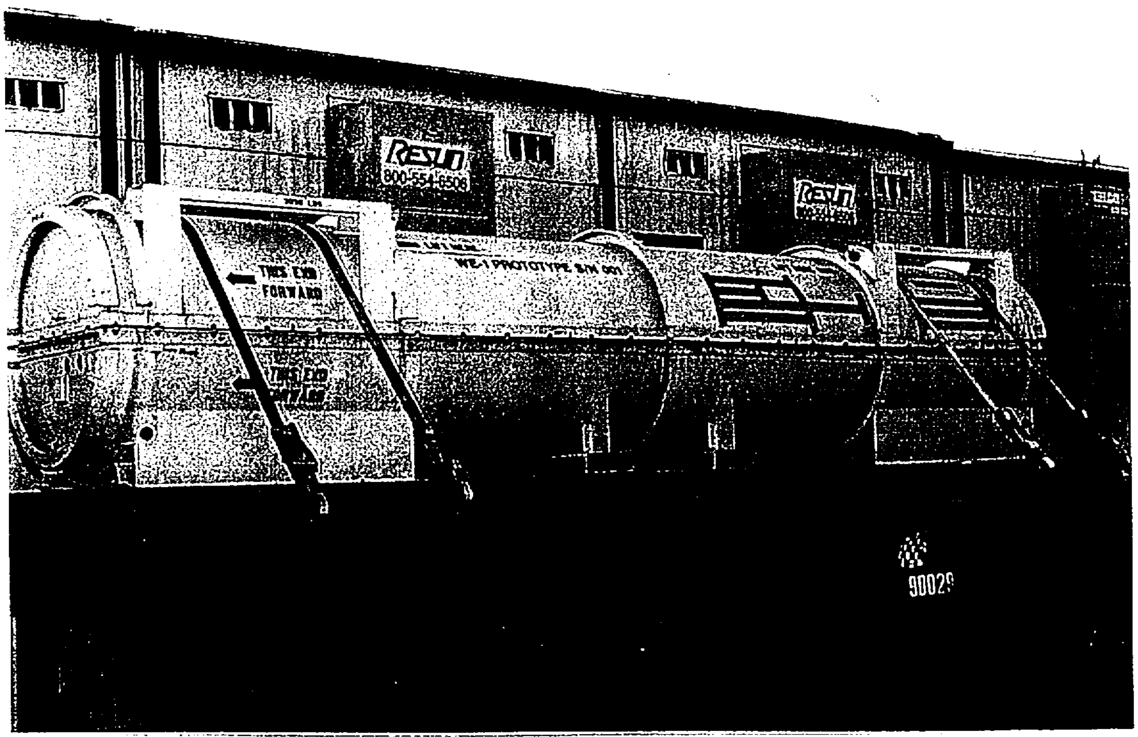
APPENDIX 2-1: WE-1 PROTOTYPE PACKAGE CERTIFICATION TESTING PHOTOGRAPHS

WE-1 CONTAINER PRIOR TO TESTING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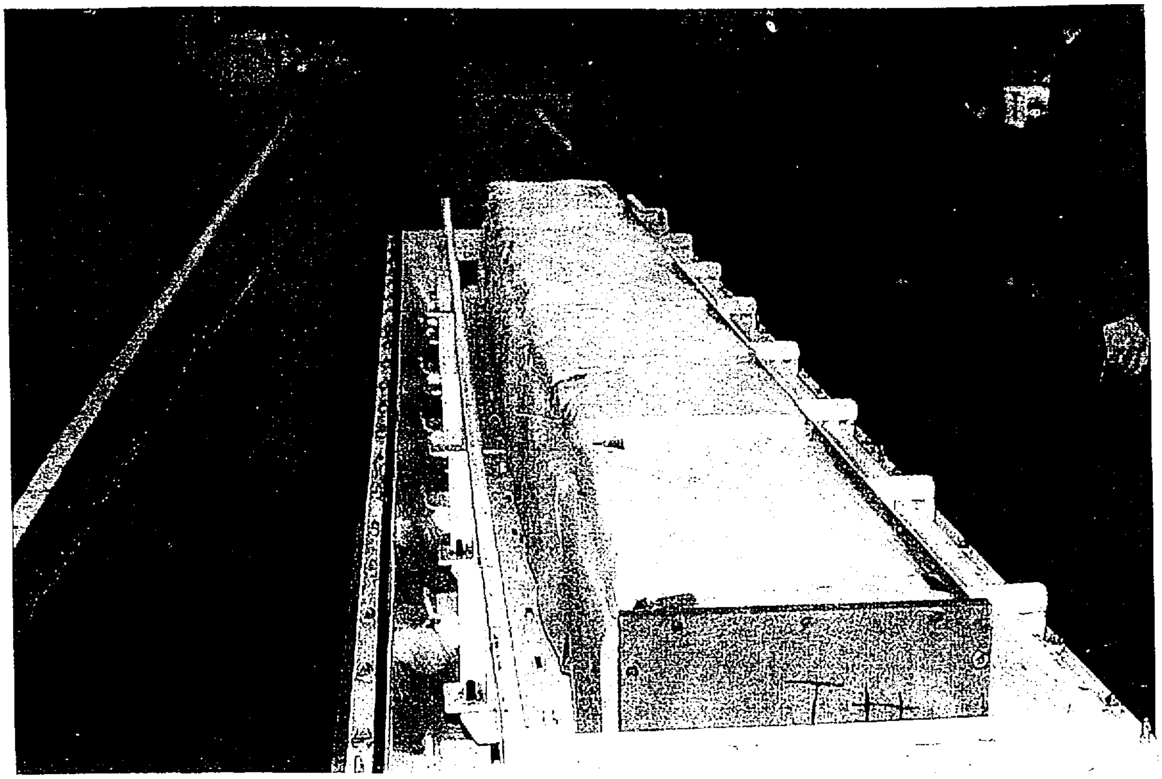
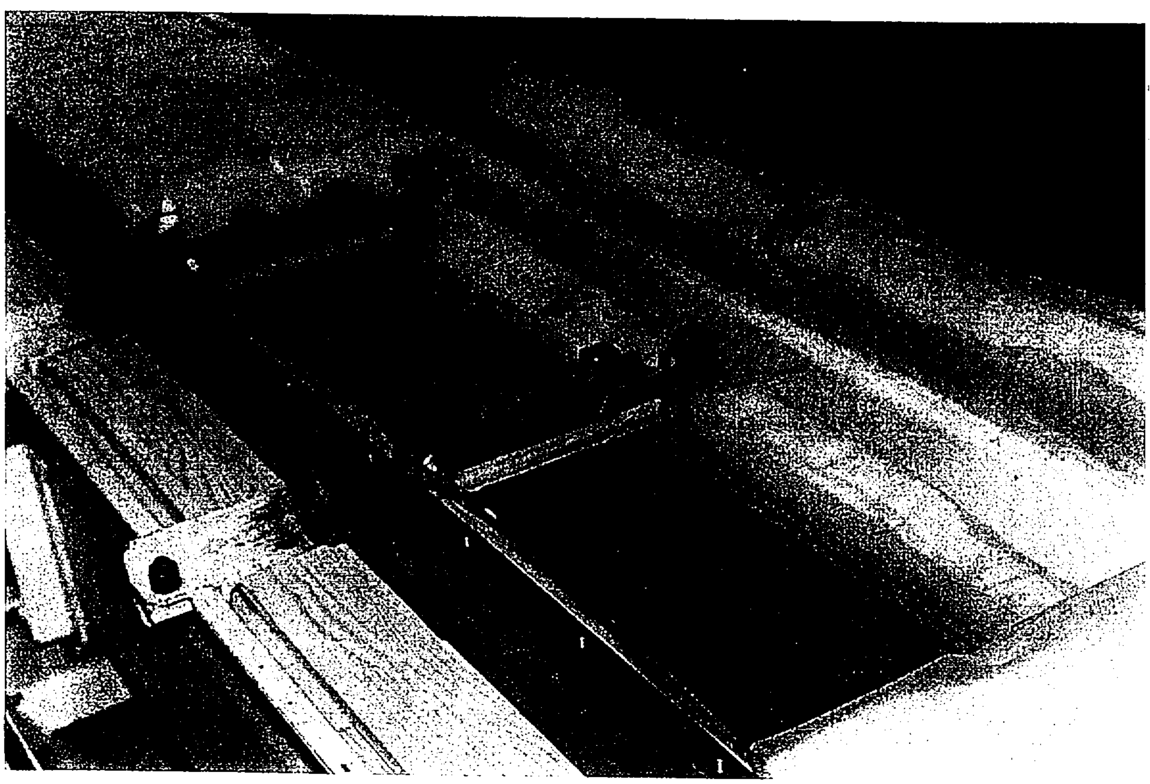
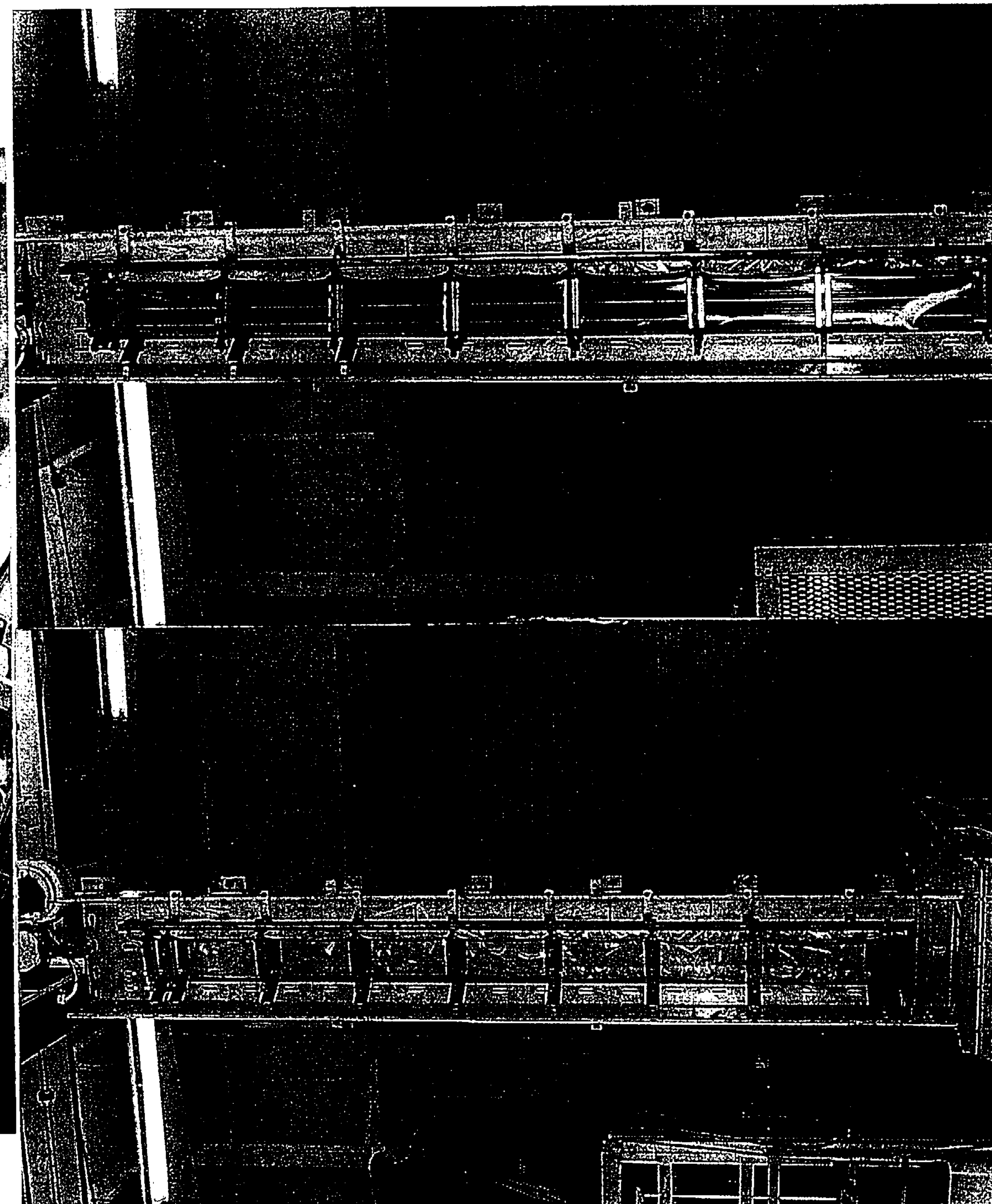
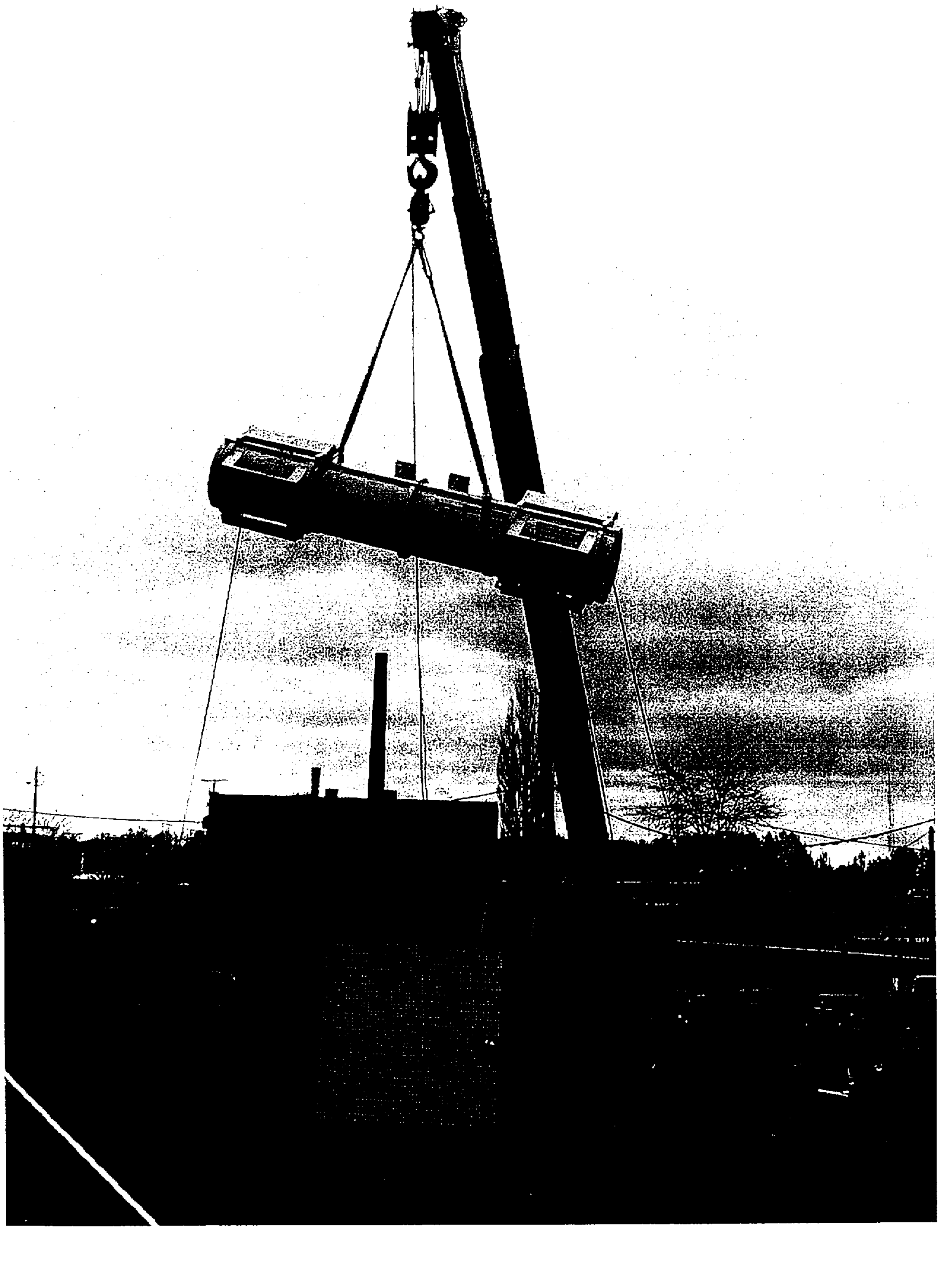
90029

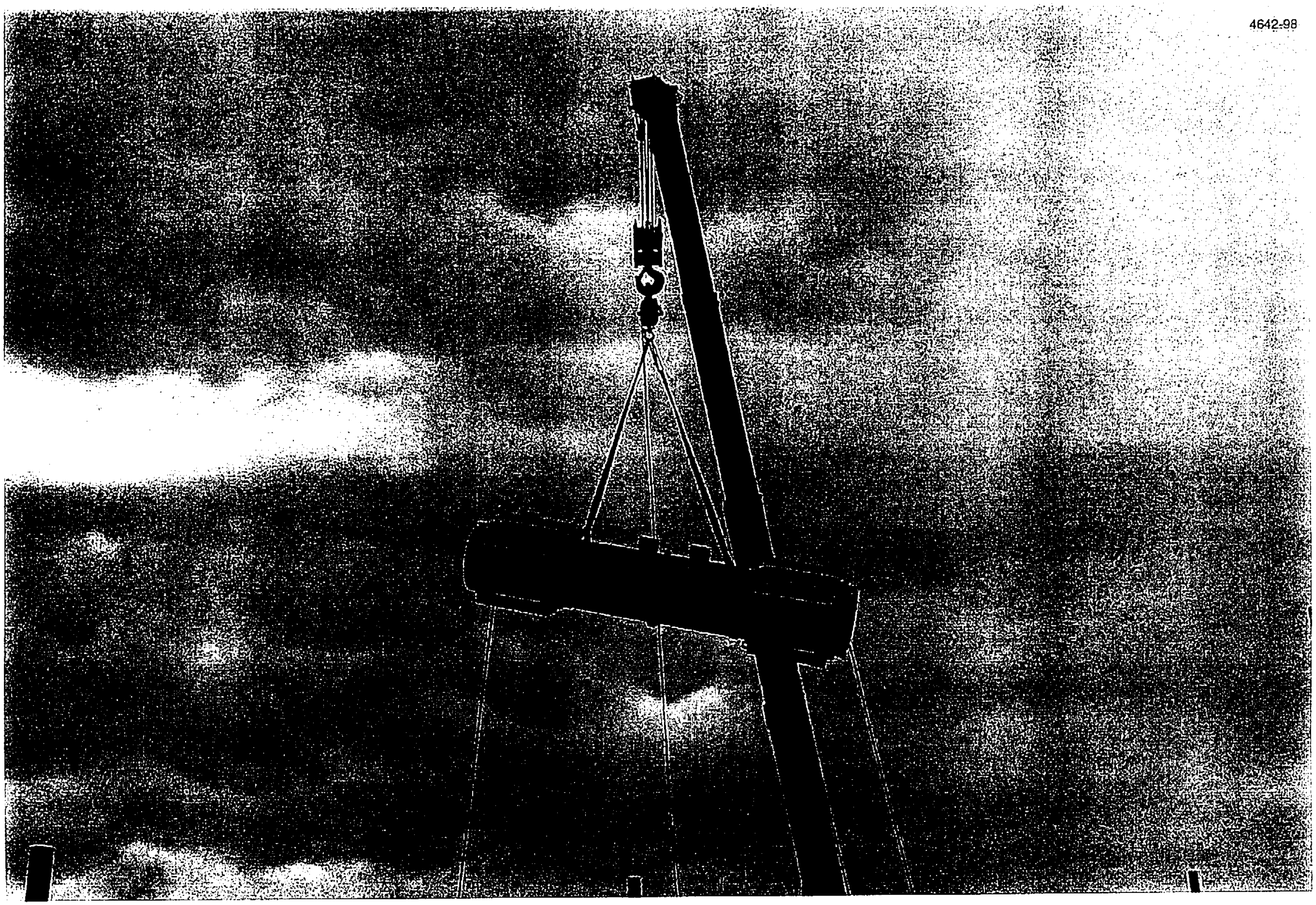






WE-1 CONTAINER 30 FT. DROP TEST

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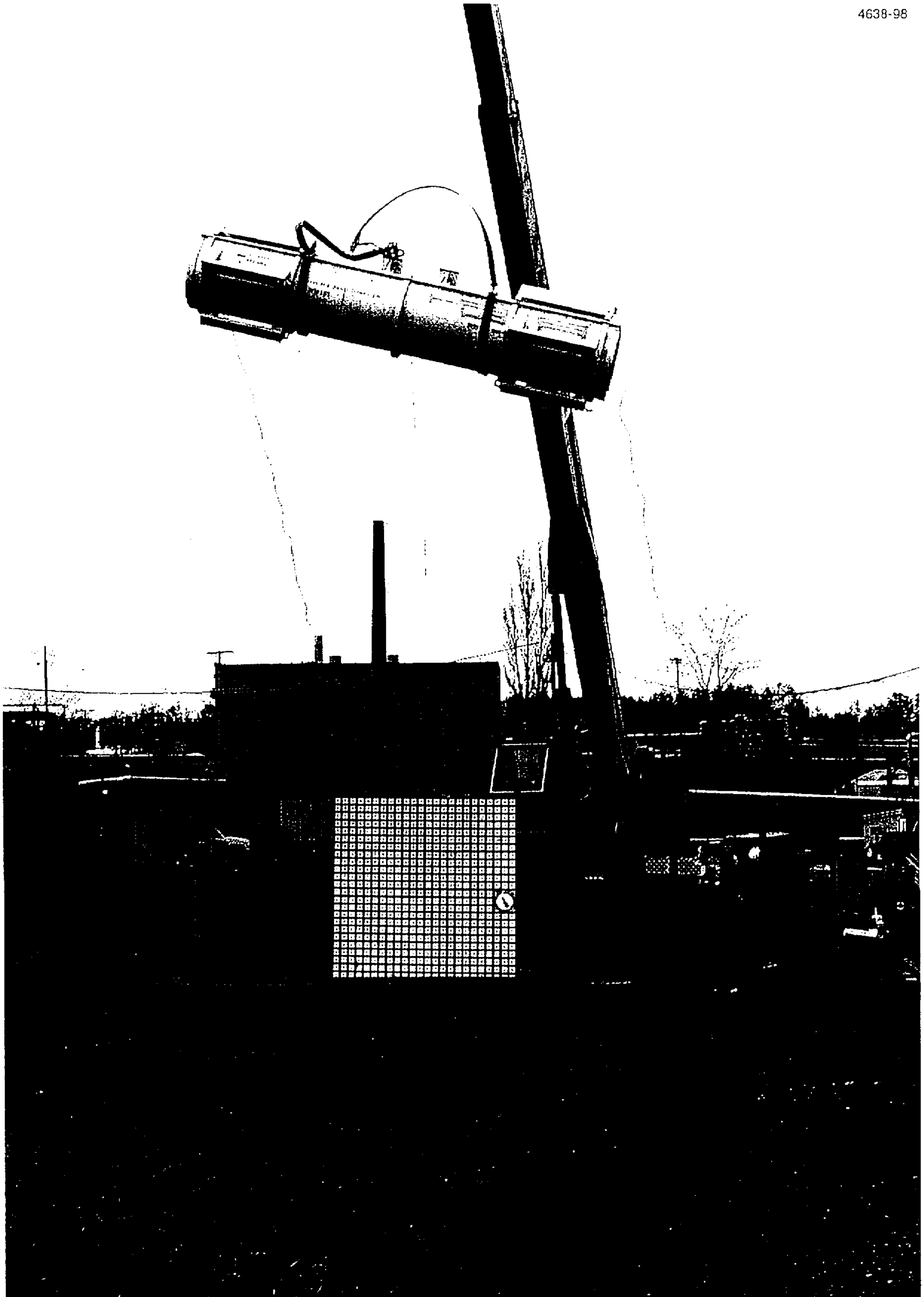
4638-98



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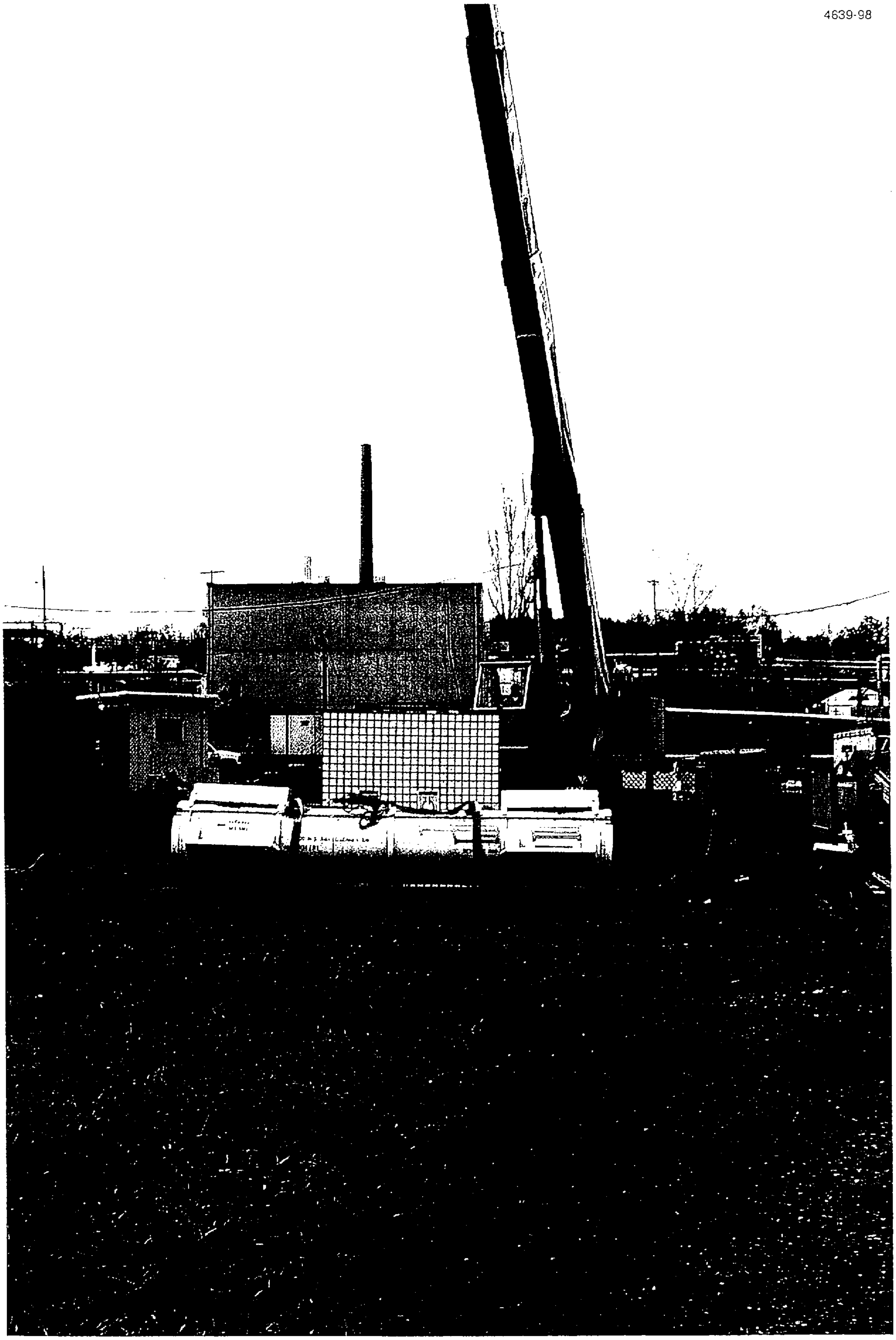
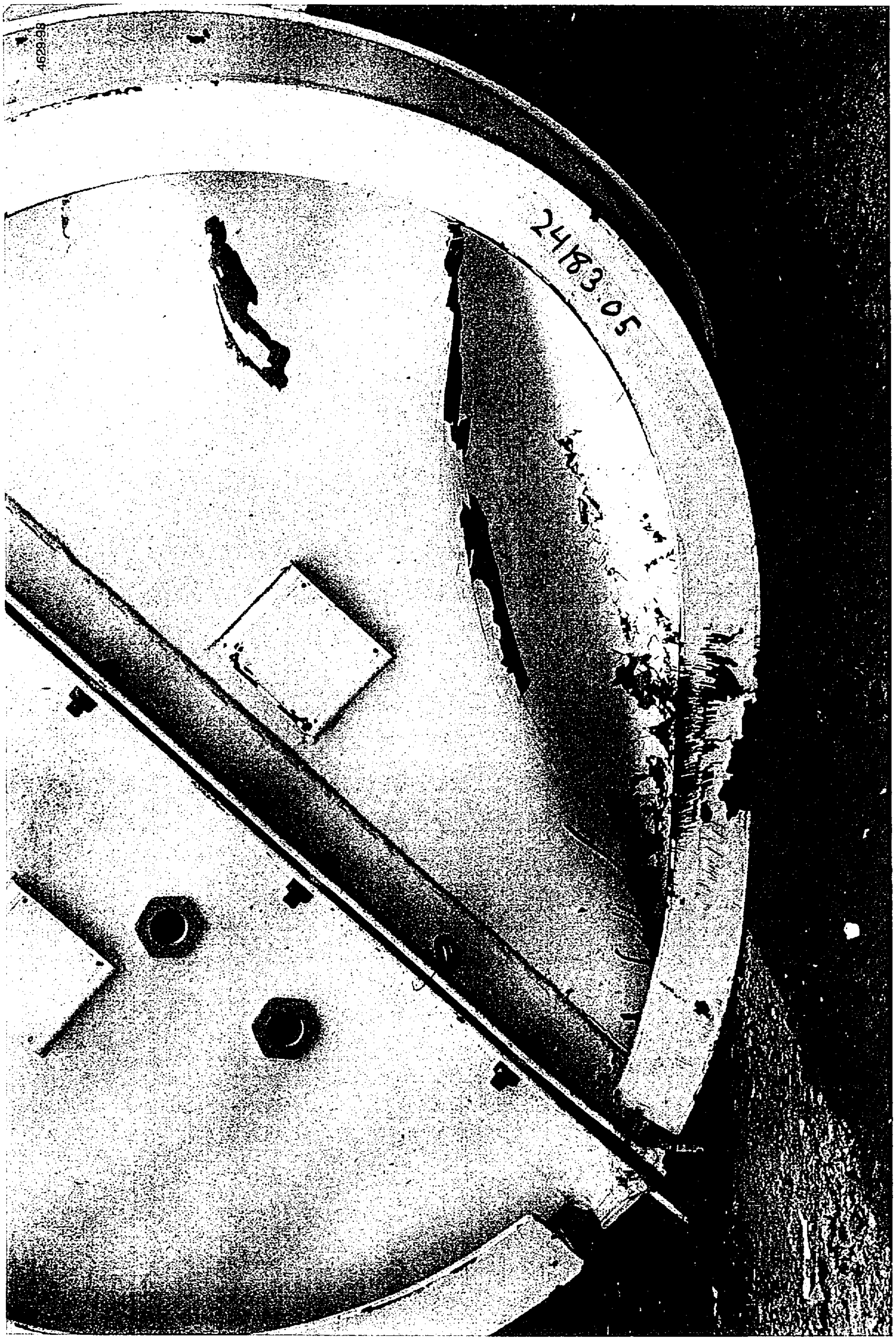


WE-1 CONTAINER DAMAGE AFTER 30 FT. DROP TEST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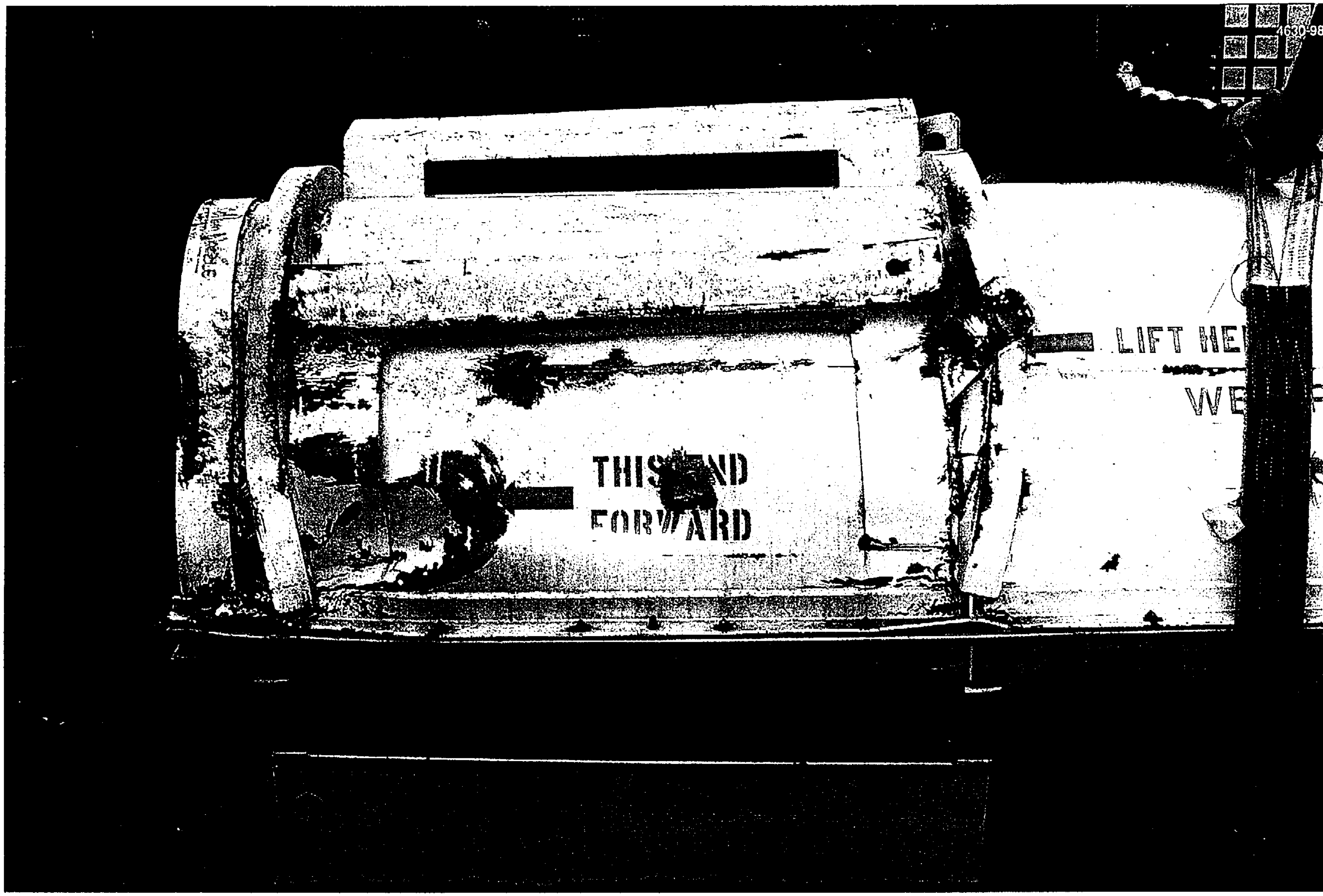
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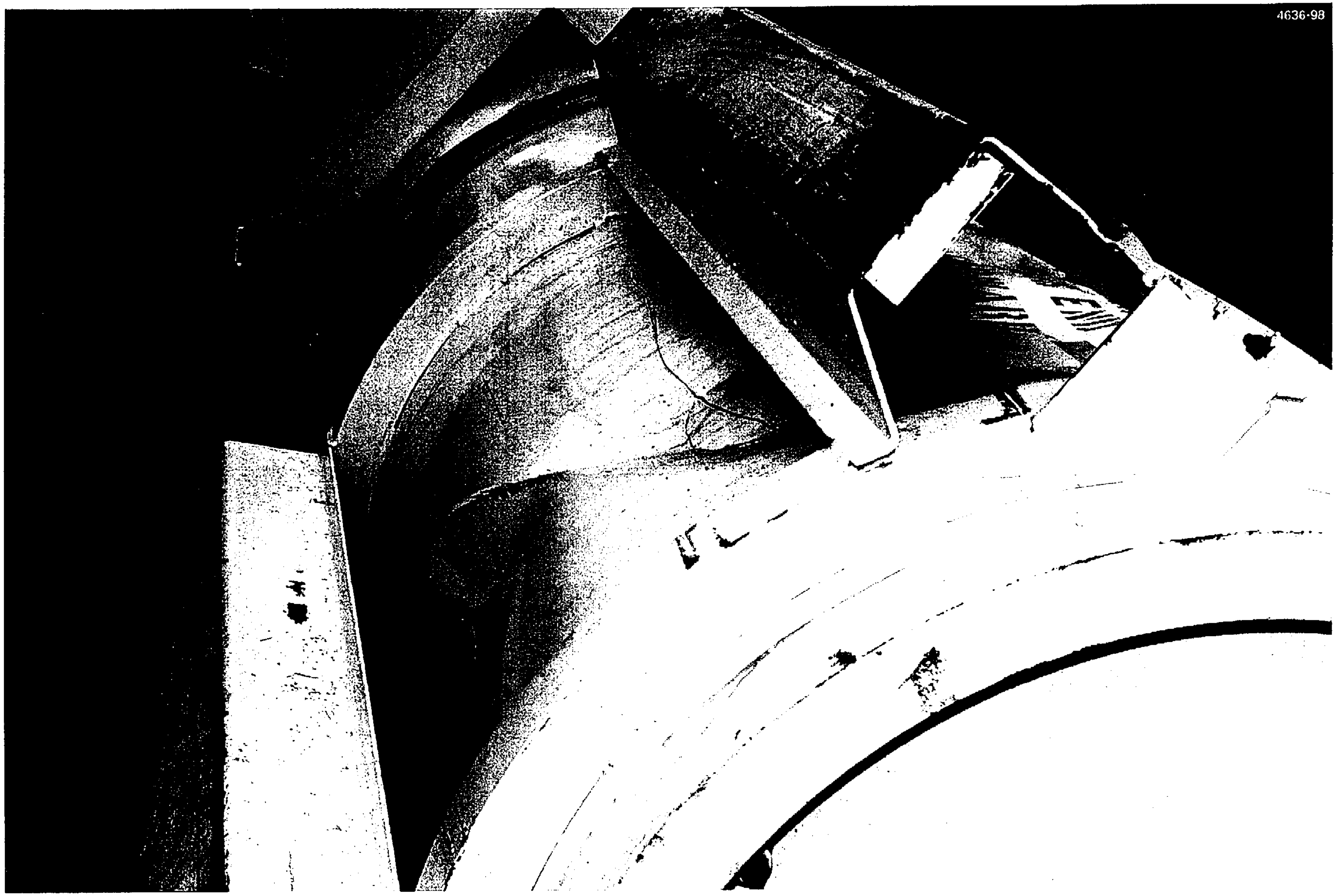
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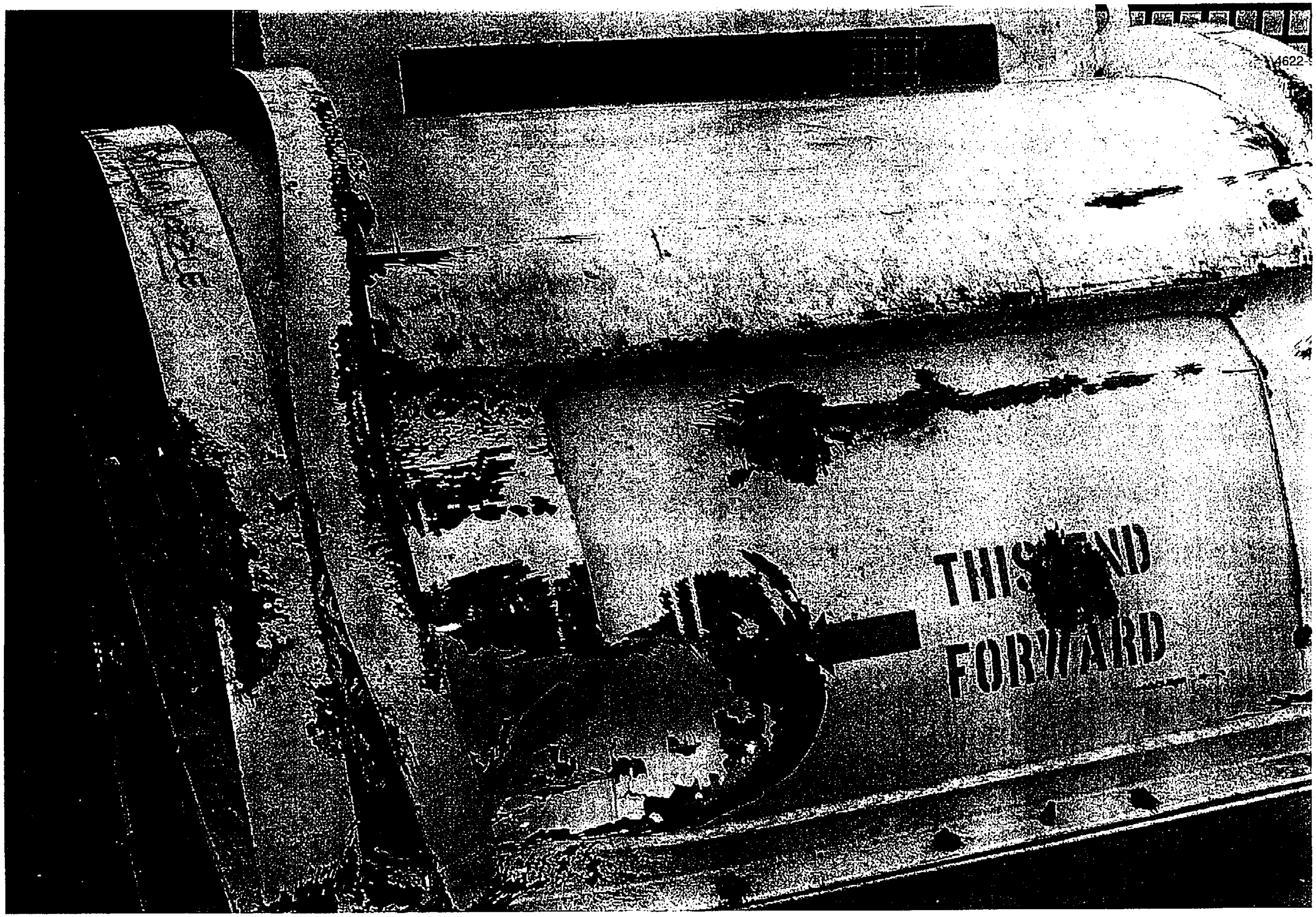
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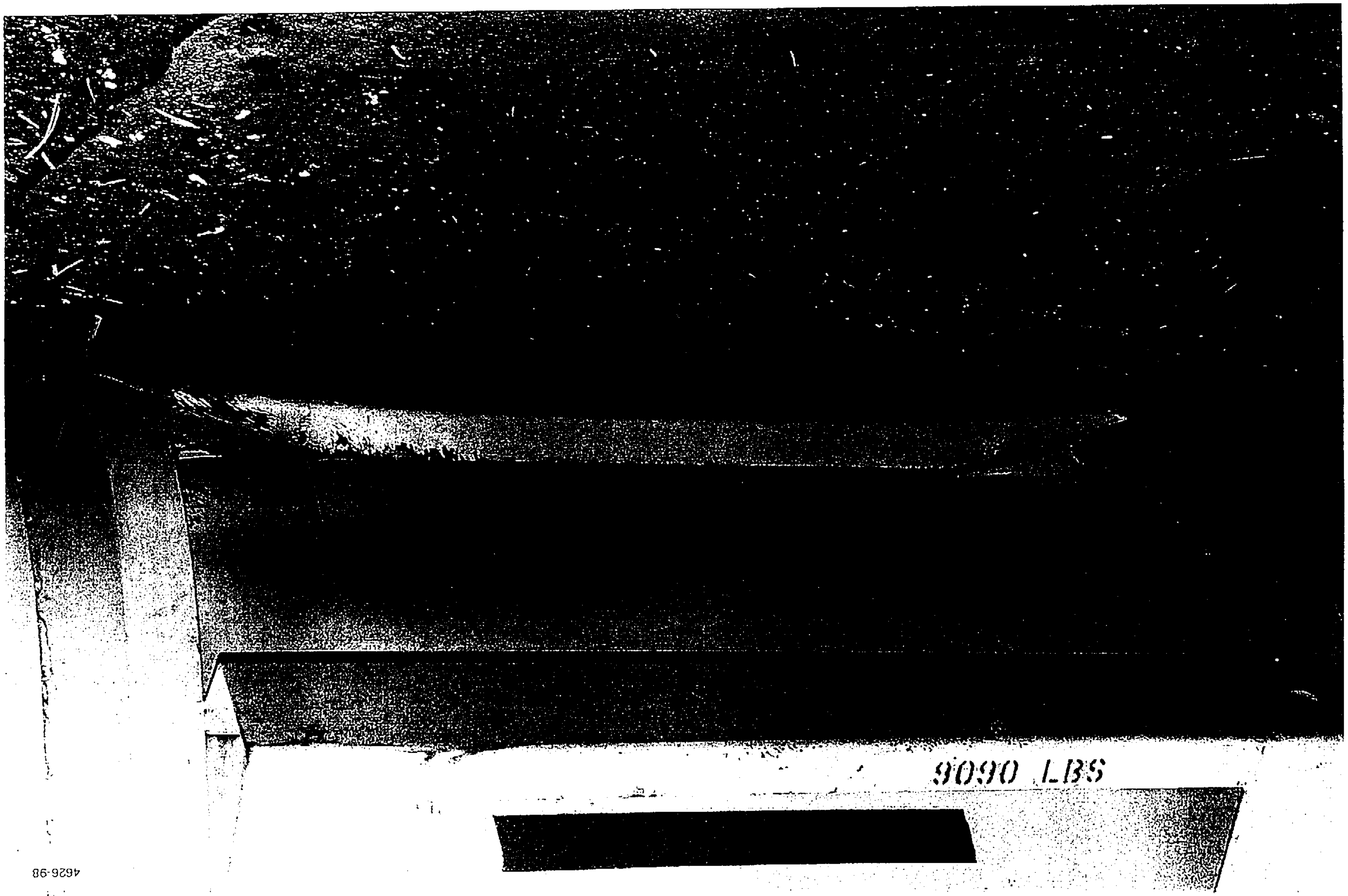
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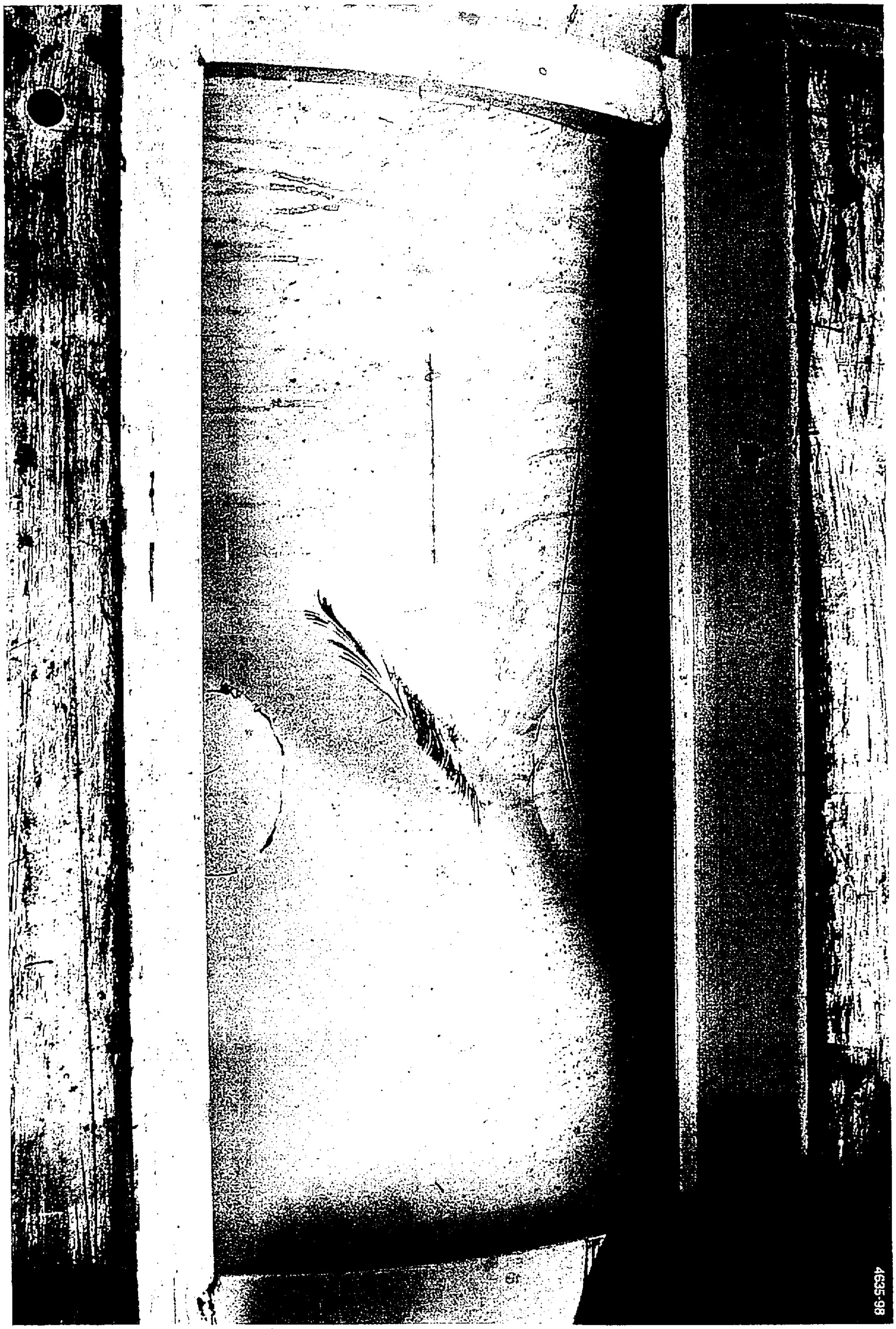
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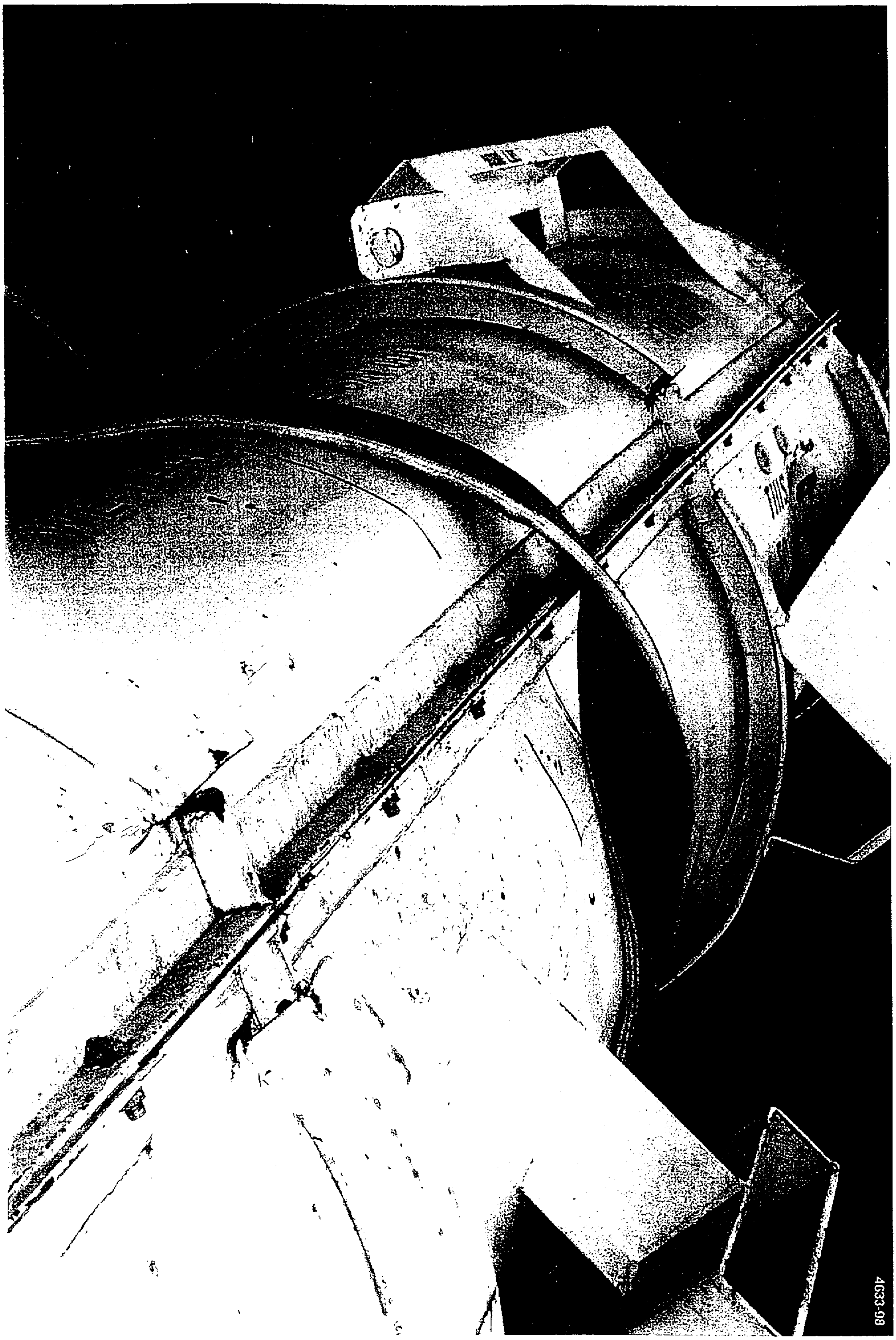
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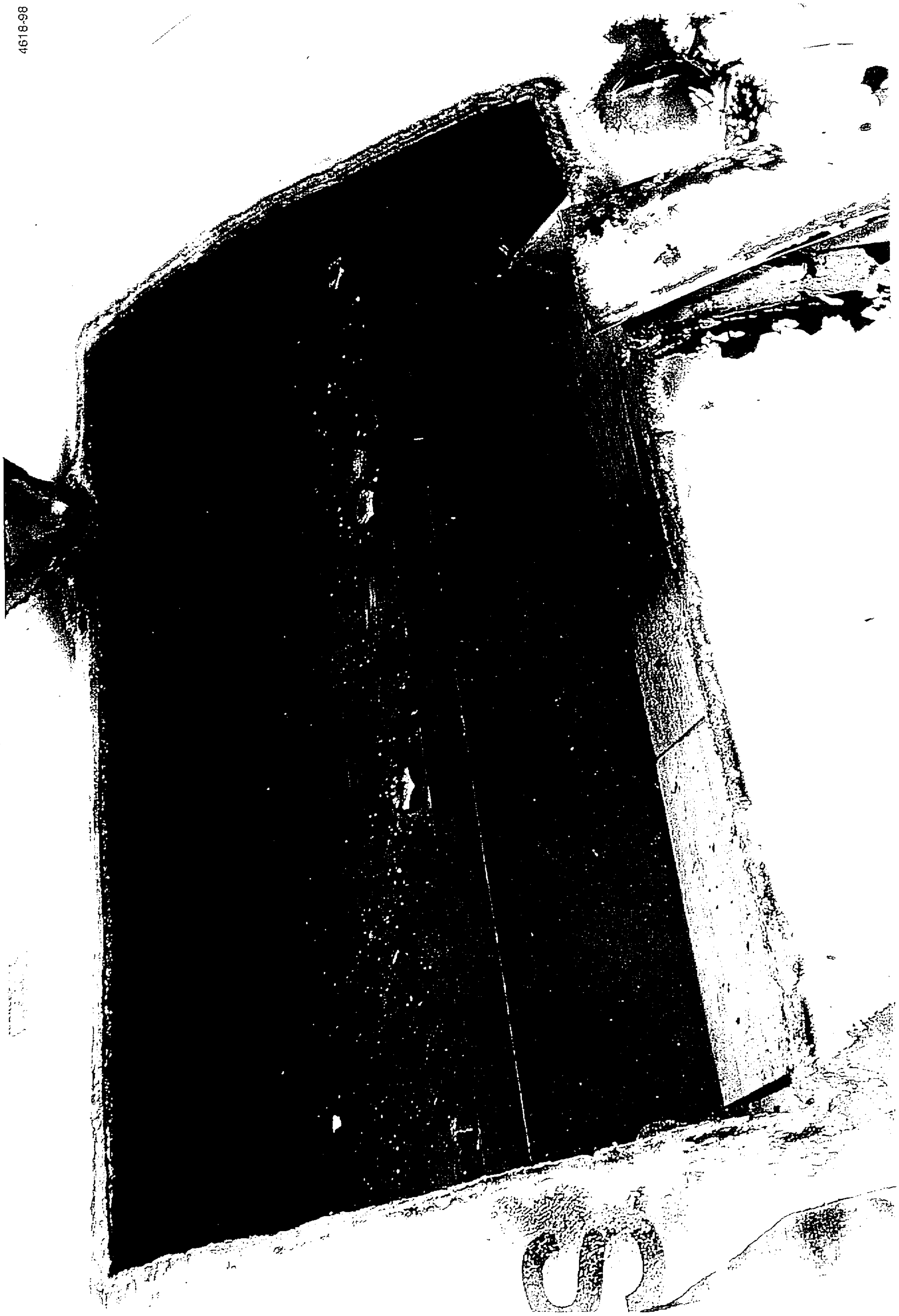
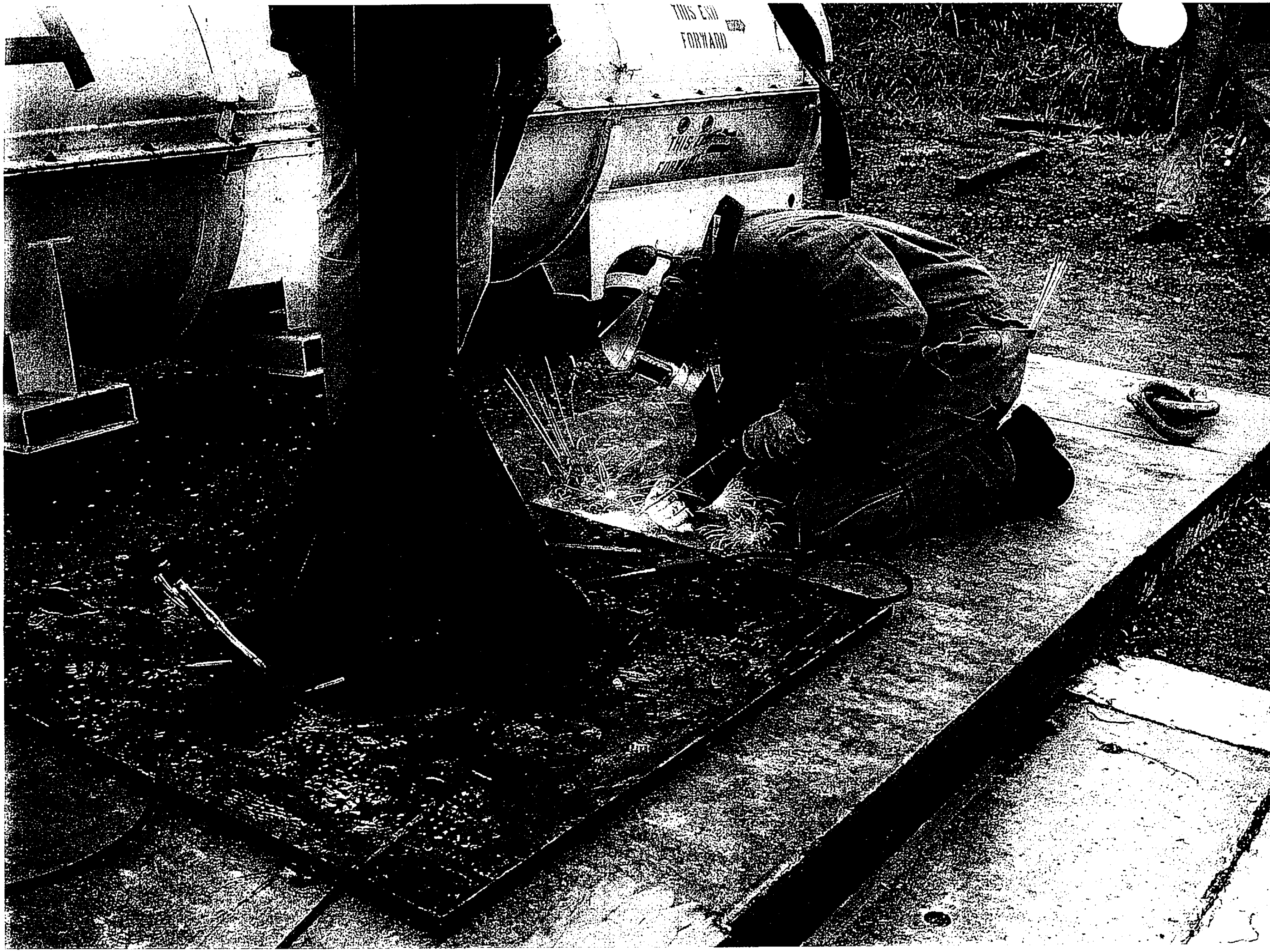


