CHAPTER 7: ROUTINE SHIPPING CONTAINER UTILIZATION SUMMARY OPERATING PROCEDURES

The following information contains the significant events relating to the routine use of WE-1 fuel assembly shipping containers. Complete detailed instructions are outlined within the individual plant operating procedures and quality control instructions pertinent to each specific operation.

The Pathfinder Canister is used to ship unirradiated Pathfinder fuel. The detailed loading and unloading procedures given are in compliance with subpart G of 10CFR71. These procedures have been prepared to meet the intent of NUREG/CR-4775, Guide for Preparing Operating Procedures for Shipping Packages.

7.1 INSPECTION PRIOR TO LOADING

7.1.1 Visually inspect the shipping container to assure that it has not been significantly damaged.

7.1.2 Closure bolts, washers, nuts, and sealing gasket are present and free of defects.

7.1.3 Visually inspect the strongback assembly to assure that it has not been significantly damaged.

7.1.4 Visually inspect fuel assembly clamps, retainer bars, bolts, and nuts to assure that they are present and in good condition.

7.2 LOADING PROCEDURE

7.2.1 BW17x17 Fuel

1. Unbolt all closure bolts on the inner container box and remove cover assembly.
2. Install the trunnion pivot pin and spacers.
3. Unbolt closure bolts on top and side of the inner containment box; remove outer portion of the inner containment box.
4. Loosen closure bolts on clamp arms.
5. Free the strongback from the container by removing the hex nuts and washers that secure the strongback to the shock mount bolts.
6. Elevate the strongback to a vertical position.
7. Install the two strut-type stabilizer braces to the strongback, making sure these braces are adequately secured and ball lock pins or bolts and nuts are in place.
8. Load the fuel assembly into the containment box.

9. Install clamp arms at the designated areas of the assembly.

10. Remove strut-type stabilizer braces and lower strongback with fuel element into a horizontal position in the container.

11. Install insulation around the assembly.

12. Place outer portion of the inner containment box back in position; tighten closure bolts.

13. Install wood wedges around the containment box.

14. Install outer closure bolts and make wrench tight.

15. Remove the trunnion pivot pin and spacers.

16. Bolt the containment box to the shock mount supports.

7.2.2 Pathfinder Fuel - Canister

1. The new canister must first be inspected by Quality Control. Shipping canisters not acceptable for use shall be marked accordingly. Assure that the WE-1 Package is to be loaded per the Certificate of Compliance and record this on the appropriate shipment documentation.

2. Remove the outer upper shell assembly, end thrust plate, end cover plate (strong back lift eye end) to the rectangular inner container (box), inner container spacer, and the wood spacer to expose the Pathfinder Canister. Take precaution to place these spacers for later use.

3. Pathfinder Canister shall be visually inspected prior to every use. Visually inspect Pathfinder Canister surfaces for damage, scratches and dents. No dents greater than ¼ inch is permitted. Inspect closure surface for scratches, dents or raised metal on the sealing surface. Inspect closure bolts and replace if damaged. Verify that the maintenance inspections per Section 8.2 have been conducted within 12 months of use. Verify that the maintenance activities are performed per Section 8.2.5 for each shipment.

4. Load Pathfinder fuel assemblies.

5. The void spaces between fuel assemblies and the Pathfinder Canister are to be filled with packing materials as required to avoid wear and impact during shipment and handling.

6. Before closure of the Pathfinder Canister, the O-rings and flange closure faces shall be examined to assure they are free of foreign material and/or defects. Seat the closure flange on the Pathfinder Canister body, lubricate the bolt threads, and check the bolts for ease of threading. If the bolts cannot be hand tightened prior to torquing, chase the threads. After applying the specified torque (40 to 50 foot-pounds), bend the lock washers to prevent subsequent loosening of the bolts.

7. Closure integrity is verified by applying a leak rate test to the O-ring annulus. This test is conducted by pressurizing the O-ring annulus to 15 psig, isolating the annulus manifold/gage from the pressure source and measuring any pressure drop over a ten minute period. Pressure drop of 1/2 psig is acceptable. Section 4.5 provides an inner seal region volume, a sample instrument line volume and a sample calculation, per ANSI N14.5, Section B.12, for pressure drop leak test. If the Pathfinder Canister does not pass the leak rate test, replace the O-rings and repeat the test. If the Pathfinder

Canister still does not pass the leak rate test, it must be unloaded and the seal surfaces dimensionally inspected for potential refurbishment.

8. Place the wood spacers and end spacer in the reverse order of their previous removal.

9. Install end cover plate to the rectangular inner container (box) and secure bolts.

10. Install end thrust plate.

11. Each shipment of the Pathfinder Canister shall require the preparation of, and retention for three years, of those records specified in 10CFR71.91 as appropriate.

