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APPENDIX 6B

DAMAGED FUEL CLADDING STRUCTURAL EVALUATION

6B.1 Introduction

The purpose of this appendix is to demonstrate structural integrity of the damaged fuel cladding in the TN-68 basket following normal and off-normal loading conditions of storage and onsite transfer (required for Part 72 License) and normal condition of offsite transport (required for Part 71 License).

In this appendix, the damaged fuel is defined as fuel assemblies containing fuel rods with known or suspected cladding defects greater than hairline cracks or pinhole leaks or with at most one missing or mislocated grid, or a grid sufficiently damaged to reduce its ability to support the fuel rods. Fuel with missing fuel rods or fuel rod sections is not acceptable for storage in the TN-68. Damaged fuel must be capable of being handled by normal means in order to be stored in the TN-68.

This appendix evaluates stresses in the damaged fuel cladding associated with normal and off-normal conditions of on-site transfer/storage and off-site transport. It also presents a fracture mechanics assessment of the cladding using conservative assumptions regarding defect size geometry and amount of oxidation in the cladding material. These evaluations demonstrate the structural integrity of the damaged fuel cladding under normal and off-normal conditions.

The TN-68 cask and fuel basket is designed to store 68 intact fuel assemblies, or no more than 8 damaged and the remainder intact, for a total of 68 standard BWR fuel assemblies per canister. All the fuel assemblies, intact or damaged, consist of BWR fuel assemblies with Zircaloy cladding. Damaged fuel assemblies may only be stored in eight peripheral compartments of the TN-68 fuel basket fitted with end caps to retain and retrieve damaged fuel fragments.

6B.2 Design Input / Data

The design inputs, taken from Reference 1, are summarized in Tables 6B-1 and 6B-2.

The design parameters of GE4 (8x8), GE5 (8x8), GE8 (8x8), GE9 (8x8) and GE10 (8x8) from the above tables are conservatively enveloped into one set and used for all 8x8 tube arrays in this calculation. They are as follows.

Irradiated Yield Stress = 80,500 psi
Young's Modulus = 10.4×10^6 psi
No of fuel rods/ assembly = 60
Active Fuel Length = 150 in.
Fuel rod outer radius = 0.485/2 = 0.2425 in.
Fuel rod maximum span = 25.0 in
Fuel tube cross sectional area = 0.0340 in^2
Total fuel tube + fuel moment of inertia = 0.00225 in^4
Outside diameter of Tube = 0.493 in.
Wall thickness of Tube = 0.024
Total fuel tube + fuel weight per rod (uncorroded) = 9.256 lb

6B.3 Loads

6B.3.a Part 72 Normal and Off-normal Condition Loads

The damaged fuel inside the TN-68 fuel basket is subjected to following normal and off normal condition Part 72 loads:

- Dead Weight
- Internal Pressure
- Thermal
- Transfer Load (Inertia Loads associated with moving the TN-68 cask from the fuel loading area to the ISFSI site), which consists of 1*g* in the longitudinal, 1*g* in the transverse and 1*g* in the vertical direction.

The stresses due to the dead weight are insignificant. No internal pressure is assumed for the damaged fuel. The cladding is assumed to be able to expand due to thermal loads and thus no thermal-induced stresses are considered. However, the temperature of the cladding is considered for selection of allowable stresses. Transfer load is bounded by the Part 71 one-foot drop load.

6B.3.b Part 71 Normal Condition Loads

The damaged fuel is evaluated for the following normal condition 10CFR Part 71 off-site transportation loads:

- 1 foot end and side drop loads
- Vibratory loads
- Shock load
- Lifting and Tie-down loads

During one-foot end and side drops, fuel assemblies are subjected to 15g and 35g loads respectively [10].

Vibratory loads of 0.30g in longitudinal direction, 0.30g in the transverse direction and 0.60g in the vertical direction, taken from Reference [4] are considered representative for a truck loaded cask. The vibration load of 0.19g in the longitudinal direction, 0.19g in the transverse direction and 0.37g in the vertical direction, taken from Reference [4], are considered representative for a rail car loaded cask [5].

The shock load of 4.7g in the longitudinal and 4.7g in the lateral and vertical directions for a rail car loaded cask (bounding values between rail and truck transport) during off-site transport are also taken from Reference [5].

Lifting load of 6g vertical is taken fromPart71-45(a). Tie-down loads 2g (vertical)/5g (lateral)/10g (longitudinal) are taken from Part71-45(b).

All of the above loads however are bounded by 1 foot end drop (15*g*) and 1 foot side drop (35*g*) transport load. Therefore, structural integrity of the damaged fuel for the normal conditions of both Part 72 and Part 71 is evaluated only for the one-foot end and side drop conditions.

Note that for the normal and accident off-site transport drops the impact limiters are attached at both ends of the horizontally loaded cask.

6B.4 Evaluation Criteria

The retrievability of the damaged fuel in the TN-68 Cask is assured if the damaged fuel cladding retains its structural integrity when subjected to normal and off normal loads. Per the damaged fuel definition in Section 6.B.1, the damaged fuel rods loaded in the TN-68 basket may have cladding defects greater than hairline cracks or pinhole leaks. However, under normal and off-normal loads, the original defects (such as cracks or pinholes or missing grid) should not change significantly so that the damaged fuel can be retrieved.

The damaged fuel cladding needs to meet the following criteria to ensure their structural integrity and thus be retrievable:

- Fuel cladding stresses under normal and off-normal load conditions are less than the irradiated yield strength of the cladding material.

- Stability of the cladding tube is maintained (i.e., no buckling occurs).

- The stress intensity factor, K_I, of the fuel cladding tube geometry considering through-wall flaw is less than experimentally determined fracture toughness, K_{Ic}, considering temperature and irradiation effects.

6B.5 One Foot End Drop (15*g*) Damaged Fuel Evaluation

During off site transport (Part 71) the damaged fuel assemblies need to be evaluated for 1 foot end drop. The maximum *g* load acting on the damaged fuel rod subjected to 1 foot end drop of the TN-68 cask is 15g.

Stress Analysis of (7×7) Fuel Assemblies (See Table 6B-1 for Design Parameters)

Number of rods per assembly = 49
Therefore, force per rod = (705×15)/49 = 216 lb
Area of the cladding = 0.040 in^2
Axial compressive stress in the rod = 216/0.040 = 5,400 psi

Stress Analysis of (8×8) Fuel Assemblies (See Section 6B.2 for Design Parameters)

Number of rods per assembly = 60
Therefore, force per rod = (705×15)/60 = 176 lb
Area of the cladding = 0.034 in^2
Axial compressive stress in the rod = 176 / 0.034 = 5,184 psi

Stress Analysis of (9×9) Fuel Assemblies (See Table 6B-2 for Design Parameters)

Number of rods per assembly = 66
Therefore, force per rod = (705×15)/66 = 161 lb
Area of the cladding = 0.0259 in^2
Axial compressive stress in the rod = 161/0.0259 = 6,216 psi

Stress Analysis of (10×10) Fuel Assemblies (See Table 6B-2 for Design Parameters)

Number of rods per assembly = 78
Therefore, force per rod = (705×15)/78 = 136 lb
Area of the cladding = 0.0214 in^2
Axial compressive stress in the rod = 136/0.0214 = 6,355 psi

The axial stresses in the fuel rod are compressive stresses and are significantly less than the irradiated yield stress of the cladding material = 80,500 psi (See Section 6B.2). Therefore, the fuel rods will maintain their structural integrity when subjected to 1 foot end drop load.

