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APPENDIX 6A

EVALUATION OF FUEL UNDER ACCIDENT ACCELERATIONS

This appendix evaluates the effect of TN-68 cask impact (tipover or bottom-end drop) on the integrity of fuel rod cladding. The material properties of irradiated zircalloy cladding and the rod impact stress analysis approach are based on LLNL Report UCID-21246(1). The fracture analysis of the fuel rod cladding is based on the ASME Code, Section XI, 1989(2). The irradiated zircalloy fracture toughness data is obtained from ASTM Special Technical Publication 551(3). Presented below are the analyses and results that are used to conclude that the fuel rod cladding will remain intact and retain the fuel pellets during all accident scenarios. The high burn up fuel assemblies give higher temperature and lower material properties, therefore, are used for this evaluation.

6A.1 Material Properties

This section establishes the basis for assuming particular material properties. The value of some of the parameters used in the analysis are temperature dependent. The maximum temperature during dry storage is not expected to exceed 622°F. However, the fuel cladding properties are conservatively taken at 750°F. Consequently, material properties will be based upon this temperature, with the expectation that the ability of the zircalloy to absorb impact loads without rupture will increase as the temperature decreases with time.

Weight Density

The weight density of both Zircalloy-2 and Zircalloy-4 is very close to the weight density of Zirconium itself. From Reference 1,

$$\rho_{tube} = 0.234 \text{ lb/in}^3$$

Young's Modulus

The Young's modulus for typical Zircalloy cladding is illustrated in Table 5 of Reference 1. Thus, at 750°F,

$$E_{tube} = 10.4 \times 10^6 \text{ psi}$$

$$E_{fuel} = 23.6 \times 10^6 \text{ psi}^{(10)}$$

Yield Strength

The yield strength for typical Zircalloy cladding is illustrated in Table 5 of Reference 1. Thus, at 750°F,

$S_{yield\text{-}tube}$ = 80,500 psi

6A.2 Tipover or Side Drop

6A.2.a Fuel Rods Supported by Spacer Grids

The fuel rod side impact stresses are computed by idealizing fuel rods as continuous beams supported at each spacer grid. Continuous beam theory is used to determine the maximum bending moments and corresponding stresses in the cladding tube. The methodology used in performing the analysis is based on work done at Lawrence Livermore National Labs (Ref. 1). The fuel gas internal pressure is assumed to be present and the resulting axial tensile stress is added to the bending tensile stress due to 80G load (Appendix 3D, Section 3D.6.2). The stresses for different General Electric fuel assemblies are computed in Table 6A-1. It is seen that the 49,422 psi is the highest stress and occurs in GE12-10×10 fuel assembly. This stress is lower than the yield strength of zircalloy (80,500 psi). It is, therefore, concluded that the fuel tube will not fail and will withstand the side drop load without excessive plastic deformations. The grid supports (spacers) are expected to crush before 80G load is developed and the actual tube stresses will be much lower than the above noted stresses.

6A.2.b Fuel Rod Overhanging at Basket Top End

The length of TN-68 fuel basket is 164 inches. The length of the cavity inside the TN-68 storage cask is 178 inches. The maximum possible overhanging fuel assembly length not supported by the basket during a cask side drop is 178 - 164 = 14 inches. The stress in this overhanging fuel rod beyond the basket is calculated and evaluated against the yield stress of the fuel rod. Assembly GE12 10×10 is calculated to have the highest stress in the fuel rod during the side drop (see Table 6A-1). The GE12 10×10 fuel assembly is therefore selected for evaluation of the fuel rod stress under the overhanging load.

The 14 inch overhanging length at the top end of the fuel assembly will include 8.34 inch long end fittings and a portion of fuel tube at a length of 5.66 inches. The end fittings weigh 5.5754 kg/assembly. This weight of the top end fittings is assumed to be uniformly distributed among all fuel tubes in an assembly. The weight exerted on each fuel tube of the GE12 10×10 fuel assembly by its top end fittings is therefore 0.1573 lb (5.5754 kg × 2.2 lb/kg / 78 tubes). The weight of 5.66 inch length of the fuel rod is 0.0409 lb (1.084 lb / 150 in. × 5.66 in. from Table 6A-1). The total weight exerted on the 14 inch overhanging length of the fuel rod is therefore 0.1982 lb (0.1573 lb + 0.0409 lb). This weight will produce a bending moment of 1.3874 in-lb (0.1982 lb × 14in. / 2) at the supported end of the overhanging fuel rod section. The resultant maximum bending stress in the fuel rod is then 560 psi ($\sigma_b = M c / I$ = 1.3874 in-lb × 0.404 in. / 2 / 0.0005 in^4, *c* and *I* are taken from Table 6A-1).

