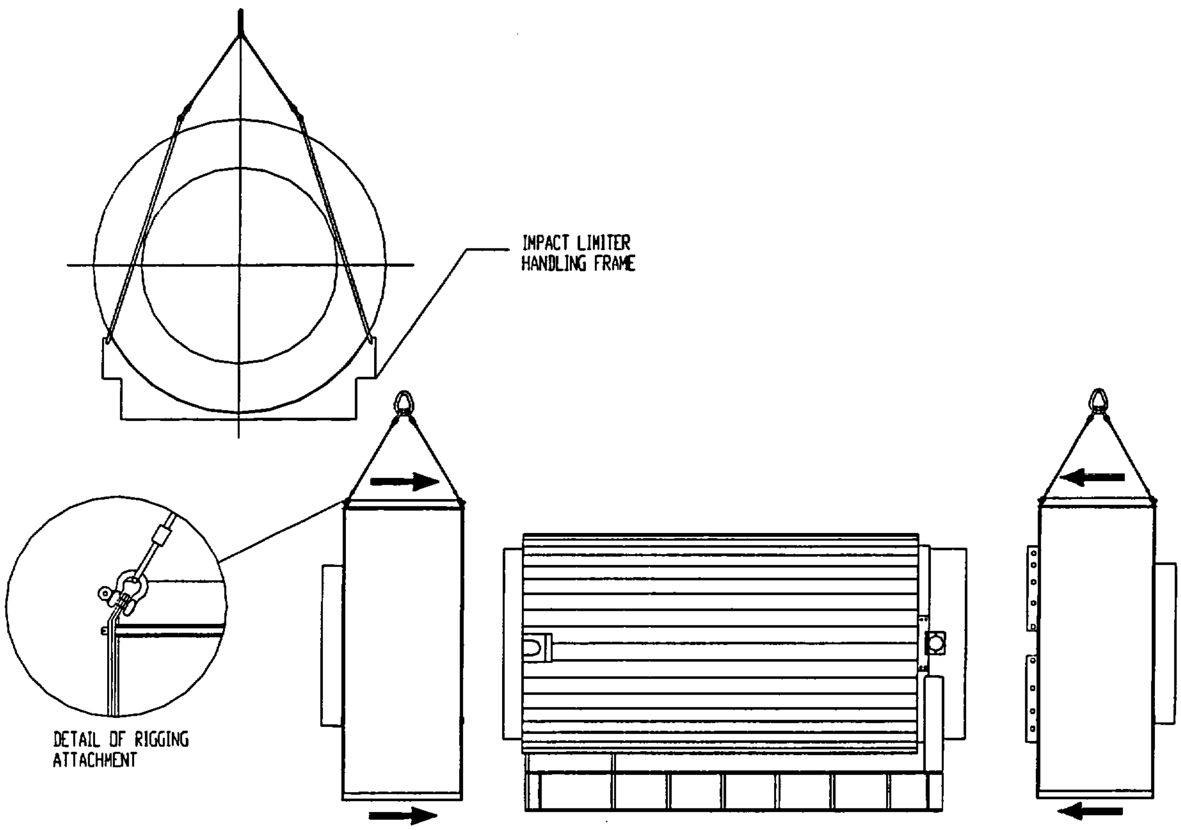


Figure 7.1.10; Impact Limiter Handling

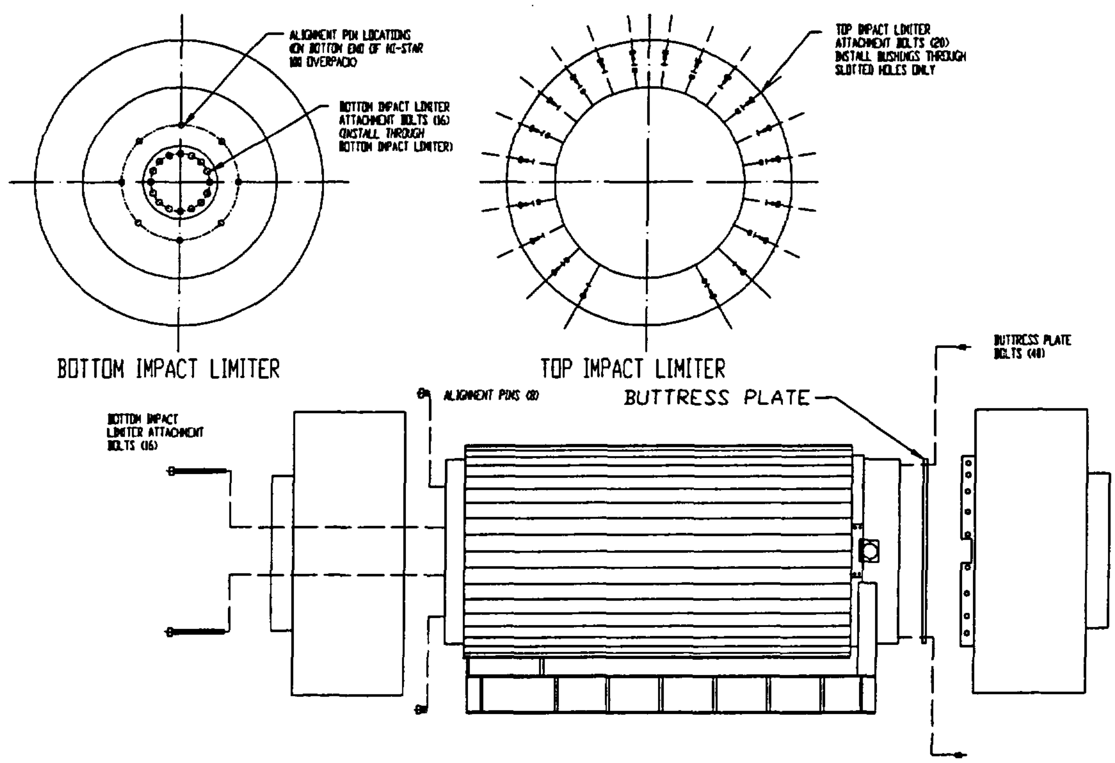


Figure 7.1.11; HI-STAR 100 Impact Limiter and Bolting

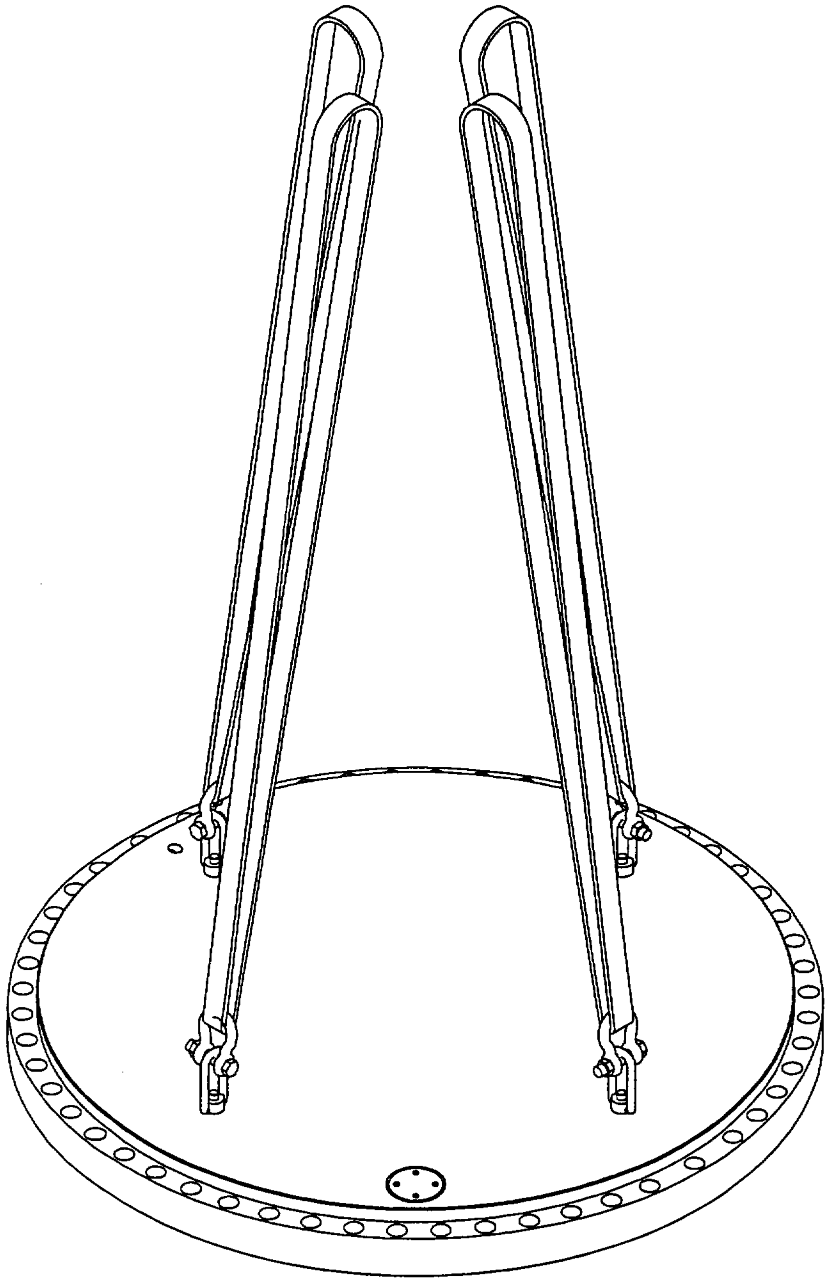
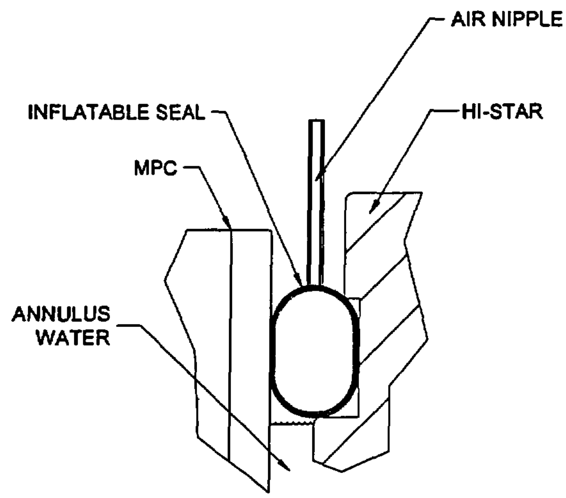
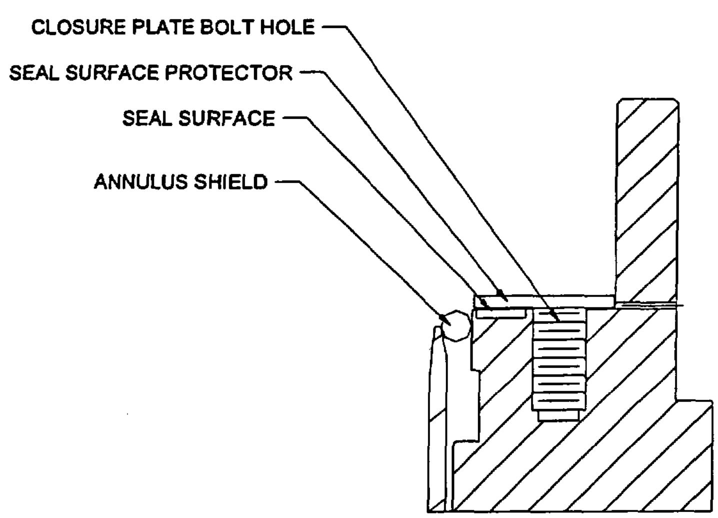


Figure 7.1.12; MPC Lid And HI-STAR Accessory Rigging (Closure Plate Shown)

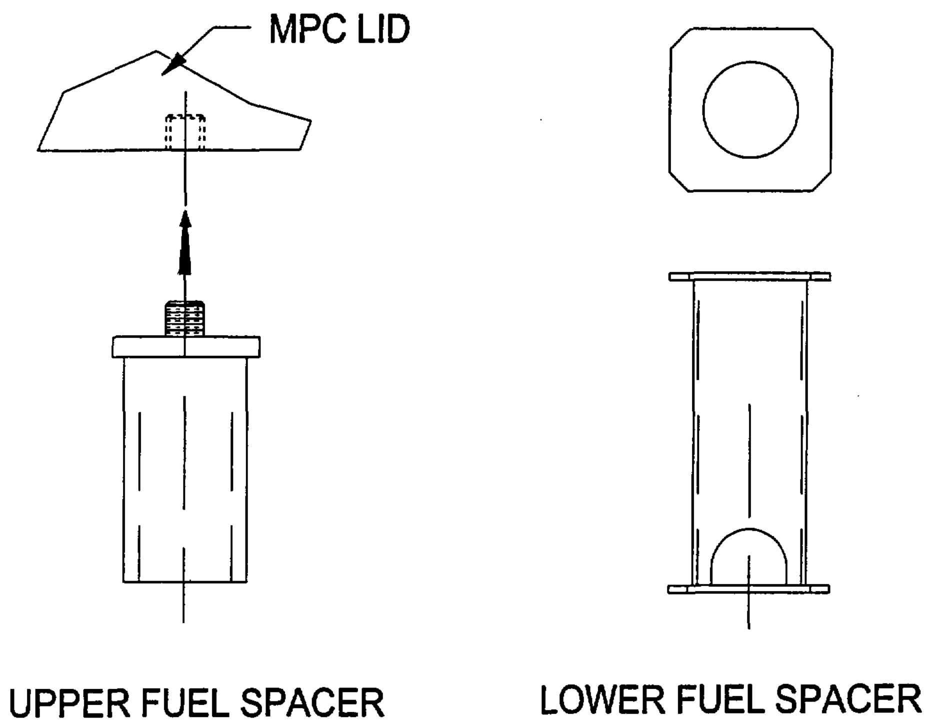


ANNULUS SEAL



ANNULUS SHIELD AND SEAL SURFACE PROTECTOR

Figure 7.1.13; Annulus Shield/Annulus Seal Surface Protector



Note: Lengths are based on specific fuel assembly type to be stored.

