available pool floor space in Pool A. The remaining 648 storage cells will be installed at a future date.

Of the 846 high density storage locations, 195 will be of the so-called Region I type, and the remainder of Region II genre. Region I racks are configured to store new or burned fuel of maximum 4.6% enrichment. Region II racks are capable of storing 4.6% enrichment fuel with 37 MWD/kg-U (min.) burnup and correspondingly reduced burnup for lower enrichment fuel. Included in the 846 locations are three storage locations for storing failed fuel containers. Figure 1.1 shows the proposed module layout for Pool A.

It is noted that the proposed reracking effort will increase the number of licensed storage locations in Pool A to 1494, which, as indicated in Table 1.2, will extend the date of loss of full core discharge capability to the year 2023, which is well past the presently licensed end-of-life date of 2014. Pool B is not contemplated to be reracked at the present time.

The new spent fuel storage racks are free-standing and self supporting. The principal construction materials for the new racks are ASTM 240-Type 304 stainless steel sheet and plate stock, and A564 (precipitation hardened stainless steel) for the adjustable support spindles. The only non-stainless material utilized in the rack is the neutron absorber material which is boron carbide and aluminum-composite sandwich available under the patented product name "Boral".

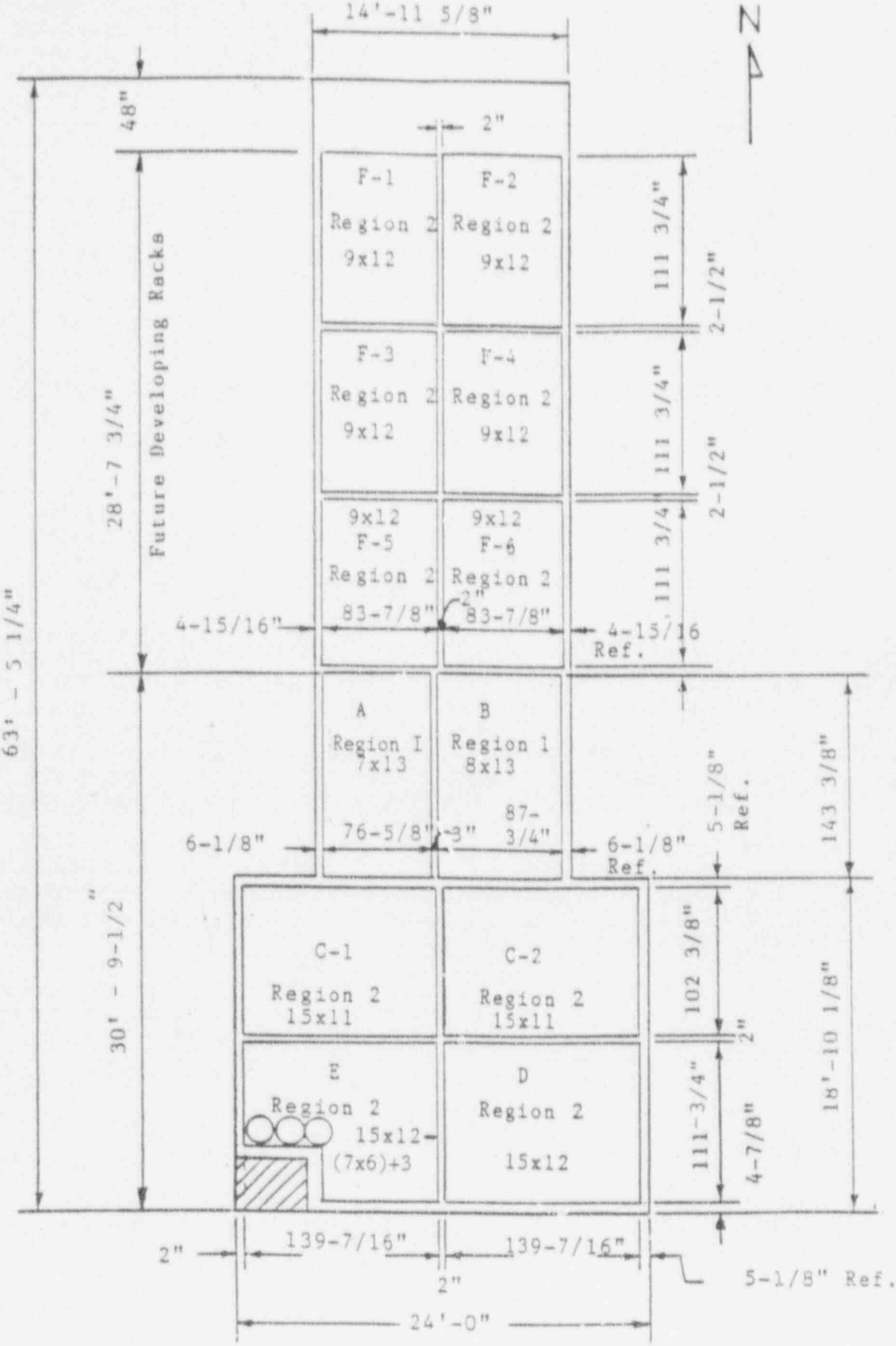

Figure 1.1 Module Layout - TMI Unit 1 (Pool A)

2.3.4 Compatibility with Coolant

All materials used in the construction of the TMI-I racks have an established history of in-pool usage. Their physical, chemical and radiological compatibility with the pool environment is an established fact at this time. As noted in Table 2.6, Boral has been used in both vented and unvented configurations in fuel pools with equal success. Austenitic stainless (304) is perhaps the most widely used stainless alloy in nuclear power plants.

2.4 EXISTING RACK MODULES AND PROPOSED RERACKING OPERATION

Pool A currently has low density rack modules containing a total of 253 storage cells. In addition, Pool B has 496 storage locations. At the time of the proposed reracking operation, 520 of these locations will be occupied with spent fuel.* There is sufficient number of open (unoccupied) cells in the pool to permit relocation of a majority of assemblies to Pool B.

A remotely engagable lift rig, meeting NUREG-0612 stress criteria, will be used to lift the empty modules. The fuel storage building crane will be used for this purpose. A module change-out scheme has been developed which ensures that all modules being handled are empty, and at least four to six feet laterally from a loaded module, when the module is more than twelve inches above the pool floor.

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* In addition, a certain number of storage locations will be filled with miscellaneous elements such as Retainers. It is also to be noted that certain peripheral cells in Pool B are not accessible by the fuel handling equipment, making them ineffective for fuel storage.

Table 2.4

Common Module Data

Storage cell inside dimension:	9 inch ± .06 inch
Storage cell height (above the baseplate):	163"
Baseplate thickness:	0.5"
Support leg height:	4-3/4" (nominal)
Support leg type:	Remotely adjustable legs
Number of support legs:	4 (minimum)
Remote lifting and handling provision:	Yes
Poison material:	Boral
Poison length:	138" - Region I 144" - Region II
Poison width:	7.5"
Cell Pitch: (P_x,P_y)	11.07" ± .06 inch (Region I)
	9.216" ± .06 inch (Region II)