6B.6 One Foot Side Drop Damaged Fuel Evaluation

The maximum *g* load acting on the damaged fuel rods under 1 foot side drop load is 35*g*. The damaged fuel rod structural integrity under 1 foot side drop load is assessed by computing the bending stress in the rod and comparing it with the yield stress of the cladding material.

Stress Analysis of (7×7) Fuel Assemblies (See Table 6B-2 for Design Parameters)

Weight per unit length of the fuel rod for 35*g*, $w_s = (12.045\times35) / (144) = 2.9276$ lb/in

From Table 2.10.7-1 of Reference [2], the maximum bending moment for a continuous beam with seven supports M is,

$M = 0.1058(w_s \times l_s^2) = 0.1058\ (2.9276 \times 24^2) = 178.4$ lb-in
Maximum Bending Stress = $(M \times r_o) / I = (178.4\times0.2775) / (0.00418) = 11{,}844$ psi

The computed maximum stress due to side drop (11,844 psi) is significantly less than the Irradiated yield stress of the cladding material (80,500 psi).

Stress Analysis of (8×8) Fuel Assemblies (See Section 6B-2 for Design Parameters)

Weight per unit length of the fuel rod for 35*g*, $w_s = (9.256\times35) / (146)$
$= 2.2189$ lb/in

From Table 2.10.7-1 of Reference [2], the maximum bending moment for a continuous beam with seven supports M is,

$M = 0.1058(w_s \times l_s^2) = 0.1058\ (2.2189 \times 25^2) = 146.7$ lb-in
Maximum Bending Stress = $(M \times r_o) / l = (146.7\times0.2465) / (0.00225) = 16{,}075$ psi

The computed maximum stress due to side drop (16,075 psi) is significantly less than the irradiated yield stress of the cladding material (80,500 psi).

Stress Analysis of (9×9) Fuel Assemblies (See Table 6B-2 for Design Parameters)

Weight per unit length of the fuel rod for 35*g* = $w_s = (7.431\times35) / (146) = 1.7814$ lb/in

From Table 2.10.7-1 of Reference [2], the maximum bending moment for a continuous beam with seven supports M is,

$M = 0.1058(w_s \times l_s^2) = 0.1058\ (1.7814 \times 24.3^2) = 111.3$ lb-in
Maximum Bending Stress = $(M \times r_o) / l = (111.3\times0.216) / (0.00153) = 15{,}712$ psi

The computed maximum stress due to side drop (15,712 psi) is significantly less than the Irradiated yield stress of the cladding material (80,500 psi).

Stress Analysis of (10×10) Fuel Assemblies (See Table 6B-2 for Design Parameters)

Weight per unit length of the fuel rod for 35*g* = w_s = (6.44×35) / (150) = 1.5027 lb/in

From Table 2.10.7-1 of Reference [2], the maximum bending moment for a continuous beam with seven supports *M* is,

$M = 0.1058(w_s \times l_s^2) = 0.1058\ (1.5027 \times 25^2) = 99.36$ lb-in
Maximum Bending Stress = $(M \times r_o) / I$ = (99.36×0.198) / (0.00108) = 18,216 psi

The computed maximum stress due to side drop (18,216 psi) is significantly less than the Irradiated yield stress of the cladding material (80,500 psi).

6B.7 Fracture Toughness Evaluation

A fracture assessment of the damaged fuel rod structural integrity is made by using two fracture geometries (ruptured sections). It is assumed that the damaged fuel tube is burst at the spacer (supports) locations, which is the location of maximum bending moment. The loading assumed is on the opposite side of the rod at the burst location. The computed stress intensity factor K_I is compared conservatively with experimentally obtained plane strain fracture toughness, K_{Ic}, for irradiated Zircaloy cladding, which is, K_{Ic} = 35 ksi in.$^{1/2}$ at 300° F [7]. The three fracture geometries and analysis methodologies are describe in following three subsections.

6B.7.a Structural Integrity Evaluation with Fracture Geometry #1

This geometry is shown in Figure 6B-1. In this damage mode, the fuel tube is assumed to bulge from diameter D to diameter W (W≥D) and rupture to a hole of diameter (2a) at the bulge location. It is assumed that (2a/w) = 0.6 to 0.7 for this geometry. Stress intensity factors are computed for a crack in a fuel tube subjected to a uniform bending moment *M* using formulae given in Reference [11].

Structural Integrity of BWR (7×7) Damaged Fuel Rods with Fractured Geometry #1

Outside diameter of the fuel tube, D = 0.555 in.
Cladding Thickness, t = 0.024 in.
R = Average radius = (0.555-0.024)/2 = 0.2655 in.
I = Moment of Inertia of the net area of the tube + fuel moment of inertia
= 0.00141/2 + 0.002761 = 0.003466 in^4

Where it is conservatively assumed that M.I. of the net area of the tube is equal to one-half of the total M.I. of the tube (See Table 6B-1).

Span lengths, $s = l_s$ = 24.0 in.
Assume $(2a / W) = 0.7$

Where,

$2a$ = ruptured hole diameter,
W = bulged fuel tube diameter $\geqslant D$ = 0.555 in.
Stress Intensity Factor, $K_I = (Y)\,(P\,a^{1/2}) / (t\times W)$
Y = 2.61 for $(2a / W) = 0.7$ (extrapolated from Figure 6B-2)

The expression for the average tensile force at the crack expressed as a function of moment on the cross section is denoted as *P*, and derived as follows:

Consider a circular tube of average radius *R*, thickness *t* subjected to a bending moment *M* (see Figure 6B-3).

At the angle θ from the neutral axis (N/A), for a segment of the tube with angle $d\theta$

Area, $A = t\,R\,d\theta$
Tensile Stress, $\sigma = MR \sin\theta / I$

Where I is the moment of inertia of the section.

Therefore,

Tensile Force, $\Delta P = (MR \sin\theta / I)\,(t\,R\,d\theta)$

Total Tensile Force, $P = \int_0^{\pi} (MR \sin\theta / \mathrm{I})(tRd\theta)$

Therefore,

$$P = (MR^2 \mathrm{t} / I) \int_0^{\pi} \sin\theta d\theta$$

$$P = (MR^2 \mathrm{t} / I)\,[-\cos\theta]_o^{\pi} = 2MR^2 t / I$$

For the (7×7) fuel assemblies,

$$P = (2\times178.4\times0.2655^2\times0.024) / 0.003466 = 174.1 \text{ lb}$$

And,

$W = \pi R = 0.8341$, $(2a / W) = 0.7$, $a = (0.7\times W / 2) = 0.2919$ in.

Therefore,

$$K_I = (2.61\times0.1741\times0.2919^{1/2}) / (0.024\times0.8341) = 12.26 \text{ ksi in}^{1/2}$$

$$K_I = 12.26 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2}$$

Therefore, the structural integrity of the (7×7) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-1, will be maintained.

<u>Structural Integrity of BWR (8×8) Damaged Fuel Rods with Fractured Geometry #1</u>

Outside diameter of the fuel tube, D = 0.485 in.
Cladding Thickness, t = 0.024 in.
R = Average radius = (0.485-0.024)/2 = 0.2305 in.
I = Moment of Inertia of the net area of the tube + fuel moment of inertia
$= 0.00087/2 + 0.001387 = 0.001822 \text{ in}^4$

Where it is conservatively assumed that M.I. of the net area of the tube is equal to one-half of the total M.I. of the tube (See Table 6B-1).