Figure 7.1.14; Fuel Spacers

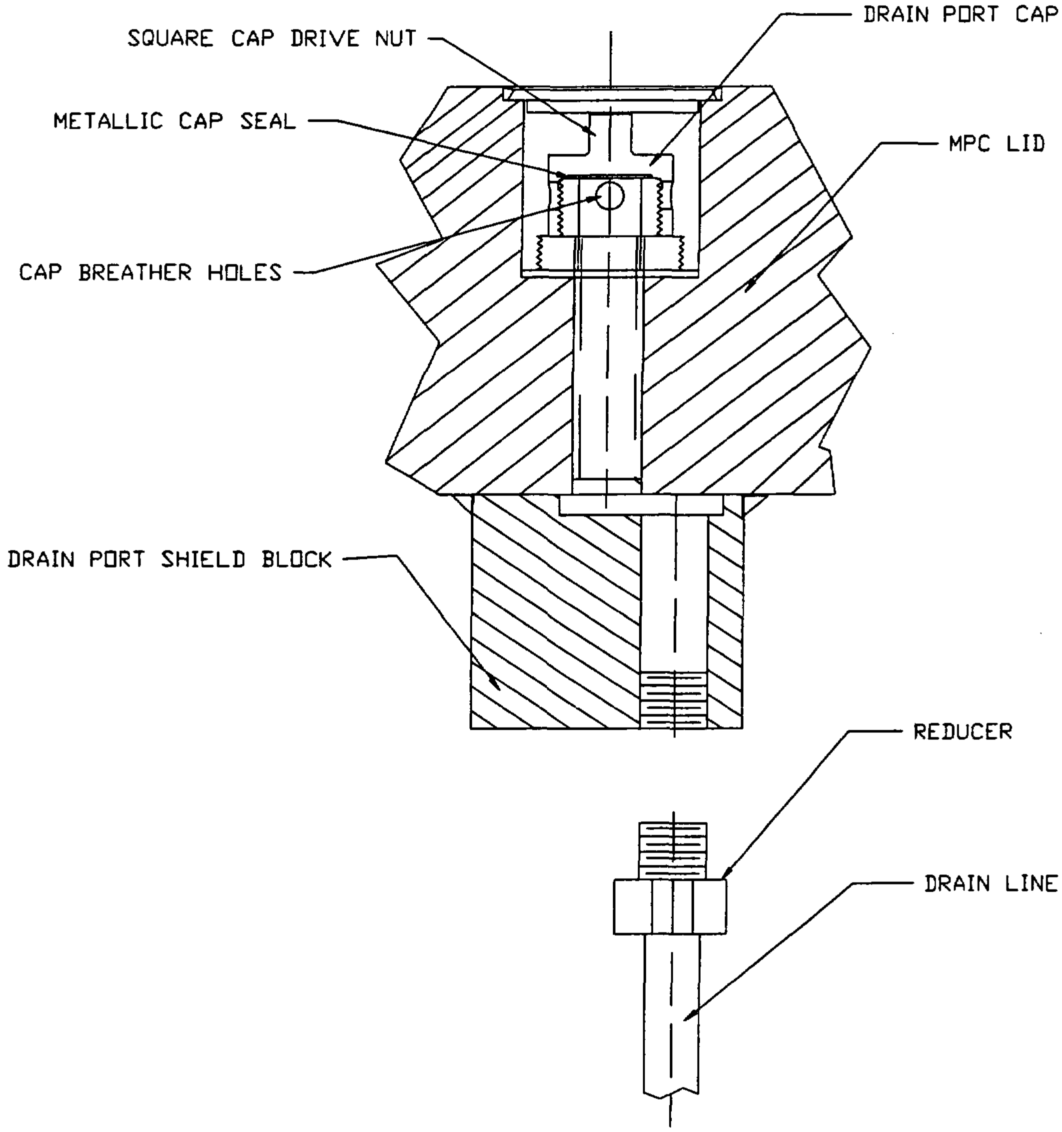


Figure 7.1.15; Drain Port Details

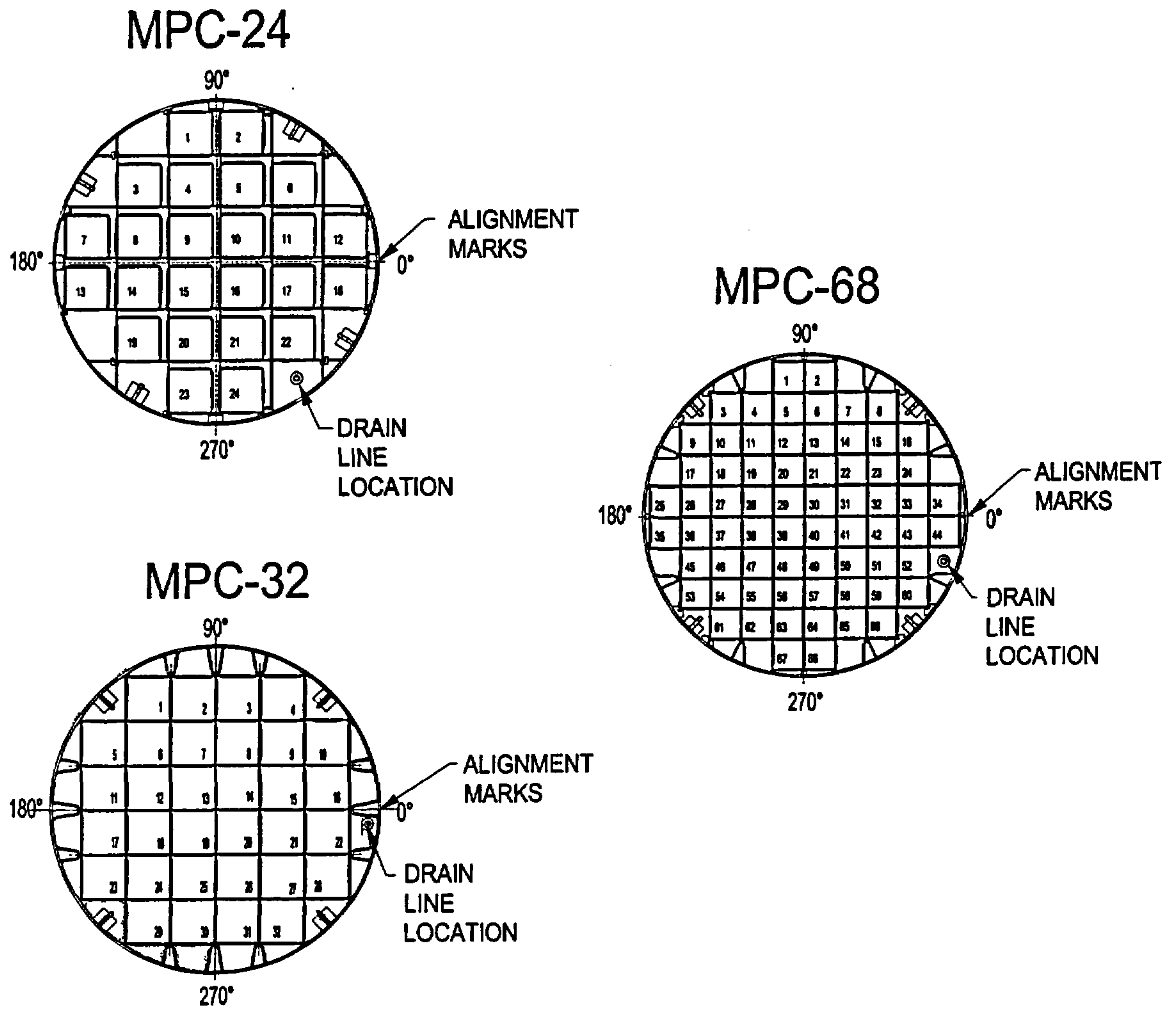


Figure 7.1.16; Drain Line Positioning

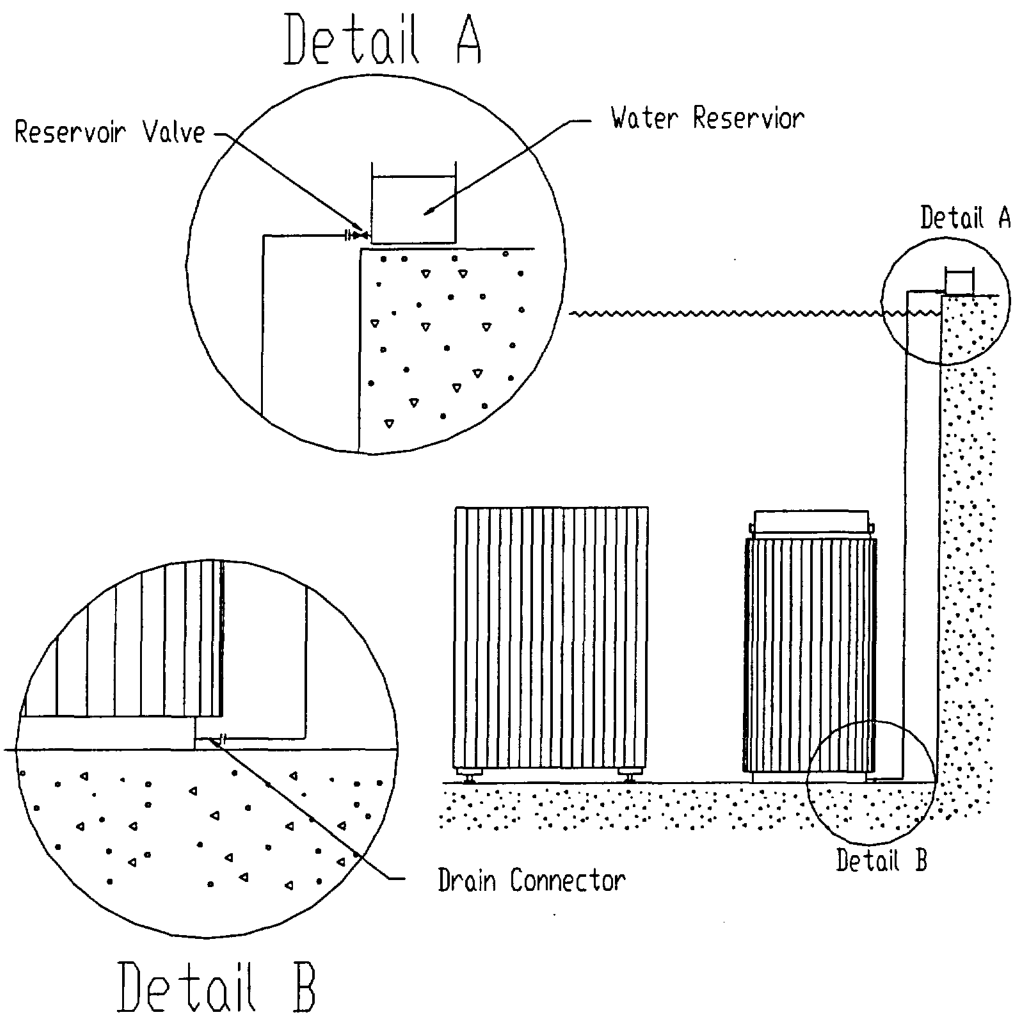


Figure 7.1.17; Annulus Overpressure System

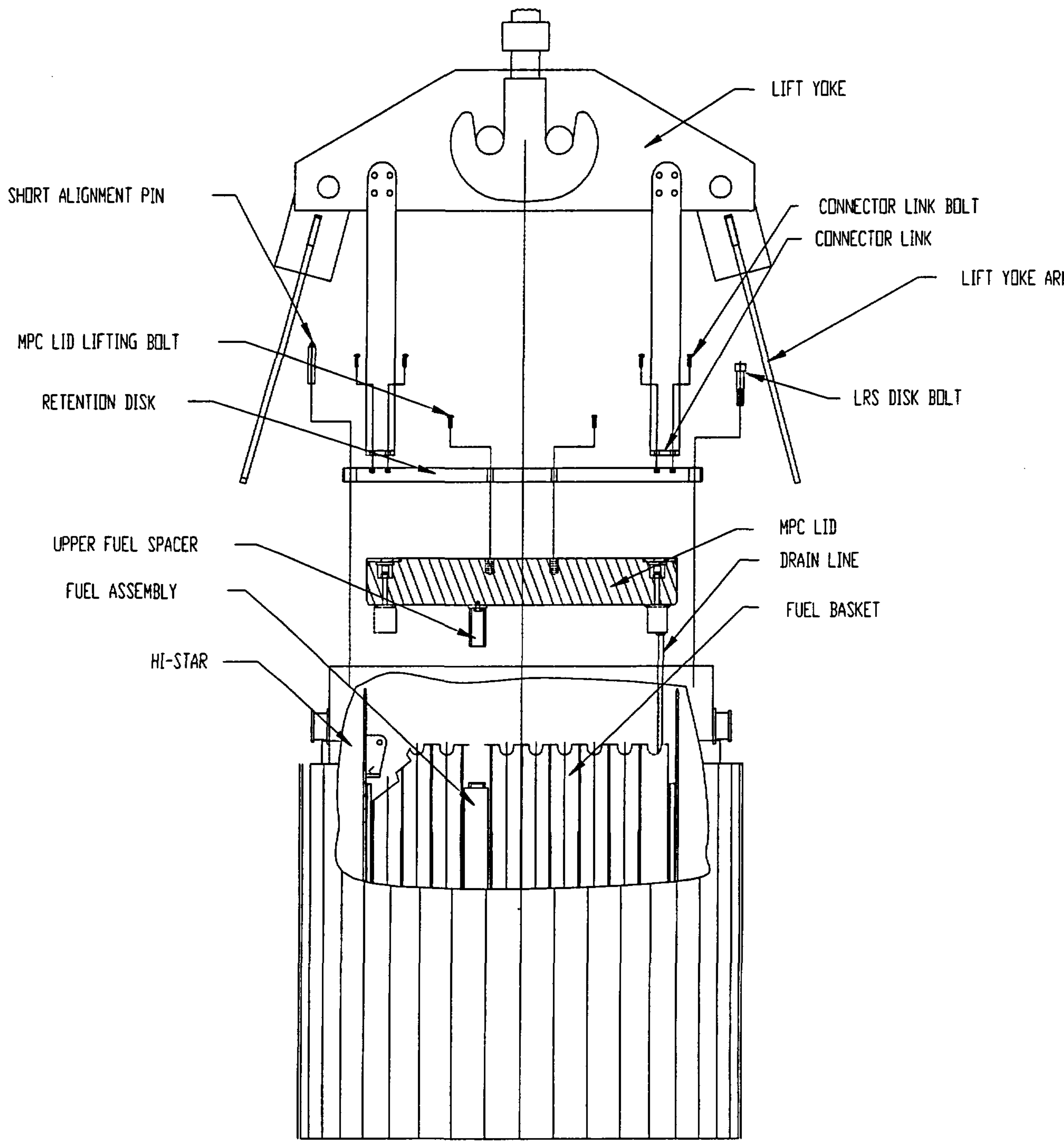


Figure 7.1.18; HI-STAR 100 Lid Retention System in Exploded View

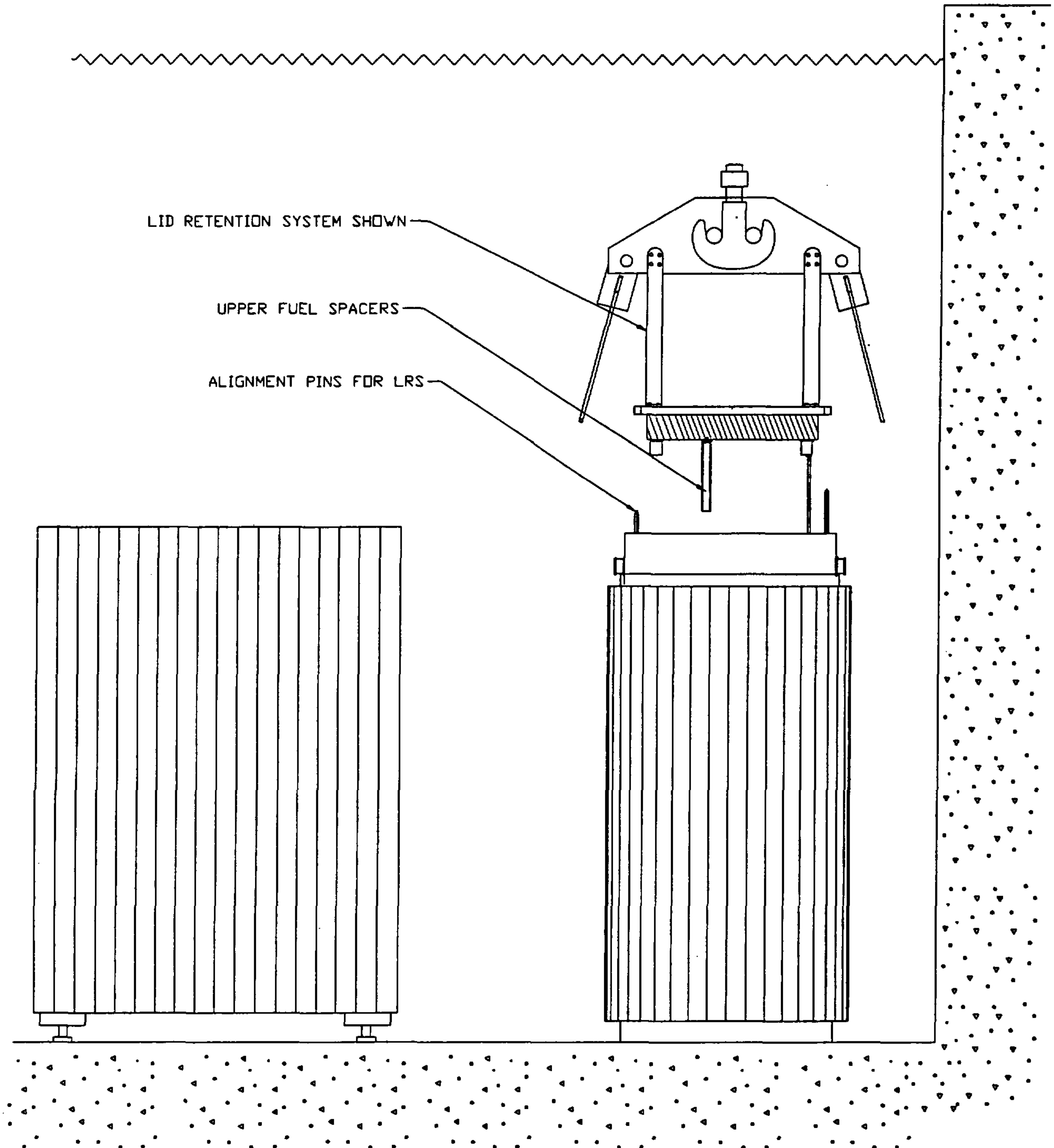


Figure 7.1.19; Drain Line Installation

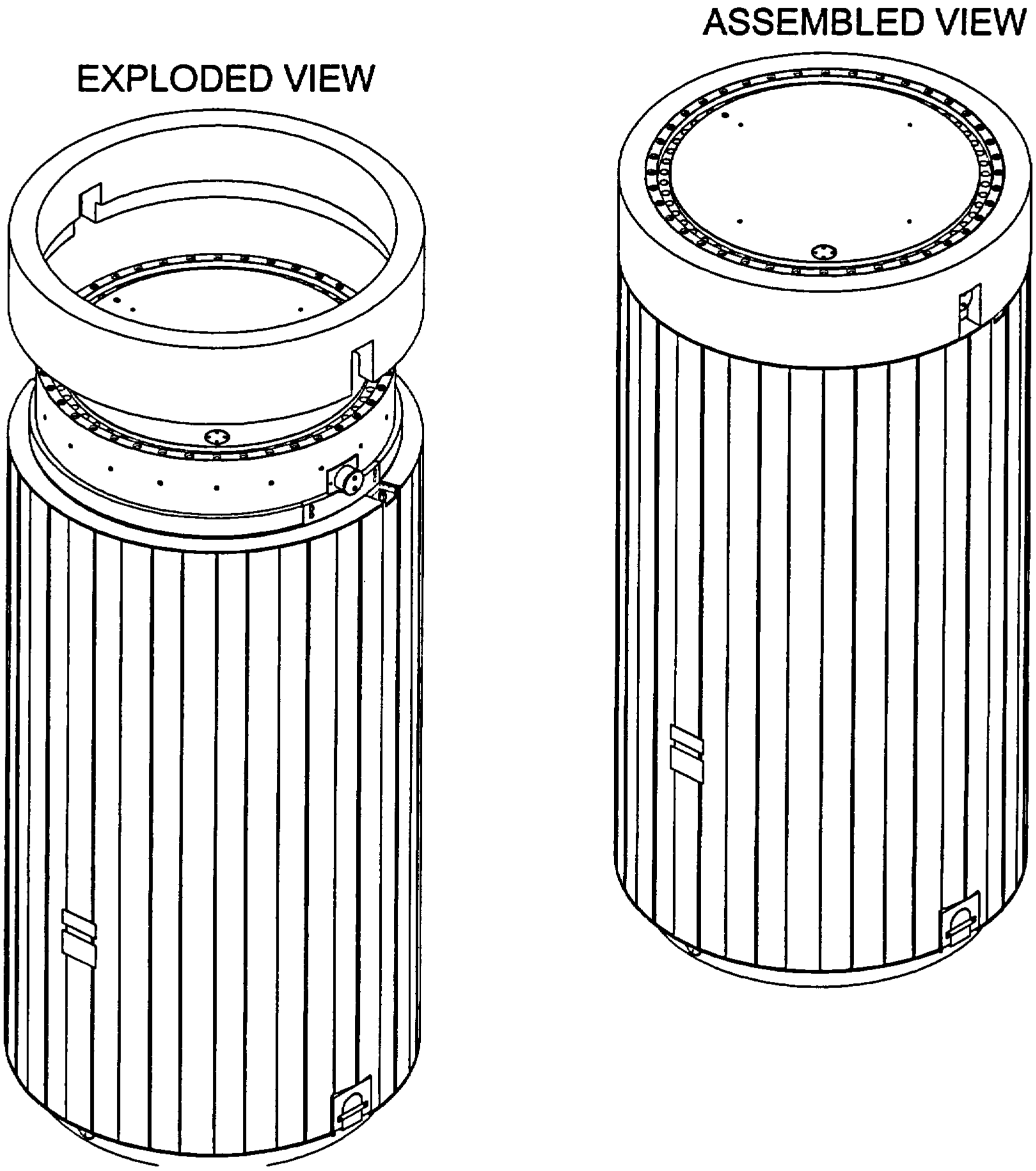


Figure 7.1.20; Temporary Shield Ring

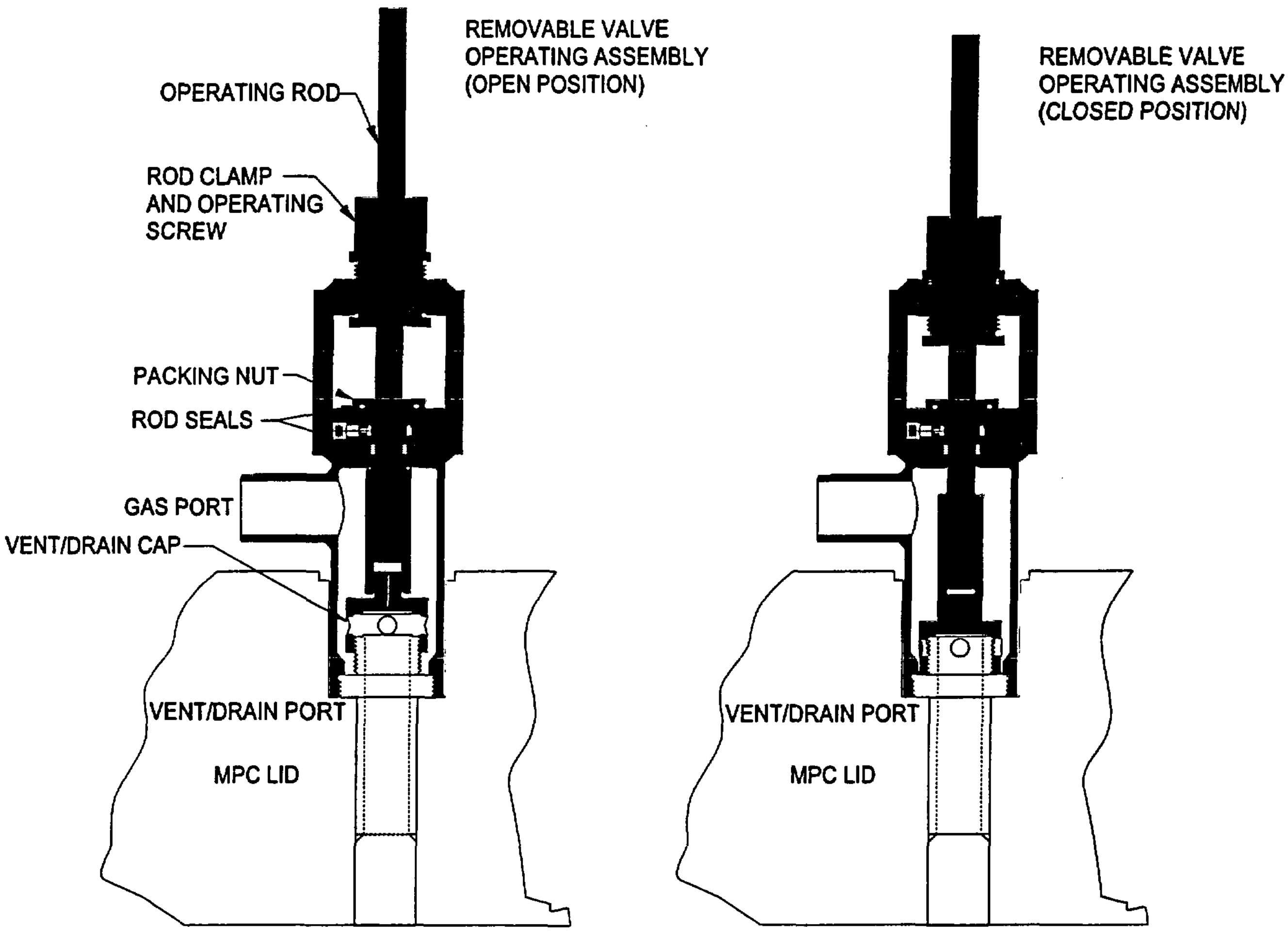


Figure 7.1.21; MPC Vent and Drain Port RVOA Connector

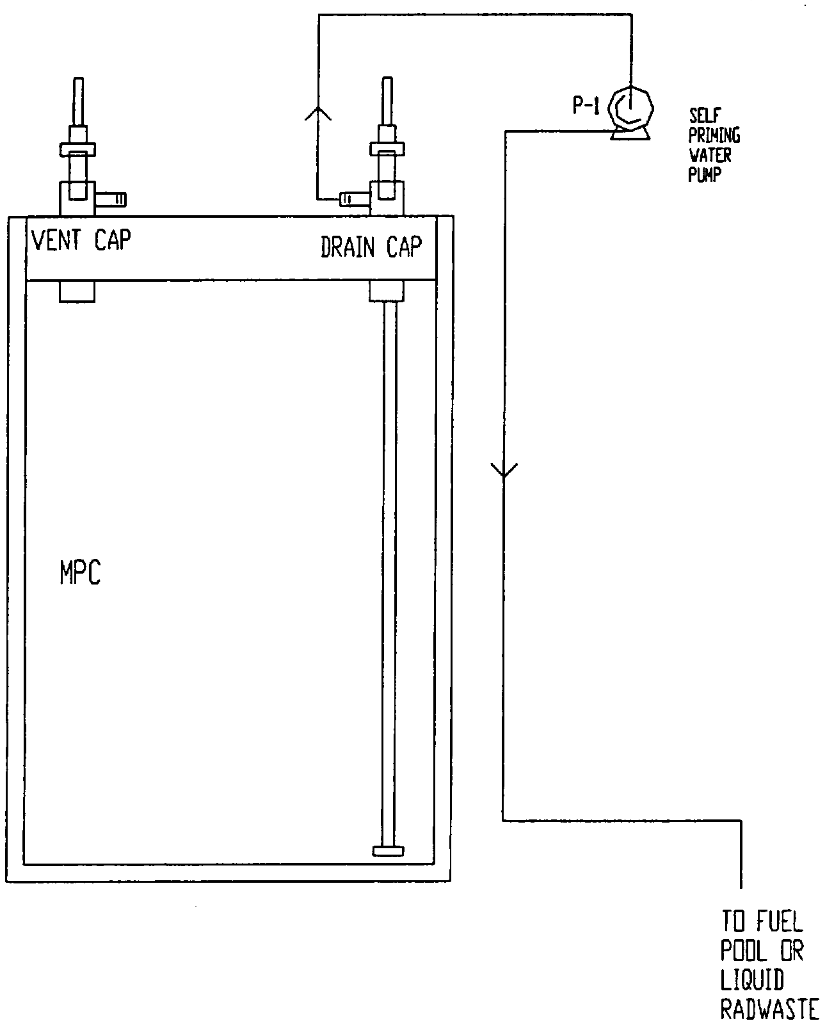


Figure 7.1.22; MPC Water Pump-Down for MPC Lid Welding Operations (Example P&I Diagram)

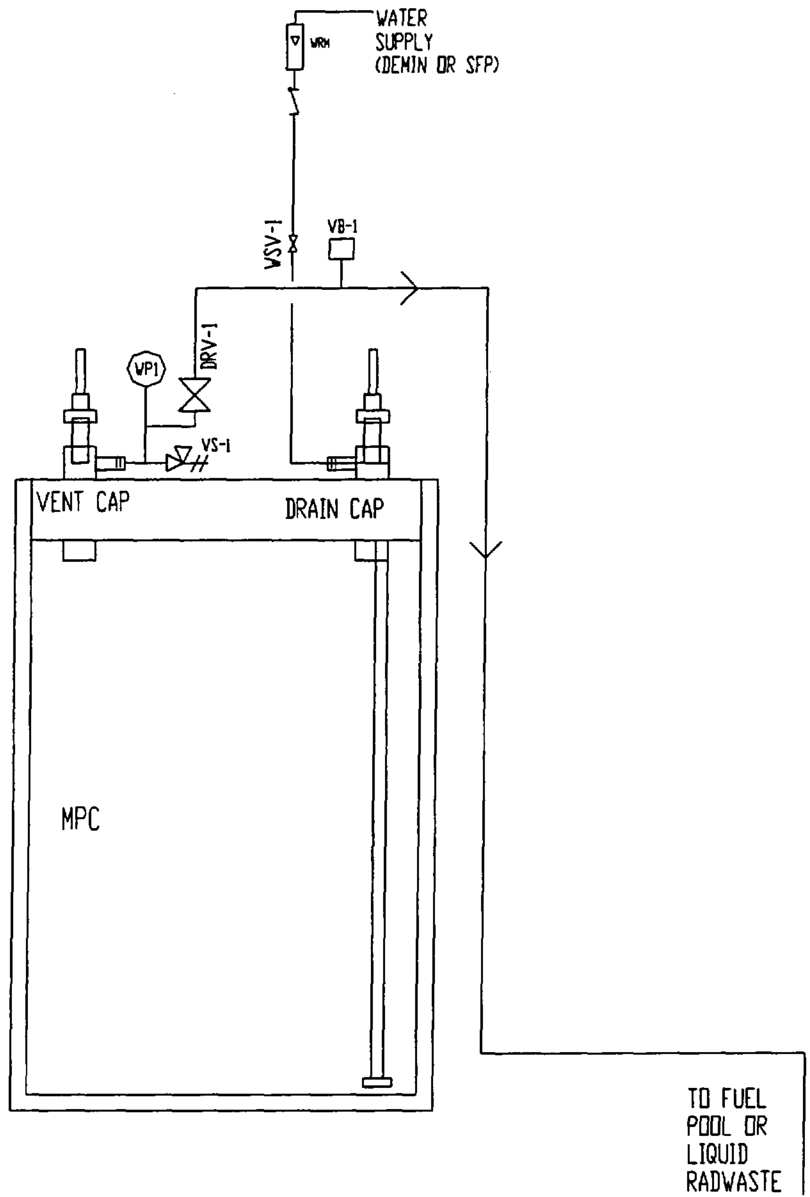


Figure 7.1.23; MPC Air Displacement and Pressure Testing (Example P&I Diagram)

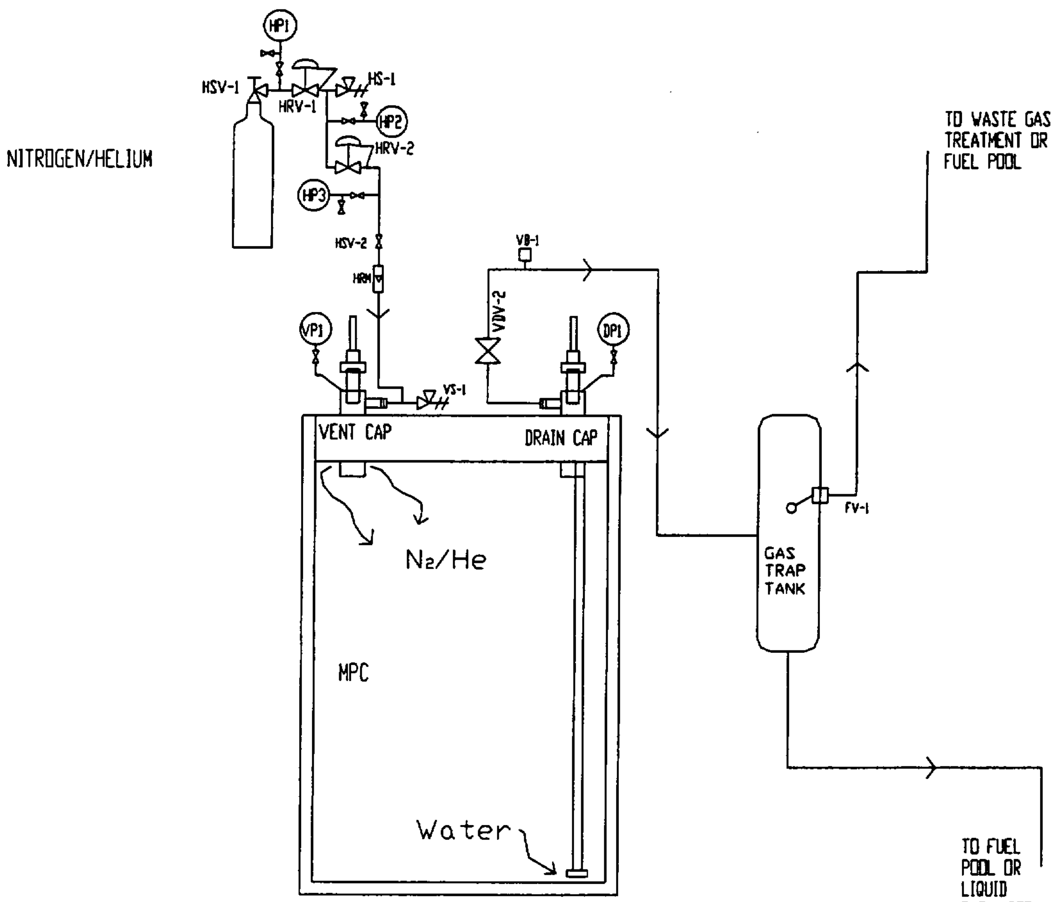


Figure 7.1.24; MPC Blowdown and Helium Injection for Leak Testing

(EXAMPLE P&I DIAGRAM)

