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APPENDIX 3E

FRACTURE TOUGHNESS EVALUATION OF TN-68 CASK

3E.1 Introduction

This appendix documents the fracture toughness requirements of the TN-68 confinement boundary and also calculates the allowable flaw sizes of the gamma shield and welds. The results of the flaw sizes can be used to develop an appropriate inspection program and select an appropriate inspection technique to properly inspect the cask. It can also be used as an initial screening criteria to disposition any indications which are detected during inspection.

The analysis is first performed for conditions corresponding to a 21.2 kW cask thermal load and is then scaled to conditions at 30 kW.

3E.1.1 Fracture Toughness Evaluation of Confinement Boundary

The TN-68 confinement boundary material is a ferritic steel and is therefore subject to fracture toughness requirements in order to assure ductile behavior at the lowest service temperature (LST) of –20°F. The confinememt boundary materials (including lid bolts) are selected to meet the fracture toughness criteria of ASME Code Section III, Division 3[(1)], Subsection WB. The cask shell & bottom plate are 1.5 inches thick, the flange is 7.5 inches thick, and the lid plate is 5 inches thick. Therefore, by interpolating between values provided in Table WB-2331.2-1 of the Section III, Subsection WB (Para. WB-2300), the nil ductility transition temperatures (T_{NDT}) of the confinement boundary materials are:

- Shell and bottom plates: -80°F
- Flange: -133°F
- Lid plate: -126°F

In addition to determining the nil ductility transition temperature, charpy v-notch testing shall be performed at a temperature no greater than 60°F above the T_{NDT}. The acceptance criteria is that the material exhibit at least 35 mils lateral expansion and not less than 50 ft-lbs absorbed energy. This testing is sufficient to ensure that the confinement boundary materials will not be susceptible to brittle fracture at –20°F.

The fracture toughness requirements of the lid bolts will meet the criteria of ASME Code, Section III, Division 3, Subsection WB (Para. WB-2333). Charpy v-notch testing shall be performed at –20°F. The acceptance criteria is that the material exhibit at least 25 mils lateral expansion (Table WB-2333-1).

3E.1.2 Fracture Toughness Evaluation of gamma shield

The gamma shield shell is forged from SA-266 Grade 2 material. The bottom shield plate is constructed from either SA-105 forging or SA-516 Grade 70 material, and

top shield plate (plate welded to the bottom of the lid) is constructed from either SA-266 Grade 2 material, or SA-516 Grade 70 material. The main function of the gamma shield is to provide shielding. It is not part of the confinement, and its shielding properties are not temperature dependent.

In storage, the gamma shielding is not subjected to any significant loads. The worst case loading is due to the non-mechanistic tipover. The TN-68 cask is shown not to tipover during storage due to normal, off-normal or accident events. Nevertheless, a tipover event is evaluated. If the cask were to tipover at an ambient temperature of -20°F, it would not crack due to its reasonable fracture toughness at low temperature. However, even if it were to crack, there would be no breach of confinement, since the confinement materials have exceptional fracture toughness at low temperatures.

Furthermore, if the cylindrical gamma shielding were to crack, there is no credible mechanism for the shielding to separate from itself or the confinement. In order for this to occur, the 6 inch thick shell must become completely severed, and there would need to be a sufficient axial force to overcome the frictional forces holding the confinement vessel and the gamma shielding together resulting from the shrink fit. The top shield plate is welded to the lid and is captured by the confinement vessel. Even, if it is postulated that the weld fails completely, the shield plate will still remain inside the confinement boundary and will not lose its shield capability. The one exception is the weld of the gamma shield shell to the bottom plate. In this region, if the weld were to completely fail, the bottom plate could become detached and have an impact on the shielding capability of the cask.

Preliminary charpy test data of the same material (SA-266) from a similarly sized shield shell has been provided by one of the material manufacturers for the shield shell, and the results are tabulated below.