Span lengths, $s = l_s = 25.0$ in.
Assume $(2a / W) = 0.7$

Where,

$2a$ = ruptured hole diameter,
W = bulged fuel tube diameter $\geqslant D = 0.485$ in.
Stress Intensity Factor, $K_I = (y)\,(P\,a^{1/2}) / (t \times W)$
$Y = 2.61$ for $(2a / W) = 0.7$ (extrapolated from Figure 6B-2)

The expression for the average tensile force at the crack expressed as a function of moment on the cross section P, derived above, is,

$$\mathrm{P} = 2MR^2t / I$$

For the (8×8) fuel assemblies,

$$P = (2\times146.7\times0.2305^2\times0.024) / 0.001822 = 205.3 \text{ lb}$$

And,

$W = \pi R = 0.7241$, $(2a / W) = 0.7$, $a = (0.7\times W / 2) = 0.2534$ in.

Therefore,

$$K_I = (2.61\times0.2053\times0.2534^{1/2}) / (0.024\times0.7241) = 15.52 \text{ ksi in}^{1/2}$$

$$K_I = 15.52 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2}$$

Therefore, the structural integrity of the (8×8) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-1, will be maintained.

Structural Integrity of BWR (9×9) Damaged Fuel Rods with Fractured Geometry # 1

Outside diameter of the fuel tube, D = 0.432 in.
Cladding Thickness, t = 0.020 in.
R = Average radius = (0.432-0.020)/2 = 0.206 in.
I = Moment of Inertia of the net area of the tube + fuel moment of inertia
= 0.00055/2 + 0.000981 = 0.001256 in^4

Where it is conservatively assumed that M.I. of the net area of the tube is equal to one- half of the total M.I. of the tube (See Table 6B-2).

Span lengths, $s = l_s$ = 24.3 in.
Assume ($2a$ / W) = 0.7

Where,

$2a$ = ruptured hole diameter,
W = bulged fuel tube diameter $\geqslant D$ = 0.432 in.
Stress Intensity Factor, $K_I = (y)\,(P\,a^{1/2}) / (t \times W)$
Y = 2.61 for ($2a$ / W) = 0.7 (from Figure 6B-2)

The expression for the average tensile force at the crack expressed as a function of moment on the cross section P, derived above, is,

$$P = 2MR^2t / I$$

For the (9×9) fuel assemblies,

$$P = (2\times111.3\times0.206^2\times0.020) / 0.001256 = 150.4 \text{ lb}$$

And,

$W = \pi R = 0.6472$, ($2a$ / W) = 0.7, $a = (0.7\times W / 2)$ = 0.2265 in.

Therefore,

$$K_I = (2.61\times0.1504\times0.2265^{1/2}) / (0.020\times0.6472) = 14.4 \text{ ksi in}^{1/2}$$

$$K_I = 14.4 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2}$$

Therefore, the structural integrity of the (9×9) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-1, will be maintained.

<u>Structural Integrity of BWR (10×10) Damaged Fuel Rods with Fractured Geometry # 1</u>

Outside diameter of the fuel tube, $D = 0.396$ in.
Cladding Thickness, $t = 0.018$ in.
R = Average radius = (0.396-0.018)/2 = 0.189 in.
I = Moment of Inertia of the net area of the tube + fuel moment of inertia
$= 0.00038/2 + 0.000695 = 0.000885 \text{ in}^4$

Where it is conservatively assumed that M.I. of the net area of the tube is equal to one- half of the total M.I. of the tube (See Table 6B-1).

Span lengths, $s = l_s = 25.0$ in.
Assume $(2a / W) = 0.7$

Where,

$2a$ = ruptured hole diameter,
W = bulged fuel tube diameter $\geqslant D = 0.396$ in.
Stress Intensity Factor, $K_I = (y)(P\, a^{1/2}) / (t \times W)$
$Y = 2.61$ for $(2a / W) = 0.7$ (from Figure 6B-2)

The expression for the average tensile force at the crack expressed as a function of moment on the cross section P, derived above, is,

$$\mathrm{P} = 2MR^2t / I$$

For the (10×10) fuel assemblies,

$$P = (2 \times 99.36 \times 0.189^2 \times 0.018) / 0.000885 = 144.38 \text{ lb}$$

And,

$W = \pi R = 0.5938$, $(2a / W) = 0.7$, $a = (0.7 \times W / 2) = 0.2078$ in.

Therefore,

$$K_I = (2.61 \times 0.144 \times 0.2078^{1/2}) / (0.018 \times 0.5938) = 16.0 \text{ ksi in}^{1/2}$$

$$K_I = 16.0 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2}$$

Therefore, the structural integrity of the (10×10) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-1, will be maintained.

6B.7.b Structural Integrity Evaluation with Fracture Geometry #2

Fracture Geometry #3 is a circumferential crack in tube and is depicted in Figure 6B-4 along with the formulae used in the analysis below.

Structural Integrity of BWR (7×7) Damaged Fuel Rods with Fractured Geometry # 2

Stress intensity factors are computed for a crack in a fuel tube subjected to a uniform bending moment *M* using formulae given in Figure 6B-4.

$$K_I = \sigma (\pi\, R_m\, \theta)^{1/2}\, F(\theta)$$

where,

$F(\theta) = 1 + 6.8\,(\theta / \pi)^{3/2} - 13.6\,(\theta / \pi)^{5/2} + 20.0\,(\theta / \pi)^{7/2}$,
σ is the bending stress due to uniform moment *M*,
$M = 178.4 \times 0.2775 / 0.003466 = 14{,}283$ psi = 14.283 ksi
R_m is the average radius of the fuel tube = 0.2655 in.

$a / R_m = 0.6 = \theta$
Half crack length, $a = R_m\, \theta = 0.2655 \times 0.6 = 0.1593$ in.
2θ is the angle which the crack makes at the center of the tube
K_I is the stress intensity factor at the crack.

Therefore,

$$\begin{aligned} F(\theta) &= 1 + 6.8\,(\theta / \pi)^{3/2} - 13.6\,(\theta / \pi)^{5/2} + 20.0\,(\theta / \pi)^{7/2} \\ &= 1 + 6.8\,(0.6 / \pi)^{3/2} - 13.6\,(0.6 / \pi)^{5/2} + 20.0\,(0.6 / \pi)^{7/2} \\ &= 1 + 0.5676 - 0.2168 + 0.0609 = 1.4117 \end{aligned}$$

$$\begin{aligned} K_I &= \sigma (\pi\, R_m\, \theta)^{1/2}\, F(\theta) \\ &= 14.283\,(\pi \times 0.1593)^{1/2} \times 1.4117 = 14.26 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2} \end{aligned}$$

Therefore, the structural integrity of the (7×7) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-4, will be maintained.

Structural Integrity of BWR (8×8) Damaged Fuel Rods with Fractured Geometry # 2

Stress intensity factors are computed for a crack in a fuel tube subjected to a uniform bending moment M using formulae given in Figure 6B-4.

$$K_I = \sigma (\pi R_m \theta)^{1/2} F(\theta)$$

where,

$F(\theta) = 1 + 6.8 (\theta / \pi)^{3/2} - 13.6 (\theta / \pi)^{5/2} + 20.0 (\theta / \pi)^{7/2}$,
σ is the bending stress due to uniform moment M,
$M = 146.7 \times 0.2425 / 0.001822 = 19{,}525$ psi = 14.525 ksi
R_m is the average radius of the fuel tube = 0.2305 in.

$a / R_m = 0.6 = \theta$
Half crack length, $a = R_m \theta = 0.2305 \times 0.6 = 0.1383$ in.
2θ is the angle which the crack makes at the center of the tube
K_I is the stress intensity factor at the crack.