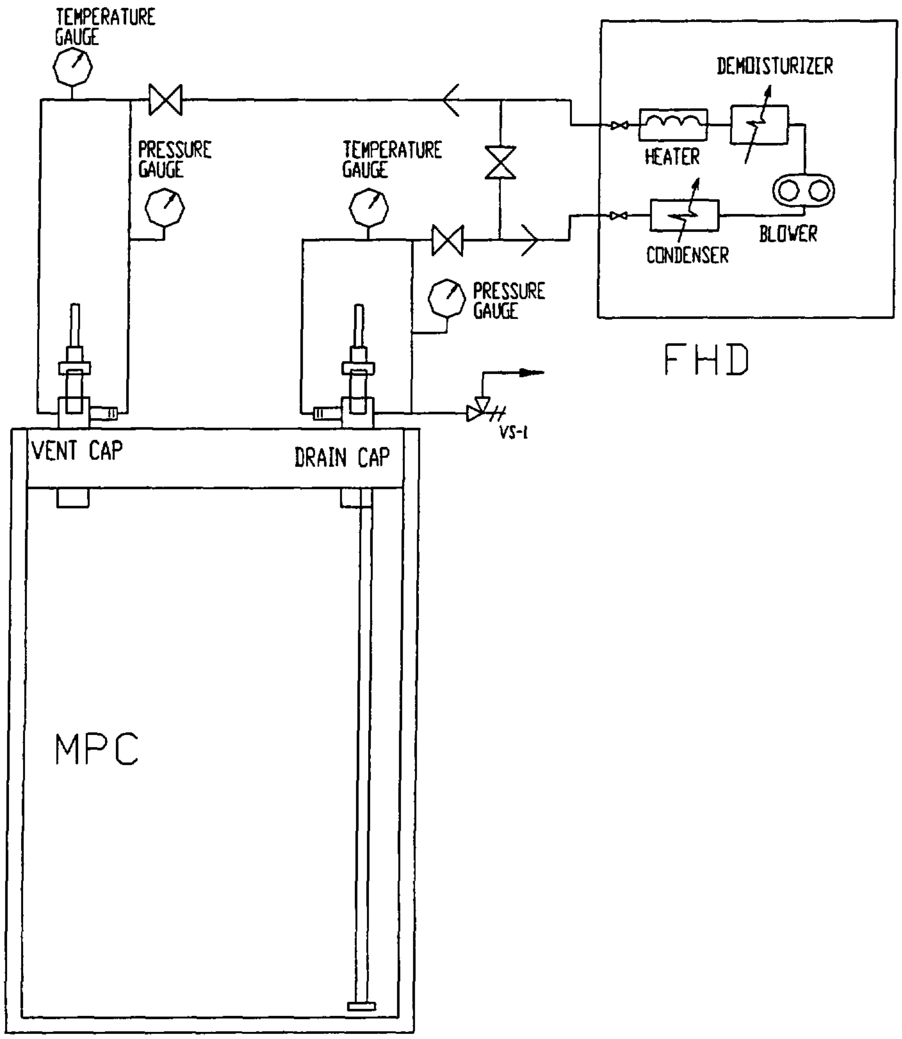


Figure 7.1.25; Forced Helium Dehydration System (Example P&I Diagram)

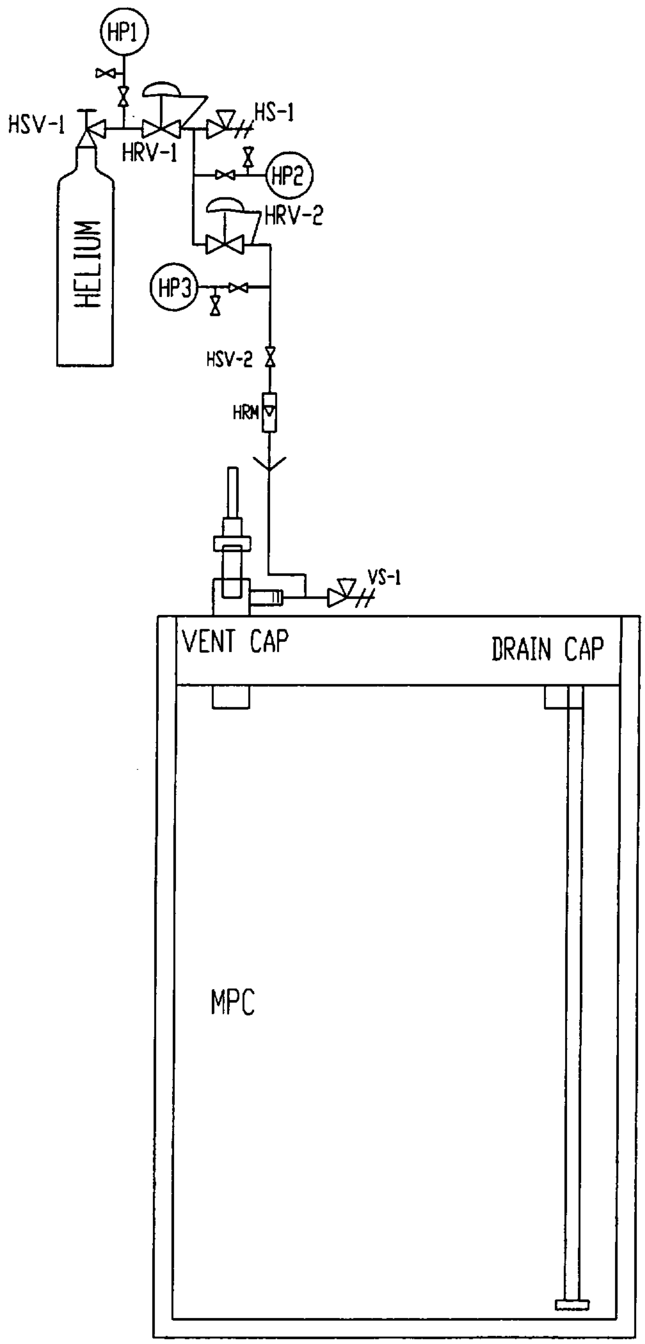


Figure 7.1.26; Helium Backfill (Example P&I Diagram)

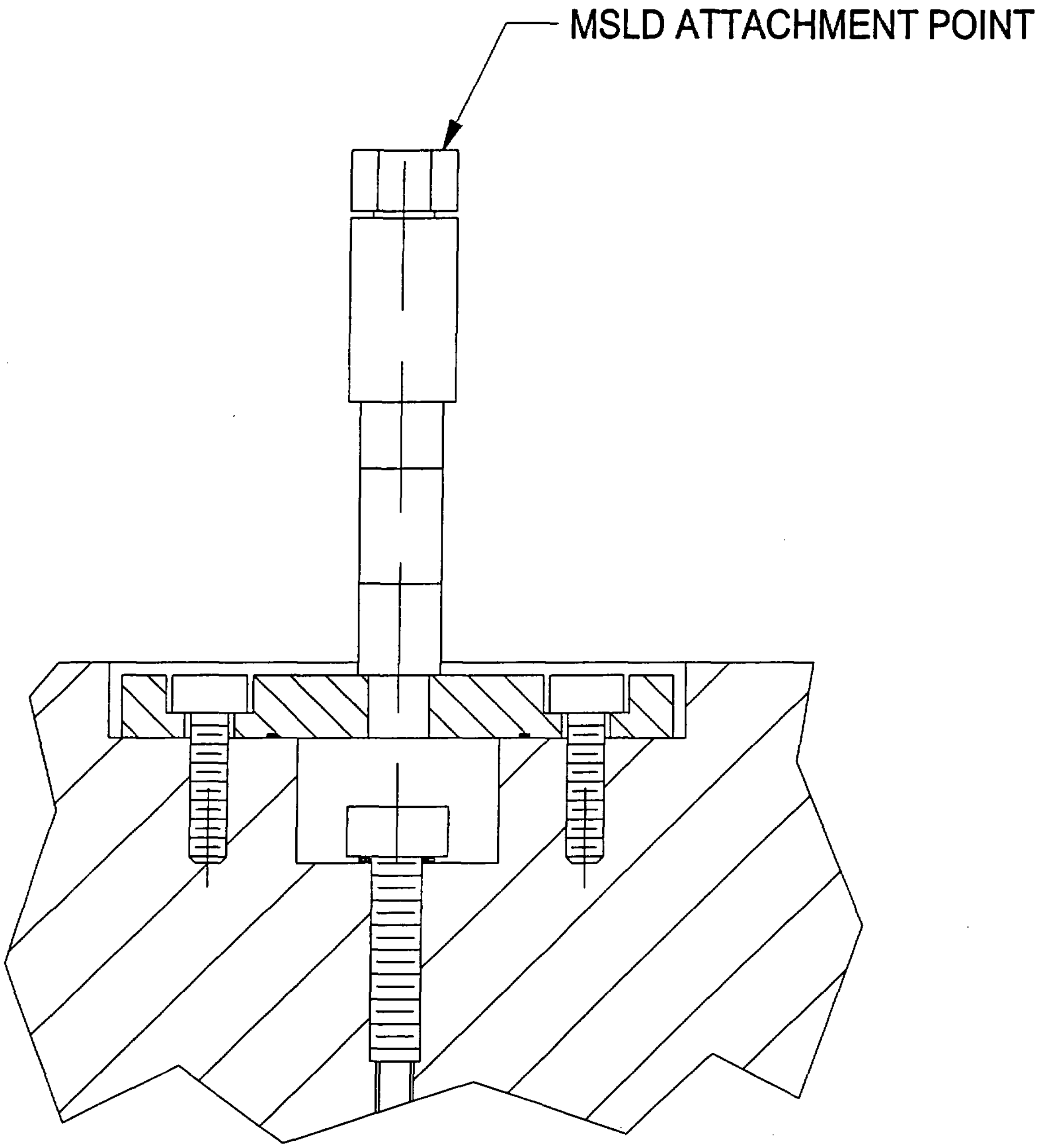


Figure 7.1.27; HI-STAR 100 Overpack Test Cover

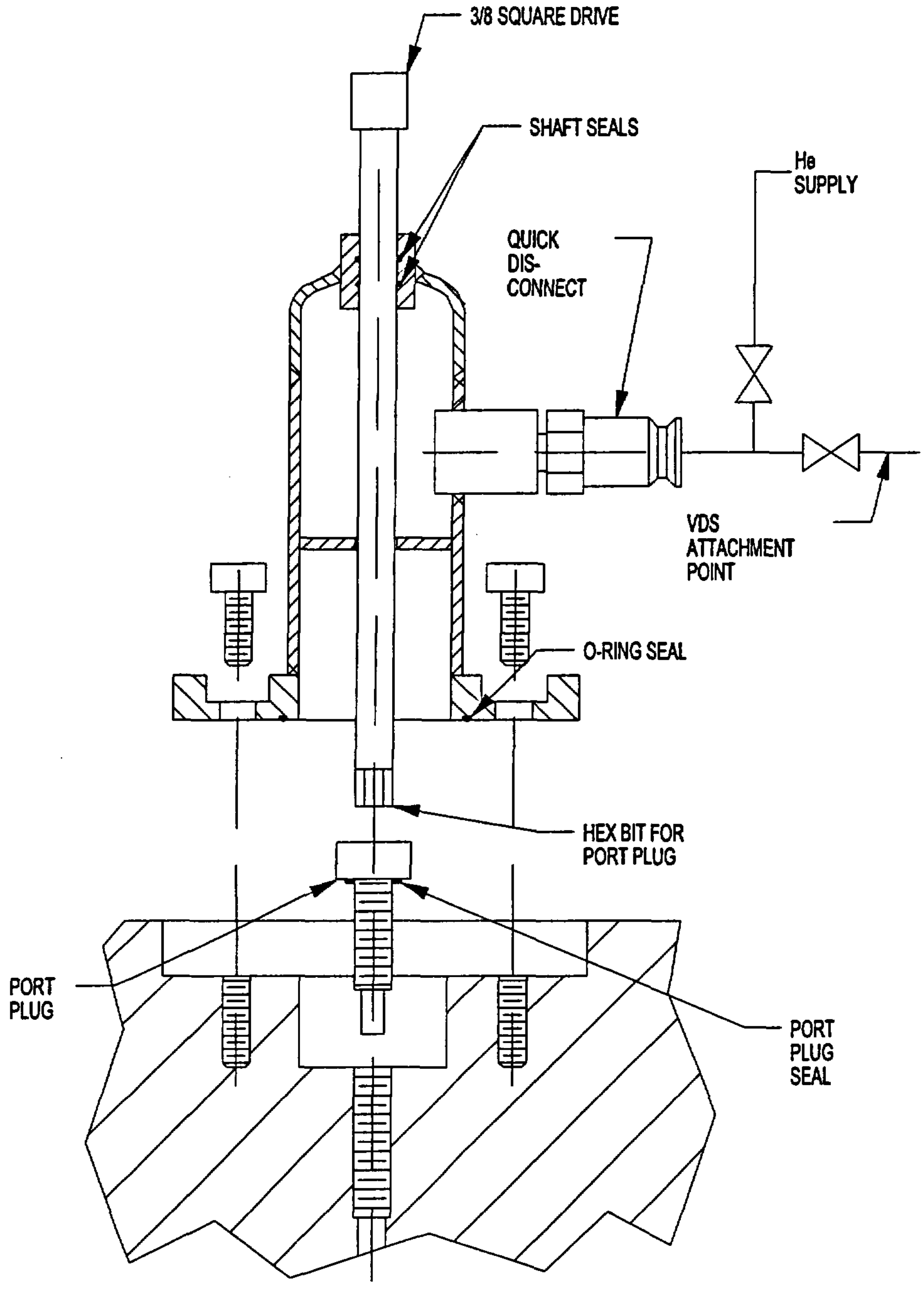


Figure 7.1.28; HI-STAR 100 Backfill Tool

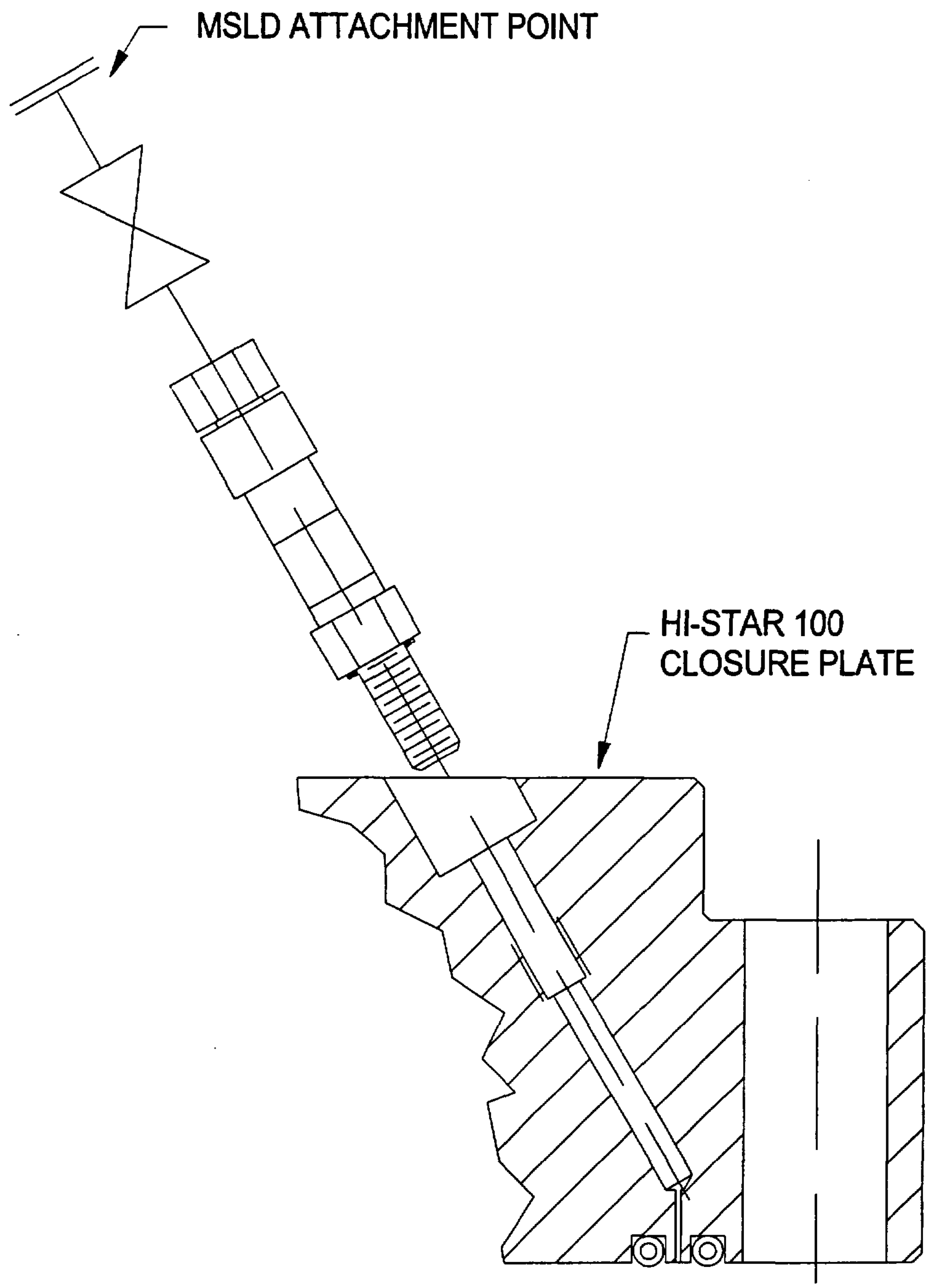


Figure 7.1.29; HI-STAR 100 Closure Plate Test Tool

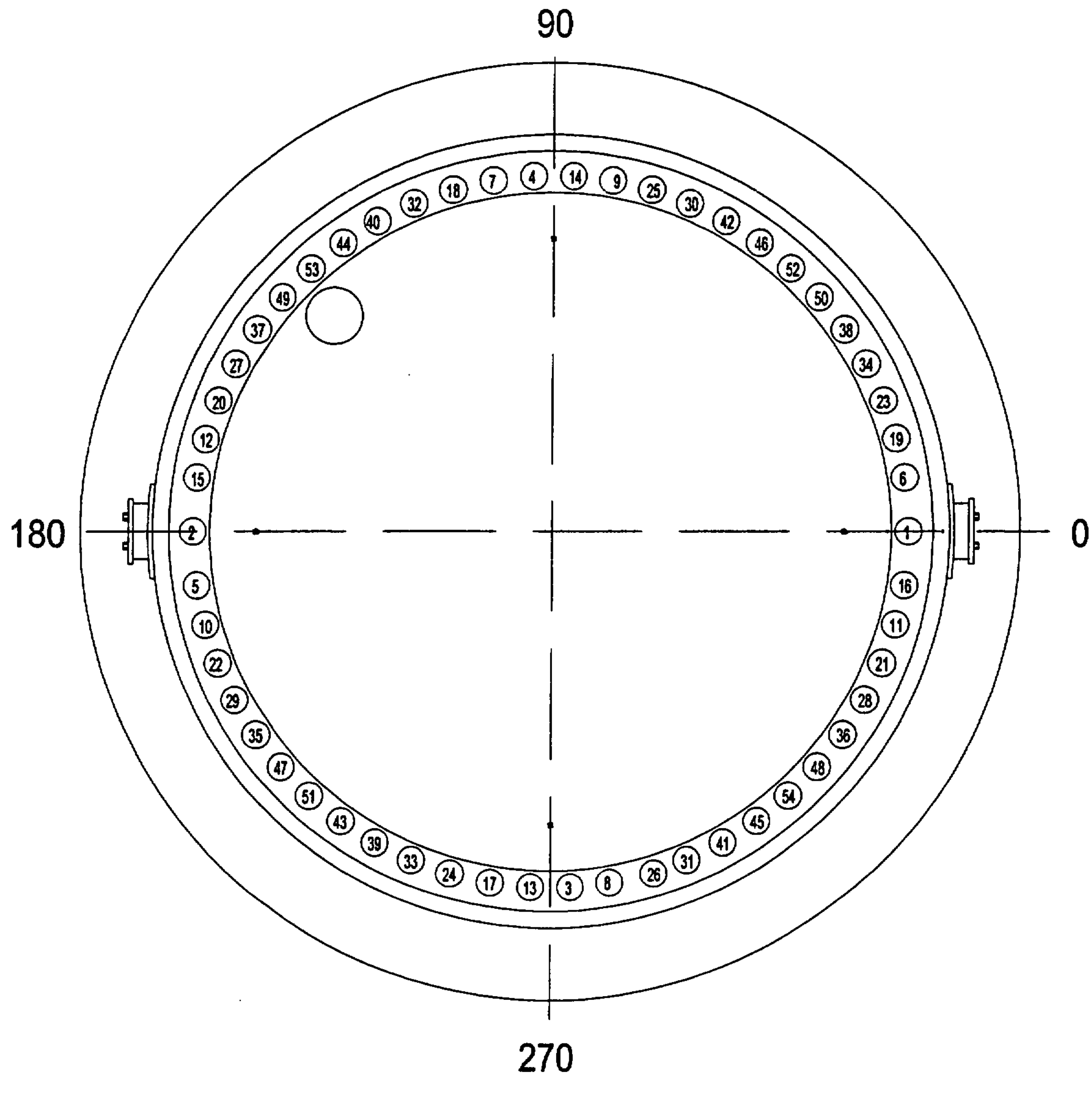


Figure 7.1.30; HI-STAR Closure Plate Bolt Torquing Pattern

7.2 PROCEDURE FOR UNLOADING THE HI-STAR 100 SYSTEM IN THE SPENT FUEL POOL

7.2.1 Overview of HI-STAR 100 System Unloading Operations

ALARA Note:
The procedure described below uses the Weld Removal System, a remotely operated system that mechanically removes the welds. Users may opt to remove some or all of the welds using hand operated equipment. The decision should be based on dose rates, accessibility, degree of weld removal, and available tooling and equipment.

The HI-STAR 100 System unloading procedures describe the general actions necessary to prepare the MPC for unloading, cool the stored fuel assemblies in the MPC, flood the MPC cavity, remove the lid welds, unload the spent fuel assemblies, and recover the HI-STAR 100 overpack and empty MPC. These procedures are only used to respond to extreme abnormal events. Special precautions are outlined to ensure personnel safety during the unloading operations, and to prevent the risk of MPC over-pressurization and thermal shock to the stored spent fuel assemblies. Figure 7.2.1 shows a flow diagram of the HI-STAR 100 overpack unloading operations. Figure 7.2.2 illustrates the major HI-STAR 100 overpack unloading operations.

Refer to the boxes of Figure 7.2.2 for the following description. The HI-STAR 100 overpack is received from the carrier and inspected. The personnel barrier is removed, the impact limiters are removed and the HI-STAR is surveyed (Box 1). The HI-STAR 100 overpack is upended and returned to the fuel building. The HI-STAR 100 overpack vent port cover plate is removed and a gas sample is drawn from the HI-STAR 100 overpack annulus to determine the condition of the MPC confinement boundary. The annulus is depressurized and the HI-STAR 100 overpack closure plate is removed (Box 2). The annulus is filled with clean water. The annulus shield is installed to protect the annulus from debris produced from the lid removal process. The MPC closure ring above the vent and drain ports and the vent and drain port cover plates are core-drilled and removed to access the vent and drain ports. (Box 3). The design of the vent and drain ports use metal-to-metal seals that prevent rapid decompression of the MPC and subsequent spread of contamination during unloading. The vent RVOA is attached to the vent port and an evacuated sample bottle is connected. The vent port is slightly opened to allow the sample bottle to obtain a gas sample from inside the MPC. A gas sample is performed to assess the condition of the fuel assembly cladding. If necessary, the MPC is cooled using a closed-loop heat exchanger or other appropriate means to reduce the MPC internal temperature to allow water flooding (Box 4). The cool-down process gradually reduces the cladding temperature to a point where the MPC may be flooded with water without thermally shocking the fuel assemblies or over-pressurizing the MPC from the formation of steam. Following the fuel cool-down (if required), the MPC is filled with water (Box 5). The Weld Removal System then removes the MPC lid to MPC shell weld (Box 6). The Weld Removal System is removed with the MPC lid left in place.

The top surfaces of the HI-STAR 100 overpack and MPC are cleared of metal shavings. The inflatable annulus seal is installed and pressurized. The MPC lid is rigged to the lift yoke or lid retention system and the lift yoke is engaged to the HI-STAR 100 overpack lifting trunnions. The HI-STAR 100 overpack is placed in the spent fuel pool and the MPC lid is removed (Box 7). All fuel assemblies are returned to the spent fuel storage racks and the MPC fuel cells are vacuumed to remove any assembly debris and crud (Box 8). The HI-STAR 100 overpack and MPC are returned to the designated preparation area (Box 9) where the MPC water is pumped back into the spent fuel pool, liquid radwaste system or other approved location. The annulus water is drained and the MPC and overpack are decontaminated (Box 10 and 11).

7.2.2 HI-STAR 100 Overpack Packaging Receipt

1. Recover the shipping documentation from the carrier along with the keys to the personnel barrier locks.

2. Remove the personnel barrier (See Figure 7.1.9) and perform a partial visual inspection of the HI-STAR 100 overpack to verify that there are no outward visual indications of impaired physical conditions. Identify any significant indications to the cognizant individual for evaluation and resolution.

ALARA Warning:
Dose rates around the unshielded bottom end of the HI-STAR 100 overpack may be higher that other locations around the overpack. Workers should exercise appropriate ALARA controls when working around the bottom end of the HI-STAR 100 overpack.

3. If necessary, remove the overpack from the transport vehicle. See Figure 7.1.5.

4. Remove the impact limiters as follows:

   a. Record the impact limiter security seal serial numbers and verify that they match the corresponding shipping documentation, as applicable.

   b. Clip the security seal wires and remove the security seals and wires.

   c. Attach the impact limiter handling frame as shown on Figure 7.1.10.

Caution:
The slings should be preloaded to the impact limiter weight plus the weight of the impact limiter handling frame prior to removal of the impact limiter bolts. (See Table 7.1.1) This will prevent movement of the impact limiter and damage to the bolts from excessive lift pressure during bolt removal.

   d. Using the load cell, apply the correct lift load. See Table 7.1.1 for approximate weights.

   e. Remove the bolts securing the impact limiter to the overpack. See Figure 7.1.11.

f. Remove the impact limiter and store the impact limiter in a site-approved location.

g. Repeat Steps 3.c. through 3.f. for the other impact limiter.

5. Complete the HI-STAR 100 overpack visual inspection to verify that there are no outward visual indications of impaired physical conditions. Identify any significant indications to the cognizant individual for evaluation and resolution.