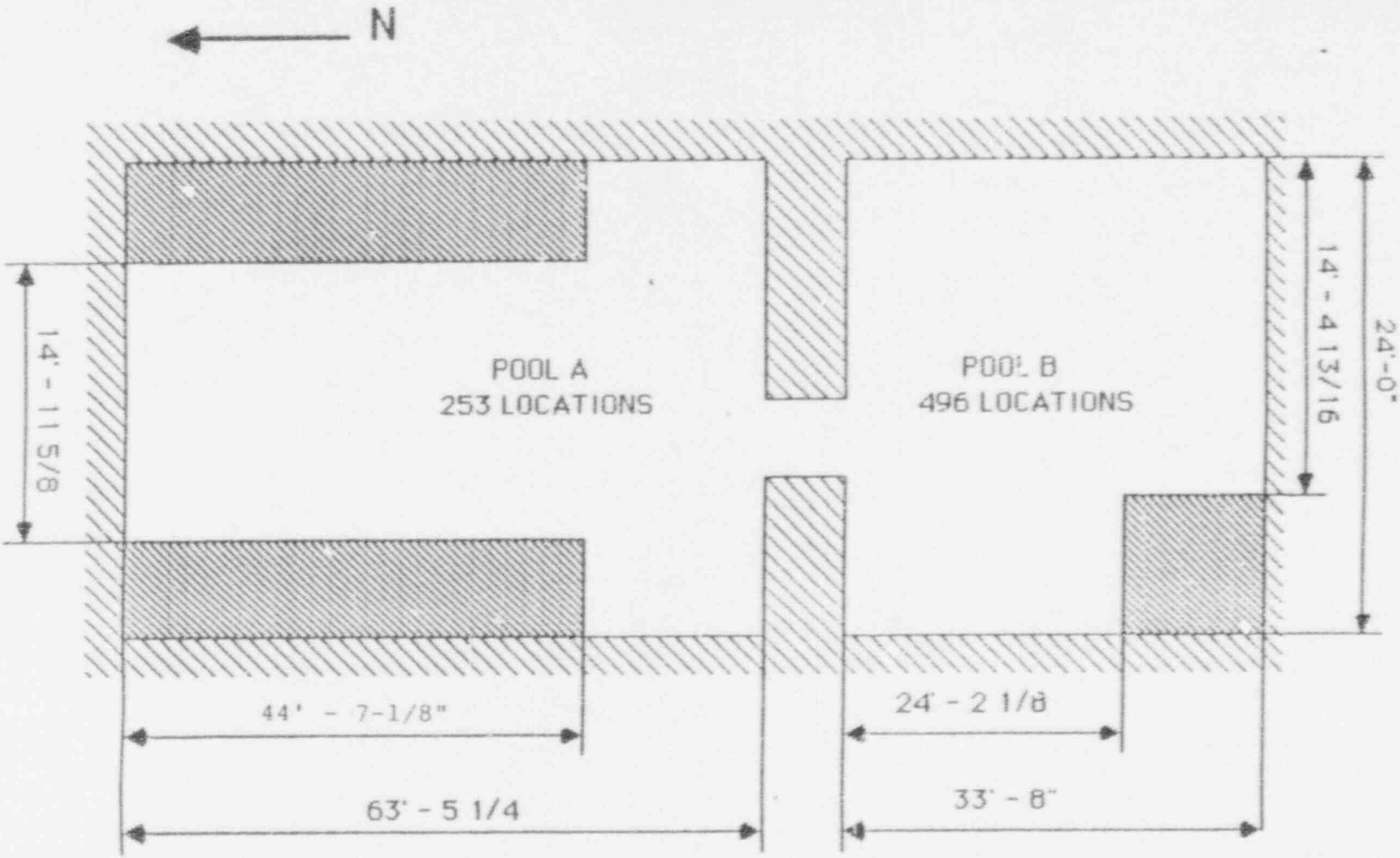

FIG.2.1 PLAN VIEW OF TMI-1 POOL SYSTEM

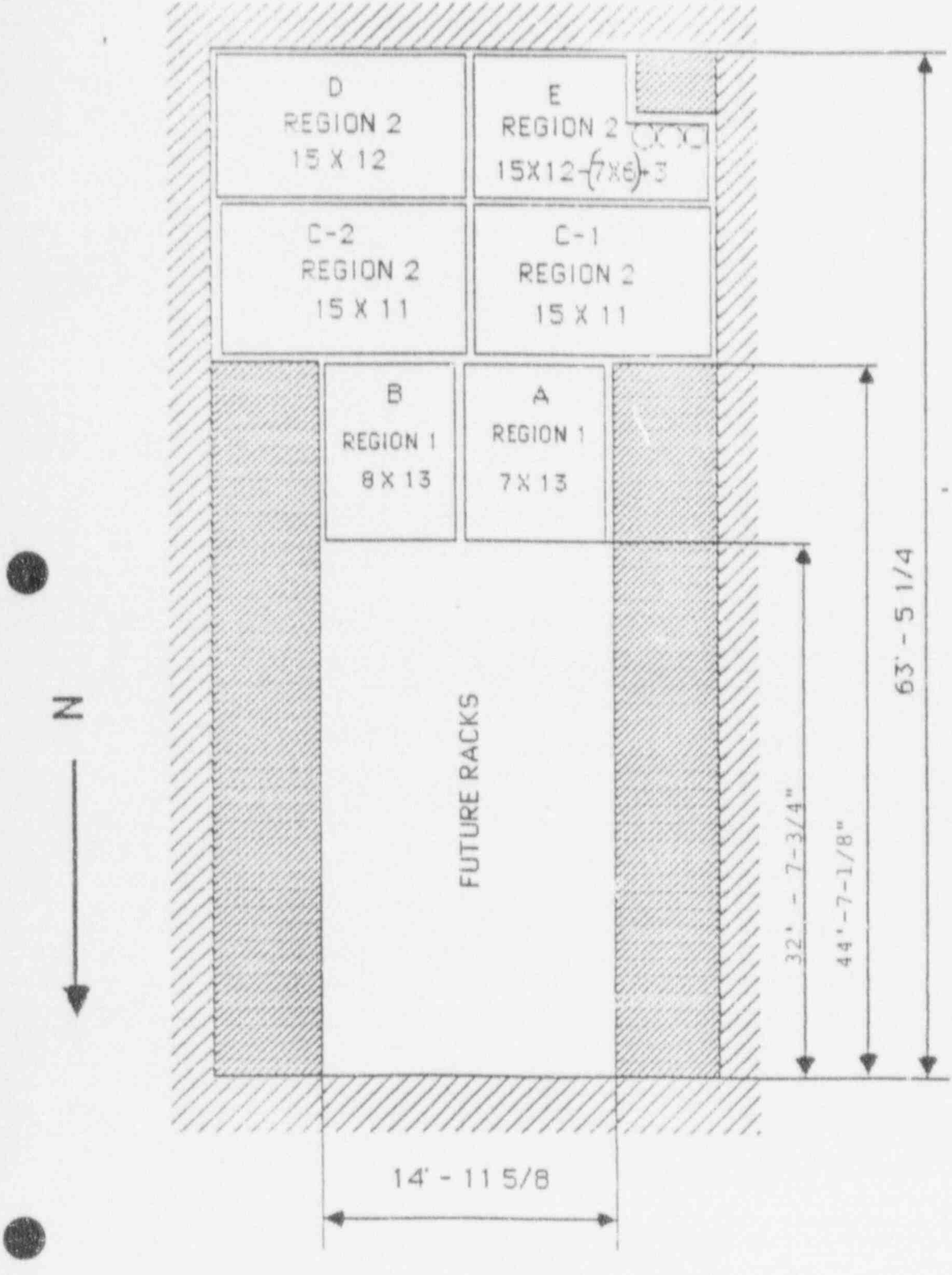

FIG. 2.2 MODULE LAYOUT - POOL A
(PRESENT RERACKING CAMPAIGN)