Therefore,

$$\begin{aligned} F(\theta) &= 1 + 6.8 (\theta / \pi)^{3/2} - 13.6 (\theta / \pi)^{5/2} + 20.0 (\theta / \pi)^{7/2} \\ &= 1 + 6.8 (0.6 / \pi)^{3/2} - 13.6 (0.6 / \pi)^{5/2} + 20.0 (0.6 / \pi)^{7/2} \\ &= 1 + 0.5676 - 0.2168 + 0.0609 = 1.4117 \end{aligned}$$

$$\begin{aligned} K_I &= \sigma (\pi R_m \theta)^{1/2} F(\theta) \\ &= 19.525 (\pi \times 0.1383)^{1/2} \times 1.4117 = 18.17 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2} \end{aligned}$$

Therefore, the structural integrity of the (8×8) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-4 will be maintained.

Structural Integrity of BWR (9×9) Damaged Fuel Rods with Fractured Geometry #2

Stress intensity factors are computed for a crack in a fuel tube subjected to a uniform bending moment M using formulae given in Figure 6B-4.

$$K_I = \sigma (\pi R_m \theta)^{1/2} F(\theta)$$

where,

$F(\theta) = 1 + 6.8 (\theta / \pi)^{3/2} - 13.6 (\theta / \pi)^{5/2} + 20.0 (\theta / \pi)^{7/2}$,
σ is the bending stress due to uniform moment M,
$M = 111.3 \times 0.216 / 0.001256 = 19{,}141$ psi = 19.141 ksi
R_m is the average radius of the fuel tube = 0.206 in.

$a / R_m = 0.6 = \theta$

Half crack length, $a = R_m\,\theta = 0.206\times0.6 = 0.1236$ in.
2θ is the angle which the crack makes at the center of the tube
K_I is the stress intensity factor at the crack.

Therefore,

$$F(\theta) = 1 + 6.8\,(\theta/\pi)^{3/2} - 13.6\,(\theta/\pi)^{5/2} + 20.0\,(\theta/\pi)^{7/2}$$
$$= 1 + 6.8\,(0.6/\pi)^{3/2} - 13.6\,(0.6/\pi)^{5/2} + 20.0\,(0.6/\pi)^{7/2}$$
$$= 1 + 0.5676 - 0.2168 + 0.0609 = 1.4117$$

$$K_I = \sigma\,(\pi\,R_m\,\theta)^{1/2}\,F(\theta)$$
$$= 19.141\,(\pi\times0.1236)^{1/2} \times 1.4117 = 16.8 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2}$$

Therefore, the structural integrity of the (9×9) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-4 will be maintained.

Structural Integrity of BWR (10×10) Damaged Fuel Rods with Fractured Geometry # 2

Stress intensity factors are computed for a crack in a fuel tube subjected to a uniform bending moment M using formulae given in Figure 6B-4.

$$K_I = \sigma\,(\pi\,R_m\,\theta)^{1/2}\,F(\theta)$$

where,

$F(\theta) = 1 + 6.8\,(\theta/\pi)^{3/2} - 13.6\,(\theta/\pi)^{5/2} + 20.0\,(\theta/\pi)^{7/2}$,
σ is the bending stress due to uniform moment M,
$M = 99.36\times0.198 / 0.000885 = 22{,}230$ psi = 22.230 ksi
R_m is the average radius of the fuel tube = 0.189 in.

$a / R_m = 0.6 = \theta$
Half crack length, $a = R_m\,\theta = 0.198\times0.6 = 0.1134$ in.
2θ is the angle which the crack makes at the center of the tube
K_I is the stress intensity factor at the crack.

Therefore,

$$F(\theta) = 1 + 6.8\,(\theta/\pi)^{3/2} - 13.6\,(\theta/\pi)^{5/2} + 20.0\,(\theta/\pi)^{7/2}$$
$$= 1 + 6.8\,(0.6/\pi)^{3/2} - 13.6\,(0.6/\pi)^{5/2} + 20.0\,(0.6/\pi)^{7/2}$$
$$= 1 + 0.5676 - 0.2168 + 0.0609 = 1.4117$$

$$K_I = \sigma\,(\pi\,R_m\,\theta)^{1/2}\,F(\theta)$$
$$= 22.230\,(\pi\times0.1134)^{1/2} \times 1.4117 = 18.7 \text{ ksi in}^{1/2} < K_{Ic} = 35.0 \text{ ksi in}^{1/2}$$

Therefore, the structural integrity of the (10×10) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-4, will be maintained.

6B.8 Evaluation of Damaged Fuel with One Missing Grid

This section evaluates fuel assemblies with one fuel grid missing when subjected to the bounding side drop and end drop loads as well as and for fracture toughness.

The design parameters of fuel assemblies are the same as those listed in Tables 6B-1 and 6B-2, except that with one grid missing, the span length between grids is doubled. All other design inputs, loads and evaluation criteria are the same as those used in Sections 6B.2 through 6B.4.

6B.8.a One Foot End Drop Damaged Fuel with One Missing Grid Evaluation

The end drop stresses computed in Section 6B.5 are not affected by a missing fuel grid spacer. Therefore, the resulting stresses are same as those computed in Section 6B.5.

6B.8.b One Foot Side Drop Damaged Fuel with One Missing Grid Evaluation

The fuel rod side impact stresses are computed by idealizing fuel rods as continuous beams simply supported at each spacer grid. One support of the spacer grid is assumed missing which results in one longer span than the other spans. During a side drop, maximum tube deflection is limited by contact of tubes with the basket fuel compartment wall. The maximum possible deflection (given the fuel assembly outer width, fuel rod outer diameter and fuel rod pitch) is computed using the longer span as simply-supported beam. This 'maximum possible deflection' is used to determine the maximum fuel rod loading per unit span which is further used to compute the maximum bending moment and stress.

A sample calculation for the GE2 & GE3 – 7×7 fuel assembly is provided here. The corroded fuel rod dimensions generate higher stresses and therefore are used in the analysis. The maximum stresses for all General Electric fuel assemblies are computed in Table 6B-5.

Fuel Rod Outer Diameter (corroded), $R_{OD} = 0.555$ in.
Fuel Assembly Outer Width, $F_{OD} = 5.44$ in.
Fuel Rod Pitch, $p = 0.738$ in.
Gap between Outer Fuel Rod and Outside of Fuel Assembly, $y_g = (F_{OD} - 6\times p - R_{OD})/2$
$y_g = (5.44 \text{ in.} - 6(0.738) - 0.555)/2 = 0.2285$ in.

Maximum Possible Deflection, $y_{\max} = y_g + 6\times(p - R_{OD})$
$= 0.2285 + 6\times(0.738 - 0.555) = 1.3265$ in.

Zircaloy Modulus of Elasticity, $E = 10.4\times10^6$ psi
Fuel Rod + Fuel Moment of Inertia, $I = 0.00418$ in^4.
Maximum Fuel Rod Span, $L = 48.00$ in. (assuming one failed grid)

Maximum Possible Load per Unit Span, w [9]

$$y_{\max} = \frac{5wL^4}{384EI} \Rightarrow w = \frac{384EIy_{\max}}{5L^4} = \frac{384(10.4\times10^6)(0.00418)(1.3265)}{5(48^4)} = 0.8343 \text{ lb/in.}$$

Maximum Bending Moment, $M = (1/8)\ w\ L^2 = (1/8)(0.8343)(48^2) = 240.027$ in.lb.
Maximum Bending Stress, $S_b = M\ (R_{OD}/2)\ /\ I = 240.027(0.555/2)/0.00418$
$= 15,951$ psi.

From Table 6B-5, it is seen that 15,951 psi is the highest stress and occurs in GE2 and GE3 – 7×7 fuel assembly. This stress is lower than the yield strength of Zircaloy (80,500 psi). It is, therefore, concluded that the fuel tube will not fail and will withstand the side drop load without any plastic deformations.