Note:
On receipt of the loaded or empty HI-STAR 100 packaging, the accessible external surfaces of the HI-STAR 100 packaging (HI-STAR 100 overpack, impact limiters, personnel barrier, tie-down, transport frame and transport vehicle) shall be surveyed for removable radiological contamination.

6. Perform a radiation survey and removable contamination survey. Record the results on the shipping documentation.

7. Verify that the HI-STAR 100 overpack neutron shield relief devicesare installed and intact. Identify any non-conformances to the cognizant individual for evaluation and resolution.

8. If necessary, upend the HI-STAR 100 overpack in accordance with Section 7.1.2.

9. Transfer the HI-STAR 100 overpack to the fuel building.

10. Remove the buttress plate. See Figure 7.1.11 and 7.1.12.

11. Place the HI-STAR 100 overpack in the designated preparation area.

7.2.3 Preparation for Unloading

ALARA Warning:
Gas sampling is performed to assess the condition of the MPC confinement boundary. If a leak is discovered in the MPC boundary, the user's Radiation Control organization may require special actions to vent the HI-STAR 100.

1. Perform annulus gas sampling as follows:

   a. Remove the overpack vent port cover plate and attach the backfill tool with a sample bottle attached. See Figure 7.2.3. Store the cover plate in a site-approved location.

   b. Using a vacuum pump, evacuate the sample bottle and backfill tool.

   c. Slowly open the vent port plug and gather a gas sample from the annulus. Reinstall the HI-STAR 100 overpack vent port plug.

d. Evaluate the gas sample and determine the condition of the MPC confinement boundary.

2. If the confinement boundary is intact (i.e., no radioactive gas is measured) then vent the overpack annulus by removing the overpack vent port seal plug (using the backfill tool). Otherwise vent the annulus gas in accordance with instructions from Radiation Protection.

3. Remove the closure plate bolts. See Table 7.1.3 for de-torquing requirements. Store the closure plate bolts in a site-approved location.

4. Remove the overpack closure plate. See Figure 7.1.12 for rigging. Store the closure plate on cribbing to protect the seal seating surfaces.

5. Install the HI-STAR 100 overpack Seal Surface Protector (See Figure 7.1.13).

Warning:
Annulus fill water may flash to steam due to high MPC shell temperatures. Water addition should be performed in a slow and controlled manner.

6. Remove the HI-STAR 100 overpack drain port cover and port plug and install the drain connector. Store the drain port cover plate and port plug in an approved storage location.

7. Slowly fill the annulus area with clean water to approximately 4 inches below the top of the MPC shell and install the annulus shield. The annulus shield reduces the dose around the annulus area and prevents debris from entering the annulus during MPC lid weld removal operations. See Figure 7.1.13.

8. Remove the MPC closure welds as follows:

ALARA Note:
The following procedures describe weld removal using the Weld Removal System. The Weld Removal System removes the welds with a high speed machine tool head. A vacuum head is attached to remove a majority of the metal shavings. Other methods of opening the MPC are acceptable.

ALARA Warning:
Weld removal may create an airborne radiation condition. Weld removal must be performed under the direction of the user's Radiation Protection organization.

a. Install bolt plugs and/or waterproof tape on the closure plate bolt holes.

b. Install the Weld Removal System on the MPC lid and core drill through the closure ring and vent and drain port cover plate welds.

9. Access the vent and drain ports.

10. Remove metal shavings from around the vent and drain ports.

ALARA Note:
The MPC vent and drain ports are equipped with metal-to-metal seals to minimize leakage and withstand the long-term effects of temperature and radiation. The vent and drain port design prevents the need to hot tap into the penetrations during unloading operation and reduce the risk of a pressurized release of gas from the MPC.

11. Take an MPC gas sample as follows:

    a. Attach the RVOA to the vent port (See Figure 7.1.21).

    b. Attach a sample bottle to the vent port RVOA as shown on Figure 7.2.4.

    c. Using a vacuum pump, evacuate the RVOA and Sample Bottle.

    d. Slowly open the vent port cap using the RVOA and gather a gas sample from the MPC internal atmosphere.

    e. Close the vent port and disconnect the sample bottle.

ALARA Note:
The gas sample analysis is performed to determine the condition of the fuel cladding in the MPC. The gas sample may indicate that fuel with damaged cladding is present in the MPC. The results of the gas sample test may affect personnel protection and how the gas is processed during MPC depressurization.

    f. Turn the sample bottle over to the site's Radiation Protection or Chemistry Department for analysis.

    g. Install the RVOA in the drain port.

12. Perform Fuel Assembly Cool-Down, if necessary, and MPC re-flooding as follows:

    a. Ensure that MPC cavity gas temperature is less than 200°F using the appropriate cooldown means as determined by a thermal evaluation. This may require no action, cooling to the exterior of the canister, or use of the helium cooldown system, based on the decay heat of contents of the MPC at the time of unloading.

Note:
If auxiliary cooling of the MPC was used to bring the internal temperature below 200 °F, water filling should commence immediately after the completion of fuel cool-down operations to minimize fuel assembly heat-up. Prepare the water fill and vent lines in advance of water filling.

    b. Attach the water fill line to the MPC and slowly open the water supply valve and establish a pressure less than 90 psi. Fill the MPC until bubbling from the vent line has terminated. Close the water supply valve on completion.

c. Disconnect both lines from the drain and vent ports leaving the drain port cap open to allow for thermal expansion of the water during MPC lid weld removal.

Caution:

Oxidation of Boral panels contained in the MPC may create hydrogen gas while the MPC is filled with water. Appropriate monitoring for combustible gas concentrations shall be performed prior to, and during MPC cutting operations. The space below the MPC lid shall be exhausted or purged with inert gas prior to, and during MPC cutting operations to provide additional assurance that flammable gas concentrations will not develop in this space.

d. Connect a combustible gas monitor to the MPC vent port and check for combustible gas concentrations prior to and periodically during weld removal activities. Purge or evacuate the gas space under the lid as necessary.

e. Remove the closure ring-to-MPC shell weld and the MPC lid-to-shell weld using the Weld Removal System and remove the Weld Removal System. See Figure 7.1.12 for rigging.

f. Clean the top surfaces of the MPC and the HI-STAR 100 overpack to remove any metal shavings.

13. Install the inflatable annulus seal as follows:

Caution:

Do not use any sharp tools or instruments to install the inflatable seal.

a. Remove the annulus shield.

b. Manually insert the inflatable seal around the MPC. See Figure 7.1.13.

c. Ensure that the seal is uniformly positioned in the annulus area.

d. Inflate the seal between 30 and 35 psig or as directed by the manufacturer.

e. Visually inspect the seal to ensure that it is properly seated in the annulus. Deflate, adjust and inflate the seal as necessary.

14. Place HI-STAR 100 overpack in the spent fuel pool as follows:

a. Engage the lift yoke to the HI-STAR 100 overpack lifting trunnions, remove the MPC lid lifting threaded inserts and attach the MPC lid slings or Lid Retention System to the MPC lid.

b. If the Lid Retention System is used, inspect the lid bolts for general condition. Replace worn or damaged bolts with new bolts.

c. Install the Lid Retention System bolts if the Lid Retention System is used.

> **ALARA Note:**
> The Annulus Overpressure System is used to provide additional protection against MPC external shell contamination during in-pool operations. The Annulus Overpressure System is equipped to prevent inadvertent draining. The reservoir valve must be closed to ensure that the annulus is not inadvertently drained through the Annulus Overpressure System when the cask is raised above the level of the annulus reservoir.

d. If used, fill the Annulus Overpressure System lines and reservoir with clean water and close the reservoir valve. Attach the Annulus Overpressure System to the HI-STAR 100 overpack. See Figure 7.1.17.

> **Warning:**
> Cask placement in the spent fuel pool is the heaviest lift that occurs during the HI-STAR 100 unloading operations. The HI-STAR 100 trunnions must not be subjected to lifted loads in excess of 250,000 lbs. Users must ensure that plant-specific lifting equipment is qualified to lift the expected load. Users may elect to pump a measured quantity of water from the MPC prior to placement of the HI-STAR 100 in the spent fuel pool. See Table 7.1.1 and 7.1.2 for weight information.

e. Position the HI-STAR 100 overpack over the cask loading area.

> **ALARA Note:**
> Wetting the components that enter the spent fuel pool may reduce the amount of decontamination work to be performed later.

f. Wet the surfaces of the HI-STAR 100 overpack and lift yoke with clean water while slowly lowering the HI-STAR 100 overpack into the spent fuel pool.

g. When the top of the HI-STAR 100 overpack reaches the approximate elevation of the reservoir, start the Annulus Overpressure System water flow. Maintain the reservoir water level at approximately 3/4 full the entire time the cask is in the spent fuel pool.

h. If the Lid Retention System is used, remove the lid retention bolts when the top of the HI-STAR 100 overpack is accessible from the operating floor.

i. Place the HI-STAR 100 overpack on the floor of the cask loading area and disengage the lift yoke. Visually verify that the lift yoke is fully disengaged.

> **Note:**
> An underwater camera or other suitable viewing device may be used for monitoring the underwater operations.

j. Apply slight tension to the lift yoke and visually verify proper disengagement of the lift yoke from the trunnions.

k. Remove the lift yoke, MPC lid and drain line from the pool in accordance with directions from the site's Radiation Protection personnel. Spray the equipment with clean water as it is removed from the pool.

Warning:
The MPC lid and unloaded MPC may contain residual contamination. All work done on the unloaded MPC should be carefully monitored and performed.

l. Disconnect the drain line from the MPC lid.

m. Store the MPC lid components in an approved location. Disengage the lift yoke from MPC lid. Remove any upper fuel spacers using the same process as was used in the installation.

n. Disconnect the Lid Retention System if used.

7.2.4 MPC Unloading

1. Remove the spent fuel assemblies from the MPC using applicable site procedures.

2. Clean the cells of the MPC to remove any debris or corrosion products.

3. Inspect the open cells for presence of any remaining items. Remove them as appropriate.

7.2.5 Post-Unloading Operations

1. Remove the HI-STAR 100 overpack and the unloaded MPC from the spent fuel pool as follows:

   a. Engage the lift yoke to the trunnions.

   b. Apply slight tension to the lift yoke and visually verify proper engagement of the lift yoke to the trunnions.

   c. Raise the HI-STAR 100 overpack until the HI-STAR 100 overpack flange is at the surface of the spent fuel pool.

ALARA Warning:
Activated debris may have settled on the top face of the HI-STAR 100 overpack during fuel unloading.

   d. Measure the dose rates at the top of the HI-STAR 100 overpack in accordance with plant radiological procedures and flush or wash the top surfaces to remove any highly-radioactive particles.

   e. Raise the top of the HI-STAR 100 overpack and MPC to the level of the spent fuel pool deck.

f. Close the Annulus Overpressure System reservoir valve if the Annulus Overpressure System was used.

g. As necessary, use a water pump to lower the water level in the MPC approximately 12 inches to prevent splashing during cask movement.

ALARA Note:
To reduce contamination of the HI-STAR 100 overpack, the surfaces of the HI-STAR 100 overpack and lift yoke should be kept wet until decontamination can begin.

h. Remove the HI-STAR 100 overpack from the spent fuel pool while spraying the surfaces with clean water.

i. Disconnect the Annulus Overpressure System from the HI-STAR 100 overpack. Drain the Annulus Overpressure System lines and reservoir.

j. Place the HI-STAR 100 overpack in the designated preparation area.

k. Disengage the lift yoke.

l. Perform decontamination on the HI-STAR 100 overpack and the lift yoke.

2. Carefully decontaminate the area above the inflatable seal. Deflate, remove, and store the seal in an approved plant storage location.

3. Pump the remaining water in the MPC to the spent fuel pool or liquid radwaste system.

4. Drain the water in the annulus.

5. Remove the MPC from the HI-STAR 100 overpack and decontaminate the MPC as necessary.

6. Decontaminate the HI-STAR 100 overpack.

7. Remove any bolt plugs, seal surface protector and/or waterproof tape from the HI-STAR 100 overpack top bolt holes.

8. Move the HI-STAR 100 overpack and MPC for further inspection, corrective actions, or disposal as necessary.

LOCATION: CASK RECEIVING AREA
REMOVE PERSONNEL BARRIER
PERFORM CASK SUVEY AND RECEIPT INSPECTION
REMOVE IMPACT LIMITERS
REMOVE TIE-DOWN
UPEND HI-STAR OVERPACK
PLACE HI-STAR IN DESIGNATED PERPARATION AREA
LOCATION: CASK PREPARATION AREA
GATHER ANNULUS GAS SAMPLE
DEPRESSURIZE HI-STAR ANNULUS
REMOVE HI-STAR CLOSURE PLATE
FILL ANNULUS
INSTALL ANNULUS SHIELD
REMOVE MPC CLOSURE RING
REMOVE MPC VENT PORT COVER PLATE AND SAMPLE MPC GAS
REMOVE MPC DRAIN PORT COVER PLATE
IF NECESSARY, PERFORM MPC COOL-DOWN
FILL MPC CAVITY WITH WATER
REMOVE MPC LID TO SHELL WELD
INSTALL INFLATABLE SEAL
PLACE HI-STAR IN SPENT FUEL POOL
LOCATION: SPENT FUEL POOL
REMOVE MPC LID
DISCONNECT DRAIN LINE
REMOVE SPENT FUEL ASSEMBLIES FROM MPC
VACCUM CELLS OF MPC
REMOVE HI-STAR FROM SPENT FUEL POOL
LOCATION: CASK PREPARATION AREA
LOWER WATER LEVEL IN MPC
PUMP REMAINING WATER IN MPC TO SPENT FUEL POOL
REMOVE MPC FROM HI-STAR
DECONTAMINATE MPC AND HI-STAR

Figure 7.2.1; Unloading Operations Flow Diagram

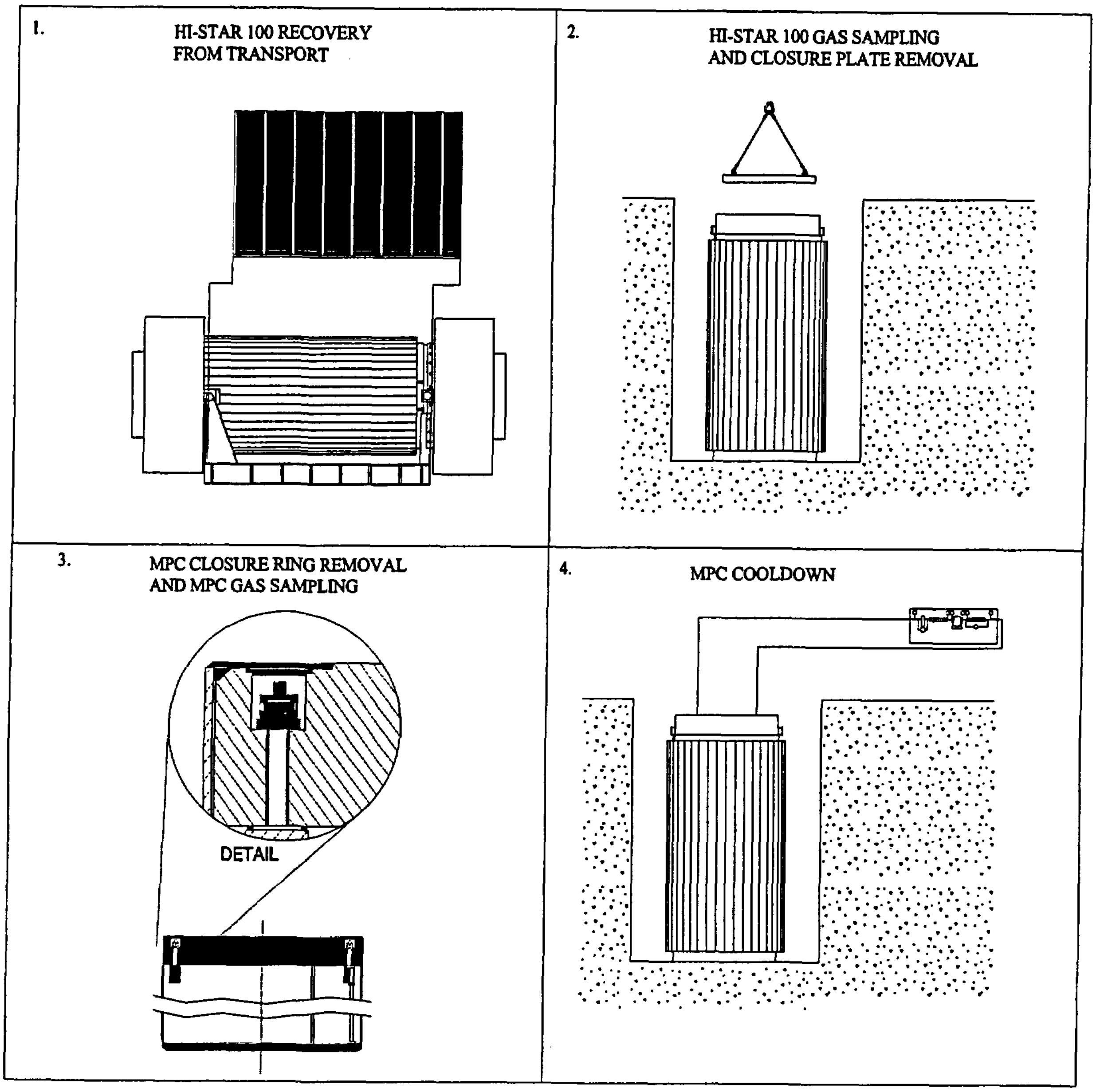


Figure 7.2.2a; Major HI-STAR 100 Unloading Operations (Sheet 1 of 3)

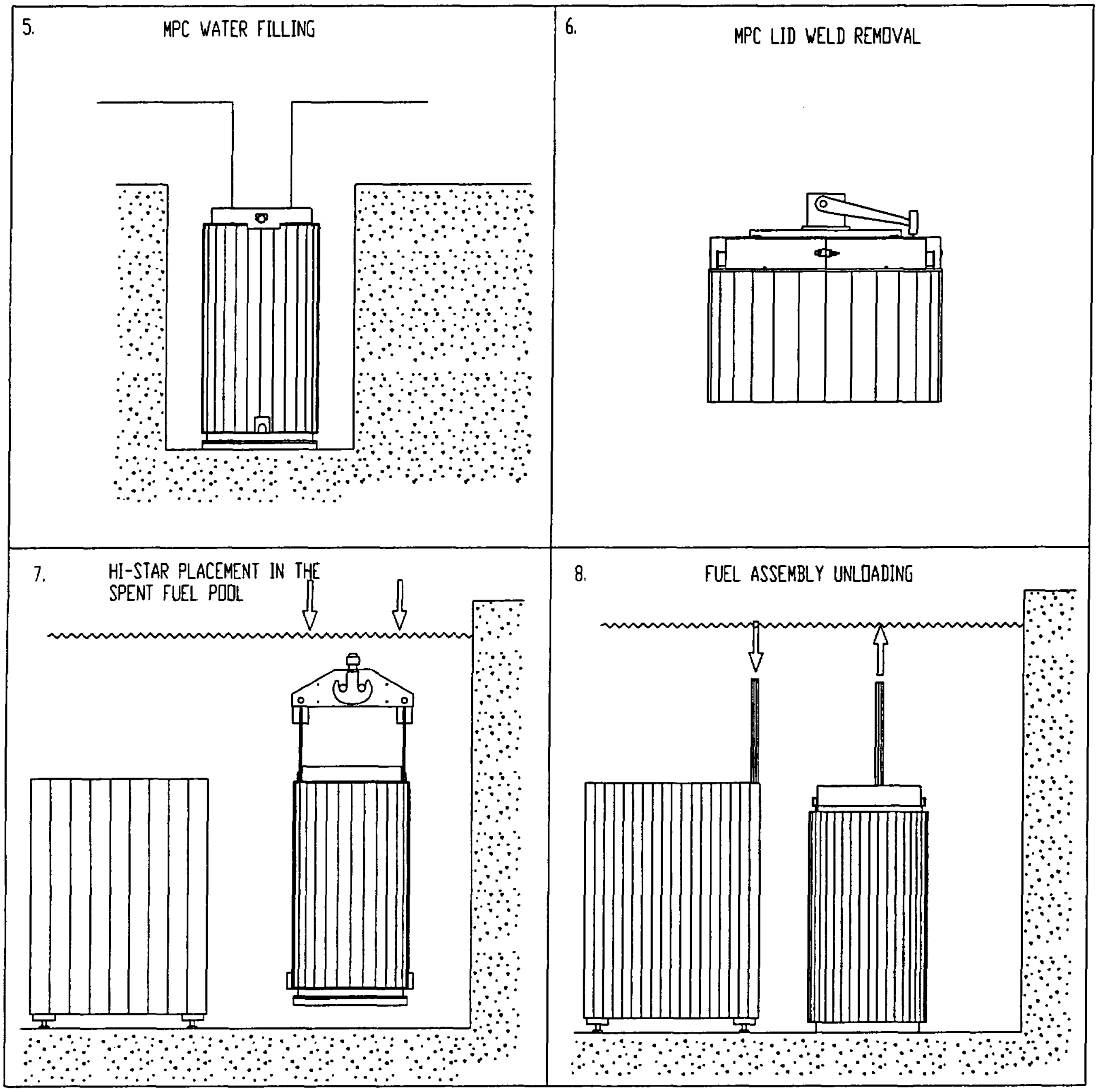


Figure 7.2.2b; Major HI-STAR 100 Unloading Operations (Sheet 2 of 3)

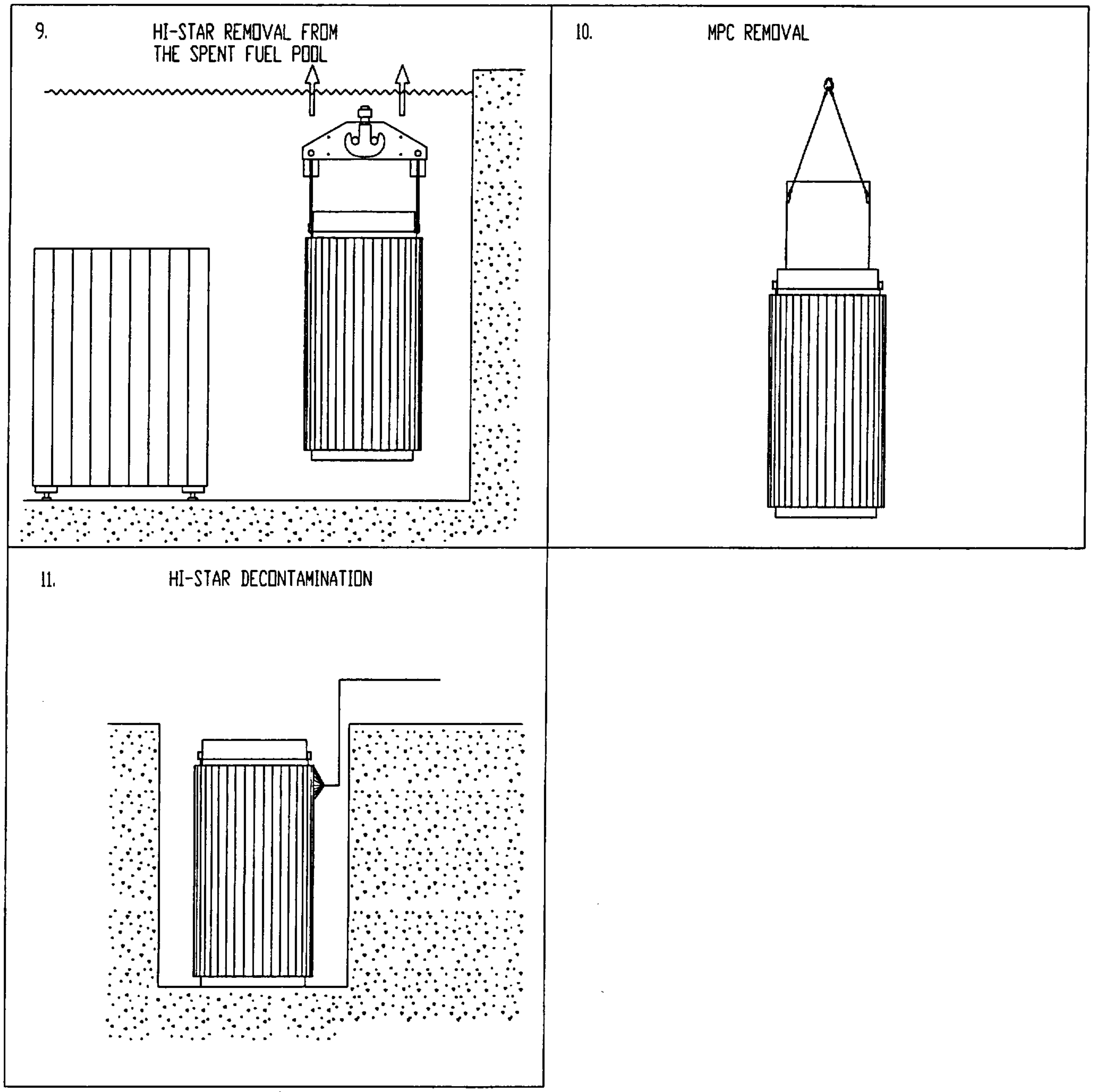


Figure 7.2.2c; Major HI-STAR 100 Unloading Operations (Sheet 3 of 3)