WE-1 CONTAINER PUNCTURE TEST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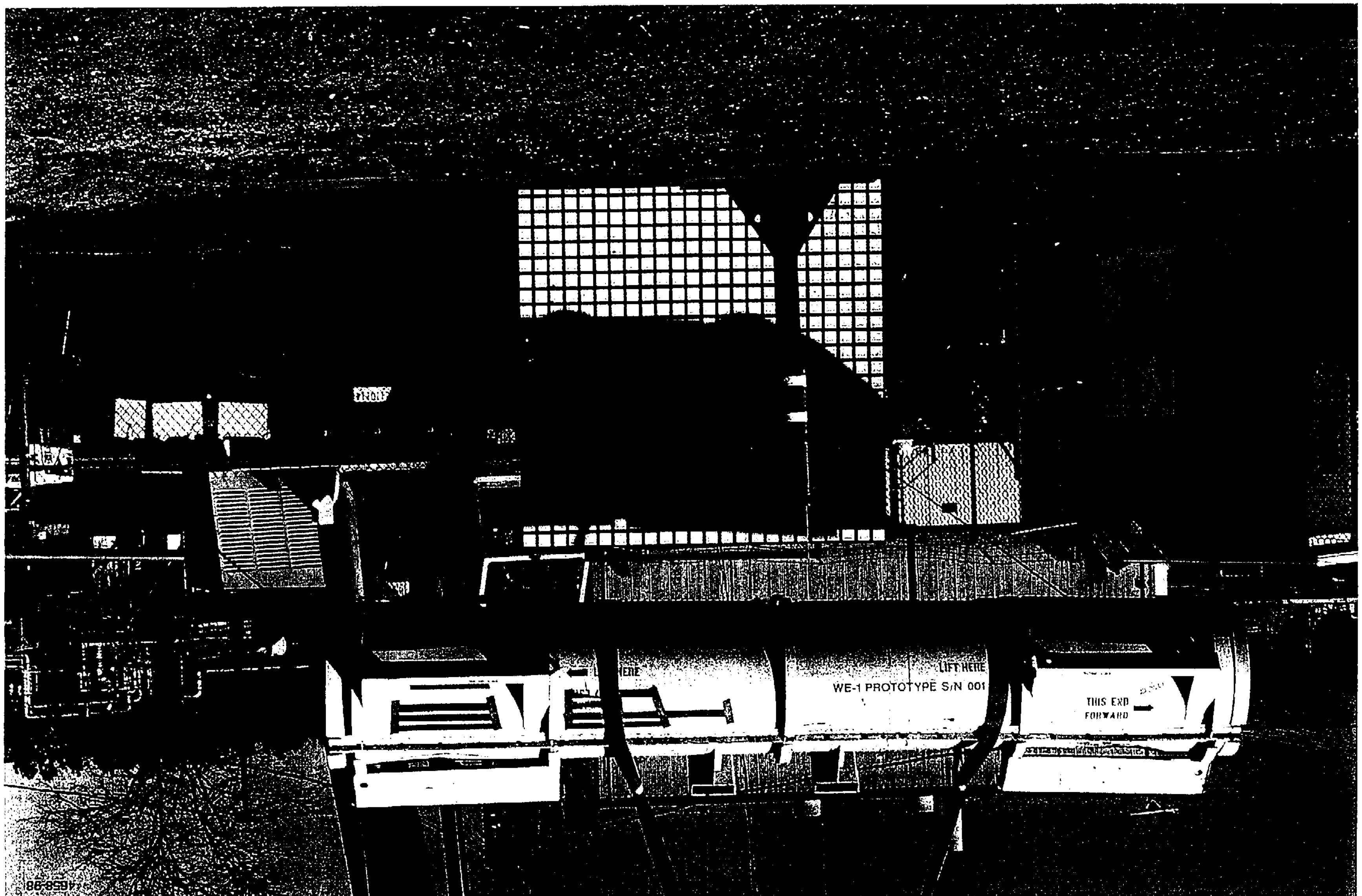
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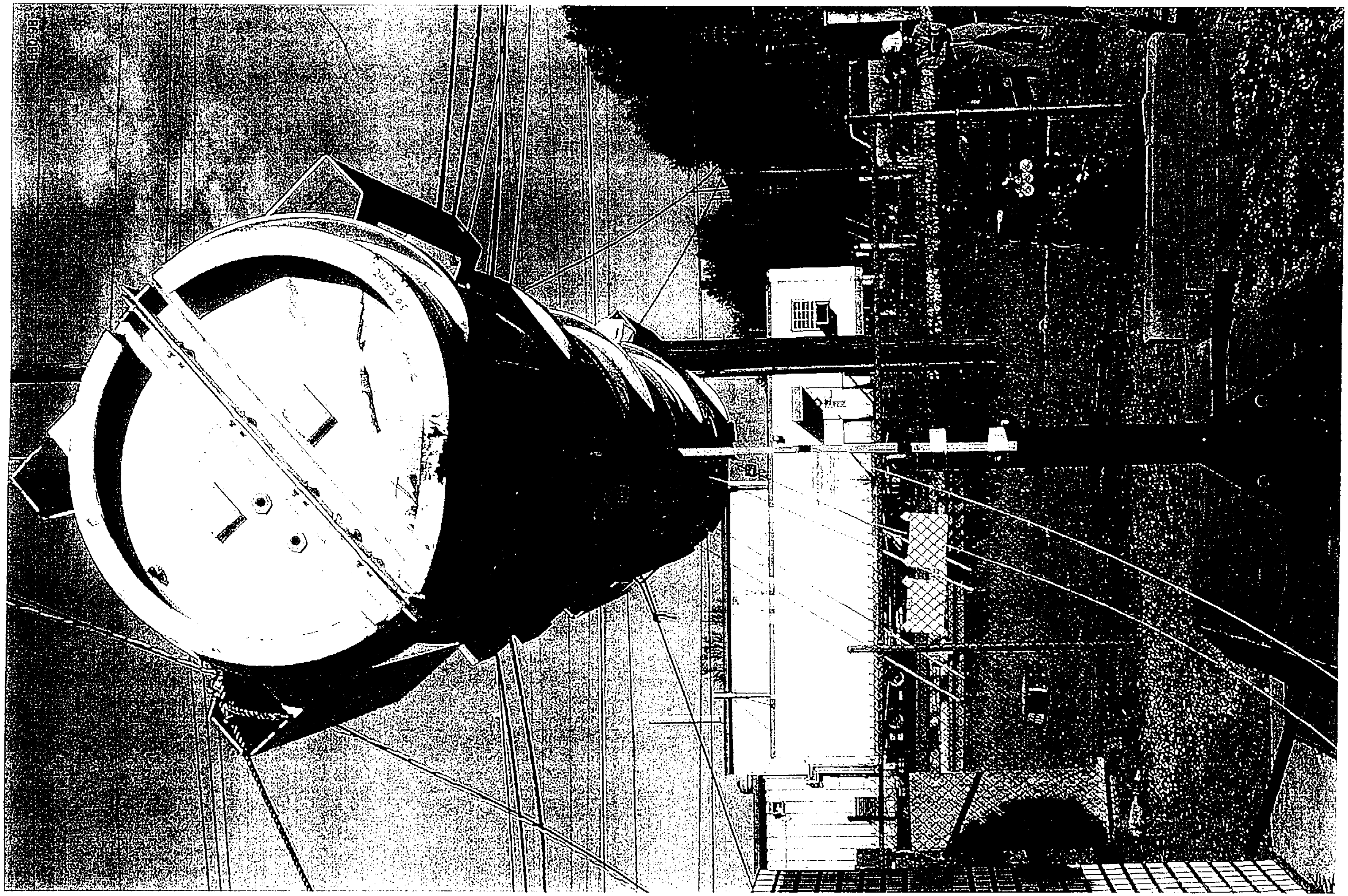

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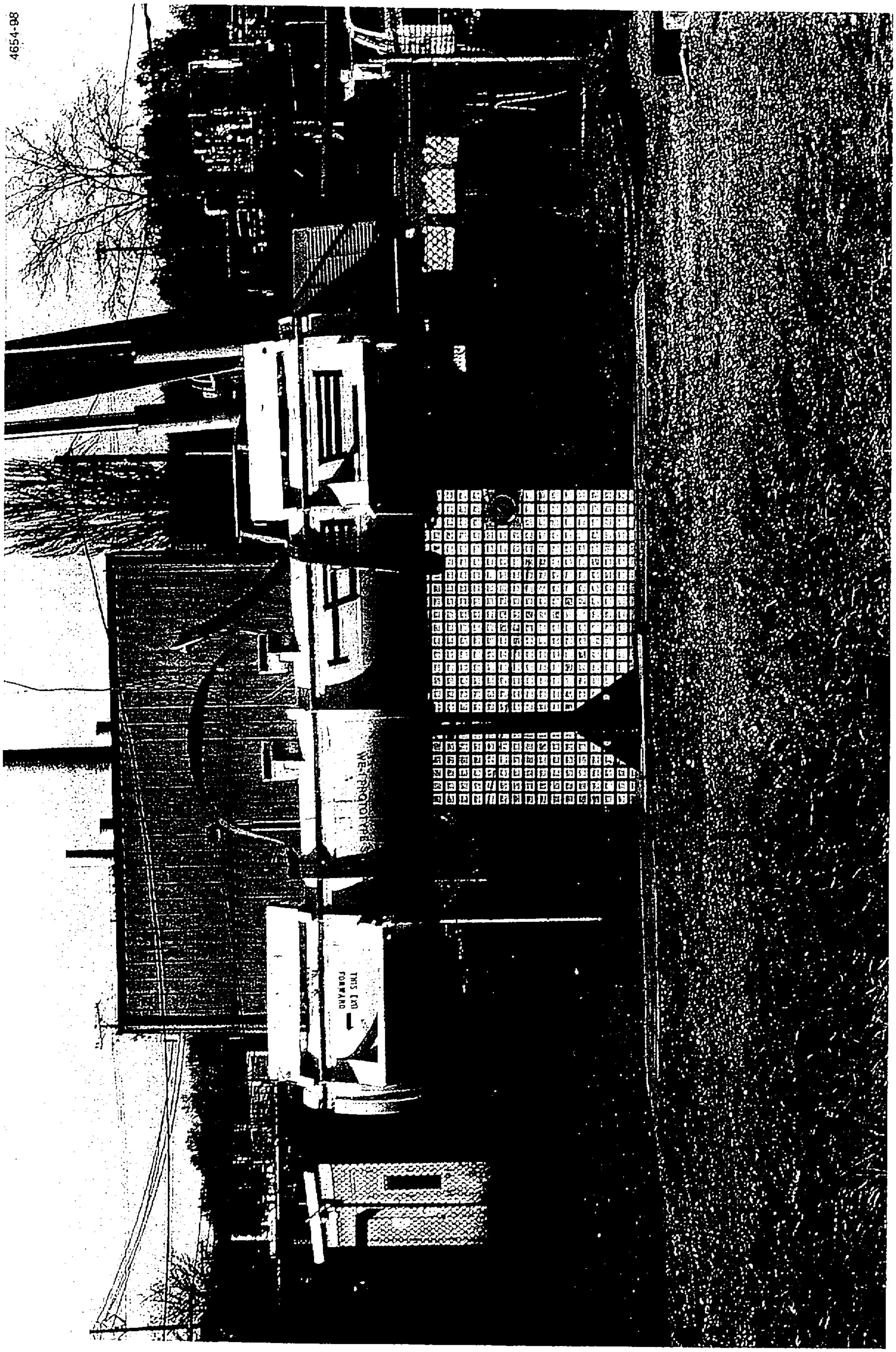

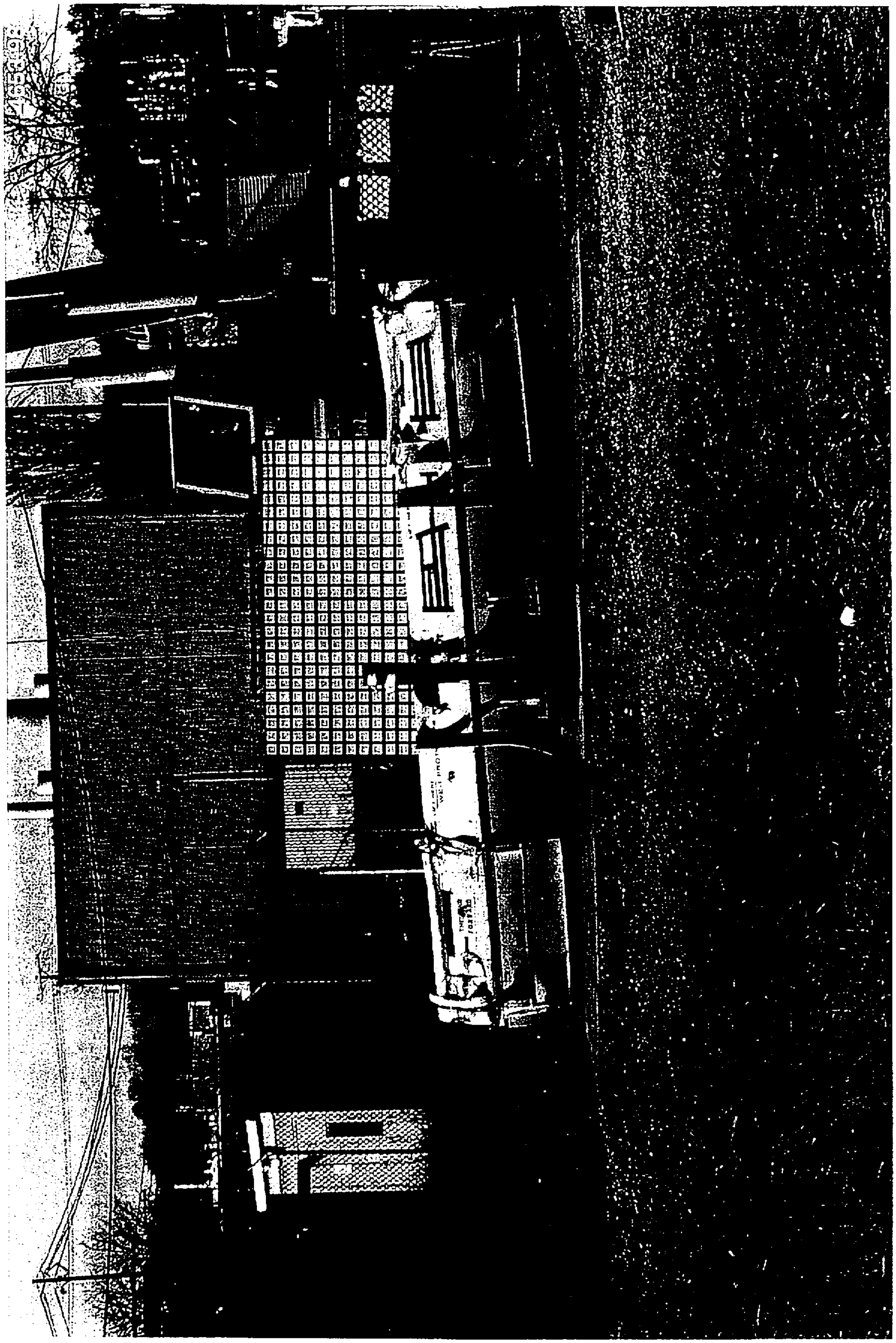

WE-1 CONTAINER DAMAGE AFTER 30 FT. DROP AND PUNCTURE TESTS

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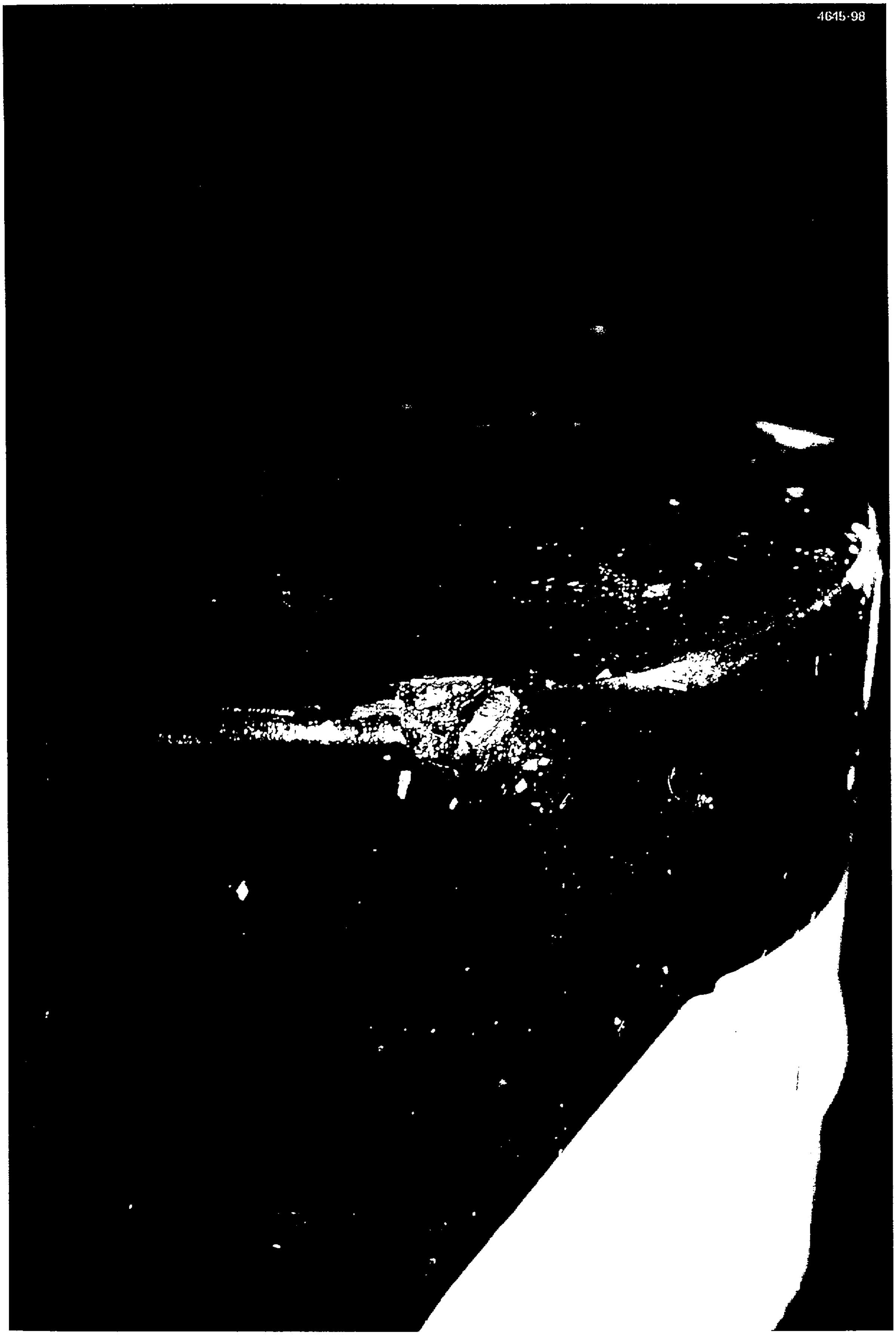
4644-98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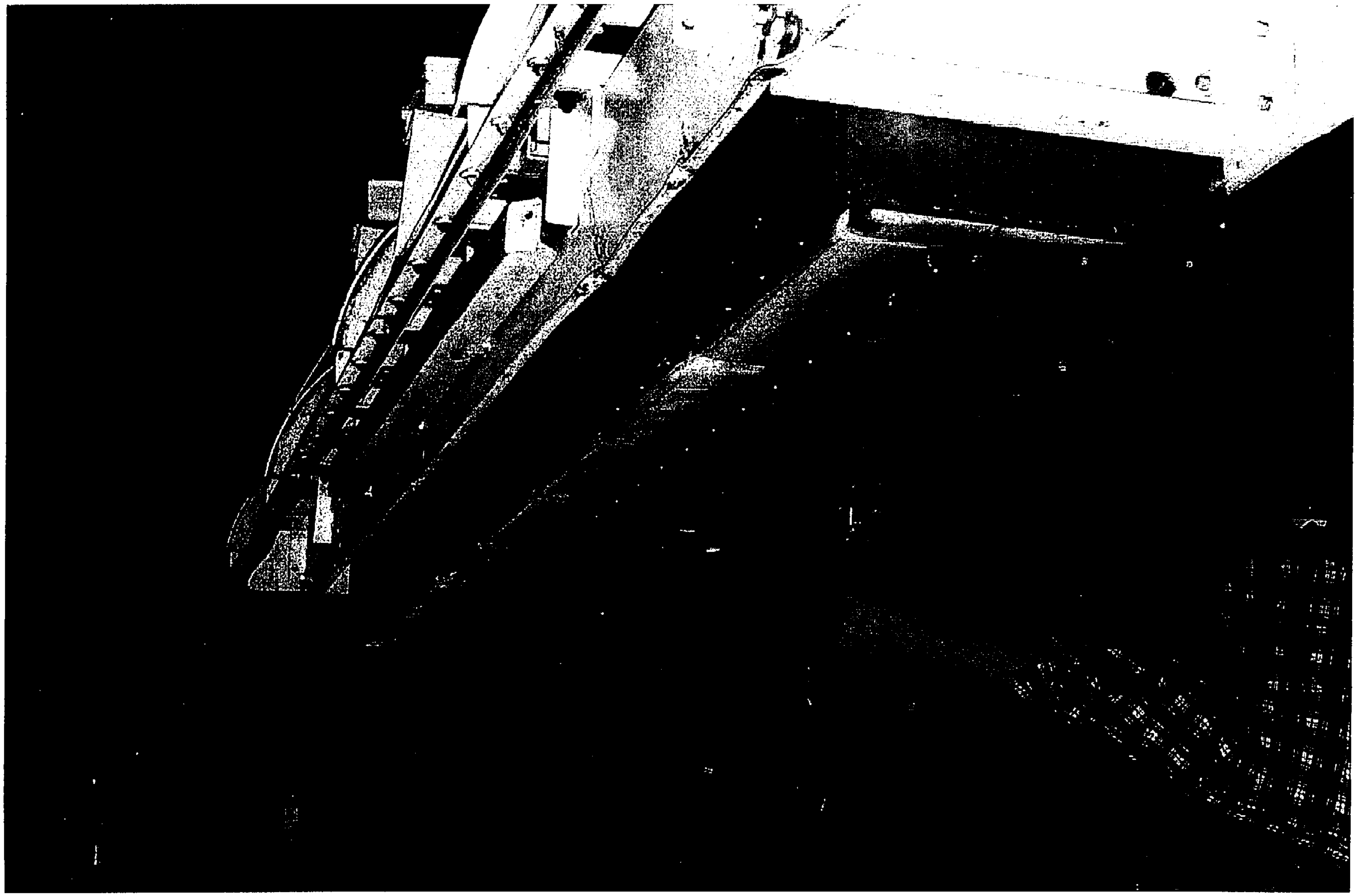
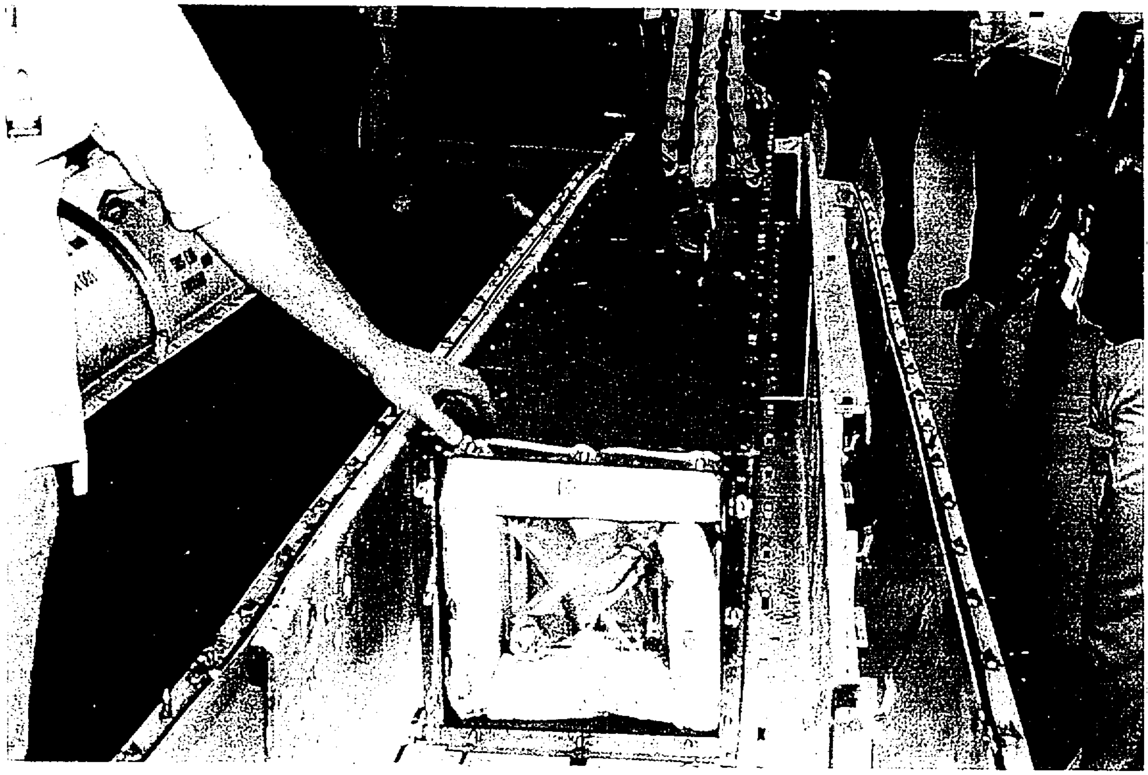
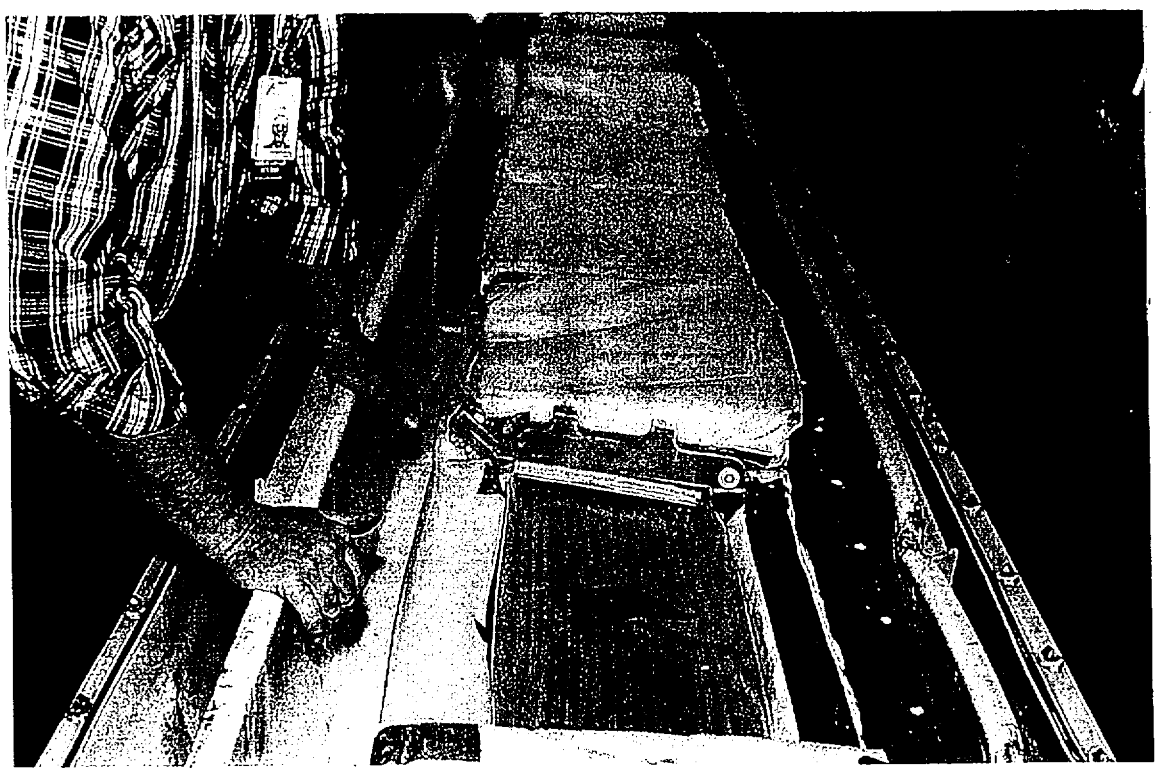
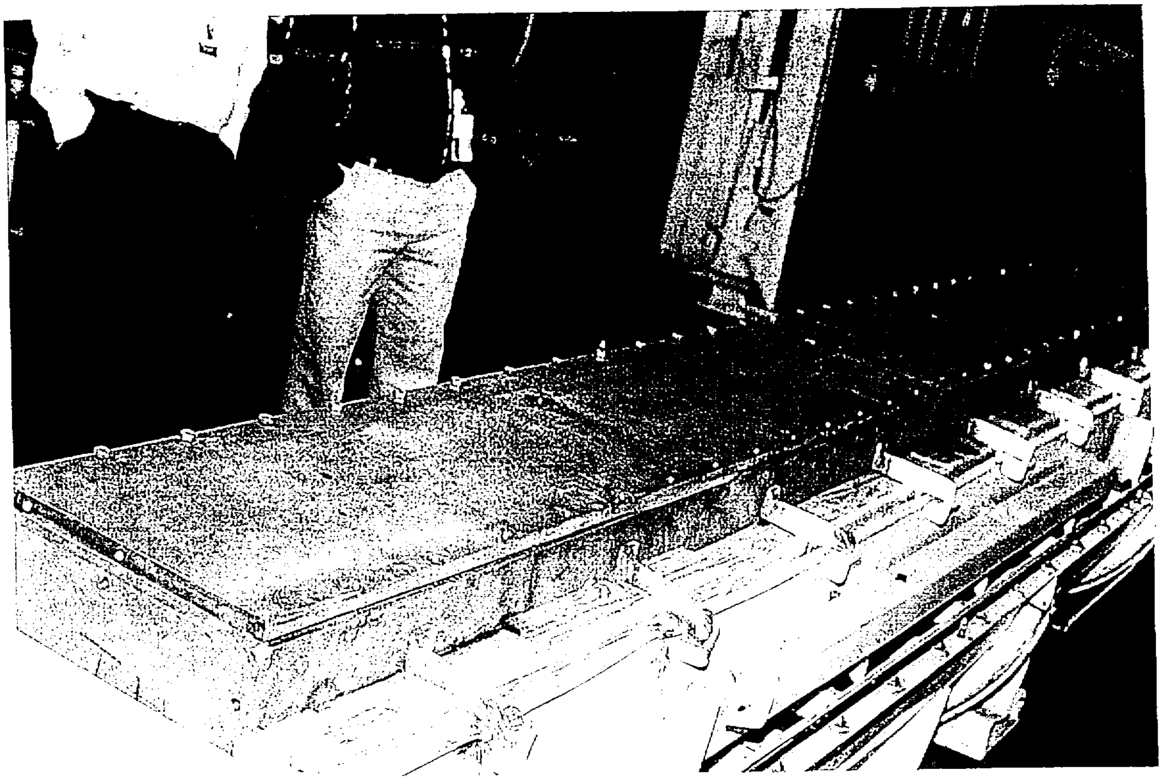
4668-98

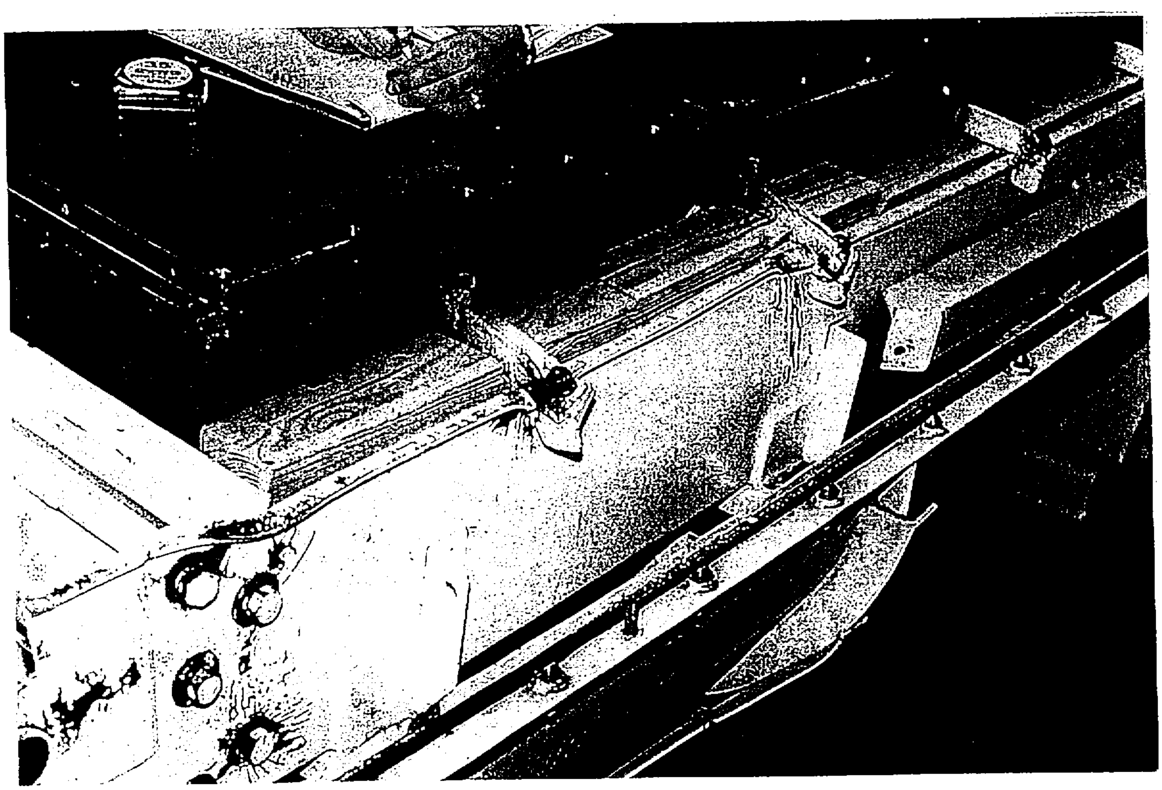
WE-1 CONTAINER DAMAGE ASSESSMENT AT LMF

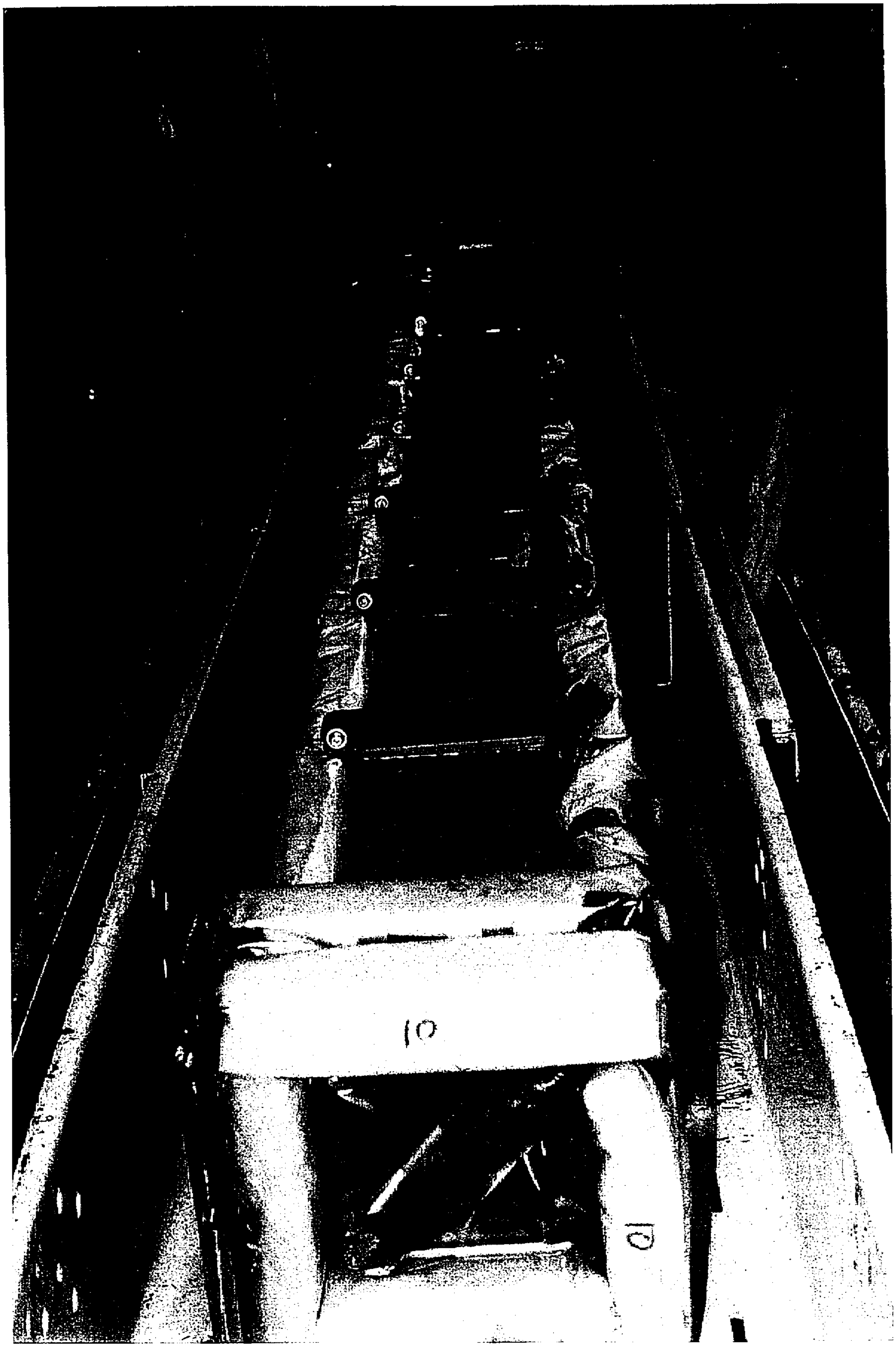








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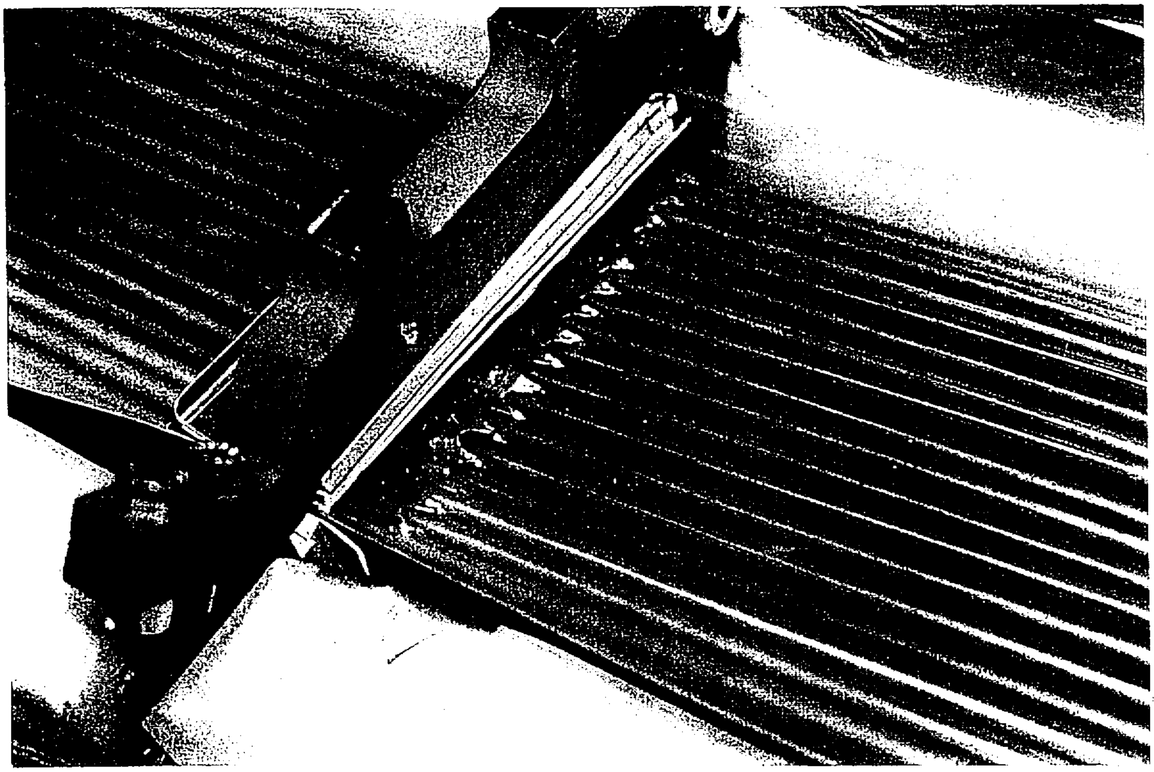
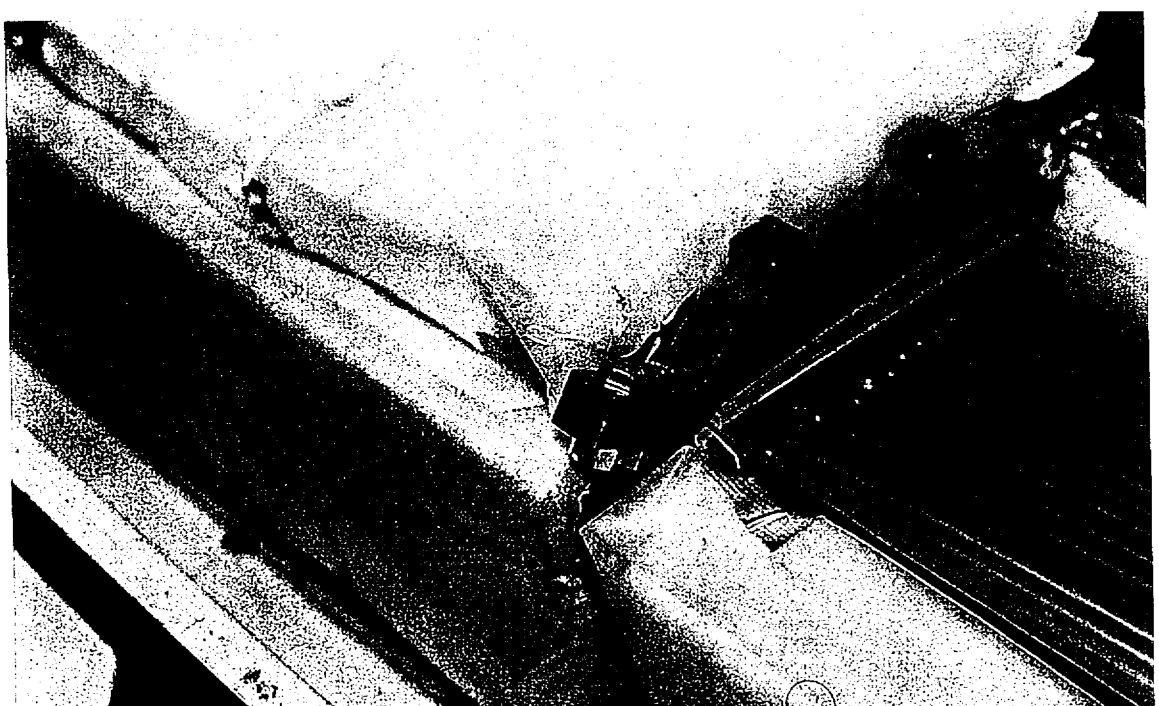
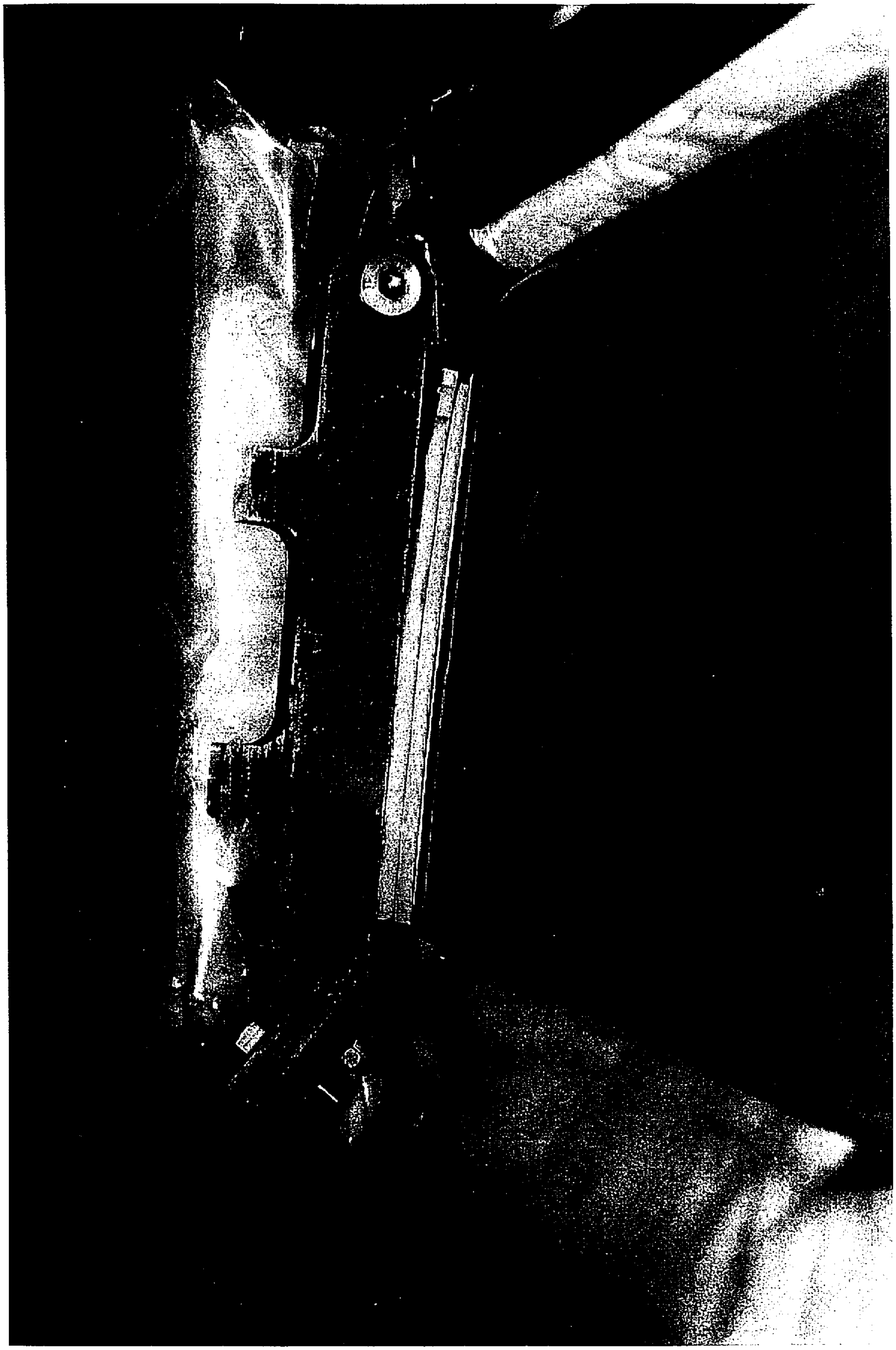
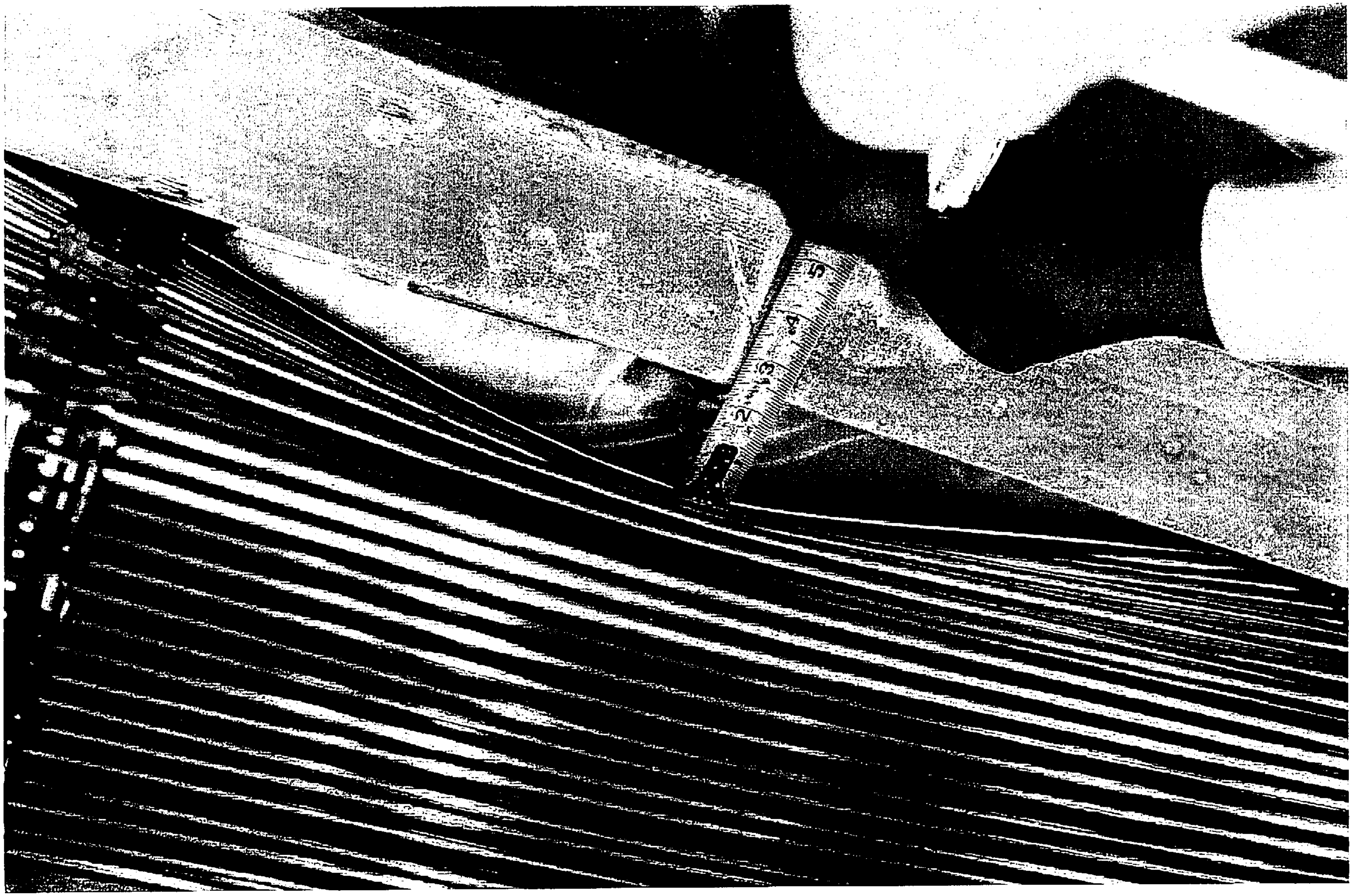
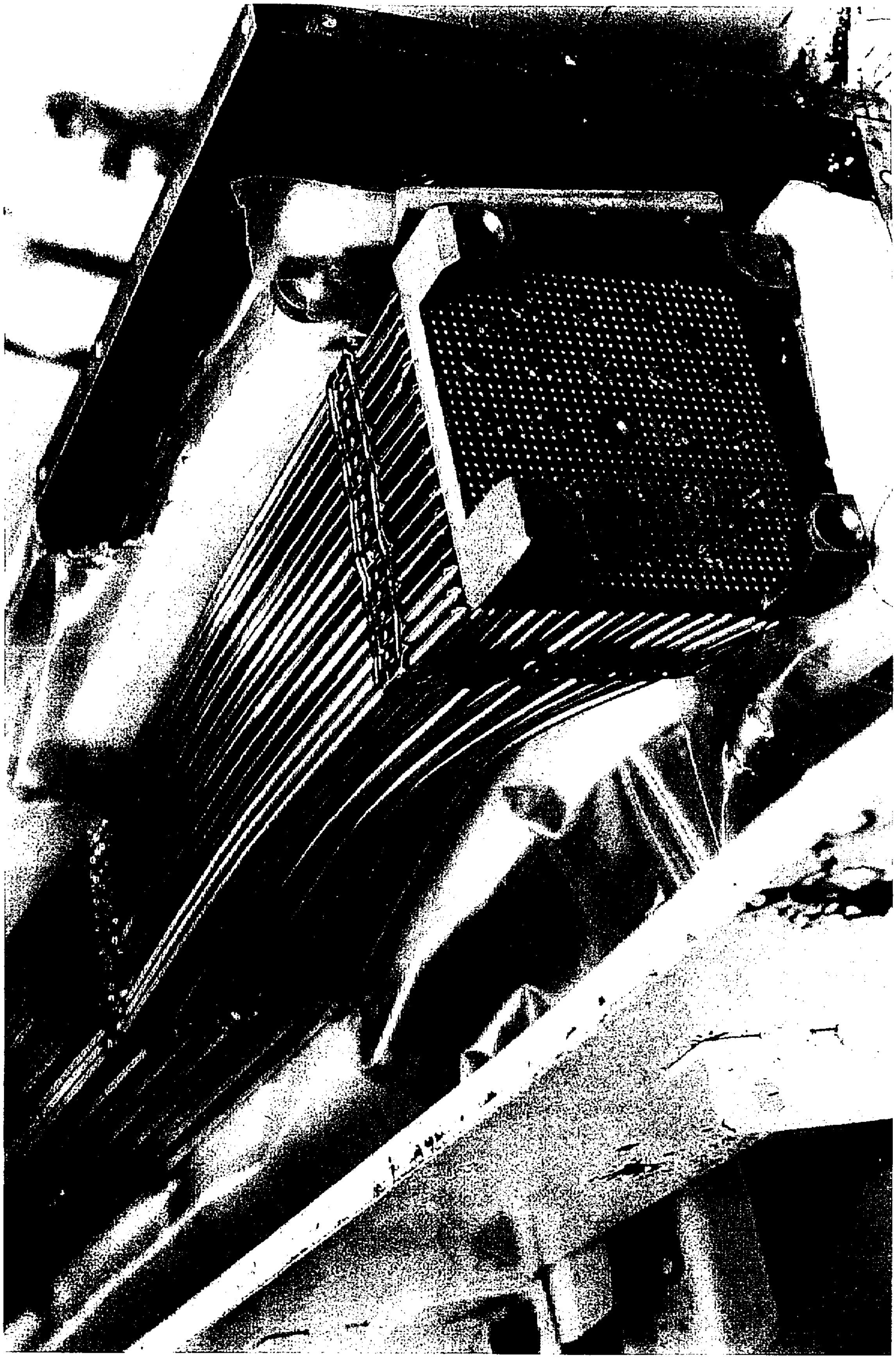










APPENDIX 2-2:
Pathfinder Canister Stress Analysis

2.10 Stress Analysis

2.10.1 Stress Analysis Pathfinder Canister

Stress analysis of the Pathfinder Canister is performed per ASME B&PV Code[2.2] Section III, Subsection NB. The loading conditions considered in the analysis are:

- Lifting (10CFR71.45)
  Shop handling only, the canister will not be lifted after the fuel is loaded.