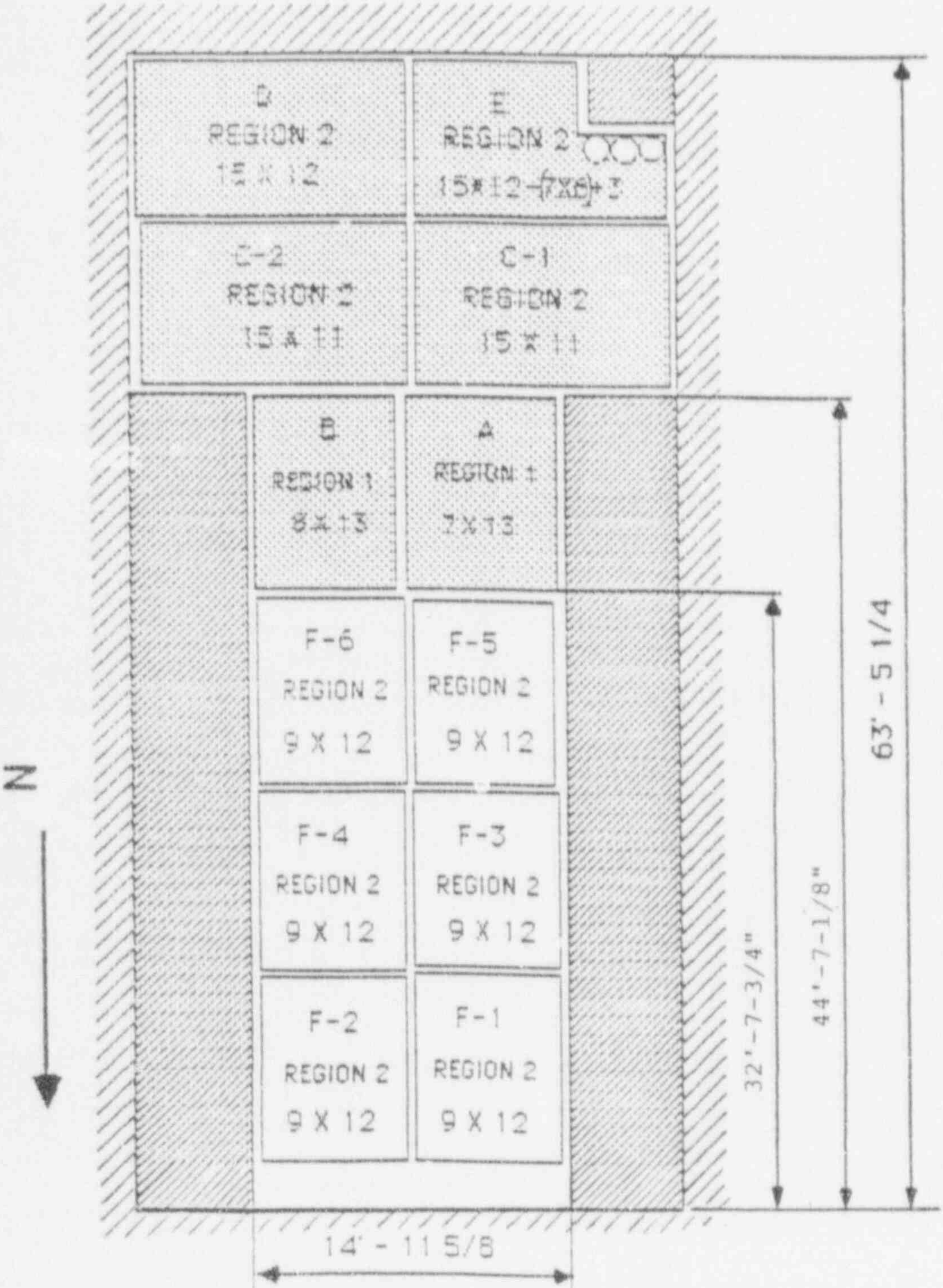

FIG. 2.3 MODULE LAYOUT - POOL A
(PRESENT & FUTURE RACKS)

The poison material is placed in the customized flat depression region of the sheathing, which is next laid on a side of the "box". The precision of the shape of the sheathing obtained by die forming guarantees that the poison sheet installed in it will not be subject to surface compression. The flanges of the sheathing (on all four sides) are attached to the box using skip welds. The sheathing serves to locate and position the poison sheet accurately, and to preclude its movement under seismic conditions.

Having fabricated the required number of the composite box assemblies, they are joined together in a fixture using connector elements in the manner shown in Figure 3.4. The pitch between the box centerlines is p_x in one principal direction and p_y in the other principal direction. The values of p_x and p_y are given in Section 2 (Table 2.4) of this Licensing Report. The fabrication procedure in either direction is identical, since the channels are fillet welded to make the inter-box connection. Figure 3.6 shows an elevation view of two storage cells of a Region I rack module.

Joining the cells by the interconnection elements results in a well defined shear flow path, and essentially makes the box assemblage into a multi-flanged beam type structure.

In the next step of manufacture, the "base plate" is attached to the bottom edge of the boxes. The base plate is a 1/2" thick austenitic stainless steel plate stock which has a 5" hole burned out in a pitch identical to the box pitch. The base plate is attached to the cell assemblage by fillet welding the box edge to the plate.

As shown in Figure 3.7, each box has two lateral holes punched near its bottom edge to provide auxiliary flow holes. A "picture frame sheathing" similar to Region I rack construction is attached to each side of the box with the poison material installed in the sheathing cavity. The edges of the sheathing and the box are welded together to form a smooth edge. The box, with integrally connected sheathing, is referred to as the "composite box".

The "composite boxes" are arranged in a checkerboard array to form an assemblage of storage cell locations (Figure 3.8). The inter-box welding and pitch adjustment are accomplished by small longitudinal connectors.

This assemblage of box assemblies is welded edge-to-edge as shown in Figure 3.8, resulting in a honeycomb structure with axial, flexural and torsional rigidity depending on the extent of intercell welding provided. It can be seen from Figure 3.8 that two edges of each interior box are connected to the contiguous boxes resulting in a well defined path for "shear flow".

(2) Base Plate: The base plate provides a continuous horizontal surface for supporting the fuel assemblies. The base plate has a concentric hole in each cell location as described in the preceding section.

The base plate is attached to the cell assemblage by fillet welds. The baseplate in each storage cell has a 5" diameter flow hole.

(3) The neutron absorber material: As mentioned in the preceding section, Boral is used as the neutron absorber material.

(4) Picture Frame Sheathing: As described earlier, the sheathing serves as the locator and retainer of the poison material. Figure 3.3 shows a schematic of the sheathing.

4.0 CRITICALITY SAFETY ANALYSES

4.1 DESIGN BASES

The high density spent fuel storage racks for Three Mile Island Unit 1 are designed to assure that the effective neutron multiplication factor (k_{eff}) is equal to or less than 0.95 with the racks fully loaded with fuel of the highest anticipated reactivity, and flooded with unborated water at the temperature within the operating range corresponding to the highest reactivity. The maximum calculated reactivity includes a margin for uncertainty in reactivity calculations including mechanical tolerances. All uncertainties are statistically combined, such that the final k_{eff} will be equal to or less than 0.95 with a 95% probability at a 95% confidence level.

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

- General Design Criteria 62, Prevention of Criticality in Fuel Storage and Handling.
- USNRC Standard Review Plan, NUREG-0800, Section 9.1.2, Spent Fuel Storage, Rev. 3 - July 1981
- USNRC letter of April 14, 1978, to all Power Reactor Licensees - OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications, including modification letter dated January 18, 1979.
- USNRC Regulatory Guide 1.13, Spent Fuel Storage Facility Design Basis, Rev. 2 (proposed), December 1981.
- ANSI ANS-8.17-1984, Criticality Safety Criteria for the Handling, Storage and Transportation of LWR Fuel Outside Reactors.

- o ANSI/ANS-57.2-1983, Design Requirements for Light Water Reactor Spent Fuel Storage Facilities at Nuclear Power Plants.
- o ANSI N210-1976, Design Objectives for Light Water Reactor Spent Fuel Storage Facilities at Nuclear Power Plants.
- o ANSI N18.2-1973, Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Plants.

USNRC guidelines and the applicable ANSI standards specify that the maximum effective multiplication factor, "k_{eff}", including uncertainties, shall be less than or equal to 0.95. The infinite multiplication factor, "k_{∞}", is calculated for an infinite array, neglecting neutron losses due to leakage from the actual storage rack, and therefore results in a higher and more conservative value. In the present evaluation of criticality safety in the Three Mile Island Unit 1 storage racks, the design basis criterion was assumed to be a "k_{∞}" of 0.95, which is more conservative than the limit specified in the regulatory guidelines.

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

- o Moderator is unborated water at a temperature that results in the highest reactivity (68°F).
- o In all cases (except for the assessment of peripheral effects and certain abnormal/accident conditions where neutron leakage is inherent), the infinite multiplication factor, k_{∞}, was used rather than the effective multiplication factor, k_{eff} (i.e., neutron loss from radial and axial leakage neglected).
- o Neutron absorption in minor structural members is neglected, i.e., spacer grids are analytically replaced by water.
The design basis fuel assembly is a 15 x 15 Babcock &

Wilcox fuel assembly containing UO_2 at a maximum initial enrichment of 4.6 wt% U-235 by weight, corresponding to 67.4 grams U-235 per axial centimeter of fuel assembly. Two separate storage regions are provided in the spent fuel storage pool, with independent criteria defining the highest potential reactivity in each of the two regions as follows:

- o Region 1 is designed to accommodate new fuel with a maximum enrichment of 4.6 wt% U-235, or spent fuel regardless of the discharge fuel burnup.
- o Region 2 is designed to accommodate fuel of various initial enrichments which have accumulated minimum burnups within the acceptable domain depicted in Figure 4.1.

The water in the spent fuel storage pool normally contains soluble boron which would result in large subcriticality margins under actual operating conditions. However, the NRC guidelines, based upon the accident condition in which all soluble poison is assumed to have been lost, specify that the limiting k_{eff} of 0.95 be evaluated in the absence of soluble boron. The double contingency principle of ANSI N-16.1-1975 and of the April 1978 NRC letter allows credit for soluble boron under other abnormal or accident conditions since only a single accident need be considered at one time. Consequences of abnormal and accident conditions have also been evaluated, where "abnormal" refers to conditions (such as higher water temperatures resulting from full-core discharge) which may reasonably be expected to occur during the lifetime of the plant and "accident" refers to conditions which are not expected to occur but nevertheless must be protected against.