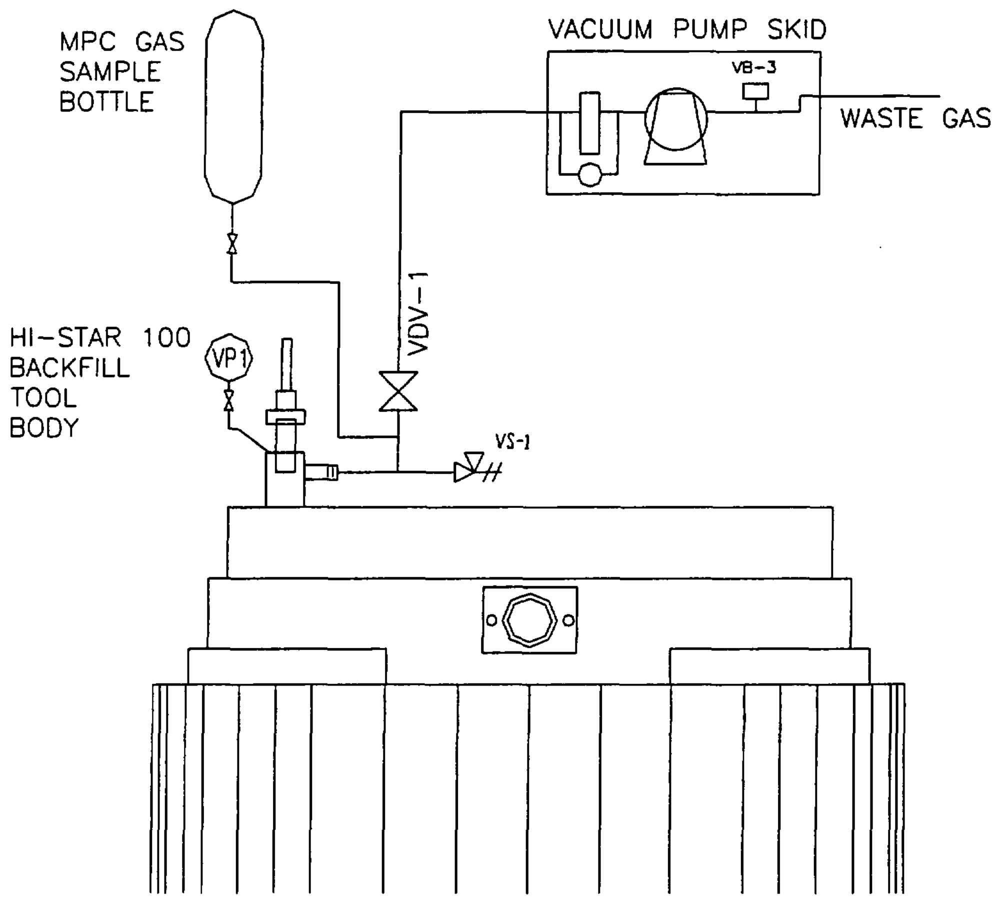


Figure 7.2.3; HI-STAR Annulus Gas Sampling

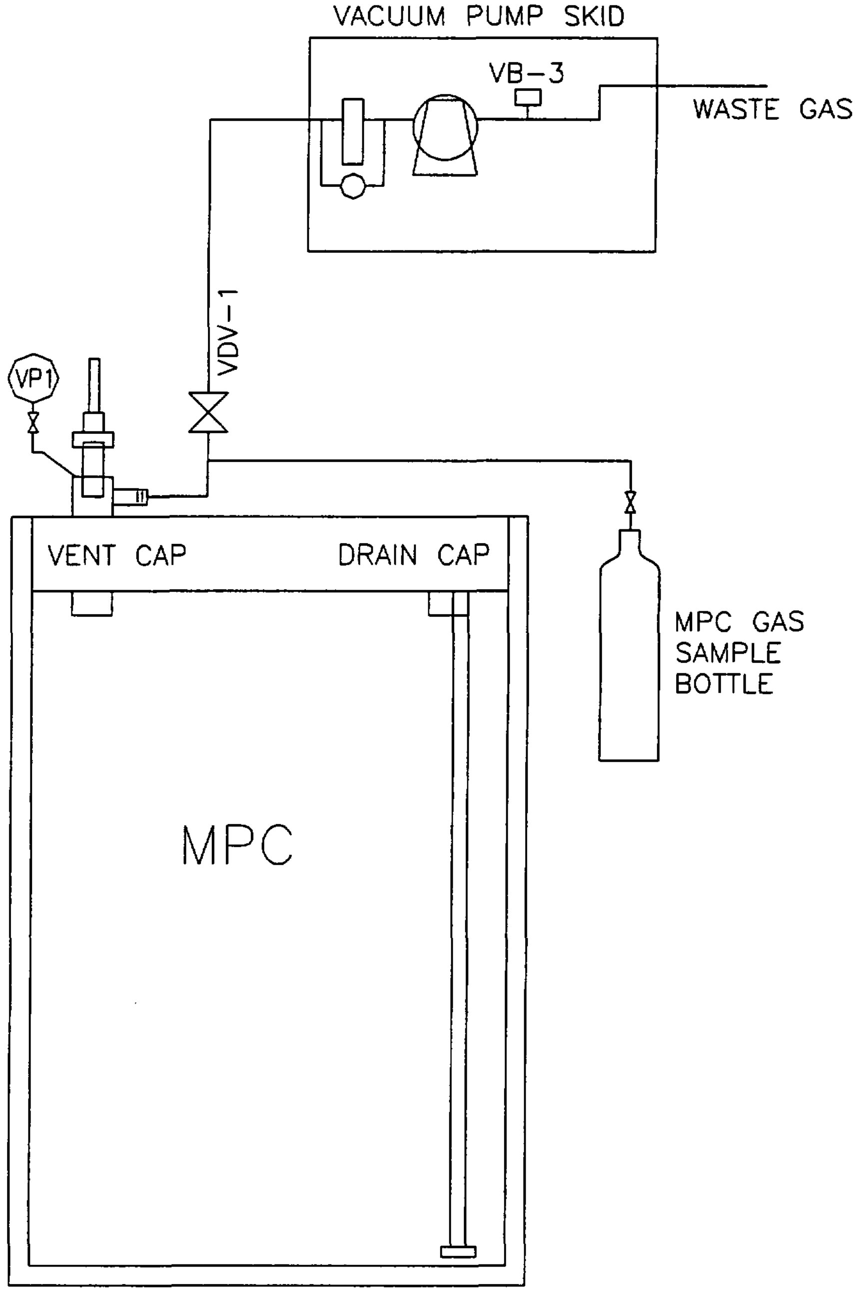


Figure 7.2.4; MPC Gas Sampling in Preparation for Unloading (Example P&I Diagram)

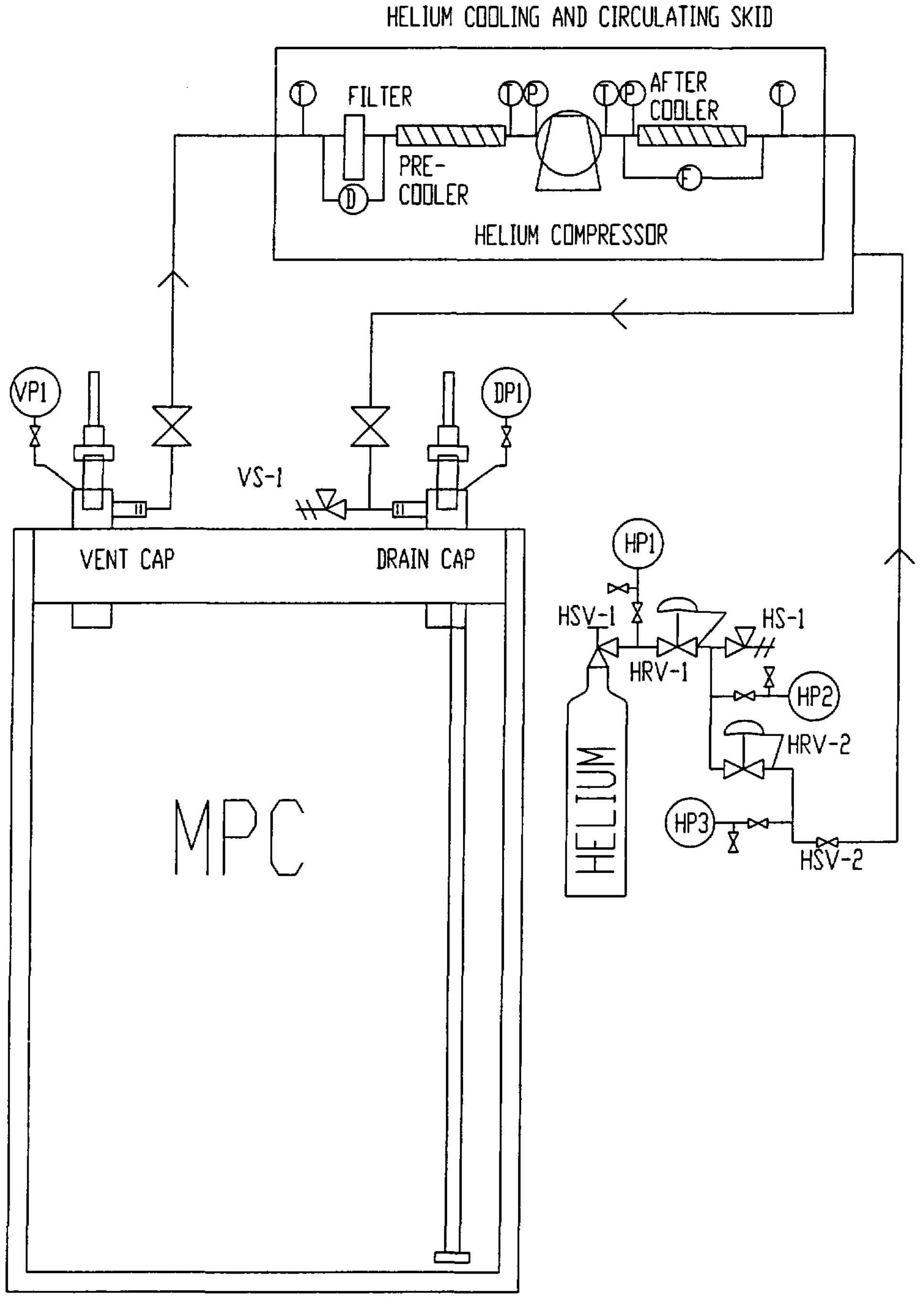


Figure 7.2.5; MPC Cooldown (Example P&I Diagram)

7.3 PREPARATION OF AN EMPTY PACKAGE FOR TRANSPORT

7.3.1 Overview of the HI-STAR 100 System Empty Package Transport

The operations for preparing an empty package (previously used) for transport are similar to those required for transporting the loaded package with several exceptions. The closure plate is installed and the bolts are torqued. The HI-STAR 100 overpack is downended . A survey for removable contamination is performed to verify that the removable contamination on the internal and external surfaces of the HI-STAR 100 overpack are ALARA and that the limits of 49CFR173.428 [7.1.3] and 10CFR71.87(i) [7.0.1] are met. At the User's discretion, impact limiters are installed and the personnel barrier is installed and locked. The procedures provided herein describe the installation of the impact limiters and personnel barrier. These steps may be omitted as needed.

7.3.2 Preparation for Empty Package Shipment

1. Install the closure plate as follows:

Note:
For empty shipments of the HI-STAR 100 overpack, used metallic seals may be reused.

   a. Remove the Seal Surface Protector from the HI-STAR 100 overpack if necessary.

   b. Perform a contamination survey of the top accessible 12-inches of the HI-STAR 100 Overpack inside surface..

   c. Verify that the HI-STAR 100 Overpack is empty and contains less than 15 gm U-235 in accordance with 49CFR173.421(a)(5) [7.3.1].

   d. Raise and install the closure plate on the HI-STAR 100 overpack. See Figure 7.1.12 for rigging.

   e. Install and torque the closure plate bolts. See Table 7.1.3 for torque requirements.

   f. If necessary, install the vent and drain cover plates.

2. Position the HI-STAR 100 overpack on the transport frame as follows:

   a. Install the HI-STAR 100 overpack buttress plate on the HI-STAR 100 overpack. See Figure 7.1.11 and 7.1.12 for rigging. See Table 7.1.3 for torque requirements.

   b. Downend the HI-STAR 100 overpack. See Section 7.1.2.

   c. Install the removable shear ring segments. See Table 7.1.3 for torque requirements.

3. Perform a final inspection of the HI-STAR 100 overpack as follows:

> **Note:**
> Prior to shipment of the HI-STAR 100 package, the accessible external surfaces of the HI-STAR 100 packaging (HI-STAR 100 overpack, impact limiters, personnel barrier, tie-down, transport frame and transport vehicle) shall be surveyed for removable radiological contamination in accordance with 49CFR173.443(a) [7.1.3].

   a. Perform a final survey for removable contamination. Record the results on the shipping documentation.

   b. Perform a radiation survey of the HI-STAR 100 Overpack and confirm that the radiation levels on any external surface of the overpack do not exceed the levels required by 49CFR173.421(a)(2) [7.1.3].

   c. Perform a visual inspection of the HI-STAR 100 overpack to verify that there are no outward visual indications of impaired physical condition and that the package is securely closed in accordance with 49CFR173.428(b) [7.1.3]. Identify any significant indications to the cognizant individual for evaluation and resolution and record on the shipping documentation.

   d. Verify that the HI-STAR 100 overpack neutron shield relief devicesare installed, intact and not covered by tape or other covering.

4. Deleted..

5. If necessary, Install the impact limiters as follows:

   a. Install the alignment pins in the bottom of the HI-STAR 100 overpack. See Figure 7.1.11. See Table 7.1.3 for torque requirements.

   b. Using the impact limiter handling frame, raise and position the impact limiter over the end of HI-STAR 100. See Figure 7.1.10.

   c. Install the impact limiter bolts. See Table 7.1.3 for torque requirements.

   d. Repeat for the other impact limiter.

> **Note:**
> The impact limiters cover all the HI-STAR 100 penetrations. The security seals are used to provide tamper detection.

   e. Install a security seal (one per impact limiter) through the threaded hole in the top and bottom impact limiter bolts. Record the security seal number on the shipping documentation.

   f. Perform final radiation surveys of the package surfaces per 10CFR71.47 [7.0.1], SAR Section 8.1.5.2, and 49CFR173.428(a) [7.1.3].

6. Install the personnel barrier as follows:

   a. Rig the personnel barrier as shown in Figure 7.1.9 and position the personnel barrier over the frame.

   b. Remove the personnel barrier rigging and install the personnel barrier locks.

   c. Transfer the personnel barrier keys to the carrier.

7. Perform a final check to ensure that the package is ready for release as follows:

   a. Verify that the receiver has been notified of the impending shipment.

   b. Verify that any labels previously applied in conformance with Subpart E of 49CFR172 [7.1.3] have been removed, obliterated, or covered and the "Empty" label prescribed in 49CFR172.450 [7.1.3] is affixed to the packaging in accordance with 49CFR173.428(d) [7.1.3].

   c. Verify that the package for shipment is prepared in accordance with 49CFR173.422 [7.1.3]

   d. Verify that all required information is recorded on the shipping documentation.

8. Release the HI-STAR 100 System for transport.

7.4 PROCEDURE FOR PREPARING THE HI-STAR 100 OVERPACK FOR TRANSPORT FOLLOWING A PERIOD OF STORAGE

7.4.1 Overview of the HI-STAR 100 System Preparation for Transport Following a Period of Storage

The operations for preparing the loaded HI-STAR 100 Overpack for transport following a period of storage (in excess of one year from the date of completion of HI-STAR 100 overpack mechanical seal leakage testing) are identical to the later portion of operations required for normal transport of the package as summarized herein. The cask is positioned and the closure plate test port plug, HI-STAR 100 overpack vent port cover and drain port cover plates are removed. The MSLD is attached and the mechanical seal leakage test is repeated as described in Section 7.1.6. Following successful completion of the leakage tests the closure plate plug and vent and drain port cover plates are reinstalled with new seals. The package is prepared for transport as described in Section 7.1.6.

For the MPC-68F/24EF, The HI-STAR 100 overpack vent port cover plate is removed and a gas sample is drawn from the HI-STAR 100 overpack annulus to determine the condition of the MPC confinement boundary. The annulus is vented (as described in Section 7.2.3), evacuated and flushed with air several times to clear residual helium from the annulus space. The MPC-68F/24EF is then leakage tested as described in Section 7.1.6. Following the leakage test of the MPC-68F/24EF, the HI-STAR 100 Overpack is prepared for transport as described in Section 7.1.6.

7.4.2 Preparation for Transport Following a Period of Storage

1. Position the HI-STAR 100 Overpack for leakage testing.

Note:
Leakage testing requirements for transport are specified in the CoC. Step 2 is only required for the MPC-68F or MPC-24EF. Skip this step if not applicable.

2. If necessary, perform a leakage test of the MPC-68F/24EF as follows:

    a. Sample the annulus gas as follows:

        1. Remove the overpack vent port cover plate and attach the backfill tool with a sample bottle attached. See Figure 7.2.3. Store the cover plate in a site-approved location.

        2. Using a vacuum pump, evacuate the sample bottle and backfill tool.

        3. Slowly open the vent port plug and gather a gas sample from the annulus. Reinstall the HI-STAR 100 overpack vent port plug.

    b. Evaluate the gas sample and determine the condition of the MPC confinement boundary.

c. If the confinement boundary is intact (i.e., no radioactive gas is measured) then vent the overpack annulus by removing the overpack vent port seal plug (using the backfill tool). Otherwise vent the annulus gas in accordance with instructions from Radiation Protection.

d. Flush the annulus and perform leakage testing of the MPC-68F/24EF as follows:

   1. Install the overpack test cover to the overpack vent port as shown on Figure 7.1.27. See Table 7.1.3 for torque requirements.

   2. Evacuate the annulus to below 5 torr and break the vacuum allowing air to fill the annulus space. Repeat this process several times to remove residual helium from the annulus space.

   3. Evacuate the annulus per the MSLD manufacturer's instructions and isolate the vacuum pump from the overpack test cover.

   4. Perform a leakage rate test of MPC-68F/24EF using the evacuated envelope-gas detector method in accordance with the MSLD manufacturer's instructions and ANSI N14.5 [7.1.5]. The MPC Helium Leak Rate shall meet the requirements of section 8.1.3.

   5. Disconnect the overpack test cover.

   6. Remove the closure plate test port plug. Discard any used metallic seals.

e. Dry and backfill the overpack annulus as follows:

   1. Load the backfill tool with the HI-STAR 100 overpack vent port plug and the vent port with a new plug seal. Attach the backfill tool to the HI-STAR 100 overpack vent port with the plug removed. See Figure 7.1.28. See Table 7.1.3 for torque requirements.

   2. Attach the Vacuum Drying System to the backfill tool and reduce the HI-STAR 100 overpack pressure to below 3 torr.

Note:
The annulus pressure may rise due to the presence of water in the HI-STAR 100 overpack. The dryness test may need to be repeated several times until all the water has been removed. Leaks in the Vacuum Drying System, damage to the vacuum pump, and improper vacuum gauge calibration may cause repeated failure of the dryness verification test. These conditions should be checked as part of the corrective actions if repeated failure of the dryness verification test is occurring.

   3. Perform a HI-STAR 100 overpack Annulus Dryness Verification. The overpack annulus shall hold stable vacuum drying pressure of $\leq$ 3 torr for $\geq$ 30 minutes.

4. Attach the helium supply to the backfill tool.

5. Verify the correct pressure on the helium supply and open the helium supply valve.

6. Backfill the HI-STAR 100 overpack annulus to the pressure required by Table 1.2.3..

7. Install the overpack vent port plug and torque. See Table 7.1.3 for torque requirements.

8. Disconnect the overpack backfill tool from the vent port.

9. Flush the overpack vent port recess with compressed air to remove any standing helium gas.

Note:
The sum of the helium leak rates from the overpack penetrations (i.e. the overpack closure plate inner mechanical seal and vent and drain port plugs) shall meet the limit established in Section 8.1.3.

3. Leak test the HI-STAR 100 overpack vent and drain port plug mechanical seals as follows:

   a. Install the overpack test cover to the overpack vent port as shown on Figure 7.1.27. See Table 7.1.3 for torque requirements.

   b. Evacuate the test cavity per the MSLD manufacturer's instructions and isolate the vacuum pump from the overpack test cover.

   c. Perform a leakage rate test of overpack vent port plug using the evacuated envelope-gas detector method in accordance with the MSLD manufacturer's instructions and ANSI N14.5 [7.1.5].

   d. Remove the overpack test cover and install a new metallic seal on the overpack vent port cover plate. Discard any used metallic seals.

   e. Install the vent port cover plate and torque the bolts. See Table 7.1.3 for torque requirements.

   f. Repeat Steps a through e for the overpack drain port.

4. Leak test the overpack closure plate inner mechanical seal as follows:

   a. Attach the closure plate test tool to the closure plate test port with the and MSLD attached. See Figure 7.1.29. See Table 7.1.3 for torque requirements.

b. Evacuate the closure plate test port tool and closure plate inter-seal area per the MSLD manufacturer's instructions.

c. Perform a leakage rate test of overpack closure plate inner mechanical seal using the evacuated envelope-gas detector method in accordance with the MSLD manufacturer's instructions and ANSI N14.5 [7.1.5].

d. Remove the closure plate test tool from the test port and install the test port plug with a new mechanical seal. See Table 7.1.3 for torque requirements. Discard any used metallic seals.

5. Sum the individual leak rates for the closure plate inner mechanical seal and the vent and drain port plugs and ensure that they meet the requirements of Section 8.1.3.

6. Continue cask loading and preparation for transport as described in Section 7.1.7.

7.5 REGULATORY COMPLIANCE

7.5.1 The special controls and precautions for transport, loading and handling, and special controls in case of accident or delay have been provided and they satisfy 10CFR71.35(c) [7.0.1].

7.5.2 The radiation survey requirements of the package exterior are provided in Section 7.1.3, 7.1.7 and 7.3.2 and the requirements of 10CFR71.47 [7.0.1] will be met.

7.5.3 The temperature measurement requirements are provided in Section 7.1.7 and the limits specified in 10CFR71.43 (g) [7.0.1] will be met.

7.5.4 The routine determinations for package use prior to transport is provided in Section 7.1.7 and Section 7.3 and the requirements of 10CFR71.87 [7.0.1] will be met.

7.5.5 The procedures needed to safely open the package are provided in Section 7.2. Verification that the consignee has the appropriate procedures is given in Section 7.1.7. The requirements of 10CFR71.89 [7.0.1] are met.

7.6 REFERENCES

[7.0.1] *U.S. Code of Federal Regulations" Packaging and Transport of Radioactive Materials*," Part 71, "Energy."

[7.1.1] U.S. Nuclear Regulatory Commission, "Control of Heavy Loads at Nuclear Power Plants," NUREG-0612.

[7.1.2] Holtec International Report HI-2012610, HI-STAR 100 System Final Safety Analysis Report.

[7.1.3] *U.S. Code of Federal Regulations,* "Shippers – General Requirements for Shipments and Packages," Part 49, "*Transportation.*"

[7.1.4] *U.S. Code of Federal Regulations,* "Standards for Protection Against Radiation", Part 20, "*Energy.*"

[7.1.5] American National Standards Institute, Institute for Nuclear Materials Management, "American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment," ANSI N14.5-1987, January 1987.

[7.1.6] American Society of Mechanical Engineers "Boiler and Pressure Vessel Code".

CHAPTER 8: ACCEPTANCE CRITERIA AND MAINTENANCE PROGRAM

8.0 INTRODUCTION

This chapter identifies the fabrication, inspection, test, and maintenance programs to be conducted on the HI-STAR 100 Package to verify that the structures, systems and components (SSCs) classified as important to safety have been fabricated, assembled, inspected, tested, accepted, and maintained in accordance with the requirements set forth in this Safety Analysis Report (SAR), the applicable regulatory requirements, and the Certificate of Compliance (CoC).

The controls, inspections, and tests set forth in this chapter, in conjunction with the design requirements described in previous chapters, ensure that the HI-STAR 100 Package will maintain containment of radioactive material; will maintain subcriticality control; will properly transfer the decay heat of the contained radioactive materials; and that radiation doses will meet regulatory requirements under all normal and hypothetical accident conditions of transport in accordance with 10CFR71 [8.0.1].

Both pre-operational and operational tests and inspections are performed throughout HI-STAR 100 loading operations to assure that the HI-STAR 100 Package is functioning within its design parameters. These include receipt inspections, nondestructive weld inspections, pressure tests, radiation shielding tests, thermal performance tests, dryness tests, and others. Chapter 7 identifies the sequence of the tests and inspections. "Pre-operation", as referred to in this chapter, defines that period of time from receipt inspection of a HI-STAR 100 Package until the empty MPC is loaded into a HI-STAR overpack for fuel assembly loading.

The HI-STAR 100 Package is classified as important to safety (ITS). Therefore, the individual structures, systems, and components (SSCs) that make up the HI-STAR 100 Package shall be designed, fabricated, assembled, inspected, tested, accepted, and maintained in accordance with a quality program commensurate with the particular SSC's graded quality category. Table 1.3.3 provides the safety classification and quality category, as applicable, for each major item or component of the HI-STAR 100 Package and required ancillary equipment and systems.

The acceptance criteria and maintenance program described in this chapter fully comply with the requirements of 10CFR Part 71.