6B.8.c Fracture Toughness Evaluation for Damaged Fuel with One Missing Grid

The fracture toughness evaluation, which is based on the analysis presented in Section 6B.7, assumes two possible fracture geometries which are denoted as Geometries #1 and #2. Only the worst case BWR 7×7 (GE2, GE3) fuel assemblies are evaluated for fracture, because the stress in BWR 7×7 fuel assembly tube is the highest (see Table 6B-5) and therefore bounds the fracture analysis of all other fuel assemblies.

Structural Integrity of BWR (7×7) Damaged Fuel Rods with Fractured Geometry # 1 (Ruptured Section shown in Figure 6B-1)

Outside diameter of the fuel tube, $D = 0.555$ in.
Cladding Thickness, $t = 0.024$ in.
Average radius, $R = (0.555 – 0.024)/2 = 0.2655$ in.
Moment of Inertia of the net area of the tube + fuel moment of inertia, I
$I = 0.00141/2 + 0.002761 = 0.003466$ in^4

Where it is conservatively assumed that moment of inertia of the net area of the tube is equal to one-half of the total M.I. of the tube (See Table 6B-1).

Span length, $s = l_s = 48.0$ in
Assume $(2a\ /W) = 0.7$

Where,

$2a$ = ruptured hole diameter, W = bulged fuel tube diameter $\geq D = 0.555$ in.
Stress Intensity Factor $K_I = (Y)\ (P\ a^{1/2})/(t\ W)$
$Y = 2.61$ for $(2\ a\ /\ W) = 0.7$ (from Figure 6B-2)

The average tensile force at the crack which is expressed as a function of moment on the cross section, denoted P, is given by,

$P = (2\ M\ R^2\ t)\ /\ I = (2\times203.37\times0.2655^2\ \times0.024)/0.003466=198.53$ lb

$W = \pi R = 0.8341, \qquad (2a / W) = 0.7, \quad a = (0.7\, W / 2) = 0.2919$ in .

Therefore,

$K_I = (2.61\times0.1985\times0.2919^{1/2}) / (0.024\times0.8341) = 13.98$ ksi in ^{½}

$I_I = 13.98$ ksi in$^{1/2} < K_{Ic} = 35.0$ ksi in$^{1/2}$

Therefore, the structural integrity of the (7 ×7) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-1, will be maintained.

<u>Structural Integrity of BWR (7×7) Damaged Fuel Rods with Fractured Geometry # 2 (Crack Shown in Figure 6B-4)</u>

Stress intensity factors are computed for a crack in a fuel tube subjected to a uniform bending moment *M* using formulae given in Reference Figure 6B-4.

$K_I = \sigma (\pi R_m \theta)^{1/2} F(\theta)$

Where,

$F(\theta) = 1 + 6.8\, (\theta / \pi)^{3/2} - 13.6\, (\theta / \pi)^{5/2} + 20.0\, (\theta / \pi)^{7/2}$
σ = Bending Stress due to Uniform Moment *M,*
= 203.37×0.2775/.003466 = 16,283 psi = 16.283 ksi
R_m = Average radius of the fuel tube = 0.2655 in.

$a / R_m = 0.6 = \theta$
Half crack length, $a = R_m\, \theta = 0.2655\times0.6 = 0.1593$ in.
2θ = Angle which the crack makes at the center of the tube
K_I = Stress Intensity Factor at the crack

$F(\theta) = 1 + 6.8\, (\theta / \pi)^{3/2} - 13.6\, (\theta / \pi)^{5/2} + 20.0\, (\theta / \pi)^{7/2}$
$= 1 + 6.8\, (0.6 / \pi)^{3/2} - 13.6\, (0.6 / \pi)^{5/2} + 20.0\, (0.6 / \pi)^{7/2}$
$= 1 + 0.5676 - 0.2168 + 0.0609 = 1.4117$

$K_I = \sigma (\pi R_m \theta)^{1/2} F(\theta)$
$= 16.283\, (\pi\, 0.1593)^{1/2} \times1.4117 = 16.26$ ksi in$^{1/2} < K_{Ic} = 35.0$ ksi in$^{1/2}$

Therefore, the structural integrity of the (7×7) damaged fuel rods, which are conservatively assumed to be ruptured as shown in Figure 6B-4, will be maintained.

6B.9 Conclusions

The maximum computed stresses in the fuel rods and their ratios to the irradiated yield stress of the cladding material are summarized in Table 6B-3. From Table 6B-3, it can be concluded that stresses for all load cases considered are significantly less than the yield stress of the Zircaloy cladding material (computed stresses are 8% to 23% of the yield stress). Table 6B-5 shows that the fuel cladding tube will remain intact during all accident scenarios even if there is one fuel grid missing.

It is important to note that, the stresses in the fuel rods for all analyzed normal and off normal load cases are compressive stresses (less than the critical buckling stress), except for the 1-foot transport condition side drop load. For the 1-foot side drop it is demonstrated by fracture mechanics procedures (by comparing computed stress intensity factors to critical crack initiation fracture toughness in Table 6B-4), that the damaged fuel rods will maintain their structural integrity.

This evaluation demonstrates that the damaged fuel assemblies in the TN-68 will retain their structural integrity when subjected to all normal condition storage and transport loads. Therefore, the retrievability of the damaged fuel assemblies is assured when subjected to any of these normal and off normal loads.

6B.10 References

1. Transnuclear document E-21003, Rev. 0, "Design Criteria for the TN-68 Spent Fuel Storage/Transportation Cask for High Burnup & Damaged Fuel"

2. UCID – 21246, "Dynamic Impact Effects on Spent Fuel Assemblies," Lawrence Livermore National Laboratory, October 20, 1987

3. SCALE NUREG/CR-0200, Vol. 3, Rev. 5

4. ANSI N14.23, "Draft American National Standard Design Basis for Resistance to Shock and Vibration of Radioactive Material Packages Greater than One Ton in Truck Transport", May 1980

5. NRC-12, SAND76-0427, NUREG766510, "Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks", June 1977

6. NUHOMS® MP-197 Multi-Purpose Cask Transportation Package, Safety Analysis Report, Rev. 4

7. T.J. Walker, et al., "Variation of Zircaloy Fracture Toughness in Irradiation" Zirconium in Nuclear Applications, ASTM STP 551, American Society for Testing and Materials, 1974, pp. 328-354

8. "The Stress Analysis of Cracks Handbook" Third Edition by Hiroshi Tada et al., ASME Press

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

10. TN-68 Transport Packaging, Safety Analysis Report, Rev. 4

11. R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Material", John Wiley & Sons, New York, 1976

Table 6B-1

Design Parameters of TN-68 (7×7) and (8×8) BWR Fuel Assemblies

Tube Arrays [1]	**7×7**	**8×8**	**8×8**	**8×8**
GE Designation	GE2, GE3	GE4	GE5	GE8
No. of Fuel Rods	49	63	62	60
Max. Active Fuel Length (in)	144	146	150	150
Fuel Tube O.D. (in)	0.563	0.493	0.483	0.483
Corroded Fuel Tube OD [2] (in)	0.555	0.485	0.475	0.475
Clad Thickness [4] (in)	0.032	0.034	0.032	0.032
Corroded Clad Thickness [4] (in)	0.024	0.026	0.024	0.024
Fuel Pellet O.D. (in)	0.487	0.416	0.41	0.41
Fuel Tube I.D. (in)	0.499	0.425	0.419	0.419
Corroded Fuel Tube I.D. (in)	0.507	0.433	0.427	0.427
Avg. Fuel Tube Radius (in)	0.2655	0.2295	0.2255	0.2255
Number of Spacers	7	7	7	7
Fuel Rod Span (in)	24.0	24.3	25.0	25.0
Fuel Tube Area (in^2)	0.0400	0.0375	0.0340	0.0340
Fuel Tube M. of I. (in^4)	0.00141	0.00099	0.00087	0.00087
Fuel Pellet M. of I. (in^4)	0.002761	0.001470	0.001387	0.001387
Total Fuel Tube + Fuel M. of I.(in^4)	0.00418	0.00246	0.00225	0.00225
Fuel Tube Weight [6] (lb)	1.799	1.675	1.592	1.592
Fuel Weight [7] (lb)	10.246	7.580	7.565	7.565
Total Fuel Tube + Fuel Wt. (lb)	12.045	9.256	9.157	9.157
Irradiated Yield Stress [5] (psi)	80,500	80,500	80,500	80,500
Young's Modulus, *E* [5] (psi)	1.04×10^7	1.04×10^7	1.04×10^7	1.04×10^7

See Notes below the following table.