4.2 SUMMARY OF CRITICALITY ANALYSES

4.2.1 Normal Operating Conditions

The criticality analyses of each of the two separate regions of the spent fuel storage pool are summarized in Table 4.1 for the design basis storage conditions which assumes the single accident condition of the loss of all soluble boron. The calculated maximum reactivity in Region 2 includes a burnup-dependent allowance for uncertainty in depletion calculations and, furthermore, provides an additional margin of more than 1 % δk below the design basis infinite multiplication factor (k_∞) of 0.95. As cooling time increases in long-term storage, decay of Pu-241 results in a significant decrease in reactivity, which will provide an increasing subcriticality margin and tends to further compensate for any uncertainty in depletion calculations.

Region 2 can safely accommodate fuel of various initial enrichments and discharge fuel burnups, provided the combination falls within the acceptable domain illustrated by the solid line in Figure 4.1. For convenience, the minimum (limiting) burnup data in Figure 4.1 for unrestricted storage in Region 2 can be described as a function of the initial enrichment, E, in weight percent U-235 by a fitted polynomial expression as follows;

For Region 2 Unrestricted Storage

Minimum Burnup in MWD/MTU =

$$- 36.0 + 27.1 E - 4.0 E^2 + .34 E^3$$

(for initial enrichments up to 5 wt% U-235)

This polynomial fit is generally accurate to within ± 0.002 δk

in reactivity, except at the lower enrichment limit (1.75%) where the fit conservatively overpredicts the limiting burnup.

The burnup criteria identified above for acceptable storage in Region 2 can be implemented in appropriate administrative procedures to assure verified burnup as specified in the proposed Regulatory Guide 1.13, Revision 2. Administrative procedures will also be employed to confirm and assure the presence of soluble poison in the pool water during fuel handling operations, as a further margin of safety and as a precaution in the event of fuel misplacement during fuel handling operations.

4.2.2 Abnormal and Accident Conditions

Although credit for the soluble poison normally present in the spent fuel pool water is permitted under abnormal or accident conditions, most abnormal or accident conditions will not result in exceeding the limiting reactivity (k_{eff} of 0.95) even in the absence of soluble poison. The effects on reactivity of credible abnormal and accident conditions are presented in detail in Section 4.7 and briefly summarized in Table 4.2. Of these abnormal/accident conditions, only one has the potential for a more than negligible positive reactivity effect.

The inadvertent misplacement of a fresh fuel assembly (either into a Region 2 storage cell or outside and adjacent to a rack module) has the potential for exceeding the limiting reactivity, should there be a concurrent and independent accident condition resulting in the loss of all soluble poison. Administrative procedures to assure the presence of soluble poison during fuel handling operations will preclude the possibility of the simultaneous occurrence of the two independent accident conditions. The largest reactivity increase would occur if a new

fuel assembly of the highest permissible reactivity were to be positioned outside and immediately adjacent to a fully loaded Region 2 storage rack module. Under this accident condition, credit for the presence of soluble poison is permitted by NRC guidelines*, and it is estimated that a minimum boron concentration of about 500 ppm boron would be adequate to assure that the limiting k_{eff} of 0.95 is not exceeded.

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*Double contingency principle of ANSI N16.1-1975, as specified in the April 14, 1978 NRC letter (Section 1.2) and implied in the proposed revision to Reg. Guide 1.13 (Section 1.4, Appendix A).

4.3 REFERENCE FUEL STORAGE CELLS

4.3.1 Reference Fuel Assembly

The design basis fuel assembly, illustrated in Figures 4.2 and 4.3, is a 15 x 15 array of fuel rods with 17 rods replaced by 16 control rod guide tubes and 1 instrument thimble. Table 4.3 summarizes the fuel assembly design specifications and the expected range of the significant manufacturing tolerances.

4.3.2 Region 1 Fuel Storage Cells

The nominal spent fuel storage cell used for the criticality analyses of Region 1 storage cells is shown in Figure 4.2. The rack is composed of Boral absorber material between an 9.00-inch I.D., 0.075-inch thick inner stainless steel box, and a 0.024-inch outer stainless steel cover plate. The fuel assemblies are centrally located in each storage cell on a nominal lattice spacing of 11.07 ± 0.06 inches. Stainless steel gap channels connect one storage cell box to another in a rigid structure and define an outer water space between boxes. This outer water space constitutes a flux-trap between the two (thermal-neutron opaque) Boral absorber panels. The Boral absorber has a thickness of 0.081 ± 0.004 inch and a nominal B-10 areal density of 0.0211 g/cm^2.

4.3.3 Region 2 Fuel Storage Cells

The design basis for Region 2 storage cells is fuel of 4.6 wt% U-235 initial enrichment burned to 37 MWD/KgU. In Region 2, the storage cells are composed of a single Boral absorber panel between the stainless steel walls of adjacent storage

cells. These cells, shown in Figure 4.3, are located on a lattice spacing of 9.216 ± 0.06 inches. The Boral absorber has a thickness of 0.098 ± .004 inch and a nominal B-10 areal density of 0.026 g/cm^2.

4.4 ANALYTICAL METHODOLOGY

4.4.1 Reference Design Calculations

In the fuel rack analyses, the primary criticality analyses of the high density spent fuel storage racks were performed with a two-dimensional multi-group transport theory technique, using the CASMO-2E[1] computer code. Independent verification calculations were made with a Monte Carlo technique utilizing the AMPX-KENO computer package[2], with the 27-group SCALE* cross-section library[3] and the NITAWL subroutine for U-238 resonance shielding effects (Nordheim integral treatment). Benchmark calculations, presented in Appendix A, indicate a bias of 0.0013 with an uncertainty of ± 0.0018 for CASMO-2E and 0.0106 ± 0.0048 (95%/95%) for NITAWL-KENO.

CASMO-2E was also used both for burnup calculations and for evaluating the small reactivity increments associated with manufacturing tolerances. In tracking long-term (30-year) reactivity effects of spent fuel stored in Region 2 of the fuel storage rack, previous CASMO-2E and EPRI-CELL calculations confirmed a continuous reduction in reactivity with time (after Xe decay) due primarily to Pu-241 decay and Am-241 growth.

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*"SCALE" is an acronym for Standardized Computer Analysis for Licensing Evaluation, a standard cross-section set developed by ORNL for the USNRC.

Two group diffusion theory constants, edited in the output of CASMO-2E, were used in PDQ07[5] for auxiliary calculations of the small incremental reactivity effect of eccentric fuel positioning and fuel assembly mis-placement. These constants were also used in a one dimensional diffusion theory routine (benchmarked against PDQ07) to evaluate reactivity effects of the Boral axial length.

In the geometric model used in the calculations, each fuel rod and its cladding were described explicitly and reflecting boundary conditions (zero neutron current) were used in the axial direction and at the centerline of the Boral and steel plates between storage cells. These boundary conditions have the effect of creating an infinite array of storage cells in all directions.

AMPX-KENO Monte Carlo calculations inherently include a statistical uncertainty due to the random nature of neutron tracking. To minimize the statistical uncertainty of the KENO-calculated reactivity, a minimum of 50,000 neutron histories in 100 generations of 500 neutrons each, are accumulated in each calculation.

4.4.2 Fuel Burnup Calculations and Uncertainties

CASMO-2E was used for burnup calculations in the hot operating condition. CASMO-2E has been extensively benchmarked (Appendix A and Refs. 2 and 7) against cold, clean, critical experiments (including plutonium-bearing fuel), Monte Carlo calculations, reactor operations, and heavy-element concentrations in irradiated fuel. In particular, the analyses[6] of 11 critical experiments with plutonium-bearing fuel gave an average k_{eff} of 1.002 ± 0.011 (95%/95%), showing adequate treatment of the

plutonium nuclides. In addition, Johansson[7] has obtained very good agreement in calculations of close-packed, high-plutonium-content, experimental configurations.

Since critical experiment data with spent fuel is not available for determining the uncertainty in burnup-dependent reactivity calculations, an allowance for uncertainty in reactivity was assigned based upon other considerations. Over a considerable portion of the burnup history in PWRs, the reactivity loss rate is approximately 0.01 δk for each MWD/KgU burnup, becoming smaller at the higher burnups. Assuming the uncertainty in depletion calculations is less than 5% of the total reactivity decrement, an uncertainty in reactivity* equal to 0.0005 δk for each MWD/KgU in burnup may be assigned. For the Three Mile Island Unit 1 storage racks at the design basis burnup of 37 MWD/KgU, the reactivity allowance for uncertainty is 0.0185 δk. Table 4.4 summarizes results of the burnup analyses and allowances for uncertainties at other burnups. At the higher burnups, this assumption results in an uncertainty greater than 5% of the reactivity decrement which provides an extra margin to allow for the existence of a small positive reactivity increment from the axial distribution in burnup (see Section 4.4.3). In addition, although the reactivity uncertainty due to burnup may be either positive or negative, it is treated as an additive term rather than being combined statistically with other uncertainties. Thus, the allowance for uncertainty in burnup calculations is believed to be a conservative estimate, particularly in view of the substantial reactivity decrease with aged fuel as discussed in Section 4.4.4.