Charpy V-Notch Test – Results for SA-266 Gr. 2

Temperature	Specimen No.	Absorbed Energy (ft-lbs) Avg. of 3 specimens
0 °C (32 °F)	V1	63
	V2	60
-10 °C (14 °F)	V3	56
	V4	50
-20 °C (-4 °F)	V5	45
	V6	40
-30 °C (-22 °F)	V7	18
	V8	20
-40 °C (-40 °F)	V9	17
	V10	10

The TN-68 cask is designed for an ambient temperature of -20°F. As can be seen from the materials testing, even at temperatures as low as -20°F the gamma shielding has relatively good charpy impact properties. It is unlikely that the gamma shield would reach -20°F, since the heat load of the fuel would keep the cask temperatures elevated.

Shipping casks are often shipped empty or loaded with non-fuel components. Therefore, it is appropriate to neglect the heat load of the cask contents in determining the minimum service temperature. Unlike shipping casks, storage casks are not subjected to severe impact loads at severe temperatures. During storage, the casks are stationary and do not tipover due to seismic loads, tornado missiles and high winds.

Despite the fact that the shielding material is not part of the confinement boundary and it is unlikely that the gamma shield would reach -20°F, a fracture of the gamma shield will have no safety implications. However, Transnuclear has performed a fracture mechanics evaluation of the TN-68 Dry Storage Cask gamma shield based on a service temperature of -20°F. The work includes the following:

- Methodology
- Loadings
- Material fracture toughness
- Fracture toughness criteria
- Primary stress criteria
- Allowable flaw calculations
- Conclusions
- NDE Inspection Plan

Methodology

The allowable flaw sizes were performed using linear elastic fracture mechanics (LEFM) methodology from Section XI of ASME[2] Code Section (1989). Flaws in the welds, if they occur, are welding defects, rather than initiated cracks. There is not an active mechanism for crack initiation and growth at any of the weld locations. Thus, the calculated allowable flaw sizes can be used during fabrication.

Loadings

The following table lists the maximum membrane and bending stresses at the gamma shield under normal and accident conditions for TN-68 contents up to 21.2 kW. Figure 3E-1 shows the selected locations on the gamma shield numbered 1 through 6 for fracture toughness analysis. These locations were selected to be representative of the stress distribution in the gamma shield with special attention given to areas subject to high stresses and weld locations. The maximum stress may occur at a different location for different load combination (bolt preload, pressure, temperature, lifting load, fabrication stress, end drop, and tipover side drop).

Summary of Stress Components (21.2 kW)
(TN-68 Gamma Shield)

	Normal Condition				Accident Condition				
	Axial Stress (ksi)		Hoop Stress (ksi)		Axial Stress (ksi)		Hoop Stress (ksi)		Residual Stress (ksi)
Location (Fig. 3E-1)	σ_m	σ_b	σ_m	σ_b	σ_m	σ_b	σ_m	σ_b	
1	-0.06	0.53	1.34	0.21	-2.43	4.55	8.73	3.11	8.0
2	0.56	0.16	0.57	0.09	10.56	3.97	-1.22	0.18	36.0
3	0.31	0.96	2.87	0.75	-11.5	17.5	-8.0	48.5	0
4	0.26	0.53	0.32	0.64	-6.62	13.15	-1.31	1.75	0
5	-0.55	2.28	-0.08	1.86	-4.34	0.57	4.25	0.15	0
6	-0.50	0.29	0.28	0.2	0.5	2.15	-3.33	0.03	8.0

The gamma shield welds at locations 1 and 6 are partially stress relieved. However, the lower gamma shield welded to the bottom shield plate (location 2) does not undergo stress relief. Weld residual stress is included in the calculations for all weld locations. The weld residual stress is reduced due to the stress relief at all weld locations except the weld at location 2.

Weld residual stresses are steady state secondary stresses. The ASME Code does not prescribe limits for weld residual stresses. These stresses are displacement (or strain) controlled, and are self equilibrating through the weld thickness. For the purpose of this calculation, residual stresses will be conservatively assumed to be a constant tensile magnitude of 36 ksi at location 2. This value corresponds to the minimum specified yield stress of the base material (SA-266, Gr. 2). For other welds, which have been stress relieved, it is conservatively assumed that not all of the weld residual stress is relieved during the stress relief process. A stress value of 8 ksi has been included for welds at locations 1 & 6 for fracture toughness evaluations. This is similar to the procedure used in evaluation of reactor pressure vessel to account for the potential for remaining residual stress after post weld heat treatment.