Table 6B-2

Design Parameters of TN-68 (8×8), (9×9) and (10×10) BWR Fuel Assemblies

Tube Arrays [1]	**8×8**	**9×9**	**10×10**
GE Designation	GE9, GE10	GE11, GE13	GE12
Number of Fuel Rods	60	66	78
Max. Active Fuel Length (in)	150	146	150
Fuel Tube O.D.(in)	0.483	0.44	0.404
Corroded Fuel Tube O.D. [2] (in)	0.475	0.432	0.396
Clad Thickness [4] (in)	0.032	0.028	0.026
Corroded Clad Thickness [4] (in)	0.024	0.02	0.018
Fuel Pellet O.D. (in)	0.411	0.376	0.345
Fuel Tube I.D. (in)	0.419	0.384	0.352
Corroded Fuel Tube I.D. [3] (in)	0.427	0.392	0.36
Avg. Fuel Tube Radius (in)	0.2255	0.206	0.189
Number of Spacers	7	7	7
Fuel Rod Span (in)	25.0	24.3	25.0
Fuel Tube Area (in^2)	0.0340	0.0259	0.0214
Fuel Tube M.1 (in^4)	0.00087	0.00055	0.00038
Fuel Pellet M. of I. (in^4)	0.001401	0.000981	0.000695
Total Fuel Tube + Fuel M. of I. (in^4)	0.00227	0.00153	0.00108
Fuel Tube Weight [6] (lb)	1.592	1.238	1.084
Fuel Weight [7] (lb)	7.602	6.193	5.356
Total Fuel Tube + Fuel Wt. (lb)	9.194	7.431	6.440
Irradiated Yield Stress [5] (psi)	80,500	80,500	80,500
Young's Modulus, E [5] psi	1.04×10^7	1.04×10^7	1.04×10^7

Notes:

(1) The Maximum Fuel Assembly Weight with Channel = 705 lb is used in this evaluation.

(2) Includes 0.008 in (200 μm) reduction in cladding outer diameter to account for water side cladding corrosion.

(3) Includes 0.008 in (200 gm) increase in cladding inner diameter to account for inner surface cladding corrosion.

(4) Includes 0.008 in (200 μm) reduction in cladding thickness to account for corrosion.

(5) These values are taken from Reference 2, Section 2.

(6) Used uncorroded dimensions and density = 0.234 lb/in^3 [Ref 2].

(7) Used uncorroded dimensions and density = 0.382 lb/in^3 [Ref 3].

Table 6B-3

Maximum Computed Fuel Rod Stresses and their Ratio to Yield Strength

Load	**Maximum Computed Stress (psi)**				**Zircaloy Cladding Yield Strength (at 750°F) (psi)**	**Ratio of Max. Computed Stress to Yield Strength**
	(7×7) Fuel	**(8×8) Fuel**	**(9×9) Fuel**	**(10×10) Fuel**		
1-foot End Drop	5,400	5,184	6,216	6,355	80,500	0.08
1-foot Side Drop	11,844	16,075	15,712	18,216	80,500	0.23

Table 6B-4

Computed Stress Intensities of Fuel Tubes and their Ratio to Critical Fracture Toughness for the One Foot Side Drop Load

Fracture Geometry	**Max Computed Stress Intensity, K_I (ksi in$^{1/2}$)**				**Critical Stress Intensity, K_{Ic} (ksi in$^{1/2}$)**	**Ratio Max K_I / K_{Ic}**
	(7×7) Fuel	**(8×8) Fuel**	**(9×9) Fuel**	**(10×10) Fuel**		
Geometry # 1	12.4	15.5	14.4	16.0	35.0	0.46
Geometry # 2	14.3	18.2	16.8	18.7	35.0	0.53

Table 6B-5

Side Drop Impact Stress Calculations for Damaged Fuel with One Missing Grid

Tube Arrays (1)	**7x7**	**8x8**	**8x8**	**8x8**	**8x8**	**9x9**	**10x10**
GE Designation	GE2, GE3	GE4	GE5	GE8	GE9, GE10	GE11, GE13	GE12
Number of Fuel Rods	49	63	62	60	60	66	78
Active Fuel Length	144	146	150	150	150	146	150
Fuel Tube O.D.	0.563	0.493	0.483	0.483	0.483	0.44	0.404
Corroded Tube O.D., R_{OD} (in) (2)	0.555	0.485	0.475	0.475	0.475	0.432	0.396
Clad Thickness (in) (4)	0.032	0.034	0.032	0.032	0.032	0.028	0.026
Corroded Clad Thickness, t (in) (4)	0.024	0.026	0.024	0.024	0.024	0.020	0.018
Fuel Pellet O.D. (in)	0.487	0.416	0.41	0.41	0.411	0.376	0.345
Fuel Tube I.D. (in)	0.499	0.425	0.419	0.419	0.419	0.384	0.352
Corroded Tube I.D. (in) (3)	0.507	0.433	0.427	0.427	0.427	0.392	0.36
Avg. Fuel Tube Radius, R_{avg} (in)	0.2655	0.2295	0.2255	0.2255	0.2255	0.206	0.189
Number of Spacers	6	6	6	6	6	6	6
Max. Fuel Span (in)	48	48.6	50	50	50	48.6	50
Fuel Tube Area (in^2)	0.0400	0.0375	0.0340	0.0340	0.0340	0.0259	0.0214
Fuel Tube M.I. (in^4)	0.00141	0.00099	0.00087	0.00087	0.00087	0.00055	0.00038
Fuel Pellet M.I. (in^4)	0.002761	0.001470	0.001387	0.001387	0.001401	0.000981	0.000695
Total Tube M.I. + Fuel M.I	0.00418	0.00246	0.00225	0.00225	0.00227	0.00153	0.00108
Fuel Tube Wt (lb) (6)	1.799	1.675	1.592	1.592	1.592	1.238	1.084
Fuel Wt (lb) (7)	10.246	7.58	7.565	7.565	7.602	6.193	5.356
Total Tube + Fuel Wt (lb)	12.045	9.256	9.157	9.157	9.194	7.431	6.44
Fuel Assembly O.D., F_{OD} (in)	5.44	5.44	5.44	5.44	5.44	5.44	5.44
Fuel Rod Pitch (in)	0.738	0.640	0.640	0.640	0.640	0.566	0.510
Spacer–tube end gap, y_g (in)	0.2285	0.2375	0.2425	0.2425	0.2425	0.24	0.227
Max. Deflection, y_{max} (in)	1.3265	1.3225	1.3975	1.3975	1.3975	1.312	1.253
Modulus of Elasticity, E (psi) (5)	1.04E+07	1.04E+07	1.04E+07	1.04E+07	1.04E+07	1.04E+07	1.04E+07
Load per Unit Span, w (lb/in.)	0.8333	0.4659	0.4026	0.4026	0.405	0.2877	0.1726
Maximum Moment, $M = wL^2/8$ (in-lb)	239.995	137.555	125.805	125.805	126.563	84.945	53.946
Max. $Sb = M \times R_{OD}/(2I)$ (psi)	**15951**	**13556**	**13255**	**13255**	**13255**	**11979**	**9908**
Yield Strength (psi) @ 750°F (5)	80500	80500	80500	80500	80500	80500	80500