7.3 INSPECTION

7.3.1 Verify that the fuel assembly has been released before loading the assembly. Note: Verify that all fuel rods have leak tested to demonstrate leak tight containment integrity (i.e., 1×10^{-7} cc/sec air or better). No leak testing of the fuel assemblies is required for the Pathfinder fuel.

7.3.2 Verify that the containment box is closed and all closure bolts are secured.

7.3.3 Verify general cleanliness and absence of debris on container internals.

7.4 CLOSE SHIPPING CONTAINER

7.4.1 Place the cover on the base assembly of the shipping container using the alignment pins on the base assembly flange to guide the cover assembly.

7.4.2 Secure the base and cover assemblies by tightening all outer shell closure bolts.

7.4.3 Install a Type E security seal at each end of the container.

7.4.4 Inspect the container for proper labeling.

7.5 TRUCK LOADING OF SHIPPING CONTAINER

7.5.1 Place shipping container on trailer equipped to permit chaining down of container.

7.5.2 Center and place container lengthwise on trailer.

7.5.3 Secure container to trailer bed with stops.

7.5.4 Chain container to trailer using "come along" tighteners and chains 3/8 inch minimum diameter.

7.5.5 Perform radiation surveys of the container.

7.6 UNLOADING

7.6.1 Remove chains from trailer using "come along" tighteners and chains 3/8 inch minimum diameter.

7.6.2 Remove stops from trailer bed.

7.6.3 Remove shipping container from trailer.

7.6.4 Pathfinder **Canister** is designed to be unloaded with commonly available tools and equipment. The unloading procedure will follow this sequence:

1. Prior to unloading, ascertain that the radiological survey data and packing list is included with the shipment.
2. Remove the outer container upper shell, end thrust plate, end cover plate (strong back lift eye end) to the rectangular inner container (box), inner container spacer, and the wood spacer to expose the Pathfinder Canister. Take precaution to retain these spacers for later use.
3. Bend the lock washers open and loosen the 8 flange closure bolts. Remove the closure flange with the bolts and washers still in the bolt hole. Place the closure flange on a clean dry surface and then remove the bolts and washers. Use caution not to damage the O-ring seals. Perform radiation survey.
4. Remove the packing material and fuel assemblies from the Pathfinder Canister.
5. After cleaning the Pathfinder Canister as necessary, replace the closure flange using original O-rings, new lock washers and the original bolts. Tighten bolts to prevent loosening of the bolts during handling and transportation. Do not crimp the lock washers nor torque the closure bolts, as this will be done at the next usage.
6. Install wood and end spacers, end cover plate, and thrust plate which had previously been removed.

7.7 EMPTY CONTAINER

7.7.1 Perform radiation surveys of the container.

7.7.2 Attach empty signs to container.

7.7.3 Pathfinder Canister

1. Empty Pathfinder Canister will be prepared for shipment by removing all loose material from the Pathfinder Canister. The Pathfinder Canister will be closed. Tighten bolts to prevent loosening of the bolts during handling and transportation. No locking washers are necessary. Appropriate labels will be affixed to the drum exterior to signify that it is empty.
2. A survey shall be performed on the WE-1 container outer surface to ascertain that there is no damage to the container.

CHAPTER 8: ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

8.1 ACCEPTANCE TESTS

8.1.1 VISUAL INSPECTION

Prior to the first use of a WE-1 Shipping Container for the shipment of licensed material, Framatome ANP, Inc. will:

(a) Ascertain that there are no cracks, pinholes, uncontrolled voids, or other defects which could significantly reduce the effectiveness of the container.

(b) Conspicuously and durably mark the container with its model number, serial number, gross weight, and an identification number assigned by the Nuclear Regulatory Commission. Prior to applying the model number, Framatome ANP, Inc. will determine that the container was fabricated in accordance with the drawings referenced in its NRC Certificate of Compliance.

8.1.2 STRUCTURAL AND PRESSURE TESTS

No structural or pressure tests are required. Supplier dimensional inspection and non-destructive tests of the welds for the Pathfinder canister are sufficient to verify structural adequacy.

8.1.3 LEAK TESTS

Leak tests of the Pathfinder Canister closure seals are required to be performed by the manufacturer to verify the O-rings will seal properly. The pressure drop test, to verify the O-ring sealing, will be performed per paragraph A.5.1 of ANSI N14.5-1997, "American National Standard for Radioactive Material – Leakage Tests on Package for Shipment." The acceptable leak rate is 1×10^{-3} atm cc/sec using a pressure drop test. Section 4.5 provides a representative example of a test method and setup. Weld joints are nondestructively examined by tests at fabrication and leak tested to verify they are sound. The fabrication leak test, to verify welds, will be performed per test method #A.5.9 of Annex A of ANSI N14.5-1997. The acceptable leak rate is 1×10^{-7} atm cc/sec.