The K due to residual stresses is applied with a safety factor of 1, as recommended in ASME, Section XI, Appendix H, Paragraph H-7300. Therefore, the total K_1 (applied) is determined from membrane, bending, and residual stresses.

Material Fracture Toughness

The gamma shield shell is a forged cylinder, nominally 6 inches thick by 180.15 inches long, made from SA-266, Gr. 2 material. The welding at the top flange and bottom plate may be performed using SAW, FCAW, or SMAW processes.

The results of the Charpy testing tabulated above are used. Figure 3E-2 shows a summary of the Charpy impact data used. The actual data points are shown along with a smoothed line that connects the average values at each test temperature. This data demonstrates that a lower bound Charpy impact value of 18 ft-lbs is appropriate for an exposure temperature of -20°F.

The Charpy impact measurement may be transformed into a fracture toughness value by using the empirical relation below (Ref.3):

$$K_{id} = [5E(C_v)]^{1/2} = 51{,}960 \text{ psi-(in)}^{1/2}$$

Where

K_{id} = Dynamic Fracture Toughness, psi -(in)$^{1/2}$
E = Modulus of Elasticity, 30×10^6
C_v = Charpy Impact Measurement, 18 ft-lbs

For conservatism, the above calculated K_{id} was reduced by another 10% to 47 ksi-(in)$^{1/2}$ (corresponding to 15 ft-lbs charpy values at -20°F) for fracture toughness evaluations.

Both the FCAW and SMAW electrodes used in the gamma shield weldments are alloyed with manganese, nickel, chromium, and vanadium. They are essentially matching filler metals for alloys such as ASME SA-533 Gr. B, the most commonly used reactor pressure vessel steel. The higher alloy content of the FCAW and SMAW electrodes and their typical usage in applications where good toughness is required indicate that the expected fracture toughness values for the FCAW and SMAW weld fillers are as good as or better than that of the SA-266 material. Use of the fracture properties from the wrought material for locations at or near the weld joints is conservative.

Fracture Toughness Criteria

Using the rule of Section XI, IWB-3613, the limiting fracture toughness values are reduced by a factor of $\sqrt{10}$ for the normal condition and $\sqrt{2}$ for the accident condition, to define the limiting allowable $K_{allowable.}$ That is,

$$K_{allowable} \leq K_{ia}/(\sqrt{10}) = 14.86 \text{ ksi-}\sqrt{\text{in}} \text{ for normal conditions}$$

$$K_{allowable} \leq K_{ic}/(\sqrt{2}) = 33.2 \text{ ksi-}\sqrt{\text{in}} \text{ for accident conditions}$$

Where:

K_{ia} = the available fracture toughness based on crack arrest

K_{ic} = the available fracture toughness based on crack initiation

The K_{ia} value is conservatively used for fracture toughness evaluation for both normal and accident conditions.

Primary Stress Criteria

ASME Section XI, IWB-3610 requires that any flaw evaluation include verification that the primary stress limits of ASME Code Section III continue to be met for the flawed component. The following formula is conservatively assumed that the available cross section is equal to the original thickness minus the allowable flaw depth.

$$a_{all} = t(1 - S/S_{all})$$

Where:

a_{all} = allowable flaw depth based on ASME Code Section III limits
t = orginal local thickness
S = maximum calculated local stress intensity
S_{all} = allowable stress intensity per ASME Section III.

All stresses are considered to be pure tensile membrane stresses and that the stresses will increase linearly with decreasing wall thickness.

Allowable Flaw Size Calculation

Using the above load definitions and fracture toughness, a series of allowable flaw size calculations was performed using the Structural Integrity Associates computer program pc-CRACK™ (Ref. 4).

- Surface Flaws

For purpose of analysis, the postulated surface flaws are oriented in both the axial and circumferential direction. The cracks selected for each location are shown in the above table. The results of the pc-CRACK calculations are shown in the following table.

- Subsurface Flaws

The above discussion addressed the determination of allowable flaw sizes for flaws that are connected to the surface of the shield shell. The shell or weld could also contain subsurface defects.