8.1 ACCEPTANCE CRITERIA

This section provides the workmanship inspections and acceptance tests to be performed on the HI-STAR 100 Package prior to or during use. These inspections and tests provide assurance that the HI-STAR 100 Package has been fabricated, assembled, inspected, tested, and accepted for use and loading under the conditions specified in this SAR and the Certificate of Compliance issued by the NRC in accordance with the requirements of 10CFR Part 71.

Noncompliances encountered during the required inspections and tests shall be corrected or dispositioned to bring the item into compliance with this SAR prior to use. Identification and resolution of noncompliances shall be performed in accordance with the Holtec International

Quality Assurance Program [8.1.1] or the licensee's NRC-approved Quality Assurance Program. The testing and inspection acceptance criteria applicable to the MPCs and the HI-STAR overpack are listed in Tables 8.1.1 and 8.1.2, respectively, and discussed in more detail in the sections that follow. These inspections and tests are intended to demonstrate that the HI-STAR 100 Package has been fabricated, assembled, and examined in accordance with the design evaluated in this SAR.

This section summarizes the test program established for the HI-STAR 100 Package.

8.1.1 Fabrication and Nondestructive Examination (NDE)

The design, material procurement, fabrication, and inspection of the HI-STAR 100 Package is performed in accordance with applicable codes and standards, including NRC-approved alternatives to the ASME Code, as specified in Tables 1.3.1 and 1.3.2, respectively, and on the drawings in Section 1.4. Additional details on specific codes used are provided below.

The following fabrication controls and required inspections shall be performed on the HI-STAR 100 Package, including the MPCs, in order to assure compliance with this SAR and the Certificate of Compliance.

1. Materials of construction specified for the HI-STAR 100 Package are identified in the drawings in Chapter 1. Important-to-safety materials shall be procured with certification and supporting documentation as required by ASME Code [8.1.2] Section II (when applicable); the applicable subsection of ASME Code Section III (when applicable); Holtec procurement specifications; and 10CFR71, Subpart H. Materials and components shall be receipt inspected for visual and dimensional acceptability, material conformance to specification requirements, and traceability markings, as applicable. Controls shall be in place to assure material traceability is maintained throughout fabrication for ITS items. Materials for the primary containment boundary of the HI-STAR overpack (bottom plate, inner shell, top flange, closure plate, port plugs, and closure plate bolts) and for the secondary containment boundary provided by the MPC (for the MPC-24EF and MPC-68F), shall also be inspected per the requirements of ASME Section III, Article NB-2500 Subsection NB.

2. The HI-STAR 100 Package primary containment boundary and the MPC (secondary containment boundary for MPC-24EF and MPC-68F) shall be fabricated and inspected in accordance with ASME Code Section III, Subsection NB (see approved Code alternatives in Table 1.3.2). Other portions of the HI-STAR 100 Package shall be fabricated and inspected in accordance with ASME Code Section III, Subsection NF (see approved Code alternatives in Table 1.3.2). The MPC basket and certain basket supports shall be fabricated and inspected in accordance with ASME Code Section III, Subsection NG (see Tables 1.3.1, 1.3.2, and 1.3.3 for Code applicability and approved Code alternatives).

3. Welding shall be performed using welders and weld procedures that have been qualified in accordance with ASME Code Section IX and the applicable ASME Section III Subsections (e.g., NB, NG, or NF, as applicable to the SSC).

4. Welds shall be visually examined in accordance with ASME Code Section V, Article 9 with acceptance criteria per ASME Code Section III, Subsection NF, Article NF-5360, except the MPC fuel basket cell plate-to-cell plate welds and fuel basket support-to-canister welds, which shall have acceptance criteria to ASME Code Section III, Subsection NG, Article NG-5360, except as clarified by the Code alternatives in Table 1.3.2. Table 8.1.3 identifies additional nondestructive examination (NDE) requirements to be performed on specific welds, and the applicable codes and acceptance criteria to be used in order to meet the requirements of the applicable portions of Section III of the ASME Code. Acceptance criteria for NDE shall be in accordance with the applicable Code for which the item was fabricated, except as modified by the Code alternatives in Table 1.3.2. These additional NDE criteria are also specified in the drawings provided in Chapter 1 for the specific welds. Weld inspections shall be detailed in a weld inspection plan that identifies the weld and the examination requirements, the sequence of examination, and the acceptance criteria. The inspection plan shall be reviewed and approved by Holtec International in accordance with its QA program. NDE inspections shall be performed in accordance with written and approved procedures by personnel qualified in accordance with SNT-TC-1A [8.1.3] or other site-specific, NRC-approved program for personnel qualification.

5. The HI-STAR 100 containment boundary shall be visually examined in accordance with ASME Code Section V, Article 9, to verify that each packaging is free of cracks, pin holes, uncontrolled voids, or other defects that could significantly reduce its effectiveness.

6. Any welds requiring weld repair shall be repaired in accordance with the requirements of the ASME Code Section III, Article NB-4450, NG-4450, or NF-4450, as applicable to the SSC, and examined after repair in the same manner as the original weld.

7. Any base metal repairs shall be performed and examined in accordance with the applicable fabrication Code.

8. Grinding and machining operations of the HI-STAR 100 overpack primary containment boundary and the MPC shall be controlled through written and approved procedures and quality assurance oversight to ensure grinding and machining operations do not reduce base metal wall thicknesses of the boundaries beyond that allowed by the design. The thicknesses of base metals shall be ultrasonically tested, as necessary, in accordance with written and approved procedures to verify base metal thickness meets design requirements. A nonconformance shall be written for areas found to be below allowable base metal

thickness and shall be evaluated and repaired as necessary per the ASME Code Section III, Subsection NB requirements.

9. Dimensional inspections of the HI-STAR 100 Package shall be performed in accordance with written and approved procedures in order to verify compliance to design drawings and fit-up of individual components. All dimensional inspections and functional fit-up tests shall be documented.

10. All required inspections, examinations, and tests shall be documented. The inspection, examination, and test documentation shall become part of the final quality documentation package.

11. The HI-STAR 100 Package shall be inspected for cleanliness and proper preparation for shipping in accordance with written and approved procedures.

12. Each HI-STAR overpack shall be durably marked with the CoC identification number assigned by the NRC, trefoil radiation symbol, gross weight, model number, and unique identification serial number in accordance with 10CFR71.85(c) at the completion of the acceptance test program.

13. Deleted.

14. A completed quality documentation record package shall be prepared and maintained during fabrication of each HI-STAR 100 Package to include detailed records and evidence that the required inspections and tests have been performed for ITS items. The quality document record package shall be reviewed to verify that the HI-STAR 100 Package or component has been properly fabricated and inspected in accordance with the design and Code construction requirements. The quality documentation record package shall include, but not be limited to:

- Completed Weld Records
- Inspection Records
- Nonconformance Reports
- Material Test Reports
- NDE Reports
- Dimensional Inspection Reports

8.1.1.1 MPC Lid-to-Shell Weld Volumetric Inspection

1. The MPC lid-to-shell (LTS) weld (the confinement boundary closure per 10CFR72, and secondary containment (inner container) boundary per 10CFR71 for the MPC-68F and MPC-24EF) shall be volumetrically or multi-layer liquid penetrant examined following completion of field welding. If volumetric examination is used, the ultrasonic test (UT) method shall be employed. Ultrasonic techniques (including, as appropriate, Time-of-Flight Diffraction,

Focussed Phased Array, and conventional pulse-echo) shall be supplemented, as necessary, to ensure substantially complete coverage of the examination volume.

2. If volumetric examination is used, then a liquid penetrant (PT) examination of the root and final pass of the LTS weld shall be performed and unacceptable indications shall be documented, repaired and re-examined.

3. If a volumetric examination is not used, a multi-layer PT examination shall be employed. The multi-layer PT must, at a minimum, include the root and final weld layers and one intermediate PT after each approximately 3/8 inch weld depth has been completed. The 3/8-inch weld depth corresponds to the maximum allowable flaw size.

4. The overall minimum thickness of the LTS weld has been increased by 0.125 inch over the size credited in the structural analyses to provide additional structural capacity (actual weld to be 0.75 inch for the standard MPC model and 1.25 inches for the "F" model). A J-groove weld 1/8" less was assumed in the structural analyses in Chapter 2.

5. For either UT or PT, the maximum undetectable flaw size must be demonstrated to be less than the critical flaw size. The critical flaw size must be determined in accordance with ASME Section XI methods. The critical flaw size shall not cause the primary stress limits of NB-3000 to be exceeded. The inspection process, including findings (indications) shall be made a permanent part of the user's records by video, photographic, or other means which provide an equivalent retrievable record of weld integrity. The video or photographic records should be taken during the final interpretation period described in ASME Section V, Article 6, T-676. The inspection of the weld shall be performed by qualified personnel and shall meet the acceptance requirements of ASME Section III, NB-5350 for PT and NB-5332 for UT.

6. Evaluation of any indications shall include consideration of any active flaw mechanisms. However, cyclic loading on the LTS weld is not significant, so fatigue will not be a factor. The LTS weld is protected from the external environment by the closure ring and the root of the LTS weld is dry and inert (He atmosphere), so stress corrosion cracking is not a concern for the LTS weld.

7. The volumetric or multi-layer PT examination of the LTS weld, in conjunction with other examinations that will be performed on this weld (PT of root and final pass, pressure test, and helium leakage test); the use of the ASME Code Section III acceptance criteria; and the additional 1/8th-inch of weld material conservatively not credited in the structural analyses, in total, provide reasonable assurance that the LTS weld is sound and will perform its secondary containment boundary function under all loading conditions. The volumetric (or multi-layer PT) examination and evaluation of indications provides reasonable assurance that

leakage of the weld or structural failure under normal or hypothetical accident conditions of transport will not occur.

8.1.2 Structural and Pressure Tests

8.1.2.1 Lifting Trunnions

Two trunnions (located near the top of the HI-STAR overpack) are provided for vertical lifting and handling of the HI-STAR 100 Package without the impact limiters installed. The trunnions are designed and shall be inspected and tested in accordance with ANSI N14.6 [8.1.5]. The trunnions are fabricated using a high-strength and high-ductility material (see overpack drawing in Section 1.4). The trunnions contain no welded components. The maximum design lifting load of 250,000 pounds for the HI-STAR 100 Package will occur during the removal of the HI-STAR overpack from the spent fuel pool after the MPC has been loaded, flooded with water, and the MPC lid is installed. The high material ductility, absence of materials vulnerable to brittle fracture, excellent stress margins, and a carefully engineered design to eliminate local stress risers in the highly-stressed regions (during lift operations) ensure that the lifting trunnions will work reliably. However, pursuant to the defense-in-depth approach of NUREG-0612 [8.1.6], acceptance criteria for the lifting trunnions have been established in conjunction with other considerations applicable to heavy load handling.

Section 5 of NUREG-0612 calls for measures to "provide an adequate defense-in-depth for handling of heavy loads...". The NUREG-0612 guidelines cite four major causes of load handling accidents, of which rigging failure (including trunnion failure) is one:

i. operator errors
ii. rigging failure
iii. lack of adequate inspection
iv. inadequate procedures

The cask loading and handling operations program shall ensure maximum emphasis to minimize the potential of load drop accidents by implementing measures to eliminate shortcomings in all aspects of the operation including the four aforementioned areas.

In order to ensure that the lifting trunnions do not have any hidden material flaws, the trunnions shall be tested at 300% of the maximum design (service) lifting load. The load (750,000 lbs) shall be applied for a minimum of 10 minutes to the pair of lifting trunnions. The accessible parts of the trunnions (areas outside the HI-STAR overpack), and the local HI-STAR 100 cask areas shall then be visually examined to verify no deformation, distortion, or cracking has occurred. Any evidence of deformation, distortion or cracking of the trunnion or adjacent HI-STAR 100 cask areas shall require replacement of the trunnion and/or repair of the HI-STAR 100 cask. Following any replacements and/or repair, the load testing shall be re-performed and the components re-examined in accordance with the original procedure and acceptance criteria. Testing shall be performed in accordance with written and approved procedures. Certified material test reports verifying trunnion material mechanical properties meet ASME Code Section

II requirements provide further verification of the trunnion load capabilities. Test results shall be documented and shall become part of the final quality documentation package.

The acceptance testing of the trunnions in the manner described above provide reasonable assurance that a handling accidents will not occur due to trunnion failure.

8.1.2.2 Pressure Testing

8.1.2.2.1 HI-STAR 100 Containment Boundary

The containment boundary of the HI-STAR Package shall be hydrostatically or pneumatically pressure tested to 150 psig +10,-0 psig, in accordance with the requirements of the ASME Code Section III, Subsection NB, Article NB-6000. The test pressure of 150 psig is 150% of the Maximum Normal Operating Pressure (established per 10CFR71.85(b) requirements). This bounds the ASME Code Section III requirement (NB-6221) for hydrostatic testing to 125% of the design pressure (100 psig). The test shall be performed in accordance with written and approved procedures. The written and approved test procedure shall clearly define the test equipment arrangement.

The overpack pressure test may be performed at any time during fabrication after the containment boundary is complete. Preferably, the pressure test should be performed after overpack fabrication is complete, including attachment of the intermediate shells. The HI-STAR overpack shall be assembled for this test with the closure plate mechanical seal (only one required) or temporary test seal installed. Closure bolts shall be installed and torqued to a value less than or equal to the value specified in Table 7.1.3.

The calibrated test pressure gage installed on the overpack shall have an upper limit of approximately twice that of the test pressure. The test pressure shall be maintained for ten minutes. During this time period, the pressure gauge reading shall not fall below 150 psig. At the end of ten minutes, and while the pressure is being maintained at a minimum of 150 psig, the overpack shall be observed for leakage. In particular, the closure plate-to-top forging joint (the only credible leakage point) shall be examined. If a leak is discovered, the overpack shall be emptied and an evaluation shall be performed to determine the cause of the leakage. Repairs and retest shall be performed until the pressure test acceptance criterion is met.

After completion of the pressure testing, the overpack closure plate shall be removed and the internal surfaces shall be visually examined for cracking or deformation. Any evidence of cracking or deformation shall be cause for rejection or repair and retest, as applicable. The overpack shall be required to be pressure tested until the examinations are found to be acceptable.

Test results shall be documented and shall become part of the final quality documentation package.

8.1.2.2.2 MPC Secondary Containment Boundary

Pressure testing (hydrostatic or pneumatic) of the MPC secondary containment boundary shall be performed in accordance with the requirements of the ASME Code Section III, Subsection NB, Article NB-6000 and applicable sub-articles, when field welding of the MPC lid-to-shell weld is completed. If hydrostatic testing is used, the MPC shall be pressure tested to 125% of design pressure. If pneumatic testing is used, the MPC shall be pressure tested to 120% of the design pressure. The MPC vent and drain ports are used for pressurizing the MPC cavity. The loading procedures in Chapter 7 define the test equipment arrangement. The calibrated test pressure gage installed on the MPC pressure boundary shall have an upper limit of approximately twice that of the test pressure. Following completion of the required hold period at the test pressure, and after determining the leakage acceptance criterion is met, the surface of the MPC lid-to-shell weld shall be re-examined by liquid penetrant examination performed in accordance with ASME Code Section V, Article 6, with acceptance criteria per ASME Code Section III, Subsection NB, Article NB-5350. Any unacceptable areas shall require repair in accordance with the ASME Code Section III, Subsection NB, Article NB-4450. Any evidence of cracking or deformation shall be cause for rejection, or repair and retest, as applicable. The performance and sequence of the test is described in Section 7.1 (loading procedures).

If a leak is discovered, the test pressure shall be reduced, the MPC cavity water level lowered, if applicable, the MPC cavity vented, and the weld shall be examined to determine the cause of the leakage and/or cracking. Repairs to the weld shall be performed in accordance with approved written procedures prepared in accordance with the ASME Code Section III, Subsection NB, NB-4450.

The MPC pressure boundary pressure test shall be repeated until all required examinations are found to be acceptable. Test results shall be documented and shall be maintained as part of the loaded MPC quality documentation package.

8.1.2.3 Materials Testing

The majority of materials used in the HI-STAR overpack are ferritic steels. ASME Code Section III and Regulatory Guides 7.11 [8.1.7] and 7.12 [8.1.8] require that certain materials be tested in order to assure that these materials are not subject to brittle fracture failures.

Each plate or forging for the HI-STAR 100 Package containment boundary (overpack inner shell, bottom plate, top flange, and closure plate) shall be required to be drop weight tested in accordance with the requirements of Regulatory Guides 7.11 and 7.12, as applicable. Additionally, per the ASME Code Section III, Subsection NB, Article NB-2300, Charpy V-notch testing shall be performed on these materials. Weld material used in welding the containment boundary shall be Charpy V-notch tested in accordance with ASME Section III, Subsection NB, Articles NB-2300 and NB-2430.

Non-containment portions of the overpack, as required, shall be Charpy V-notch tested in accordance with ASME Section III, Subsection NF, Articles NF-2300, and NF-2430. The non-containment materials to be tested include the intermediate shells, overpack port cover plates, and applicable weld materials.

Tables 2.1.22 and 2.1.23 provide the test temperatures or T_{NDT}, and test requirements to be used when performing the testing specified above.

Test results shall be documented and shall become part of the final quality documentation record package.

8.1.2.4 Pneumatic Testing of the Neutron Shield Enclosure Vessel

A pneumatic pressure test of the neutron shield enclosure vessel shall be performed following final closure welding of the enclosure shell returns and enclosure panels. The pneumatic test pressure shall be 37.5+2.5,-0 psig, which is 125 percent of the relief device set pressure. The test shall be performed in accordance with approved written procedures.

During the test, the relief devices on the neutron shield enclosure vessel shall be removed. One of the relief device threaded connections is used for connection of the air pressure line and the other connection will be used for connection of the pressure gauge.

Following the introduction of pressurized gas into the neutron shield enclosure vessel, a 15 minute pressure hold time is required. If the neutron shield enclosure vessel fails to hold pressure, an approved soap bubble solution shall be applied to determine the location of the leak. The leak shall be repaired using weld repair procedures prepared in accordance with the ASME Code Section III, Subsection NF, Article NF-4450. The pneumatic pressure test shall be re-performed until no pressure loss is observed.

Test results shall be documented and shall become part of the final quality documentation package.

8.1.3 Leakage Testing

Leakage testing shall be performed in accordance with the requirements of ANSI N14.5 [8.1.9]. Testing shall be performed in accordance with written and approved procedures.

8.1.3.1 HI-STAR Overpack

A Containment System Fabrication Verification Leakage test of the welded structure shall be performed at any time after the containment boundary fabrication is complete. Preferably, this test should be performed at the completion of overpack fabrication, after all intermediate shells have been attached. The leakage test instrumentation shall have a minimum test sensitivity of 2.15×10^{-6} atm cm^3/s (helium). Containment boundary welds shall have indicated leakage rates not exceeding 4.3×10^{-6} atm cm^3/s (helium). If a leakage rate exceeding the acceptance criterion is detected, the area of leakage shall be determined using the sniffer probe method or other

means, and the area shall be repaired per ASME Code Section III, Subsection NB, NB-4450 requirements. Following repair and appropriate NDE, the leakage testing shall be re-performed until the test acceptance criterion is satisfied.

At the completion of overpack fabrication, the total helium leakage through all helium retention penetrations (consisting of the inner mechanical seal between the closure plate and the top flange and the vent and drain port plug seals) shall be demonstrated to not exceed the leakage rate of 4.3×10^{-6} atm cm^3/sec (helium) at a minimum test sensitivity of 2.15×10^{-6} atm cm^3/sec (helium). This may be performed simultaneously with the Containment System Fabrication Verification Leakage test or may be performed separately using the methods described in the paragraph below.

At the completion of fabrication, a Containment System Fabrication Verification Leakage test shall be performed on the HI-STAR overpack closures. Helium leakage through the containment penetrations (consisting of the inner mechanical seal between the closure plate and top flange, and the vent and drain port plug seals) shall be demonstrated to not exceed a leakage rate of 4.3×10^{-6} atm cm^3/s (helium) at a minimum test sensitivity of 2.15×10^{-6} atm cm^3/s (helium).

The leakage testing of the penetrations is performed by evacuating and backfilling the overpack with helium gas to an appropriate pressure. A helium Mass Spectrometer Leak Detector (MSLD) with a minimum calibrated sensitivity of 2.15×10^{-6} atm cm^3/s (helium) shall be used in parallel with a vacuum pump and a test cover (see Chapter 7 for details) designed for testing the penetration seals. The test cover is connected. The cavity on the external side of the port plug to be tested is evacuated and the vacuum pump is valved out. The MSLD detector measures the leakage rate of helium into the test cavity. If the leakage rate exceeds a leakage rate of 4.3×10^{-6} atm cm^3/s (helium), the test chamber is vented and removed. The corresponding plug seal is removed, seal seating surfaces are inspected and cleaned, and the plug with a new seal is reinstalled and torqued to the required value. The test process is then repeated until the seal leakage rate is successfully achieved. The same process is repeated for the remaining overpack vent or drain port. The process is used for the closure plate seals except the closure plate test tool (see Chapter 7 for details) is used in lieu of the test cover.

If the total measured leakage rate for all tested penetrations does not exceed 4.3×10^{-6} atm cm^3/sec, the leakage tests are successful. If the total leakage rate exceeds 4.3×10^{-6} atm cm^3/sec, an evaluation should be performed to determine the cause of the leakage, repairs made as necessary, and the overpack must be re-tested until the total leakage rate is within the required acceptance criterion. Leak testing results for the HI-STAR overpack shall become part of the quality record documentation record package.

8.1.3.2 MPC Secondary Containment Boundary

After the completion of welding the MPC shell to the baseplate, a confinement boundary weld leakage test shall be performed using a helium MSLD as described in Chapter 7.. These leakage tests are performed on all MPCs as a good practice to confirm the CoC leakage rate limits are not exceeded. However, the MPC only performs a secondary containment function for MPC-68F and MPC-24EF, which transport fuel debris. The MPC leakage test used to demonstrate compliance

with the CoC leakage acceptance criterion for MPC-68F and MPC-24EF is performed prior to shipment as later in this section. The pressure boundary welds of the MPC canisters shall have indicated leakage rates not exceeding 5×10^{-6} atm cm^3/s (helium) with a minimum test sensitivity of 2.5×10^{-6} atm cm^3/sec (helium). If leakage rates exceeding the test criteria are detected, then the area of leakage shall be determined and the area repaired per ASME Code Section III, Subsection NB, NB-4450, requirements. Re-testing of the MPC shall be performed until the leakage rate acceptance criterion is met.

Leakage testing of the field welded MPC lid-to-shell weld shall be performed following completion of the MPC pressure test performed per Subsection 8.1.2.2.2. Leakage testing of the vent and drain port cover plate welds shall be performed after welding of the cover plates and subsequent NDE. The description and procedures for these field tests are provided in Section 7.1.

All leak testing results for the MPC shall be documented and shall become part of the quality record documentation package.

Prior to the transport of an MPC-68F or MPC-24EF containing fuel debris in the HI-STAR 100 Package, a Containment Fabrication Verification Leakage Test shall be performed on the secondary containment boundary of the MPC. The test is performed with the MPC loaded into the HI-STAR overpack. The HI-STAR overpack annulus is sampled to inspect for radioactive material and then evacuated to an appropriate vacuum condition. The HI-STAR overpack annulus is then isolated from the vacuum pump. Following an appropriate isolation period, the HI-STAR overpack annulus atmosphere is sampled for helium leakage from the MPC. The test is considered acceptable if the detected leakage from the MPC does not exceed 5×10^{-6} atm cm^3/s (helium) with a test sensitivity of 2.5×10^{-6} atm cm^3/s (helium). If the acceptance criterion is not met, transport of the MPC-68F or MPC-24EF is not authorized. Corrective actions from re-testing, up to and including off-loading of the MPC, shall be taken until the leakage rate acceptance criterion is met.

8.1.4 Component Tests

8.1.4.1 Valves, Relief Devices, and Fluid Transport Devices

There are no fluid transport devices associated with the HI-STAR 100 Package. The only valve-like components in the HI-STAR 100 Package are the specially designed caps installed in the MPC lid for the drain and vent ports. These caps are recessed inside the MPC lid and covered by the fully-welded vent and drain port cover plates. No credit is taken for the caps' ability to confine helium or radioactivity. After completion of drying and backfill operations, the drain and vent port cover plates are welded in place on the MPC lid and are leak tested to verify the MPC secondary containment (MPC-68F and MPC-24EF) boundary.

The vent and drain ports in the HI-STAR overpack are accessed through port plugs specially designed for removal and installation using connector tools. The tools are described and presented in figures in Chapter 7.

There are two relief devices (e.g., rupture discs) installed in the upper ledge surface of the neutron shield enclosure vessel of the HI-STAR overpack. These relief devices are provided for venting purposes under hypothetical fire accident conditions in which vapor formation from neutron shielding material degradation may occur. The relief devices are designed to relieve at 30 psig (± 5 psig).

8.1.4.2 Seals and Gaskets

Two concentric mechanical seals are provided on the HI-STAR overpack closure plate to provide containment boundary sealing. Mechanical seals are also used on the overpack vent and drain port plugs of the HI-STAR overpack containment boundary. Each primary seal is individually leak tested in accordance with Subsection 8.1.3.1. prior to the HI-STAR 100 Package's first use and during each loading operation. An independent and redundant seal is provided for each penetration (e.g., closure plate, port cover plates, and closure plate test plug). No containment credit is taken for these redundant seals and they are not leakage tested. Details on these seals are provided in Chapter 4.