8.1.4 COMPONENT TESTS

Pathfinder Canister O-rings shall be visually inspected for surface defects that would impair their sealing capability. Flange surfaces shall be visually inspected to assure there is no raised metal on the mating seal surfaces, or scratches or dents.

8.2 MAINTENANCE PROGRAM

The WE-1 container is processed through routine refurbishment activities after each use. Details of each step are included in Chapter 7. Repairs will be done in accordance with license drawings provided in Appendix 1-1. Documentation relating to these inspections, repairs, part replacements, etc., will be produced and subsequently maintained via the existing plant records program.

8.2.1 STRUCTURAL AND PRESSURE TESTS

A visual inspection of the Pathfinder Canister shall be made annually. Visually inspect for damage, scratches and dents. Visually inspect O'ring seal surfaces for dents, sratches, or raised metal. Such defects shall be sanded off. Inspect closure bolts and replace if damaged.

8.2.2 LEAK TESTS

A positive pressure leak test of the closure seal will be made before each fuel assembly shipment. The pressure drop test, to verify the O-ring sealing, will be performed per paragraph A.5.1 of ANSI N14.5-1997, "American National Standard for Radioactive Material – Leakage Tests on Package for Shipment." The acceptable leak rate is $1\text{x}10^{-3}$ atm cc/sec using a pressure drop test. Section 4.5 provides a representative example of a test method and setup. If maintenance or repair is performed that affect other part of the containment besides the seal, the weld test of the affected component will be performed per test method #A.5.9 of Annex A of ANSI N14.5-1997. The acceptable leak rate is $1\text{x}10^{-7}$ atm cc/sec.

8.2.3 SUBSYSTEM MAINTENANCE

Not applicable.

8.2.4 VALVES, RUPTURE DISCS, AND GASKETS ON CONTAINMENTVESSEL

If Pathfinder Canister O-ring damage is apparent or suspect when the canister is loaded for shipment, the O-rings shall be replaced.

8.2.5 PRIOR TO EVERY SHIPMENT

1. Inspect Pathfinder Canister components for damage.

2. Pathfinder Canister O-rings shall be visually inspected for surface defects that would impair their sealing capability.

3. Inspect closure surfaces for damage. Dents, scratches, or raised metal on the closure flange sealing surface shall be cause for rework. The minimum thickness to which the weldneck flange can be reduced is 0.75 inches.

4. Pathfinder Canister O-rings shall be changed. While the O-rings are removed check the O-ring seal surfaces for dents, scratches, or raised metal.

APPENDIX 1-1:
LIST OF LICENSE DRAWINGS

02-1273964-00	
02-1273965-01	
02-1273966-00	
02-1273967-00	
02-1273968-00	
02-5016270-01	WE-1 Configuration with Internal Pathfinder Canister
02-5021426-00	WE-1 Pathfinder Canister (Sheets 1 of 2 and 2 of 2)

FIGURE WITHHELD UNDER 10 CFR 2.390

DWN BY WE BAILEY	CHK'D BY DA BARGER	WE-1 CONFIGURATION WITH INTERNAL PATHFINDER CANISTER (LICENSE DRAWING)	PROJ NO. PTE_SHIPCON_1	SCALE NTS	DATE 04/23/02
PASSED BY MK PUNATAR	APP'D BY RA FREEMAN		SIZE B DOC ID 02	DWG NO. 5016270	REV 1

FIGURE WITHHELD UNDER 10 CFR 2.390

DWN BY WE Bailey
WE, BAILEY

CHK'D BY DA SAGER

PASSED BY MK Punatar
M K PUNATAR

APP'D BY R. FREEMAN

WE-1 PATHFINDER CANISTER
(LICENSE DRAWING)
SHEET 1 OF 2

PROJ NO. PTE_SHIPCON_1
SCALE NTS
DATE 10/15/02
SIZE B
DOC ID 02
DWG NO. 5021426
REV 0

FIGURE WITHHELD UNDER 10 CFR 2.390

DWN BY WE BAILEY	CHK'D BY DA BARGER	WE-I PATHFINDER CANISTER (LICENSE DRAWING) SHEET 2 OF 2	PROJ NO. PTE_SHIPCON_I		SCALE NTS	DATE 10/15/02
PASSED BY M K PUNATAR	APP'D BY		SIZE B	DOC ID 02	DWG NO. 5021426	REV 0