- Normal Condition of Transportation (10CFR71.71)
  - a) Reduced external pressure to 3.5 psia (ambient air -40 °F to 100 °F)
  - b) Increased external pressure to 20.3 psia (ambient air -40 °F to 100 °F)
  - c) Vibration - normal incident to transportation.
  - d) Water spray - rain at 2 in/hr for at least one hour.
  - e) Free drop - 4 feet on an unyielding flat surface.
  - f) Penetration - 13 pound object dropped from 40 inches.

- Hypothetical Accident Conditions (10CFR71.73)
  - a) Impact from 30-foot drop on unyielding horizontal surface.
  - b) Immersion - water head of 50 feet.
  - c) Thermal - Fire 1475 °F for 30 minutes

For all other loading conditions of 10CFR71[2.1], the stresses for the canister are negligible.

The Pathfinder Canister, support spacer, energy absorber design parameters (See Figure 2.10-1:

Cylinder	8"-schedule 40S pipe (300 series sst) OD = 8.625", ID = 7.981", wall thickness = 0.322", weighs 28.55 lb/ft
Weld Neck Flange:	8" - 150 lb. (300 series sst), ANSI B16.5[2.14] Flange diameter 13.5", flange thickness 1 1/8", hub length 4", approximate weight 42 lbs.
Blind Flange:	8" - 150 lb. (300 series sst), raised face, ANSI B16.5[2.14] Flange diameter 13.5", flange thickness 1 1/8", 8 boltholes at 11.75" diameter bolt circle, approximate weight 47 lbs.

End Plate:	8.625" diameter, 1" thick (300 series sst)
Canister Cavity	88″ long, 7.9″ diameter minimum envelope
Spacer Tube	8″-schedule 40S pipe, Length 61" (approximately) OD = 8.625″, ID = 7.981″, wall thickness = 0.322″, weighs 28.55 lb/ft
Spacer Tube Plate:	14.5" x 14.5" x 0.5" thick (300 series sst)
Wood	14.5" x 14.5" x 8" thick, oak wood, density of 48 $lbs/ft^3 \pm 15\%$
Bolts:	eight 3/4-10UNRC-2A by 2 1/2 long (ASTM-A193-B8M class 2)
Bolt Torque:	40 ft-lbs minimum, 50 ft-lbs maximum
Lubrication:	Neolube
Inner Seal:	Garlock Helicoflex metallic o'ring (U5410-09250 NPA) 9.25" OD, 0.125" tube diameter, 0.010" thick, Alloy 600
Outer Seal:	Garlock Helicoflex metallic o'ring (U5410-10250 NPA) 10.25" OD, 0.125" tube diameter, 0.010" thick, Alloy 600
Support Spacers	2″ thick plate, material ASTM B-209 Alloy 6061, Temper T6 Individual spacers are separated by approximately 0.5"
Rubber:	3/16" thickness at clamp location.

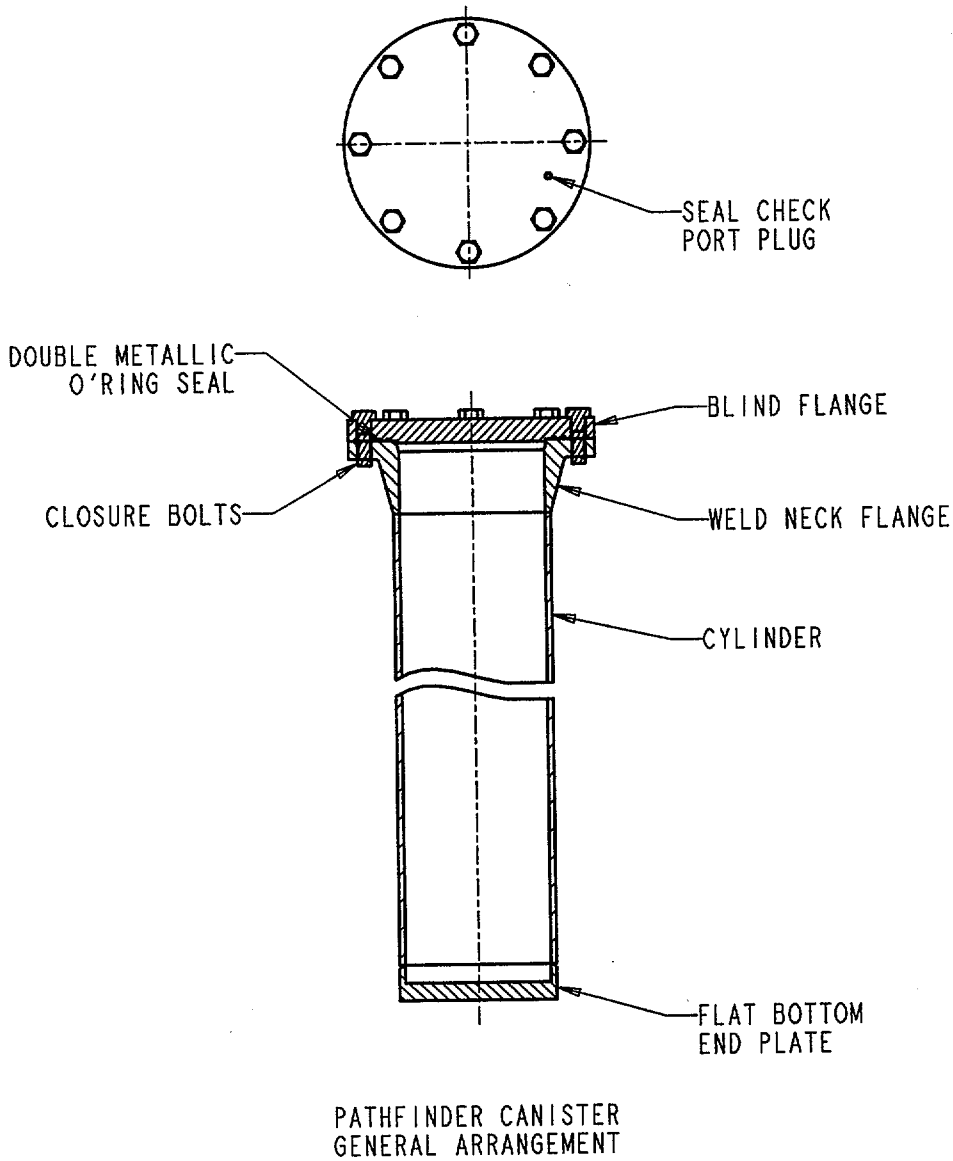


Figure 2.10-1 Pathfinder Canister Arrangement

2.10.1.1 Pressure and Temperature

For all normal and accident conditions, the temperature of the Pathfinder Canister never exceeds 800°F (Section 2.7.4). Zircar insulation is used to insulate the Pathfinder Canister. For various loading conditions, the pressure of the canister is calculated using the gas law:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

It is unlikely that the pathfinder fuel assemblies were pressurized during manufacturing. However, it will conservatively be assumed that the fuel was pressurized to 315 psig, typical Mark BW fuel pressure. If the fuel were to leak during shipping this gas would create an internal pressure for the canister some amount Δp above atmospheric. The pressurized volume in the fuel assembly consists of the void above the fuel pellet and the annular gap between the fuel pellet and the cladding ID.

Where:

Plenum Length = 3″

Fuel Stack Length = 72″

Fuel Clad ID = 0.211″

Fuel Pellet Diameter = 0.207″

No. Of Fuel Pins = 6 per fuel assembly

$V_{f1} = 6\ ((\pi/4)\ (0.211)^2)\ 3 = 0.6294\ \text{in.}^3$ neglecting plenum springs

$V_{f2} = 6\ ((\pi/4)\ ((0.211)^2 - (0.207)^2)\ 72 = 0.5672\ \text{in.}^3$

For 48 fuel assemblies: $V_f = 48\ (0.6294 + 0.5672) = 57\ \text{in.}^3$ gas volume in the pin per fuel assembly

The maximum void in the canister consists of the volume of the canister minus that occupied by the fuel assemblies and sheaths. The total weight of a fuel assembly and sheath is 10 lbs. The density of Inconel is 0.297 lbs/in.^{3} For conservative volume calculations the density of the heavier fuel pellet is used to be the same as Inconel.

$V_{cyl} = (\pi/4)\ (8.625 - 2(0.322))^2)88 = 4402\ \text{in.}^3$ empty canister cavity volume

$V_{fuel} = W/\rho = 48(10)/0.297 = 1616\ \text{in.}^3$

$V_{void} = 4402 - 1616 = 2786\ \text{in.}^3$ fully loaded Pathfinder Canister

$\Delta p = 315(57 / 2876) = 6.24$ psig use 7 psig

If all 48 fuel assemblies break open, the pressure inside the canister will increase by 7 psig. This pressure will be lower for a less than full payload, or less than 48 assemblies.

At room temperature the pressure in the canister will be one atmosphere + 7 psi. Using the gas law listed above and considering constant volume, the pressures for various temperatures are calculated.

$$P @ 70^oF = 14.7 + 7 = 21.7 \text{ psia}$$

$$P @ 150^oF = \frac{150^o F + 460}{70^o F + 460}(14.7+7) = 25.0 \text{ psia}$$

$$P @ 800^oF = \frac{800^o F + 460}{70^o F + 460}(14.7 + 7) = 51.6 \text{ psia}$$

The external pressure during the 50-foot immersion loading is:

$$P = (62.4 \text{ lb/Ft}^3)(50 \text{ ft})/(144 \text{ in}^2/\text{Ft}^2) + 14.7 = 36.4 \text{ psia}$$

Summary of Pressure and Temperature

Loading condition	Max Temp °F	Internal Pressure Psia	External Pressure psia	Max Δ Pressure psid
Reduced External Press 3.5 psia	150	14.7 to 25.0	3.5	21.5
Increased External Press 20.3 psia	150	14.7 to 25.0	20.3	-5.6
Thermal fire accident	800	14.7 to 51.6	14.7	36.9
Immersion 50 feet of Water	150	14.7 to 25.0	36.4	-21.7

The detail stress analysis of the canister at 21.5 psid is performed. For the linear elastic structure, stresses are directly proportional to the product of the ratio of load times the inverse ratio of elastic modulus. Using this, stresses at other loading conditions are obtained by:

$$\sigma_2 = \sigma_1 (P_2/P_1) * (E_1/E_2)$$

Stress Ratio for Loading Conditions:

Reduced External Pressure:	1.0
Increased External Pressure:	(5.6/21.5) * (27.95/27.95)= 0.26
Thermal fire accident:	(36.9/21.5) * (27.95/24.1) = 1.99
Immersion 50 feet of water:	(21.7/21.5) * (27.95/27.95)= 1.01

2.10.2 Component Stress Analysis

The Pathfinder Canister stress analysis is performed on a component basis. For the stress analysis, the Pathfinder Canister is subdivided into:

1) A cylindrical vessel
2) A bottom plate
3) A weldneck flange and a [blind] closure flange
4) Closure bolts

The stress analysis addresses each in the order delineated. ASME B&PV Code standard nomenclature is used in the equations.

2.10.2.1 Cylindrical Vessel

The cylindrical vessel is an 8" SCH 40S Pipe made of ASTM-A312-TP 304L. Its evaluation is based on the requirements of ASME B&PV Code[2.2]. The minimum wall thickness of a pipe per Code[2.2] Para. NB-3641 is:

$$t_m = \frac{PDo}{2(Sm+Py)} + A \quad or \quad t_m = \frac{Pd+2A(Sm+Py)}{2(Sm+Py-P)}$$

Where: P = 25.0-3.5 = 21.5 psid
D_o = 8.625 + .062 = 8.687 in [Table 2.3-1, and ASTM Spec[2.12]]
S_m = 16,700 psi @ 150°F
y = 0.4
A = 0.0

t_m = 21.5(8.687)/(2(16700+21.5(0.4))) = 0.0056 <<(.322-12.5%), Section 2.10.1

The tentative thickness for vessel per Code[2.2] Para. NB-3324.1 is:

$t_m = (P R_o) / (S_m + 0.5P)$
t_m = 21.5(8.687)/(2(16700+21.5(0.5))) = 0.0056 <<(.322-12.5%), Section 2.10.1

Allowable external pressure per Code[2.2] Para. NB-3641.2 and NB-3133.3

T = 0.322- 12.5% => 0.281 in
Do = 8.625 + .062 = 8.687 in

$L = 20.6$ in (distance between supports)

$\therefore$ L/Do = 20.6/8.687 = 2.371 A=.0029 [Ref 2.2, Fig VII-1100-1]

Do/T = 8.687/0.281 = 30.9 A=.0029 [Ref 2.2, Fig VII-1100-1]

ASME Code[2.2], Figure VII-1102-5

B = 10000 @ 150°F

Pa = 4B / (3Do/T)

P_a = 4(10000)/(3(30.9)) = 431 psi >> 21.7 psi (50-foot immersion condition)

2.10.2.1.1 Normal Condition Stresses per ASME Code[2.2] Paragraph NB-3200:

a) Midsection Internal Pressure

Axial Stress = $PR_i/2t$ = (25-3.5)(8.687/2-0.322)/(2(0.322) = 134 psi

Hoop Stress = PR_i/t = 2(134) = 268 psi

Principal Stress: S1 = 134; S2 = 268; S3=-25

Stress Intensities: S12 = 134; S23 = 293; S31 = 159

Max. Stress Intensity: S23 = 293 « 16,700 S_m @ 150°F

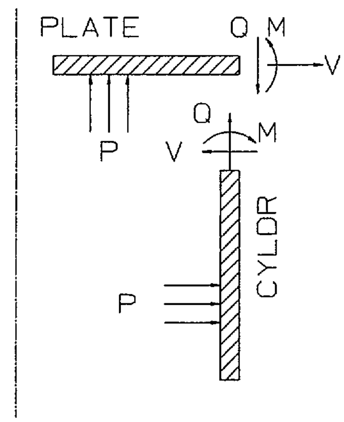
b) Cylinder Bottom Plate Juncture

For internal Pressure 1 atmosphere or Greater
The following analysis is consistent with ASME Code[2.2], Articles A-2000, A-3000, A-5000, and A-6000

$$\lambda \text{ for cylinder} = \sqrt[4]{\frac{3(1-\mu^2)}{(Rt)^2}},\ \mu = 0.3 \qquad \textit{Table XIII} \text{ of Roark}^{2.24}$$

$$\lambda = \sqrt[4]{\frac{3(1-.3^2)}{[(8.687/2-.322/2)(.322)]^2}} = 1.108$$

L = 18$^+$ > 6/λ = 6/1.108 = 5.415 ($\therefore$ Long Cylinder)



$$Q = \pi(R - \frac{1}{2}t_c)^2 P/2\pi R = \left[\frac{(R - \frac{1}{2}t_c)^2}{2R}\right]P$$

Q = [((4.183-0.5(0.322))^2/(2(4.183))] [21.5] = 41.57 lbs/in

Per Roark[2.24], Table XIII, Cases 1, 14 and 15:

$$\delta_{CLY} = -\frac{V}{2D\lambda^3} + \frac{M}{2D\lambda^2} + \frac{PR^2}{Et_c}\left(1 - \frac{1}{2}\mu\right)$$

$$\theta_{CLY} = -\frac{V}{2D\lambda^2} + \frac{M}{D\lambda}$$

$$\delta_{PLT} = \frac{R}{Et_p}(1 - \mu)V$$

$$\theta_{PLT} = \frac{3P\pi R^3[\frac{1}{\mu} - 1]}{2\pi E[\frac{1}{\mu}]t_p^3} + \frac{12[\frac{1}{\mu} - 1]MR}{E[\frac{1}{\mu}]t_p^3}$$

Parameter Values (Internal Pressure, 25 psia @ 150°F)

$P = 25 - 3.5 = 21.5$ psid
$\lambda = 1.108$
$R = 8.687/2 - 0.322/2 = 4.183$ in mean radius
$E = 27.95 \times 10^6$ psi @ 150°F
$\mu = 0.3$
$t_c = 0.322$ in minimum cylinder wall thickness
$t_p = 1. - 0.003 = 0.997$ in minimum plate thickness
$D = Et_c^3/12(1-\mu^2) = 27.95 \times 10^6(0.322^3)/12(1-0.3^2) = 85{,}453$ lb/in

Substituting:

$\delta_{CLY} = -4.30153 \times 10^{-6}V + 4.76610 \times 10^{-6}M + 35.53001 \times 10^{-6}$
$\theta_{CLY} = -4.76610 \times 10^{-6}V + 10.56168 \times 10^{-6}M$
$\theta_{PLT} = 1.26853 \times 10^{-6}M - 59.6519 \times 10^{-6}$
$\delta_{PLT} = 0.10508 \times 10^{-6}V$

Boundary Conditions

$\theta_{CYL} = -\theta_{PLT}$; $\delta_{CLY} = \delta_{PLT}$

Solving
$-4.30153 \times 10^{-6}V + 4.76610 \times 10^{-6}M + 35.53001 \times 10^{-6} = 0.10508 \times 10^{-6}V$
$-4.76610 \times 10^{-6}V + 10.56168 \times 10^{-6}M = -1.26853 \times 10^{-6}M + 59.6519 \times 10^{-6}$
$-4.40661 \times 10^{-6}V + 4.76610 \times 10^{-6}M = -35.53001 \times 10^{-6}$
$-4.76610 \times 10^{-6}V + 11.83021 \times 10^{-6}M = 59.6519 \times 10^{-6}$

$V = +23.95$ lb/in $\quad$ $Q = 41.57$ lb/in
$M = +14.69$ in-lb/in

b.1) Membrane Stresses

Average Stress Components
$\sigma_R = -\frac{1}{2}(P_i + P_o) = -\frac{1}{2}(25.0 + 3.5) = -14$ psi

$$\sigma_H = -\frac{2V}{t_c}\lambda R + \frac{2M}{t_c}\lambda^2 R$$ *Table XIII, Cases 14, 15* of Roark[2.24]

σ_H = -[2(23.95)(1.108)(4.183)/0.322] + [2(14.69)(1.108)^2(4.183)/0.322]

σ_H = -221 psi

$\sigma_Z = Q/t_c$ = 41.57/0.322 = 129 psi

$\tau = V/t_c$ = 23.95/0.322 = 74 psi

Principal Stresses

S1,2 = (-221+129)/2 ± 0.5((-221-129)^2 + 4(74)^2)$^{0.5}$

S1 = 143 psi

S2 = -235

S3 = -14

Stress Intensities

S12 = | 143 + 235 | = 378 psi

S23 = | -235 + 14 | = 221 psi

S31 = | -14 -143 | = 157 psi

Maximum Stress Intensity is S12

S12 = 378 < 16,700 psi S_m @ 150°F ∴ O.K.

b.2) Membrane + Bending at Surface

Since there is no shear on the surface, the stress components are the principal stresses.

b.2.1) Inside Surface

Principal Stresses

$$S1 = \frac{6\mu M}{t_c^2} - \frac{2V}{t_c}\lambda R + \frac{2M}{t_c}\lambda^2 R$$ Roark[2.24]

S1 = [6(0.3)(14.69)/(0.322)^2] - [2(23.95)(1.108)(4.183)/0.322]
+ [2(14.69)(1.108)^2(4.183))/0.322]

S1 = 34 psi

$$S2 = \frac{6M}{t_c^2} + \frac{Q}{t_c}$$ Roark[2.24]

S2 = [6(14.69)/(0.322)^2] + [41.57/0.322] = 979 psi

S3 = Pressure = -25 psi

Stress Intensities

S12 = | 34 - 979 | = 945 psi
S23 = | 979 + 25 | = 1004 psi
S31 = | -25 - 34 | = 59 psi

The maximum stress intensity is S23
S23 = 1004 < 25,050 psi $1.5S_m$ @ 150°F

b.2.2) Outside Surface

$$S1 = -\frac{6\mu M}{t_c^2} - \frac{2V}{t_c}\lambda R + \frac{2M}{t_c}\lambda^2 R = -476 \quad psi$$

$$S2 = \frac{-6M}{t_c^2} + \frac{Q}{t_c}$$

S2 = [-6(14.69)/(0.322)^2] + [41.57/0.322] = -721 psi

S3 = -3.5 psi

S12 = | -476 + 721 | = 245 psi
S23 = | -721 + 3.5 | = 718 psi
S31 = | -3.5 + 476 | = 473 psi

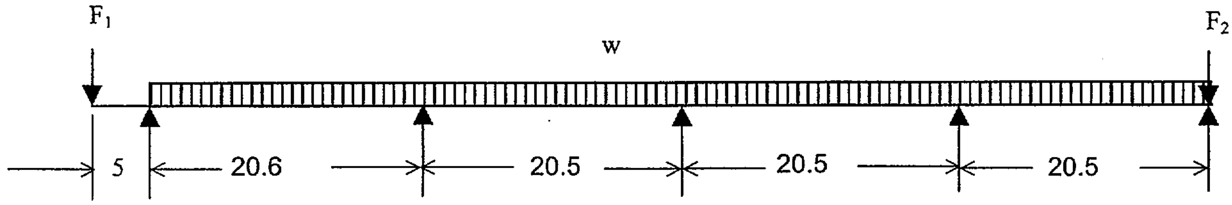
Maximum Stress Intensity is S23
S23 = 718 < 25,050 psi $1.5S_m$ @ 150°F ∴ O.K.

2.10.2.1.2 Accident Condition Stresses per ASME Code[2.2] Paragraph F-1331

In this section the local stresses in the container at a support location are determined considering all loads during an accident condition.

2.10.2.1.2.1 Canister Dead Weight Loads and Reactions

The reaction forces and bending moments on the canister are determine for a dead weight load (i.e., 1g). The canister acts as a four-span continuous beam with an overhang at the bolted joint end.



The force F_1 is the sum of the weights of the blind flange, welded neck flange and the bolts.

Blind Flange = 47 lbs	(for 8"-150 lb blind flange)
Welded Neck Flange = 42 lbs	(for 8"-150 lb weld neck flange)
Bolts = 3 lbs	estimated for 3/4" bolts (8 total)
$F_1 = 47 + 42 + 3 = 92$ lbs	

The force F_2 is the weight of the welded end cap plate.

$F_2 = \rho V$	
$\rho = 0.290$ lbs/in^3	ASTM Spec[2.29]
$V = [\pi/4]\,[(8.625)^2]\,[1] = 58.426$ in.^{3}	Section 2.10.1
$F_2 = 0.290\,(58.426) = 16.9$ lbs use 17 lbs	

The uniformly distributed weight (w) is the sum of the weights for the fuel assemblies, sheaths for the fuel assemblies, and the canister.

Fuel Assemblies + Sheath = N x weight / length

Where: N = 48 fuel assemblies per canister

weight = 10 lbs weight per Pathfinder fuel assembly

length = 82.55 in. length of Pathfinder fuel

Fuel Assemblies + Sheaths = 48 (10) / 82.55 = 5.815 lbs/in

Canister = 28.55 lbs/ft = 2.379 lbs/in (for 8" schedule 40S pipe)

$w = 5.815 + 2.379 = 8.194$ lbs/in

This continuous beam problem was solved using ANSYS[2.28]. The ANSYS beam element BEAM3 was used to model the canister. The required real constants for the beam elements are:

$A = [\pi/4]\,[(8.625)^2 - (7.981)^2] = 8.399$ in.^{2} for 8" schedule 40S

$I = [\pi/64]\,[(8.625)^4 - (7.981)^4] = 72.489$ in.^{4}

$H = 8.625$ in.

The material properties used are:

$E = 28.3 \times 10^6$ psi	Table 2.3-1
$\mu = 0.3$	Poisson's ratio for steel

The input listing is given on next page. Figure 2.10-2 shows the deflected shape of the beam. The maximum reaction force occurs at the fourth support from the bolted joint and is 189.61 lbs. The maximum moment along the canister is 460.0 in-lbs and occurs at the left support (nearest the bolted joint).

The ANSYS results are summarized below for the reaction forces and the moments over the supports, from left to right for 1g dead weight loading.

	Force (lbs)	Moment (in-lbs)
	186.70	460.00
	156.61	247.88
	165.43	278.25
	189.61	360.88
	83.39	0.00
Total =	781.73	

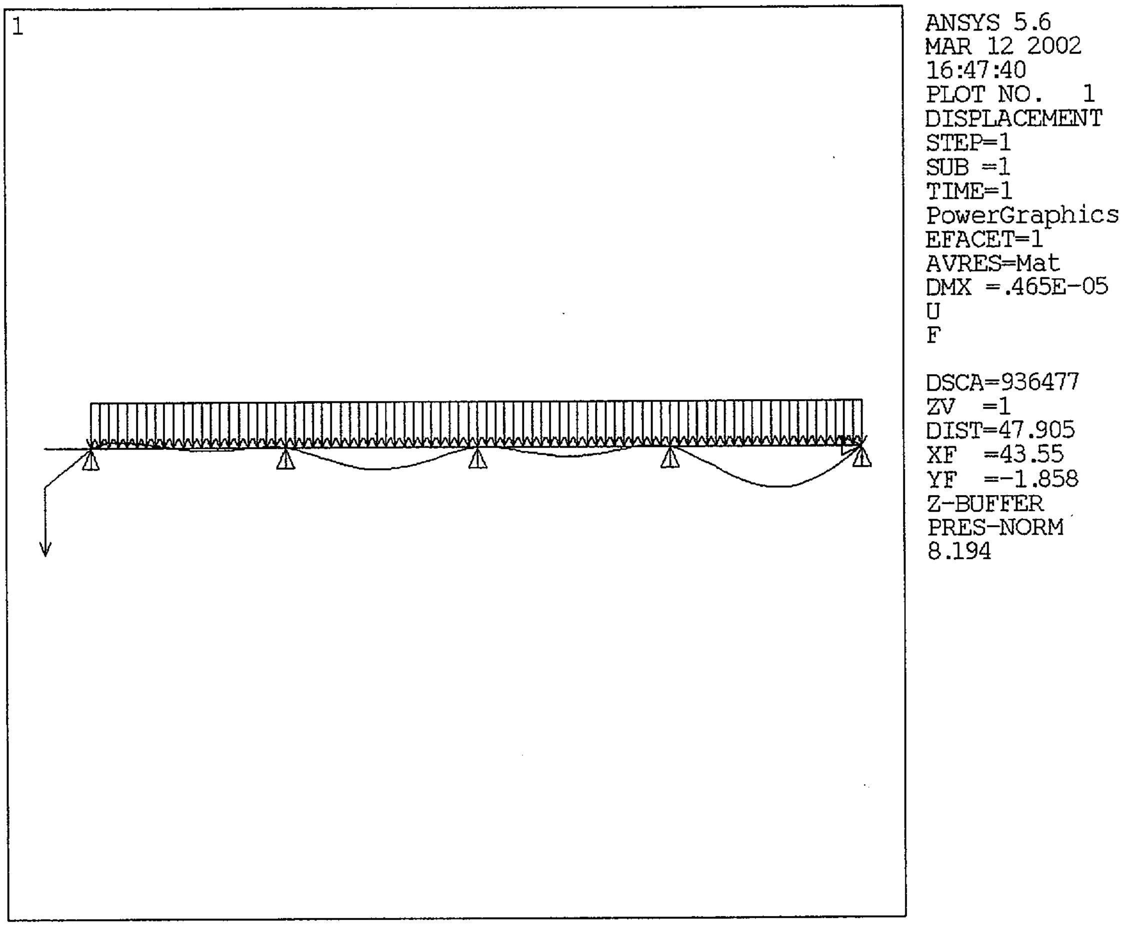


Figure 2.10-2 Pathfinder Canister Loading and Displaced Shape – 1g Side Loading

ANSYS Command Listing for Canister 1 g Side Loading Reaction Loads

```
/PREP7
/TITLE, PATHFINDER CONTAINER DEAD WEIGHT (1G) LOADS
ET,1,BEAM3,,,,,,1
MP,EX,1,28.3E6
MP,NUXY,1,0.3
R,1,8.399,72.489,8.625
N,1,0
N,2,5.
N,23,25.6
FILL
N,44,46.1
FILL
N,65,66.6
FILL
N,86,87.1
FILL
E,1,2
EGEN,85,1,-1
NLIST
FINISH
/SOLU
ANTYPE,STATIC,NEW
TIME,1
OUTRES,ALL,LAST
OUTPR,ALL,LAST
KBC,1
D,2,UY,0.0,,86,21
D,86,UX,0.0
F,1,FY,-92
F,86,FY,-17
ESEL,S,ELEM,,2,85,1
SFBEAM,ALL,1,PRES,8.194,8.194
ESEL,ALL
SFELIST
LSWRITE
SAVE
LSSOLVE,1,1,1
FINISH
```

2.10.2.1.2.2 Container Stresses at a Support

The canister stresses at a saddle support are primarily due to the reaction load of the support but also consist of beam bending, internal pressure and an effective internal pressure of the fuel rods pressing against the inner surface of the canister.

The canister stresses due to the reaction load are determined by finite element analysis using the ANSYS[2.28] code. A quarter symmetry model of the canister is modeled using the eight noded SHELL93 element type. The geometry and material inputs for the model are:

$t = 0.322$ in.	cylinder wall thickness
$R_m = (8.625 - 0.322)/2 = 4.1515$ in.	mean radius of cylinder
$L = 8$ in.	(end boundary condition is sufficiently remote from high stress region)
$w = 1$ in.	conservative, actual saddle is 2" wide
$E = 28.3 \times 10^6$ psi	Table 2.3-1
$\mu = 0.3$	Poisson's ratio for steel

Symmetry boundary conditions are used on all edges except the end remote from the pressure loading where the nodes are restrained in the circumferential direction to simulate a beam shear load.

The saddle reaction load is idealized to act as a pressure over a one-inch width of the saddle and to vary in the circumferential direction by a typical cosine distribution. Pressure loadings at supports for tanks or pipes with large radius to thickness ratio are typically assumed to extend 90 or 120 degrees along the saddle. However, since the canister's radius to thickness ratio is relatively small, the contact area is conservatively assumed to extend only 60 degrees. Also, since a complete saddle consist of four individual pieces separated by a 0.5 inch gap, the contact area in the saddle's worse orientation, would extend from approximately 3 to 30 degrees (θ_1 to θ_2) on each side of the gap. The pressure distribution for a unit reaction load of 10,000 lbs is calculated as follows:

$$\text{Reaction Force} = 4\int_{\theta_1}^{\theta_2} (P_{max}\cos(\theta))\,(\cos(\theta))\,\left((w/2)R_m\,d\theta\right)$$

$$\text{Reaction Force} = 4\,(P_{max})(w/2)R_m\,[0.5(\sin\theta_2\cos\theta_2 - \sin\theta_1\cos\theta_1) + 0.5\,(\theta_2 - \theta_1)]$$

substituting for known values:

$P_{max} = 2{,}827$ psi for a 10,000 lbs reaction force

The ANSYS input command listing is given on following pages. The maximum stress and displacement values for a unit 10,000 lbs load are given below (X-radial, Y-hoop, Z-axial):

Maximum radial displacement occurs at node 1: UX = -0.01255 in.
Maximum stress intensity for the middle surface occurs at node 6, the stresses at this node are:

Top Surface	Middle Surface	Bottom Surface
SI = 31742 psi	SI = 13538 psi	SI = 12074 psi
SX = 0 psi	SX = 0 psi	SX = 0 psi
SY = -27856 psi	SY = -13426 psi	SY = 1004 psi
SZ = -31717 psi	SZ = -10087 psi	SZ = 11543 psi
SXY = -835 psi	SXY = -869 psi	SXY = -903 psi
SYZ = 0 psi	SYZ = 0 psi	SYZ = -2 psi
SXZ = 8 psi	SXZ = 8 psi	SXZ = 8 psi

Figure 2.10-3 shows the finite element model with the cosine pressure loading at the saddle support. Figure 2.10-4 shows the stress intensity (membrane) plot for the middle surface.

ANSYS Command Listing for Canister Local Stresses- Slapdown Drop

```
/PREP7
/TITLE, PATHFINDER CONTAINER STRESSES AT A SUPPORT CLAMP LOCATION
C***ASSUME REACTION LOAD IS TRANSMITTED INTO THE SHELL AS A COSINE FUNCTION
ET,1,SHELL93
MP,EX,1,28.3E6
MP,NUXY,1,0.3
T=0.322                          ! container wall thickness
RM=(8.625-T)/2                   ! container midplane radius
L=8                              ! length of model
W=1                              ! contact width on saddle
RF=10000                         ! reaction force at saddle
PHIMIN=3                         ! minimum contact angle on saddle (deg)
PHIMAX=30                        ! maximum contact angle on saddle (deg)
PHIMINR=(PHIMIN/180)*3.14159     ! phimin in radians
PHIMAXR=(PHIMAX/180)*3.14159     ! phimax in radians
R,1,T,T,T,T                      ! real constants for container elements
C***GENERATE CONTAINER SHELL ELEMENTS
CSYS,1
*AFUN,DEG
K,1,0,0,0
K,2,RM,0,0
K,3,RM,90,0
K,4,RM,180,0
LARC,2,3,1,RM
LARC,3,4,1,RM
```

```
LGEN,2,1,2,1,,,W/2
LGEN,2,3,4,1,,,L-W/2
L,2,5
*REPEAT,3,1,1
L,5,8
*REPEAT,3,1,1
AL,1,8,3,7
AL,2,9,4,8
AL,3,11,5,10
AL,4,12,6,11
LESIZE,1,,1
LESIZE,2,,2
LESIZE,7,W/4
LESIZE,10,W/4
MSHKEY,1
TYPE,1
MAT,1
REAL,1
AMESH,1,4,1
NROTATE,ALL
FINISH
/SOLU
ANTYPE,STATIC,NEW
TIME,1
OUTRES,ALL,LAST
KBC,1
CSYS,1
NSEL,S,LOC,Z,0
DSYM,SYMM,Z,0
NSEL,ALL
NSEL,S,LOC,Y,0
NSEL,A,LOC,Y,180
DSYM,SYMM,Y,0
NSEL,ALL
NSEL,S,LOC,Z,L
D,ALL,UY,0.0
NSEL,ALL
D,NODE(RM,180,L),UX,0.0
PMAX=RF/(W*RM*(SIN(PHIMAX)*COS(PHIMAX)-SIN(PHIMIN)*COS(PHIMIN)+(PHIMAXR-PHIMINR)))
*DO,I,PHIMIN,PHIMAX-1,1
        NSEL,S,LOC,Z,0,W/2
        NSEL,R,LOC,Y,I-0.1,I+1+0.1
        ESLN,R,1,ALL
        SFE,ALL,2,PRES,,PMAX*COS((2*I+1)/2)
        ALLSEL
*ENDDO
*STATUS
SFLIST
LSWRITE
SAVE
LSSOLVE,1,1,1
FINISH
/POST1
```

```
RSYS,1
DSYS,1
NSEL,S,LOC,Z,0,W
NSEL,R,LOC,Y,0,PHIMAX+5
NLIST,ALL
PRNSOL,U,COMP
SHELL,TOP
PRNSOL,S,COMP
PRNSOL,S,PRIN
SHELL,MID
PRNSOL,S,COMP
PRNSOL,S,PRIN
SHELL,BOT
PRNSOL,S,COMP
PRNSOL,S,PRIN
NSEL,ALL
NSEL,S,LOC,Z,L
NLIST,ALL
PRRSOL
RSYS,0
DSYS,0
PRRSOL
NSEL,ALL
FINISH
```

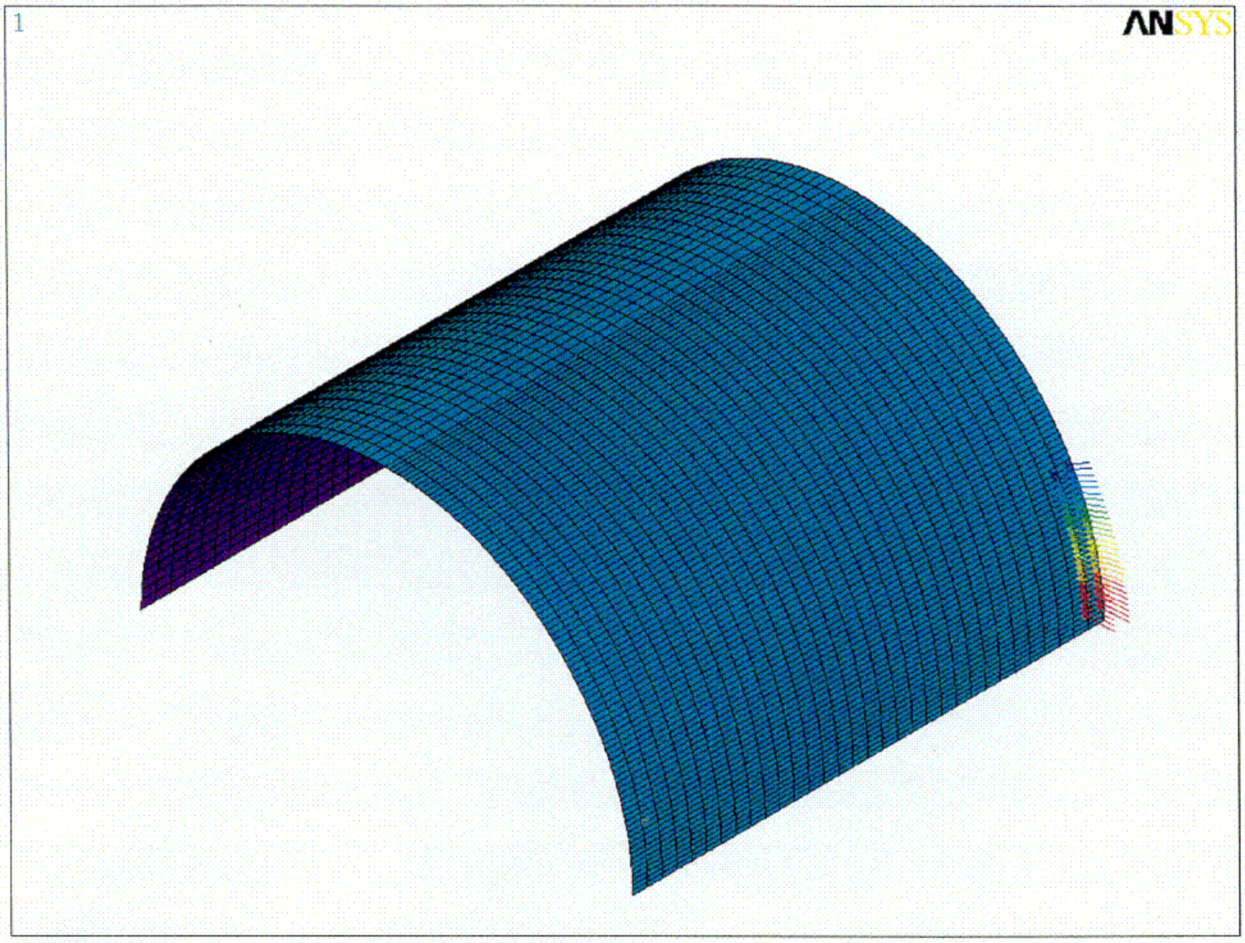


Figure 2.10-3 Pathfinder Canister Loading at a Saddle Support – Drop Analysis

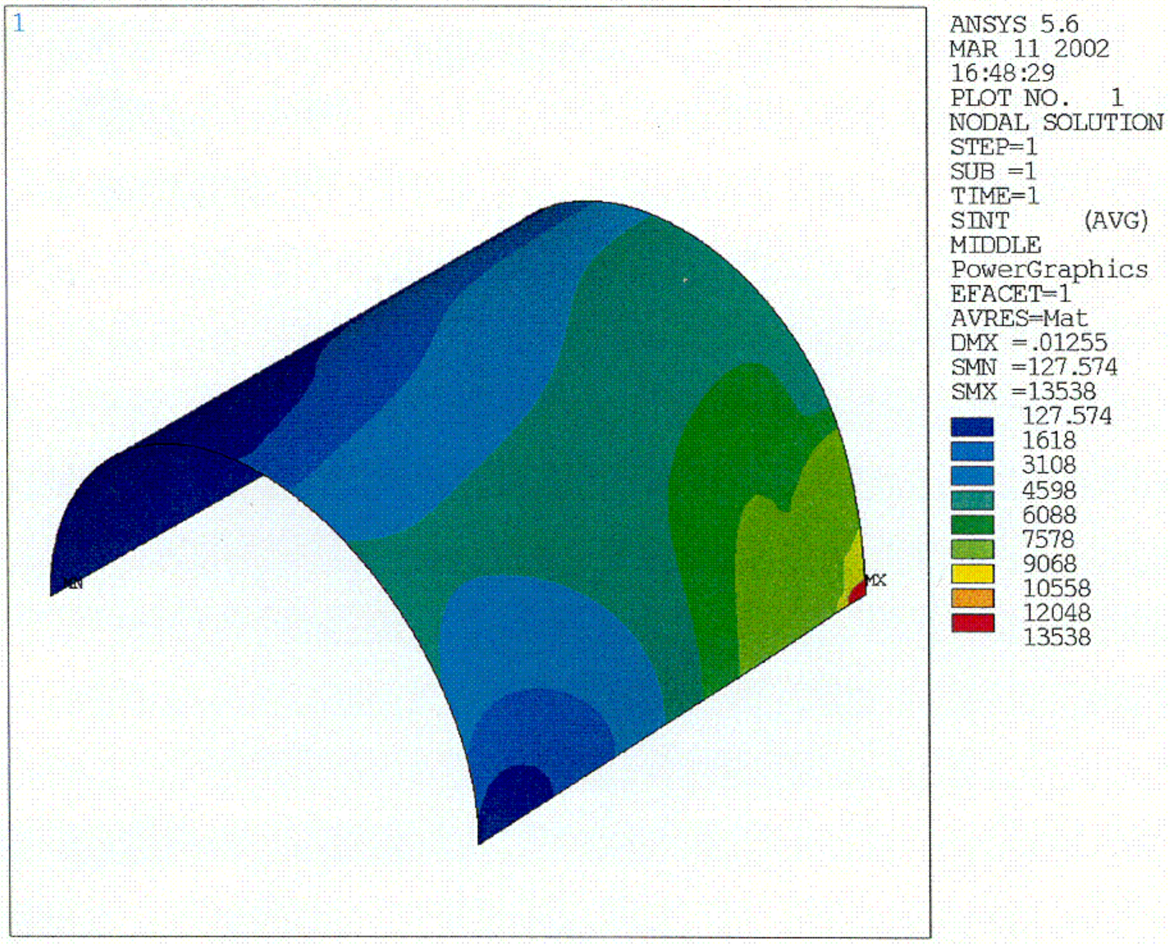


Figure 2.10-4 Pathfinder Canister Membrane Stress Intensity at a Saddle Support Due to a 10,000 lb Load

C02

From Section 2.10.2.1.2.1, the maximum moment and reaction force acting on the canister for a 1g load is 460 in-lbs and 189.61 lbs, respectively. During the accident condition the lateral acceleration is 135 g (see Section 2.10.3). Thus, the maximum 30-foot drop accident loads are:

$$M = 135\ (460) = 62{,}100 \text{ in-lbs}$$
$$F = 135(189.61) = 25{,}597 \text{ lbs}$$

These maximum loads are conservatively taken occur at the same support location (maximum moment actually occurs at 1st support and maximum force at 4th support).

<u>Membrane Stress</u>
Stresses due to overall bending is classified as a membrane stress per ASME Code[2.2], Table NB-3217-1 and is:

$$SZ_{beam} = MR_m/I = 62100\ (4.1515)\ /\ 72.489 = \pm\ 3{,}557 \text{ psi}$$

For the saddle pressure loads, the membrane stresses are:

$$SI = (25597\ /\ 10000)\ (13538) = 34{,}653 \text{ psi}$$
$$SY = (25597\ /\ 10000)\ (-13426) = -34{,}367 \text{ psi}$$
$$SZ = (25597\ /\ 10000)\ (-10087) = -25{,}820 \text{ psi}$$
$$SXY = (25597\ /\ 10000)\ (-869) = -2{,}224 \text{ psi}$$

Since SZ_{beam} is compressive on the bottom half of the canister, it is clear that this stress would have an negligible effect on the total SI since the SY stress component is larger and still controls. From Section 2.10.1.1, the external pressure (-5.6 psig) which would produce a compressive stress to combine with the above support induced stress is small and may be neglected. Also, the fuel rods pressing against the canister during the high g load produces a load similar to an internal pressure. However, this causes a hoop tension stress, which would decrease the total SY stress component and therefore it is conservative to neglect it. Thus, for the 30-foot drop slapdown accident condition, the maximum membrane stress intensity for the canister is 34,653 psi.

From the Figure 2.10-4, the maximum membrane stress is localized near the saddle contact area, but significant stress levels exist outside this area. Per ASME Code[2.2], Table NB-3217-1, shell membrane stresses near a nozzle or opening due to an external load is classified as a local membrane stress. However, NB-3213.10 places restrictions on the distance the stress can exceed 1.1 S_m. Due to this restriction, the membrane stresses are classified as primary.

$P_m \leq$ (lesser of 2.4 S_m or 0.7 S_u)	ASME Code[2.2], F1313.1(a)
$2.4\ S_m = 2.4\ (16700) = 40{,}080$ psi	Table 2.3-1

$0.7\ Su = 0.7\ (70000) = 49{,}000$ psi — Table 2.3-1

$34{,}653\ psi \leq 40{,}080\ psi$

Bending Stress

Per ASME Code[2.2], Table NB-3217-1, shell bending stresses near a nozzle or opening due to an external load is classified as a secondary stress. Therefore, the bending stresses near the saddle are considered secondary and the applicable stress limit for a Faulted condition is:

$S_n < 2\ Sa$ at 10 cycles — (Table 2.1-1)

$\sigma = (25597 / 10000)(31742) = 81{,}250$ psi

K_t = stress concentration factor = maximum of 4 — NRC R.G. 7.6[2.3], Section C

7.

$S_n = (E_{cold} / E_{hot})\ K_t\ \sigma = (28.3 \times 10^6 / 27.95 \times 10^6)(4)(81250) = 329{,}070$ psi

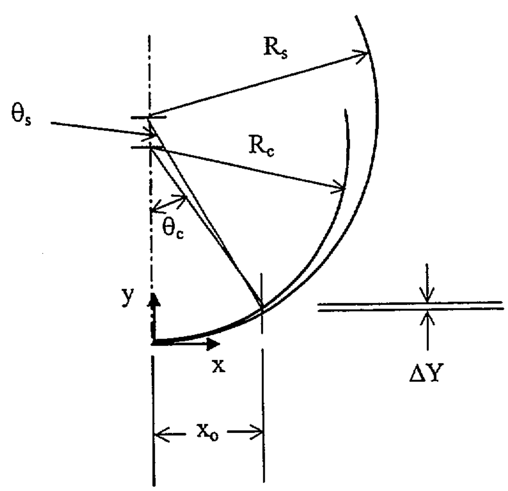
Sa at 10 cycles = 708,000 psi — ASME Code[2.2], Table I-9.1, Fig. I-9.2.1

329,070 psi < 2(708,000)

329,070 psi < 1,416,000 psi — Therefore, OK

2.10.2.1.2.3 Gap Between Canister and Saddle

The purpose of this section is to demonstrate that adequate contact between the saddle and the canister occurs to justify the pressure distribution used in 2.10.2.1.2.2. The nominal gap between the canister and saddle is conservatively calculated using infinitely stiff parts.



The vertical line at $x = x_o$ intersects the canister of radius R_c at y_c and the saddle of radius R_s at y_s.

$\theta_c = 30$ deg	used in stress analysis
$R_c = 8.625 / 2 = 4.3125$ in.	cylinder outer radius
$R_s = R_c + 0.1 = 4.3125 + 0.1 = 4.4125$ in.	design of saddle support

$x_o = R_c \sin(\theta_c) = 4.3125 \sin(30) = 2.15625$ in.
$y_c = R_c (1 - \cos(\theta_c)) = 4.3.125 (1 - \cos(30)) = 0.57777$ in.
$x_o = R_s \sin(\theta_s)$
$\theta_s = \sin^{-1}(x_o / R_s) = \sin^{-1}(2.15625 / 4.4125) = 29.25311$ deg.
$y_s = R_s (1 - \cos(\theta_s)) = 4.4125 (1 - \cos(29.25311)) = 0.56273$ in.
$\Delta y = y_c - y_s = 0.57777 - 0.56273 = 0.01504$ in.

The component of Δy that is perpendicular to the tangent of the R_c circle at (x_o, y_c) and to the tangent of the R_s circle at (x_o, y_s) is δ_c and δ_s, respectively.

$\delta_c = \Delta y \cos(\theta_c) = 0.01504 \cos(30) = 0.01303$ in.
$\delta_s = \Delta y \cos(\theta_s) = 0.01504 \cos(29.25311) = 0.01312$ in.

From ANSYS results, the radial deflection under the load is -0.01255 (node 1) for the 10,000 lb unit load. Thus, for the full load of 25,597 lbs:

$\delta_r = (25597 / 10000)(-0.01255) = -0.03212$ in.

Since $\delta_r > \delta_s$, the gap between the canister and saddle at the 30 degree location is most likely closed. In addition, local yielding ($S_y = 25000$ psi) and the 3/16 in. rubber liner between the two components will help distribute the load to at least the 30 degree mark. Thus, the assumption of a cosine load distribution over a 60 degree (30 degrees on each side of the load center) contact area between the canister and saddle is a valid.

In the above calculation the saddle radius was 0.1 inch larger than the pipe OD. If the as built dimensions are less than this, the contact area will be larger and thus the canister stresses would be less than calculated in Section 2.10.2.1.2.2.

2.10.2.1.2.4 Canister Column Buckling

Since the canister is supported at the clamped positions the unsupported length is 20.5 in. The maximum axial compressive load on the canister occurs for an end drop when the acceleration is 1,010 g's (Section 2.10.3, Case 2). The axial load on the canister near the bolted connection is

$W_{max} = G_A W$

$W = 782 - 47 - 42 - 480 = 213$ lbs

$W_{max} = 1010 (213) = 215{,}130$ lbs

$A = (\pi/4)((8.625)^2 - (7.981)^2) = 8.399$ in.^{2}

$\sigma = W_{max} / A = 215130 / 8.399 = -25{,}614$ psi   axial stress in canister

The yield strength for the canister is 23,150 psi at 150 °F (Table 2.3-1).

radius of gyration = $r = [0.25((8.625)^2 + (7.981)^2)]^{0.5} = 5.88$ in.

$L/r = 20.5 / 5.88 = 3.49$

This is indicative of a very short column that does not fail in buckling and tensile limits are applicable.

$P_m \leq$ (lesser of 2.4 S_m or 0.7 S_u)   Per ASME Code[2.2], F1313.1(a)

$2.4 S_m = 2.4 (16700) = 40{,}080$ psi   Table 2.3-1

or

$0.7 Su = 0.7 (70000) = 49{,}000$ psi   Table 2.3-1

$25{,}614 \text{ psi} \leq 40{,}080$ psi

As an additional check, buckling formula for a thin walled cylindrical tube is used. Per Roark[2.24], page 274, tests indicate that the critical buckling stress is usually only 40 to 60% of the theoretical value given by:

$s' = (E / (3(1 - \nu^2))^{0.5}) (t / R)$

$s' = (27.95 \times 10^6 / (3(1 - (0.3)^2))^{0.5}))(0.322 / 4.1515) = 1.312 \times 10^6$ psi

$0.4 s' = 0.4 (1.312 \times 10^6) = 524{,}800 \text{ psi} >> 25{,}614$ psi   therefore no buckling

2.10.2.2 Bottom Plate

The bottom plate stresses at the cylindrical vessel juncture are bounded by those calculated in Section 2.10.2.1.1.b. This is due to fact that bottom plate thickness is greater than the minimum wall thickness of the cylindrical vessel. The stresses for center of the plate are calculated below.

2.10.2.2.1 Normal Condition Stresses

At Bottom Plate Center

a) Membrane + Bending

Internal Pressure (21.5 psid @ 150^{0}F) a.1) Outside Surface

Roark[2.24], Table X, cases 1 and 12

$$S1 = \frac{3\pi R^2 P}{8\pi\left(\frac{1}{\mu}\right)t_p^2}\left(\frac{3}{\mu}+1\right) - \frac{6M}{t_p^2} + \frac{V}{t_p}$$

S1 = {[3(4.183)^2(21.5)(3/.3 + 1)/(8(1/0.3)(0.997)^2
- [6(14.69)/(0.997)^2] + [23.95/0.997]

S1 = 404 psi
S2 = S1 = 404 psi
S3 = -3.5 psi

S12 = 0
S23 = 408 psi
S31 = 408 psi

Max Stress Intensity is S23 or S31
S23 = 408 < 25,050 psi 1.5S_m @ 150°F ∴ O.K.

a.2) Inside Surface

$$S1 = -\frac{3\pi R^2 P}{8\pi\left(\frac{1}{\mu}\right)t_p^2}\left(\frac{3}{\mu}+1\right) + \frac{6M}{t_p^2} + \frac{V}{t_p}$$

S1 = -356 psi
S2 = -356 psi
S3 = -25 psi

S12 = 0
S23 = 331 psi
S31 = 331 psi

Max Stress Intensity is S23 or S31
S23 = 331 < 25,050 psi 1.5S_m @ 150°F ∴ O.K.

b) Membrane

$$S1 = \frac{V}{t} = \frac{23.95}{.997} = 24\ psi$$

S2 = S1 = 24 psi

S3 = -½ (P_i + P_o) = -½ (25 + 3.5) = -14 psi

Stress Intensities

S12 = | 24 - 24 | = 0

S23 = | 24 + 14 | = 38 psi

S31 = |-14 - 24 | = 38 psi

Maximum Stress Intensity

S23 = 38 < 16,700 psi 1.0S_m @ 150°F ∴ O.K.

c) Buckling

Buckling is addressed for external pressure load case. For the analysis, the 50-foot immersion condition is the worst external pressure load case.