An evaluation of allowable subsurface defects was performed using the same linear elastic fracture mechanics (LEFM) techniques as were described above for surface defects. For this case, a center cracked panel (CCP) model was used to evaluate an assumed length flaw. The flaw must be sufficiently embedded such that treatment as a subsurface flaw is justified. In general, if a flaw is closer to the surface than 0.4 of its half-depth, it must be considered a surface flaw.

The results of the pc-CRACK calculations are shown in the following table.

Allowable Surface Flaws Depth (inches)
(TN-68 Gamma Shield)

Location	Normal Condition		Accident Condition	
	⊥ to Axial Stress	⊥ to Hoop Stress	⊥ to Axial Stress	⊥ to Hoop Stress
1	-- (0.39)	-- (0.39)	-- (0.44)	-- (0.44)
2	0.32	0.27	0.34	0.29
3	-- (4.55)	2.05	-- (1.26)	0.192
4	5.79 (4.03)	5.54 (4.03)	-- (2.84)	-- (2.84)
5	-- (4.01)	3.24	-- (4.18)	2.23
6	0.5	0.46	0.48 (0.38)	0.48 (0.38)

Allowable Sub-Surface Flaws (Embedded) Depth (inches)

Location	Normal Condition		Accident Condition	
	⊥ to Axial Stress	⊥ to Hoop Stress	⊥ to Axial Stress	⊥ to Hoop Stress
1	-- (0.39)	-- (0.39)	-- (0.44)	0.44
2	0.71	0.72	0.4	0.8
3	--	4.38	5 (1.26)	0.41
4	-- (4.03)	-- (4.03)	6.06 (2.84)	-- (2.84)
5	-- (4.01)	-- (4.01)	-- (4.18)	-- (4.18)
6	-- (0.63)	-- (0.63)	-- (0.38)	-- (0.38)

Note:
"- -" Indicates that the allowable flaw depth is not limited by fracture mechanics calculation.
"( )" Indicates that the allowable flaw depth is limited by primary stress criteria.

Specific conservatisms included in the above analysis are listed below:

- All factors of safety on applied stress required by ASME Section XI (1989 Edition) were included in the evaluation.
- Weld residual stresses were treated as constant tensile stresses normal to the flaw orientation. Flaws were assumed to be long (infinitely long or full circumference)
- Lower bound material properties were used.

Stresses in the TN-68 cask gamma shield are also calculated based on cask contents up to 30 kW. The following table lists the maximum membrane and bending stresses at the gamma shield under normal and accident conditions for storing 30 kW.

Summary of Stress Components (for TN-68 Cask with 30 kW)
(TN-68 Gamma Shield)

	Normal Condition				Accident Condition				
	Axial Stress (ksi)		Hoop Stress (ksi)		Axial Stress (ksi)		Hoop Stress (ksi)		Residual Stress (ksi)
Location (Fig. 3E-1)	σ_m	σ_b	σ_m	σ_b	σ_m	σ_b	σ_m	σ_b	
1	-0.69	0.83	0.7	0.32	-3.03	4.81	-7.75	3.21	8.0
2	1.15	0.09	2.03	0.10	11.25	3.64	0.22	0.07	36.0
3	0.29	1.56	2.53	0.91	-11.8	17.15	-9.34	49.12	0
4	0.75	1.14	0.93	0.15	-6.28	12.68	-0.6	1.24	0
5	-0.64	1.72	-0.29	1.40	-4.43	0.02	4.04	0.81	0
6	-0.27	0.09	-0.08	0.25	0.75	2.37	-3.67	0.09	8.0

The different between the stresses in this table and previous calculated stress table based on 21.2 kW are very small. Therefore, the flaw sizes from the stresses calculated from the TN-68 cask with 30 kW contents are scaled from the previous table by using the following formula (only flaw sizes limited by fracture mechanic calculations are ratioed).

$a_1 = a_2 \times (\sigma_1/\sigma_2)^2$

Where a_1 = Flaw size for the stresses based on TN-68 cask with high burn up fuel
a_2 = Flaw size for the stresses based on TN-68 cask with fuel up to 21.2 kW
σ_1 = Stresses calculated based on TN cask with fuel up to 21.2 kW
σ_2 = Stresses calculated based on TN cask with high burn up fuel

The results are listed in the flowing table.