Notes:
(1) Maximum fuel assembly weight with channel = 705 lb in this evaluation.
(2) Includes 0.008 in (200 μm) reduction in cladding outer diameter to account for water side cladding corrosion.
(3) Includes 0.008 in (200 gm) increase in cladding inner diameter to account for inner surface cladding corrosion.
(4) Includes 0.008 in (200 μm) reduction in cladding thickness to account for corrosion.
(5) These values are taken from Reference 2, Section 2.
(6) Used uncorroded dimensions and density = 0.234 lb/in^3 [Ref 2]
(7) Used uncorroded dimensions and density = 0.382 lb/in^3 [Ref 3]

Figure 6B-1
Fracture Geometry # 1 - Ruptured Section

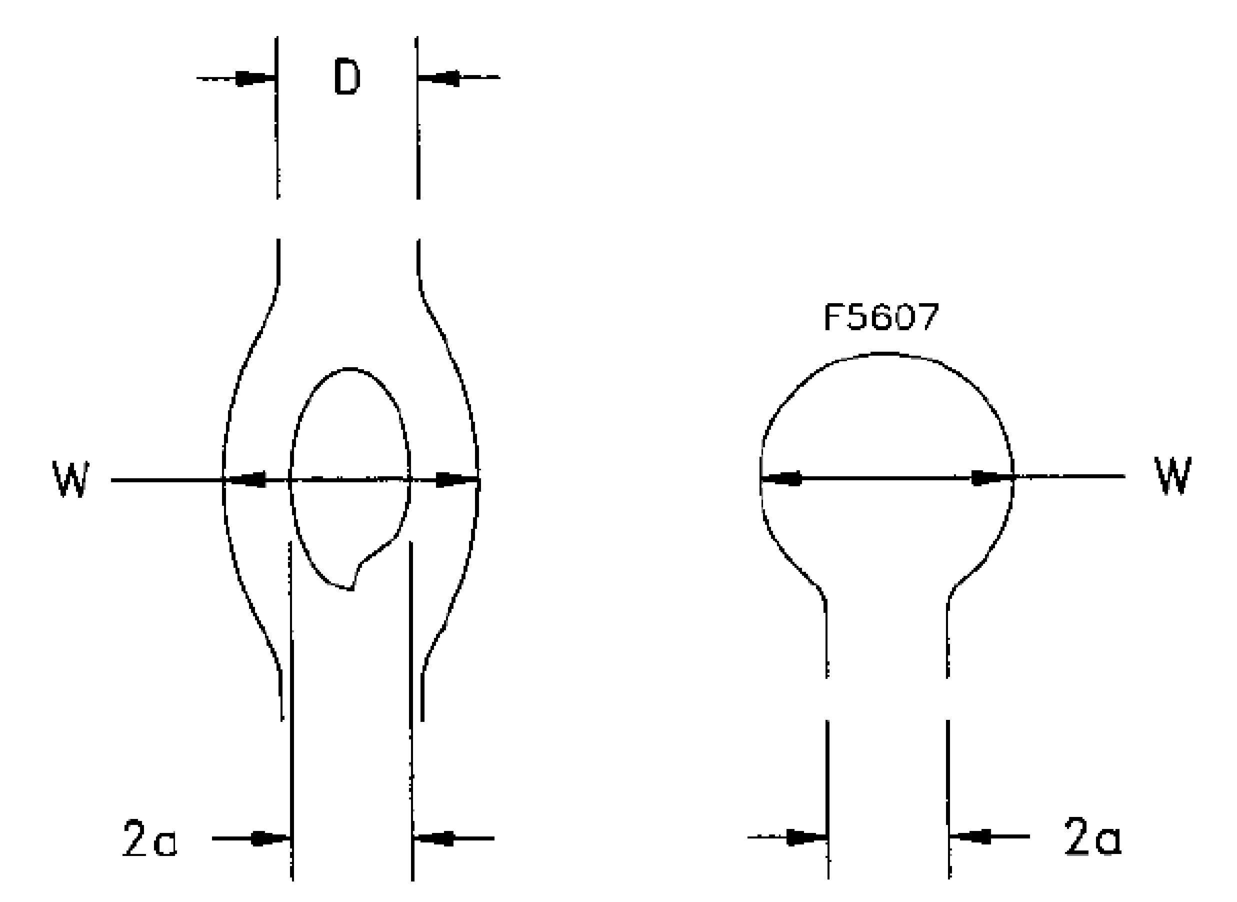


Figure 6B-2
Stress Intensity Factor Solutions for Several Specimen Configurations
(Figure 8.7 (c) of Reference [11])