Per Roark[2.24], Table XVI, Case H (This is also valid for a circular plate loaded laterally with a uniform load.)

$$S' = 0.35 \frac{E}{1-\mu^2}\left(\frac{t_p}{R}\right)^2$$

$$= 0.35 \frac{28.3x10^6}{1-.3^2}\left(\frac{.997}{4.18}\right)^2$$

= 618,340 psi

Above the proportional limit, E decreases. Since the proportional limit is < Sy = 30,000 @ -40°F, and since S' is twenty times Sy, the critical stress is assumed Sy. [Elastic-Perfect Plastic Material]

$V_{CRITICAL}$ = 30,000(t_p) = 30,000(.997) = 29,910 lb/in

$$V_{CAL'D} = V_{21.5psid} \frac{\Delta P \text{ 50 Feet Immersion Case}}{\Delta P \text{ Reduced External Press. Case}}$$

$V_{CAL'D}$ = 23.95 (21.7/21.5) = 24.2 lb/in

$V_{CAL'D} = 24.2 << 29{,}910$ lb/in $= V_{CRITICAL}$

2.10.2.2.2 30-foot Drop Accident Condition Stresses

For impact, Section 2.10.3, Case 2 acceleration will produce the largest load on the end cap plate. The end cap plate is conservatively assumed to act as a simply supported circular plate (Roark[2.24], page 216, case 1). The edge support is assumed to be at the midwall of the canister (a = (8.625 - 0.322)/2 = 4.1515"). At the center of the plate the bending stress is:

$\sigma_r = \sigma_t = 3\ W\ (3\ m + 1)\ /\ (8\ \pi\ m\ t^2)$

$W = W_{flg}\ (G_A)$

$W_{flg} = 17$ lbs	Section 2.10.2.1.2.1
$G_A = 1010$ g	Section 2.10.3, Case 2
t = 1 in.	Section 2.10.1

m = 1/0.3

$\sigma_r = \sigma_t = 3\ (1010)(17)\ (3(1/.3) + 1)\ /\ (8\ \pi\ (1/.3)\ (1^2) = 6{,}763$ psi

conservatively use membrane stress allowable

$P_m \leq$ (lesser of 2.4 S_m or 0.7 S_u)	ASME Code[2.2], F1313.1(a)
2.4 S_m = 2.4 (16700) = 40,080 psi	Table 2.3-1
or	
0.7 Su = 0.7 (70000) = 49,000 psi	Table 2.3-1
6,763 psi $\leq$ 40,080 psi	

2.10.2.3 Weldneck Flange and (Blind) Closure Flange

Weld Neck Flange and Cylinder (Pipe) Junction

Working Internal Pressure of 8" Schedule 40 [ASME Code[2.2], Para. NB-3641]

$Pa = 2\ S_m\ t\ /\ (D_o - 2\ y\ t)$

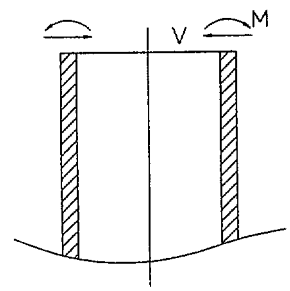
Where S_m, maximum allowable stress intensity at design temperature (the accident condition temperature of 800°F is used to envelop all conditions).

Pa = [2(13000)(0.322)/(8.687 - 2(0.4)(0.322)) = 993 psid @ 800 °F

Working Internal Pressure of 8"-150 lb Weld Neck Flange and Blind Closure Flange:

Pa = 80 psid @ 800°F [ANSI B16.5[2.14], Table 2-150]

The maximum differential pressure caused by internal pressure is 36.9 psid at 800°F. This is less than the allowable working pressure. Notwithstanding this, for completeness the juncture is analyzed. For conservatism and simplicity of analysis, the flange is considered rigid.



$$\delta_R = 0 = \frac{-1}{2D\lambda^3}V + \frac{1}{2D\lambda^2}M + \frac{PR^2}{Et_c}\left(1 - \frac{1}{2}\mu\right)$$

$$\theta = 0 = -\frac{1}{2D\lambda^2}V + \frac{1}{D\lambda}M$$

Or as shown before in Section 2.10.2.1

$0 = -4.30153\text{x}10^{-6}V + 4.76610\text{x}10^{-6}M + 35.53001\text{x}10^{-6}$
$0 = -4.76610\text{x}10^{-6}V + 10.5617\text{x}10^{-6}M$

Solving:
V = 16.52 lb/in
M = 7.45 in-lb/in

Since these loads are lower than the cylinder-bottom plate juncture loads for the accident condition, the cylinder-bottom plate juncture stresses govern. No additional stress calculations are needed. The cylinder-weld neck flange juncture is OK!

Weld Neck and Blind Flange Stresses

The weld neck flange and blind flange are manufactured from a standard (ANSI B16.5)[2.14] 8"-150lb, Class RF, weld neck flange and blind flange (F304L or similar material). Using a standard assembly with low strength bolts, these components are rated at 212 psig at 150 °F and 80 psig at 800 °F (ANSI B16.5[2.14], Table 2-150). From Section 2.10.1.1, the maximum differential pressure at 150 °F and 800 °F is 21.5 psig and 36.9 psig, respectively. Therefore, the components are qualified for the non-impact loading conditions.

For 30-foot end drop impact, Section 2.10.3, Case 3 acceleration will produce the largest load on the blind flange since Case 2 impact is balanced by the crushing of the wood. The blind flange is conservatively assumed to act as a simply supported circular plate (Roark[2.24], page 216, case 1). The edge support is assumed to be at the outer radius of the raised face (a = 10.625/2 = 5.3125"). At the center of the plate the bending stress is:

$\sigma_r = \sigma_t = 3\ W\ (3\ m + 1)\ /\ (8\ \pi\ m\ t^2)$

$W = W_{flg}\ (G_A)$

$W_{flg} = 47$ lbs — for 8"-150 lb flange

$G_A = 92$ g — Section 2.10.3, Case 3

t = 1.125 in. — for 8"-150 lb flange

m = 1/0.3

$\sigma_r = \sigma_t = 3\ (92)(47)\ (3(1/.3) + 1)\ /\ (8\ \pi\ (1/.3)\ (1.125)^2) = 1346$ psi

conservatively use membrane stress allowable

$P_m \leq$ (lesser of 2.4 S_m or 0.7 S_u) — ASME Code[2.2], F1313.1(a)

2.4 S_m = 2.4 (16700) = 40,080 psi — Table 2.3-1

or

0.7 Su = 0.7 (70000) = 49,000 psi — Table 2.3-1

1,346 psi ≤ 40,080 psi

2.10.2.4 Closure Bolts

The blind flange (closure lid) bolts to the canister body by eight 3/4-10UNRC-2A by 2.0 inch long bolts. Bolt stresses and fatigue usage factor are calculated. Part (f.) below uses the method outlined in NUREG/CR-6007[2.30] to determine the bolt loads for the impact loading condition. The following summarizes the major structural parameters used in the non-impact bolt stress analysis.

Eight 3/4-10UNRC-2A bolts

Tensile bolt area = 0.334 in^2

Thread engagement length = 0.9475" minimum (1 1/16 - chamfers)

Bolt circle diameter d_{bc} = 11.75"
Material ASTM-A193-B8M Class 2 (Class 1 properties used)
Circle diameter of O-ring seal = 9.25" for inner seal
Circle diameter of O-ring seal = 10.25" for outer seal
Lubrication - Neolube, nut friction factor 0.14 to 0.20
Bolt torque: 40 ft-lb minimum, 50 ft-lb maximum

a) <u>Bolt Preload Stress</u>

Bolt torque T_{min} = 40 ft-lb, T_{max} = 50 ft-lb
Nut friction factor K_{min} = .14, K_{max} = 0.20 (EPRI-NP-5067[2.8], Table G)
Nominal bolt diameter D = 0.75 in
T = KDF/12 or F = 12T/KD
F_{min} = 12 (40) / 0.20 (0.75) = 3,200 lbs. (total bolt load=25600 lbs)
F_{max} = 12 (50) / 0.14 (0.75) = 5,714 lbs. (total bolt load=45712 lbs)

Preload stress

Stress area for 3/4-10UNRC=0.3340 in.^{2} Machinery's Handbook[2.15], pg. 1266

$S_{1,min}$ = 3200 / 0.3340 = 9,581 psi
$S_{1,max}$ = 5714 / 0.3340 = 17,108 psi < 18,600 $2S_m$ @ 150°F
[ASME Code[2.2] NB 3232.1]

b) <u>O-ring Seal Compression Load</u>

The required bolt preload to compress both inner and outer O-ring seal is calculated. The seals are Alloy 600, 1/8" diameter, 0.010" wall metallic O-rings.

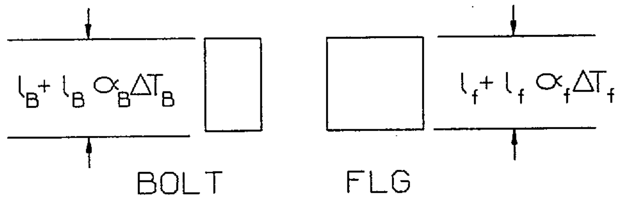
O-ring compression force =(1.1)(0.9)(343)= 340 lb/in, Ref.[2.32],page 6,alloy 600
O-ring circle diameters 9.25" and 10.25"

Total load require to compress both seals:
= π (9.25) (340) + π (10.25) (340)
= 20,829 lb for eight bolts

Load per bolt to compress seals:
= 20829 / 8
= 2,604 lb < 3,200 lb minimum bolt preload ∴ OK

c) <u>Thermal Effect on Bolt Preload</u>

As a result of different coefficients of expansion, at non-standard temperature (70°F), bolt load will change.



Elastic Strain

$$\delta_B = P / K_B \quad \& \quad \delta_F = P / k_f$$

Continuity requires bolt and flange be of the same length

$$l_B + l_B \alpha_B \Delta T_B + P / K_B = l_f + l_f \alpha_f \Delta T_f - P / K_f$$

$$(l_B - l_f) + l_B \alpha_B \Delta T_B - l_f \alpha_f \Delta T_f = -[(K_B + K_f) / K_B K_f)] P$$

For isothermal conditions $\Delta T_B = \Delta T_f = \Delta T$

$$(l_B - l_f) + l_B \alpha_B \Delta T - l_f \alpha_f \Delta T = -[(K_B + K_f) / K_B K_f)] P$$

Let $\delta \equiv l_B - l_f \Rightarrow l_f = l_B - \delta$

$$\delta + l_B (\alpha_B - \alpha_f) \Delta T + \delta \alpha_f \Delta T = -[(K_B + K_f) / K_B K_f] P$$

$$\delta (1 + \alpha_f \Delta T) + l_B (\alpha_B - \alpha_f) \Delta T = -[(K_B + K_f) / K_B K_f] P$$

$$\delta + l_B \alpha_B \Delta T - (l_B - \delta) \alpha_f \Delta T = -[(K_B + K_f) / K_B K_f] P$$

Now $\delta << l_B$, therefore $l_B - \delta \cong l_B$

$$\delta + l_B (\alpha_B - \alpha_f) \Delta T = -(K_B + K_f) / K_B K_f) P$$

If $\Delta T = 0$, then P equals the initial preload P_p

$$P_p = -[K_B K_f / (K_B + K_f)] \delta \qquad \text{and}$$

$P = -[K_B K_f / (K_B + K_f)]\ \delta - [K_B K_f / (K_B + K_f)]\ l_B (\alpha_B - \alpha_f)\ \Delta T$

Hence, the change in preload, ΔP, due to isothermal change in material temperature,

$\Delta P = P - P_P = -[K_B K_f / (K_B + K_f)]\ l_B (\alpha_B - \alpha_f)\ \Delta T$

Now, since $E_B = E_f = E$

$K_B K_f / (K_B + K_f) = (E_B A_B A_f / A_B l_f + A_f l_B)$

But, $l_f \cong l_B = l$

$K_B K_f / (K_B + K_f) = [A_B A_f / (A_B + A_f)]\ (E/l)$

$$\boxed{\Delta P = E\ [A_B A_f / (A_B + A_f)]\ [\alpha_f - \alpha_B]\ \Delta T}$$

$A_B = n\ \pi / 4\ d_B^2 = 8\ (\pi / 4)\ (0.75)^2 = 3.534\ in^2$

The effective area of the flange is assumed to be 50% of the actual area.
$A_f \cong 0.5(\pi / 4)\ (OD^2 - ID^2) = (\pi / 8)\ ((13.5)^2 - (7.98)^2) = 46.56\ in^2$

$\Delta P = 3.285\ E\ (\alpha_f - \alpha_B)\ \Delta T$

At the isothermal temperature of 150°F ($\Delta T = 80^oF$)

$\alpha_B = 8.65 \times 10^{-6}$ in/in/°F
$\alpha_f = 8.67 \times 10^{-6}$ in/in/°F
$E = 27.95 \times 10^6\ lb/in^2$
$\Delta P = 3.285\ (27.95 \times 10^6)\ (8.67 \times 10^{-6} - 8.65 \times 10^{-6})\ (80) = 147$ lb
Therefore, ΔP/ bolt = 18 lb per bolt

At the isothermal temperature of -40°F ($\Delta T = -110^oF$)

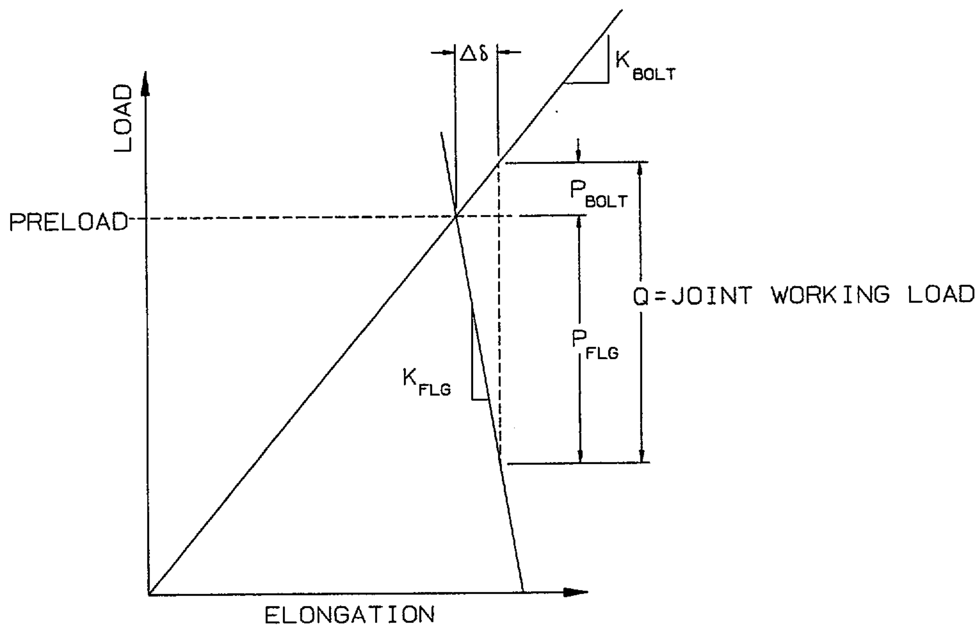
$\alpha_B = 8.26 \times 10^{-6}$ in/in/°F
$\alpha_f = 8.21 \times 10^{-6}$ in/in/°F
$E = 29.3 \times 10^6\ lb/in^2$
$\Delta P = 3.285\ (29.3 \times 10^6)\ (8.21 \times 10^{-6} - 8.26 \times 10^{-6})\ (-110) = 529$ lb
Therefore, ΔP/ bolt = 66 lb per bolt

At the isothermal temperature of 800°F ($\Delta T = 730^oF$)

$\alpha_B = 9.90 \times 10^{-6}$ in/in/°F

$\alpha_f = 9.82 \times 10^{-6}$ in/in/°F
$E = 24.1 \times 10^6$ lb/in^2
$\Delta P = 3.285\,(24.1\text{x}10^6)\,(9.82\text{x}10^{-6}-9.90\text{x}10^{-6})\,(730) = -4{,}623$ lb
Therefore, ΔP / bolt = -578 lb per bolt

d) Change in Load Due to Mechanical Loading of Joint



$\Delta\delta = (1 / K_{flg})\, \Delta P_{flg}$

$\Rightarrow (1 / K_{flg})\, \Delta P_{flg} = (1 / K_{bolt})\, \Delta P_{bolt}$

$\Delta\delta = (1 / K_{bolt})\, \Delta P_{bolt}$

$\Delta P_{bolt} + \Delta P_{flg} = Q \Rightarrow \Delta P_{flg} = Q - \Delta P_{bolt} \Rightarrow (Q - \Delta P_{bolt}) / K_{flg} = (1/K_{bolt})\, \Delta P_{bolt}$

or $Q = [(K_{flg} / K_{bolt})+1]\, \Delta P_{bolt}$

$$\Delta P_{bolt} = [K_{bolt} / (K_{flg} + K_{bolt})]\, Q$$

The elasticity modulus, E, is the same for both the flange and bolt. Also the length of the bolt and flange can be assumed equal for this calculation. Therefore,

$$\frac{K_{bolt}}{K_{flg}+K_{bolt}}=\frac{A_{bolt}}{A_{flg}+A_{bolt}}=\frac{3.534}{46.56 \quad +3.534}=0.071$$

The working mechanical loads are due to internal pressurization, external pressurization, and impact acceleration.

Reduce External Pressure:

$Q = (\pi / 4)(10.25^2)(21.5) = 1{,}774$ lbs

$\Delta P_{BOLT} = 0.071 (1774) / 8 = 16$ lb per bolt

50-Foot Immersion:

$Q = (\pi / 4)(10.25^2)(-21.7) = -1791$ lbs

$\Delta P_{BOLT} = 0.071 (-1791) / 8 = -16$ lb per bolt

Fire:

$Q = (\pi / 4)(10.25^2)(36.9) = 3045$ lbs

$\Delta P_{BOLT} = 0.071(3045) / 8 = 27$ lb per bolt

e) Load Combination and Fatigue Life

Using worst load combinations per Regulatory Guide 7.8[2.4]:

Bolt load - Normal Condition of Transport:

Preload + Reduced External Pressure + Thermal Effects at –40 °F

5714 + 16 + 66 = 5,796 lb

Bolt load - Hypothetical Accident Conditions:

50 ft Immersion

Preload + 50 ft. Immersion + Thermal Effects at –40 °F

5714 – 16 + 66 = 5,764 lb

Fire

Preload + Fire Effects at 800 °F

5714 +27 – 578 = 5,163 lb

The bolting-and-unbolting load is the largest portion of the load and the number of bolt stress cycles is, when applying stress concentration factor (SCF) of 4.0,

$\sigma = 5796 / 0.334 = 17{,}353$ psi

$S_{range} = 4\sigma = 4(17353) = 69{,}412$ psi

The alternating stress is:

$$S_{alt} = S_{range} / 2 = 69412 / 2 = 34{,}706 \text{ psi}$$

S_{ALT} corrected for elastic modulus = 34706 (30 / 27.95) = 37,252 psi. Allowable cycle per ASME Code[2.2], conservatively use fatigue curve for high strength bolting, Figure I-9.4 (and Table I-9.1) is 8,000 cycles. The bolts will be torqued twice per shipment. One for the loading and shipment and one time for return journey. Therefore, the number of shipments allowed is 4,000.

f) <u>Impact from 30-Foot Drop</u>

The maximum acceleration for this condition is 140 g's from Section 2.10.3, Case 1, 30-foot slapdown drop. Note, Case 2 does not control since this force is balanced by the crushing force of the wood and Case 3 would tend to unload the bolts since the flange joint would be in compression. The maximum bolt load is determined using the procedure from NUREG/CR-6007[2.30], page 17, Table 4.6. Using the nomenclature from Reference [2.30]. The tensile bolt force per bolt (Fa) and the shear bolt force per bolt (Fs) are given as

$$Fa = 1.34 \sin(xi)\,(DLF)\,(ai)\,(W_L + W_C) / Nb$$

$$Fs = \cos(xi)\; ai\; W_{CK} / Nb$$

where: xi = 15 degrees

ai = 140 g	Section 2.10.3, Case 1
DLF = 1	since it is based on test results
W_L = 47 + 3 = 50 lbs	8"-150 lb flange + 3 lbs for bolts
W_C = 48(10) = 480 lbs	Pathfinder fuel weight 10 lb/ assy
W_{CK} = W_L = 50 lbs	For bolt shear loading, the only unsupported weight is the blind flange and bolts since the fuel canister is supported at the clamp locations.

Nb = 8 bolts

Fa = 1.34 sin(15) (1) (140) (50 + 480) / 8 = 3217 lbs/bolt

Fa' = Fa + Fp

Fp = 1774/8 = 222 lbs/bolt   from pressure, part d of this section

Fa' = 3217 + 222 = 3,439 lbs/bolt   Load combination: 30 ft. drop + pressure load

Fs = cos(15) (140) (50) / 8 = 845 lbs/bolt

The above tensile bolt load calculation neglects preload. As an additional conservative check for bolt tensile loads, the maximum bolt preload and joint stiffness is also used below with the above calculated Fa and Fp.

$F = \max F_{preload} + 0.071\ (Fa + Fp\ )$
$F = 5714 + 0.071\ (3217 + 222)$
$F = 5{,}958$ lbs/bolt

Since F is greater than Fa', F is used in the stress calculation below.

$\sigma = F / A_b = 5958 / 0.334 = 17{,}838$ psi
$\tau = Fs / A_b = 845 / 0.334 = 2{,}530$ psi

The Faulted Condition stress limits of ASME Code[2.2], F-1335 are used below.

Tensile

σ_{allow} = lesser of 0.7 S_u or S_y at 150 °F (impact loads will be gone before fire starts)
$0.7\ S_u = 0.7\ (69750) = 48{,}825$ psi
$S_y = 27{,}900$ psi
$\sigma \leq S_y$
17,838 psi ≤ 27,900 psi Therefore, OK

Shear

τ_{allow} = lesser of 0.42 S_u or 0.6 S_y at 150 °F
$0.42\ S_u = 0.42\ (69750) = 29{,}295$ psi
$0.6\ S_y = 0.6\ (27900) = 16{,}740$ psi
$\tau \leq 0.6\ S_y$
2,530 psi ≤ 16,740 psi Therefore, OK

Combined Tensile and Shear

$(f_t / F_{tb})^2 + (f_v / F_{vb})^2 \leq 1$
$(17838 / 27900)^2 + (2530 / 16740)^2 \leq 1$
$0.43 \leq 1$

g) Thread Engagement

The bolt is screwed into the weld neck flange. The flange is made of a material of lesser strength. The flange material dictates the required engagement. The flange thread is 3/4 - 10UNC - 2B. From Machinery's Handbook[2.15], pages 1068 & 1069:

$$L_e = \frac{2\,A_t\,J}{\pi\,K_{n,\max}\left[\frac{1}{2} + .57735N(E_{s,\min} - K_{n,\max})\right]}$$

$A_S = \pi N\ K_{n,max}\ [1/2N+0.57735\ (E_{s,min}-K_{n,max})]\ L_e$ Shear area of external thread

$A_n = \pi N\ D_{s,min}\ [1/2N+0.57735\ (D_{s,min}-E_{n,max}]\ L_e$ Shear area of internal thread

$A_t = 0.334\ in^2$ Tensile area of bolt

$N = 10$ Number of threads per inch

$K_{n,max} = 0.663$ in Maximum minor diameter of internal thread

$E_{n,max} = 0.6927$ in Minimum pitch diameter of internal thread

$D_{n,max} = 0.7353$ in Minimum major diameter of external thread

$E_{s,min} = 0.6773$ in Minimum pitch diameter of external thread

$S_{bolt} = 75,000$ psi @ 70°F Bolt tensile strength

$S_{flg} = 70,000$ psi @ 70°F Flange tensile strength

$A_s = \pi(10)(.663)[1/20+.57735(.6773-.663)]\ L_e = 1.2134\ L_e$

$A_n = \pi(10)(.7353)[1/20+.57735(.7353-.6927)]\ L_e = 1.7232\ L_e$

$$J = \frac{A_s S_{bolt}}{A_n S_{flg}} = \left(\frac{1.2134}{1.7232}\right)\left(\frac{75000}{70000}\right) = 0.7545$$

Therefore, J is set equal to 1.0

$$L_e = \frac{2(.334)(1.0)}{1.2134} = 0.5505$$

The thread length available is

$L_{avail} = 1.0625 - 0.1 - .015 = 0.9475 > 0.5505\ \therefore$ OK

2.10.2.5 Saddle Supports – Pathfinder Canister

The saddle supports the dead weight of the fuel canister and the only significant loads occur during an accident condition. From Section 2.10.2.1.2.2, the maximum load on a support is 25,597 lbs. From the same section, the maximum distributed (cosine) pressure load is p_{max} = 2,827 psi for a 10,000 lb load. Thus, the bearing stress acting on the aluminum saddle is:

σ_{brg} = 2,827 (25,597 / 10,000) = 7,236 psi

Per ASME Code[2.2], F-1331.3, except for pinned and bolted joints, bearing stresses need not be evaluated. However, a Normal condition limit as given in ASME Code[2.2], NB-3227.1 is S_y. For ASTM B-209 6061 T6 plate aluminum, the room temperature yield is 35000 psi (ASME Code[2.2], Table Y-1). Thus,

$\sigma_{brg} < S_y$

7,236 psi < 35,000 psi OK, very conservative.

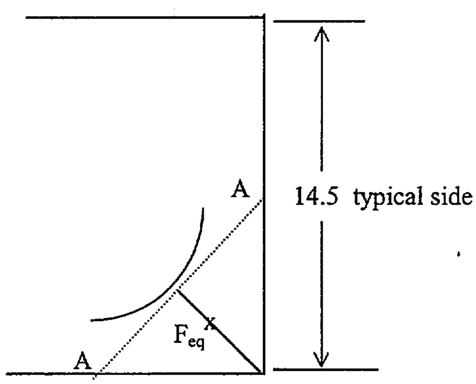
2.10.2.6 Spacer Pipe and End Plate

The spacer pipe is 8"-schedule 40S pipe and is the same size and schedule as the Pathfinder Canister. Since the loads on the spacer pipe are less than or equal to the fuel canister, it is adequate by inspection. The stress on the end plate for the spacer pipe is calculated below.

The load on the end plate is equal to the wood crush load from Section 2.10.3, Case 3, F_{max} = 71,898 lbs. Conservatively this load is uniformly distributed over the end plate.

$$w = 71{,}898 / (14.5)^2 = 342 \text{ psi}$$

The critical location for plate bending is across a corner (A-A) as shown below.



The area on this corner of the plate is:

$$A1 = (((2)^{0.5}(14.5) - 8.625) / 2)^2 = 35.29 \text{ in.}^2$$

The equivalent force (F_{eq}) is located at the centroid of this area:

$$F_{eq} = 342(35.29) = 12{,}069 \text{ lbs}$$

The moment arm from F_{eq} to line A-A is:

$$L1 = 0.333(((2)^{0.5}(14.5) - 8.625)/2) = 1.98 \text{ in.}$$

$$M = 1.98\ (12069) = 23{,}897 \text{ in-lbs} \quad \text{bending moment}$$

$$\sigma_b = 6\ (M / b) / t^2 \quad \text{bending stress}$$

Where b is the base of the triangle (i.e. 11.88 in.) and t is the thickness of the plate (0.5 in.)

$$\sigma_b = 6\ (23{,}897 / 11.88) / (0.5)^{0.5} = 48{,}277 \text{ psi}$$

This exceeds the yield strength of the material (25 ksi) but well below the ultimate strength of 75 ksi. This is considered satisfactory since the primary function of the end plate is to hold the wood is place. Note, the majority of the load will transmit through the wood within the area of the outer diameter of the spacer and canister.

2.10.2.7 Hypothetical Fire Accident Condition Container Stresses

From Figure 3.5-3 (Chapter 3), the maximum temperature for the fire accident condition on the inner surface of the clamps is 792 °F. The Pathfinder Canister temperature at a saddle support will be below this 792 °F since the resistance of the saddle support and two interfaces are between the clamp and the canister wall. The bolted closure is insulated from the end plate of the inner box by pine wood. The pine wood is treated with a fire retardant and with the restricted air flow through the bolted joints, will not burn. Thus, the primary heat source for this region is heat conducted from the nearest saddle support, which is 4 inches from the joint. This additional resistance in the heat flow path will reduce the temperature at the bolted closure below the 792 °F maximum clamp temperature.

From Figure 3.5-3 (Chapter 3), the maximum temperature gradient between points 90 degrees apart on the inner surface of the clamp is approximately 35 F°. The linear circumferential temperature gradient of the fuel canister is less then $35 / ((\pi/4)(8.625)) = 5.2$ F° / inch since the saddle supports will help distribute the temperature. The thermal stresses due to this gradient are considered negligible. The axial temperature gradients may be significant. The space between the fuel canister and inner box (except at clamp locations) is filled with Zircar insulation and the temperature transient for the maximum clamp temperature point is approximately 1100 F°/hr (Figure 3.5-2). Thus, as a worse case, a linear temperature gradient from the bolted joint to the nearest clamp is $(792 - 122)/4 = 168$ F° / inch.

Note the maximum circumferential and maximum axial gradients can not occur at the same location and the axial gradient stresses will obviously bound those due to the circumferential gradient. The thermal stresses due to an axial gradient in a cylinder can be approximated by using Hartog[2.33]. For a finite tube of length L, hot in the center and cold at the ends with a half sine-wave of temperature (Hartog[2.33], Fig. 13b), the solution is given in Fig. 14 of Hartog[2.33]. Note this solution should approximate or be conservative for a linear temperature gradient since a portion of the sine-wave will have a slope greater than a straight linear representation.

$L =$ 2 times distance from clamp center to bottom flange surface of weld neck flange

$L = 2(4) = 8"$

$t = 0.322"$

$R = (8.625 - 0.322) / 2 = 4.1515"$

$L/(R\ t)^{0.5} = 8/(4.1515(0.322))^{0.5} = 6.92$

$\tau_{max} / E\alpha T_o = 0.06$ — Hartog[2.33]. Fig. 14

$\sigma_{thm} = 2\ \tau_{max} = 2(0.06)E\alpha T_o = 0.12\ E\alpha T_o$

$E = 27.0 \times 10^6$ psi — Table 2.3-1, at 300 °F, max Eα

$\alpha = 9.00 \times 10^{-6}$ in/in/F° — Table 2.3-1, at 300 °F, max Eα

$T_o = 792 - 122 = 670$ F° — Figure 3.5-2

$\sigma_{thm} = 0.12(27.0 \times 10^6)(9.00 \times 10^{-6})(670) = 19{,}537$ psi

The hoop pressure stress due to the 36.9 psig internal pressure is:

$\sigma_{press} = 36.9(4.1515)/0.322 = 476$ psi

$\sigma = \sigma_{thm} + \sigma_{press} = 19537 + 476 = 20{,}013$ psi

$S_n = (E_{cold} / E_{hot})\ K_t\ \sigma = (28.3 \times 10^6 / 27.95 \times 10^6)(4)(20013) = 81{,}054$ psi

Since this thermal stress is due to an accident condition, the allowable stress is 2 Sa at 10 cycles (Ref. Table 2.1-1):

$S_n < 2$ Sa at 10 cycles

Sa at 10 cycles = 708,000 psi ASME Code[2.2], Table I-9.1, Fig. I-9.2.1

81,054 psi < 2(708,000)

81,054 psi < 1,416,000 psi — Therefore, OK

2.10.2.8 Removal of WE-1 Clamp

Due to space required for the bolted closure and wood impact absorber, the first clamp from the one end plate (slap down end) will be removed. The effect on the stiffness of the WE-1 inner container and ultimately the g-load on the Pathfinder Canister is considered to be small due to this modification to the original test configuration. This region of the container still has one clamp, the inner container spacer, and the end plate to provide additional stiffness to that of the bolted container itself. In addition, the low strength bolts attaching the end plate will be replaced with high strength bolts to prevent shear off of the bolts during an accident. Note, the opposite end of the original WE-1 inner container has only one clamp and no inner container spacer so the end with the clamp removed is stronger than the opposite end.

2.10.2.9 Weight and Center of Gravity WE-1 With Pathfinder Canister

The component weight for the Pathfinder Canister and its support are summarized here:

Pathfinder Canister		
	Blind Flange	47 lb
	Weldneck Flange	42
	Cylinder	200
	Bottom Plate	17
	Bolt / Washer	3
	Sub total	309 lb
Pathfinder Fuel		480 lb, approximate weight for 48 fuel assemblies
Spacer Tube Assy		
	Tube	145 lb
	End Plate	30
Wood Spacer (Oak wood)		47 lb
Inner Rectangular box, strong Back, outer shell, insulation, etc		7,480 lb
WE-1 Package with	Pathfinder Canister	8,500 lb

The C.G. shift from the WE-1 with BW 17x17 Fuel Assembly to the WE-1 with Pathfinder Canister and fuel is 2.4 inches.

The total weight of the WE-1 package with BW 17x17 fuel is 9,090 lbs. Of that weight, the BW 17x17 fuel assembly is 1,610 lbs. The center of gravity is situated near the geometric center of the package.

The WE-1 package with Pathfinder Canister is approximately 600 lb lighter and center of gravity is 2.4 inches from geometric center toward Pathfinder Canister closure end. These changes are considered negligible or conservative and the impact data from the WE-1 30-foot drop is appropriate to use with the Pathfinder Canister in the WE-1 shipping container.

2.10.2.10 <u>WE-1 Normal Condition 4-foot Drops</u>

Regulation 10CFR71.71(c)(7) requires a package of less than 11,000 pounds to withstand a free drop of four foot onto a flat, unyielding horizontal surface. Previous 4-foot drop tests of similar type packages have experienced acceleration levels of approximately 10 g's for this Normal condition. The acceleration values used in the Pathfinder Canister 30-foot drop accident condition analysis are 135 g's and higher. Since the Faulted condition stresses are acceptable, the Normal condition stresses are also acceptable if

$$(G_{Normal} / G_{Faulted}) < (\text{Normal stress allowable} / \text{Faulted stress allowable})$$

Primary membrane stress is most limiting and from Table 2.1-1

$$(10/135) < (S_m / 2.4\ S_m)$$
$$0.074 < 0.42$$

Therefore, the stress margins from the Faulted condition drops will bound those drops under Normal conditions.

2.10.2.11.1 Penetration

Regulation 10CFR71.71(c)(10) requires that a package withstand the impact of the hemispherical end of a vertical steel cylinder of 1¼ in diameter and weighing 13 pound dropped from a height of 40 inches onto the exposed surface of the package, which is expected to be most vulnerable to puncture.

The contents (Pathfinder Canister) of the WE-1 inner box obviously have no effect on this test. Thus, the conclusion of Section 2.6.10 remains unchanged (i.e. the penetration test has negligible consequence for the WE-1 package).

2.10.2.12 Vibration

By inspection, the Pathfinder Canister is securely clamped at five locations and any large void above the stack of fuel rods in the fuel canister is packed with filler material to prevent fuel rod movement. Thus, the conclusion of Section 2.6.5 remains unchanged (i.e. vibration normally incident to transportation, as delineated in 10CFR71.71(c)(5), will have a negligible effect on the package).

2.10.2.13 Water Spray

Regulation 10CFR71.71(c)(6) requires a package to withstand water spray that simulates exposure to rainfall of approximately 2 inches per hour for at least one hour. The contents (Pathfinder Canister) of the WE-1 inner container obviously have no effect on this test since the canister is constructed of metal and is sealed with metal gaskets. Thus, the conclusion of Section 2.6.6 remains unchanged (i.e. the water spray will have negligible effect on the package).

2.10.3 30-Foot Drop Accident - Pathfinder Canister Accelerations

The purpose of this section is to determine the design g-loadings for the Pathfinder Canister.

2.10.3.1 Lateral Acceleration

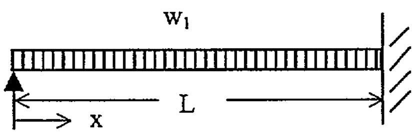
The WE-1 Shipping Container containing a MK-BW Prototype Fuel Assembly was drop tested from the 30 foot height. The results are documented in Section 2.7.1.4 and indicate that some of the fuel rods in the bottom span of the fuel assembly experienced a permanent set of approximately 2.25 inches. Since the test was not instrumented, the purpose of this section is to determine the decelaration (g-level) necessary to produce the 2.25-inch deflection. This acceleration will be used to establish the design lateral loads for the Pathfinder Canister when installed in the WE-1 Shipping Container.

Both the bottom Inconel spacer grid and the intermediate Zircaloy spacer grid of the MK-BW Fuel Assembly are designed to support the fuel rod with five tabs, one middle tab and a pair of tabs at each of the outermost support locations. The WE-1 fuel assembly clamps are at the spacer grid locations except the bottom clamp, which supports both the bottom spacer and the bottom nozzle at a middle location (about 1.86 inches beyond the center of the bottom spacer grid). Rubber shims between the clamp and a thin piece of aluminum sheet metal that contacts the spacer grid provide a secure fit during normal transportation. A special design for the bottom clamp uses a stainless steel sheet metal to bridge the span between the bottom spacer and bottom nozzle.

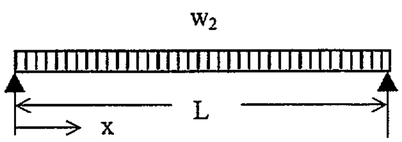
For a lateral load during an accident condition, the spacer grid design should provide significant moment restraint of the fuel rods. However, the photos from the drop test (Appendix 2-1) indicate that the bottom span of the test fuel rod experienced significant moment restraint only at the intermediate grid spacer. This is due, in part, to the stiffness of the adjacent span whereas the end of the fuel rod is slightly beyond the bottom spacer grid and just rotates with that spacer grid. Therefore, the following plastic limit analysis will assume that the bottom span of the fuel rod acts as a fixed-pinned beam as shown in configuration 1 (below). In addition, any secondary effects such as the spring load on dummy fuel pellets, internal pressure, slip force between spacer grid tabs and fuel rod, shear stress, fuel rod stiffening effect of the dummy fuel pellets, and high strain rate tensile properties of the fuel rod are conservatively omitted herein.

The limit analysis assumes that, at small strain levels, the fuel rod behaves as an elastic-perfectly plastic material. The plastic hinge location does not rotate until the plastic moment is reached at which time unlimited rotation occurs when any small additional load is applied (i.e. a hinge is formed). The analysis proceeds as follows:

First the w_1 uniform load for configuration 1 is determined which will produce a plastic hinge at the maximum moment location (fixed end). The fixed end with the plastic hinge now can only support additional shear load as shown in configuration 2 (below). The additional uniform load w_2 is determined which will produce a plastic hinge at the maximum moment location in configuration 2.



Configuration 1



Configuration 2

L = Length of bottom span (distance between mid height of spacer grids).

L = 24.1395 in.

$M_p = K\,M_y$

$K = (16\,r_o / 3\,\pi)((r_o^3 - r_i^3)/(r_o^4 - r_i^4))$ Timoshenko[2.25], page 353, Fig. 222 (b)

$r_o = 0.187$ in.

$r_i = 0.163$ in.

K = 1.3563

$M_y = I\,S_y / r_o$

$I = (\pi / 4)(r_o^4 - r_i^4) = 0.000406\text{ in.}^4$

The fuel rod clad material is cold worked and stress relieved Zircaloy-4. The material tensile properties for the fuel clad material are given below.

S_y = 83,330 psi

Su = 109,370 psi

$M_y = 0.000406\,(83330) / 0.187 = 180.920$ in-lbs

$M_p = 1.3563\,(180.920) = 245.382$ in-lbs

For Configuration 1 , Roark[2.24], page 109, case 23.

$M_{max} = M_p = 0.125\,w_1\,L^2$

$w_1 = 8\,M_p / L^2 = 8\,(245.382) / (24.1395)^2 = 3.3688$ lbs/in

$M_{x1} = w_1\,L\,(0.375\,x - 0.5\,x^2 / L)$

$M_{x1} = -\,1.6844\,x^2 + 30.4954\,x$

For Configuration 2 , Roark[2.24], page 106, case 13.

$M_{x2} = 0.5\,w_2\,L\,(x - x^2 / L)$

$M_{x2} = -\,0.5\,w_2\,x^2 + 12.0698\,w_2\,x$

The location of the final plastic hinge is near midspan but must be determined by setting the slope of the total moment equation to zero.

$M_x = M_{x1} + M_{x2}$

$M_x = = - 1.6844\, x^2 - 0.5\, w_2\, x^2 + 30.4954\, x + 12.0698\, w_2\, x$

$dMx/dx = - 3.3688\, x - w_2\, x + 30.4954 + 12.0698\, w_2$

$0 = (-3.3688 - w_2)x + (30.4954 + 12.0698\, w_2)$

$x = (30.4954 + 12.0698\, w_2) / (3.3688 + w_2)$

Since $M_x = M_p$ at the location of the plastic hinge, the value of x in terms of w_2 can be substituted into the equation for M_x and solved by iteration for w_2. Thus,
$w_2 = 1.5399$ lbs/in at x = 9.999 in. from the left support

Thus, the total uniform load when the fuel rod in the bottom span becomes a mechanism with two plastic hinges and a pinned support is:

$w = w1 + w2 = 3.3688 + 1.5399 = 4.9087$ lbs/in

The g-level is determined by dividing w by the dead weight (lbs/in) of the fuel rod.

$G's = w / w_{dw}$

$w_{dw} = \rho_p A_p + \rho_c A_c$

$\rho_p = 10.4$ g/cc = 0.3757 lbs/in.^{3} (dummy fuel pellet density)

$\rho_c = 0.237$ lbs/in^3 (for Zircaloy-4)

$A_p = \pi\, (0.15975)^2 = 0.08017$ in.^{2} (pellet cross section area)

$A_c = \pi\, ((0.187)^2 - (0.163)^2\,) = 0.02639$ in.^{2}

$w_{dw} = 0.3757(0.08017) + 0.237(0.02639) = 0.03637$ lbs/in

$G's = 4.9087 / 0.03637 = 134.95$ g

As a means to verify the acceleration load, the lower bound deflection is determined and compared to the drop test results. The maximum deflection can be approximated by setting the slope of the deflection equation to zero (Roark[2.24], Table III, cases 23 and 13).

$\delta_x = \delta_{x1} + \delta_{x2}$

$\delta_x = (w_1 / 48\, E\, I)(3\, L\, x^3 - 2\, x^4 - L^3\, x) - (w_2\, x / 24\, E\, I)(L^3 - 2\, L\, x^2 + x^3)$

$d\delta_x /dx = (w_1 / 48\, E\, I)(9\, L\, x^2 - 8\, x^3 - L^3\,) - (w_2 / 24\, E\, I)(L^3 - 2\, L\, x^2 + x^3)$
$- (w_2\, x / 24\, E\, I)(- 4\, L\, x + 3\, x^2) = 0$

Multiply by 48 EI gives

$d\delta_x/dx = w_1\, (9\, L\, x^2 - 8\, x^3 - L^3\,) - 2\, w_2\, (L^3 - 2\, L\, x^2 + x^3) - (2\, w_2\, x\,)(- 4\, L\, x + 3\, x^2)$
$= 0$

by iteration, the solution is x = 11.038 in. from the left support.

Rearranging the equation for δ_x gives

$\delta_x = (1 / 48\ E\ I)\ [\ w_1 (3\ L\ x^3 - 2\ x^4 - L^3\ x) - (2\ w_2\ x)(L^3 - 2\ L\ x^2 + x^3)]$
$E = 12.40 \times 10^6$ psi (for Zircaloy-4)

Substituting known values for the remaining variables, I, L, w_1, w_2, and x into the above equation gives:

$\delta_x = -1.22 - 1.34 = -2.56$ in.

However, the above displacement occurs when the maximum load is applied. When the load is removed a significant elastic springback will occur. The final or permanent set deflection can be conservatively (lower bound) estimated as:

$\delta_{x,set} = \delta_x - \delta_x / K = (-2.56) - (-2.56 / 1.3563) = -0.67$ in.

The drop test results indicated a maximum 2.25 in. permanent set (Section 2.7.1.4) occurred for some of the fuel rods in the bottom span. This indicates that some relatively small load, in addition to that calculated above, occurred to produce a larger permanent set as the plastic hinges rotated as a mechanism. The % elongation of the Zr-4 fuel rod tubing at ultimate strength is 19.49%. Since the difference between S_u = 109 ksi and S_y = 83 ksi is a relatively small fraction of the S_y value, it is reasonable to believe, significant strain hardening will not occur at the small strain levels necessary to produce this additional displacement. Therefore, the lateral G-level determined using an elastic-perfectly plastic material is appropriate and the design lateral G-level is

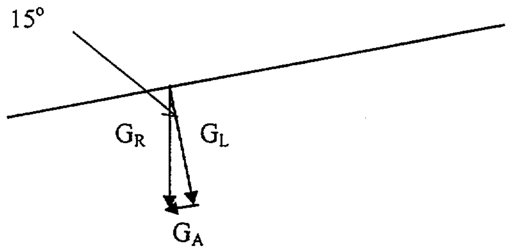
$G_L = 135$ g

2.10.3.2 30-Foot Drop Accident - Axial Acceleration

The purpose of this section is to determine the design axial accelerations for the Pathfinder Canister. Three axial accelerations will be calculated, one which is acting with the worse case lateral acceleration and the other two for a 30-foot end-drop (container is oriented with the axial length in the vertical direction).

Case 1

The 135 g lateral acceleration calculated in Section 2.10.3.1 occurred during the second hit or slapdown. The angle of the container at the time of the slapdown is not known but can conservatively be estimated as the same as the initial drop angle (i.e., 15 degrees, Section 2.7.1.4) for the initial hit. The axial acceleration (G_A)
can be approximated from the sketch below as:



$G_A = G_L \tan(15) = 135 \tan(15) = 36.2$ g's
$G_R = G_L / \cos(15) = 135 / \cos(15) = 139.8$ g's use 140 g's for design

Case 2

For an end drop impacting on the bolted connection end of the canister, a worse case is assumed whereby all the potential energy (P.E.) of the fuel and fuel canister is absorbed by the crushing of a 2" thick pine wood. Pine wood grains oriented parallel to the axis of the impacting container.

P.E. = W h
W = 782 lbs Pathfinder canister with fuel
h = 30 ft. = 360 in.
P.E. = 782 (360) = 281,520 in-lbs
P.E. = Work = $F_{max}\,\delta$
$F_{max} = \sigma_{crush}\,A$
σ_{crush} = 4,800 psi ± 15% Mark's Handbook[2.7], pg. 6-124, for Eastern White Pine. The ± 15% is a standard range for wood crush strength.
$A = (\pi/4)(13.5)^2 = 143.14$ in.^{2} blind flange surface area
$F_{max} = 1.15(4{,}800)(143.14) = 790{,}133$ lbs
$\delta = P.E. / F_{max} = 281{,}520 / 790{,}133 = 0.36$ in.
$F_{max} = m\,G_A$
$G_A = F_{max} / m = 790{,}133 / (782 / 386.4) = 390{,}419$ in/in/sec = 1,010 g's

Case 3

For an end drop impacting on the welded end cap of the canister, a worse case is assumed whereby all the potential energy (P.E.) of the fuel and fuel canister must be absorbed by the crushing of a 8" thick oak wood with grains oriented perpendicular to the axis of the impacting container.

$P.E. = Work = F_{max}\, \delta$

$F_{max} = \sigma_{crush}\, A$

$\sigma_{crush} =$ 1,070 psi ± 15% Mark's Handbook[2.7], pg. 6-124, for White Oak. The ± 15% is a standard range for wood crush strength.

$A = (\pi/4)\,(8.625)^2 = 58.43$ in.^{2} bottom plate surface area

$F_{max} = 1.15(1{,}070)\,(58.43) = 71{,}898$ lbs

$\delta = P.E. / F_{max} = 281{,}520 / 71{,}898 = 3.92$ in.

$F_{max} = m\, G_A$

$G_A = F_{max} / m = 71{,}898 / (782 / 386.4) = 35{,}526$ in/in/sec = 92 g's

Note, the worse case assumption used above assumes the 4 bolts attaching the clamp (nearest the bolted closure) to the WE-1 inner container are sheared off. The load required to do this is calculated as follow:

$\tau_u = 0.75\, S_u = 0.75\,(75{,}000) = 56{,}250$ psi approximate for steel

$\tau_u = 0.75\,(75{,}000) = 56{,}250$ psi Section 2.3

$A_s = A_t = 0.1419$ in.^{2} Machinery's Handbook[2.15], pg. 1,266 for 1/2"-13 UNC

$F_{shear} = 4(0.1419)(56{,}250) = 31{,}928$ lbs

From Section 2.10.2.1.2.1, the total weight of the canister and fuel is approximately 782 lbs. Thus, the acceleration required to produce the F_{shear} load is:

a = 31,928/782 = 40.8 g's

30-Foot Drop Accident Accelerations Summary:

30-Foot Drop		Impact Acceleration	Direction	
			Lateral – g's	Axial g's
Slapdown Drop	Case 1	140	135	36
CG Over Corner Drop		Enveloped by other drops		
End Drop – Closure End	Case 2	1,010	0	1,010
End Drop – Bottom Plate End	Case 3	92	0	92

2.10.4 Stress Summary

Results show that the Pathfinder Fuel shipping canister stresses are below ASME Code and Regulatory Guide 7.6 allowables. The canister also has adequate margin to preclude buckling during normal and hypothetical accident conditions. As demonstrated by analysis performed herein, the Pathfinder Fuel shipping canister meets the structural design criteria of 10CFR71.

Reduced External Pressure Load Condition (21.5 psid) – Stress Summary

Component	Location	Stress Intensity - psi			
		Membrane	Membrane Allowable	Membrane + Bending	Membrane + Bending Allowable
Cylinder	Mid Section	293	16,700	293	25,050
	Flat Head Juncture	378	16,700	1,004	25,050
	Weld Neck Flange Juncture	Bounded by flat head juncture stresses			
Flat Head	Cylinder Vessel Juncture	Bounded by cylinder vessel-flat head juncture streses			
	Center	38	16,700	408	25,050

The weld neck flange and blind flange are both standard class 150 lb components with pressure-temperature ratings of 212 psid at 150 ^oF which is greater than the Normal conditions of 21.5 psid at 150 ^oF.

50-Foot Immersion Condition (-21.7 psid)

Stresses are multiplied by following ratio to the reduced external pressure load case:

Cylinder and bottom flat plate: 1.01
Weld neck and blind flange: <1.00

The biggest contribution to the flange stress is due to compression of seals. For internal pressure case, the compression of seal and pressure load add to produce total stress. For 50-foot immersion condition, stress due to seal compression and pressure load are opposite. For this reason, the flange stresses due to 50-foot immersion will be lower than the reduced external pressure case.

50-foot Immersion Load Case Buckling Stability Summary

COMPONENT	CRITICAL LOAD	ACTUAL LOAD
Vessel Cylinder	431 psig	21.7 psig
Vessel Flat Head	29,910 lb/in	24 lb/in
Blind Flange	Adequate by comparison to flat head	

Hypothetical Accident Condition Stress summary

Component	Stress Intensity - psi		
	Actual	Allowable	Margin of Safety
30-Foot Slapdown Drop			
Cylinder – Primary*	34,653	40,080	0.16
Cylinder – Secondary*	329,070	1,416,000	3.3
Saddle Support	7,236	35,000	3.84
30-Foot end Drop			
End Plate	6,763	40,800	9.84
Buckling of Cylinder	25,614	524,800	Large
Fire			
Cylinder - Secondary	81,054	1,416,000	Large

Note: * Cylinder stress bounds end plate, weld neck flange

Closure Bolts

Preload 45 $\pm$ 5 ft-lbs less thermal expansion effects

- Minimum preload of 3,200 lbs at 70°F
- Minimum preload of 3,182 lb at 150°F
- Minimum preload 3,182 lbs > 2,604 lb to compress seals

Working load (preload + working-mechanical + thermal load)

- Normal Condition of Transport 5,796 lbs
- Hypothetical Accident Condition 5,958 lbs, 5,764 lbs

Pathfinder Canister Closure Bolt Stress Summary

Component	Stress - psi		
	Actual	Allowable	Margin of Safety
Normal condition of Transport	17,353	18,600	0.007
Hypothetical Accident			
30-foot slapdown drop			
Tensile Stress	17,838	27,900	0.56
Shear Stress	2,530	16,740	5.62
Combined	0.43	1.	1.33
50-foot Immersion	17,257	18,600	0.08
Fire	15,458	17,400	0.13
Fatigue life of the bolt	➢ 4,000 shipment		
Minimum thread engagement	$L_{e,\ available}$ = 0.948 > 0 551		0.72

2.10.5 References

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2.5 NUREG/CR-3854, "Fabrication Criteria for Shipping Containers," March 1985.

2.6 NUREG/CR-3019, "Recommended Welding Criteria for Use in the Fabrication of Shipping Containers for Radioactive Materials," March 1985.

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APPENDIX 3-1:
CONVECTION COEFFICIENT CALCULATIONS

3-1.1 FIRE FORCED CONVECTION COEFFICIENT CALCULATION

During a hypothetical accident condition (HAC) hydrocarbon fire, the heated gasses surrounding the package will achieve velocities sufficient to induce forced convection on the surface of the package. Measurements obtained during actual hydrocarbon tests predict average induced gas velocities of between 6 m/s (19.7 ft/s)[1] and 9 m/s (29.5 ft/s)[2]. Peak measured velocities have been as high as 15 m/s (49.2 ft/s), although these occurred 6.1 meters (20 ft) from the fire surface. Peak velocities 2.2 meters from the fire surface (7.2 ft) peak measured velocities were under 10 m/s (32.8 ft/s)[7].

Assuming a gas velocity of 9 m/s (29.5 ft/s) and a horizontally oriented package with an effective outer diameter of 1.75 feet (based on the perimeter of the inner container outer surface), per *Elements of Heat Transfer*[3], the convection coefficient can be expressed as:

$$h = Nu \frac{k}{D} \text{ Btu/hr-in}^2\text{-°F}$$

Where k is the conductivity of gas at film temperature (Btu/hr-in-°F) and L is the effective length of the vertical surface (inches). For a horizontal cylinder being subjected to turbulent flow (Re > 5,000), the Nusselt number, Nu, can be expressed as:

$$\text{Nu} = 0.3 + \frac{0.62\,\text{Re}^{1/2}\,\text{Pr}^{1/3}}{\left[1 + (0.4/\text{Pr})^{2/3}\right]^{1/4}} \left[1 + \left(\frac{\text{Re}}{282{,}000}\right)^{5/8}\right]^{4/5}$$

where Pr is the Prandtl Number, and the Reynolds Number, Re, is expressed as:

$$\text{Re} = \frac{u_\infty D}{\nu}$$

and u_∞ is average air velocity, D is effective diameter of the inner container, ν is dynamic viscosity.

A film temperature of 1,350 °F is assumed for determining air material properties. Specifically, Pr = 0.702, k = 0.037 Btu/hr-ft-°F, and ν = 0.00129 ft^2/sec. The resulting

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[1] Schneider, M. E., L. A. Kent, *Measurements of Gas Velocities and Temperatures in a Large Open Pool Fire, Heat and Mass Transfer in Fire*, HTD-Volume 73.

[2] Gregory, J. J., N. R. Keltner, R. Mata, *Thermal Measurements in Large Pool Fires*, Heat and Mass Transfer in Fire, HTD-Volume 73.

[3] Y. Bayazitoglu and M. Ozisik, *Elements of Heat Transfer*, McGraw-Hill Publishing, New York, 1988, pp211-212.

Reynolds number is 39,720, and the Nusselt number is 118.7. The resulting heat transfer coefficient is 2.5 Btu/hr-ft^2-°F, and is applied to the outer surface of the inner container for the duration of the half-hour fire event.

3-1.2 POST-FIRE NATURAL CONVECTION COEFFICIENT CALCULATION

During the post-fire HAC package conditions, it is conservatively assumed that there is negligible wind and that heat is transferred from the inner container to the environment via natural convection. Natural heat transfer coefficients from the outer surface of the square inner container are calculated as follows.

From *Elements of Heat Transfer*, the convective heat transfer coefficient, h, is:

$$h = Nu\frac{k}{L}\ \text{Btu/hr-in}^2\text{-°F}$$

where k is the conductivity of the gas at a film temperature (Btu/hr-in-°F) and L is the effective length of the vertical surface (inches).

The Nusselt number, Nu, for vertical heated surfaces is:

$$Nu = \left(0.825 + \frac{0.387(Gr\,Pr)^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}}\right)^2 \qquad \text{for } 10^{-1} < GrPr < 10^{12}$$

The Nusselt number, Nu, for horizontal heated surfaces facing upward is:

$$Nu = 0.54(Gr\,Pr)^{1/4} \qquad \text{for } 10^5 < GrPr < 2\times10^7$$

$$Nu = 0.14(Gr\,Pr)^{1/3} \qquad \text{for } 10^7 < GrPr < 10^{10}$$

and, for horizontal heated surfaces facing downward:

$$Nu = 0.27(Gr\,Pr)^{1/4} \qquad \text{for } 3\times10^5 < GrPr < 3\times10^{10}$$

For both horizontal and vertical heated surfaces, the Grashof number, Gr, is:

$$Gr = \frac{g\beta\Delta TL^3}{\nu^2}$$

gravitational acceleration constant (in/s^2), β is the gas coefficient of thermal expansion (°F^{-1}), where $\beta = (T_{abs})^{-1}$ for an ideal gas, ΔT is the differential temperature (°F), where $\Delta T = |T_{wall} - T_\infty|$, ν is the kinematic viscosity of gas at the film temperature (in^2/hr), and Pr is the Prandtl number. Note that k, ν and Pr are each a function of air temperature, and are described in Table 3.2-2.