At 80g,

$\sigma_b = 80 \times 560 = 44{,}800$ psi

Axial Pressure Stress = 11,519 psi (See Table 6A-1)

Combined Stress = 44,800 + 11,519 = 56,319 psi

This stress is significantly less than the yield stress of 80,500 psi for the fuel rod. It is therefore concluded that the overhanging fuel rod during a side drop is structurally acceptable.

6A.3 Bottom End Drop

In case of an end drop, the inertial forces load the rod as a column having intermediate supports at each grid support (spacer). The tube limit load is that at which the fuel rod segments between the supports become unstable.

An elastic-plastic stress analysis was performed using the ANSYS Finite Element Program (Ref. 6). A three-dimensional finite element model of entire active tube length was constructed using plastic PIPE20 element for cladding tube and elastic PIPE16 element for fuel. The hinge supports were modeled at 7 grid support locations. The finite element model and support conditions for a typical tube model are shown in Figure 6A-1. The tube and fuel nodes were coupled in X, Y and Z directions. The following material properties (at 750°F) were input as a bilinear kinematic stress-strain curve for Zircalloy cladding tube. These properties are taken from Reference 1.

Yield Strength = 80,500 psi
Ultimate Strength = 92,000 psi
Modulus of elasticity = 10.4×10^6 psi
Poisson's ratio = 0.3
Elongation = 1.6%
Max. elastic strain = $80{,}500/10.4\times10^6$ = 0.00774 in/in
Tangent Modulus = (92,000 – 80500) / (0.016 – 0.00774) = 1.39×0^6 psi

For fuel elements,

Modulus of elasticity = 23.6×10^6 psi (Ref. 10, Fig. A-5.1)
Poisson's ratio = 0.316 [10]

The tube densities were modified to compensate for the extra tube length and the components, which were included in the finite element model. The calculations of equivalent tube and fuel densities are shown in Table 6A.2.

In order to get the tube-buckling load, the large displacement option of ANSYS was used. The maximum inertia force of 200G was used. This load was applied gradually in a number of sub-steps. A small lateral load (0.0005 lb) was applied at the middle of the lowest segment to introduce an initial deflection and bending. The analysis was continued to load sub-step till the tube model became unstable and did not converge. The last converged load sub-step was taken as the plastic instability load. The above analysis was repeated for one fuel rod of each fuel subassembly. All the input data and the resulting plastic instability

loads are summarized in Table 6A-2. 70% of ANSYS plastic instability load is used as the allowable buckling load (Reference 7, Para. F-1341.4).

Since the internal pressure produces tensile stresses in the cladding, it will reduce the compressive stresses caused by the end drop impact. The pressure is therefore conservatively neglected in this analysis.

From the results in Table 6A-2, it is seen that the lowest tube-buckling load of 105G occurs in GE2, GE3 - 7×7, fuel assemblies. It may be noted that the axial stresses in the fuel rods are also quite small (105 × 12.045 / (0.0499 + 0.1863) = 5,354 psi). The actual end drop impact load is 80 G (Appendix 3D, Section 3D.7.3). It is, therefore, concluded that the fuel cladding tubes will not be damaged during an end drop.

6A.4 Brittle Fracture Evaluation

The following section is to demonstrate that the fracture toughness of the irradiated zircalloy cladding is sufficiently high to preclude brittle fracture failure during accident conditions.

The EPRI report, reference 5, provides a definition of pin holes or hairline cracks to include cracks of maximum width about 100µm (0.004") but whose length could be anywhere between 200-300 µm (.008" – 0.012") and several millimeters. For conservatism, the following surface flaw size is used for brittle fracture evaluation of the fuel rod cladding:

a= flaw depth = 150 µm = 0.006"
l = flaw length = 4 mm = 0.16"

Stress intensity factor K_I is calculated using the equation in ASME Code, Section XI, Appendix A, Article A-3000. The crack location and orientation are assumed as to be most detrimental to the rod cladding:

$$K_I = (\sigma_m M_m + \sigma_b M_b) \sqrt{\pi} \sqrt{a/Q}$$

Where

σ_m, σ_b = membrane and bending stresses in psi

a = flaw depth

Q = flaw shape parameter as determined from Appendix A, Fig. A-3300-1

M_m = correction factor for membrane stress from Appendix A, Fig. A-3300-3

M_b = correction factor for bending stress from Appendix A,
Fig. A-3300-5

It is seen from the above analysis that the combined tensile stress in GE12-10×10 fuel rod cladding is the highest (56,319 psi). This fuel rod is, therefore, selected for a fracture evaluation. It is conservatively assumed that all the stresses are membrane stresses.