*Only that portion of the uncertainty due to burnup. Other uncertainties are accounted for elsewhere.

4.4.3 Effect of Axial Burnup Distribution

Initially, fuel loaded into the reactor will burn with a slightly skewed cosine power distribution. As burnup progresses, the burnup distribution will tend to flatten, becoming more highly burned in the central regions than in the upper and lower ends. This effect may be clearly seen in the curves compiled in Ref. 9. At high burnup, the more reactive fuel near the ends of the fuel assembly (less than average burnup) occurs in regions of lower reactivity worth due to neutron leakage. Consequently, it would be expected that over most of the burnup history, distributed burnup fuel assemblies would exhibit a slightly lower reactivity than that calculated for the average burnup. As burnup progresses, the distribution, to some extent, tends to be self-regulating as controlled by the axial power distribution, precluding the existence of large regions of significantly reduced burnup.

Among others, Turner[9] has provided generic analytic results of the axial burnup effect based upon calculated and measured axial burnup distributions. These analyses confirm the minor and generally negative reactivity effect of the axially distributed burnup. The trends observed, however, suggest the possibility of a small positive reactivity effect at the high burnup values (estimated to be less than about 0.007 δk at 37 MWD/KgU) and the uncertainty in k_∞ due to burnup, assigned at the higher burnups (Section 4.4.2) is considered adequate to encompass the potential for a small positive reactivity effect of axial burnup distributions. Furthermore, reactivity significantly decreases with time in storage (Section 4.4.4 below) providing a continuously increasing margin below the 0.95 limit.

4.4.4 Long-term Changes in Reactivity

Since the fuel racks in Region 2 are intended to contain spent fuel for long periods of time, calculations were made using CASMO-2E to follow the long-term changes in reactivity of spent fuel over a 30-year period. Early in the decay period, Xenon grows from Iodine decay (reducing reactivity) and subsequently decays, with the reactivity reaching a maximum at 100-200 hours. The decay of Pu-241 (13-year half-life) and growth of Am-241 substantially reduce reactivity during long term storage, as indicated in Table 4.5. The reference design criticality calculations do not take credit for this long-term reduction in reactivity, other than to indicate an increasing subcriticality margin in Region 2 of the spent fuel storage pool.

4.5 Region 1 CRITICALITY ANALYSES AND TOLERANCES

4.5.1 Nominal Design

For the nominal storage cell design in Region 1, the CASMO-2E calculation resulted in a bias-corrected k_∞ of 0.9221 ± 0.0018, which, when combined with all known uncertainties, results in a maximum k_∞ of 0.9285. Independent calculations with AMPX-KENO gave a bias-corrected k_∞ of 0.9065 ± 0.0089, including a one-sided tolerance factor(10) for 95% probability at a 95% confidence level. Combining all known uncertainty factors, the calculated k_∞ becomes 0.908 ± 0.011 or a maximum k_∞ value of 0.919. This generally confirms the reference CASMO-2E calculations and suggests that the CASMO calculation may be conservatively high.

4.5.2 Uncertainties Due to Tolerances

4.5.2.1 Boron Loading Tolerances

The Boral absorber panels used in the storage cells are nominally 0.081 inch thick, 7.50-inch wide and 136-inch long, with a nominal B-10 areal density of 0.0211 g/cm^2. The vendors manufacturing tolerance limit is ± 0.0011 g/cm^3 in B-10 content which assures that at any point, the minimum B-10 areal density will not be less than 0.020 g /cm^2. Differential CASMO-2E calculations indicate that these tolerance limits result in incremental reactivity uncertainties of ±0.0018 δk.

4.5.2.2 Boral Width Tolerance

The reference storage cell design uses a Boral panel with an initial width of 7.50 ± 0.06 inches. For the maximum tolerance of 0.06 inch, the calculated reactivity uncertainty is +0.0007 δk.

4.5.2.3 Tolerances in Cell Lattice Spacing

The design storage cell lattice spacing between fuel assemblies is 11.07 ± 0.06. A decrease in storage cell lattice spacing may or may not increase reactivity depending upon other dimensional changes that may be associated with the decrease in lattice spacing. Decreasing the water spacing between the fuel and the inner stainless steel box results in a small decrease in reactivity. However, decreasing the flux-trap water spacing increases reactivity and both of these effects have been evaluated for their independent design tolerances.

The inner stainless steel box dimension, 9.00 ± 0.06 inches, defines the inner water thickness between the fuel and the inside box. For the tolerance limit of ± 0.06 inches, the uncertainty in reactivity is ±0.0012 δk as determined by differential CASMO-2E calculations. The design flux-trap water thickness is 1.697 ± 0.06 inches, which results in an uncertainty of ±0.0036 δk due to the tolerance in flux-trap water thickness, assuming the water thickness is simultaneously reduced on all four sides. Since the manufacturing tolerances on each of the four sides are statistically independent, the actual reactivity uncertainties would be less than ± 0.0036 δk, although the more conservative value has been used in the criticality evaluation.

4.5.2.4 Stainless Steel Thickness Tolerances

The nominal stainless steel thickness is 0.075 ± 0.005 inc for the inner stainless steel box and 0.0235 ± 0.0030 inch for the Boral cover plate. The maximum positive reactivity effect of the expected stainless steel thickness tolerance variations, was calculated (CASMO-2E) to be ±0.0008 δk.

4.5.2.5 Fuel Enrichment and Density Tolerances

The design maximum enrichment is 4.60 ± 0.05 wt% U-235. Calculations of the sensitivity to small enrichment variations by CASMO-2E yielded a coefficient of 0.0052 δk per 0.1 wt% U-235 at the design enrichment. For the assumed tolerance on U-235 enrichment of ± 0.05 wt%, the uncertainty on k_∞ is ± 0.0026 δk.

Calculations were also made with the UO_2 fuel density increased to the m ximum expected value of 10.44 g/cm^3 (stack density). For the reference design calculations, the uncertainty in reactivity is ± 0.0025 δk over the maximum expected range of UO_2 densities.

4.5.3 Eccentric Fuel Positioning

The fuel assembly is assumed to be normally located in the center of the storage rack cell. Calculations were also made with the fuel assemblies assumed to be in the corner of the storage rack cell (four-assembly cluster at closest approach). These calculations indicated that, in Region 1, the reactivity remains essentially the same (within 0.0001 δk), as determined by differential PDQ07 calculations with diffusion coefficients generated by CASMO-2E. This uncertainty is included in the

evaluation of the highest potential reactivity of the Region 1 storage cells.

4.5.4 Reactivity Effects of Boral Length

Based upon diffusion theory constants edited in the CASMO-2E output (reference design and a special case with water replacing the Boral), one-dimensional axial calculations were made to evaluate the reactivity effect of reduced Boral axial lengths. Reduced length of the Boral leaves small regions of active fuel without poison at each end of the fuel assembly. The unpoisoned region at each end is referred to as "cutback".

The axial calculations used a thick (30 cm.) water reflector, neglecting the higher absorption of the stainless-steel structural material at the ends of the fuel assembly. Results of the calculations showed that the k_{eff} remains less than the reference k_{∞} of the storage cells until the axial reduction in Boral length substantially exceeds the design 3 inch cutback top and bottom, corresponding to an overall Boral length of 136 inches. Thus, the axial neutron leakage more than compensates for the 3-inch design cutback and the reference k_{∞} remains a conservative over-estimate of the true k_{eff}.

4.6 REGION 2 CRITICALITY ANALYSES

4.6.1 Nominal Design Case

The principal method of analysis in Region 2 was the CASMO-2E code, using the restart option in CASMO-2E to analytically transfer fuel of a specified burnup into the storage rack configuration at a reference temperature of 20°C (68°F). Calculations were made for fuel of several different initial enrichments and, at each enrichment, a limiting k_∞ value was established which included an additional factor for uncertainty in the burnup analyses and for the axial burnup distribution. The restart CASMO-2E calculations (cold, no-Xenon, rack geometry) were then interpolated to define the burnup value yielding the limiting k_∞ value for each enrichment, as indicated in Table 4.6. These converged burnup values define the boundary of the acceptable domain shown in Figure 4.1. Burnup values calculated with the polynomial function given below are shown in Table 4.6 and on Figure 4.1.