For use in the ANSYS® computer code, these correlations are simplified into a relationship that is based on the temperature difference between the inner container and the ambient air. The air thermal properties are assumed to correspond to an ambient temperature of 100 °F. The heat transfer coefficients used in the post-fire thermal analysis are presented in Table 3.2-4.

APPENDIX 6.1:
KENO V.a INPUT FILE LISTINGS

A. B&W MkBW 17x17

6-1.1 KENO V.a Input File Listings

6-1.1.1 Normal Condition – Inner and Outer Container

```
=csas25
Mk BW17 4.6  wt% assembly in water 0.975 TD
44g lat
'2345678901234567890123456789012345678901234567890123456789012
'fresh fuel
  uo2         1  den=10.686  1.0  293  92235 4.6  92238 95.4  end
'clad
 zr           2              1.0  293                 end
'moderator
  h2o         3  den=0.0001  1.0  293                 end
'moderator
  h2o         4  den=0.0001  1.0  293                 end
'moderator
  h2o         5  den=1.0     1.0  293                 end
' carbon steel
  carbonsteel   6            1.0  293                 end
end comp
'
'pitch data based on fuel pins
'        pitch   pel OD   fuelid modid cladOD cladid#  gapOD   gapid#
squarepitch 1.25984 0.820928   1    3   0.94488  2    0.84074 0 end
KENO
read parm  tme=3000  gen=1003 npg=1000 plt=yes run=yes end parm
read geom
unit 31
  cylinder  1  1  0.410464   366.0  0.0
  cylinder  0  1  0.42037    366.0  0.0
  cylinder  2  1  0.47244    366.0  0.0
  cuboid    3  1  4p0.62992  366.0  0.0
unit 32
  cylinder  3 1 0.57404      366.0  0.0
  cylinder  2 1 0.60960      366.0  0.0
  cuboid    3 1 4p0.62992    366.0  0.0
unit 33
  cylinder  3 1 0.57404      366.0  0.0
  cylinder  2 1 0.60960      366.0  0.0
  cuboid    3 1 4p0.62992    366.0  0.0
' assembly  in armour plate
unit 35
  array 34   0  0  0
  replicate 4 1 2*7.70636 8.00354 7.40918  2*0.0 1
```

```
  replicate 6 1 4*2.54 2*0.00 1
global
unit 36
  cylinder 4 1 52.07 366.0 0.0
  hole 35 -10.70684 -10.70684  0.0
  cylinder 6 1 52.2978   366.0 0.0
  cuboid   5 1 4p82.78  366.0 0.0
end geom
read array
'fresh fuel assembly
  ara=34   nux=17   nuy=17   nuz=1
  fill   31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 32 31 31 32 31 31 32 31 31 31 31 31
         31 31 31 32 31 31 31 31 31 31 31 31 31 32 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 32 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 33 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 32 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 32 31 31 31 31 31 31 31 31 31 32 31 31 31
         31 31 31 31 31 32 31 31 32 31 31 32 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31

  end fill
end array
read bounds
  xyf=vacuum
  zfc=mirror
end bounds
read plot
ttl='x-y slice of  at z=50'
xul=-55.0     yul=55.0   zul=50
xlr=55.0   ylr=-55.0   zlr=50
uax=1 vdn=-1 nax=260  nch=' 12 467'  end
 nch=' 12 467'  end
end plot
end data
end
```

6-1.1.2 Flooded Inner Container – Single Flooded Container/Accident Condition

```
=csas25
Mk BW17 4.60 wt% assembly in water 0.975 TD
44g lat
'23456789012345678901234567890123456789012345678901234567890123456789012
'fresh fuel
  uo2         1  den=10.686  1.0  293  92235 4.6 92238 95.4  end
```

```
'clad
 zr           2            1.0  293                     end
'moderator
  h2o        3  den=1.0    1.0  293                     end
'moderator
  h2o        4  den=1.0    1.0  293                     end
'moderator
  h2o        5  den=1.0    1.0  293                     end
' carbon steel
  carbonsteel   6           1.0  293                    end
end comp
'
'pitch data based on fuel pins
'         pitch   pel OD   fuelid modid cladOD cladid#  gapOD   gapid#
squarepitch 1.25984 0.820928    1     3   0.94488  2     0.84074 0 end
KENO
read parm  tme=3000  gen=1003 npg=1000 plt=yes run=yes end parm
read geom
unit 31
  cylinder  1  1  0.410464   366.0  0.0
  cylinder  0  1  0.42037    366.0  0.0
  cylinder  2  1  0.47244    366.0  0.0
  cuboid    3  1  4p0.62992  366.0  0.0
unit 32
  cylinder  3 1 0.57404      366.0  0.0
  cylinder  2 1 0.60960      366.0  0.0
  cuboid    3 1 4p0.62992    366.0  0.0
unit 33
  cylinder  3 1 0.57404      366.0  0.0
  cylinder  2 1 0.60960      366.0  0.0
  cuboid    3 1 4p0.62992    366.0  0.0
' assembly in inner container
global
unit 35
  array 34   0  0  0
  replicate 4 1 2*7.70636 8.00354 7.40918  2*0.0 1
  replicate 6 1 4*2.54 2*0.00 1
  replicate 5 1 4*30.48    2*0.0 1
end geom
read array
'fresh fuel assembly
  ara=34   nux=17   nuy=17   nuz=1
  fill   31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 32 31 31 32 31 31 32 31 31 31 31 31
         31 31 31 32 31 31 31 31 31 31 31 31 31 32 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 32 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 33 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
```

```
      31 31 32 31 31 32 31 31 32 31 31 32 31 31 32 31 31
      31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
      31 31 31 32 31 31 31 31 31 31 31 31 31 32 31 31 31
      31 31 31 31 31 32 31 31 32 31 31 32 31 31 31 31 31
      31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
      31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31

  end fill
end array
read bounds
  xyf=vacuum
  zfc=mirror
end bounds
read plot
ttl='x-y slice of  at z=50'
xul=-4     yul=50.0   zul=50
xlr=50.0   ylr=-4     zlr=50
uax=1 vdn=-1 nax=260  nch=' 12 467'  end
 nch=' 12 467'  end
end plot
end data
end
```

6-1.2 KENO V.a Input File Listing: Water filling outer cylinder.

```
Mk BW17 4.6  wt% assembly in water 0.975 TD
44g lat
'23456789012345678901234567890123456789012345678901234567890123456789012
'fresh fuel
  uo2          1  den=10.686  1.0  293  92235 4.6  92238 95.4  end
'clad
  zr           2              1.0  293                      end
'moderator
  h2o          3  den=0.0001  1.0  293                      end
'moderator
  h2o          4  den=0.0001  1.0  293                      end
'moderator
  h2o          5  den=1.0     1.0  293                      end
' carbon steel
  carbonsteel  6              1.0  293                      end
'insulation 50% Al2O3 50% SiO2 - 8 lbs/cuft
  al           7              0.0  0.00075696               end
  si           7              0.0  0.00064231               end
  o            7              0.0  0.0024201                end
'insulation 50% Al2O3 50% SiO2 - 6 lbs/cuft
  al           8              0.0  0.00056772               end
  si           8              0.0  0.00048173               end
  o            8              0.0  0.0018150                end
end comp
'
'pitch data based on fuel pins
'        pitch  pel OD  fuelid modid cladOD cladid#  gapOD  gapid#
```

```
squarepitch 1.25984 0.820928    1     3   0.94488  2     0.84074 0 end
KENO
read parm  tme=3000  gen=1003 npg=1000 plt=yes run=yes end parm
read geom
unit 31
  cylinder  1  1  0.410464   366.0  0.0
  cylinder  0  1  0.42037    366.0  0.0
  cylinder  2  1  0.47244    366.0  0.0
  cuboid    3  1  4p0.62992  366.0  0.0
unit 32
cylinder  3 1 0.57404      366.0  0.0
  cylinder  2 1 0.60960      366.0  0.0
  cuboid    3 1 4p0.62992    366.0  0.0
unit 33
  cylinder  3 1 0.57404      366.0  0.0
  cylinder  2 1 0.60960      366.0  0.0
  cuboid    3 1 4p0.62992    366.0  0.0
' assembly  in armour plate
unit 35
  array 34   0  0  0
  replicate 4 1 2*0.08636 0.30734 0.00000  2*0.0 1
  replicate 8 1 2*2.54    2.54    2.3918   2*0.0 1
  replicate 7 1 2*5.08    5.08    5.08     2*0.0 1
  replicate 6 1 4*2.54 2*0.00 1
unit 36
  cylinder 4 1 52.07 366.0 0.0
  hole 35 -10.70684 -10.70684  0.0
  cylinder 6 1 52.2978   366.0 0.0
global
unit 37
  cylinder 5 1 112.7  366.0 0.0
  hole 36 0.0 60.389  0.0
  hole 36 -52.298 -30.19415 0.0
  hole 36  52.298 -30.19415 0.0
  cuboid 5 1 4p146.0 366.0 0.0
end geom
read array
'fresh fuel assembly
  ara=34   nux=17   nuy=17   nuz=1
  fill   31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 32 31 31 32 31 31 32 31 31 31 31 31
         31 31 31 32 31 31 31 31 31 31 31 31 31 32 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 32 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 33 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 32 31 31 32 31 31 32 31 31 32 31 31 32 31 31
         31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
         31 31 31 32 31 31 31 31 31 31 31 31 31 32 31 31 31
```

```
        31 31 31 31 31 32 31 31 32 31 31 32 31 31 31 31 31
        31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31
        31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31 31

  end fill
end array
read bounds
  xyf=vacuum
  zfc=mirror
end bounds
read plot
ttl='x-y slice of  at z=50'
xul=-115.0     yul=115.0   zul=50
xlr=115.0   ylr=-115.0   zlr=50
uax=1 vdn=-1 nax=260  nch=' 12 467'  end
 nch=' 1234567'  end
end plot
end data
end
```

B. Pathfinder Fuel Elements

6.2.1 3 WE-1 Shipping Containers Each Containing 48 Pathfinder Fuel Assemblies

```
Pathfinder fuel 7.51w/0 Incoloy 48 assm hex lat round pkg  3 dry assm.
cat>input1<<!eof
=csas25   PARM=SIZE=150000
 we1027 Pathfinder 7.51w/o Incoloy Clad/Sheath
238groupndf5    latticecell
U-235  1  0  1.800-3    293  end
U-238  1  0  2.188-2    293  end
O      1  0  4.736-2    293  end
c      2  0  3.9810-4   293  end
al     2  0  1.0633-3   293  end
si     2  0  1.7025-3   293  end
ti     2  0  5.9894-4   293  end
cu     2  0  5.6434-4   293  end
cr     2  0  1.7472-2   293  end
mn     2  0  1.3055-3   293  end
fe     2  0  3.9770-2   293  end
ni     2  0  2.4437-2   293  end
H      3  0  6.686-2    293  end
O      3  0  3.343-2    293  end
end comp
triangpitch  0.7341  0.5258  1  3  0.6274  2  0.5359  0  end
Pathfinder 7.51w/o Incoloy 48 assm hex lat round pkg  3 dry assm.
Read PARA   TME=120   GEN=1003  NPG=1000
        FDN=YES   PLT=no
End PARA
Read GEOM
Unit 1
COM='Fuel Pin'
Cylinder   1   1   0.2629  182.88   0.0
Cylinder   0   1   0.2680  182.88   0.0
Cylinder   2   1   0.3137  182.88   0.0
Unit 2
COM='Center rod'
Cylinder   0   1   0.2680  182.88   0.0
Cylinder   2   1   0.3137  182.88   0.0
Unit 3
COM='Assembly'
Cylinder   0   1   1.2002    182.88   0.0
hole  1    0.0     0.7341  0
hole  1    0.6357  0.3670  0
hole  1    0.6357 -0.3670  0
hole  1    0.0    -0.7341  0
hole  1   -0.6357  0.3670  0
hole  1   -0.6357 -0.3670  0
hole  2    0.0     0.0     0
Unit 4
COM='In Incoloy Rod'
Cylinder   2   1   1.2700   182.88  0.0
hole   3   0.0   0.0  0.0
```

```
Unit 5
COM='48 Assemblies in water in close pack hex lattice, circular package'
Cylinder   0   1  52.07   182.8801  -0.0001
hole   4  -1.2713  -8.8076  0.0
hole   4   1.2713  -8.8076  0.0
hole   4  -5.0851  -6.6057  0.0
hole   4  -2.5425  -6.6057  0.0
hole   4   0.0000  -6.6057  0.0
hole   4   2.5425  -6.6057  0.0
hole   4   5.0851  -6.6057  0.0
hole   4  -6.3564  -4.4038  0.0
hole   4  -3.8138  -4.4038  0.0
hole   4  -1.2713  -4.4038  0.0
hole   4   1.2713  -4.4038  0.0
hole   4   3.8138  -4.4038  0.0
hole   4   6.3564  -4.4038  0.0
hole   4  -7.6276  -2.2019  0.0
hole   4  -5.0851  -2.2019  0.0
hole   4  -2.5425  -2.2019  0.0
hole   4   0.0000  -2.2019  0.0
hole   4   2.5425  -2.2019  0.0
hole   4   5.0851  -2.2019  0.0
hole   4   7.6276  -2.2019  0.0
hole   4  -8.8989   0.0000  0.0
hole   4  -6.3564   0.0000  0.0
hole   4  -3.8138   0.0000  0.0
hole   4  -1.2713   0.0000  0.0
hole   4   1.2713   0.0000  0.0
hole   4   3.8138   0.0000  0.0
hole   4   6.3564   0.0000  0.0
hole   4   8.8989   0.0000  0.0
hole   4  -7.6276   2.2019  0.0
hole   4  -5.0851   2.2019  0.0
hole   4  -2.5425   2.2019  0.0
hole   4   0.0000   2.2019  0.0
hole   4   2.5425   2.2019  0.0
hole   4   5.0851   2.2019  0.0
hole   4   7.6276   2.2019  0.0
hole   4  -6.3564   4.4038  0.0
hole   4  -3.8138   4.4038  0.0
hole   4  -1.2713   4.4038  0.0
hole   4   1.2713   4.4038  0.0
hole   4   3.8138   4.4038  0.0
hole   4   6.3564   4.4038  0.0
hole   4  -5.0851   6.6057  0.0
hole   4  -2.5425   6.6057  0.0
hole   4   0.0000   6.6057  0.0
hole   4   2.5425   6.6057  0.0
hole   4   5.0851   6.6057  0.0
hole   4  -1.2713   8.8076  0.0
hole   4   1.2713   8.8076  0.0
global
Unit 6
```

```
cylinder  3   1   142.6862  212.88  -30.0
hole  5   0.0  60.3383   0.0
hole  5   -52.297801    -30.194201   0.0
hole  5    52.297801    -30.194201   0.0
End GEOM
read Bounds
    -XB=vacuum
    +XB=vacuum
    YFC=vacuum
    ZFC=vacuum
End Bounds
End Data
end KENO
End
!eof
scale44a input1
```

6.2.2   48 Fully Flooded Pathfinder Fuel Assemblies in Close Pack

```
Pathfinder 7.51w/0 Incoloy 48 assm hex lattice round pkg no gap
cat>input1<<!eof
=csas25   PARM=SIZE=150000
 we1025 Pathfinder 7.51w/o Incoloy Clad/Sheath
238groupndf5    latticecell
U-235   1  0  1.800-3    293  end
U-238   1  0  2.188-2    293  end
O       1  0  4.736-2    293  end
c       2  0  3.9810-4   293  end
al      2  0  1.0633-3   293  end
si      2  0  1.7025-3   293  end
ti      2  0  5.9894-4   293  end
cu      2  0  5.6434-4   293  end
cr      2  0  1.7472-2   293  end
mn      2  0  1.3055-3   293  end
fe      2  0  3.9770-2   293  end
ni      2  0  2.4437-2   293  end
H       3  0  6.686-2    293  end
O       3  0  3.343-2    293  end
end comp
triangpitch  0.7341  0.5258  1  3  0.6274  2  0.5359  0  end
Pathfinder 7.51w/o Incoloy 48 assm hex lattice round package
Read PARA   TME=120   GEN=1003  NPG=1000
        FDN=YES   PLT=no
End PARA
Read GEOM
Unit 1
COM='Fuel Pin'
Cylinder  1   1   0.2629  182.88   0.0
Cylinder  3   1   0.2680  182.88   0.0
Cylinder  2   1   0.3137  182.88   0.0
Unit 2
```

```
COM='Center rod'
Cylinder  3  1  0.2680  182.88   0.0
Cylinder  2  1  0.3137  182.88   0.0
Unit 3
COM='Assembly'
Cylinder  3  1  1.2002   182.88  0.0
hole  1   0.0     0.7341  0
hole  1   0.6357  0.3670  0
hole  1   0.6357 -0.3670  0
hole  1   0.0    -0.7341  0
hole  1  -0.6357  0.3670  0
hole  1  -0.6357 -0.3670  0
hole  2   0.0     0.0     0
Unit 4
COM='In Incoloy Rod'
Cylinder  2  1  1.2700   182.88  0.0
hole  3  0.0  0.0  0.0
global
Unit 5
COM='48 Assemblies in water in close pack hex lattice, circular package'
Cylinder   3   1  40.1702  212.88  -30
hole   4  -1.2713  -8.8076  0.0
hole   4   1.2713  -8.8076  0.0
hole   4  -5.0851  -6.6057  0.0
hole   4  -2.5425  -6.6057  0.0
hole   4   0.0000  -6.6057  0.0
hole   4   2.5425  -6.6057  0.0
hole   4   5.0851  -6.6057  0.0
hole   4  -6.3564  -4.4038  0.0
hole   4  -3.8138  -4.4038  0.0
hole   4  -1.2713  -4.4038  0.0
hole   4   1.2713  -4.4038  0.0
hole   4   3.8138  -4.4038  0.0
hole   4   6.3564  -4.4038  0.0
hole   4  -7.6276  -2.2019  0.0
hole   4  -5.0851  -2.2019  0.0
hole   4  -2.5425  -2.2019  0.0
hole   4   0.0000  -2.2019  0.0
hole   4   2.5425  -2.2019  0.0
hole   4   5.0851  -2.2019  0.0
hole   4   7.6276  -2.2019  0.0
hole   4  -8.8989   0.0000  0.0
hole   4  -6.3564   0.0000  0.0
hole   4  -3.8138   0.0000  0.0
hole   4  -1.2713   0.0000  0.0
hole   4   1.2713   0.0000  0.0
hole   4   3.8138   0.0000  0.0
hole   4   6.3564   0.0000  0.0
hole   4   8.8989   0.0000  0.0
hole   4  -7.6276   2.2019  0.0
hole   4  -5.0851   2.2019  0.0
hole   4  -2.5425   2.2019  0.0
hole   4   0.0000   2.2019  0.0
```

```
hole   4   2.5425   2.2019  0.0
hole   4   5.0851   2.2019  0.0
hole   4   7.6276   2.2019  0.0
hole   4  -6.3564   4.4038  0.0
hole   4  -3.8138   4.4038  0.0
hole   4  -1.2713   4.4038  0.0
hole   4   1.2713   4.4038  0.0
hole   4   3.8138   4.4038  0.0
hole   4   6.3564   4.4038  0.0
hole   4  -5.0851   6.6057  0.0
hole   4  -2.5425   6.6057  0.0
hole   4   0.0000   6.6057  0.0
hole   4   2.5425   6.6057  0.0
hole   4   5.0851   6.6057  0.0
hole   4  -1.2713   8.8076  0.0
hole   4   1.2713   8.8076  0.0
End GEOM
read Bounds
   -XB=vacuum
   +XB=vacuum
   YFC=vacuum
   ZFC=vacuum
End Bounds
Read PLOT
ttl= 'Horizontal Cross of Fuel Assembly'
pic=mat
xul=0  yul=77.7944  zul=100.
xlr=81.4173  ylr=0  zlr=100.
uax=1.0  vdn=-1.0  nax=130  end  plhoriz
end PLOT
End Data
end KENO
End
!eof
scale44a input1
```

6.2.3 40 Fully Flooded Pathfinder Fuel Assemblies in Close Pack

```
Pathfinder 7.51w/0 Incoloy 40 assm hex lattice round pkg no gap
cat>input1<<!eof
=csas25  PARM=SIZE=150000
 we1025c Pathfinder 7.51w/o Incoloy Clad/Sheath
238groupndf5   latticecell
U-235  1  0  1.800-3   293  end
U-238  1  0  2.188-2   293  end
O      1  0  4.736-2   293  end
c      2  0  3.9810-4  293  end
al     2  0  1.0633-3  293  end
si     2  0  1.7025-3  293  end
ti     2  0  5.9894-4  293  end
cu     2  0  5.6434-4  293  end
```

```
cr     2  0  1.7472-2   293  end
mn      2  0  1.3055-3   293  end
fe     2  0  3.9770-2   293  end
ni     2  0  2.4437-2   293  end
H      3  0  6.686-2    293  end
O      3  0  3.343-2    293  end
end comp
triangpitch  0.7341  0.5258  1  3  0.6274  2  0.5359  0  end
Pathfinder 7.51w/o Incoloy 40 assm hex lattice round package
Read PARA   TME=120   GEN=1003   NPG=1000
        FDN=YES   PLT=no
End PARA
Read GEOM
Unit 1
COM='Fuel Pin'
Cylinder   1   1   0.2629  182.88   0.0
Cylinder   3   1   0.2680  182.88   0.0
Cylinder   2   1   0.3137  182.88   0.0
Unit 2
COM='Center rod'
Cylinder   3   1   0.2680  182.88   0.0
Cylinder   2   1   0.3137  182.88   0.0
Unit 3
COM='Assembly'
Cylinder   3   1   1.2002    182.88   0.0
hole  1    0.0      0.7341  0
hole  1    0.6357  0.3670  0
hole  1    0.6357 -0.3670  0
hole  1    0.0     -0.7341  0
hole  1   -0.6357  0.3670  0
hole  1   -0.6357 -0.3670  0
hole  2    0.0      0.0      0
Unit 4
COM='In Incoloy Rod'
Cylinder   2   1   1.2700   182.88  0.0
hole   3   0.0    0.0  0.0
global
Unit 5
COM='40 Assemblies in water in close pack hex lattice, circular package'
COM='remove assemblies 4,3  4,5  6,3  6,5 2,3 5,2 5,7 8,3'
Cylinder    3    1   40.1702   212.88  -30
hole    4   -1.2713    -8.8076  0.0
hole    4    1.2713    -8.8076  0.0
hole    4   -5.0851    -6.6057  0.0
hole    4   -2.5425    -6.6057  0.0
hole    4    2.5425    -6.6057  0.0
hole    4    5.0851    -6.6057  0.0
hole    4   -6.3564    -4.4038  0.0
hole    4   -3.8138    -4.4038  0.0
hole    4   -1.2713    -4.4038  0.0
hole    4    1.2713    -4.4038  0.0
hole    4    3.8138    -4.4038  0.0
hole    4    6.3564    -4.4038  0.0
```

```
hole   4  -7.6276  -2.2019  0.0
hole   4  -5.0851  -2.2019  0.0
hole   4   0.0000  -2.2019  0.0
hole   4   5.0851  -2.2019  0.0
hole   4   7.6276  -2.2019  0.0
hole   4  -8.8989   0.0000  0.0
hole   4  -3.8138   0.0000  0.0
hole   4  -1.2713   0.0000  0.0
hole   4   1.2713   0.0000  0.0
hole   4   3.8138   0.0000  0.0
hole   4   8.8989   0.0000  0.0
hole   4  -7.6276   2.2019  0.0
hole   4  -5.0851   2.2019  0.0
hole   4   0.0000   2.2019  0.0
hole   4   5.0851   2.2019  0.0
hole   4   7.6276   2.2019  0.0
hole   4  -6.3564   4.4038  0.0
hole   4  -3.8138   4.4038  0.0
hole   4  -1.2713   4.4038  0.0
hole   4   1.2713   4.4038  0.0
hole   4   3.8138   4.4038  0.0
hole   4   6.3564   4.4038  0.0
hole   4  -5.0851   6.6057  0.0
hole   4  -2.5425   6.6057  0.0
hole   4   2.5425   6.6057  0.0
hole   4   5.0851   6.6057  0.0
hole   4  -1.2713   8.8076  0.0
hole   4   1.2713   8.8076  0.0
End GEOM
read Bounds
    -XB=vacuum
    +XB=vacuum
    YFC=vacuum
    ZFC=vacuum
End Bounds
End Data
end KENO
End
!eof
scale44a input1
```

6.2.3   48 Fully Flooded Pathfinder Fuel Assemblies Spaced 0.5 in Apart

```
we1030  Pathfinder 7.51w/0  48 assm hex 0.5in gap
cat>input1<<!eof
=csas25  PARM=SIZE=150000
 we1030  Pathfinder 7.51w/o Incoloy Clad/Sheath
238groupndf5    latticecell
U-235  1  0  1.800-3   293  end
U-238  1  0  2.188-2   293  end
O      1  0  4.736-2   293  end
```

```
c    2 0 3.9810-4  293  end
al   2 0 1.0633-3  293  end
si   2 0 1.7025-3  293  end
ti   2 0 5.9894-4  293  end
cu   2 0 5.6434-4  293  end
cr   2 0 1.7472-2  293  end
mn   2 0 1.3055-3  293  end
fe   2 0 3.9770-2  293  end
ni   2 0 2.4437-2  293  end
H    3 0 6.686-2   293  end
O    3 0 3.343-2   293  end
end comp
triangpitch 0.7341 0.5258 1 3 0.6274 2 0.5359 0 end
Pathfinder 7.51w/o Incoloy 48 assm hex lattice round package 0.5in gap
Read PARA  TME=120  GEN=1003  NPG=1000
        FDN=YES  PLT=no
End PARA
Read GEOM
Unit 1
COM='Fuel Pin'
Cylinder  1  1  0.2629  182.88  0.0
Cylinder  3  1  0.2680  182.88  0.0
Cylinder  2  1  0.3137  182.88  0.0
Unit 2
COM='Center rod'
Cylinder  3  1  0.2680  182.88  0.0
Cylinder  2  1  0.3137  182.88  0.0
Unit 3
COM='Assembly'
Cylinder  3  1  1.2002   182.88  0.0
hole  1   0.0     0.7341  0
hole  1   0.6357  0.3670  0
hole  1   0.6357 -0.3670  0
hole  1   0.0    -0.7341  0
hole  1  -0.6357  0.3670  0
hole  1  -0.6357 -0.3670  0
hole  2   0.0     0.0     0
Unit 4
COM='In Incoloy Rod'
Cylinder  2  1  1.2700   182.88  0.0
hole  3  0.0  0.0  0.0
global
Unit 5
COM='48 Assemblies in water in hex lattice, 0.5in gap circular package'
Cylinder   3   1   45.24   212.88  -30
hole   4  -1.9050 -13.1982  0.0
hole   4   1.9050 -13.1982  0.0
hole   4  -7.6200 -9.8987 0.0
hole   4  -3.8100 -9.8987 0.0
hole   4   0.0000 -9.8987 0.0
hole   4   3.8100 -9.8987 0.0
hole   4   7.6200 -9.8987 0.0
hole   4  -9.5250 -6.5991 0.0
```

```
hole   4   -5.7150 -6.5991 0.0
hole   4   -1.9050 -6.5991 0.0
hole   4    1.9050 -6.5991 0.0
hole   4    5.7150 -6.5991 0.0
hole   4    9.5250 -6.5991 0.0
hole   4  -11.4300 -3.2996 0.0
hole   4   -7.6200 -3.2996 0.0
hole   4   -3.8100 -3.2996 0.0
hole   4    0.0000 -3.2996 0.0
hole   4    3.8100 -3.2996 0.0
hole   4    7.6200 -3.2996 0.0
hole   4   11.4300 -3.2996 0.0
hole   4  -13.3350  0.0000  0.0
hole   4   -9.5250  0.0000  0.0
hole   4   -5.7150  0.0000  0.0
hole   4   -1.9050  0.0000  0.0
hole   4    1.9050  0.0000  0.0
hole   4    5.7150  0.0000  0.0
hole   4    9.5250  0.0000  0.0
hole   4   13.3350  0.0000  0.0
hole   4  -11.4300  3.2996  0.0
hole   4   -7.6200  3.2996  0.0
hole   4   -3.8100  3.2996  0.0
hole   4    0.0000  3.2996  0.0
hole   4    3.8100  3.2996  0.0
hole   4    7.6200  3.2996  0.0
hole   4   11.4300  3.2996  0.0
hole   4   -9.5250  6.5991  0.0
hole   4   -5.7150  6.5991  0.0
hole   4   -1.9050  6.5991  0.0
hole   4    1.9050  6.5991  0.0
hole   4    5.7150  6.5991  0.0
hole   4    9.5250  6.5991  0.0
hole   4   -7.6200  9.8987  0.0
hole   4   -3.8100  9.8987  0.0
hole   4    0.0000  9.8987  0.0
hole   4    3.8100  9.8987  0.0
hole   4    7.6200  9.8987  0.0
hole   4   -1.9050  13.1982 0.0
hole   4    1.9050  13.1982 0.0
End GEOM Read Bounds
    -XB=vacuum
    +XB=vacuum
    YFC=vacuum
    ZFC=vacuum
End Bounds
End Data
end KENO
End
!eof
scale44a input1
```

APPENDIX 6-2: BENCHMARK DATA

A. B&W MkBW 17x17

KENO V.a Benchmark Data

The benchmark data for the 44 SCALE43 cross section set is discussed in this section.

6-2.1 44-Group Cross Section Results

The results for the 44-group cross section set for three sets of critical experiments are listed and discussed in this section. This section also includes the comparison with the Handbook data. Bias values are obtained for each set of data. However, a bounding bias is determined (Section 6-2.5) based upon the complete set of data as follows:

$$\Delta k = -0.0048 - 0.0008354\, x + 7.1414E\text{-}05\, x^2.$$

where x is the spacing between fuel assemblies in centimeters for a spacing between assemblies between 0 and 12 cm. Beyond 12 centimeters, a bias of 0.0048 applies.

6-2.2 B&W Critical Experiments Results

The KENO V.a geometrical modeling for the B&W critical configurations are rather detailed to ensure that minor model and/or material effects were not overlooked. The average KENO V.a results for these cases are listed in Table 6-1 as a function of array spacing for about 400,000 neutron histories. Similar results for one million neutron histories are listed in Table 6-2. These tables are based upon the individual results contained in Tables 6-2.3 and 6-2.4. These latter tables list the calculated critical $k_{eff,}$ the experimental results and the Δk difference between calculational and experimental results. This Δk effectively provides the bias for the CSAS system with the 44-group cross section set. Note that the uncertainty in the difference between measured and calculated is given as:

$$\text{uncertainty} = \sqrt{(1.763\sigma_c)^2 + \sigma_m^2}$$

A review of the Table 6-2.4 for 1 million histories indicates a maximum bias of 0.01135 ± 0.00196 for Core XV containing borated aluminum separation plates. For 400K histories, Table 6-2.3 indicates a maximum bias of 0.01086 ± 0.00245 for Core XVI with the same aluminum separation plates. A further review of both tables indicates a trend in the data of increasing bias with increasing separation between fuel arrays. This trend is better illustrated in Figures 6-2.1 and
6-2.2. These figures plot the data in Tables 6-2.3 and 6-2.4 as a function of array separation distance. It clearly indicates the trend for all cases, with and without interspersed separation plates. Also plotted are the average values of all points at a particular spacing, i.e., the dark dashed line. The data points for these curves are contained in Table 6-2.1 and 6-2.2. The dark line in each plot represents a polynomial fit to the average values. The polynomials are:

$\Delta k = -0.00259 - 0.00185\, x + 0.000177x^2 + 9.85E\text{-}06\, x^3$ for 400K histories

$\Delta k = -0.00193 - 0.00344\, x + 0.000774x^2 - 5.145E\text{-}05\, x^3$ for 1,000K histories

Note that in a later section, a polynomial will be developed to define the bias as a function of fuel array spacing. A review of the average values in Tables 6-2.1 and 6-2.2 show agreement within one sigma for all cases but imply a trend toward increasing bias with the number of histories. Two additional cases were executed to examine the effect of additional neutron histories. The first extended the number of histories to about 2300K histories and second to 10 million histories for COREIX. The results of these two cases are 0.99762 ± 00042 and 0.99771 ± 00021, respectively. A comparison of the four cases for COREIX gives the following results. They indicate that there is no bias associated with the number of histories above about 500K neutron histories:

Histories	k_{eff}	σ	Δk	σ
10,000,000	0.997710.00021	-		
2,317,158	0.997620.00043	0.00009	0.00047	
1,000,000	0.997260.00067	0.00045	0.00070	
480,000	0.998630.00095	-0.00092	0.00097	

As noted from the comparison, if it is assumed that the 10 million-history case provides the most accurate result, all others are within 1 sigma uncertainty of this 'true' value. Thus, use of about 0.5 to 1 million histories will generally be sufficient for accurate results.

Table 6-2.1 Average Bias for 400K Histories

Spacing, cm	average bias, Δk	1 σ	1.763 σ	poly value of bias
0.00	-0.00262	0.00160	0.00281462	-0.00259
1.64	-0.00497	0.00261	0.00460042	-0.00509
3.27	-0.00658	0.00234	0.00412945	-0.00639
4.91	-0.00611	0.00190	0.00335091	-0.00623
6.54	-0.00437	0.00190	0.00335208	-0.00434

Table 6-2.2 Average Bias for 1,000K Histories				
Spacing, cm	average bias, Δk	1 σ	1.763 σ	poly value of bias
0.00	-0.00194	0.00111	0.00195	-0.00193
1.64	-0.00568	0.00167	0.00294	-0.00571
3.27	-0.00677	0.00146	0.00258	-0.00671
4.91	-0.00623	0.00123	0.00217	-0.00626
6.54	-0.00574	0.00149	0.00262	-0.00573

Figure 6-2.1 KENO Va Results for B&W Criticals for 400,000 Histories

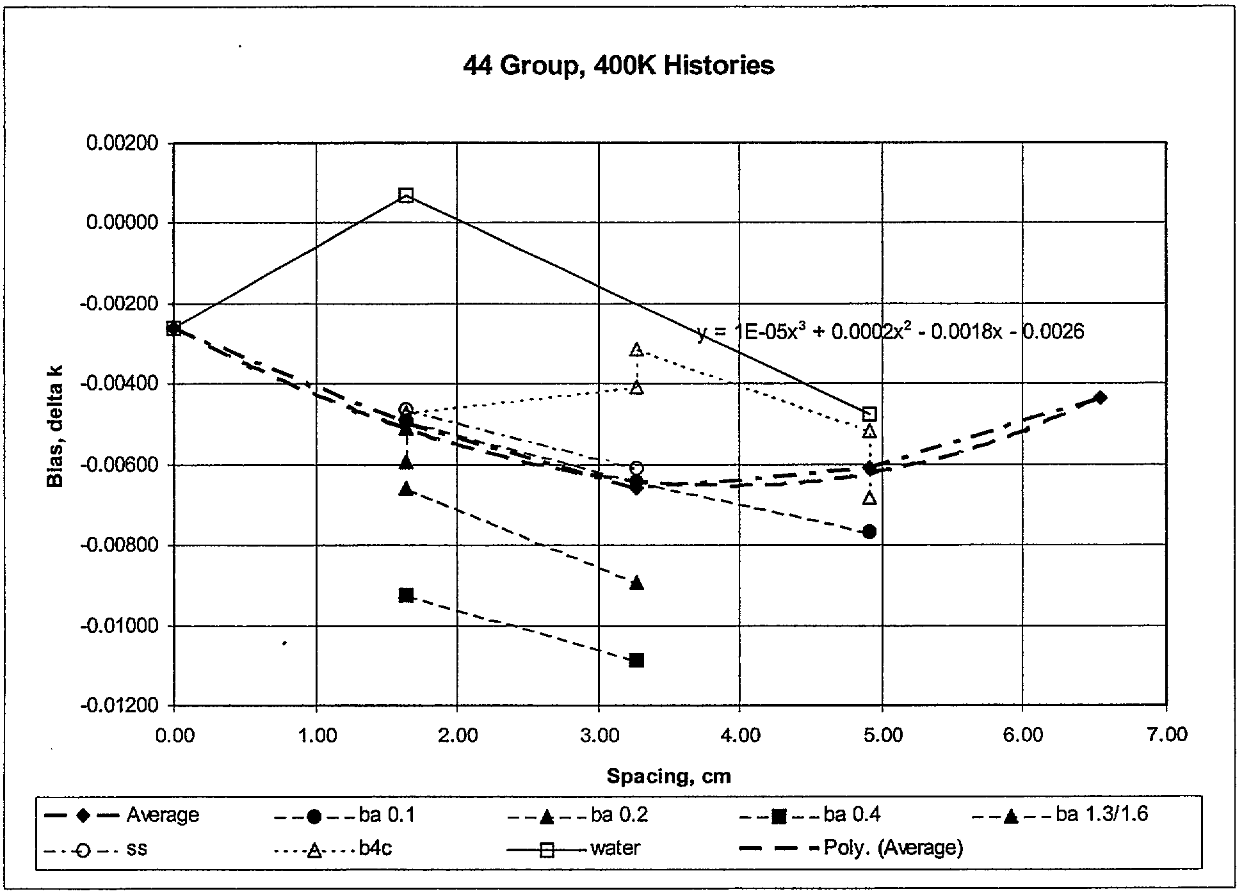


Figure 6-2.2 KENO Va Results for B&W Criticals 1,000,000 Histories

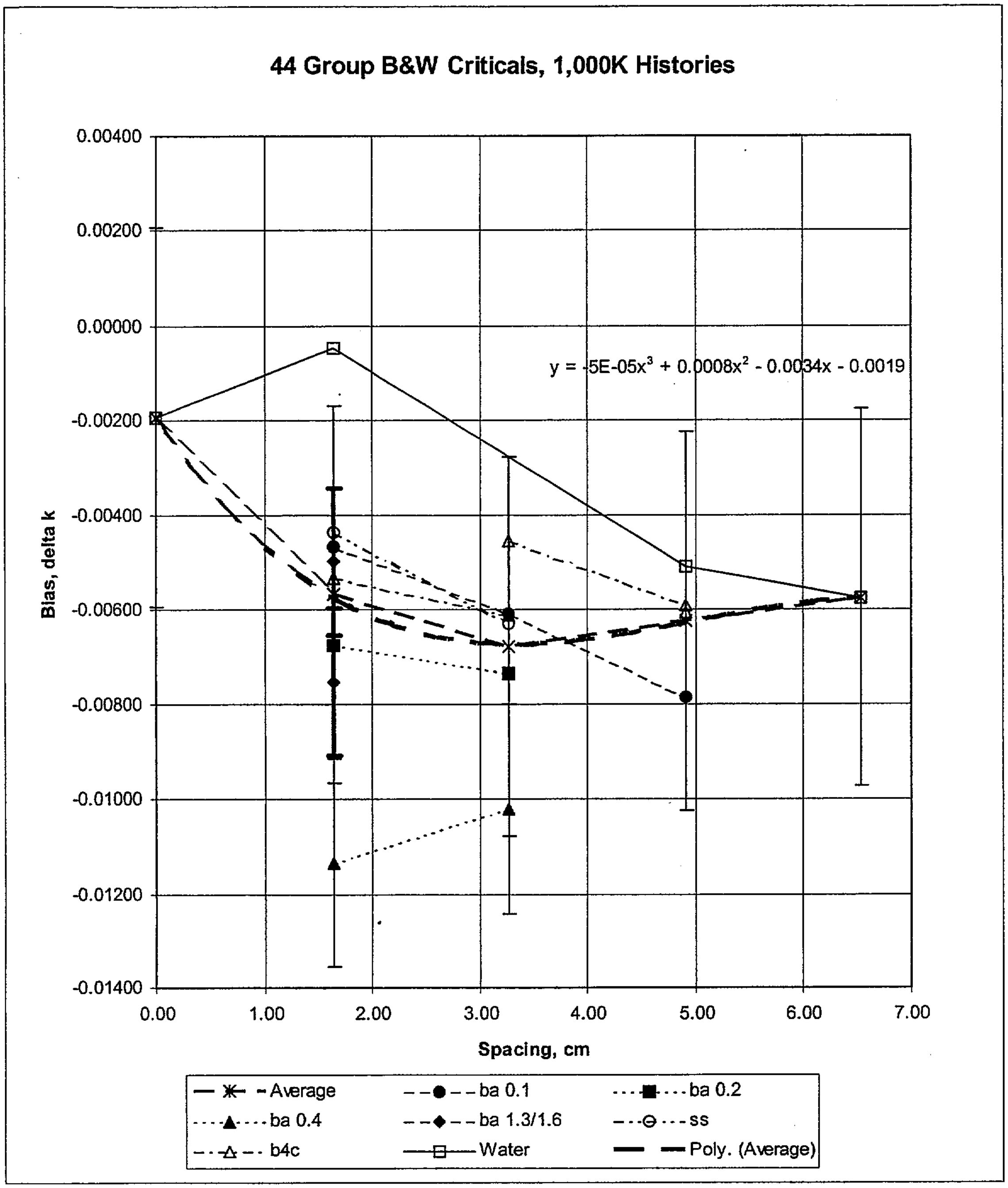


Table 6-2.3 44-group B&W Criticals Results (400K Histories)											
Case	Core	Spacing cm	fiche	Boron Ppm	Pins/Plates	Calculated		Experimental		Bias	
						k_{eff}	1σ	k_{eff}	1σ	Δk	1σ
1	i	--	b17260	0	--	0.99647	0.00101	1.00020	0.00050	**-0.00373**	0.00185
2	ii	0.00	b17611	1037	0	0.99748	0.00086	1.00010	0.00050	**-0.00262**	0.00160
3	iii	1.64	b17612	764	0	1.00070	0.00087	1.00000	0.00060	**0.00070**	0.00165
4	iv	1.64	b17263	0	84	0.99518	0.00100	0.99990	0.00060	**-0.00472**	0.00186
5	v	3.27	b17264	0	64	0.99592	0.00103	1.00000	0.00070	**-0.00408**	0.00195
6	vi	3.27	b17265	0	64	1.00658	0.00099	1.00970	0.00120	**-0.00312**	0.00212
7	vii	4.91	b17266	0	34	0.99464	0.00093	0.99980	0.00090	**-0.00516**	0.00187
8	viii	4.91	b17267	0	34	1.00149	0.00098	1.00830	0.00120	**-0.00681**	0.00210
9	ix	6.54	b17613	0	0	0.99863	0.00095	1.00300	0.00090	**-0.00437**	0.00190
10	x	4.91	b17614	143	--	0.99533	0.00092	1.00010	0.00090	**-0.00477**	0.00185
11	xi	1.64	b17615	514	SS	0.99536	0.00088	1.00000	0.00060	**-0.00464**	0.00166
12	xii	3.27	b17616	217	SS	0.99392	0.00092	1.00000	0.00070	**-0.00608**	0.00177
13	xiii	1.64	b17272	15	1.614%B/AL	0.99491	0.00098	1.00000	0.00100	**-0.00509**	0.00200
14	xiv	1.64	b17273	92	1.257%B/AL	0.99416	0.00097	1.00010	0.00100	**-0.00594**	0.00198
15	xv	1.64	b17274	395	0.401%B/AL	0.99057	0.00090	0.99980	0.00160	**-0.00923**	0.00225
16	xvi	3.27	b17275	121	0.401%B/AL	0.98924	0.00094	1.00010	0.00190	**-0.01086**	0.00245
17	xvii	1.64	b17617	487	0.242%B/AL	0.99341	0.00088	1.00000	0.00100	**-0.00659**	0.00198
18	xviii	3.27	b17618	197	0.242%B/AL	0.99129	0.00097	1.00020	0.00110	**-0.00891**	0.00192
19	xix	1.64	b17622	634	0.100%B/AL	0.99530	0.00089	1.00020	0.00100	**-0.00490**	0.00100
20	xx	3.27	b17620	320	0.100%B/AL	0.99387	0.00088	1.00030	0.00110	**-0.00643**	0.00110
21	xxi	4.91	b17621	72	0.100%B/AL	0.99202	0.00097	0.99970	0.00150	**-0.00768**	0.00150
			Average =			**0.99555**		**1.00102**		**-0.00548**	
			Std Dev=			**0.00382**		**0.00268**		**0.00244**	

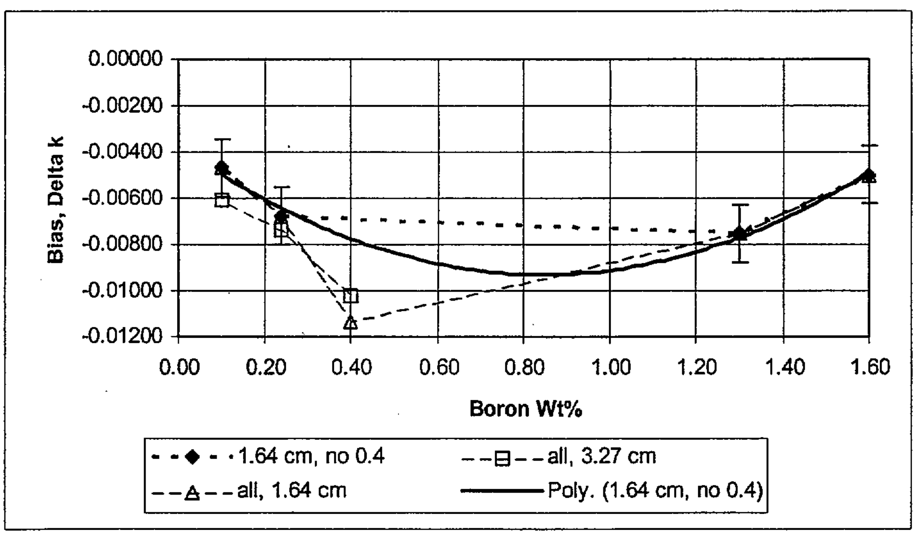
Table 6-2.4 44-group B&W Criticals Results (1000K Histories)											
Case	Core	Spacing cm	fiche	Boron ppm	Pins/Plates	Calculated		Experimental		Bias	
						k_{eff}	1σ	k_{eff}	1σ	Δk	1σ
1	i	--	b29229	0	--	0.99655	0.00071	1.00020	0.00050	**-0.00365**	0.00135
2	ii	0.00	b17261	1037	0	0.99816	0.00056	1.00010	0.00050	**-0.00194**	0.00111
3	iii	1.64	b17262	764	0	0.99955	0.00056	1.00000	0.00060	**-0.00045**	0.00116
4	iv	1.64	b29230	0	84	0.99458	0.00067	0.99990	0.00060	**-0.00532**	0.00132
5	v	3.27	b29231	0	64	0.99389	0.00065	1.00000	0.00070	**-0.00611**	0.00134
6	vi	3.27	b29232	0	64	1.00515	0.00070	1.00970	0.00120	**-0.00455**	0.00172
7	vii	4.91	b29233	0	34	0.99390	0.00069	0.99980	0.00090	**-0.00590**	0.00151
8	viii	4.91	b29318	0	34	1.00226	0.00065	1.00830	0.00120	**-0.00604**	0.00166
9	ix	6.54	b17268	0	0	0.99726	0.00067	1.00300	0.00090	**-0.00574**	0.00149
10	x	4.91	b17269	143	--	0.99501	0.00064	1.00010	0.00090	**-0.00509**	0.00144
11	xi	1.64	b17270	514	SS	0.99563	0.00060	1.00000	0.00060	**-0.00437**	0.00122
12	xii	3.27	b17271	217	SS	0.99371	0.00064	1.00000	0.00070	**-0.00629**	0.00133
13	xiii	1.64	b29234	15	1.614%B/AL	0.99502	0.00066	1.00000	0.00100	**-0.00498**	0.00153
14	xiv	1.64	b29235	92	1.257%B/AL	0.99258	0.00067	1.00010	0.00100	**-0.00752**	0.00155
15	xv	1.64	b29236	395	0.401%B/AL	0.98845	0.00064	0.99980	0.00160	**-0.01135**	0.00196
16	xvi	3.27	b29237	121	0.401%B/AL	0.98988	0.00065	1.00010	0.00190	**-0.01022**	0.00205
17	xvii	1.64	b17276	487	0.242%B/AL	0.99324	0.00043	1.00000	0.00100	**-0.00676**	0.00127
18	xviii	3.27	b17277	197	0.242%B/AL	0.99285	0.00044	1.00020	0.00110	**-0.00735**	0.00134
19	xix	1.64	b17278	634	0.100%B/AL	0.99554	0.00043	1.00020	0.00100	**-0.00466**	0.00128
20	xx	3.27	b17279	320	0.100%B/AL	0.99422	0.00045	1.00030	0.00110	**-0.00608**	0.00137
21	xxi	4.91	b17280	72	0.100%B/AL	0.99183	0.00046	0.99970	0.00150	**-0.00787**	0.00150
				Average =		**0.99520**		**1.00102**		**-0.00582**	
				Std Dev=		**0.00372**		**0.00268**		**0.00235**	

The B&W criticals enable evaluation of the trend of bias with fuel array spacing. An indication of any trends related to the material between the fuel arrays is also possible. The borated aluminum plates comprise four different boron weight percents with critical configurations at two primary pin pitches, 1 and 2. Thus, a comparison of the bias associated with the boron content between the fuel arrays is possible. Table 6-2.5 provided the borated aluminum data that is plotted in Figure 6-2.3. It is noted that the 0.4 wt% boron content has a large uncertainty and the KENO results seem to have a large uncertainty also. Excluding this data indicates a slight trend of increasing bias with boron concentration to about 0.8 wt% and then a decrease of bias (see the bold solid line in Figure 6-2.3). However, there are a small number of points and all the biases are within one sigma of each other. Thus, until additional data is available, no trend can be associated with the boron content of absorber plates.

Table 6-2.5 Bias of Borated Aluminum Plates

Pin Pitch	Core	Boron wt%	k_{eff}	1σ
2	Xiii	0.40	-0.01022	0.00205
2	Xvi	0.24	-0.00735	0.00134
2	Xviii	0.10	-0.00608	0.00137
1	Xx	0.10	-0.00466	0.00128
1	Xix	0.24	-0.00676	0.00127
1	Xvii	0.40	-0.01135	0.00196
1	Xiv	1.30	-0.00752	0.00155
1	Xiii	1.60	-0.00498	0.00153

Figure 6-2.3 Bias of Borated Aluminum Plates

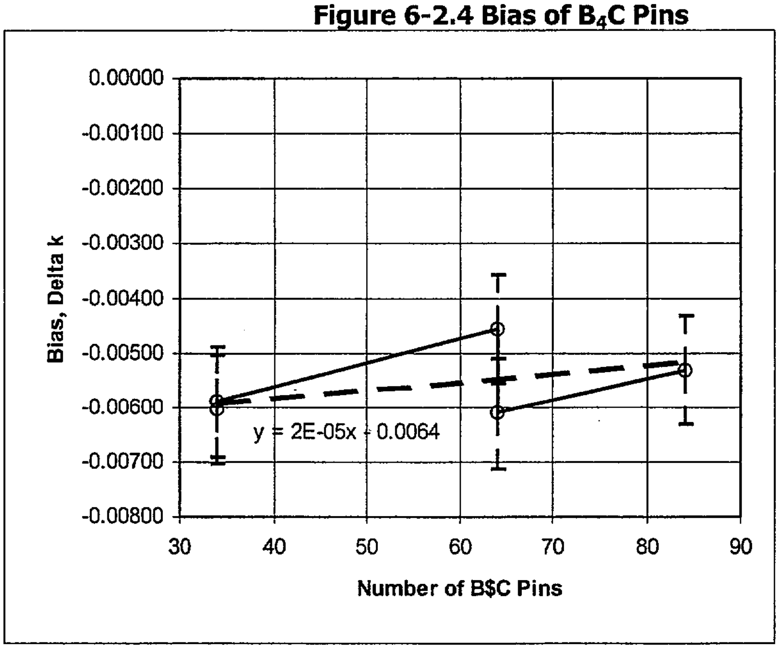


In addition to the borated aluminum plates, several cases with B_4C rods interspersed between the fuel arrays were examined. In these cases the number of rods also varies with the spacing between the fuel arrays. Table 6-2.6 lists the B_4C rod cases that are plotted in Figure 6-2.4 with a linear fit to the data. The biases are within one sigma of each other except for the zero rod case. This occurs even with increased spacing which has previously been shown to increase the bias. Thus, there may be some bias associated with the rods since the bias remains essentially constant as the number of rods is decreased. However, due to lack of sufficient data and the overlap of the results within one sigma, no bias can be associated with the rod cases.

Table 6-2.6 Bias of B_4C Pins

Core	Pin Pitch	No. B_4C Rods	k_{eff}	1σ
iv	1	84	-0.00532	0.00132
v	2	64	-0.00611	0.00134
vi	2	64	-0.00455	0.00172
vii	3	34	-0.00590	0.00151
viii	3	34	-0.00604	0.00166
iii	1	0	-0.00045	0.00116

Figure 6-2.4 Bias of B_4C Pins



In addition to the cases with boron absorber plates/rods, there are two cases with stainless steel separation plates. They are at different array separations so that no conclusive statement of bias can be associated with these plates. However, the results suggest that there will be no bias associated with the stainless steel plates, if the bias associated with the separation distance is considered.

6-2.2 Additional UO_2 and Mixed Oxide Critical Experiments Results

The results for the additional UO_2 critical experiments are listed in Table 6-2.7 and for the mixed oxide experiments in Table 6-28. The mixed oxide cases show essentially no trend for type of absorber plate between fuel arrays, for the pitch of rods in the arrays, or for enrichment differences. It is noted that for both experimental sets, no estimate of the error in the experimental critical k, nor the k itself, was given. Thus, a value of 1.0 is assumed for k with no uncertainty. The mixed oxide cases show similar results with essentially no trends noted. The results for both sets of experiments show an average bias of about ± 0.0023.