Allowable Surface Flaws Depth (inches) for TN-68 Cask with 30 kW Fuel
(TN-68 Gamma Shield)

Location	Normal Condition		Accident Condition	
	⊥ to Axial Stress	⊥ to Hoop Stress	⊥ to Axial Stress	⊥ to Hoop Stress
1	-- (0.39)	-- (0.39)	-- (0.44)	-- (0.44)
2	0.31	0.25	0.335	0.27
3	-- (4.55)	2.27	-- (1.26)	0.199
4	1.01 (4.03)	4.38 (4.03)	-- (2.84)	-- (2.84)
5	-- (4.01)	--	-- (4.18)	1.835
6	0.496	0.495	0.44 (0.38)	0.545 (0.38)

Allowable Sub-Surface Flaws Depth (inches) for TN-68 Cask with 30 kW Fuel
(TN-68 Gamma Shield)

Location	Normal Condition		Accident Condition	
	⊥ to Axial Stress	⊥ to Hoop Stress	⊥ to Axial Stress	⊥ to Hoop Stress
1	-- (0.39)	-- (0.39)	-- (0.44)	0.44
2	0.68	0.66	0.39	0.74
3	--	4.85	6.288 (1.26)	0.42
4	-- (4.03)	-- (4.03)	6.3 (2.84)	-- (2.84)
5	-- (4.01)	-- (4.01)	-- (4.18)	-- (4.18)
6	-- (0.63)	-- (0.63)	-- (0.38)	-- (0.38)

Note:

- - Indicates that the allowable flaw depth is not limited by fracture mechanics calculation.
( ) Indicates that the allowable flaw depth is limited by primary stress criteria.

Conclusions

The gamma shield is not part of the confinement boundary. Cracks postulated in the gamma shield will not propagate into the confinement boundary due to the geometry of the cask. If the gamma shield were to fracture along the length or around the circumference or around the weld between the gamma shield and top flange, there is no credible mechanism which would result in the gamma shielding separating from the confinement boundary. The top shield plate is welded to the lid and is captured by the confinement vessel. Therefore, if the weld were to completely fail the shield plate will still remain inside the confinement boundary and will not lose its shielding capability. Therefore, even if a fracture were to occur in the gamma shield shell or the weld between the gamma shield and top flange or top shield plate or weld between top shield plate and lid, there would be no safety significance, since confinement would be maintained, and shielding would not be impaired. The one exception is in the region of the weld of the gamma shield shell to the bottom plate. In this region, if the weld were to completely fail, the bottom plate could become detached and have an impact on the shielding capability of the cask.

NDE Inspection Plan

The results of the fracture toughness analysis shows that the flaws in the gamma shield shell and top and bottom shield plates which would result in unstable crack growth or brittle fracture are larger than those generally observed in forged steel and plate components. No special examination requirements on the gamma shield shell, top and bottom shield plates are required.

The flaw sizes in the welds which could result in brittle fracture at -20°F will be detected by NDE methods. The welds at locations 1 if it were to completely fail, would be no safety significance. Therefore, only PT or MT of the final is be specified.

If the bottom plate weld were to completely fail, the bottom plate could become detached and have an impact on the shielding capability of the cask. The minimum allowable flaw sizes for surface and subsurface are 0.25 in. and 0.39 in., respectively. Therefore, the following NDE will be used to ensure defects of the minimum flaw sizes calculated are detected and repaired prior to used for fuel storage.

- PT or MT at weld preparation surfaces (base metal)
- PT or MT at root pass
- PT or MT for each 0.375 inches of weld
- PT or MT at final surface

The weld at location 6, if it were to completely fail, could result in a drop of the shield plug into the cask cavity. Therefore the NDE requirements specified for the location 6 weld will be the same as that specified for the location 2 weld above.

The liquid penetrant or magnetic particle method will be in accordance with Section V, Article 6 of ASME Code.

3E.1.3 References

1. ASME Section III, Division 3, Containment System and transport Packaging for spent Nuclear Fuel and High Level Radioactive waste.