For Region 2 Unrestricted Storage

Minimum Burnup in MWD/MTU =

$$- 36.0 + 27.1\ E - 4.0\ E^2 + 0.34\ E^3$$

(for initial enrichments up to 5 wt% U-235)

At a burnup of 37 MWD/KgU, the sensitivity to burnup is calculated to be 0.007 δk per MWD/KgU. During long-term storage, the k_∞ values of the Region 2 fuel rack will decrease continuously as indicated in Section 4.4.4.

An independent AMPX-KENO calculation was used to provide additional confidence in the reference Region 2 criticality analyses. Fuel of 1.75 wt% initial enrichment (equivalent to the reference rack design for burned fuel) was analyzed by AMPX-KENO and by the CASMO-2E model used for the Region 2 rack analysis. For this case, the CASMO-2E k_∞ (0.9270) at 1.75 wt% enrichment was slightly lower than the bias-corrected KENO value (0.9324 ± 0.0051, 95%/95%) obtained in the AMPX-KENO calculations. For conservatism, the nominal difference in reactivity (0.0054 δk) was added to the CASMO result in the final evaluation.

4.6.2 Uncertainties Due to Tolerances

4.6.2.1 Boron Loading Tolerances

The Boral absorber panels used in the Region 2 storage cells are 0.098 inch thick with a nominal B-10 areal density of 0.026 g/cm^2. The manufacturing limit of ± 0.006 g/cm^3 in B-10 loading assures that at any point the minimum B-10 areal density will not be less than 0.024 g/cm^2. Differential CASMO-2E calculations indicate that this tolerance limit results in an incremental reactivity uncertainty of ± .0035 δk.

4.6.2.2 Boral Width Tolerance

The reference storage cell design for Region 2 (Figure 4.3) uses a Boral absorber width of 7.50 ± 0.06 inches. This tolerance results in a reactivity uncertainty of ± 0.0009 δk.

4.6.2.3 Tolerance in Cell Lattice Spacing

The manufacturing tolerance on inner box dimension affects the storage cell lattice spacing between fuel assemblies in Region 2 is ± 0.06 inches. This corresponds to an uncertainty in reactivity of ± 0.0016 δk.

4.6.2.4 Stainless Steel Thickness Tolerance

The nominal thickness of the stainless steel box wall is 0.075 inch with a tolerance of ±0.005 inch, resulting in an uncertainty in reactivity of ±0.0001 δk.

4.6.2.5 Fuel Enrichment and Density Tolerances

Uncertainties in reactivity due to tolerances on fuel enrichment and UO_2 density in Region 2 are assumed to be the same as those determined for Region 1.

4.6.3 Eccentric Fuel Positioning

The fuel assembly is assumed to be normally located in the center of the storage rack cell. Calculations were also made with the fuel assemblies assumed to be in the corner of the storage rack cell (four-assembly cluster at closest approach). These calculations indicated that eccentric fuel positioning results in a decrease in reactivity by about 0.003 δk, as determined by PDQ07 calculations with diffusion coefficients generated by CASMO-2E. The highest reactivity, therefore, corresponds to the reference design with the fuel assemblies positioned in the center of the storage cells.

4.6.4 Reactivity Effect of Boral Length

Because the ends of the fuel assemblies in Region 2 have less burnup than the average, and hence are more reactive, an axial cutback is not used in this region.

4.7 ABNORMAL AND ACCIDENT CONDITIONS

4.7.1 Temperature and Water Density Effects

The moderator temperature coefficient of reactivity is negative; a moderator temperature of 20°C (68°F) was assumed for the reference designs, which assures that the true reactivity will always be lower over the expected range of water temperatures. Temperature effects on reactivity have been calculated and the results are shown in Table 4.7. Introducing voids in the water internal to the storage cell (to simulate boiling) decreased reactivity, as shown in the table. Since, at saturation temperature there is no significant thermal driving force, voids due to boiling will not occur in the outer (flux-trap) water region of Region 1.

With soluble poison present, the temperature coefficients of reactivity would differ from those inferred from the data in Table 4.7. However, the reactivities would also be substantially lower at all temperatures with soluble boron present, and the data in Table 4.7 is pertinent to the higher-reactivity unborated case.

4.7.2 Dropped Fuel Assembly

For a drop on top of the rack, the fuel assembly will come to rest horizontally on top of the rack with a minimum separation distance from the fuel in the rack of more than 9 $^1/_2$ inches, including an estimated allowance for deformation under seismic or accident conditions (1 inch). Calculations show that, at this separation distance, the effect on reactivity is insignificant (<0.0001 δk). Furthermore, soluble boron in the pool water would substantially reduce the reactivity and assure that the true reactivity is always less than the limiting value

for any conceivable dropped fuel accident.

4.7.3 Lateral Rack Movement

Lateral motion of the rack modules under seismic conditions could potentially alter the spacing between rack modules. However, the maximum rack movement has been determined to be less than 0.35 inches under the design basis seismic event (See Table 6.6, Section 6). In Region 1, the water gap between rack modules nominally 3 inches, which, if reduced by 0.35 inches, would still be larger than the corresponding design water-gap spacing (1.697") internal to the rack modules. Region 2 storage cells do not use a flux-trap and the reactivity is therefore insensitive to the spacing between modules. The spacing between Region 1 and Region 2 modules is sufficiently large to preclude adverse interaction even with the maximum seismically-induced reduction in spacing. Furthermore, soluble poison would assure that a reactivity less than the design limitation is maintained under all accident or abnormal conditions.

4.7.4 Abnormal Location of a Fuel Assembly

The abnormal location of a fresh unirradiated fuel assembly of 4.6 wt% enrichment could, in the absence of soluble poison, result in exceeding the design reactivity limitation (k_{eff} of 0.95). This could occur if a fresh fuel assembly of the highest permissible enrichment were to be either positioned outside and adjacent to a storage rack module or inadvertently loaded into a Region 2 storage cell. Calculations (2-dimensional PDQ) showed that the highest reactivity, including uncertainties, for these postulated accident conditions were as follows:

- o Assembly outside Region 1, maximum k_{eff} = 0.992
- o Assembly outside Region 2, maximum k_{eff} = 1.001

o Fresh assembly in Region 2, maximum k_{∞} = 0.9744

Soluble boron in the spent fuel pool water, for which credit is permitted under these accident conditions, would assure that the reactivity is maintained substantially less than the design limitation. It is estimated that a soluble poison concentration of about 500 ppm boron would be sufficient to maintain a k_{∞} less than 0.95 (including uncertainties) under the maximum postulated accident condition.

4.8 REFERENCES

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5. W.R. Cadwell, PDQ07 Reference Manual, WAPD-TM-678, Bettis Atomic Power Laboratory, January 1967.

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Table 4.1

SUMMARY OF CRITICALITY SAFETY ANALYSES

	Region 1	Region 2
Design Basis burnup at 4.6% initial enrichment	0	37 MWD/KgU
Temperature for analysis	20°C (68°F)	20°C (68°F)
Reference k_∞ (CASMO-2E)	0.9208	0.9082
Calculational bias, δk[1]	0.0013	0.0013
Uncertainties		
Bias	± 0.0018[1]	± 0.0018[1]
B-10 loading	± 0.0018[2]	± 0.0035[3]
Boral width	± 0.0007[2]	± 0.0009[3]
Inner box dimension	± 0.0012[2]	± 0.0016[3]
Water gap thickness	± 0.0036[2]	NA
SS thickness	± 0.0008[2]	± 0.0001[3]
Fuel enrichment	± 0.0026[2]	± 0.0026[4]
Fuel density	± 0.0025[2]	± 0.0025[4]
Eccentric position	± 0.0025[5]	Negative[6]
Statistical combination of uncertainties[7]	± 0.0064	± 0.0056
Allowance for Burnup Uncertainty	NA	+ 0.0185
Adjustment from Keno Calculation	Negative	+ 0.0054
Total	0.9221 ± 0.0064	0.9334 ± 0.0056
Maximum Reactivity (k_∞)	0.9285	0.9390

(1) Section 4.4.1
(2) Section 4.5.2
(3) Section 4.6.2
(4) For fuel tolerances, uncertainties in Region 2 assumed to be the same as those for Region 1.
(5) Section 4.5.3
(6) Section 4.6.3
(7) Square root of sum of squares.