Table 6-2.7 44-group Results for UO_2 Criticals										
Case	Case	Fiche	Case Description ID	Wt% U-235	B ppm	Calculated		Bias		Average Bias/wt%
						k_{eff}	1 σ	Δ k_{eff}	1 σ	
1	p2438x05	b17626	No Absorber Plates	2.35	0	0.9968	0.0009	-0.0032	0.0009	
2	p2438x17	b17294	Boral Absorber Plates	2.35	0	0.9961	0.0009	-0.0039	0.0009	
3	p2438x28	b17627	Stainless Steel Absorber Plates	2.35	0	0.9958	0.0010	-0.0042	0.0010	-0.0038
4	p2615x14	b17628	Stainless Steel Absorber Plates	4.31	0	0.9979	0.0011	-0.0021	0.0011	
5	p2615x23	b17629	Cadmium Absorber Plates	4.31	0	0.9995	0.0011	-0.0005	0.0011	
6	p2615x31	b17630	Boral Absorber Plates	4.31	0	0.9987	0.0011	-0.0013	0.0011	
7	p3314a	b17631	0.226 cm Boraflex Absorber Plates	4.31	0	1.0027	0.0011	0.0027	0.0011	
8	p3314b	b17300	0.452 cm Boraflex Absorber Plates	4.31	0	1.0016	0.0011	0.0016	0.0011	0.0001
9	e196u6n	b17637	0.615" Pitch	2.35	0	0.9951	0.0010	-0.0049	0.0010	
10	Epru615b	b17624	0.615" Pitch	2.35	464	0.9947	0.0010	-0.0053	0.0010	
11	Epru75	b17290	0.750" Pitch	2.35	0	0.9943	0.0010	-0.0057	0.0010	
12	Epru75b	b17291	0.750" Pitch	2.35	568	0.9986	0.0008	-0.0014	0.0008	
13	e196u87c	b17638	0.870" Pitch	2.35	0	0.9976	0.0009	-0.0024	0.0009	
14	Epru87b	b17625	0.870" Pitch	2.35	286	0.9999	0.0008	-0.0001	0.0008	-0.0033
15	Saxu56	b17636	2 Lattice PItches,SS Clad, 0.56" Pitch	5.74	0	0.9950	0.0011	-0.0050	0.0011	
16	Saxu792	b17308	2 Lattice PItches,SS Clad, 0.792" Pitch	5.74	0	0.9988	0.0011	-0.0012	0.0011	-0.0031
Average =						**0.9977**		**-0.0023**		
Standard Deviation =						**0.0025**		**0.0025**		

Table 6-2.8 44-group Results for PuO_2 Criticals									
Case	Case ID	Fiche	Case Description	Wt% Pu	Boron ppm	Calculated		Bias	
						k_{eff}	1 σ	Δ k_{eff}	1 σ
1	Epri70un	b17640	UO2/PuO2 Square Lattice, 0.700" Pitch	2	0	0.9969	0.0011	-0.0031	0.0011
2	Epri70b	b19153	UO2/PuO2 Square Lattice, 0.700" Pitch	2	681	1.0008	0.0010	0.0008	0.0010
3	Epri87un	b17286	UO2/PuO2 Square Lattice, 0.870" Pitch	2	0	1.0018	0.0011	0.0018	0.0011
4	Epri87b	b17641	UO2/PuO2 Square Lattice, 0.870" Pitch	2	1090	1.0083	0.0009	0.0083	0.0009
5	Epri99un	b17623	UO2/PuO2 Square Lattice, 0.990" Pitch	2	0	1.0051	0.0011	0.0051	0.0009
6	Epri99b	b17287	UO2/PuO2 Square Lattice, 0.990" Pitch	2	767	1.0072	0.0009	0.0072	0.0009
7	Saxton52	b17305	UO2/PuO2 Square Lattice, 0.52" Pitch	6.6	0	1.0001	0.0011	0.0001	0.0011
8	Saxton56	b19154	UO2/PuO2 Square Lattice, 0.56" Pitch	6.6	0	0.9993	0.0011	-0.0007	0.0011
9	Saxtn56b	b17633	UO2/PuO2 Square Lattice, 0.56" Pitch	6.6	337	1.0006	0.0010	0.0006	0.0010
10	Saxtn792	b19151	UO2/PuO2 Square Lattice, 0.792" Pitch	6.6	0	1.0031	0.0011	0.0031	0.0011
11	Saxtn735	b17634	UO2/PuO2 Square Lattice, 0.735" Pitch	6.6	0	1.0010	0.0012	0.0010	0.0012
12	Saxtn104	b17632	UO2/PuO2 Square Lattice, 1.04" Pitch	6.6	0	1.0036	0.0011	0.0036	0.0011
Average =						**1.0023**		**0.0023**	
Standard Deviation =						**0.0033**		**0.0033**	

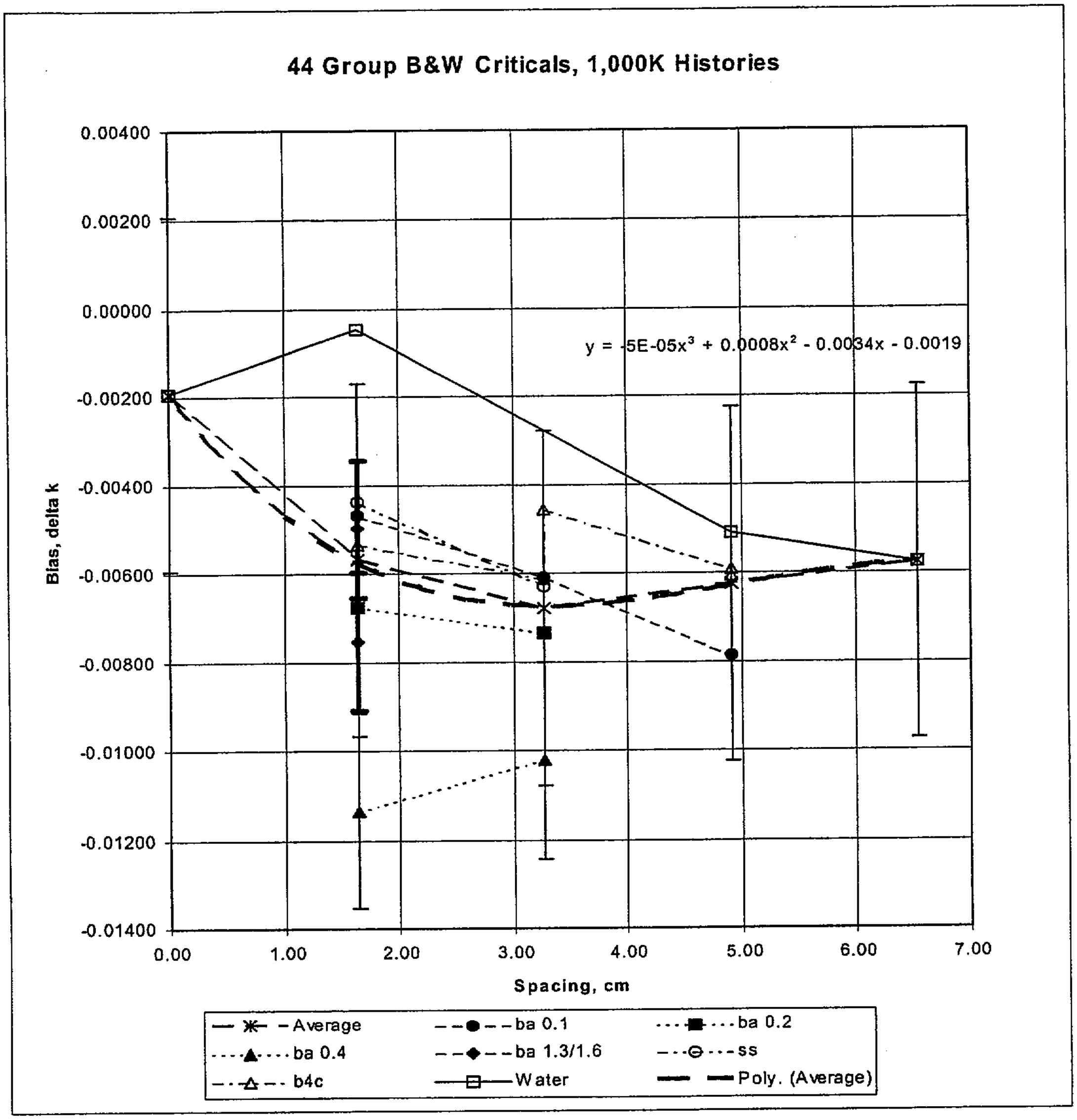
6-2.3 International Handbook Critical Experiments

The B&W critical data provides a good set for benchmarking methodologies for storage configurations. However, the data stops at a critical configuration with a spacing that has a large bias. Additional data is not available from these experiments to illustrate the expected reduction in the bias as the spacing continues to increase. The data obtained from the International Handbook supplies several spacing points beyond those from B&W for water between the fuel arrays. In addition, it provides comparisons of results from other analysis methodologies. This data enables verification of the expected trend for larger spacings. Additionally, it provides independent verification of the calculational techniques. Table 6-2.9 provides the results from the Handbook and those calculated with KENO V.a using the 44-group cross section set. The Handbook critical experiments have a critical k_{eff} of 0.9998. Results are provided in the Handbook for a) KENO V.a with the 27 groups SCALE set, and b) MCNP with the MCNP continuous energy cross section set. Figure 6-2.5 illustrates the trends in the biases contained in Table 6-2.10. The figure shows substantial agreement for the trend with the edge-to-edge spacing among the different methods. However, the absolute biases differ. The MCNP results, with a continuous energy set, give the smallest bias, as would be expected from the cross section representation. The 44-group set gives intermediate results both for the Handbook benchmarks and for the B&W experiments. The 27-group set has the largest bias that illustrates the rationale for the migration to the 44-group set for criticality analyses. The figure shows a minimum in the bias curve for a spacing between six and eight centimeters. As expected the bias decreases as the spacing increases beyond this range and seems to be approaching the bias for a spacing of zero centimeters. Figure 6-2.5 also shows least square fits to the data and the defining polynomial equation for the fit. The fit curves clearly indicate the trend of the data with a valley around eight centimeters and a return to the zero spacing bias as the spacing increases beyond the valley.

Table 6-2.9 Handbook Critical Experiment Results							
PNL Exp. No.	Array Spacing, cm	Hdbk k_{eff} Values			FCF KENO V.a 44 Gp k_{eff} Values		
		Exp k_{eff}	KENO	MCNP	fiche	k_{eff}	1σ
1	0	0.9998	0.9914	0.9987	b19141	0.99594	0.00055
2	11.92	0.9998	0.9904	0.9977	b19142	0.99563	0.00052
3	8.41	0.9998	0.9888	0.9956	b19143	0.99382	0.00052
4	10.05	0.9998	0.9962	0.9992	b19144	0.99555	0.00052
5	6.39	0.9998	0.9890	0.9970	b19145	0.99262	0.00053
6	8.01	0.9998	0.9931	0.9955	b19146	0.99582	0.00052
7	4.46	0.9998	0.9919	0.9968	b19147	0.99500	0.0005
8	7.57	0.9998	0.9906	0.9921	b19148	0.99298	0.00053

Table 6-2.10 Bias Associated With Handbook Critical Experiment Results				
Case	Spacing, cm	Bias, Δ k ($k_{critical}$ = 0.9998)		
		27 Group	MCNP	FCI 44 Group
PNL 1	0	-0.0084	-0.0011	-0.0039
PNL 2	4.46	-0.0079	-0.0030	-0.0048
PNL 3	6.39	-0.0108	-0.0028	-0.0072
PNL 4	7.57	-0.0092	-0.0077	-0.0068
PNL 5	8.01	-0.0067	-0.0043	-0.0040
PNL 6	8.41	-0.0110	-0.0042	-0.0060
PNL 7	10.05	-0.0036	-0.0006	-0.0042
PNL 8	11.92	-0.0094	-0.0021	-0.0042
B&W ii	0	-	-	-0.0019
B&W iii	1.636	-	-	-0.0004
B&W x	4.907	-	-	-0.0051
B&W ix	6.54	-	-	-0.0087

Figure 6-2.5 Handbook and 44-group Bias Results



6-2.4 SCALE 4.3 Comparison

The SCALE 4.2 code system is used for the criticality analyses. However, the 44-group cross section set was obtained as part of the SCALE 4.3 code package. To ensure that these cross sections are compatible with the SCALE 4.2 system, a comparison is made with the results from the SCALE 4.3 system for a set of benchmark cases. It is noted that the SCALE 4.3 system has not been implemented on the workstation for production usage, i.e., undergone a certification process. The source files have only been implemented from the transmittal CD, compiled into executables, and executed for these cases. However, based upon execution without error messages and results from the cases, it is judged that the system is operating correctly for this task.

Table 6-2.11 provides the results for SCALE 4.3 and SCALE 4.2. Note that the SCALE 4.2 results were taken from Table 6-2.4. As noted the difference between results from the two systems is within 1.763 sigma, the 95% confidence level, even though the cases were not run to the same number of neutron histories. Base upon this agreement, it is demonstrated that the SCALE 4.2 system can adequately use the SCALE 4.3 cross section sets. It is further judged that the bias associated with the SCALE 4.2 system with these cross sections adequately encompasses any minor differences in the processing of cross sections by the two codes.

6-2.5 Bias Determination

As illustrated in the previous subsections, the only significant trend in the bias associated with the 44-group cross section set is related to the spacing between the fuel arrays. This conclusion is based upon both the B&W critical experiments and those in the International Handbook. The bias to be applied to KENO V.a results using the 44-group cross section set includes this trend for water gap cases. The bias will be based upon the bias values for the B&W criticals listed in Table 6-2.2 and the 44-group results for Handbook cases in Table 6-2.10. Note that for the zero spacing, an average of the values from the B&W and Handbook critical results was obtained. The applicable case results as a function of distance are listed in Table 6-2.12 and plotted in Figure 6-2.6. A polynomial least squares fit was made through the data points and is shown by the upper dark line. The equation of this line is

$$\Delta k = -0.001307 - 0.0011699\,x + 7.9193E\text{-}05\,x^2.$$

Column 4 in Table 6-2.12 lists the calculated points from this equation. The error bars shown on the plot represent the 95% confidence factor for the number of histories for the largest uncertainty. It is noted that the uncertainty quoted is 1.763 times the sigma for cases without an experimental uncertainty and the square root of 1.763 times the calculated sigma squared plus the measurement uncertainty squared. As is noted the error bars overlap the fit line described above. To ensure that the bias plus uncertainty bounds all the calculated bias point plus uncertainty, the zero intercept of the above polynomial was changed from -0.00131 to -0.00295. The adjusted equation is

$$\Delta k = -0.00295 - 0.0011699\,x + 7.9193E\text{-}05\,x^2.$$

Table 6-2.11 Comparison of Results for SCALE 4.3 and SCALE 4.2								
		Scale 4.3			Scale 4.2		SCALE 4.3 - 4.2	
Spacing	Core	Fiche	k_{eff}	1σ	k_{eff}	1σ	Δk	1σ
0	i	b17338	0.99943	0.00104	0.99655	0.00071	**0.00288**	0.00197
0	ii	b17339	0.99830	0.00082	0.99816	0.00056	**0.00014**	0.00155
0.644	iii	b17340	0.99874	0.00085	0.99955	0.00056	**-0.00081**	0.00160
0.644	iv	b17341	0.99508	0.00097	0.99458	0.00067	**0.00050**	0.00184
1.288	v	b17343	0.99570	0.00101	0.99389	0.00065	**0.00181**	0.00190
1.288	vi	b17344	1.00253	0.00094	1.00515	0.00070	**-0.00262**	0.00180
1.932	vii	b17345	0.99570	0.00093	0.99390	0.00069	**0.00180**	0.00178
1.932	viii	b17346	1.00348	0.00098	1.00226	0.00065	**0.00122**	0.00185
2.576	ix	b17342	0.99812	0.00064	0.99726	0.00067	**0.00086**	0.00131
1.932	x	b17347	0.99604	0.00064	0.99501	0.00064	**0.00103**	0.00130
0.644	xi	b17348	0.99791	0.00088	0.99563	0.00060	**0.00228**	0.00166
1.288	xii	b17349	0.99416	0.00089	0.99371	0.00064	**0.00045**	0.00169
0.644	xiii	b17350	0.99721	0.00095	0.99502	0.00066	**0.00219**	0.00180
0.644	xiv	b17351	0.99212	0.00095	0.99258	0.00067	**-0.00046**	0.00180
0.644	xvb	b17353	0.99012	0.00089	0.98845	0.00064	**0.00167**	0.00169
1.288	xvi	b17354	0.99093	0.00091	0.98988	0.00065	**0.00105**	0.00129
0.644	xvii	b17355	0.99297	0.00063	0.99324	0.00043	**-0.00027**	0.00121
1.288	xviii	b17356	0.99179	0.00064	0.99285	0.00044	**-0.00106**	0.00116
0.644	xix	b17352	0.99550	0.00061	0.99554	0.00043	**-0.00004**	0.00043
1.288	xx	b17357	0.99406	0.00063	0.99422	0.00045	**-0.00016**	0.00045
1.932	xxi	b17358	0.99109	0.00065	0.99183	0.00046	**-0.00074**	0.00046
Average =			**0.99576**		**0.99520**		**0.00056**	
Std Dev=			**0.00356**		**0.00372**		**0.00130**	

Column 5 lists the calculated bias at the spacing points for the criticals. It is noted that the polynomial points bound all the KENO V.a calculated biases. If an uncertainty of 0.00149 is assumed, i.e. the maximum uncertainty for any calculated spacing, the bias plus uncertainty will bound the calculated values plus uncertainty.

Based upon this polynomial, the minimum of the curve, representing the largest bias occurs at a spacing of 7.386 cm. The bias at this spacing is -0.00727 Δk.

Table 6-2.12 Critical Results for Various Array Spacings - Water Gap				
Array Spacing, cm	B&W and Handbook Criticals Average Bias, Δk	$\square = (\square\square_i^2)^{1/2}$	2nd Order Polynomial Fit Bias Value	Adjusted 2nd Order Polynomial Fit Bias Value
0.000	-0.00290	0.00147	-0.00131	-0.00295
1.636	-0.00045	0.00116	-0.00301	-0.00465
4.460	-0.00480	0.00087	-0.00495	-0.00659
4.907	-0.00509	0.00132	-0.00514	-0.00678
6.390	-0.00718	0.00092	-0.00555	-0.00719
6.540	-0.00574	0.00149	-0.00557	-0.00721
7.570	-0.00682	0.00092	-0.00563	-0.00727
8.010	-0.00398	0.00090	-0.00560	-0.00724
8.410	-0.00598	0.00090	-0.00554	-0.00719
10.050	-0.00425	0.00090	-0.00507	-0.00671
11.920	-0.00417	0.00090	-0.00400	-0.00564

The above equation represented only the cases without absorber plates. If all cases are included in the average, the following equation is obtained. The basis of the equation and values obtained from the equation are listed in Table 6-2.13 and plotted in Figure 6-2.7.

$$\Delta k = -0.0037099 - 0.0008354\, x + 7.1414E\text{-}05\, x^2.$$

To encompass all data points, the intercept is adjusted to -0.0048 as shown in the figure and the equation becomes:

$$\Delta k = -0.0048 - 0.0008354\, x + 7.1414E\text{-}05\, x^2.$$

The maximum uncertainty is 0.004 for the 1.64 cm spacing that is based upon 8 data points. This uncertainty is shown in the figure. This minimum for the above equation occurs at 5.85 cm with a bias of -0.00724. It is noted that this equation covers most points in the B&W criticals but not for the 0.401 wt% BSS with uncertainties. Based upon this equation the total bias with interspersed absorber plates should be calculated with the above equation with an uncertainty of 0.004. This will give a maximum bias of -0.00724 - 0.004 = -0.01124.

Table 6-2.13 Critical Results for Various Array Spacings Total Bias				
Array Spacing, cm	B&W & Handbook Average Bias, Δk	$\square = (\square \square_i^2)^{1/2}$	2nd Order Polynomial Fit Bias Value	Adjusted 2nd Order Polynomial Fit Bias Value
0.000	-0.00290	0.00147	-0.00371	-0.00480
1.636	-0.00568	0.00404	-0.00489	-0.00598
4.460	-0.00677	0.00087	-0.00602	-0.00711
4.907	-0.00480	0.00317	-0.00609	-0.00718
6.390	-0.00623	0.00092	-0.00613	-0.00722
6.540	-0.00718	0.00149	-0.00612	-0.00721
7.570	-0.00574	0.00092	-0.00594	-0.00703
8.010	-0.00682	0.00090	-0.00582	-0.00691
8.410	-0.00398	0.00090	-0.00568	-0.00677
10.050	-0.00598	0.00090	-0.00489	-0.00598
11.920	-0.00425	0.00090	-0.00352	-0.00461

Figure 6-2.6 KENO V.a Bias For 44-group Cross Section Set - Water Gap

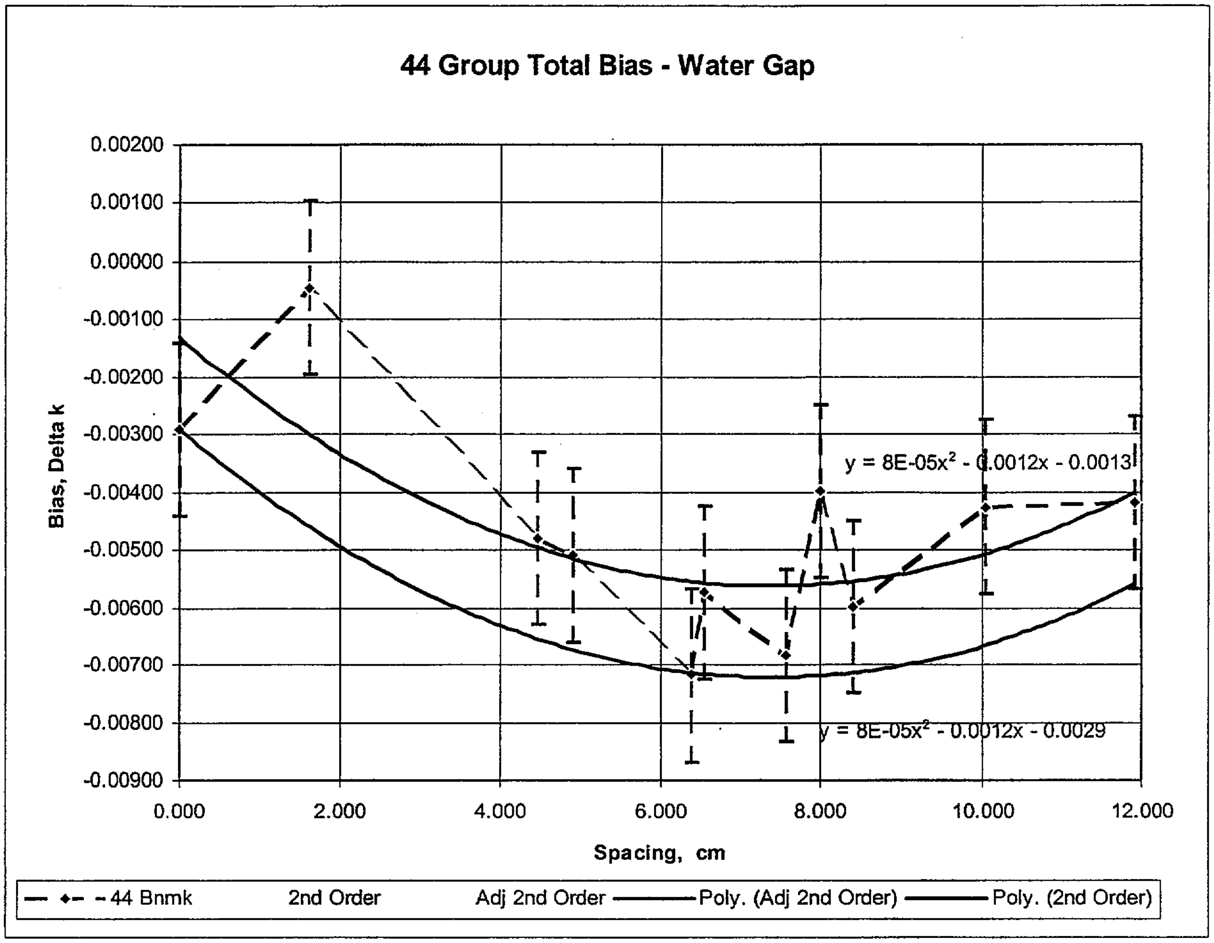
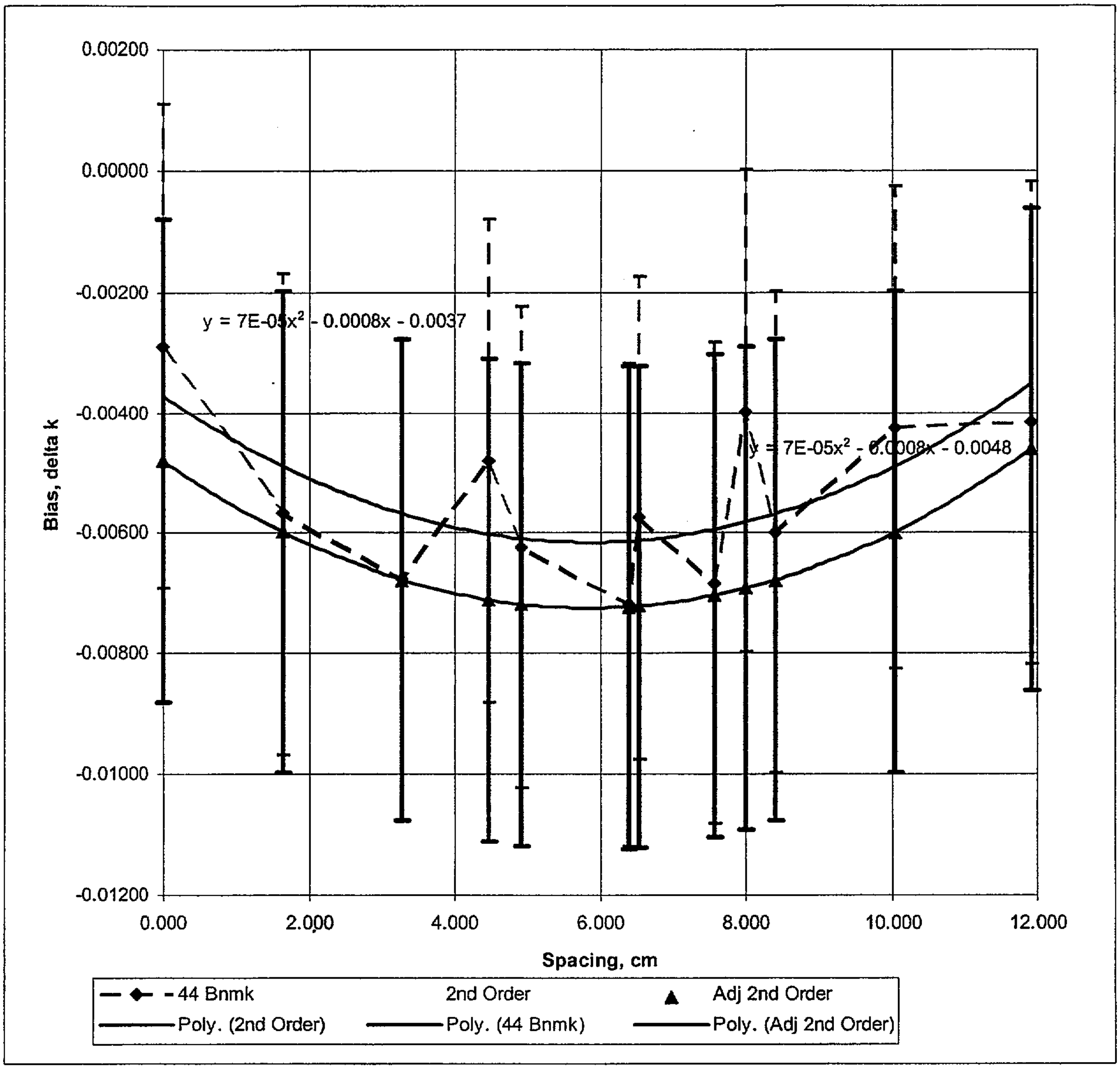


Figure 6-2.7 KENO V.a Bias For 44-group Cross Section Set Total Bias



6-6.3 References

1 "SCALE 4.2, Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," NUREG/CR-0200, Revision 4, November 1993, Oak Ridge National Laboratory.

2 "SCALE 4.3, Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers," Volume 3, Section M4, NUREG/CR-0200, Revision 5, September 1995, Oak Ridge National Laboratory. (Note the revised library released in May 1996 was used for the analysis).

3 COC-6206, 'Certificate of Compliance for Model B', Docket No. 6206, U.S. NRC, January 22, 1996 – see Attachment 3.

4 FCF DWG 1273873, Rev 0, "WE-1 F/A Shipping Container Inner Container Assembly," Sheets 1 and 2, 11/9/98.

5 BAW-1484-7, "Critical Experiments Supporting Close Proximity Water Storage of Power Reactor Fuel," N. M. Baldwin, et al., July 1979.

6 The UO_2 Criticals Data were obtained from the following:

a. S.R. Bierman, et al., "Critical Separation Between Subcritical Clusters of 2.35 wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons," PNL-2438, Battelle Pacific Northwest Laboratories, October 1977.

b. S.R. Bierman, et al., "Critical Separation Between Subcritical Clusters of 4.31 wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons," NUREG/CR-0073 (PNL-2615), Battelle Pacific Northwest Laboratories, March 1978.

c. S.R. Bierman et al., "Criticality Experiments with Subcritical Clusters of 2.35 wt% and 4.31 wt% ^{235}U Enriched UO_2 Rods in Water with Uranium or Lead Reflecting Walls," NUREG/CR-0796 (PNL-2827), Pacific Northwest Laboratory, April 1979.

d. R.I. Smith and G.J. Konzek, "Clean Critical Experiment Benchmarks for Plutonium Recycle in LWRs," EPRI NP-196, Vols I and II, Electric Power Research Institute, April 1976 and September 1978.

e. E.G. Taylor et al., "Saxton Plutonium Program Critical Experiments for the Saxton Partial Plutonium Core," WCAP-3385-54, Westinghouse Electric Corp., Atomic Power Division, December 1965.

7 The Mixed Oxide Criticals Data were obtained from the following:

a. R.I. Smith and G.J. Konzek, "Clean Critical Experiment Benchmarks for Plutonium Recycle in LWRs," EPRI NP-196, Vols I and II, Electric Power Research Institute, April 1976 and September 1978.

b. E.G. Taylor et al., "Saxton Plutonium Program Critical Experiments for the Saxton Partial Plutonium Core," WCAP-3385-54, Westinghouse Electric Corp., Atomic Power Division, December 1965.

c. S.R. Bierman, et al., "Criticality Experiments with Low Enriched UO_2 Fuel Rods in Water Containing Dissolved Gadolinium," PNL-4976, Battelle Pacific Northwest Laboratory, February 1984.

8 "International Handbook of Evaluated Criticality Safety Benchmark Experiments," Volume IV, LEU-COMP-THERM-002, 'Low Enriched Uranium Systems, Water-Moderated $U(4.31)O_2$ Fuel Rods In 2.54-Cm Square-Pitched Arrays,' NEA/NSC/DOC(95)03/IV, Nuclear Energy Agency, Paris.

9 "MCNP4, Monte Carlo N-Particle Transport Code System," using Continuous Energy ENDF/B-V cross sections.

B. Pathfinder Fuel Assemblies

6-2B.1. Purpose

The purpose of this document is to determine the bias and Upper Safety Limit(USL) associated with the SCALE4.4a code package[1]. This revision examines uranium fuel rods with enrichments between 2 and 10 wt% ^{235}U. These critical experiments primarily examine hexagonal arrays of fuel rods, although there are a couple with square pitches. Later revisions of this document will examine additional heterogeneous fuel rod configurations.

The USL concept for criticality calculations is described in NUREG/CR-6698[2]. This concept is an attempt by the NRC to provide a uniform method of assessing the bias inherent in the calculational methodology.

6-2B.2. Background and Method of Solution

The validation method described in NUREG/CR-6698 provides for the determination of an upper safety limit based upon statistical evaluation of the calculational bias. This bias is defined as usual as the difference between the k_{eff} of the critical experiment and the calculated $k_{eff\ for}$ the model of the experiment. With a USL defined, any calculated k_{eff} values plus calculational uncertainty must fall below the USL to be considered subcritical. The NUREG provides three types of USL's, the single-sided tolerance limit, the non-parametric statistical treatment, and the lower tolerance band. The single-sided tolerance limit method provides a single lower k_{eff} for normal distributions. It is based upon the weighted average k_{eff},, the pooled variance of the data, and a 95/95 single sided confidence factor. If the experimental distribution is not normal, the alternate single USL is obtained by the non-parametric statistical method. This method develops a USL based upon the lowest calculated k_{eff}, the uncertainty of that k_{eff}, and a non-parametric margin based upon the degree of confidence for 95% of the distribution population. This will generally provide the smallest USL. An alternate to the single USL is the definition of a lower tolerance band. The band is based upon a linear fit to the calculated k_{eff} values and the variance of the values. This method results in a USL curve as a function of the independent variable, e.g., the pitch, rather than a single value. In all cases, the USL is obtained from the 'limit' K_L developed in each method less two safety margins. The first is an administrative margin based upon the ability to control the parameters of the system to which the USL is applied, e.g., the pitch or pellet diameter for a fuel assembly. The second is the area of applicability margin. This is zero if the parameters of the system fall within the parameters of the critical experiments. If not, then a margin must be applied that is related to the degree of extension of the experimental parameters necessary to encompass those of the system being considered.

From the brief discussion above, it is implied that to the use of the NUREG methodology seems to require a large database of critical experiments that span the range of parameters for any systems to be evaluated. For a specific system, that system's defining parameters are then used to pick critical experiments whose parameters encompass those of the system. These experiments are then used to define the USL for the system. Thus, with this method a

[1] SCALE, A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluation," NUREG/CR-0200, Rev 6, SCALE4.4a, Oak Ridge National Laboratory.
[2] "Guide for Validation of Nuclear Criticality Safety Calculational Methodology," U.S. NRC Dividison of Fuel Cycle Safety and Safeguards, Office of Nuclear Material Safety and Safeguards, NUREG/CR-6698, January 2001.

single average bias applicable to all systems is not developed that precludes further bias calculations. Rather, a set of experiments is compiled and used to determine the USL for each evaluation in which the control parameters are changed. While this may require more effort, it should enable a higher limit, given well-controlled systems, than available from a single bias that must have higher safety margins to bound all allowable systems.

This revision, Rev 0, considers lattices of low enriched fuel rods (<10 wt%). The USL's values from the three methods are calculated and applied to a system of fuel rods placed in a hexagonal array for shipping. A final USL is determined that will be used in the licensing application for the shipping container for this configuration.

6.2B.3. Assumptions

No assumptions requiring verification are included in this analysis. The following general analytic assumptions have been made:

1. The critical-experiment description provided in the International Handbook[3] is assumed to be correct. No review of the reference documents for the experiments will be preformed to ensure their correctness.
2. It is further assumed that the critical k-eff and total uncertainty provided in the International Handbook are also correctly calculated.

6.2B.4. Summary of Results

The results of this evaluation for experiments with enrichment ranging from about 2.5 to 10 wt% ^{235}U, provide the following information relative to the KENOva bias and USL. The NUREG suggest a USL approach but will allow alternate validation and bias methodologies if they are justified. The following summary provides the historical approach and the USL approach results. If the historical bias evaluation and application is desired with a 0.95 criticality safety limit is utilized from this data, the following equation should be used to obtain the K_{Max}:

$$K_{Max} = k_{calc} + bias + ({}^{95/59}Factor)\sqrt{(\sigma_{calc})^2 + (\sigma_{bias})^2}$$

where, based upon these experiments,
bias = -0.00003,
95./95 single sided confidence factor = 2.0458, and
σ_{bias} = 0.0066.

Thus, the equation becomes:

$$K_{Max} = k_{calc} + \mathbf{0.00003} + (2.0458)\sqrt{(\sigma_{calc})^2 + (0.0066)^2}$$

Assuming about a million histories are used in the calculation, $\sigma_{cals} \approx 0.0011$ (from the benchmark cases), thus $k_{eff} \leq 0.936$ to satisfy the criticality safety criterion. If the single-sided upper tolerance limit is used and a 0.02 Δk can be assumed as the administrative safety margin for cases residing within the area of applicability, then the USL is 0.9656. Assuming the same safety margins, the upper tolerance band obtained for the trend versus energy causing fission

[3] : "International Handbook of Evaluated Criticality Safety Benchmark Experiments," Nuclear Energy Agency, NEA/NSC/DOC(95)03, September 2001 Edition.

(ECF) would be used. The USL for a particular case is obtained at the ECF point of the system being examined. Using the ECF trending, the area of applicability is 0.0539 ev ≤ ECF ≤3.508 ev.

6.2B.5. Computer Programs

Computer Program:

SCALE Version 4.4.a	Full Certification
usls	Open shop Unix program, see Attachment 6.2B.A.

6.2B.6. References

(Note: Footnotes are used through out this document for references with many documents referenced multiple times. The following is a summary list of documents referenced in these footnotes.)

1. SCALE, A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluation," NUREG/CR-0200, Rev 6, SCALE4.4a, Oak Ridge National Laboratory.

2. "Guide for Validation of Nuclear Criticality Safety Calculational Methodology," U.S. NRC Dividison of Fuel Cycle Safety and Safeguards, Office of Nuclear Material Safety and Safeguards, NUREG/CR-6698, January 2001.

3. Critical benchmark data from: "International Handbook of Evaluated Criticality Safety Benchmark Experiments," Nuclear Energy Agency, NEA/NSC/DOC(95)03, September 2001 Edition:
   a. COMP-THERM-005, "Critical Experiments with Low Enriched Uranium Dioxide Fuel Rods in Water Containing Dissolved Gadolinium," Pacific Northwest Laboratories, S.R. Bierman, etal.
   b. LEU-COMP-THERM-018, "Light Water Moderated and Reflected Low Enriched Uranium Dioxide (7 wt%) Rod Lattice," D. Hanlon, AEA-RS 5652, March 1994.
   c. LEU-COMP-THERM-019, "Water-Moderated Hexagonally Pitched lattices of U(5 %) O_2 Stainless Steel Clad Fuel Rods," Kurchatov Institute.
   d. LEU-COMP-THERM-020, "Water-Moderated Hexagonally Pitched lattices of U(5 %) O_2 Zirconium Clad Fuel Rods,", Kurchatov Institute.
   e. LEU-COMP-THERM-021, "Hexagonally Pitched lattices of U(5 %) O_2 Zirconium Clad Fuel Rods Moderated by Water and Boric Acid," Kurchatov Institute.
   f. LEU-COMP-THERM-022, "Uniform Water-Moderated Hexagonally Pitched lattices of U(10 %) O_2 Fuel," Kurchatov Institute.
   g. LEU-COMP-THERM-023, "Partially Flooded Uniform Lattices of Rods with U(10%)O_2 Fuel," Kurchatov Institute.
   h. LEU-COMP-THERM-024, "Water-Moderated Square-Pitched Uniform Lattices of Rods with U(10 %) O_2 Fuel," Kurchatov Institute.
   i. LEU-COMP-THERM-025, "Water-Moderated Square-Pitched Uniform Lattices of U(7.5 wt%) O_2 Stainless-Steel-Clad Fuel Rods," Kurchatov Institute.
   j. LEU-COMP-THERM-026, "Water-Moderated U(4.92) O_2 Fuel Rods in 1.29, 1.09, and 1.01 cm Pitch Hexagonal Lattices at Different Temperatures ," Obninsh.
   k. LEU-COMP-THERM-032, "Uniform Water-Moderated Lattices of Rods With U(10%)$_{O2}$ Fuel in Range From 20 °C to 274 °C," Kurchatov Institute.

4 S.S. Shapiro and M.B.Wilk, "An analysis of variance test for normality (complete samples," Biometricka(1965), Volume 52, 3 and 4, Pp 591-611..

6.2B.7. Critical Experiments

A licensing evaluation was necessary to support shipping ~7.5 wt% fuel rods. Since most previous analyses at Framatome ANP have been concerned with enrichments less than ~5 wt%, validation of SCALE, i.e., KENOva with the CSAS modules, for this enrichment is necessary. Thus, a review of the International Handbook of Evaluated Criticality Safety Benchmark Experiments was made and indicated several experiments consisting of fuel rod arrays with enrichments between 5 and 10 wt% ^{235}U. Table 7.1 lists the experiments and the key parameters relative to trending of the results. A review of the table indicates that most of the experiments comprised hex arrays of fuel rods. The enrichments considered range from 2.3 to 9.8 wt% ^{235}U. The enrichments less than 5 wt% were included to allow trending over a wider range of enrichments. In the table there are several sets of data that have the same enrichment, pitch, and temperature values. These cases are not the results of multiple measurement of the same configuration but represent different size arrays of rods that result in different water critical water heights. Thus, while they have the same parameters, they represent distinct experiments. The reader is referred to the International Handbook for a complete description of the experiments, however, a brief description of the experiments is given below. The SCALE input files for the benchmark cases were either prepared at Framatome ANP, extracted from the International Handbook, if available, or obtained from ORNL and used as received or slightly modified to better represent the experiments. Those cases not prepared at Framatome ANP were carefully reviewed to ensure that they correctly represented the experimental configuration.

6.2B.7.1 Low Enriched (2.35 and 4.31 Wt%) in Water Containing Dissolved Gadolinium – LCT 005

This set of experiments was performed at the Pacific Northwest Laboratories. Sixteen experiments were performed with the enrichments of 2.35 and 4.31 clad wt% fuel rods with four different lattice pitches and varying concentrations of Gd in the moderator. All experiments arranged the fuel rods in hexagonal arrays. Only 5 experiments did not have dissolved Gd in the moderator. These five have been modeled in KENOva for inclusion in this validation file to provide hexagonal date for enrichments less than 5 wt%. The International Handbook did not contain KENOva models of the experiments, so they were formulated as part of this validation file. The pitches of some of the hexagonal arrays are small enough that portions of the rods from a row overlap the rods in adjacent rows. This arrangement precludes a simple KENOva model so that use of holes is necessary to model the overlapping fuel rods. For consistency, all five cases were modeled with the same geometry options. Figure 7.1 presents sketches of the experimental arrangement, the two types of fuel rods, and a typical 'core' configuration. All these items were modeled rather explicitly except for the polyethylene lattice plates. These plates were explicitly modeled to at least two rows of lattice holes beyond the 'core' along the central axes. The lattice holes did not extend evenly around the core in all directions. Thus, some of the holes were filled with polyethylene in rows outside the core that should have been filled with water. However, the radius of these plates was modeled as the actual 45.73 cm radius. This should have a negligible effect on the results since the thickness of the plates are small, the filled holes are at least two lattice locations away from the core, and the density of polyethylene is about that of water. For a complete description of the experimental dimensions and number densities, the reader is referred to the description of experiment LEU-COMP-THERm-005 in the international handbook.

Table 7.1. Critical Experiments Examined with Parameters										
	Case	Wt%	Pitch	Clad	Lattice	T, °C	Sol. B-10, ppm	k_{exp}	σ_{exp}	Reference
1	lct00501	4.31	2.398	Al	Hex	19	-	1.0000	0.0023	Int. Hdbk[a]
2	lct00505	4.31	1.801	Al	Hex	14	-	1.0000	0.0047	Int. Hdbk[a]
3	lct00512	4.31	1.598	Al	Hex	14	-	1.0000	0.0066	Int. Hdbk[a]
4	lct00514	2.35	1.895	Al	Hex	30	-	1.0000	0.0020	Int. Hdbk[a]
5	lct00516	2.35	1.598	Al	Hex	19	-	1.0000	0.0032	Int. Hdbk[a]
6	lct01801	7.00	1.32	ss	square	20	-	1.0000	0.0020	Int. Hdbk[b]
7	lct01901	5.256	0.7	ss	Hex	16	-	1.0000	0.0063	Int. Hdbk[v]
8	lct01902	5.256	0.8	ss	Hex	19	-	1.0000	0.0058	Int. Hdbk[c]
9	lct01903	5.256	1.4	ss	Hex	23	-	1.0000	0.0061	Int. Hdbk[c]
10	lct02001	5.059	1.3	Zirc	Hex	20	-	1.0000	0.0061	Int. Hdbk[d]
11	lct02002	5.059	1.3	Zirc	Hex	20	-	1.0000	0.0061	Int. Hdbk[d]
12	lct02003	5.059	1.3	Zirc	Hex	20	-	1.0000	0.0061	Int. Hdbk[d]
13	lct02004	5.059	1.3	Zirc	Hex	20	-	1.0000	0.0061	Int. Hdbk[d]
14	lct02005	5.059	1.3	Zirc	Hex	20	-	1.0000	0.0061	Int. Hdbk[d]
15	lct02006	5.059	1.3	Zirc	Hex	20	-	1.0000	0.0061	Int. Hdbk[d]
16	lct02007	5.059	1.3	Zirc	Hex	20	-	1.0000	0.0061	Int. Hdbk[d]
17	lct02101	5.059	0.1	Zirc	Hex	20	6.1051	1.0000	0.0072	Int. Hdbk[e]
18	lct02102	5.059	0.1	Zirc	Hex	20	6.1051	1.0000	0.0072	Int. Hdbk[e]
19	lct02103	5.059	0.1	Zirc	Hex	20	6.1051	1.0000	0.0072	Int. Hdbk[e]
20	lct02104	5.059	0.13	Zirc	Hex	20	4.574	1.0000	0.0050	Int. Hdbk[e]
21	lct02105	5.059	0.13	Zirc	Hex	20	4.574	1.0000	0.0050	Int. Hdbk[e]
22	lct02106	5.059	0.13	Zirc	Hex	20	4.574	1.0000	0.0050	Int. Hdbk[e]
23	lct02201	9.83	0.7	ss	Hex	20	-	1.0000	0.0046	Int. Hdbk[f]
24	lct02202	9.83	0.8	ss	Hex	20	-	1.0000	0.0046	Int. Hdbk[f]
25	lct02203	9.83	1.0	ss	Hex	20	-	1.0000	0.0036	Int. Hdbk[f]
26	lct02204	9.83	1.22	ss	Hex	20	-	1.0000	0.0037	Int. Hdbk[f]
27	lct02205	9.83	1.4	ss	Hex	20	-	1.0000	0.0038	Int. Hdbk[f]
28	lct02206	9.83	1.83	ss	Hex	20	-	1.0000	0.0046	Int. Hdbk[f]
29	lct02207	9.83	1.852	ss	Hex	20	-	1.0000	0.0046	Int. Hdbk[f]
30	lct02301	9.83	0.7	ss	Hex	20	-	1.0000	0.0036	Int. Hdbk[g]
31	lct02302	9.83	0.7	ss	Hex	20	-	1.0000	0.0036	Int. Hdbk[g]
32	lct02303	9.83	0.7	ss	Hex	20	-	1.0000	0.0036	Int. Hdbk[g]
33	lct02304	9.83	0.7	ss	Hex	20	-	1.0000	0.0036	Int. Hdbk[g]
34	lct02305	9.83	0.7	ss	Hex	20	-	1.0000	0.0036	Int. Hdbk[g]
35	lct02306	9.83	0.7	ss	Hex	20	-	1.0000	0.0036	Int. Hdbk[g]
36	lct02401	9.83	0.62	ss	square	20	-	1.0000	0.0054	Int. Hdbk[h]
37	lct02402	9.83	0.877	ss	square	20	-	1.0000	0.0040	Int. Hdbk[h]
38	lct02501	7.41	0.7	ss	Hex	20	-	1.0000	0.0041	Int. Hdbk[i]
39	lct02502	7.41	0.8	ss	Hex	20	-	1.0000	0.0044	Int. Hdbk[i]
40	lct02503	7.41	1.0	ss	Hex	20	-	1.0000	0.0047	Int. Hdbk[i]
41	lct02504	7.41	1.22	ss	Hex	20	-	1.0000	0.0052	Int. Hdbk[I]

Table 7.1 Critical Experiments Examined with Parameters (Cont.)										
42	lct02601	4.92	1.29	Zirc	Hex	20.1	-	1.0004	0.0033	Int. Hdbk[j]
43	lct02602	4.92	1.29	Zirc	Hex	231.4	-	1.0000	0.0033	Int. Hdbk[j]
44	lct02603	4.92	1.09	Zirc	Hex	19.3	-	1.0023	0.0062	Int. Hdbk[j]
46	lct0321	10	0.07	ss	Hex	20	-	1.0000	0.0045	Int. Hdbk[j]
47	lct0322	10	0.07	ss	Hex	166	-	1.0000	0.0041	Int. Hdbk[k]
48	lct0323	10	0.07	ss	Hex	263	-	1.0000	0.0042	Int. Hdbk[k]
49	lct0324	10	1.4	ss	Hex	20	-	1.0000	0.0037	Int. Hdbk[k]
50	lct0325	10	1.4	ss	Hex	206	-	1.0000	0.0032	Int. Hdbk[k]
51	lct0326	10	1.4	ss	Hex	274	-	1.0000	0.0033	Int. Hdbk[k]
52	lct0327	10	1.852	ss	Hex	20	-	1.0000	0.0045	Int. Hdbk[k]
53	lct0328	10	1.852	ss	Hex	193	-	1.0000	0.0038	Int. Hdbk[k]
54	lct0329	10	1.852	ss	Hex	263	-	1.0000	0.0037	Int. Hdbk[k]

a. LEU-COMP-THERM-005, "Critical Experiments with Low Enriched Uranium Dioxide Fuel Rods in Water Containing Dissolved Gadolinium," Pacific Northwest Laboratories, S.R. Bierman, etal.

b. LEU-COMP-THERM-018, "Light Water Moderated and Reflected Low Enriched Uranium Dioxide (7 wt%) Rod Lattice," D. Hanlon, AEA-RS 5652, March 1994.

c. LEU-COMP-THERM-019, "Water-Moderated Hexagonally Pitched lattices of U(5 %) O_2 Stainless Steel Clad Fuel Rods," Kurchatov Institute.

d. LEU-COMP-THERM-020, "Water-Moderated Hexagonally Pitched lattices of U(5 %) O_2 Zirconium Clad Fuel Rods,", Kurchatov Institute.

e. LEU-COMP-THERM-021, "Hexagonally Pitched lattices of U(5 %) O_2 Zirconium Clad Fuel Rods Moderated by Water and Boric Acid," Kurchatov Institute.

f. LEU-COMP-THERM-022, "Uniform Water-Moderated Hexagonally Pitched lattices of U(10 %) O_2 Fuel," Kurchatov Institute.

g. LEU-COMP-THERM-023, "Partially Flooded Uniform Lattices of Rods with U(10%)O_2 Fuel," Kurchatov Institute.

h. LEU-COMP-THERM-024, "Water-Moderated Square-Pitched Uniform Lattices of Rods with U(10 %) O_2 Fuel," Kurchatov Institute.

i. LEU-COMP-THERM-025, "Water-Moderated Square-Pitched Uniform Lattices of U(7.5 wt%) O_2 Stainless-Steel-Clad Fuel Rods," Kurchatov Institute.

j. LEU-COMP-THERM-026, "Water-Moderated U(4.92) O_2 Fuel Rods in 1.29, 1.09, and 1.01 cm Pitch Hexagonal Lattices at Different Temperatures ," Obninsh.

k. LEU-COMP-THERM-032, "Uniform Water-Moderated Lattices of Rods With U(10%)$_{O2}$ Fuel in Range From 20 °C to 274 °C," Kurchatov Institute.

Figure 7.1 **LCT 005** Sketches

1LrUCOMPMThERM,4)01f

FIGURE WITHHELD UNDER 10 CFR 2.390

F'PrL **9-** kic*l DCU"PtiOm UF4-3 I-WM, 23511-EnrkIM **TJOJ**(Rt) Rods.

I *ON *A011 ZO AWN ST :a:tu(j raillinqnS uoisTA., I-am -ox;asUQoT-j
'84JO 6Z *ox o2va 'Z-9 xTpueddV 66 mvr st :;wma jupTurqnS repTul 6SZ6-14 *oK 49:qooa

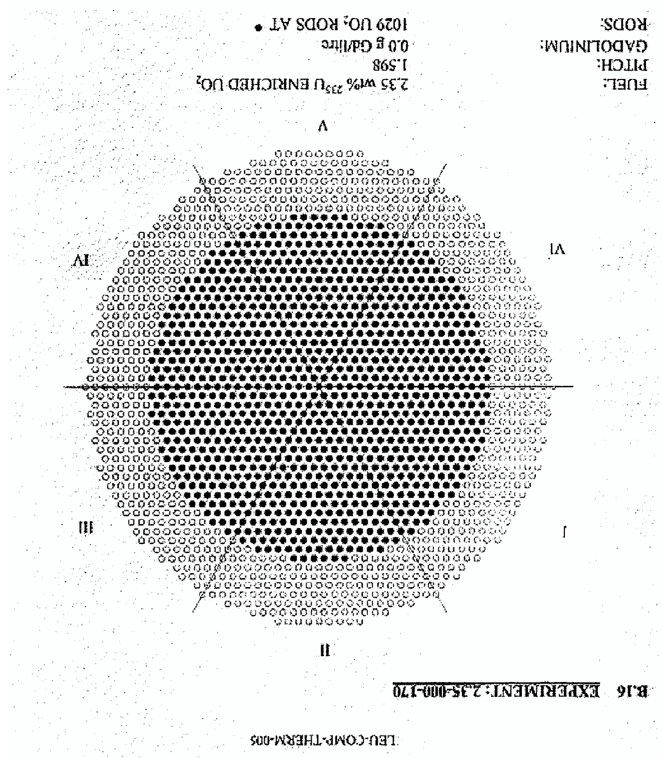


FIGURE WITHHELD UNDER 10 CFR 2.390

6.2B.7.1 Low Enriched (2.35 and 4.31 Wt%) in Water Containing Dissolved Gadolinium – LCT 018

This single experimental configuration was extracted from a set of experiments performed at AEA Technologies' site at Winfrith, Great Britain. The experimental configuration consisted of an array of fuel rods places in a large aluminum vessel (2.6 m diameter, 4 m high) containing water. The square pitched (1.32 cm) array of rods had a critical water height of 53.893 cm above the base of the fuel stack in the rods. The stainless steel clad fuel rods were supported by upper and lower aluminum lattice plates and rested upon an aluminum support plate. Figure 7.2 provides sketches of various components of the experiment.

Figure 7.2 LCT018 Sketches

LEU-COMP-THERM-018

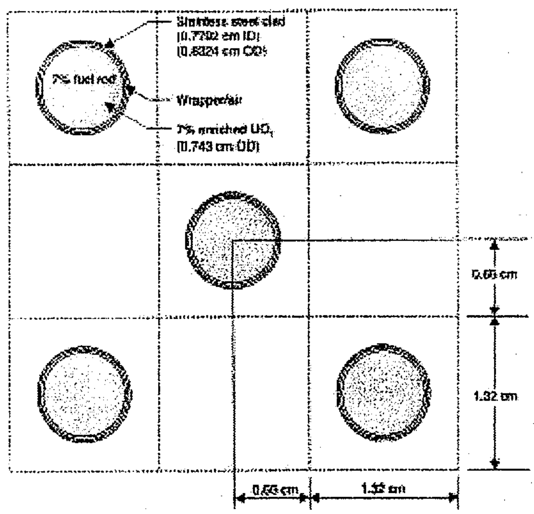


Figure 1. Composite Sectional Plan View of Fuel Rods.

Figure 7.2 **LCT018** Sketches (cont.)

FIGURE WITHHELD UNDER 10 CFR 2.390

Figure 2, C•mposite Seetloan Eevation View of Fuel Rods.

Figure 7.2 LCT018 Sketches (cont.)

LEU-COMP-THERM-018

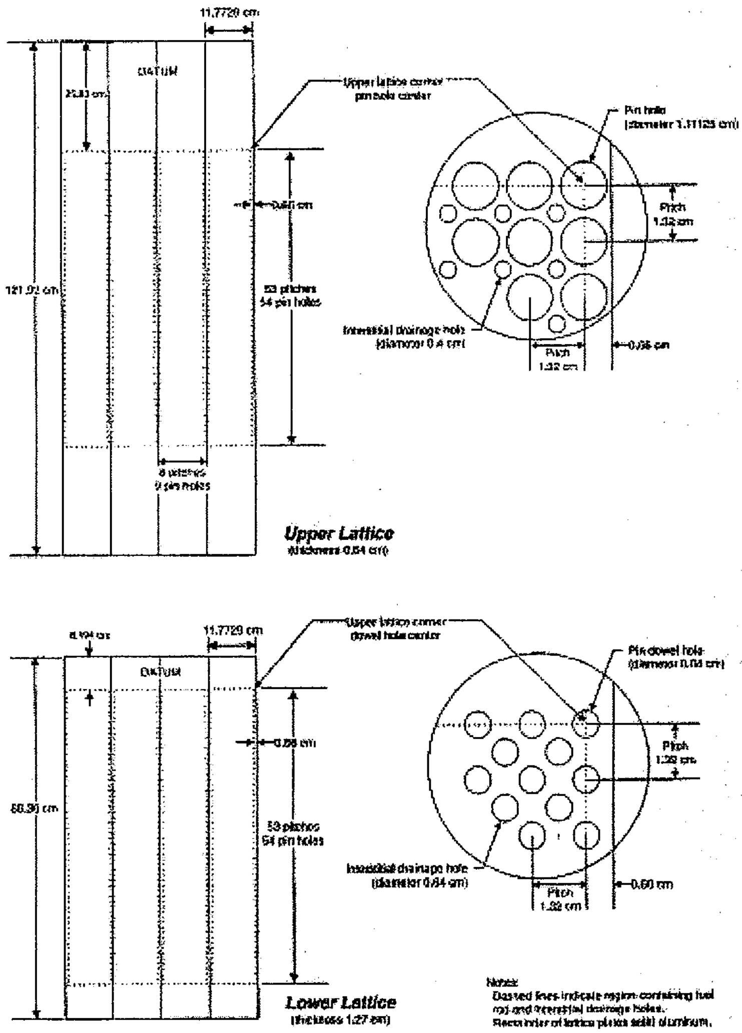


Figure 4. Simplified Plan Views of Upper and Lower Lattice Plates.

Figure 7.2 LCT018 Sketches (cont.)

LEU-COMP-THERM-018

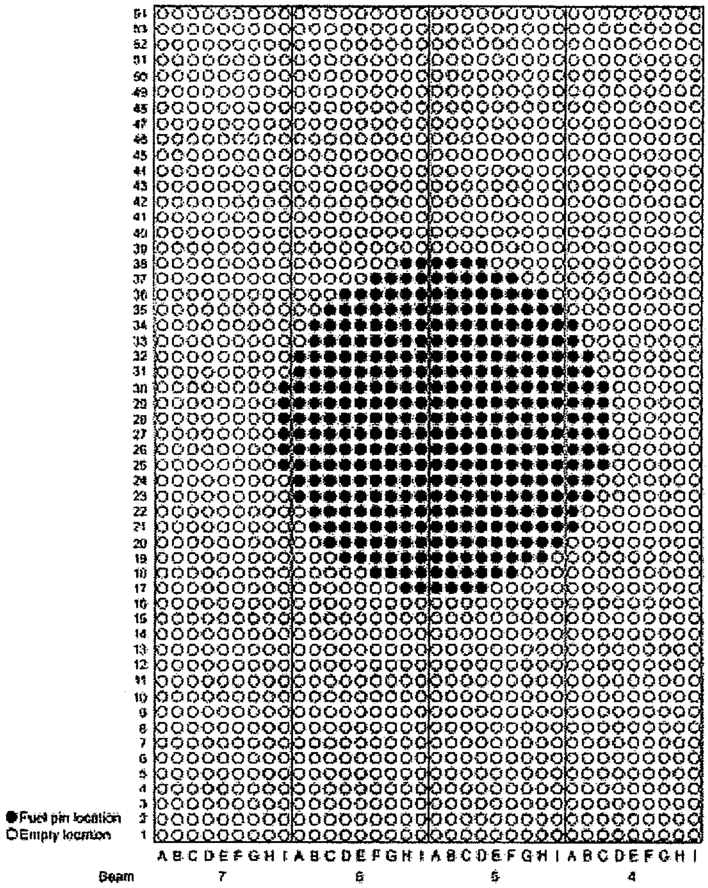


Figure 5. Dimple Experimental Configuration.