The following flaw size is assumed in the fracture evaluation:

t = cladding thickness = 0.024 inch
a = crack depth = 0.006 inch
l = crack length = 0.16 inch
a/t = 0.006/0.024 = 0.25
a/l = 0.006/0.16 = 0.0375
Zircaloy yield strength, S_y = 80,500 psi
$(\sigma_m + \sigma_b) / S_y = (56{,}319)/ 80{,}500 \approx 0.7$
Flaw shape parameter, Q (from Fig. A-3300-1) = 0.9
Membrane stress factor, M_m, (from Fig. A-3300-3) = 1.38

$K_I = [(56{,}319 \times 1.38) (\sqrt{\pi} \times \sqrt{0.006/0.9})]$
$= 11{,}248$ psi $\sqrt{\text{inch}} \approx 11.25$ ksi $\sqrt{\text{in}}$

The calculated Stress Intensity Factor for the flaw should satisfy the code faulted condition criteria (ASME Code Section XI, para. IWB-3612):

$$K_I < K_{ic} / \sqrt{2}$$

Where K_{ic} is the material fracture toughness based on fracture initiation for the corresponding crack tip temperature.

K_{ic} from Ref. 3 at 200^{o} F (conservatively use lower temp.) = 30.0 ksi $\sqrt{\text{in}}$

Allowable fracture toughness = 30.0 / 1.414
= 21.2 ksi $\sqrt{\text{in}}$ > 11.25 ksi $\sqrt{\text{in}}$

Based on the above evaluations, it is concluded that the fracture toughness of the irradiated Zircalloy cladding is sufficiently high to preclude a brittle fracture failure during accident conditions. Therefore, the fuel cladding tube will remain intact to retain the fuel pellets during the accident conditions

6A.5 References

1. LLNL Report UCID-21246, Dynamic Impact Effects on Spent Fuel Assemblies.

2. ASME Boiler and Pressure Vessel Code, Section XI, 1989.

3. ASTM Special Technical Publication 551, Variation of Zircalloy Fracture Toughness in Irradiation, Walker and Kass.

4. PNL-6189, Recommended Temperature Limits for Dry Storage of Spent Light Water Reactor Zircalloy-Clad Fuel Rods in Inert Gas, May 1987.

5. EPRI report, 1994, Irradiation Damage to Fuel Assemblies.

6. ANSYS Engineering Analysis System User's Manual, Rev. 6.0.

7. ASME Code Section III, Division 1 Appendices, 1995.

8. Timoshenko, "Strength of Materials", Part II, 3rd Edition.

9. Roark, "Formulas for Stress and Strain", 4th Edition.

10. NUREG/CR-0497, TREE-1280, MATPRO-Version 11, A Hand Book of Materials Properties for use in the Analysis of Light Water Reactor Fuel Rod Behavior.