Table 4.2

REACTIVITY EFFECTS OF ABNORMAL AND ACCIDENT CONDITIONS

Accident/Abnormal Conditions	Reactivity Effect
Temperature increase (above 68°F)	Negative (Table 4.7)
Void (boiling)	Negative (Table 4.7)
Assembly dropped on top of rack	Negligible (<0.0001 δk)
Lateral rack module movement	Negligible (<0.0001 δk)
Misplacement of a fuel assembly	Positive (0.062 Max δk)

Table 4.3

DESIGN BASIS FUEL ASSEMBLY SPECIFICATIONS

<u>FUEL ROD DATA</u>	
Outside diameter, in.	0.430
Cladding thickness, in.	0.0265
Cladding inside diameter, in.	0.377
Cladding material	Zr-4
Pellet density, % T.D.	95.0
Stack density, g UO_2/cc	10.225 ± 0.21
Pellet diameter, in.	0.369
Maximum enrichment, wt % U-235	4.60 ± 0.05
<u>FUEL ASSEMBLY DATA</u>	
Fuel rod array	15x15
Number of fuel rods	208
Fuel rod pitch, in.	0.568
Number of control rod guide and instrument thimbles	17
Thimble O.D., in. (nominal)	0.530
Thimble I.D., in. (nominal)	0.498

Table 4.4

ALLOWANCE FOR UNCERTAINTIES IN REACTIVITY DUE TO DEPLETION CALCULATIONS

Initial Enrichment	Design Burnup MWD/KgU	Uncertainty due to Burnup, δk	Design limit k_∞ [1]
1.75	0	0	0.9270
2.0	4.928	0.0025	0.9245
2.5	11.93	0.0060	0.9210
3.0	18.32	0.0092	0.9178
3.5	24.41	0.0122	0.9148
4.0	30.36	0.0152	0.9118
4.6	37.00	0.0185	0.9085
5.0	41.58	0.0208	0.9062

(1) The design limit k_∞ is determined by subtracting the burnup-dependent allowance for uncertainty (Column 3) from the design basis k_∞ (0.9270) for unburned fuel of 1.75% enrichment. With all uncertainties added (Table 4.1), the maximum k_∞ is 0.9393 in all cases.

Table 4.5

LONG-TERM CHANGES IN REACTIVITY IN STORAGE RACK
CALCULATED BY CASMO-2E

Storage Time, years	δk from Shutdown (Xenon-free) at 4.6 wt% E and 37 MWD/KgU
1.0	+0.0012
4.0	-0.0056
10.0	-0.0198
20.0	-0.0371
30.0	-0.0477

Table 4.6

FUEL BURNUP VALUES FOR REQUIRED REACTIVITIES (k_∞)
WITH FUEL OF VARIOUS INITIAL ENRICHMENTS

Calculated Initial Enrichment	Uncertainty [1] in Burnup, δk	Design[2] Limit k_∞	Burnup limit[3] MWD/KgU	
1.75	0	0.9270	0.	(0.997)
2.0	0.0025	0.9245	4.928	(4.920)
2.5	0.0060	0.9210	11.93	(12.06)
3.0	0.0092	0.9178	18.32	(18.48)
3.5	0.0122	0.9148	24.41	(24.43)
4.0	0.0152	0.9118	30.36	(30.16)
4.6	0.0185	0.9085	37.00	(37.11)
5.0	0.0208	0.9062	41.58	(42.00)

(1) See Section 4.4.2

(2) See Table 4.4

(3) Parenthetical values are calculated from the polynomial fit for unrestricted storage in Region 2.

Table 4.7

EFFECT OF TEMPERATURE AND VOID ON CALCULATED REACTIVITY OF STORAGE RACK

Case	Incremental Reactivity Change, δk	
	Region 1	Region 2
20°C (68°F)	Reference	Reference
40°C (104°F)	-0.003	-0.002
60°C (140°F)	-0.007	-0.005
90°C (194°F)	-0.013	-0.010
120°C (248°F)	-0.022	-0.016
120°C (248°F) + 20% void	-0.083	-0.061

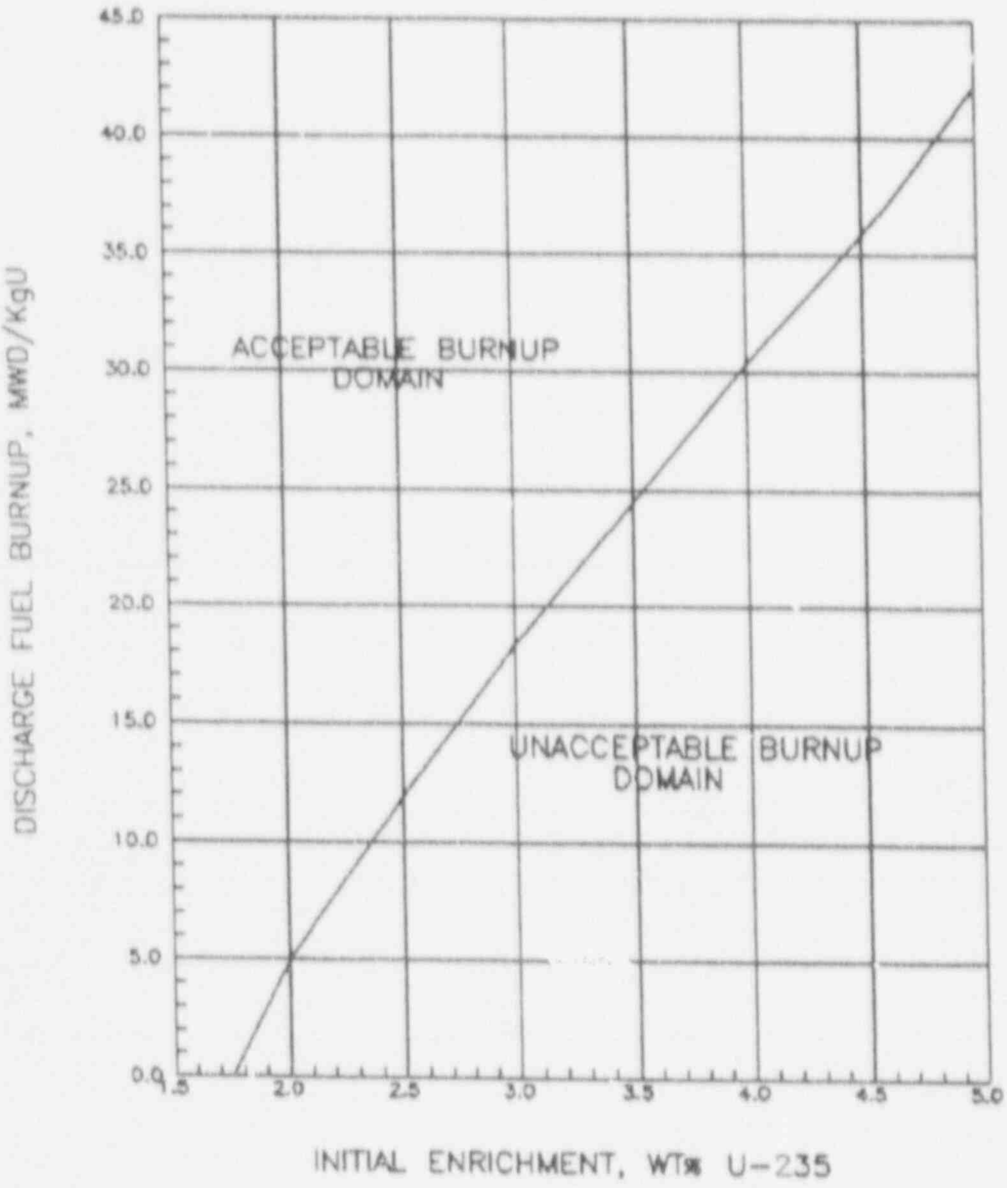

Fig 4.1 Relationship between Initial Enrichment and Acceptable Fuel Burnup (Region II)