2. ASME Code Section XI, 1989.

3. NUREG/CR-1815, Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping containers up to four Inches Thick.

4. Structural Integrity Associates, pc-CRACK™ for Windows, Version 3.0, March 27, 1997.

Figure 3E-1
Locations of Fracture Toughness Evaluations
(TN-68 Gamma Shield)

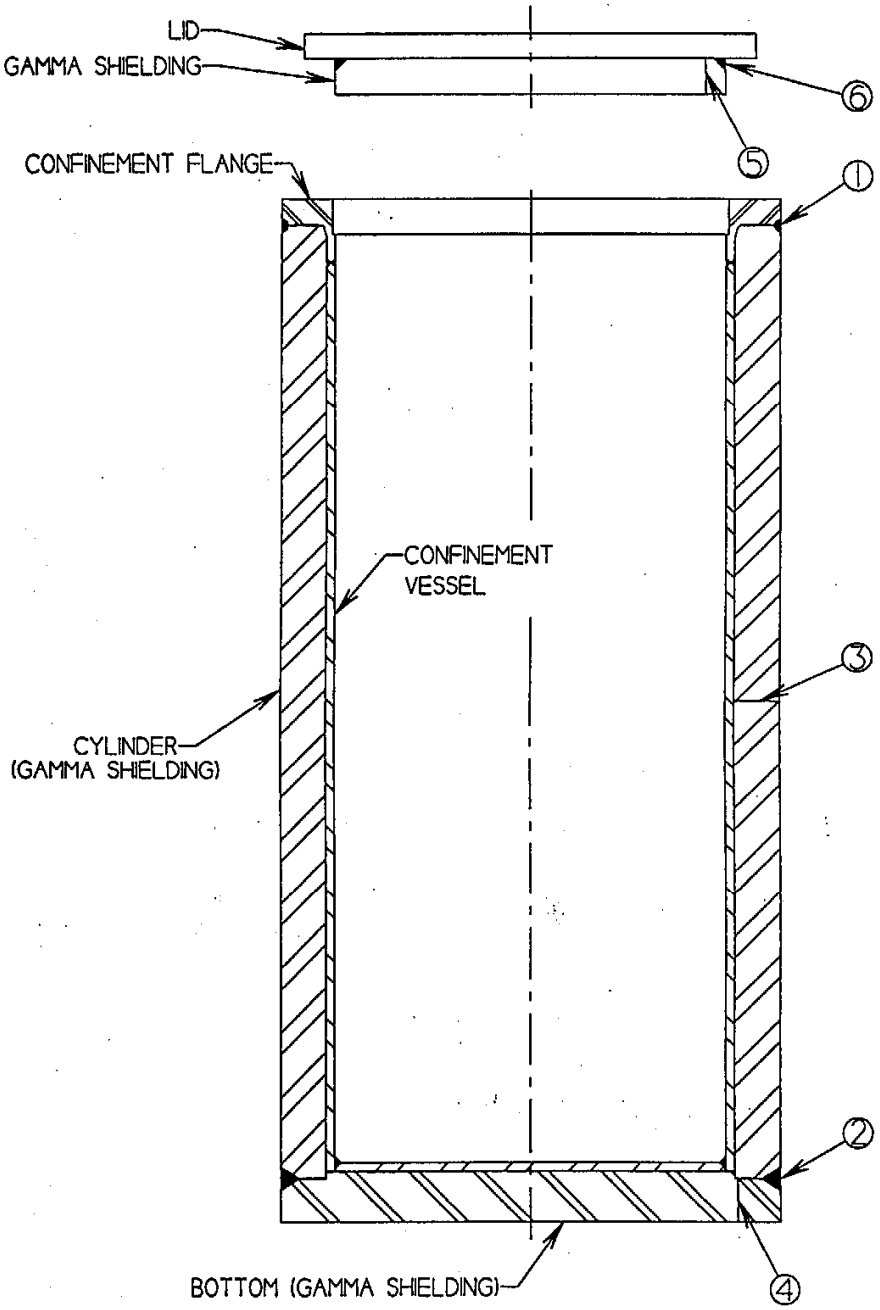

Figure 3E-2
Charpy V-Notch Test -Results for SA-266 Gr. 2