6.2B.7.3 Water Moderated Hexagonally Pitched Lattices of U(5 wt%) SS Fuel Rods – LCT 019

This set of three experiments was performed at the Russian Research Center "Kurchatov Institute." Three hexagonal fuel arrays with pitches of 0.7, 0.8, and 1.4 cm were placed in a 2.5 cm steel tank. The tank ID was 180 cm and its height 220 cm. Sufficient stainless steel clad fuel rods were placed on a steel support plate suspended from the top of the tank (see Figure 7.3) to provide a critical array with a top water reflector of at least 20 cm. Two aluminum lattice plates maintained the desired pitch. Figure 7.3 provides sketches of the experimental configuration and a typical arrangement of fuel rods in the array.

Figure 7.3 LCT019 Sketches

LEU-COMP-THERM-019

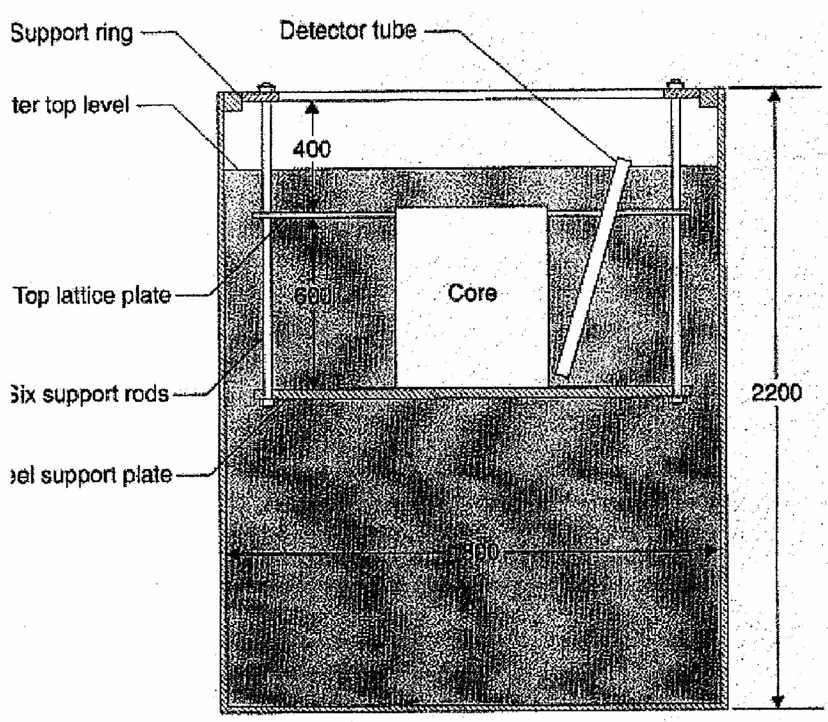


Figure 1. Configuration of the Critical Assembly with Water Tank.
(dimensions given in mm)

FIGURE WITHHELD UNDER 10 CFR 2.390

Figure 3. Fuel Rod. (dimensions given in mam)

Hpigre5. Ful Roe&vlmrn"Mo pwmv III, saw

Figure 7.3 LCT019 Sketches (cont.)

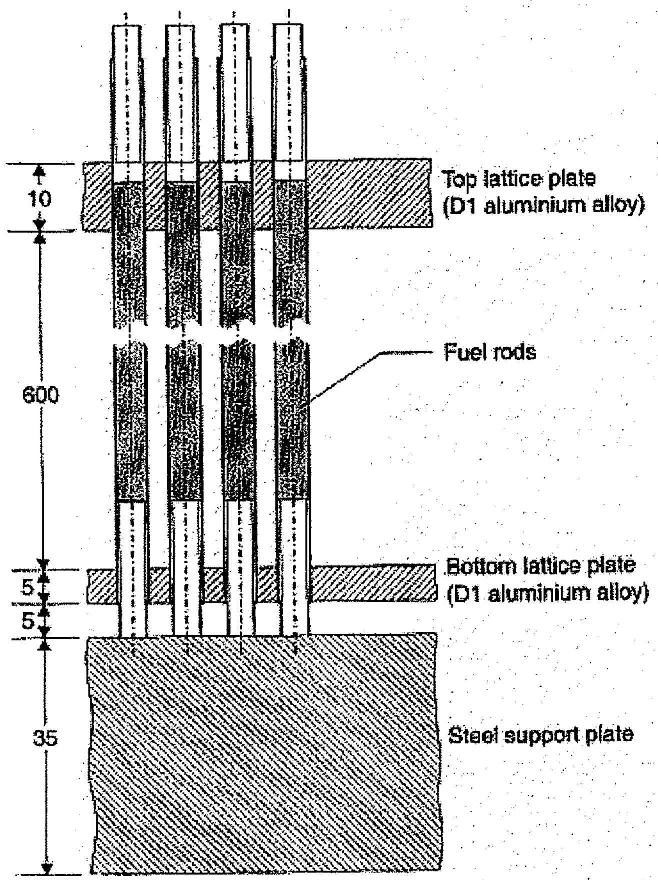


Figure 2. Schematic of the Fuel Rods Placement in the Core.
(dimensions given in mm)

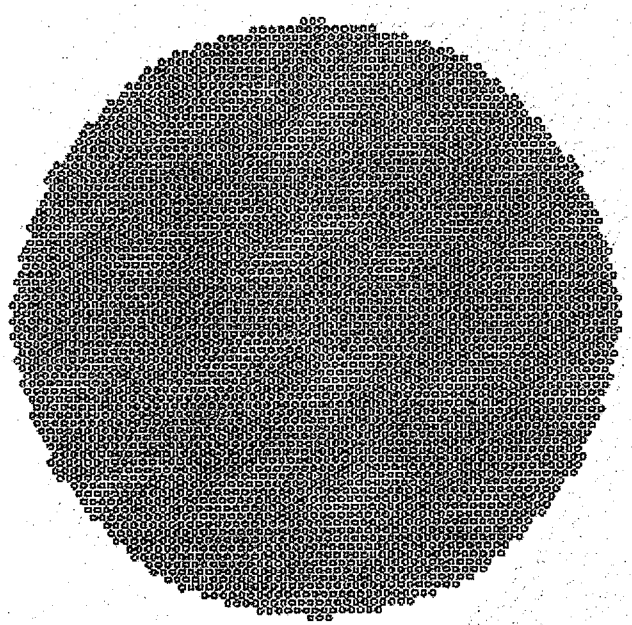


Figure 4. Critical Configuration for Case 1.

6.2B.7.4 Water Moderated Hexagonally Pitched Partially Flooded Lattices of U(5 wt%) Zirc Clad Fuel Rods, 1.3 CM Pitch – LCT 020

This set of seven experiments was performed in the same Kurchatov Institute facility as the LCT019 and the experimental arrangement is not repeated in Figure 7.4. The difference is primarily in the fuel rod configuration and how criticality was achieved. The zirconium clad fuel rod and a typical core configuration are illustrated in Figure 7.4. The water height in the fuel rod array was increased until criticality was reached for a fixed number of rods in the array.

Figure 7.4 LCT020 Sketches

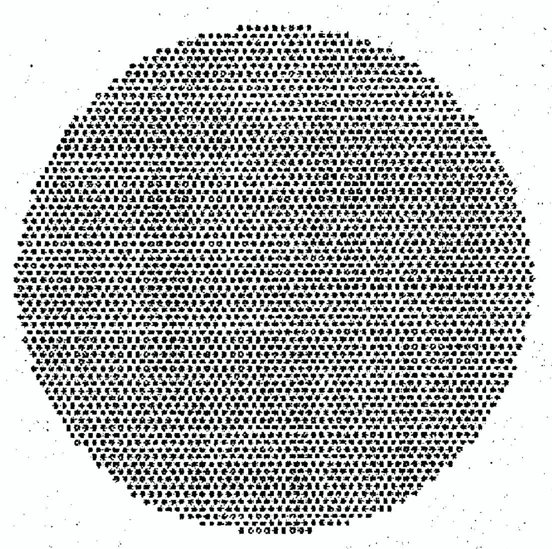


Figure 4. Critical Configuration for Case 1.

FIGURE WITHHELD UNDER 10 CFR 2.390

Figure 3. F~uel Rod, mem.i~ons given i mi)

6.2B.7.5 Hexagonally Pitched Partially Flooded Lattices of U(5 wt%) Zirc Clad Fuel Rods Moderated By Water with Boric Acid – LCT 021

This set of six experiments from same Kurchatov Institute facility as the previous experiments is identical in confirguration with the LCT020 experiments. The only difference is the addition of boric acid to the moderator. Since the configuration is the same as LCT020, only a sketch of a typical core configuration is provided in Figure 7.5.

Figure 7.5 LCT021 Sketches

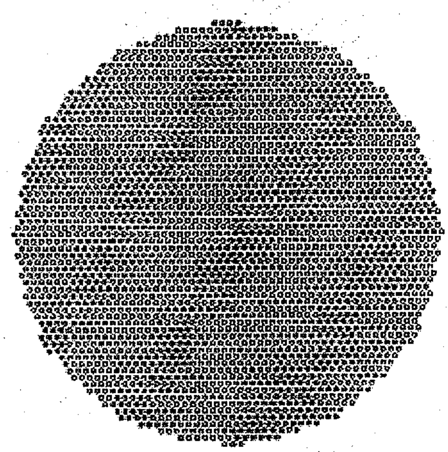


Figure 4. Critical Configuration for Case 1.

6.2B.7.6 Uniform Water-Moderated Hexagonally Pitched Lattices of Rods With U(10%)O_2 Fuel – LCT 022

This set of seven critical experiments performed at the Kurchatov Institute facility uses a different facility than the previous experiments. The hexagonal core is placed in a 1.5 cm thick, stainless steel tank that has a 255 cm height and an inner diameter of 159 cm. The core is positioned on an aluminum support plate suspended from the top of the tank. The fuel rods are positioned to pitches of 0.7, 0.8, 1.0, 1.22, 1.4, and 1.852 cm by two 0.3 cm thick aluminum lattice plates. The core is fully flooded with at least a 20 cm reflector above the top of the fuel rods. Criticality is achieved by addition of fuel rods. Figure 7.6 provides sketches of the experimental arrangement, the fuel assembly positioning, the fuel assembly, and a typical core cross section.

Figure 7.6 **LCT022** Sketches

FIGURE WITHHELD UNDER 10 CFR 2.390

Figure **I.** Th• Placcment of Aclive Cove in Tank•
(dimensions given in mnm)

Figure 7.6 LCT022 Sketches(cont.)

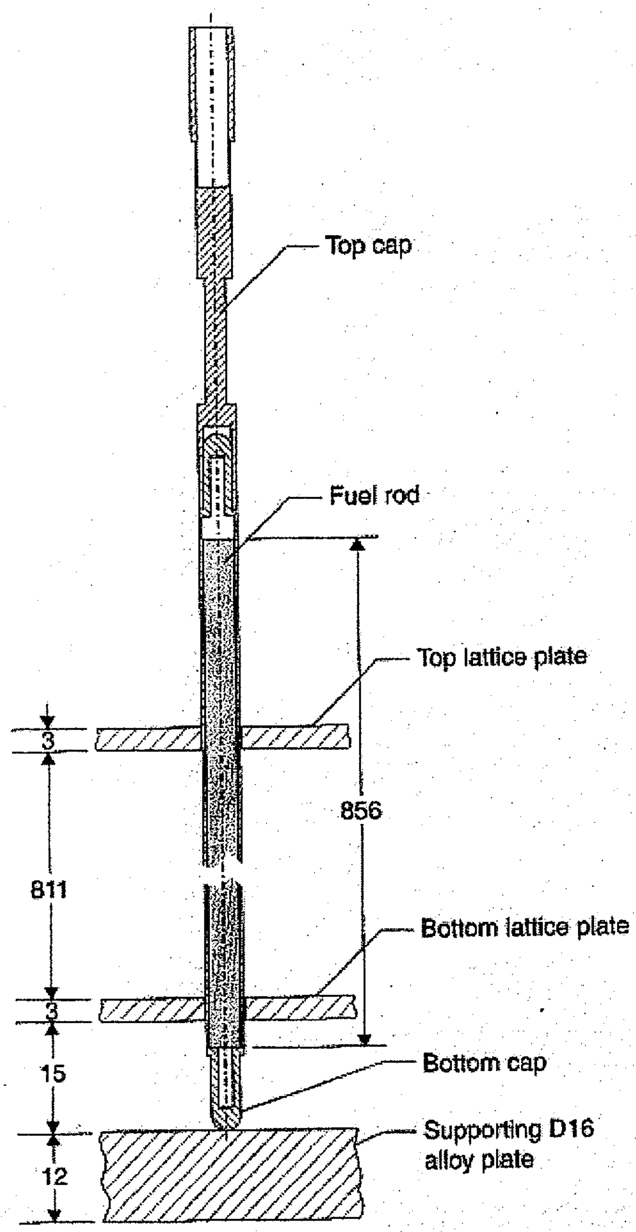


Figure 2. The Placement of Fuel Rod in Active Core.
(dimensions given in mm)

FIGURE WITHHELD UNDER 10 CFR 2.390

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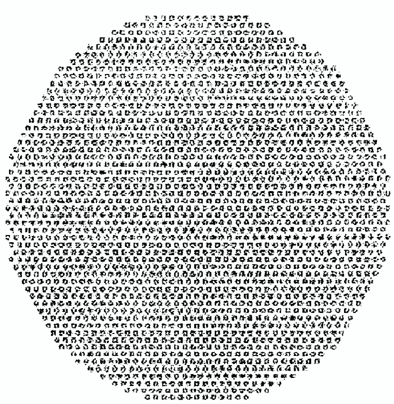

Figure 4. Configuration of Array 1. (N_{cell}=1969, p=0.7 cm)

6.2B.7.7 Partially Flooded Uniform Lattices of Rods With U(10%)O_2 Fuel – LCT 023

This set of six critical experiments was performed in the same Kurchatov Institute facility as LCT022 with some changes. The fuel rod configuration has changed slightly and criticality is obtained by adding water to cores with fixed numbers of rods. Due to the similarity with LCT022, only sketches the different fuel assembly configuration and a typical core loading pattern are provided in Figure 7.7

Figure **7.7** **LCT023** Sketches

FIGURE WITHHELD UNDER 10 CFR 2.390

Figure **10.** Model of the Fuel Rod. (~dirnensions giveu *in min)*

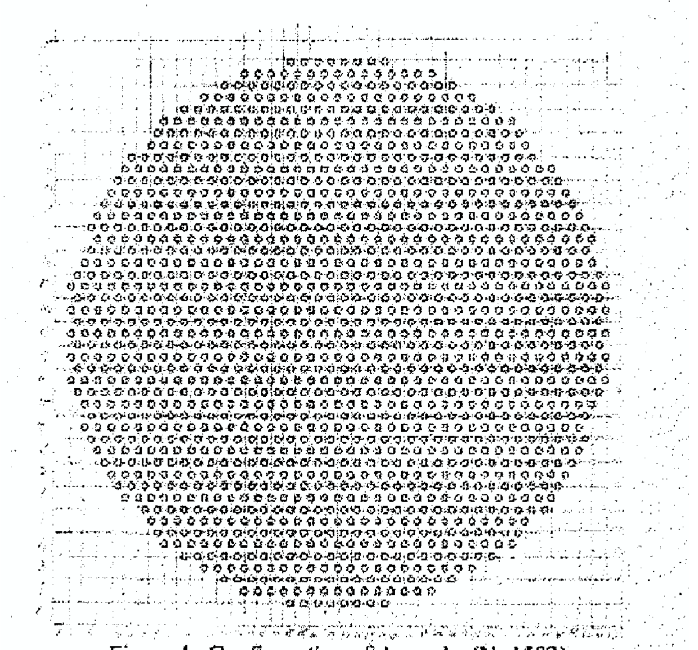

Figure 4. Configuration of Array 1. (N=1503)

6.2B.7.8 Water-Moderated Square-Pitched Uniform Lattices of Rods With U(10%)O_2 Fuel – LCT 024

The same facility at the Kurchatov Institute used for the previous two experiments was also used for this set of two experiments. The fuel rods used in LCT022 were placed in a square pitched array for these two experiments. Criticality was obtained addition of rods for the core fully flooded with at least a 20 cm reflector above the top of the fuel rods.

Figure 7.8 provides sketch of one of the square pitched core arrays. It also provides a skech of the fuel rod and how it was modeled. Most of these Kurchatov cases had similar approximate models which should have an insignificant effect of the results.

Figure 7.8 LCT024 Sketches

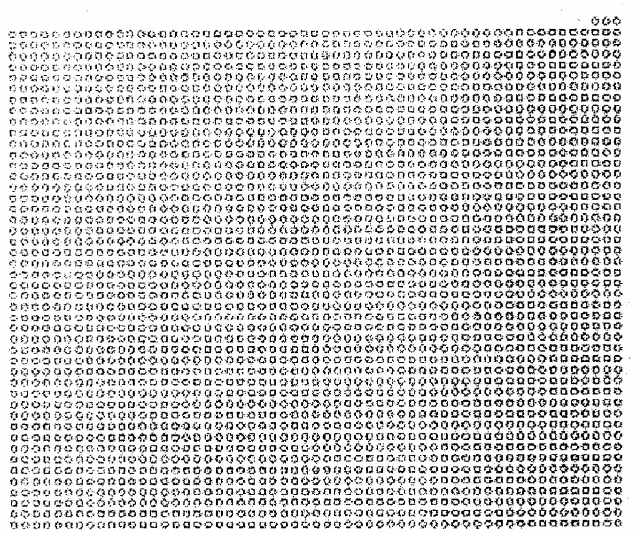

Figure 4. Uniform Lattice of Fuel Rod with Pitch of 0.62 cm (N_{cell}=2625).

FIGURE WITHHELD UNDER 10 CFR 2.390

6.2B.7.9 Water-Moderated Hexagonally-Pitched Uniform Lattices Of $U(7.5\%)O_2$ Stainless-Steel-Clad Fuel Rods – LCT 025

The core configuration in the Kurchatov facility was returned to an hexagonal array for this set four experiments. The fuel rod pitch variations for this set were 0.7, 0.8. 1.0, and 1.22 cm. Since the facility and fuel rods were the same as those described previously, Figure 7.9 only contains a sketch of a typical core loading pattern. Criticality for this set of case was obtained by adding fuel rods to a fully flooded core configuration.

Figure 7.9 LCT025 Sketches

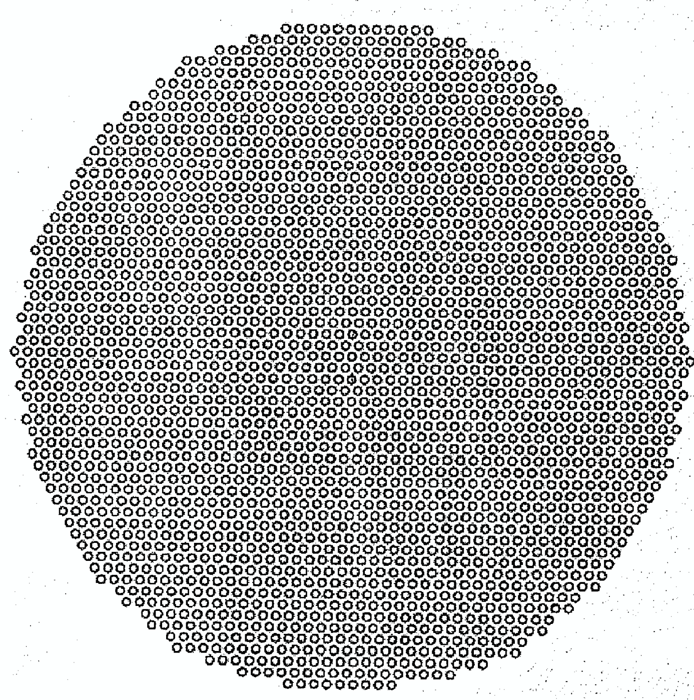

FIGURE WITHHELD UNDER 10 CFR 2.390

6.2B.7.10 Water-Moderated **U(4.92)0 2** Fuel Rods in **1.29,1.09,** and **1.01** Cm Pitch Hexagonal Lattices At Different Temperatures - **LCT 026**

This set of six experiments were performed at the Institute of Physics and Power Engineering, Obninsk, Russia. The experiments were performed in a 15 cm this stainless steel tank with a 1.5 m OD and a height of 2.2 m. The fuel rods were supported on a 2.5 cm thick steel support plate positioned 66 cm above the bottom of the tank by a stainless steel cylindrical shell. Fuel rod pitches of 1.29, 1.09, and 1.01 cm were maintained by two 0.8 cm thick steel lattice plates. Criticality for cold ('20"C) and hot (>200^{0}C) was obtained by rod addition with at least as 20 cm reflector above the fuel for the cold condition and a **-80** cm reflector for the hot conditions. Figure 7.10 provides sketches of the experimental configuration, the fuel assembly, and a typical core-loading pattern.

Figure 7.10 LCT026 Sketches

FIGURE WITHHELD UNDER 10 CFR 2.390

figure **1. Configuma aiOw Itical** Assmw , (dimeolsin mm).

Figure **7.10 LCT026** Sketches (cont.)

FIGURE WITHHELD UNDER 10 CFR 2.390

Fig= 2. FuI Rod (dim **tL1x4 ii• m})**

PFrth3. LoaingWfeeCak I (sbdd)=dCz.iX'

6.2B.7.11 Uniform Water-Moderated Lattices of Rods With **U(10%)**O_2 Fuel Range From 20 °C to 274 °C

This set of nine experiments was performed at the same facility in the Kurchatov Institute in Russia in two configurations. The room temperature cases used the tank described for experiments LCT-022 listed above. For the high temperature cases the experiments were positioned in a pressure vessel with an inside diameter of 140 cm, an inside height of 300 cm and with an average thickness of 15 cm. The critical assembly had an active core whose central portion could be moved up or down for compensation of reactivity changes. Criticality was controlled by shifting the central portion up or down. In some cases at particular temperatures the central portion was completely pushed in to make a uniform lattice of fuel rods. Three lattice pitches were examined (0.7, 1.4, and 1.852 cm hexagonal pitch) for three temperature ranging from 20 up to 274 °C. The fuel rods are also the same as those for LCT-022, see Figure 7.6. Figure 7.11 provides a sketch illustrating the movement of the central portion and a sketch of a typical core arrangement with the central portion indicated by the darker hexagon.

Figure **7.10 LCT032** Sketches

FIGURE WITHHELD UNDER 10 CFR 2.390

Figure **3.** The Placement of Fuel Rods in the Activo Core.. (dirensionis given in mim)

FIGURE WITHHELD UNDER 10 CFR 2.390

6.2B.8. USL

The results of the KENOva calculations with the SCALE package for the 54 experiments are listed in Table 8.1. The table lists the possible trending parameters including the 'Average Energy of Neutrons Causing Fission' that is calculated by KENOva. The calculated k_{eff} and its uncertainty are listed. The difference of the calculated k_{eff} and the experimental value in Table 7.1 provides the bias listed in the table. The bias uncertainty is just the square root of the sum of the squares of the experimental and calculated k_{eff} values. Note that the series lct02101 to lct02106 are the only experimental cases that have a soluble poison in the moderator. Since the number of experiments according to the NUREG must be between 10 and 50, these 6 cases will be deleted from the data set used to generate the USL values.

To facilitate the generation of the USL values an open-shop Fortran program 'usls' was written. This program is described in Attachment 6.2B.A. The final part of the output for a usls case is a summary of parameters for the statistical evaluation of the validation cases that define the USL values. The Fortran file for usls, usls.f, in contained in the COLD system. Results from the usls cases all have file names beginning with 'lec238'. Several subsets of data from that presented in Table 8.1 were manipulated with usls for the four trending parameters listed in Table 8.1, i.e. enrichment, pitch, temperature, and energy causing fission. As noted the lct021 series of cases were ignored and only cases with pure water as the moderator were considered to reduce the number of experiments to below 50. Three subsets of data were examined: the 48 data points for pure water data, only the 45 data points for hexagonal arrays, and finally the 44 data points for the hex arrays with lct02501, number 38 in Table 8.2 deleted. This particular value seems to be an outlier and its effect on the USL values is examined here. A review of LCT2501 MCNP results in the Handbook also shows this case to have a lower value,i.e., 0.9948 (Table 13). Thus, the results may be valid for SCALE and shows the largest bias.

Table 8.2 lists some of the usls results for the trending calculations. The first three sets of for energy causing fission with all 48 points (.out case), with only hex (h.out case), and with the lowest point removed (hl.out case). The same trending cases follow for enrichment, pitch, and temperature. From the table it s seen that the weighed k_{eff} for any of the cases is very close to 1.0. Thus the weighed bias is small and is actually smaller that the bias uncertainty. These results, i.e., weighed k_{eff}, weighed bias, and the uncertainty, provided by usls are those historically used to calculated the maximum k of a system, i.e.

$$K_{Max} = k_{calc} + bias + (^{95/59}Factor)\sqrt{(\sigma_{calc})^2 + (\sigma_{bias})^2}$$

This is an alternate manner of including the bias if the historical criticality safety limit of 0.95 is acceptable. It is noted that the 95/95 tolerance factor is that related to the bias, i.e., based upon the number of experiments rather than the number of histories in the KENOva case.

Table 8.1 Calculated Values and Bias

	Case[b]	Wt%	Pitch	T, °C	ECF[a]	σ_{ecf}	k_{calc}	σ_{calc}	Bias	σ_{bias}
1	lct00501	4.31	2.398	19	0.15194	3.24E-04	1.00111	0.00101	0.00111	0.00251
2	lct00505	4.31	1.801	14	0.68574	2.08E-03	0.99628	0.00091	-0.00372	0.00479
3	lct00512	4.31	1.598	14	3.50801	1.38E-02	0.99790	0.00094	-0.00210	0.00667
4	lct00514	2.35	1.895	30	0.14675	3.26E-04	0.99513	0.00087	-0.00487	0.00218
5	lct00516	2.35	1.598	19	0.36284	1.03E-03	1.00990	0.00077	0.00990	0.00329
6	lct01801	7	1.32	20	0.20211	0.00047	0.99743	0.00099	-0.00257	0.00223
7	lct01901	5.256	0.7	16	0.33250	0.00083	1.00663	0.00082	0.00663	0.00635
8	lct01902	5.256	0.8	19	0.16351	0.00034	1.00323	0.00091	0.00323	0.00587
9	lct01903	5.256	1.4	23	0.05394	0.00007	1.00528	0.00073	0.00528	0.00614
10	lct02001	5.059	1.3	20	0.07952	0.00017	0.99320	0.00087	-0.00680	0.00616
11	lct02002	5.059	1.3	20	0.06856	0.00012	0.99861	0.00089	-0.00139	0.00616
12	lct02003	5.059	1.3	20	0.06667	0.00011	1.00161	0.00095	0.00161	0.00617

Table 8.1 Calculated Values and Bias										
	Case[b]	Wt%	Pitch	T, °C	ECF[a]	σ_{ecf}	k_{calc}	σ_{calc}	Bias	σ_{bias}
13	lct02004	5.059	1.3	20	0.06568	0.00011	1.00103	0.00089	0.00103	0.00616
14	lct02005	5.059	1.3	20	0.06463	0.00010	1.00183	0.00097	0.00183	0.00618
15	lct02006	5.059	1.3	20	0.06398	0.00010	1.00097	0.00085	0.00097	0.00616
16	lct02007	5.059	1.3	20	0.06187	0.00009	1.00226	0.00086	0.00226	0.00616
17	lct02101	5.059	0.1	20	0.13409	0.00028	1.00702	0.00081	0.00702	0.00725
18	lct02102	5.059	0.1	20	0.12927	0.00026	1.00855	0.00097	0.00855	0.00727
19	lct02103	5.059	0.1	20	0.12711	0.00025	1.00968	0.00089	0.00968	0.00725
20	lct02104	5.059	0.13	20	0.07496	0.00013	1.01094	0.00088	0.01094	0.00508
21	lct02105	5.059	0.13	20	0.07385	0.00012	1.01208	0.00081	0.01208	0.00507
22	lct02106	5.059	0.13	20	0.07194	0.00012	1.00995	0.00078	0.00995	0.00506
23	lct02201	9.83	0.7	20	0.70186	0.00196	0.99771	0.00097	-0.00229	0.00470
24	lct02202	9.83	0.8	20	0.29432	0.00074	1.00338	0.00084	0.00338	0.00468
25	lct02203	9.83	1	20	0.12669	0.00025	1.00258	0.00089	0.00258	0.00371
26	lct02204	9.83	1.22	20	0.08368	0.00015	1.00528	0.00110	0.00528	0.00386
27	lct02205	9.83	1.4	20	0.06933	0.00011	1.00034	0.00088	0.00034	0.00390
28	lct02206	9.83	1.83	20	0.05442	0.00008	1.00085	0.00083	0.00085	0.00467
29	lct02207	9.83	1.852	20	0.05385	0.00008	1.00430	0.00075	0.00430	0.00466
30	lct02301	9.83	0.7	20	0.08307	0.00043	0.99477	0.00084	-0.00523	0.00370
31	lct02302	9.83	0.7	20	0.07711	0.00031	0.99647	0.00080	-0.00353	0.00369
32	lct02303	9.83	0.7	20	0.07530	0.00025	0.99777	0.00072	-0.00223	0.00367
33	lct02304	9.83	0.7	20	0.07309	0.00021	1.00098	0.00081	0.00098	0.00369
34	lct02305	9.83	0.7	20	0.07163	0.00014	1.00239	0.00088	0.00239	0.00371
35	lct02306	9.83	0.7	20	0.07011	0.00011	1.00186	0.00070	0.00186	0.00367
36	lct02401	9.83	0.62	20	1.05739	0.00277	0.99451	0.00086	-0.00549	0.00547
37	lct02402	9.83	0.877	20	0.14510	0.00027	1.00284	0.00090	0.00284	0.00410
38	lct02501	7.41	0.7	20	0.44592	0.00119	**0.98113**	0.00096	-0.01887	0.00421
39	lct02502	7.41	0.8	20	0.20491	0.00045	0.99111	0.00082	-0.00889	0.00448
40	lct02503	7.41	1	20	0.09975	0.00019	0.99649	0.00086	-0.00351	0.00478
41	lct02504	7.41	1.22	20	0.06952	0.00011	1.00111	0.00086	0.00111	0.00527
42	lct02601	4.92	1.29	20.1	0.24677	0.00058	0.99761	0.00095	-0.00279	0.00343
43	lct02602	4.92	1.29	231.4	0.42182	0.00109	0.99431	0.00107	-0.00569	0.00347
44	lct02603	4.92	1.09	19.3	1.03722	0.00336	0.99892	0.00092	-0.00338	0.00627
45	lct02604	4.92	1.09	20	1.64222	0.00555	0.99572	0.00084	-0.00428	0.00626
46	lct0321	10	0.07	166	0.70243	0.00207	0.99869	0.00083	-0.00131	0.00458
47	lct0322	10	0.07	263	0.93581	0.00274	0.99827	0.00097	-0.00173	0.00421
48	lct0323	10	0.07	20	1.35783	0.00393	0.99796	0.00084	-0.00204	0.00428
49	lct0324	10	1.4	206	0.06908	0.00011	1.00668	0.00086	0.00668	0.00380
50	lct0325	10	1.4	274	0.10404	0.00016	1.00387	0.00093	0.00387	0.00333
51	lct0326	10	1.4	20	0.12250	0.00020	1.00215	0.00091	0.00215	0.00342
52	lct0327	10	1.852	193	0.05401	0.00008	1.00775	0.00072	0.00775	0.00456
53	lct0328	10	1.852	263	0.07923	0.00012	1.00959	0.00081	0.00959	0.00389
54	lct0329	10	1.852	263	0.09198	0.00013	1.00815	0.00098	0.00815	0.00383

a) Average Energy Causing Fission (ECF) from KENO output file.
b) Output files are named 'CASE'.out or 'CASE'out or 'CASEa'out

Table 8.2 also lists the single-sided tolerance limit, the Shapiro-Welk test, and the non-parametric tolerance limit. It is noted that if the distribution is shown to be normal by the Shapiro-Welk test, than the single-side tolerance limit is applicable. If not, than the non-parametric limit is to be used. In all the trending cases, the data is shown to be normal. One additional case only looked at the hexagonal stainless steel experiments trended with enrichment, case lec238enhs.out. For this case, the Shapiro-Welk test fails, indicating a non-normal distribution. Thus, the non-parametric tolerance limit must be used for this case. It is noted that both of the tolerance limits are based upon the statistical results related to the weighted-mean data that is dependent on the number of experiments. This is the reason that there is very little difference between the sets of trending values since the weighted k_{eff} and its uncertainty are independent of the trending parameter. The non-parametric limit is based upon Table 2.2 in the NUREG which dependent upon the number of experiments considered. Hence the lower value for lec238enhs.out case which has only 29 histories.

The 'Summary Output' table for each of the cases listed in Table 8.2 are contained in Attachment 6.2B.B. In addition to the statistical and limit results, the summary table lists the USL for the three methods based upon the administrative and area of applicability values supplied in the input file. In addition, it provides the range (area) of applicability for the trending parameter chosen. The USL are provided for the single-sided lower tolerance limit, the non-parametric lower tolerance limit, and lower tolerance band. If any of the limits are greater than one, than the value is set to one, i.e., no positive bias allowed. Plots of the trending data are provide in Figures 8.1 through 8.9 for enrichment, pitch, energy causing fission, and moderator temperature. Only the k vs enrichment plot for the low k point deleted trend is provided to show that deleting that point will have little effect except for the non-parametric tolerance limit which is based upon the lowest calculated k_{eff} and shows a slight increase in the USL. Since the low point k_{eff} from the MCNP for LCT02501 does not show the large difference shown by KENOva, it is assumed that the KENOva model and results are correct. Thus, this point can not be ignored.

Table 8.2 Statistical Results and Tolerance Limits From USLS Summary

Usls Output File	No. Exps	Weighted Mean k_{eff}[a]	Bias[b] (kexp-kcal)	σ_{bias}[c]	95/95 Factor[d]	SSTL[e]	S-W Test[f]	NPTL[g]
lec238ecf.out	48	0.99997	**-0.00003**	**0.00660**	**2.07580**	0.96626	1.00789	0.95692
lec238ecfh.out	45	1.00017	0.00017	0.00680	2.09200	0.96577	1.00635	0.95692
lec238ecfhl.out	45	1.00017	0.00017	0.00680	2.09200	0.96577	1.00635	0.95692
lec238en.out	48	0.99997	**-0.00003**	**0.00660**	**2.07580**	0.96626	1.00789	0.95692
lec238enh.out	45	1.00017	0.00017	0.00680	2.09200	0.96577	1.00635	0.95692
lec238enhl.out	44	1.00059	0.00059	0.00621	2.09880	0.96697	1.03636	0.95663
lec238enhs.out	29	1.00089	0.00089	0.00703	2.23440	0.96429	0.97731	0.93692
lec238pit.out	48	0.99997	**-0.00003**	**0.00660**	**2.07580**	0.96626	1.00789	0.95692
lec238pith.out	45	1.00017	0.00017	0.00680	2.09200	0.96577	1.00635	0.95692
lec238pithl.out	45	1.00017	0.00017	0.00680	2.09200	0.96577	1.00635	0.95692
lec238tmp.out	48	0.99997	**-0.00003**	**0.00660**	**2.07580**	0.96626	1.00789	0.95692
lec238tmph.out	45	1.00017	0.00017	0.00680	2.09200	0.96577	1.00635	0.95692
lec238tmphl.out	45	1.00017	0.00017	0.00680	2.09200	0.96577	1.00635	0.95692

a. Equation 6 of NUREG.
b. Equation 8 of NUREG.
c. Equation 7 of NUREG.
d. 95/95 Single Sided Tolerance Factor, U in NUREG for Table 2.1
e. Single-Side Lower Tolerance Limit, equation 20 of NUREG.
f. Shiparo-Welk Normalcy Test, Test Static/Percentage Point (Table A.5 of NUREG), if ratio is greater than 1.0 the distribution is normal, see page 10 of NUREG for discussion of normalcy test.
g. Non-Parametric Tolerance Limit, equation 34 of NUREG.

Reviewing the figures indicates that there is essentially no trend for either enrichment or temperature. The largest trend is seen for energy causing fission but the pitch also shows a slight trend. Due to the larger negative values exhibited for the energy causing fission trend, it will provide the most conservative Singe-Sided Lower Tolerance Band (designated TB in figures). However, a review of the values in Tables 8.3 through 8.7 indicates that for a large portion of the SSLT bands, the USL values do not vary by much. It is only for the larger ECF values where the statistics are sparse that this USL band provides conservative results.

A review of Tables 8.3 through 8.7 indicates that the lowest single-sided upper tolerance limit is 0.9677 for the hex only arrays for any of the trending variables. Again this is expected since this tolerance value is based upon the average mean k_{eff} and it's uncertainty, which is the same for any of the trends with the same k_{eff} data points. Since all the trends listed in these tables are normal, the non-parametric tolerance limit is not applicable.

The area (range) of applicability is defined as the parametric values that lie between the maximum and minimum trending values associated with the experiments. Using the ECF trending, the area of applicability is 0.0539 ev $\leq$ ECF $\leq$3.508 ev.

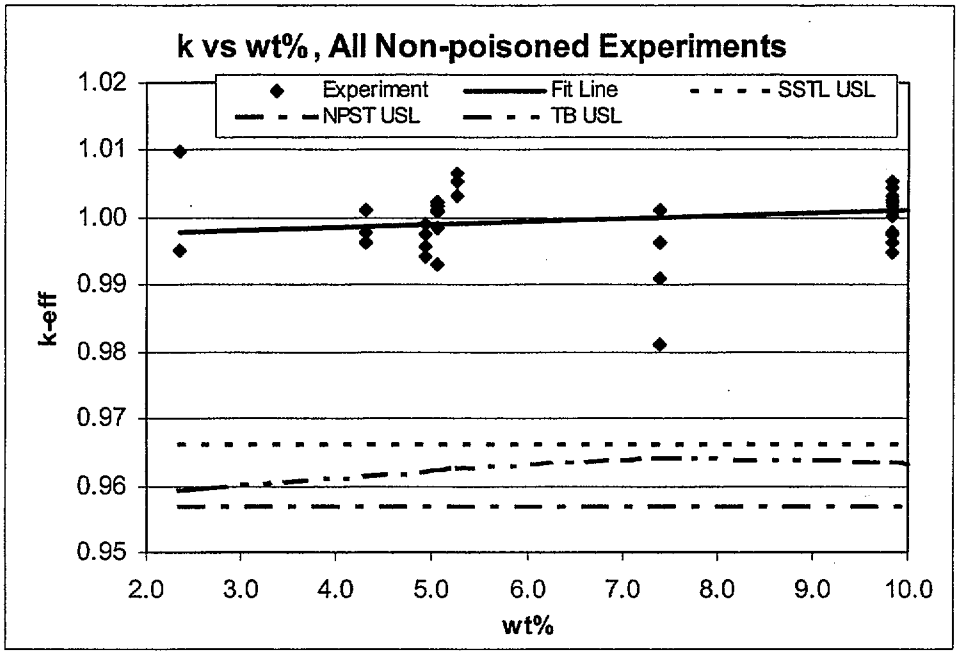

Figure 8.1 k vs enrichment, all experiments wo dissolved absorbers, fit equation: k-eff =0.9968116+(0.0004200326)*wt%.

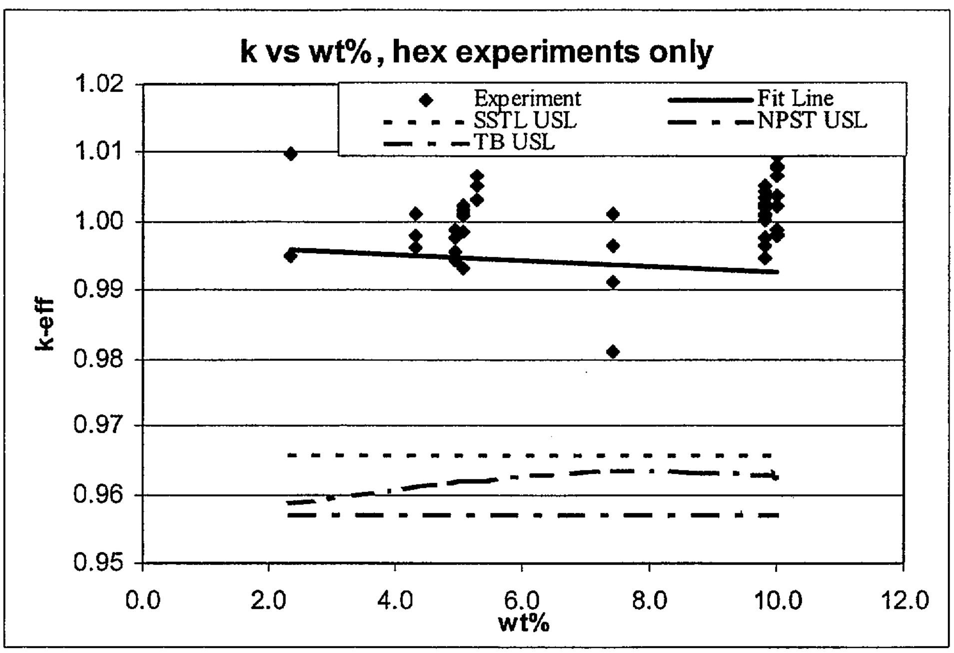

Figure 8.2 k vs enrichment, hex experiments wo dissolved absorbers, fit equation: k-eff = 0.9970209-0.0004211385*wt%.

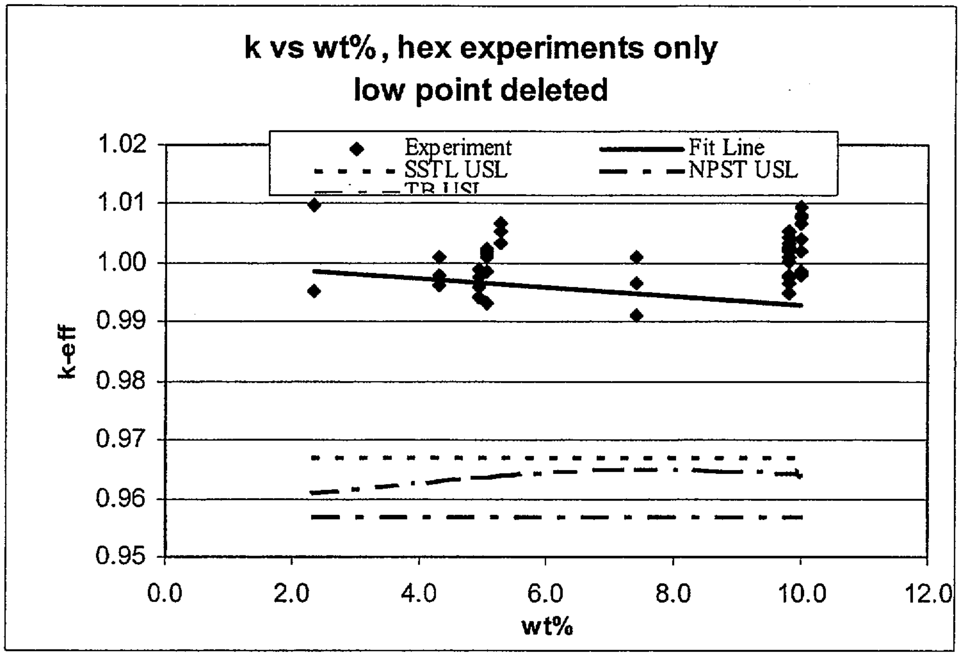

Figure 8.3 k vs enrichment, hex experiments wo dissolved absorbers, low point deleted, fit equation: k-eff =0.9970209-0.0004211385*wt%.

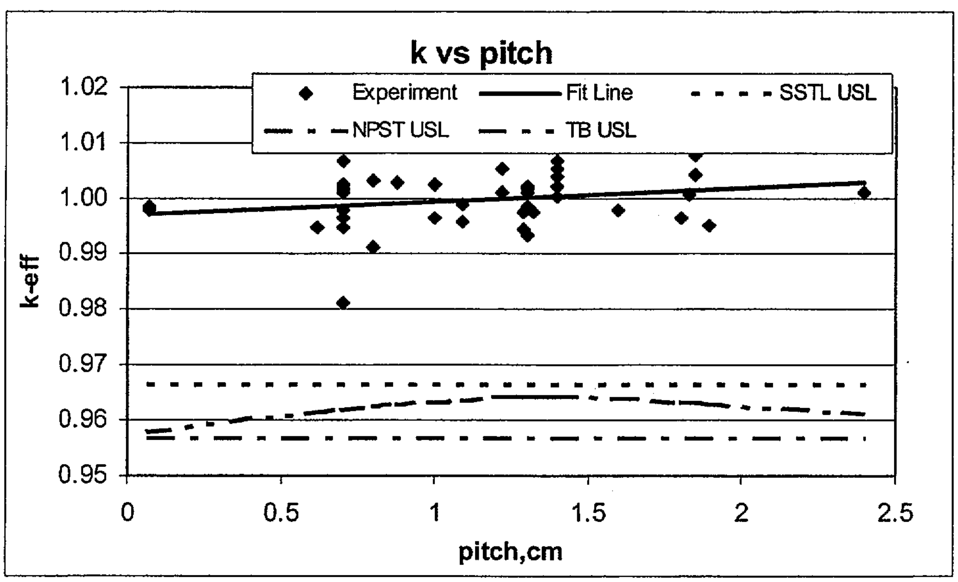

Figure 8.4 k vs pitch, all experiments wo dissolved absorbers, fit equation: k-eff = 0.9968463+(0.002504747)*pitch.

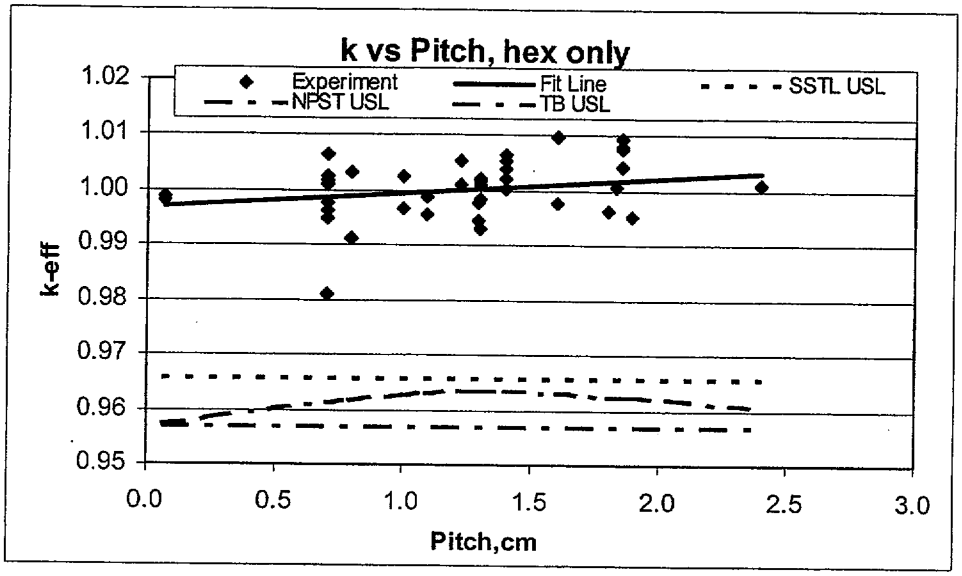

Figure 8.5 k vs pitch, hex experiments wo dissolved absorbers, fit equation: k-eff =0.9969635+(0.002548853)*pitch.

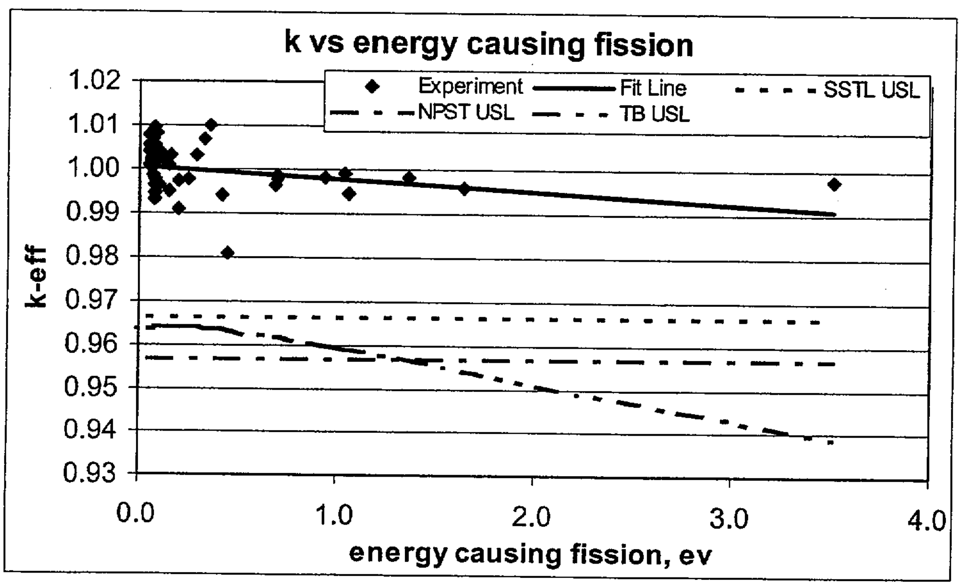

Figure 8.6 k vs energy causing fission, all experiments wo dissolved absorbers, fit equation: k-eff =1.000725+(-0.002837212)*ECF.

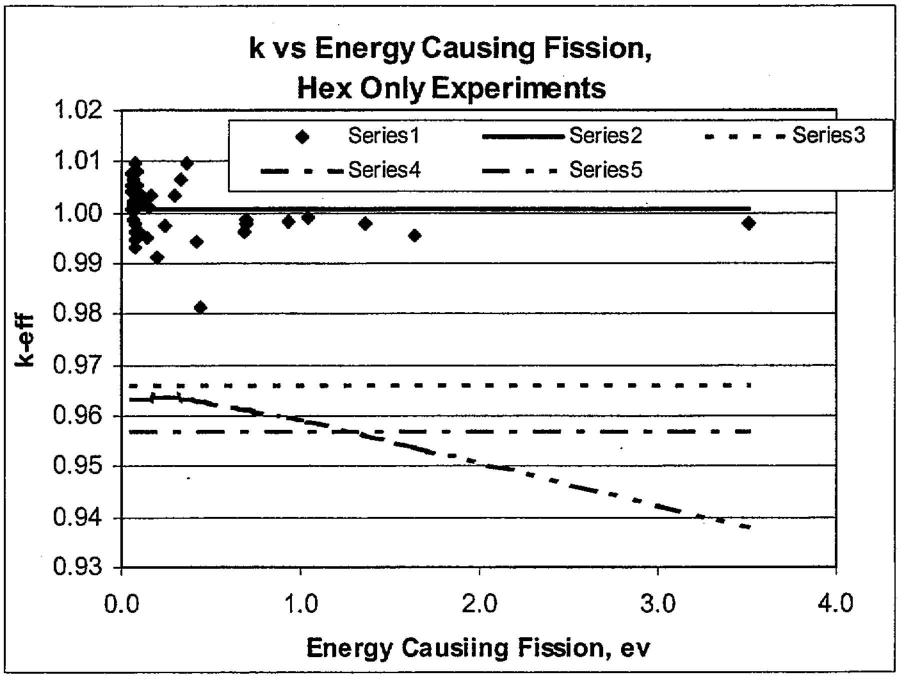

Figure 8.7 k vs energy causing fission, hex experiments wo dissolved absorbers, fit equation: k-eff = 1.000879+(-0.002692876)*ECF.

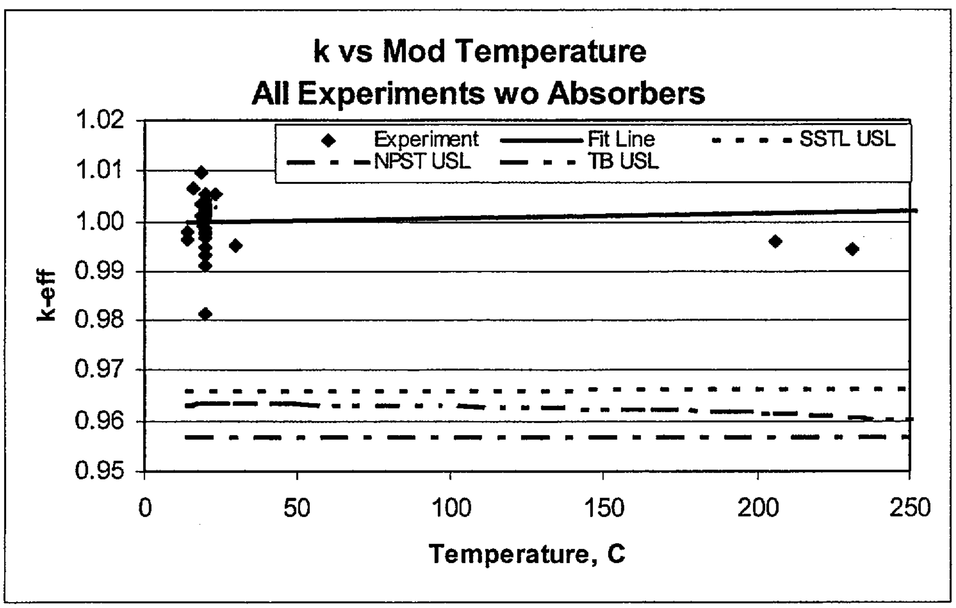

Figure 8.8 k vs temperature, all experiments wo dissolved absorbers, fit equation: k-eff =0.9994713+(0.00001810387)*TEMP.

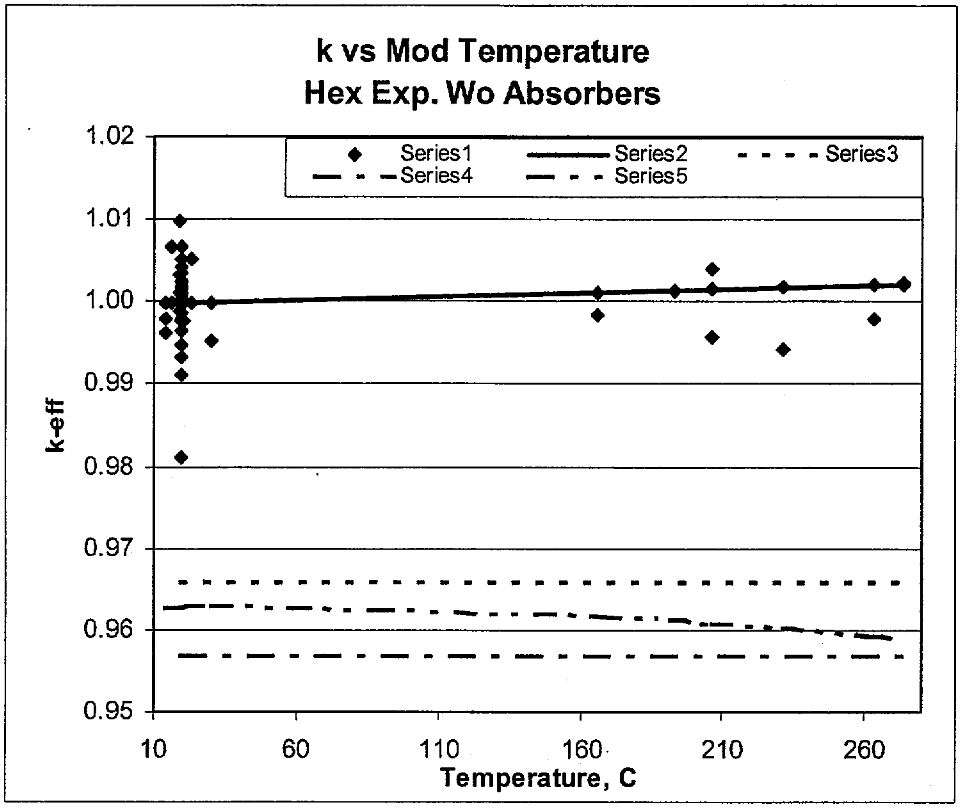

Figure 8.9 k vs temperature, hex experiments wo dissolved absorbers, fit equation: k-eff = 0.9996139+(0.000008789311)*TEMP.