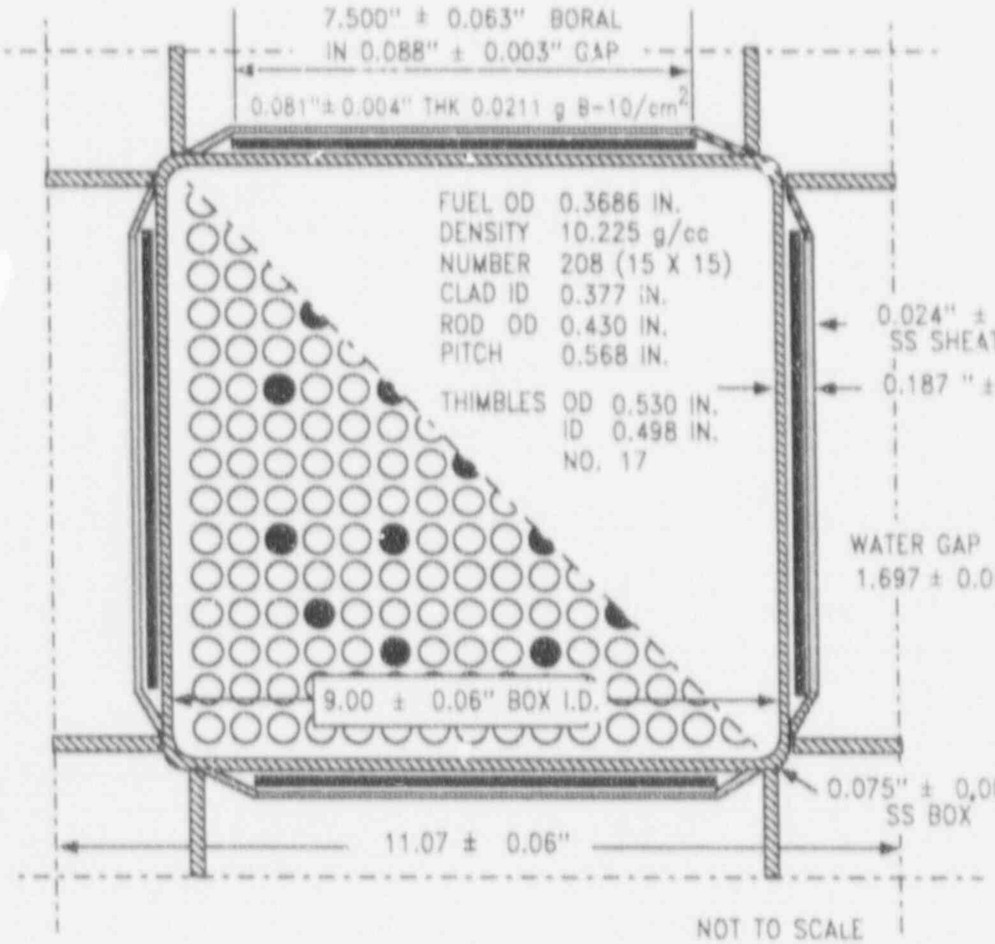

Fig. 4.2 CROSSECTION OF REGION 1 STORAGE CELL

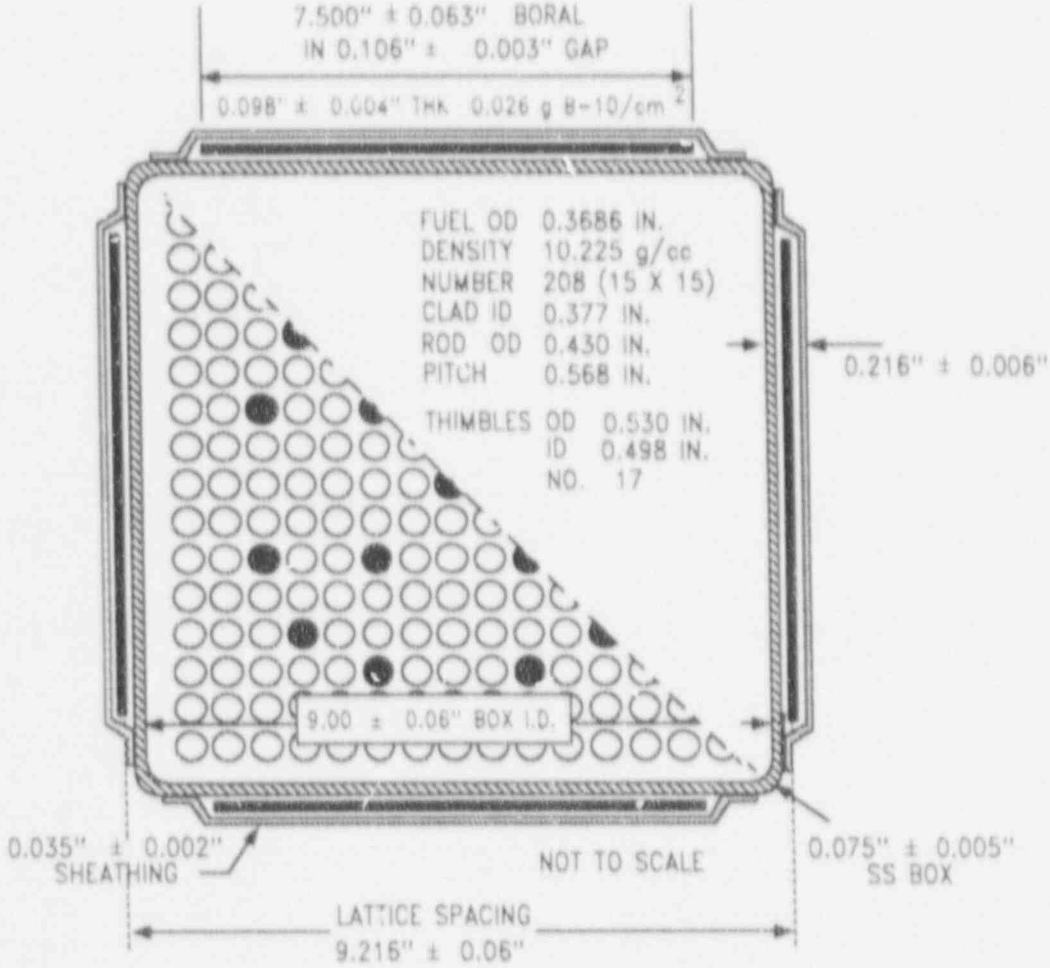

Fig. 4.3 CROSSECTION OF REGION 2 STORAGE CELL

Table 5.6.2

Data for Local Temperature

Type of Fuel Assembly	PWR (15x15)
Fuel Cladding Outer Diameter, inches	0.43
Fuel Cladding Inside Diameter, inches	0.377
Storage Cell inside Dimension, inches	9.0
Active fuel length, inches	141.8
No. of Fuel Rods/Assembly	208
Operating Power per Fuel Assembly P_o x -6, Btu/hr	49.53
Cell pitch, inches	9.216
Cell height, inches	163
Plenum radius, feet	20.5
Bottom height, inches	4.25
Min. gap between pool wall and outer rack periphery, inches	2

b. Dropped Fuel Assembly Accident II

One fuel assembly dropping from elevation 355'-0" above the rack and hitting the top of the rack. Permanent deformation of the rack is acceptable, but is required to be limited to the top region such that the rack cross-sectional geometry at the level of the top of the active fuel (and below) is not altered. Analysis dictates that the maximum local stress at the elevation of the top of the active fuel region is less than material yield point. Thus, the functionality of the rack is not affected. Although local deformation occurs, it is confined to a region above the active fuel area.

c. Dropped Fuel Assembly Accident III

This postulated accident is identical to (a) above except that the fuel assembly is assumed to drop in an inclined manner on top of the rack. Analyses show that the straight drop case (case b above) bounds the results.

Other heavy objects carried over the fuel racks are smaller in weight than the fuel assembly. Therefore, fuel assembly drop scenario governs the rack design. This analysis limits the maximum elevation of the bottom of all heavy objects carried over the pool to 355'-0". Analysis of Drop Case I indicated that if the drop were to occur on to a cell directly above a support leg then the local slab bearing stress will be exceeded. Bearing pads are interposed between the rack feet and the pool liner to diffuse the pressure, and bring the pool slab surface pressure to within the ACI allowable value.

it is surrounced by a random batch of spent fuel discharged from the pool. This batch of coupons is designated for "long term surveillance".

The batch of coupons in the second "tree" is intended for accelerated exposure. This tree is placed in the center of a group of freshly discharged fuel assemblies each time a new batch is discharged to the pool. The group of assemblies surrounding the accelerated exposure tree should be those which have the highest values of radial peaking factor. The object, of course, is to subject this "tree" to the maximum radiation exposure in the fuel pool in the minimum amount of time.

Direct Surveillance

In contrast to "coupon surveillance", direct surveillance involves testing the poison panels themselves. As a result, cracks in the poison panel, or even depletion of boron carbide can be identified. However, since the testing is essentially a remotely executed operation, the physical state of the poison (viz its state of embrittlement, warpage, etc.) cannot be ascertained.

The principal direct testing technique is the so-called Blackness Testing Method. It is a rapid, albeit imprecise, method. It is well suited for an expeditious assay of all storage locations to detect the incidence of B-10 deficiencies. If the test yields suspect locations, then those shall be examined by the much slower, but markedly more accurate, procedure of neutron radiography. This two step process was successfully used to conclusively identify the cracks in the Quad Cities rack module poison panels.