<u>Table 6A-1</u>
<u>Tipover/ Side Drop Impact Stress Calculations</u>

Tube Arrays	7x7	8x8	8x8	8x8	8x8	9x9	10x10
GE Designation	GE2, GE3	GE4	GE5	GE8	GE9, GE10	GE11, GE13	GE12
No. of Fuel Rods	49	63	62	60	60	66	78
Active Fuel Length (inch)	144	146	150	150	150	146	150
Fuel Rod O.D. (in)	0.563	0.493	0.483	0.483	0.483	0.44	0.404
Corroded Fuel Rod O.D.[(2)] (in)	0.559	0.489	0.479	0.479	0.479	0.436	0.4
Clad Thickness (in)	0.032	0.034	0.032	0.032	0.032	0.028	0.026
Corroded Clad Thickness[(3)] (in)	0.03	0.032	0.03	0.03	0.03	0.026	0.024
Fuel Pellet O.D. (in)	0.487	0.416	0.41	0.41	0.411	0.376	0.345
Fuel Rod I.D. (in)	0.499	0.425	0.419	0.419	0.419	0.384	0.352
Fuel Tube Radius Avg (in)	0.2645	0.2285	0.2245	0.2245	0.2245	0.205	0.188
Number Of Spacers	7	7	7	7	7	7	7
Fuel Span (in)	24.0	24.3	25.0	25.0	25.0	24.3	25.0
Fuel Tube Area (in^2)	0.0499	0.0459	0.0423	0.0423	0.0423	0.0335	0.0283
Fuel Tube M.I. (in^4)	0.00175	0.00121	0.00107	0.00107	0.00107	0.00071	0.00050
Fuel Pellet M.I. (in^4)	0.00276	0.00147	0.00139	0.00139	0.00140	0.00098	0.00070
Total Tube M.I.+ FUEL M.I.	0.00451	0.00268	0.00246	0.00246	0.00247	0.00169	0.00120
Uncorroded Fuel Tube Wt (lb) [(3)]	1.799	1.675	1.592	1.592	1.592	1.238	1.084
Fuel Wt (lb) [(3)]	10.246	7.580	7.565	7.565	7.602	6.193	5.357
Total Tube + Fuel Wt (lb)	12.045	9.256	9.157	9.157	9.194	7.431	6.440
$M=0.1058wl^2$ (in-lb)	5.098	3.971	4.037	4.037	4.053	3.188	2.839
Sb for 1g = MC/I (psi)	315.9	362.9	393.3	393.3	392.7	411.9	473.8
Sb for 80g (psi)	25,269	29,035	31,461	31,461	31,414	32,949	37,903
Yield Strength(psi) @ 750°F	80,500	80,500	80,500	80,500	80,500	80,500	80,500
Max. internal pressure (psia)	2,177	2,181	2,925	3,013	2,974	3,052	2,941
S_p Axial Stress (psi) [(1)]	9,597	7,787	10,944	11,274	11,128	12,032	11,519
Total Combined Stress (psi)	**34,866**	**36,822**	**42,405**	**42,735**	**42,542**	**44,981**	**49,422**

Notes:
(1) S_p, axial stress = p x R_{avg}/2t
(2) Includes 0.004 in. reduction in cladding OD to account for water side cladding corrosion (Ref 4).
(3)Thickness is reduced by 0.002 in. to account for corrosion (Ref 4).

Table 6A-2
Tube Buckling Loads Due to End drop Impact

Tube Arrays	7x7	8x8	8x8	8x8	8x8	9x9	10x10
GE Designation	GE2, GE3	GE4	GE5	GE8	GE9, GE10	GE11, GE13	GE12
No. of Fuel Rods	49	63	62	60	60	66	78
Max. Tube Length (in)[(2)]	176.2	176.2	176.2	176.2	176.2	176.2	176.2
Active Fuel Length (in)	144	146	150	150	150	146	150
Number Of Spacers	7	7	7	7	7	7	7
Fuel Span (in)	24.0	24.3	25.0	25.0	25.0	24.3	25.0
Fuel Rod O.D. (in)	0.563	0.493	0.483	0.483	0.483	0.44	0.404
Corroded Fuel Rod O.D. (in)	0.559	0.489	0.479	0.479	0.479	0.436	0.4
Clad Thickness (in)	0.032	0.034	0.032	0.032	0.032	0.028	0.026
Corroded Clad Thickness (in)	0.03	0.032	0.03	0.03	0.03	0.026	0.024
Fuel Pellet O.D. (in)	0.487	0.416	0.41	0.41	0.411	0.376	0.345
Fuel Rod I.D. (in)	0.499	0.425	0.419	0.419	0.419	0.384	0.352
Fuel Tube Area (in^2)	0.0499	0.0459	0.0423	0.0423	0.0423	0.0335	0.0283
Fuel Area (in^2)	0.1863	0.1359	0.1320	0.1320	0.1327	0.1110	0.0935
Uncorroded Fuel Tube Wt (lb)	1.799	1.675	1.592	1.592	1.592	1.238	1.084
Fuel Wt (lb)	10.246	7.580	7.565	7.565	7.602	6.193	5.357
Total Tube + Fuel Wt (lb)	12.045	9.256	9.157	9.157	9.194	7.431	6.440
Equiv. Density Tube [(1)] (lb/in^3)	0.286	0.282	0.275	0.275	0.275	0.282	0.275
Equiv. Density Fuel[(2)] (lb/in^3)	0.382	0.382	0.382	0.382	0.382	0.382	0.382
ANSYS Plastic Instability Load (G)	149.5	≥ 200	≥ 200	≥ 200	≥ 200	≥ 200	≥ 200
Allowable Buckling Load (70%) (G)	**105**	≥140	≥140	≥140	≥140	≥140	≥140

Notes:
(1) Equivalent. Density Tube = (0.234 x Max. tube length)/ Active tube length modeled
(2) Equivalent. Density Fuel = Fuel Weight / (Fuel area x Active tube length modeled)
(3) Zircaloy Density = 0.234 $lb/in.^3$

Figure 6A-1
Tube and Fuel Pellets Finite Element Model Simulation