8.1.4.3 Transport Impact Limiter

The removable HI-STAR transport impact limiters consist of aluminum honeycomb crush material arranged around a carbon steel structure and enclosed by a stainless steel shell. The drawings in Chapter 1 specify the crush strength of the aluminum honeycomb materials (nominal +/- 7%) for each zone of the impact limiter. For manufacturing purposes, verification of the impact limiter material is accomplished by performance of a crush test of sample blocks of aluminum honeycomb material for each large block manufactured. The verification tests are performed by the aluminum honeycomb supplier in accordance with approved procedures. The certified test results shall be submitted to Holtec International with each shipment.

All welds on the HI-STAR impact limiter shall be visually examined in accordance with the ASME Code, Section V, Article 9, with acceptance criteria per ASME Section III, Subsection NF, Article NF-5360.

8.1.5 Shielding Integrity

The HI-STAR 100 System has three specifically designed shields for neutron and gamma ray attenuation. For gamma shielding, there are successive carbon steel intermediate shells attached onto the outer surface of the overpack inner shell. The details of the manufacturing process are discussed in Chapter 1. Holtite-A neutron shielding is provided in the outer enclosure of the overpack. Additional neutron attenuation is provided by the encased Boral neutron absorber attached to the fuel basket cell surfaces inside the MPCs. Test requirements for each of the three shielding items are described below.

8.1.5.1 Fabrication Testing and Controls

Holtite-A:

Neutron shield properties of Holtite-A are provided in Chapter 1. Each manufactured lot of neutron shield material shall be tested to verify that the material composition (aluminum and hydrogen), boron concentration, and neutron shield density (or specific gravity) meet the requirements specified in Chapter 1. A manufactured lot is defined as the total amount of material used to make any number of mixed batches comprised of constituent ingredients from the same lot/batch identification numbers supplied by the constituent manufacturer. Testing shall be performed in accordance with written and approved procedures and/or standards. Material composition, boron concentration, and density (or specific gravity) data for each manufactured lot of neutron shield material shall become part of the quality record documentation package.

The installation of the neutron shielding material shall be performed in accordance with written, approved, and qualified procedures. The procedures shall ensure that mix ratios and mixing methods are controlled in order to achieve proper material composition, boron concentration and distribution, and that pours are controlled in order to prevent gaps or voids from occurring in the material. Samples of each manufactured lot of neutron shield material shall be maintained by Holtec International.

Steel:

The steel plates utilized in the construction of the HI-STAR 100 Package shall be dimensionally inspected to assure compliance with the drawings in Section 1.4.

The total measured thickness of the inner shell plus intermediate shells shall be nominally 8.5 inches over the total surface area of the overpack shell. The top flange, closure plate, and bottom plate of the overpack shall be measured to confirm their thicknesses meet drawing requirements of Section 1.4. Measurements shall be performed in accordance with written and approved procedures. Measurements shall be made through a combination of receipt inspection thickness measurements on individual plates and actual measurements taken prior to welding the forgings and shells. Any area found to be under the specified minimum thickness shall be repaired in accordance with applicable ASME Code requirements.

No additional gamma shield testing of the HI-STAR 100 Package is required. A shielding effectiveness test as described in Subsection 8.1.5.2 shall be performed on each fabricated HI-STAR 100 Package after the first fuel loading.

General Requirements for Shield Materials:

1. Test results shall be documented and become part of the quality documentation package.

2. Dimensional inspections of the cavities containing poured neutron shielding materials shall assure that the amount of shielding material specified in the design documents is incorporated into the fabricated item.

8.1.5.2 Shielding Effectiveness Tests

Users shall implement procedures which verify the integrity of the Holtite-A neutron shield once for each overpack. Neutron shield integrity shall be verified via measurements either at first use or with a check source using, at a maximum, a 6x6 inch test grid over the entire surface of the neutron shield, including the impact limiters.

Following the first fuel loading of each HI-STAR 100 Package, a shielding effectiveness test shall be performed to verify the effectiveness of the neutron shield. This test shall be performed either with a check source or with loaded contents. If the test is performed using loaded contents, the test shall be performed after the HI-STAR 100 Package has been, drained, sealed, and backfilled with helium.

The shielding effectiveness tests shall be performed using written and approved procedures. Calibrated radiation detection equipment shall be used to take measurements at the surface of the HI-STAR overpack. Measurements shall be taken at three cross sectional planes through the radial shield and at four points along each plane's circumference. Measurements shall be documented and become part of the quality documentation package. The average measurement results from each sectional plane shall be compared to calculated values to assess the continued effectiveness of the neutron shield. The calculated values shall be representative of the loaded contents (i.e., fuel type, enrichment, burnup, cooling time, etc.) or the particular check source used for the measurements.

8.1.5.3 Neutron Absorber Tests

Each plate of Boral shall be visually inspected by the manufacturer for damage (e.g., scratches, cracks, burrs, and peeled cladding) and foreign material embedded in the surfaces. In addition, the MPC fabricator shall visually inspect the Boral plates on a lot sampling basis. The sample size shall be determined in accordance with MIL-STD-105D or equivalent. The selected Boral plates shall be inspected for damage such as inclusions, cracks, voids, delamination, and surface finish.

After manufacturing, a statistical sample of each lot of Boral shall be tested using wet chemistry and/or neutron attenuation techniques to verify a minimum ^{10}B content at the ends of the panel. The minimum ^{10}B loading of the Boral panels for each MPC model is provided in Table 1.2.3 Any panel in which ^{10}B loading is less than the minimum allowed per the drawings in Section 1.4 shall be rejected.

Tests shall be performed using written and approved procedures. Results shall be documented and become part of the quality records documentation package.

Installation of Boral panels into the fuel basket shall be performed in accordance with written and approved procedures (or shop travelers). Travelers and/or quality control procedures shall be in place to assure each required cell wall of the MPC basket contains a Boral panel in accordance with the drawings in Section 1.4. These quality control processes, in conjunction with Boral manufacturing testing, provide the necessary assurances that the Boral will perform its intended function. The criticality design for the HI-STAR 100 System is based on favorable geometry and fixed neutron poisons. The inert helium environment inside the MPC cavity where the Boral is located ensures that the poisons will remain effective for the life of the canister. Given the design and service conditions, there are no credible means to lose the fixed neutron poisons. Therefore, no additional testing is required to ensure the Boral is present and in proper condition per 10 CFR 71.87(g).

8.1.6 Thermal Acceptance Test

The first fabricated HI-STAR overpack shall be tested to confirm its heat transfer capability. The test shall be conducted after the radial channels, enclosure shell panels, and neutron shield material have been installed and all inside and outside surfaces are painted per the drawings in Section 1.4. A test cover plate shall be used to seal the overpack cavity. Testing shall be performed in accordance with written and approved procedures.

Steam heating of the overpack cavity surfaces is the preferred method for this test instead of electric heating. There are several advantages with steam heated testing as listed below:

(i) Uniform cavity surface temperatures are readily achieved as a result of high steam condensation heat transfer coefficient (about 2,000 Btu/ft^2 hr-°F compared to about 1 Btu/ft^2 hr-°F for air) coupled with the steam's uniform distribution throughout the cavity.

(ii) A reliable constant temperature source (steam at atmospheric pressure condenses at 212°F compared to variable heater surface temperatures in excess of 1,000°F) eliminates concerns of overpack cavity surface overheating.

(iii) Interpretation of isothermal test data is not susceptible to errors associated with electric heating systems due to heat input measurement uncertainties, leakage of heat from electrical cables, thermocouple wires, overpack lid, bottom baseplate, etc.

(iv) The test setup is simple requiring only a steam inlet source and drain compared to numerous power measurement and control instruments, switchgear and safety interlocks required to operate an electric heater assembly.

Twelve (12) calibrated thermocouples shall be installed on the external walls of the overpack as shown in Figure 8.1.2. Three calibrated thermocouples shall be installed on the internal walls of the overpack in locations to be determined by procedure. Additional temperature sensors shall be used to monitor ambient temperature, steam supply temperature, and condensate drain temperature. The thermocouples shall be attached to strip chart recorders or other similar mechanism to allow for continuous monitoring and recording of temperatures during the test. Instrumentation shall be installed to monitor overpack cavity internal pressure.

After the thermocouples have been installed, dry steam will be introduced through an opening in the test cover plate previously installed on the overpack and the test initiated. Temperatures of the thermocouples, plus ambient, steam supply, and condensate drain temperature shall be recorded at hourly intervals until thermal equilibrium is reached. Appropriate criteria defining when thermal equilibrium is achieved shall be determined based on a variety of potential ambient test conditions and incorporated into the test procedure. In general, thermal equilibrium is expected approximately 12 hours after the start of steam heating. Air will be purged from the overpack cavity via venting during the heatup cycle. During the test, the steam condensate flowing out of the overpack drain shall be collected and the mass of the condensate measured with a precision weighing instrument.

Once thermal equilibrium is established, the final ambient, steam supply, and condensate drain temperatures and temperatures at each of the thermocouples shall be recorded. The strip charts, hand-written logs, or other similar readout shall be marked to show the point when thermal equilibrium was established and final test measurements were recorded. The final test readings along with the hourly data inputs and strip charts (or other similar mechanism) shall become part of the quality records documentation package for the HI-STAR 100 Package.

The heat rejection capability of the overpack at test conditions shall be computed using the following formula:

$$Q_{hm} = (h_1 - h_2)\, m_c \qquad (8\text{-}1)$$

Where:

Q_{hm} = Heat rejection rate of the overpack (Btu/hr)

h_1 = Enthalpy of steam entering the overpack cavity (Btu/lbm)

h_2 = Enthalpy of condensate leaving the overpack cavity (Btu/lbm)

m_c = Average rate of condensate flow measured during thermal equilibrium conditions (lbm/hr)

Based on the HI-STAR 100 overpack thermal model, a design basis minimum heat rejection capacity (Q_{hd}) shall be computed at the measured test conditions (i.e., steam temperature in the overpack cavity and ambient air temperature). The thermal test shall be considered acceptable if the measured heat rejection capability is greater than the design basis minimum heat rejection capacity ($Q_{hm} > Q_{hd}$).

The summary of reference ambient inputs that define the thermal test environment are provided in Table 8.1.4. In Figure 8.1.3, a steady-state temperature contour plot of a steam heated overpack is provided based on the thermal analysis methodology described in SAR Chapter 3. Transient heating of the overpack is also determined to establish the time required to approach (within 2° F) the equilibrium temperatures. The surface temperature plot shown in Figure 8.1.4 demonstrates that a 12-hour steam heating time is adequate to closely approach the equilibrium condition.

If the acceptance criteria above are not met, then the HI-STAR 100 Package shall not be accepted until the root cause is determined, appropriate corrective actions are completed, and the overpack is re-tested with acceptable results.

Test results shall be documented and shall become part of the quality record documentation package.

8.1.7 Cask Identification

Each HI-STAR 100 Package shall be provided with unique identification plates with appropriate markings per 10CFR71.85(c) and 10CFR72.236(k). The identification plates shall not be installed until each HI-STAR 100 Package component has completed the fabrication acceptance test program and been accepted by authorized Holtec International personnel. A unique identifying serial number shall also be stamped on the MPC to provide traceability back to the MPC specific quality records documentation package.

Table 8.1.1

MPC INSPECTION AND TEST ACCEPTANCE CRITERIA

Function	Fabrication	Pre-operation	Maintenance and Operations
Visual Inspection and Nondestructive Examination (NDE)	a) Examination of MPC components per ASME Code Section III, Subsections NB, NF, and NG, , per NB-5300, NF-5300, and NG-5300, as applicable. b) A dimensional inspection of the fuel basket assembly and canister shall be performed to verify compliance with design requirements. c) A dimensional inspection of the MPC lid and MPC closure ring shall be performed prior to inserting into the canister shell to verify compliance with design requirements. d) NDE of weldments are defined on the drawings using standard American Welding Society NDE symbols and/or notations. e) Cleanliness of the MPC shall be verified upon completion of fabrication. f) The packaging of the MPC at the completion of fabrication shall be verified prior to shipment.	a) The MPC shall be visually inspected prior to placement in service at the licensee's facility. b) MPC protection at the licensee's facility shall be verified. c) MPC cleanliness and exclusion of foreign material shall be verified prior to placing in the spent fuel pool.	a) None.

Table 8.1.1 (continued)

MPC INSPECTION AND TEST ACCEPTANCE CRITERIA

Function	Fabrication	Pre-operation	Maintenance and Operations
Structural	a) Assembly and welding of MPC components shall be performed per ASME Code Section IX and III, Subsections NB, NF, and NG, as applicable. b) Materials analysis (steel, Boral, etc.), shall be performed and records shall be kept in a manner commensurate with "important to safety" classifications.	a) None.	a) An ultrasonic (UT) examination or multi-layer liquid penetrant (PT) examination of the MPC lid-to-shell weld shall be performed per ASME Section V, Article 5 (or ASME Section V, Article 2). Acceptance criteria for the examination are defined in Subsection 8.1.1.1. b) ASME Code NB-6000 pressure test shall be performed after MPC closure welding. Acceptance criteria are defined in Subsection 8.1.2.2.2.
Leak Tests	a) Helium leak rate testing shall be performed on all MPC pressure boundary shop welds.	a) None.	a) Helium leak rate testing shall be performed on MPC lid-to-shell, and vent and drain ports-to-MPC lid field welds after closure welding. Acceptance criteria are defined in Subsection 8.1.3.2. b) A Containment System Fabrication Verification Leakage Test shall be performed on the MPC-68F and MPC-24EF prior to the transport of the HI-STAR 100 Package containing fuel debris. Acceptance criteria are defined in Subsection 8.1.3.2.

Table 8.1.1 (continued)

MPC INSPECTION AND TEST ACCEPTANCE CRITERIA

Function	Fabrication	Pre-operation	Maintenance and Operations
Criticality Safety	a) The boron content shall be verified at the time of neutron absorber material manufacture. b) The installation of Boral panels into MPC basket plates shall be verified by inspection.	a) None.	a) None.
Shielding Integrity	a) Material compliance shall be verified through CMTRs. b) Dimensional verification of MPC lid thickness shall be performed.	a) None.	a) None.
Thermal Acceptance	a) None.	a) None.	a) None.
Fit-Up Tests	a) Fit-up of the following components is to be tested during fabrication. - MPC lid - vent/drain port cover plates - MPC closure ring b) A gauge test of all basket fuel compartments.	a) Fit-up of the following components is to be verified during pre-operation. - MPC lid - MPC closure ring vent/drain cover plates	a) None.
Canister Identification Inspections	a) Verification of identification marking applied at completion of fabrication.	a) Identification marking shall be checked for legibility during pre-operation.	a) None.

Table 8.1.2

HI-STAR OVERPACK INSPECTION AND TEST ACCEPTANCE CRITERIA

Function	Fabrication	Pre-operation	Maintenance and Operations
Visual Inspection and Nondestructive Examination (NDE)	a) Examination of the HI-STAR overpack shall be performed per ASME Code, Subsection NB, NB-5300 for containment boundary components, and Subsection NF, NF-5300 for non-containment boundary components. b) A dimensional inspection of the overpack internal cavity, external dimensions, and closure plate shall be performed to verify compliance with design requirements. c) The HI-STAR overpack shall be visually examined in accordance with the ASME Code Section V, Article 9, to verify that the overpack is free of cracks, pinholes, uncontrolled voids, or other defects that could significantly reduce its effectiveness. d) NDE of weldments shall be defined on drawings using standard American Welding Society NDE symbols and/or notations. e) Cleanliness of the HI-STAR overpack shall be verified upon completion of fabrication. f) Packaging of the HI-STAR overpack at the completion of fabrication shall be verified prior to shipment. g) Examination of the AL-STAR impact limiters shall be performed per ASME Code, Subsection NF, NF-5300.	a) The HI-STAR overpack shall be visually inspected prior to placement in service at the licensee's facility. b) HI-STAR overpack protection at the licensee's facility shall be verified. c) HI-STAR overpack cleanliness and exclusion of foreign material shall be verified prior to use.	a) Inspect overpack cavity and accessible external surfaces prior to each fuel loading. b) Visually inspect impact limiters for damage and compliance to drawing requirements prior to each transport.

Table 8.1.2 (continued)

HI-STAR OVERPACK INSPECTION AND TEST ACCEPTANCE CRITERIA

Function	Fabrication	Pre-operation	Maintenance and Operations
Structural	a) Assembly and welding of HI-STAR overpack components shall be performed per ASME Code, Subsection NB and NF, as applicable. b) Verification of structural materials shall be performed through receipt inspection and review of certified material test reports (CMTRs) obtained in accordance with the item's quality classification category. c) A load test of the lifting trunnions shall be performed during fabrication. d) A pressure test of the containment boundary in accordance with ASME Code Section III, Subsection NB-6000 and 10CFR71.85(b) shall be performed. e) A pneumatic pressure test of the neutron shield enclosure shall be performed during fabrication.	a) None.	a) The relief devices on the neutron shield vessel shall be replaced every 5 years.

Table 8.1.2 (continued)

HI-STAR OVERPACK INSPECTION AND TEST ACCEPTANCE CRITERIA

Function	Fabrication	Pre-operation	Maintenance and Operations
Leak Tests	a) Containment Fabrication Verification Leakage rate testing of the HI-STAR containment boundary welds shall be performed in accordance with ANSI N14.5. b) A Containment System Fabrication Verification Leakage rate test shall be performed on all HI-STAR overpack containment boundary mechanical seal boundaries in accordance with ANSI N14.5 at the completion of fabrication.	a) None.	a) Containment System Periodic Verification Leakage Test of the HI-STAR 100 Package shall be performed prior to each loaded transport (if not previously tested within 12 months). b) Containment System Fabrication Verification Leakage Test of the HI-STAR 100 Package shall be performed after the third use.
Criticality Safety	a) None.	a) None.	a) None.
Shielding Integrity	a) Material verifications (Holtite-A, shell plates, etc.), shall be performed in accordance with the item's safety classification. The required material certifications shall be obtained. b) The placement of Holtite-A shall be controlled through written special process procedures.	a) None.	a) A shielding effectiveness test of the neutron shield shall be performed every five years while in service. b) Verify the integrity of the Holtite-A neutron shield once at first use or with a check source.

Table 8.1.2 (continued) HI-STAR OVERPACK INSPECTION AND TEST ACCEPTANCE CRITERIA			
Function	**Fabrication**	**Pre-operation**	**Maintenance and Operation**
Thermal Acceptance	a) A thermal acceptance test is performed at completion of fabrication of the first HI-STAR overpack to confirm the heat transfer capabilities.	a) None.	a) An in-service thermal test shall be performed every five years during transport operations, or prior to transport if period exceeds five years from previous test. Acceptance criteria are defined in Section 8.2.6.
Cask Identification Inspection	a) Identification plates shall be installed on the HI-STAR overpack at completion of the acceptance test program.	a) The identification plates shall be checked prior to loading.	a) The identification plates shall be periodically inspected per licensee procedures and shall be repaired or replaced if damaged.
Fit-Up Tests	a) Fit-up tests of HI-STAR 100 Package components (closure plates, port plugs, cover plates impact limiters (if available)), shall be performed during fabrication.	a) Fit-up test of the HI-STAR overpack lifting trunnions with the lifting yoke shall be performed. b) Deleted c) Fit-up test of the MPC into the HI-STAR overpack shall be performed prior to loading.	a) Fit-up of all removable components shall be verified during each loading operation.

Table 8.1.3 HI-STAR 100 NDE REQUIREMENTS			
MPC			
Weld Location	**NDE Requirement**	**Applicable Code**	**Acceptance Criteria (Applicable Code)**
Shell longitudinal seam	RT PT (surface)	ASME Section V, Article 2 (RT) ASME Section V, Article 6 (PT)	RT: ASME Section III, Subsection NB, Article NB-5320 PT: ASME Section III, Subsection NB, Article NB-5350
Shell circumferential seam	RT PT (surface)	ASME Section V, Article 2 (RT) ASME Section V, Article 6 (PT)	RT: ASME Section III, Subsection NB, Article NB-5320 PT: ASME Section III, Subsection NB, Article NB-5350
Baseplate-to-shell	RT or UT PT (surface)	ASME Section V, Article 2 (RT) ASME Section V, Article 5 (UT) ASME Section V, Article 6 (PT)	RT: ASME Section III, Subsection NB, Article NB-5320 UT: ASME Section III, Subsection NB, Article NB-5330 PT: ASME Section III, Subsection NB, Article NB-5350

Table 8.1.3 (continued) HI-STAR 100 NDE REQUIREMENTS			
MPC			
Weld Location	**NDE Requirement**	**Applicable Code**	**Acceptance Criteria (Applicable Code)**
Lid-to-shell	PT (root and final pass) and multi-layer PT (if UT is not performed). PT (surface following pressure test) UT (if multi-layer PT is not performed)	ASME Section V, Article 6 (PT) ASME Section V, Article 5 (UT)	PT: ASME Section III, Subsection NB, Article NB-5350 UT: ASME Section III, Subsection NB, Article NB-5332
Closure ring-to-shell	PT (final pass)	ASME Section V, Article 6 (PT)	PT: ASME Section III, Subsection NB, Article NB-5350
Closure ring-to-lid	PT (final pass)	ASME Section V, Article 6 (PT)	PT: ASME Section III, Subsection NB, Article NB-5350
Closure ring radial welds	PT (final pass)	ASME Section V, Article 6 (PT)	PT: ASME Section III, Subsection NB, Article NB-5350
Port cover plates-to-lid	PT (root and final pass)	ASME Section V, Article 6 (PT)	PT: ASME Section III, Subsection NB, Article NB-5350
Vent and drain port cover plate plug welds	PT (surface)	ASME Section V, Article 6 (PT)	PT: NG, ASME Section III, Subsection Article NG-5350

Table 8.1.3 (continued) HI-STAR 100 NDE REQUIREMENTS			
HI-STAR OVERPACK			
Weld Location	**NDE Requirement**	**Applicable Code**	**Acceptance Criteria (Applicable Code)**
Inner shell-to-top flange	RT	ASME Section V, Article 2 (RT)	RT: ASME Section III, Subsection NB, Article NB-5320
	MT or PT (surface)	ASME Section V, Article 7 (MT)	MT: ASME Section III, Subsection NB, Article NB-5340
		ASME Section V, Article 6 (PT)	PT: ASME Section III, Subsection NB, Article NB-5350
Inner shell-to-bottom plate	RT	ASME Section V, Article 2 (RT)	RT: ASME Section III, Subsection NB, Article NB-5320
	MT or PT (surface)	ASME Section V, Article 7 (MT)	MT: ASME Section III, Subsection NB, Article NB-5340
		ASME Section V, Article 6 (PT)	PT: ASME Section III, Subsection NB, Article NB-5350
Inner shell longitudinal seam	RT	ASME Section V, Article 2 (RT)	RT: ASME Section III, Subsection NB, Article NB-5320
	MT or PT (surface)	ASME Section V, Article 7 (MT)	MT: ASME Section III, Subsection NB, Article NB-5340
		ASME Section V, Article 6 (PT)	PT: ASME Section III, Subsection NB, Article NB-5350

Table 8.1.3 (continued)

HI-STAR 100 NDE REQUIREMENTS

HI-STAR OVERPACK			
Weld Location	**NDE Requirement**	**Applicable Code**	**Acceptance Criteria (Applicable Code)**
Inner shell circumferential seam	RT MT or PT (surface)	ASME Section V, Article 2 (RT) ASME Section V, Article 7 (MT) ASME Section V, Article 6 (PT)	RT: ASME Section III, Subsection NB, Article NB-5320 MT: ASME Section III, Subsection NB, Article NB-5340 PT: ASME Section III, Subsection NB, Article NB-5350
Intermediate shell welds (as noted on drawings)	MT or PT (surface)	ASME Section V, Article 6 (PT) ASME Section V, Article 7 (MT)	PT: ASME Section III, Subsection NF, Article NF-5350 MT ASME Section III, Subsection NF, Article NF-5340

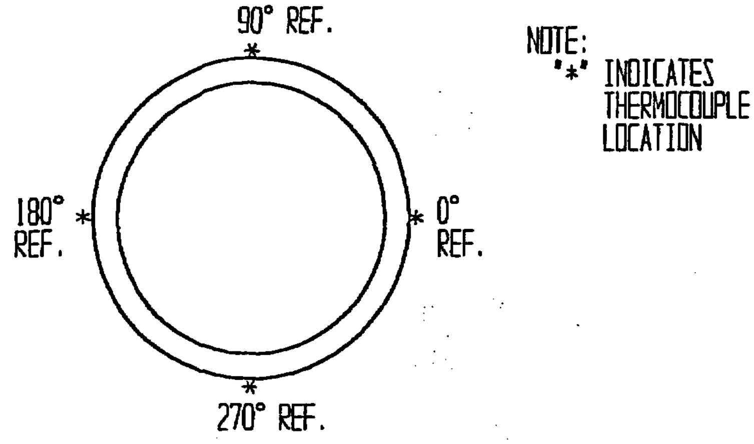
Table 8.1.4

SUMMARY OF OVERPACK THERMAL ANALYSIS
REFERENCE AMBIENT INPUTS

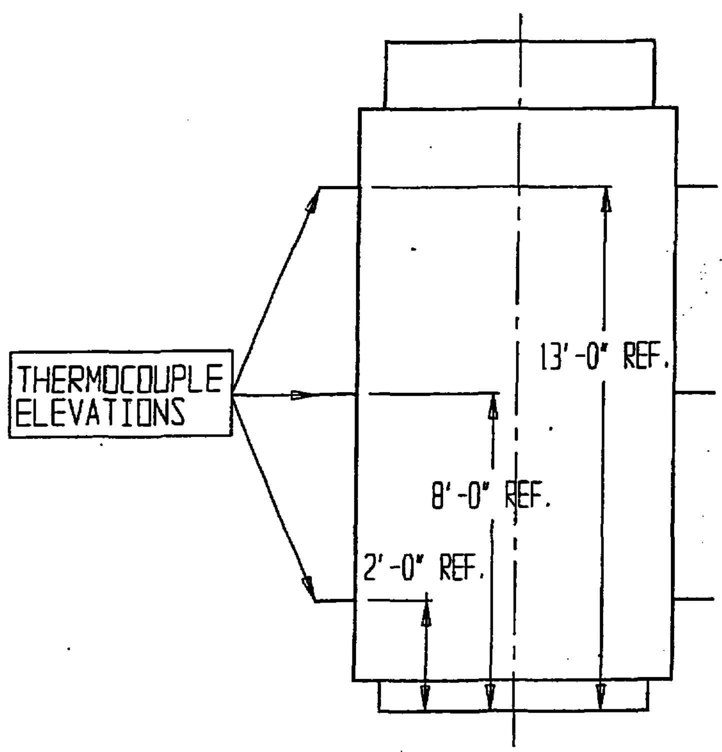
PARAMETER	VALUE
Steam Temperature	212°F
Ambient Temperature	70°F
Radiative Blocking	None[1]
Exposed Surfaces Insolation	None

1 The test shall be performed on an isolated overpack. Thus, cask radiation blocking at an ISFSI array is not applicable to test conditions.