Table 8.3 USL's and USTB for Enrichment Trending			
Wt%	All	Hex	Hex,lower deleted
SSTL	0.96626	**0.96577**	0.96697
NPTL	0.95692	0.95692	0.95663
2.350	0.95921	0.95875	0.96088
4.310	0.96144	0.96100	0.96299
4.920	0.96208	0.96164	0.96359
5.059	0.96222	0.96178	0.96372
5.256	0.96242	0.96197	0.96390
7.000	0.96381		
7.410	0.96402	0.96341	0.96485
9.830	0.96336	0.96265	0.96417
10.000	0.96326	0.96255	0.96408

Table 8.4 USL's and USTB for Pitch Trending					
Pitch	All	Hex	Pitch	All	Hex
SSTL	0.96626	**0.96577**			
NPTL	0.95692	0.95692			
0.07	0.95800	0.95739	1.3	0.96419	0.96353
0.62	0.96138		1.32	0.96418	
0.7	0.96184	0.96129	1.4	0.96411	0.96346
0.8	0.96238	0.96183	1.598	0.96376	0.96312
0.877	0.96277		1.801	0.96321	0.96257
1	0.96333	0.96281	1.83	0.96312	0.96249
1.09	0.96369	0.96317	1.852	0.96305	0.96242
1.22	0.96411	0.96353	1.895	0.96291	0.96228
1.29	0.96420	0.96353	2.398	0.96107	0.96043

Table 8.5 USL's and USTB for Temperature Trending					
Temp	All	Hex	Temp	All	Hex
SSTL	0.96577	**0.96577**			
NPTL	0.95692	0.95692			
14	0.96316	0.96258	30	0.96351	0.96293
16	0.96321	0.96263	166	0.96239	0.96176
19	0.96328	0.9627	193	0.96173	0.9611
19.3	0.96328	0.9627	206	0.96139	0.96077
20	0.9633	0.96272	231.4	0.96073	0.96009
20.1	0.9633	0.96272	263	0.95987	0.95923
23	0.96337	0.96279	274	0.95957	0.95892

Table 8.6 USL's and USTB for ECF Trending					
ECF	**All**	**Hex**	**ECF**	**All**	**Hex**
SSTL	0.96626	**0.96577**			
NPTL	0.95692	0.95692			
0.0539	0.96381	**0.96309**	0.104	0.96393	**0.96321**
0.0539	0.96381	**0.96309**	0.1225	0.96396	**0.96324**
0.054	0.96381	**0.96309**	0.1267	0.96397	**0.96325**
0.0544	0.96381	**0.96309**	0.1451	0.96400	
0.0619	0.96383	**0.96311**	0.1467	0.96401	**0.96329**
0.064	0.96383	**0.96311**	0.1519	0.96401	**0.96329**
0.0646	0.96384	**0.96311**	0.1635	0.96403	**0.96331**
0.0657	0.96384	**0.96312**	0.2021	0.96408	
0.0667	0.96384	**0.96312**	0.2049	0.96408	**0.96336**
0.0686	0.96385	**0.96312**	0.2468	0.96410	**0.96338**
0.0691	0.96385	**0.96313**	0.2943	0.96399	**0.96338**
0.0693	0.96385	**0.96313**	0.3325	0.96386	**0.96333**
0.0695	0.96385	**0.96313**	0.3628	0.96374	**0.96322**
0.0701	0.96385	**0.96313**	0.4218	0.96347	**0.96296**
0.0716	0.96385	**0.96313**	0.4459	0.96335	**0.96284**
0.0731	0.96386	**0.96314**	0.6857	0.96188	**0.96138**
0.0753	0.96386	**0.96314**	0.7019	0.96177	**0.96127**
0.0771	0.96387	**0.96315**	0.7024	0.96176	**0.96127**
0.0792	0.96387	**0.96315**	0.9358	0.96003	**0.95954**
0.0795	0.96387	**0.96315**	1.0372	0.95924	**0.95875**
0.0831	0.96388	**0.96316**	1.0574	0.95908	
0.0837	0.96388	**0.96316**	1.3578	0.95665	**0.95615**
0.092	0.96390	**0.96318**	1.6422	0.95429	**0.95378**
0.0998	0.96392	**0.9632**	3.508	0.93845	**0.93783**

6.2B.9. Conclusions

In summary, if the historical bias evaluation and application is desired with a 0.95 criticality safety limit is utilized from this data, the following equation should be used to obtain the K_{Max}:

$$K_{Max} = k_{calc} + bias + (^{95/59}Factor)\sqrt{(\sigma_{calc})^2 + (\sigma_{bias})^2}$$

where, based upon these experiments,

bias = -0.00003,
95./95 single sided confidence factor = 2.0458, and
σ_{bias} = 0.0066.

Thus, the equation becomes:

$$K_{Max} = k_{calc} + 0.00003 + (2.0458)\sqrt{(\sigma_{calc})^2 + (0.0066)^2}$$

Assuming about a million histories are used in the calculation, $\sigma_{cals} \approx$ 0.0011 (from the benchmark cases), thus $k_{eff} \leq$ 0.936 to satisfy the criticality safety criterion. If the single-sided upper tolerance limit is used and a 0.02 Δk can be assumed as the administrative safety margin for cases residing within the area of applicability, then the USL is 0.9656. Assuming the same safety margins, the upper tolerance band obtained for the trend versus energy causing fission would be used. The USL for a particular case is obtained at the ECF point of the system being examined. Using the ECF trending, the area of applicability is 0.0539 ev $\leq$ ECF $\leq$3.508 ev.

Attachment 6.2B.A. USLS Code Description and Verification

The USLS code was generated to automate the procedures described in NUREG-CR-6698[4] that may be used to validate calculational techniques used for criticality safety analyses. As stated in the NUREG, this is one method of validation. However, it further states that: "use of these procedures can ensure that validations are performed and documented with sufficient rigor to demonstrated compliance with safety limits during facility operations." These procedures are based upon an Upper Safety Limit (USL) that adequately ensures a subcritical system. The USL is defined as:

$$USL = 1.0 + Bias - \sigma_{Bias} - \Delta_{SM} - \Delta_{AOA}$$

and is the highest calculated k_{eff} that can be used in establishing subcritical safety limits and operating controls. The bias is the difference between an experimental k_{eff} and that from the calculational model of that experiment. To ensure conservatism, the bias is set to zero positive, i.e., the calculated k_{eff} is greater than the experimental value. The statistical uncertainty in the bias is represented by σ_{Bias}. The subcritical margin, Δ_{SM} is based upon the reactivity worth and ability to control the parameters and areas of applicability for the validation. The final term, Δ_{AOA} is an additional margin applied if an extension of the area of applicability beyond the validation parameters is made. The USL is applied such that:

$$k_{calc} + 2\sigma_{Calc} < USL$$

for all normal and credible abnormal operating conditions for the system being evaluated.

Use of the USLS code assumes that appropriate experiments have been chosen for the particular application and that they have been correctly modeled by the analysis code. It is further assumed that the parameters of the experiments have been defined to allow trending of the calculated biases. USLS uses the experimental and calculational k_{eff} values with their uncertainty plus user supplied statistical level of confidence values to determine the USL value(s) for each of the three procedures described in the NUREG. These are weighted a single-sided tolerance limit (K_L) and a single-sided tolerance band for normal distributions and a non-parametric method for values that do not satisfy the conditions for a normal distribution. A normality test (Shapiro-Wilk[5]) is included in USLS to assist is choosing the USL appropriate to the system being evaluated.

Input Description

The input requirements are relatively simple with three sets of data provided in Fortran free-format. The first set is the title line (≤ 80 characters). Note that if the first four characters are 'test' or 'TEST', then the verification case is executed from internally supplied data (see description below) and the remainder of the input data, if any, is ignored. The second set are 6 problem specific parameters: p, $F^{(fit,n-2)}$, $Z_{(2p-1)}$, $X^2_{(1-\gamma,n-2)}$, Δ_{SM}, and Δ_{AOA}, where:

- p = the desired confidence (generally 0.95),
- $F^{(fit,n-2)}$ = the F distribution percentile with degree of fit (2 for linear fit) and n-2 degrees of freedom. Use Excel function FINIV(1-p,2,n-2),
- $Z_{(2p-1)}$ = the symmetric percentile of normal distribution that contains the p fraction. Use Excel function NORMSINV(p),
- $X^2_{(1-\gamma,n-2)}$= the upper Chi-square percentile. Use Excel function CHIINV(1-γ,n-2), where γ =(1-p)/2,
- Δ_{SM} = administrative subcritical margin,
- Δ_{AOA} = subcritical margin for being outside the area of applicability.

The first four values are defined on page 13 of the NUREG. These Excel functions could have been included in USLS, however, to ensure consistency with the NUREG the Excel function results are provided by the user. The margin values are those discussed

[4] NUREG/CR-6698, "Guide for Validation of Nuclear Criticality Safety Calculational Methodology," US NRC, Division of Fuel Cycle Safety and Safeguards, Office of Nuclear Material Safety and Safeguards,, January, 2001.
[5] Shapiro and Wilk, (19650 Biometricka, Volume 52.

in the previous section for the definition of USL. The last set of data is sets of the five parameters x, k_{exp}, σ_{exp}, k_{calc}, σ_{calc} for each of up to 50 benchmark experiments. Note that a minimum of 10 experiments is required for any USL calculations by the NUREG. However, the tables listed in the NUREG have been supplemented to provide data for as little as 3 experiments. These data have been obtained primarily from the Shapiro and Welk paper. If less than 10 experiments are used, warning messages are printed in the output to indicate that less than 10 experiments have been used, see output file test10.out. In this last set of data, x is the independent variable used for trending, e.g., pitch, H/U, enrichment, k_{exp} and σ_{exp} are the experimental k_{eff} and σ, and k_{calc} and σ_{calc} are those from the calculation. The experimental k_{eff} is generally 1.0, however, in some cases it may differ slightly from 1.0. Thus, this value is included in the input to allow calculation of a normalized calculated k_{eff}, such that $k_{norm} = k_{calc}/k_{exp}$. The normalized k_{eff} is then used in the USL calculations (see NUREG page 8).

The input for the NUREG test problem and the verification case for this program is listed in Table 1. This case provides the input for the NUREG sample problem discussed in Section 3 of the NUREG.

Output Description

Table 2 contains a listing of the output for the sample problem. The first block of data is an edit of the input data. This includes the title, the user specified parameters, and the set of four values for each independent variable. In addition, the number of experimental data sets is also listed as calculated by USLS. The benchmark and experimental data is printed in a slightly different order than as input with two addition values. They are the normalized k_{eff} and the total sigma. The total sigma is defined as (see eq. 3 NUREG):

$$\sigma_{Total} = \sqrt{\sigma_{Exp}^2 + \sigma_{Calc}^2}$$

The next blocks of data provide the bias and fitting calculational results, the single-side tolerance USL, the normality result, the non-parametric USL, and finally the single-sided tolerance band data. Each of these blocks provides the results for each interim calculation described in the NUREG to determine the fitting coefficients and the USL values. These listed values enable independent calculation using the equations in the NUREG to check the values calculated with USLS. The final block is a summary listing of the calculated data containing only the significant results of the calculation, such as the USL values, the results of the normalcy test, etc.

Executing USLS

USLS is executed simply as follows:

Usls < 'inputfile' >'outputfile'

Execution is completed in a matter of seconds.

Table 1. Sample Input File

```
NUREG/CR-6689 SAMPLE PROBLEM/VERIFICATION CASE
0.95 3.422 1.645 11.689 0.02 0.03
421.8 1.0 0.0049 0.9848 0.0014
421.8 1.0 0.0049 0.9869 0.0015
421.8 1.0 0.0049 0.9864 0.0013
195.2 1.0 0.0049 0.9990 0.0015
195.2 1.0 0.0049 0.9961 0.0015
293.9 1.0 0.0049 1.0004 0.0018
293.9 1.0 0.0049 0.9963 0.0014
406.3 1.0 0.0049 0.9964 0.0015
495.9 1.0 0.0049 0.9969 0.0018
613.6 1.0 0.0049 0.9927 0.0013
613.6 1.0 0.0049 0.9921 0.0016
971.7 1.0 0.0049 0.9881 0.0013
971.7 1.0 0.0049 0.9856 0.0015
133.4 1.0 0.0049 1.0039 0.0016
133.4 1.0 0.0049 1.0114 0.0018
133.4 1.0 0.0049 1.0108 0.0017
133.4 1.0 0.0049 1.0071 0.0018
133.4 1.0 0.0049 1.0064 0.0022
133.4 1.0 0.0049 1.0113 0.0018
133.4 1.0 0.0049 1.0128 0.0021
133.4 1.0 0.0049 1.0067 0.0018
276.9 1.0 0.0049 1.0054 0.0018
276.9 1.0 0.0049 1.0053 0.0016
276.9 1.0 0.0049 1.0071 0.0020
276.9 1.0 0.0049 1.0112 0.0019
```

Table2. Sample Problem Output Listing

```
*************** BEGINNING OF CASE ***************
        NUREG/CR-6689 SAMPLE PROBLEM/VERIFICATION CASE


     ***********          INPUT DATA           ***********

            Desired confidence, P                         =     .950
            F distribution percentile, F                  =    3.422
            Normal dist. containing P fraction, Z         =    1.645
            Upper Chi-square percentile, X                =   11.689
            Administrative margin, delta k-sm             =     .020
            Area of Applicability margin, delta k-aoa =     .030
            Number of experiments input, n                =   25

        Title: NUREG/CR-6689 SAMPLE PROBLEM/VERIFICATION CASE

     *** Experimental and Calculational Input Data ***
```

Indepdnt Varble x	k-eff Expmnt	k-eff Calcultd	k-eff Normalzd	Sigma Expmnt	Sigma Calcultd	Sigma Total
421.8000	1.00000	.98480	.98480	.00140	.00490	.00510
421.8000	1.00000	.98690	.98690	.00150	.00490	.00512
421.8000	1.00000	.98640	.98640	.00130	.00490	.00507
195.2000	1.00000	.99900	.99900	.00150	.00490	.00512
195.2000	1.00000	.99610	.99610	.00150	.00490	.00512
293.9000	1.00000	1.00040	1.00040	.00180	.00490	.00522
293.9000	1.00000	.99630	.99630	.00140	.00490	.00510
406.3000	1.00000	.99640	.99640	.00150	.00490	.00512
495.9000	1.00000	.99690	.99690	.00180	.00490	.00522
613.6000	1.00000	.99270	.99270	.00130	.00490	.00507
613.6000	1.00000	.99210	.99210	.00160	.00490	.00515
971.7000	1.00000	.98810	.98810	.00130	.00490	.00507
971.7000	1.00000	.98560	.98560	.00150	.00490	.00512
133.4000	1.00000	1.00390	1.00390	.00160	.00490	.00515
133.4000	1.00000	1.01140	1.01140	.00180	.00490	.00522
133.4000	1.00000	1.01080	1.01080	.00170	.00490	.00519
133.4000	1.00000	1.00710	1.00710	.00180	.00490	.00522
133.4000	1.00000	1.00640	1.00640	.00220	.00490	.00537
133.4000	1.00000	1.01130	1.01130	.00180	.00490	.00522
133.4000	1.00000	1.01280	1.01280	.00210	.00490	.00533
133.4000	1.00000	1.00670	1.00670	.00180	.00490	.00522
276.9000	1.00000	1.00540	1.00540	.00180	.00490	.00522
276.9000	1.00000	1.00530	1.00530	.00160	.00490	.00515
276.9000	1.00000	1.00710	1.00710	.00200	.00490	.00529
276.9000	1.00000	1.01120	1.01120	.00190	.00490	.00526

```
     ********* BIAS AND FIT CALCULATED DATA *********

            Weighted mean k-eff                     =    .99983
            Average total uncertainty, sigbar2      = 2.679909E-05
            Bias = Weighted Avg Keff - 1            =-1.659174E-04
            Variance, s2 of pooled variance         = 8.479933E-05
            Sqrt of pool variance, Sp               = 1.056402E-02
            Delta used to obtain a, b               = 4.949075E+16
            Weighted mean independent variable      = 3.435761E+02
            Linear-correlation coefficeint, r       =-7.566964E-01
        *** Fit constant, a in k=a + bx             = 1.009670E+00
        *** Fit constant, b in k=a + bx             =-2.862935E-05
        *** r-squared                               = 5.725894E-01

     ******** USL VALUES BY VARIOUS METHODS ********

            **** SINGLE SIDED TOLERANCE LIMIT ****

            Weighted mean k-eff                     =   .99983
            Single Sided Lower Tol. Factor U        =  2.29200
```

```
      Sqrt of pool variance, Sp              = 1.056402E-02
      Single Sided Tol. Limit Kl             =   .97562
      Administrative margin, delta k-sm      =    .020
      Area of Applblty margin, delta k-aoa   =    .030
 ***  Single Sided Tol. Limit USL            =   .92562

      ****** Shapiro-Wilk Test for Normality ******
      ** for use of Single Sided Tolerance Limit **

      Number of Experiments, n                       =  25
      Unweighted average k-eff                       =  1.00004
      Y value in Shapiro-Wilk  equation              = 4.314720E-02
      S2 value in Shapiro-Wilk  equation             = 2.027562E-03
      Test static Wt = Y2S2 (Sh-Welk eq)             = 9.181871E-01
      Sh-Welk percentage point for n expmts,SWpp     = 9.180000E-01
      Normal Distribution if Wt/SWpp>1.0, Wt/SWpp    =  1.00020


      **** NON-PARAMETRIC STATISTICAL TREATMENT ****

      Non-parametric stat. treatment beta    =   .72261
      Non-parametric stat. treatment margin  =   .02000
      Smallest calculated k-eff              =   .98480
      Total uncertainty for smallest k-eff   = 5.096077E-03
      Non-parametric stat. treatment Kl      =   .95970
      Administrative margin, delta k-sm      =    .020
      Area of Applblty margin, delta k-aoa   =    .030
 ***  Non-parametric stat. treatment USL     =   .90970


      **** SINGLE-SIDED TOLERANCE BAND - WEIGHTED LIMIT****

      *** Data Used in Tolerance Band Calculation of KL ***

      F-distribution                         =  3.42200
      Znorm                                  =  1.64500
      xchi2                                  = 11.68900
      Fit constant, a in k=a + bx            = 1.009670E+00
      Fit constant, b in k=a + bx            =-2.862935E-05
      Sigma average                          = 2.679909E-05
      S-fit2                                 = 3.781996E-05
      S-Pfit                                 = 8.038598E-03
      Average indpendent variable, xbar      = 3.435761E+02
      Administrative Margin                  =    .020
      Range of Applicability Margin          =    .030

      *** Tolerance Band and USL Values ***

           x        knorm     kfit or 1     KL        USL    ***
      421.8000     .98480      .99759     .97462     .92462
      421.8000     .98690      .99759     .97462     .92462
      421.8000     .98640      .99759     .97462     .92462
      195.2000     .99900     1.00000     .97650     .92650
      195.2000     .99610     1.00000     .97650     .92650
      293.9000    1.00040     1.00000     .97715     .92715
      293.9000     .99630     1.00000     .97715     .92715
      293.9000     .99630     1.00000     .97715     .92715
      406.3000     .99640      .99804     .97514     .92514
      495.9000     .99690      .99547     .97193     .92193
      613.6000     .99270      .99210     .96720     .91720
      613.6000     .99210      .99210     .96720     .91720
      971.7000     .98810      .98185     .95145     .90145
      971.7000     .98560      .98185     .95145     .90145
      133.4000    1.00390     1.00000     .97584     .92584
      133.4000    1.01140     1.00000     .97584     .92584
      133.4000    1.01080     1.00000     .97584     .92584
      133.4000    1.00710     1.00000     .97584     .92584
      133.4000    1.00640     1.00000     .97584     .92584
      133.4000    1.01130     1.00000     .97584     .92584
      133.4000    1.01280     1.00000     .97584     .92584
      133.4000    1.00670     1.00000     .97584     .92584
```

```
276.9000   1.00540   1.00000    .97708    .92708
276.9000   1.00530   1.00000    .97708    .92708
276.9000   1.00710   1.00000    .97708    .92708
276.9000   1.01120   1.00000    .97708    .92708


*********************************************************
                    OUTPUT SUMMARY
NUREG/CR-6689 SAMPLE PROBLEM/VERIFICATION CASE
*********************************************************

Number of Experimental Points, n         =  25
Weighted Mean keff                       =  .99983
Bias = Mean keff -1                      = -.00017
Uncertainty in Mean keff and bias        =  .01056
Single Sided Lower Tol. Factor U         = 2.29200

Fit Equation: k-eff = 1.009670E+00 + (-2.862935E-05 )X
Square of Linear-Correlation Coef., r2   =   .57259

Area of Applicability:  133.400 <= x <=  971.700

Administrative Margin Assumed            =    .020
Range of Applicablity Margin Assumed     =    .030

Single-Sided Tolerance Limit USL         =   .92562
Normal Dist if Wt/SWpp>1.0, Wt/SWpp      =  1.00020

Non-parametric statistical treatment USL =   .90970

  *** Ordered Tolerance Band and USL Values ***
     x         kfit    kfit or 1    KL         USL
133.4000   1.00585   1.00000    .97584    .92584
195.2000   1.00408   1.00000    .97650    .92650
276.9000   1.00174   1.00000    .97708    .92708
293.9000   1.00126   1.00000    .97715    .92715
406.3000    .99804    .99804    .97514    .92514
421.8000    .99759    .99759    .97462    .92462
495.9000    .99547    .99547    .97193    .92193
613.6000    .99210    .99210    .96720    .91720
971.7000    .98185    .98185    .95145    .90145


***********          END OF CASE         ***********
```

Verification of USLS

Verification of USLS is provided by the sample problem listed in the NUREG. A comparison of the data detailed output blocks with the corresponding calculation results listed in Section 3 of the NUREG provides the verification of correct calculations by USLS. In particular, a comparison of the fit coefficients and USL values in the summary table listed in Table 2 (from output file tstinp.out) with the corresponding values in the NUREG shows that USLS is correctly calculating the sample problem values. Note that the single-sided tolerance band USL values differ from those in the NUREG table by –0.02. This is due to the need to set Δ_{AOA} equal to 0.02 for the other two USL calculations. It cannot be changed during the execution of USLS to zero for the SS tolerance band calculation as in the NUREG.

Since this in an open shop program, verification of correct operation with each use must be provided. To facilitate this process, the sample problem input has been incorporated into a subroutine of USLS. If the first four characters of the title are either 'test' or 'TEST', the input values will be set to those for the sample problem and executed. Note that any additional data provided in the input file other than 'test' on the title card will be ignored. A modified output format is provided for this case, as seen from Table 3 taken from output file test.out. The modification is an additional data block at the beginning of the output that lists selected constants from the NUREG. This facilitates checking of the values calculated by USLS for the individual use verification.

Table 3. 'TEST' Case Output Listing

```
**************************************************

                  THE FOLLOWING INPUT TAKEN FROM NUREG/CR-6698 SAMPLE PROBLEM
                  CHECK THE FOLLOWING SELECTED VALUES FROM THE NUREG WITH
                  THE RESULTS BELOW TO VERIFY CORRECT OPERATIOON OF THIS PROGRAM:

                       Weighted mean k-eff                           = 0.99983
                       Square Root of pooled variance, Sp            = 1.056e-02
                       Weighted linear fit equation intercept, a     = 1.00967
                       Weighted linear fit equation slope,     b     = 2.863e-5
                       Square of linear-correlation coefficient, r2= 0.57
                       Single-Sided USL                              = 0.92562
                       Shapiro-Wilk test statistic, WL               = 0.9182
                       Non-parametric statistical treatment USL      = 0.9097
                       Single-Sided Tol. Band KL for x=421.8         = 0.9746
                       (note: SS Tol. Band USL differs since aoa =0.03
                       in results below, while NUREG assumes aoa = 0.0)

                       **************************************************


      *************** BEGINNING OF CASE ***************
         NUREG/CR-6698 SAMPLE PROBLEM/VERIFICATION CASE


      ***********          INPUT DATA          ***********

            Desired confidence, P                        =    .950
            F distribution percentile, F                 =   3.422
            Normal dist. containing P fraction, Z        =   1.645
            Upper Chi-square percentile, X               =  11.689
            Administrative margin, delta k-sm            =    .020
            Area of Applicability margin, delta k-aoa =      .030
            Number of experiments input, n               =  25

         Title: NUREG/CR-6698 SAMPLE PROBLEM/VERIFICATION CASE

      *** Experimental and Calculational Input Data ***
```

Indepdnt Varble x	k-eff Expmnt	k-eff Calcultd	k-eff Normalzd	Sigma Expmnt	Sigma Calcultd	Sigma Total
421.8000	1.00000	.98480	.98480	.00140	.00490	.00510
421.8000	1.00000	.98690	.98690	.00150	.00490	.00512
421.8000	1.00000	.98640	.98640	.00130	.00490	.00507
195.2000	1.00000	.99900	.99900	.00150	.00490	.00512
195.2000	1.00000	.99610	.99610	.00150	.00490	.00512
293.9000	1.00000	1.00040	1.00040	.00180	.00490	.00522
293.9000	1.00000	.99630	.99630	.00140	.00490	.00510
406.3000	1.00000	.99640	.99640	.00150	.00490	.00512
495.9000	1.00000	.99690	.99690	.00180	.00490	.00522
613.6000	1.00000	.99270	.99270	.00130	.00490	.00507
613.6000	1.00000	.99210	.99210	.00160	.00490	.00515
971.7000	1.00000	.98810	.98810	.00130	.00490	.00507
971.7000	1.00000	.98560	.98560	.00150	.00490	.00512
133.4000	1.00000	1.00390	1.00390	.00160	.00490	.00515
133.4000	1.00000	1.01140	1.01140	.00180	.00490	.00522
133.4000	1.00000	1.01080	1.01080	.00170	.00490	.00519
133.4000	1.00000	1.00710	1.00710	.00180	.00490	.00522
133.4000	1.00000	1.00640	1.00640	.00220	.00490	.00537
133.4000	1.00000	1.01130	1.01130	.00180	.00490	.00522
133.4000	1.00000	1.01280	1.01280	.00210	.00490	.00533
133.4000	1.00000	1.00670	1.00670	.00180	.00490	.00522
133.4000	1.00000	1.00670	1.00670	.00180	.00490	.00522
276.9000	1.00000	1.00540	1.00540	.00180	.00490	.00522
276.9000	1.00000	1.00530	1.00530	.00160	.00490	.00515

```
276.9000   1.00000  1.00710  1.00710   .00200   .00490   .00529
276.9000   1.00000  1.01120  1.01120   .00190   .00490   .00526


    ********* BIAS AND FIT CALCULATED DATA *********

            Weighted mean k-eff                      =    .99983
            Average total uncertainty, sigbar2       = 2.679909E-05
            Bias = Weighted Avg Keff - 1             =-1.659242E-04
            Variance, s2 of pooled variance          = 8.479930E-05
            Sqrt of pool variance, Sp                = 1.056401E-02
            Delta used to obtain a, b                = 4.949075E+16
            Weighted mean independent variable       = 3.435761E+02
            Linear-correlation coefficeint, r        =-7.566967E-01
       ***  Fit constant, a in k=a + bx              = 1.009670E+00
       ***  Fit constant, b in k=a + bx              =-2.862936E-05
       ***  r-squared                                = 5.725899E-01


    ******** USL VALUES BY VARIOUS METHODS ********

            **** SINGLE SIDED TOLERANCE LIMIT ****

            Weighted mean k-eff                      =    .99983
            Single Sided Lower Tol. Factor U         =   2.29200
            Sqrt of pool variance, Sp                = 1.056401E-02
            Single Sided Tol. Limit Kl               =    .97562
            Administrative margin, delta k-sm        =     .020
            Area of Applblty margin, delta k-aoa     =     .030
       ***  Single Sided Tol. Limit USL              =    .92562

            ****** Shapiro-Wilk Test for Normality ******
            ** for use of Single Sided Tolerance Limit **

            Number of Experiments, n                        =  25
            Unweighted average k-eff                        =  1.00004
            Y value in Shapiro-Wilk  equation               = 4.314718E-02
            S2 value in Shapiro-Wilk  equation              = 2.027561E-03
            Test static Wt = Y2S2 (Sh-Welk eq)              = 9.181867E-01
            Sh-Welk percentage point for n expmts,SWpp      = 9.180000E-01
            Normal Distribution if Wt/SWpp>1.0, Wt/SWpp     =  1.00020


            **** NON-PARAMETRIC STATISTICAL TREATMENT ****

            Non-parametric stat. treatment beta      =    .72261
            Non-parametric stat. treatment margin    =    .02000
            Smallest calculated k-eff                =    .98480
            Total uncertainty for smallest k-eff     = 5.096077E-03
            Non-parametric stat. treatment Kl        =    .95970
            Administrative margin, delta k-sm        =     .020
            Area of Applblty margin, delta k-aoa     =     .030
       ***  Non-parametric stat. treatment USL       =    .90970


            **** SINGLE-SIDED TOLERANCE BAND - WEIGHTED LIMIT****

            *** Data Used in Tolerance Band Calculation of KL ***

            F-distribution                           =  3.42200
            Znorm                                    =  1.64500
            xchi2                                    = 11.68900
            Fit constant, a in k=a + bx              = 1.009670E+00
            Fit constant, b in k=a + bx              =-2.862936E-05
            Sigma average                            = 2.679909E-05
            S-fit2                                   = 3.781991E-05
            S-Pfit                                   = 8.038594E-03
            Average indpendent variable, xbar        = 3.435761E+02
            Administrative Margin                    =     .020
            Range of Applicability Margin            =     .030
```

*** Tolerance Band and USL Values ***

x	knorm	kfit or 1	KL	USL ***
421.8000	.98480	.99759	.97462	.92462
421.8000	.98690	.99759	.97462	.92462
421.8000	.98640	.99759	.97462	.92462
195.2000	.99900	1.00000	.97650	.92650
195.2000	.99610	1.00000	.97650	.92650
293.9000	1.00040	1.00000	.97715	.92715
293.9000	.99630	1.00000	.97715	.92715
406.3000	.99640	.99804	.97514	.92514
495.9000	.99690	.99547	.97193	.92193
613.6000	.99270	.99210	.96720	.91720
613.6000	.99210	.99210	.96720	.91720
971.7000	.98810	.98185	.95145	.90145
971.7000	.98560	.98185	.95145	.90145
133.4000	1.00390	1.00000	.97584	.92584
133.4000	1.01140	1.00000	.97584	.92584
133.4000	1.01080	1.00000	.97584	.92584
133.4000	1.00710	1.00000	.97584	.92584
133.4000	1.00640	1.00000	.97584	.92584
133.4000	1.01130	1.00000	.97584	.92584
133.4000	1.01280	1.00000	.97584	.92584
133.4000	1.00670	1.00000	.97584	.92584
276.9000	1.00540	1.00000	.97708	.92708
276.9000	1.00530	1.00000	.97708	.92708
276.9000	1.00710	1.00000	.97708	.92708
276.9000	1.01120	1.00000	.97708	.92708

****

OUTPUT SUMMARY

NUREG/CR-6698 SAMPLE PROBLEM/VERIFICATION CASE

****

Number of Experimental Points, n = 25
Weighted Mean keff = .99983
Bias = Mean keff -1 = -.00017
Uncertainty in Mean keff and bias = .01056
Single Sided Lower Tol. Factor U = 2.29200

Fit Equation: k-eff = 1.009670E+00 + (-2.862936E-05)X
Square of Linear-Correlation Coef., r2 = .57259

Area of Applicability: 133.400 <= x <= 971.700

Administrative Margin Assumed = .020
Range of Applicablity Margin Assumed = .030

Single-Sided Tolerance Limit USL = .92562

Single-Sided Tolerance Limit USL = .92562
Normal Dist if Wt/SWpp>1.0, Wt/SWpp = 1.00020

Non-parametric statistical treatment USL = .90970

*** Ordered Tolerance Band and USL Values ***

x	kfit	kfit or 1	KL	USL
133.4000	1.00585	1.00000	.97584	.92584
195.2000	1.00408	1.00000	.97650	.92650
276.9000	1.00174	1.00000	.97708	.92708
293.9000	1.00126	1.00000	.97715	.92715
406.3000	.99804	.99804	.97514	.92514
421.8000	.99759	.99759	.97462	.92462
495.9000	.99547	.99547	.97193	.92193
613.6000	.99210	.99210	.96720	.91720
971.7000	.98185	.98185	.95145	.90145

*********** END OF CASE ***********

References

1. NUREG/CR-6698, "Guide for Validation of Nuclear Criticality Safety Calculational Methodology," US NRC, Division of Fuel Cycle Safety and Safeguards, Office of Nuclear Material Safety and Safeguards,, January, 2001.
2. S.S. Shapiro and M.B.Wilk, "An analysis of variance test for normality (complete samples," Biometricka(1965), Volume 52, 3 and 4, Pp 591-611.

Attachment 6.2B.B. USLS Output Summary for Trending Evaluation

lec238ecf.out

```
*********************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Gp All vs Energy causing fission
*********************************************************

Number of Experimental Points, n          =  48
Weighted Mean keff                        =  .99997
Bias = Mean keff -1                       = -.00003
Uncertainty in Mean keff and bias         =  .00660

Fit Equation: k-eff = 1.000725E+00 + (-2.837212E-03 )X
Square of Linear-Correlation Coef., r2    =   .05217

Area of Applicability:      .054 <= x <=    3.508

Administrative Margin Assumed             =    .020
Range of Applicablity Margin Assumed      =    .000

Single-Sided Tolerance Limit USL          =   .96626
Normal Dist if Wt/SWpp>1.0, Wt/SWpp       =  1.00789

Non-parametric statistical treatment USL =   .95692

  *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
.0539	1.00057	1.00000	.98381	.96381
.0539	1.00057	1.00000	.98381	.96381
.0540	1.00057	1.00000	.98381	.96381
.0544	1.00057	1.00000	.98381	.96381
.0619	1.00055	1.00000	.98383	.96383
.0640	1.00054	1.00000	.98383	.96383
.0646	1.00054	1.00000	.98384	.96384
.0657	1.00054	1.00000	.98384	.96384
.0667	1.00054	1.00000	.98384	.96384
.0686	1.00053	1.00000	.98385	.96385
.0691	1.00053	1.00000	.98385	.96385
.0693	1.00053	1.00000	.98385	.96385
.0695	1.00053	1.00000	.98385	.96385
.0701	1.00053	1.00000	.98385	.96385
.0716	1.00052	1.00000	.98385	.96385
.0731	1.00052	1.00000	.98386	.96386
.0753	1.00051	1.00000	.98386	.96386
.0771	1.00051	1.00000	.98387	.96387
.0792	1.00050	1.00000	.98387	.96387
.0795	1.00050	1.00000	.98387	.96387
.0831	1.00049	1.00000	.98388	.96388
.0837	1.00049	1.00000	.98388	.96388
.0920	1.00046	1.00000	.98390	.96390
.0998	1.00044	1.00000	.98392	.96392
.1040	1.00043	1.00000	.98393	.96393
.1225	1.00038	1.00000	.98396	.96396
.1267	1.00037	1.00000	.98397	.96397
.1451	1.00031	1.00000	.98400	.96400
.1467	1.00031	1.00000	.98401	.96401
.1519	1.00029	1.00000	.98401	.96401
.1635	1.00026	1.00000	.98403	.96403
.2021	1.00015	1.00000	.98408	.96408

.2049	1.00014	1.00000	.98408	.96408
.2468	1.00002	1.00000	.98410	.96410
.2943	.99989	.99989	.98399	.96399
.3325	.99978	.99978	.98386	.96386
.3628	.99970	.99970	.98374	.96374
.4218	.99953	.99953	.98347	.96347
.4459	.99946	.99946	.98335	.96335
.6857	.99878	.99878	.98188	.96188
.7019	.99873	.99873	.98177	.96177
.7024	.99873	.99873	.98176	.96176
.9358	.99807	.99807	.98003	.96003
1.0372	.99778	.99778	.97924	.95924
1.0574	.99772	.99772	.97908	.95908
1.3578	.99687	.99687	.97665	.95665
1.6422	.99607	.99607	.97429	.95429
3.5080	.99077	.99077	.95845	.93845

lec238ecfh.out

```
*********************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Gp:only hex arrays vs Energy causing fission, wo absorbers
*********************************************************

Number of Experimental Points, n          =  45
Weighted Mean keff                        = 1.00017
Bias = Mean keff -1                       =  .00017
Uncertainty in Mean keff and bias         =  .00680

Fit Equation: k-eff = 1.000879E+00 + (-2.692876E-03 )X
Square of Linear-Correlation Coef., r2    =    .04662

Area of Applicability:     .054 <= x <=    3.508

Administrative Margin Assumed             =     .020
Range of Applicablity Margin Assumed      =     .000

Single-Sided Tolerance Limit USL          =    .96577
Normal Dist if Wt/SWpp>1.0, Wt/SWpp       =  1.00635

Non-parametric statistical treatment USL =    .95692

  *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
.0539	1.00073	1.00000	.98309	.96309
.0539	1.00073	1.00000	.98309	.96309
.0540	1.00073	1.00000	.98309	.96309
.0544	1.00073	1.00000	.98309	.96309
.0619	1.00071	1.00000	.98311	.96311
.0640	1.00071	1.00000	.98311	.96311
.0646	1.00071	1.00000	.98311	.96311
.0657	1.00070	1.00000	.98312	.96312
.0667	1.00070	1.00000	.98312	.96312
.0686	1.00069	1.00000	.98312	.96312
.0691	1.00069	1.00000	.98313	.96313
.0693	1.00069	1.00000	.98313	.96313
.0695	1.00069	1.00000	.98313	.96313
.0701	1.00069	1.00000	.98313	.96313
.0716	1.00069	1.00000	.98313	.96313
.0731	1.00068	1.00000	.98314	.96314
.0753	1.00068	1.00000	.98314	.96314
.0771	1.00067	1.00000	.98315	.96315
.0792	1.00067	1.00000	.98315	.96315

.0795	1.00066	1.00000	.98315	.96315
.0831	1.00066	1.00000	.98316	.96316
.0837	1.00065	1.00000	.98316	.96316
.0920	1.00063	1.00000	.98318	.96318
.0998	1.00061	1.00000	.98320	.96320
.1040	1.00060	1.00000	.98321	.96321
.1225	1.00055	1.00000	.98324	.96324
.1267	1.00054	1.00000	.98325	.96325
.1467	1.00048	1.00000	.98329	.96329
.1519	1.00047	1.00000	.98329	.96329
.1635	1.00044	1.00000	.98331	.96331
.2049	1.00033	1.00000	.98336	.96336
.2468	1.00021	1.00000	.98338	.96338
.2943	1.00009	1.00000	.98338	.96338
.3325	.99998	.99998	.98333	.96333
.3628	.99990	.99990	.98322	.96322
.4218	.99974	.99974	.98296	.96296
.4459	.99968	.99968	.98284	.96284
.6857	.99903	.99903	.98138	.96138
.7019	.99899	.99899	.98127	.96127
.7024	.99899	.99899	.98127	.96127
.9358	.99836	.99836	.97954	.95954
1.0372	.99809	.99809	.97875	.95875
1.3578	.99722	.99722	.97615	.95615
1.6422	.99646	.99646	.97378	.95378
3.5080	.99143	.99143	.95783	.93783

lec238ecfhl.out

```
**********************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Gp:only hex arrays vs Energy causing fission, wo absorbers
**********************************************************

Number of Experimental Points, n          =  45
Weighted Mean keff                        = 1.00017
Bias = Mean keff -1                       =  .00017
Uncertainty in Mean keff and bias         =  .00680

Fit Equation: k-eff = 1.000879E+00 + (-2.692876E-03 )X
Square of Linear-Correlation Coef., r2    =    .04662

Area of Applicability:      .054 <= x <=    3.508

Administrative Margin Assumed             =    .020
Range of Applicablity Margin Assumed      =    .000

Single-Sided Tolerance Limit USL          =   .96577
Normal Dist if Wt/SWpp>1.0, Wt/SWpp       =  1.00635

Non-parametric statistical treatment USL =   .95692

  *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
.0539	1.00073	1.00000	.98287	.96287
.0539	1.00073	1.00000	.98287	.96287
.0540	1.00073	1.00000	.98287	.96287
.0544	1.00073	1.00000	.98287	.96287
.0619	1.00071	1.00000	.98289	.96289
.0640	1.00071	1.00000	.98290	.96290
.0646	1.00071	1.00000	.98290	.96290
.0657	1.00070	1.00000	.98290	.96290
.0667	1.00070	1.00000	.98291	.96291

.0686	1.00069	1.00000	.98291	.96291
.0691	1.00069	1.00000	.98291	.96291
.0693	1.00069	1.00000	.98291	.96291
.0695	1.00069	1.00000	.98291	.96291
.0701	1.00069	1.00000	.98291	.96291
.0716	1.00069	1.00000	.98292	.96292
.0731	1.00068	1.00000	.98292	.96292
.0753	1.00068	1.00000	.98293	.96293
.0771	1.00067	1.00000	.98293	.96293
.0792	1.00067	1.00000	.98294	.96294
.0795	1.00066	1.00000	.98294	.96294
.0831	1.00066	1.00000	.98295	.96295
.0837	1.00065	1.00000	.98295	.96295
.0920	1.00063	1.00000	.98297	.96297
.0998	1.00061	1.00000	.98298	.96298
.1040	1.00060	1.00000	.98299	.96299
.1225	1.00055	1.00000	.98303	.96303
.1267	1.00054	1.00000	.98304	.96304
.1467	1.00048	1.00000	.98307	.96307
.1519	1.00047	1.00000	.98308	.96308
.1635	1.00044	1.00000	.98310	.96310
.2049	1.00033	1.00000	.98314	.96314
.2468	1.00021	1.00000	.98317	.96317
.2943	1.00009	1.00000	.98316	.96316
.3325	.99998	.99998	.98312	.96312
.3628	.99990	.99990	.98300	.96300
.4218	.99974	.99974	.98274	.96274
.4459	.99968	.99968	.98263	.96263
.6857	.99903	.99903	.98117	.96117
.7019	.99899	.99899	.98106	.96106
.7024	.99899	.99899	.98106	.96106
.9358	.99836	.99836	.97933	.95933
1.0372	.99809	.99809	.97853	.95853
1.3578	.99722	.99722	.97593	.95593
1.6422	.99646	.99646	.97356	.95356
3.5080	.99143	.99143	.95761	.93761

lec238en.out

```
*******************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Gp:All exp vs Wt%
*******************************************************

Number of Experimental Points, n          =  48
Weighted Mean keff                        =  .99997
Bias = Mean keff -1                       = -.00003
Uncertainty in Mean keff and bias         =  .00660

Fit Equation: k-eff = 9.968116E-01 + ( 4.200326E-04 )X
Square of Linear-Correlation Coef., r2     =   .05034

Area of Applicability:    2.350 <= x <=   10.000

Administrative Margin Assumed              =    .020
Range of Applicablity Margin Assumed       =    .000

Single-Sided Tolerance Limit USL           =   .96626
Normal Dist if Wt/SWpp>1.0, Wt/SWpp        =  1.00789

Non-parametric statistical treatment USL =   .95692

  *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
2.3500	.99780	.99780	.97921	.95921
4.3100	.99862	.99862	.98144	.96144
4.9200	.99888	.99888	.98208	.96208
5.0590	.99894	.99894	.98222	.96222
5.2560	.99902	.99902	.98242	.96242
7.0000	.99975	.99975	.98381	.96381
7.4100	.99992	.99992	.98402	.96402
9.8300	1.00094	1.00000	.98336	.96336
10.0000	1.00101	1.00000	.98326	.96326

lec238enh.out

```
*******************************************************
                  OUTPUT SUMMARY
LEU Cases:238 Gp: only hex arrays vs Wt% wo soluble poison
*******************************************************

Number of Experimental Points, n         =  45
Weighted Mean keff                       = 1.00017
Bias = Mean keff -1                      =  .00017
Uncertainty in Mean keff and bias        =  .00680

Fit Equation: k-eff = 9.970209E-01 + ( 4.211385E-04 )X
Square of Linear-Correlation Coef., r2   =   .05124

Area of Applicability:    2.350 <= x <=   10.000

Administrative Margin Assumed            =    .020
Range of Applicablity Margin Assumed     =    .000

Single-Sided Tolerance Limit USL         =   .96577
Normal Dist if Wt/SWpp>1.0, Wt/SWpp      =  1.00635

Non-parametric statistical treatment USL =   .95692

  *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
2.3500	.99801	.99801	.97313	.95313
4.3100	.99884	.99884	.97542	.95542
4.9200	.99909	.99909	.97607	.95607
5.0590	.99915	.99915	.97621	.95621
5.2560	.99923	.99923	.97640	.95640
7.4100	1.00014	1.00000	.97785	.95785
9.8300	1.00116	1.00000	.97708	.95708
10.0000	1.00123	1.00000	.97698	.95698

lec238enhl.out

```
*******************************************************
                  OUTPUT SUMMARY
LEU Cases:238 Gp: only hex arrays vs Wt% wo sol psn,low pt deleted.
*******************************************************

Number of Experimental Points, n         =  44
Weighted Mean keff                       = 1.00059
Bias = Mean keff -1                      =  .00059
Uncertainty in Mean keff and bias        =  .00621

Fit Equation: k-eff = 9.974620E-01 + ( 4.182449E-04 )X
Square of Linear-Correlation Coef., r2   =   .07034

Area of Applicability:    2.350 <= x <=   10.000
```

```
Administrative Margin Assumed                  =    .020
Range of Applicablity Margin Assumed           =    .000

Single-Sided Tolerance Limit USL               =   .96697
Normal Dist if Wt/SWpp>1.0, Wt/SWpp            =  1.03636

Non-parametric statistical treatment USL =   .95663

  *** Ordered Tolerance Band and USL Values ***
     x         kfit     kfit or 1     KL        USL
  2.3500     .99844     .99844     .98088    .96088
  4.3100     .99926     .99926     .98299    .96299
  4.9200     .99952     .99952     .98359    .96359
  5.0590     .99958     .99958     .98372    .96372
  5.2560     .99966     .99966     .98390    .96390
  7.4100    1.00056    1.00000     .98485    .96485
  9.8300    1.00157    1.00000     .98417    .96417
 10.0000    1.00164    1.00000     .98408    .96408
```

lec238enhs.out

```
*********************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Grp:hex arrays wo absorber vs wt% SS clad
*********************************************************

Number of Experimental Points, n              =  29
Weighted Mean keff                            = 1.00089
Bias = Mean keff -1                           =  .00089
Uncertainty in Mean keff and bias             =  .00703

Fit Equation: k-eff = 9.890157E-01 + ( 1.262552E-03 )X
Square of Linear-Correlation Coef., r2    =   .07561

Area of Applicability:    5.256 <= x <=   10.000

Administrative Margin Assumed                  =    .020
Range of Applicablity Margin Assumed           =    .000

Single-Sided Tolerance Limit USL               =   .96429
Normal Dist if Wt/SWpp>1.0, Wt/SWpp            =   .97731

Non-parametric statistical treatment USL =   .93692

  *** Ordered Tolerance Band and USL Values ***
     x         kfit     kfit or 1     KL        USL
  5.2560     .99565     .99565     .96825    .94825
  7.4100     .99837     .99837     .97643    .95643
  9.8300    1.00143    1.00000     .98094    .96094
 10.0000    1.00164    1.00000     .98076    .96076
```

lec238pit.out

```
*********************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Gp:All exps  vs Pitch
*********************************************************

Number of Experimental Points, n              =  48
Weighted Mean keff                            =  .99997
Bias = Mean keff -1                           = -.00003
Uncertainty in Mean keff and bias             =  .00660
```

```
Fit Equation: k-eff = 9.968463E-01 + ( 2.504747E-03 )X
Square of Linear-Correlation Coef., r2   =   .07156

Area of Applicability:      .070 <= x <=    2.398

Administrative Margin Assumed              =    .020
Range of Applicablity Margin Assumed       =    .000

Single-Sided Tolerance Limit USL           =   .96626
Normal Dist if Wt/SWpp>1.0, Wt/SWpp        =  1.00789

Non-parametric statistical treatment USL =   .95692
```

*** Ordered Tolerance Band and USL Values ***

x	kfit	kfit or 1	KL	USL
.0700	.99702	.99702	.97800	.95800
.6200	.99840	.99840	.98138	.96138
.7000	.99860	.99860	.98184	.96184
.8000	.99885	.99885	.98238	.96238
.8770	.99904	.99904	.98277	.96277
1.0000	.99935	.99935	.98333	.96333
1.0900	.99958	.99958	.98369	.96369
1.2200	.99990	.99990	.98411	.96411
1.2900	1.00008	1.00000	.98420	.96420
1.3000	1.00010	1.00000	.98419	.96419
1.3200	1.00015	1.00000	.98418	.96418
1.4000	1.00035	1.00000	.98411	.96411
1.5980	1.00085	1.00000	.98376	.96376
1.8010	1.00136	1.00000	.98321	.96321
1.8300	1.00143	1.00000	.98312	.96312
1.8520	1.00149	1.00000	.98305	.96305
1.8950	1.00159	1.00000	.98291	.96291
2.3980	1.00285	1.00000	.98107	.96107

lec238pith.out

```
*******************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Gp:only hex arrays vs Pitch wo absorbers
*******************************************************

Number of Experimental Points, n          =  45
Weighted Mean keff                        = 1.00017
Bias = Mean keff -1                       =  .00017
Uncertainty in Mean keff and bias         =  .00680

Fit Equation: k-eff = 9.969635E-01 + ( 2.548853E-03 )X
Square of Linear-Correlation Coef., r2   =   .07500

Area of Applicability:      .070 <= x <=    2.398

Administrative Margin Assumed              =    .020
Range of Applicablity Margin Assumed       =    .000

Single-Sided Tolerance Limit USL           =   .96577
Normal Dist if Wt/SWpp>1.0, Wt/SWpp        =  1.00635

Non-parametric statistical treatment USL =   .95692
```

*** Ordered Tolerance Band and USL Values ***

x	kfit	kfit or 1	KL	USL
.0700	.99714	.99714	.97739	.95739

.7000	.99875	.99875	.98129	.96129
.8000	.99900	.99900	.98183	.96183
1.0000	.99951	.99951	.98281	.96281
1.0900	.99974	.99974	.98317	.96317
1.2200	1.00007	1.00000	.98353	.96353
1.2900	1.00025	1.00000	.98353	.96353
1.3000	1.00028	1.00000	.98353	.96353
1.4000	1.00053	1.00000	.98346	.96346
1.5980	1.00104	1.00000	.98312	.96312
1.8010	1.00155	1.00000	.98257	.96257
1.8300	1.00163	1.00000	.98249	.96249
1.8520	1.00168	1.00000	.98242	.96242
1.8950	1.00179	1.00000	.98228	.96228
2.3980	1.00308	1.00000	.98043	.96043

```
lec238pithl.out
             *******************************************************
                                OUTPUT SUMMARY
             LEU Cases:238 Gp:only hex arrays vs Pitch wo absorbers
             *******************************************************

             Number of Experimental Points, n          =  45
             Weighted Mean keff                        = 1.00017
             Bias = Mean keff -1                       =  .00017
             Uncertainty in Mean keff and bias         =  .00680

             Fit Equation: k-eff = 9.969635E-01 + ( 2.548853E-03 )X
             Square of Linear-Correlation Coef., r2    =    .07500

             Area of Applicability:     .070 <= x <=    2.398

             Administrative Margin Assumed             =     .020
             Range of Applicablity Margin Assumed      =     .000

             Single-Sided Tolerance Limit USL          =    .96577
             Normal Dist if Wt/SWpp>1.0, Wt/SWpp       =   1.00635

             Non-parametric statistical treatment USL =    .95692

               *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
.0700	.99714	.99714	.97718	.95718
.7000	.99875	.99875	.98108	.96108
.8000	.99900	.99900	.98162	.96162
1.0000	.99951	.99951	.98260	.96260
1.0900	.99974	.99974	.98296	.96296
1.2200	1.00007	1.00000	.98332	.96332
1.2900	1.00025	1.00000	.98332	.96332
1.3000	1.00028	1.00000	.98332	.96332
1.4000	1.00053	1.00000	.98325	.96325
1.5980	1.00104	1.00000	.98291	.96291
1.8010	1.00155	1.00000	.98236	.96236
1.8300	1.00163	1.00000	.98227	.96227
1.8520	1.00168	1.00000	.98220	.96220
1.8950	1.00179	1.00000	.98206	.96206
2.3980	1.00308	1.00000	.98021	.96021

```
lec238tmp.out
             *******************************************************
                                OUTPUT SUMMARY
             LEU Cases:238 Gp:All exps  vs Pitch
```

```
*******************************************************

Number of Experimental Points, n          =  48
Weighted Mean keff                        =  .99997
Bias = Mean keff -1                       = -.00003
Uncertainty in Mean keff and bias         =  .00660

Fit Equation: k-eff = 9.993982E-01 + ( 9.718758E-06 )X
Square of Linear-Correlation Coef., r2    =   .02376

Area of Applicability:   14.000 <= x <=  274.000

Administrative Margin Assumed             =    .020
Range of Applicablity Margin Assumed      =    .000

Single-Sided Tolerance Limit USL          =   .96626
Normal Dist if Wt/SWpp>1.0, Wt/SWpp       =  1.00789

Non-parametric statistical treatment USL =   .95692

  *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
14.0000	.99953	.99953	.98316	.96316
16.0000	.99955	.99955	.98321	.96321
19.0000	.99958	.99958	.98328	.96328
19.3000	.99959	.99959	.98328	.96328
20.0000	.99959	.99959	.98330	.96330
20.1000	.99959	.99959	.98330	.96330
23.0000	.99962	.99962	.98337	.96337
30.0000	.99969	.99969	.98351	.96351
166.0000	1.00101	1.00000	.98239	.96239
193.0000	1.00127	1.00000	.98173	.96173
206.0000	1.00140	1.00000	.98139	.96139
231.4000	1.00165	1.00000	.98073	.96073
263.0000	1.00195	1.00000	.97987	.95987
274.0000	1.00206	1.00000	.97957	.95957

lec238tmph.out

```
*******************************************************
                  OUTPUT SUMMARY
LEU Cases:238 Gp:only hex arrays vs Moderator Temperaturn, wo absorbers
*******************************************************

Number of Experimental Points, n          =  45
Weighted Mean keff                        = 1.00017
Bias = Mean keff -1                       =  .00017
Uncertainty in Mean keff and bias         =  .00680

Fit Equation: k-eff = 9.996139E-01 + ( 8.789311E-06 )X
Square of Linear-Correlation Coef., r2    =   .01968

Area of Applicability:   14.000 <= x <=  274.000

Administrative Margin Assumed             =    .020
Range of Applicablity Margin Assumed      =    .000

Single-Sided Tolerance Limit USL          =   .96577
Normal Dist if Wt/SWpp>1.0, Wt/SWpp       =  1.00635

Non-parametric statistical treatment USL =   .95692

  *** Ordered Tolerance Band and USL Values ***
```

x	kfit	kfit or 1	KL	USL
14.0000	.99974	.99974	.98258	.96258
16.0000	.99975	.99975	.98263	.96263
19.0000	.99978	.99978	.98270	.96270
19.3000	.99978	.99978	.98270	.96270
20.0000	.99979	.99979	.98272	.96272
20.1000	.99979	.99979	.98272	.96272
23.0000	.99982	.99982	.98279	.96279
30.0000	.99988	.99988	.98293	.96293
166.0000	1.00107	1.00000	.98176	.96176
193.0000	1.00131	1.00000	.98110	.96110
206.0000	1.00142	1.00000	.98077	.96077
231.4000	1.00165	1.00000	.98009	.96009
263.0000	1.00193	1.00000	.97923	.95923
274.0000	1.00202	1.00000	.97892	.95892

lec238tmphl.out

```
*********************************************************
                    OUTPUT SUMMARY
LEU Cases:238 Gp:only hex arrays vs Moderator Temperaturn, wo absorbers
*********************************************************

Number of Experimental Points, n          =  45
Weighted Mean keff                        = 1.00017
Bias = Mean keff -1                       =  .00017
Uncertainty in Mean keff and bias         =  .00680

Fit Equation: k-eff = 9.996139E-01 + ( 8.789311E-06 )X
Square of Linear-Correlation Coef., r2    =    .01968

Area of Applicability:   14.000 <= x <=  274.000

Administrative Margin Assumed             =     .020
Range of Applicablity Margin Assumed      =     .000

Single-Sided Tolerance Limit USL          =   .96577
Normal Dist if Wt/SWpp>1.0, Wt/SWpp       =  1.00635

Non-parametric statistical treatment USL =   .95692
```

*** Ordered Tolerance Band and USL Values ***

x	kfit	kfit or 1	KL	USL
14.0000	.99974	.99974	.98236	.96236
16.0000	.99975	.99975	.98241	.96241
19.0000	.99978	.99978	.98248	.96248
19.3000	.99978	.99978	.98249	.96249
20.0000	.99979	.99979	.98250	.96250
20.1000	.99979	.99979	.98251	.96251
23.0000	.99982	.99982	.98257	.96257
30.0000	.99988	.99988	.98271	.96271
166.0000	1.00107	1.00000	.98155	.96155
193.0000	1.00131	1.00000	.98089	.96089
206.0000	1.00142	1.00000	.98055	.96055
231.4000	1.00165	1.00000	.97988	.95988
263.0000	1.00193	1.00000	.97901	.95901
274.0000	1.00202	1.00000	.97870	.95870