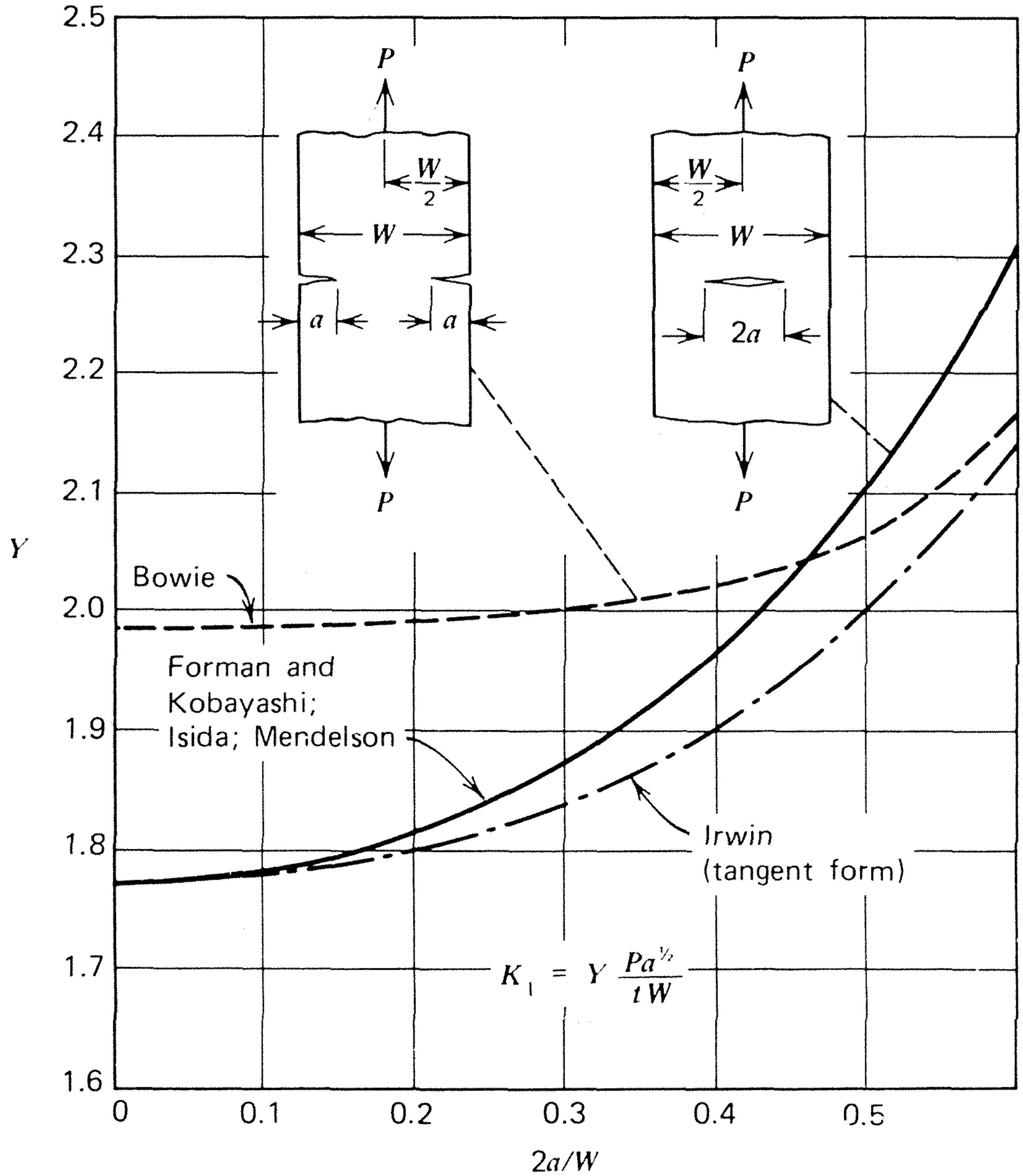


Figure 6B-3

Dimensions for Derivation of Tensile Force at the Geometry # 1 Rupture Section

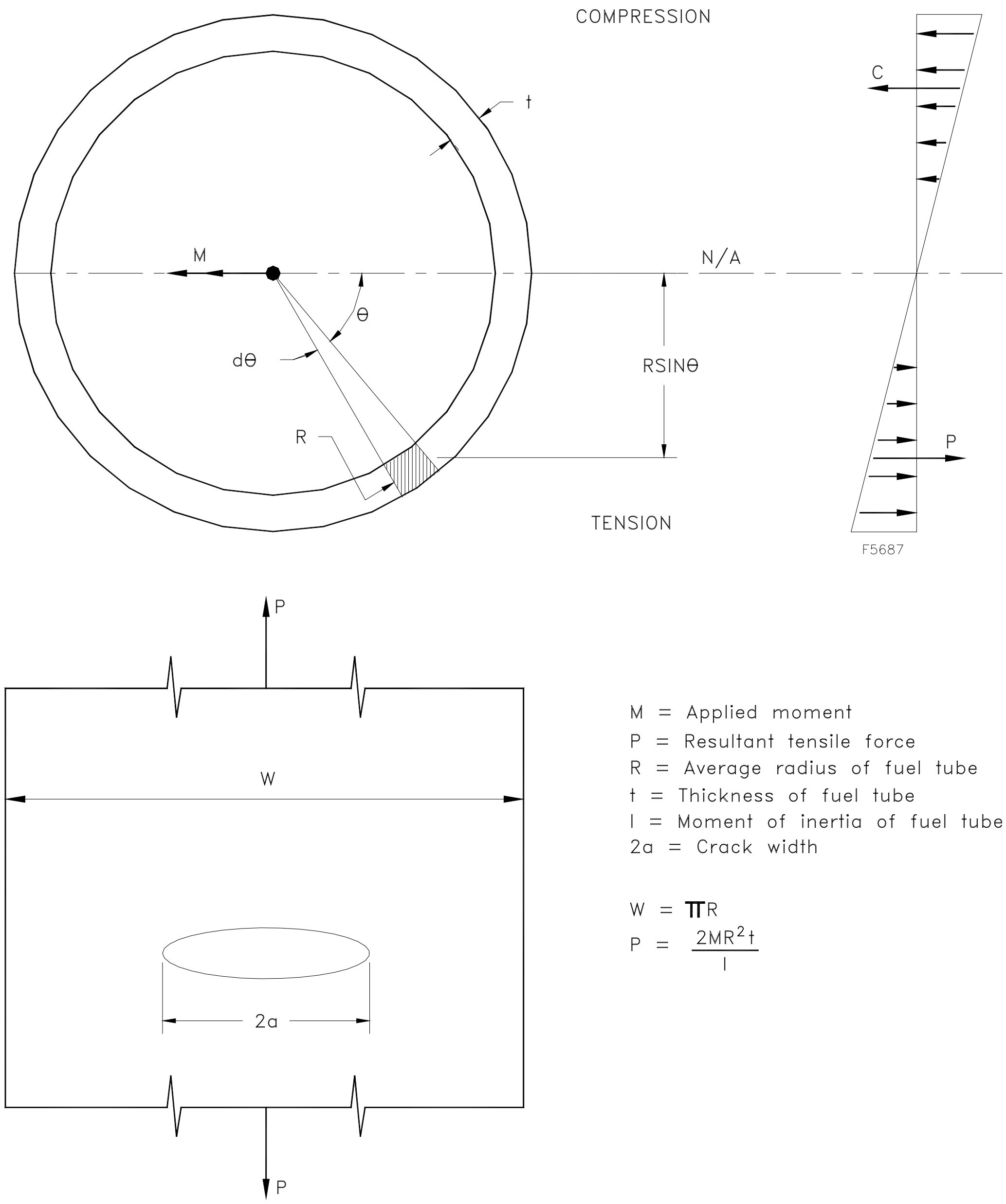
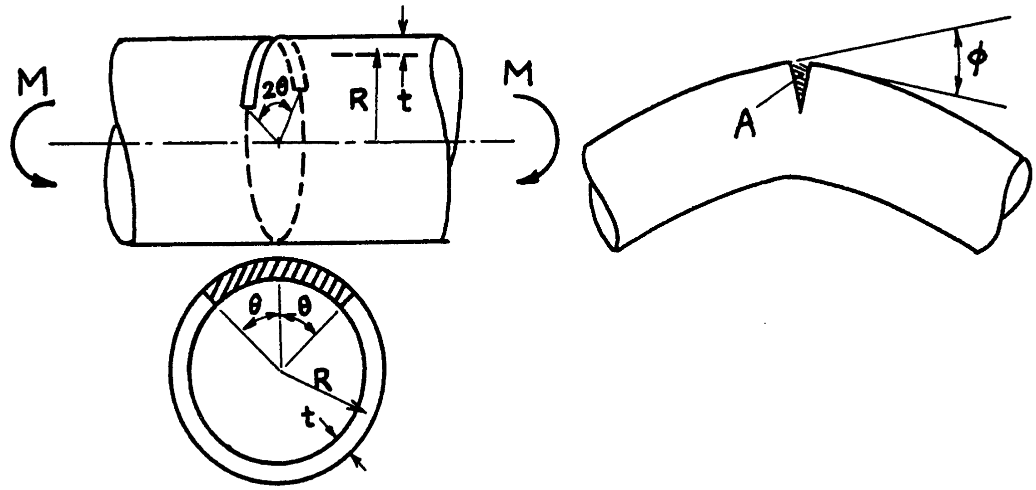


Figure 6B-4
<u>Geometry Model # 2, Through-Wall Circumferential Crack in Cylinder under Bending</u>
(Reference 8, page 472, Part VII)



$$\underline{R/t \simeq 10} \qquad \left(\theta < 110^{\circ}\right)$$

$$\sigma = M/\left(\pi R^2 t\right)$$

$$K_I = \sigma\sqrt{\pi(R\theta)} \cdot F(\theta)$$

$$F(\theta) = 1 + 6.8\left(\frac{\theta}{\pi}\right)^{3/2} - 13.6\left(\frac{\theta}{\pi}\right)^{5/2} + 20.0\left(\frac{\theta}{\pi}\right)^{7/2}$$