Figure 8.1.1 Deleted



PLAN VIEW



ELEVATION

FIGURE 8.1.2; THERMOCOUPLE LOCATIONS

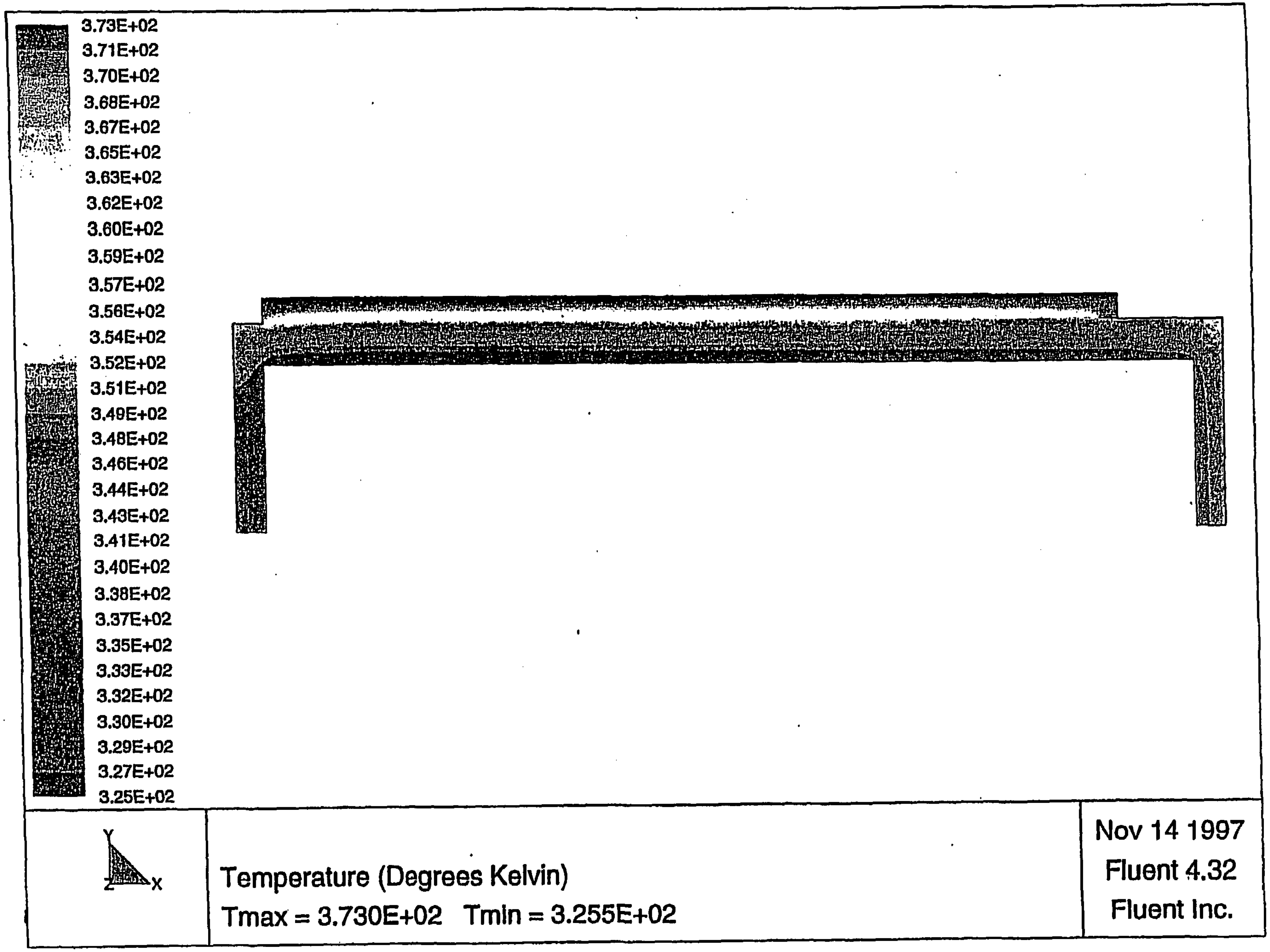


FIGURE 8.13 : OVERPACK STEAM HEATED TEST TEMPERATURE CONTOURS PLOT

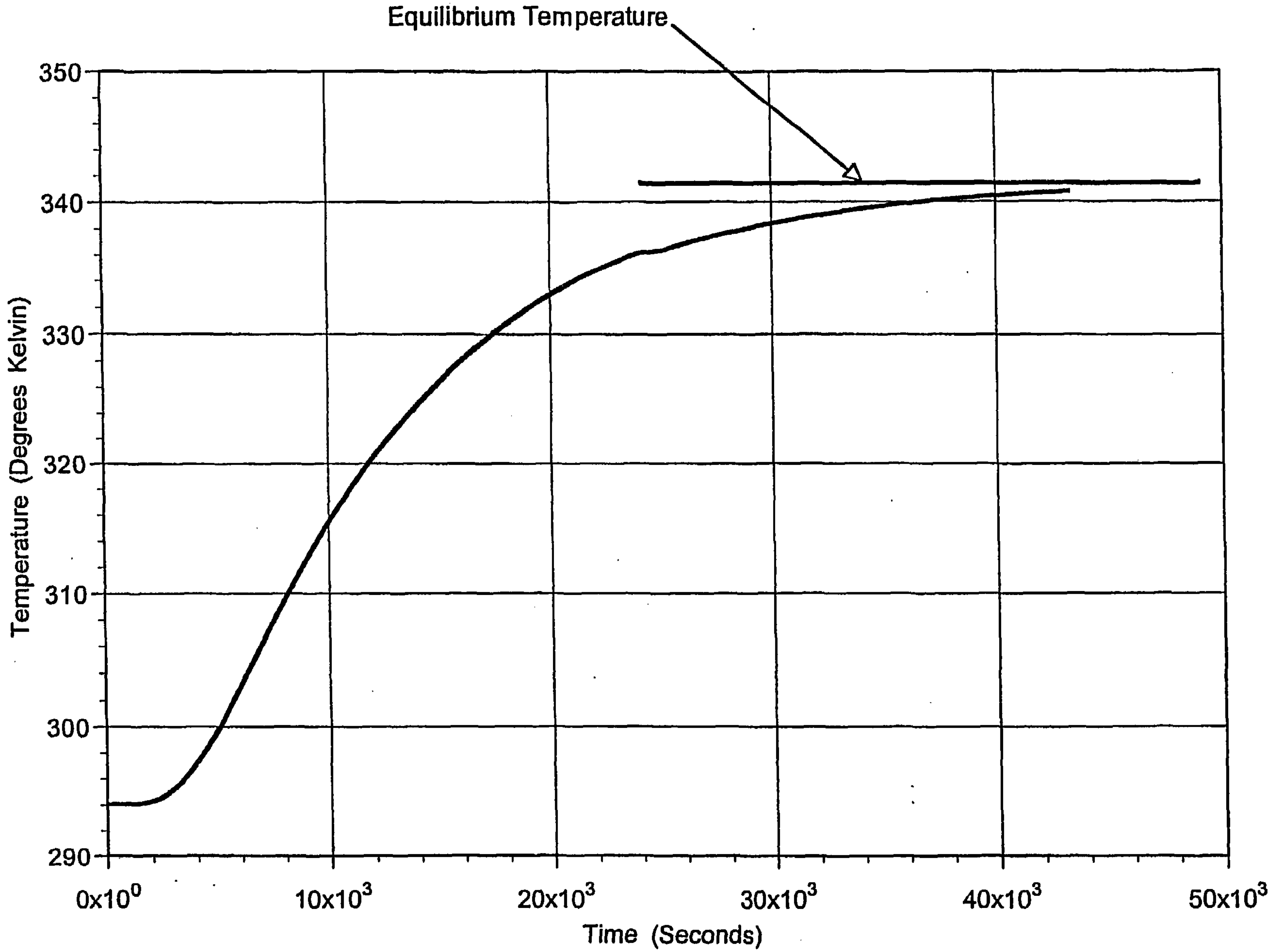


FIGURE 8.1.4: OVERPACK SURFACE TEMPERATURE HISTORY DURING A STEAM HEATED TEST

8.2 MAINTENANCE PROGRAM

An ongoing maintenance program is defined and incorporated in the HI-STAR 100 System Operations Manual which will be prepared and issued prior to the delivery and first use of the HI-STAR 100 Package. This document shall delineate the detailed inspections, testing, and parts replacement necessary to ensure continued radiological safety, proper handling, and containment performance of the HI-STAR 100 Package in accordance with 10CFR71 regulations, conditions in the Certificate of Compliance, and the design requirements and criteria contained in this Safety Analysis Report (SAR).

The HI-STAR 100 Package is totally passive by design. There are no active components or systems required to assure the continued performance of its safety functions. As a result, only minimal maintenance will be required over its lifetime, and this maintenance would primarily result from weathering effects, and pre- and post-usage requirements for transportation. Typical of such maintenance would be the reapplication of corrosion inhibiting materials on accessible external surfaces, and seal replacement and leak testing following replacement. Such maintenance requires methods and procedures are no more demanding than those currently in use at power plants.

A maintenance program schedule for the HI-STAR 100 Package is provided in Table 8.2.1.

8.2.1 Structural and Pressure Parts

Prior to each fuel loading, a visual examination in accordance with a written and approved procedure shall be required of the following HI-STAR 100 Package components: lifting trunnions (area outside of the overpack); overpack internals and externals; and impact limiters. The examination shall inspect for indications of overstress such as cracking, deformation or wear marks, gross damage to components, or areas of chipped or missing surface coatings. Repairs or replacement in accordance with written and approved procedures shall be required if unacceptable conditions are identified.

No periodic structural or pressure tests on the overpack or MPCs following the initial acceptance tests are required to verify continuing performance.

8.2.2 Leakage Tests

There are no seals in the MPC secondary containment boundary (of the "F" model MPCs) because the MPC lid, port cover plates, and closure ring are welded closures. Mechanical seals are used on the HI-STAR 100 overpack containment boundary to ensure the retention of the radioactive material contents in the HI-STAR 100 Package. These seals are not temperature sensitive within the design temperature range, are resistant to corrosion and radiation environments, and are helium leak tested after fuel loading. The containment system has been designed to withstand normal and accident conditions of transport without loss of containment integrity. The overpack containment penetration seals shall be leakage tested in accordance with Chapter 7 and the acceptance criteria of Subsection 8.1.3.1 prior to transport if not previously tested within 12 months of the commencement of transport.

The mechanical seals on the overpack containment boundary shall be replaced as defined in Table 8.2.1. After each replacement, the helium leak test of the overpack containment seals described in Chapter 7 shall be performed to verify the leakage rate does not exceed 4.3×10^{-6} atm cm^3/s (helium) at a test sensitivity of 2.15 atm-cc/sec. Prior to replacement of each seal, the mating surfaces shall be cleaned and visually inspected for scratches, pitting or roughness, and affected surface areas shall be polished smooth or repaired as necessary in accordance with written and approved procedures. The bolting for the closure plate and the vent and drain port cover plates, and port plugs shall also be inspected for indications of wear, galling, or indentations on the threaded surfaces prior to reinstallation and closure torquing. Any bolt or port plug showing any of these indications shall be replaced.

8.2.3 Subsystem Maintenance

The HI-STAR 100 Package does not include any subsystems that provide auxiliary cooling or shielding. Normal maintenance and calibration testing is performed on the vacuum drying, helium backfill, and leakage testing systems based on manufacturer's recommendations. Rigging, remote welders, cranes, and lifting beams shall also be inspected in accordance with the operations manual to ensure proper maintenance and continued performance is achieved.

8.2.4 Relief Devices

The relief devices on the overpack neutron shield enclosure shell shall be visually inspected prior to each use of the HI-STAR 100 Package for damage or indications of excessive corrosion. If the inspection determines an unacceptable condition, the relief devices shall be replaced. The relief devices shall be replaced with approved spares every five years while the cask is in transport service.

8.2.5 Shielding

The gamma and neutron shielding materials in the HI-STAR 100 degrade negligibly over time or as a result of usage. To ensure continuing compliance of the HI-STAR 100 Package to the design basis shielding values, the Shielding Effectiveness Test in accordance with Subsection 8.1.5.2 shall be performed every five years while the cask is in transport service.

The post-loading and receipt radiation surveys performed in accordance with 10CFR71 and 10CFR20 prior to, and at the completion of transport, as described in the operating procedures in Chapter 7, provide ongoing evidence and confirmation of shield integrity.

8.2.6 In-Service Thermal Test

A thermal performance test shall be performed on each HI-STAR 100 Package prior to commencing transportation operations. This test shall be performed immediately after a HI-STAR Package is loaded with spent nuclear fuel prior to transport or when a previously loaded HI-STAR 100 System is prepared for transport if the test has not been successfully performed in the preceding five years. The in-service test is performed to verify an adequate rate of heat

dissipation from the cask to the environs. Acceptable performance under test conditions ensures that design basis fuel cladding temperature limits to which the HI-STAR 100 Package is qualified under design basis heat loads will not be exceeded during transport.

Prior to performing the test, thermal equilibrium of the HI-STAR 100 Package shall be verified by measuring the temperature using a calibrated thermocouple or surface pyrometer at a defined point near the mid-plane of the HI-STAR 100 Package at one hour intervals for two hours. Appropriate criteria defining when thermal equilibrium is achieved shall be determined based on a variety of ambient test conditions and incorporated into the test procedure.

After thermal equilibrium is established, temperatures shall be measured and recorded using a calibrated thermocouple or surface pyrometer at the locations shown on Figure 8.2.1. The decay heat load and fuel cycle history of the fuel assemblies loaded in the HI-STAR 100 Package shall also be recorded. These records shall become part of the maintenance program quality records for the HI-STAR 100 Package.

The HI-STAR 100 Package is considered acceptable if the average measured surface to ambient temperature differential shown in Table 8.2.2, when adjusted for environmental conditions, is not exceeded.

8.2.7 Miscellaneous

The impact limiters shall be visually inspected in accordance with a written procedure prior to each use to inspect for surface denting, surface penetrations, and weld cracking. Any areas found to not meet the defined acceptance criteria shall be repaired and/or replaced in accordance with written and approved procedures.

Table 8.2.1

MAINTENANCE AND INSPECTION PROGRAM SCHEDULE

Task	Frequency
Overpack cavity and external surface (accessible) visual inspection	Prior to each fuel loading
Overpack bolting and port plug visual inspection	Prior to installation and prior to each transport
Lifting trunnion and pocket trunnion recess visual inspection	Prior to each fuel loading and prior to each transport
Containment System Periodic Leakage Test of closure plate, and vent and drain port plugs	Following each fuel loading, and prior to off-site transport if period from last test exceeds 1 year
Containment System Fabrication Verification Leakage Test of containment boundary closures	After third use
Containment System Fabrication Verification Leakage Test of "F" model MPC secondary containment boundary	Prior to each transport
Transport impact limiter visual inspection	Prior to each transport
Shielding effectiveness test	Every five years during transportation operation, or prior to transport if period exceeds five years from previous test.
Closure plate mechanical seal replacement	Following removal of closure plate bolting
Closure plate bolt replacement	Every 240 bolting cycles (assumes 20 years at 12 cycles per year)
Port plug seal replacement	Following removal of applicable port plug
Port cover plate seal replacement	Following removal of applicable cover plate
Relief Device visual inspection	Prior to each transport
Relief Device replacement	Every five years
In-service thermal test	Every five years during transportation operations, or prior to transport if period exceeds five years from previous test.

Table 8.2.2

HI-STAR 100 PACKAGE TEST CONDITION OVERPACK SURFACE TO AMBIENT TEMPERATURE DIFFERENTIAL[1] UNDER DESIGN BASIS DECAY HEAT LOADS AND INSOLATION

	PWR MPCs ΔT (°F)	BWR MPCs ΔT (°F)
Overpack Enclosure Active Fuel Mid-Height Location	122	117

1 This information is obtained from Tables 3.4.9 through 3.4.11 in SAR Chapter 3.

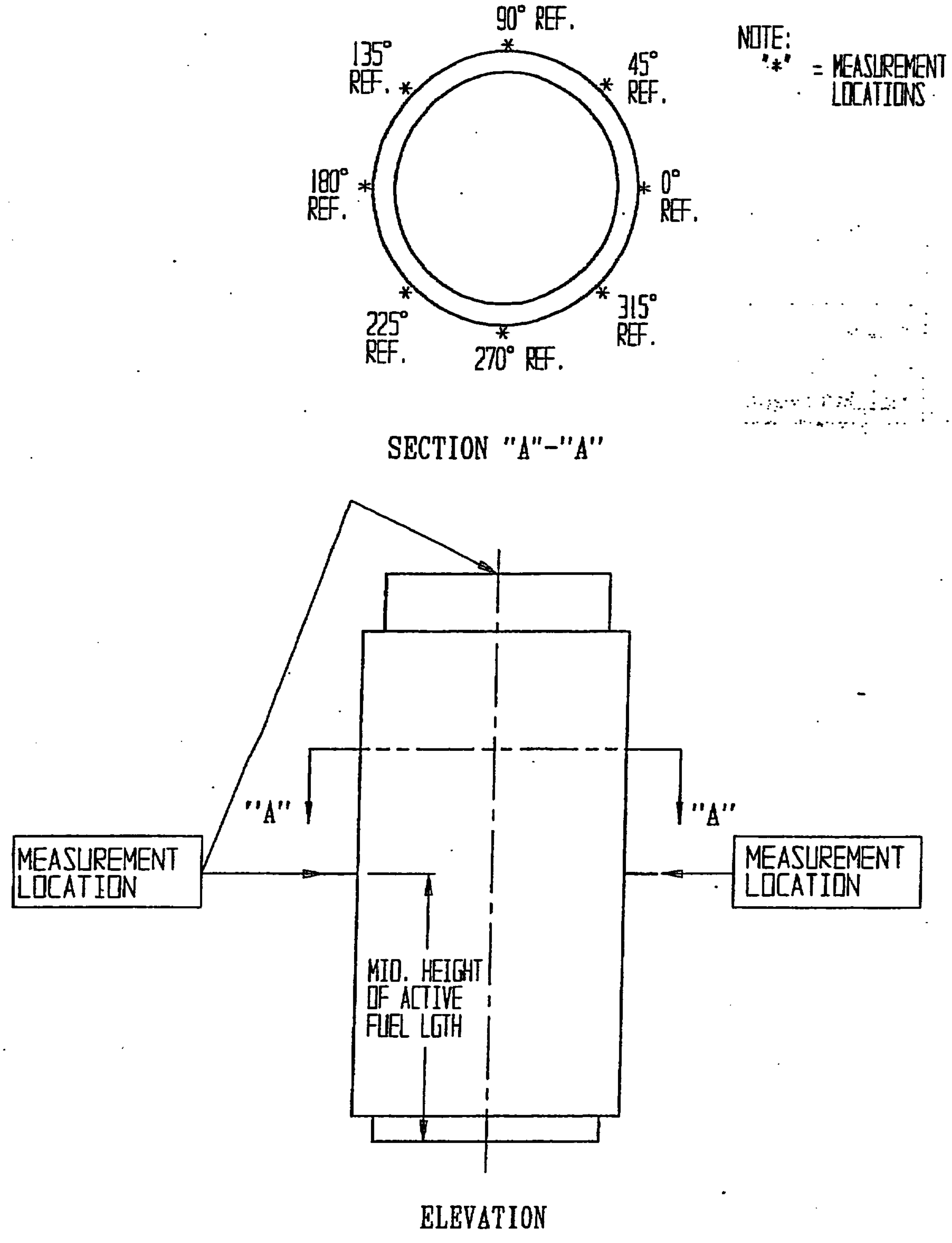


FIGURE 8.2.1; TEMPERATURE MEASUREMENT LOCATIONS FOR PERIODIC THERMAL TEST

8.3 REGULATORY COMPLIANCE

This chapter summarizes the commitments of Holtec International to design, construct, inspect, and test the HI-STAR 100 Package in accordance with the Codes and Standards identified in Chapter 1. Completion of the defined acceptance test program for each HI-STAR 100 Package will provide assurance that the SSCs important to safety will perform their design function. The performance of the maintenance program by Holtec International or the licensee for each HI-STAR 100 Package will provide assurance for the continued effectiveness of the Package.

The described acceptance criteria and maintenance programs can be summarized in the following evaluation statements:

1. Section 8.1 of this SAR describes Holtec International's proposed program for preoperational testing and initial operations of the HI-STAR 100 Package. Section 8.2 describes the proposed HI-STAR 100 maintenance program. The preliminary determinations for the HI-STAR 100 Package prior to first use meets the requirements of 10CFR71.85 and 10CFR71.87(g).

2. Structures, systems, and components (SSCs) of the HI-STAR 100 Package designated as important to safety shall be designed, fabricated, erected, assembled, inspected, tested, and maintained to quality standards commensurate with the importance to safety of the function they are intended to perform. Table 1.3.3 of this SAR identifies the safety and quality classifications of SSCs of the HI-STAR 100 Package, and Table 1.3.1 presents the applicable standards for their design, fabrication, and inspection, as clarified by the ASME Code alternatives in Table 1.3.2.

3. Holtec International shall examine and test the HI-STAR 100 Package to ensure that it does not exhibit any defects that could significantly reduce its containment effectiveness.

4. Holtec International shall durably mark each HI-STAR 100 Package with a data plate indicating the COC identification number assigned by the NRC, trefoil radiation symbol, gross weight, model number, and unique identification serial number in accordance with 10CFR71.85(c) at the completion of the acceptance test program.

5. The description of the routine determinations defined in the maintenance program in Section 8.2 for the HI-STAR 100 Package prior to transport use meets the requirements of 10CFR71.87(b) and 10CFR71.87(g).

6. It can be concluded that the acceptance tests and maintenance program for the HI-STAR 100 Package are in compliance with 10CFR71 [8.0.1], and that the applicable acceptance criteria have been satisfied. The acceptance tests and maintenance program provide reasonable assurance that the HI-STAR 100 Package will allow safe transport of spent fuel throughout its certified life. This conclusion is based on a review that considers the regulation itself, appropriate regulatory guides, applicable codes and standards, and accepted industry practices.

8.4 REFERENCES

[8.0.1] U.S. Code of Federal Regulations, Title 10, "Energy", Part 71, "Packaging and Transportation of Radioactive Materials."

[8.1.1] Holtec International Quality Assurance Manual, current revision.

[8.1.2] American Society of Mechanical Engineers, " Boiler and Pressure Vessel Code," Sections II, III, V, IX, and XI, 1995 Edition with 1996 and 1997 Addenda.

[8.1.3] American Society for Nondestructive Testing, "Personnel Qualification and Certification in Nondestructive Testing," Recommended Practice No. SNT-TC-1A, December 1992.

[8.1.4] HI-STAR 100 Final Safety Analysis Report, Holtec Report No. HI-2012610, current revision.

[8.1.5] American National Standards Institute, Institute for Nuclear Materials Management, "American National Standard for Radioactive Materials - Special Lifting Devices for Shipping Containers Weighing 10,000 Pounds (4500 kilograms) or More", ANSI N14.6, September 1993.

[8.1.6] NUREG-0612, "Control of Heavy Loads at Nuclear Power Plants", U.S. Nuclear Regulatory Commission, Washington, D.C., July 1980.

[8.1.7] U.S. Nuclear Regulatory Commission, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches (0.1m)," Regulatory Guide 7.11, June 1991.

[8.1.8] U.S. Nuclear Regulatory Commission, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Wall Thickness Greater than 4 Inches (0.1m) But Not Exceeding 12 Inches (0.3m)," Regulatory Guide 7.12, June 1991.

[8.1.9] American National Standards Institute, Institute for Nuclear Materials Management, "American National Standard for Radioactive Materials Leakage Tests on Packages for Shipment", ANSI N14.5, 1997.