APPENDIX 1-2:
Pathfinder Documentation

Historical Documentation

Pathfinder Fuel Element - Sketch

Pathfinder Fuel Element Specifications

Allis-Chalmers Drawing No. 41-500-693, "Superheater Fuel Element Core II" (Pathfinder Fuel)

Allis-Chalmers Drawing No. 41-500-693, "Superheater Fuel Element Core II" (Pathfinder Fuel) - Enlarged Notes

Historical Documentation

Personnel at Pennsylvania State University reviewed historic documents and reported the following:

415 Pathfinder Elements had an enrichment of 6.9327%
2 Pathfinder Elements had an enrichment of 7.499%

Also, they measured over a dozen of the sheaths holding the assemblies, and each measured 7 feet long, exactly, and had inner diameters of 0.945 inches and outer diameters of 1.00 inches. All were the same size.

The following three pages are from an early application document for the Pathfinder fuel, which specifies the mass loadings in each element. The dimensions reported there are consistent with the Allis-Chalmers drawing of the Pathfinder element, which follows.

APPLICATION FOR THE USE OF
PATHFINDER FUEL ELEMENTS
IN THE
PENN STATE FAST REACTOR SPECTRUM ASSEMBLY

FIGURE WITHHELD UNDER 10 CFR 2.390

Pathfinder Fuel Element Specifications

Element Configuration	7-rod Cluster
Overall element length	82.55 in.
Envelope diameter	0.805 in.
Nominal weight	9.0 lb.
Fuel	Sintered UO_2 Pellet
UO_2 enrichment	6.95 w/o U-235
Loading per element	2.206 KgU
UO_2 pellet diameter	0.207 ± 0.0005 in.
UO_2 pellet length	0.207 - 0.414 in.
Active fuel length	72.0 ± 0.125 in.
Cladding of Fuel and Poison Rods	Free Standing Tube
Material	Incoloy 800, mill annealed
Outside diameter	0.247 ± 0.001 in.
Inside diameter	0.211 ± 0.001 in.
Wall thickness	0.018 in.
Poison	Boron-Stainless Steel Wire
Poison loading per element	0.978 g natural boron
Poison wire diameter	0.105 in.
Poison spacer	Sintered Al_2O_3 pellets
Spacing Arrangement	Spiral Wire, 3 per Fuel Rod
Wire diameter	0.042 in.
Spiral pitch	6 in.
Wire material	Incoloy 800, mill annealed
Fission Gas Plenum Length	3 in.

FIGURE WITHHELD UNDER 10 CFR 2.390

PC	NAME	GROUP NO. & QUANTITY					DWG. NO & REFERENCE PART NO. OR SPECIFICATION OF MATERIAL
		G1	G2	G3			
17	PIN	2					41-500-693-017 .0940 DIA X .328 LG
							SST 304 ASTM A276
16	SPACER WIRE			AR			41-500-693-016 INCOLOY 800 AC SPEC 41-720
15	LOWER END FITTING	1					41-500-693-015 CF-8A CASTING AC SPEC 41-721
14	RETAINER RING	1					41-500-693-014 INCOLOY 800 ASTM B 408
13	POISON WIRE		1				41-500-693-013 BORON-SST AC SPEC 41-714
12	SPRING		1	1			41-500-693-012 ASTM A 313 SEE SPRING DATA
11	SPACER		1				41-500-693-011 SST 304L ASTM A-276
10	POISON PIN SPACER		AR				41-500-693-010 ALUMINA AC-SPEC 41-715
9	FUEL PELLET			AR			41-500-693-009 URANIUM DIOXIDE AC SPEC 41-1001
8	TUBE		1	1			41-500-693-008 INCOLOY 800 AC-SPEC 41-718
7	UPPER FITTING			1			41-500-693-007 INCOLOY 800 AC-SPEC 41-719
6	SLOTTED FITTING			1			41-500-693-006 INCOLOY 800 AC-SPEC 41-719
5	LOWER FITTING		1				41-500-693-005 INCOLOY 800 AC-SPEC 41-719
4	LIFTING FITTING		1				41-500-693-004 INCOLOY 800 AC-SPEC 41-719
3	POISON PIN	1	/	-			41-500-693-G2
2	FUEL PIN	6	-	/			41-500-693-G3
1	FUEL ELEMENT	/					41-500-693-G1

G1 - FUEL ELEMENT ASSY
G2 - POISON PIN ASSY
G3 - FUEL PIN ASSY

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

WE-1 CONTAINER PRIOR TO TESTING

Figure 2-1-1 WE-1 shipping Package on a Truck Bed

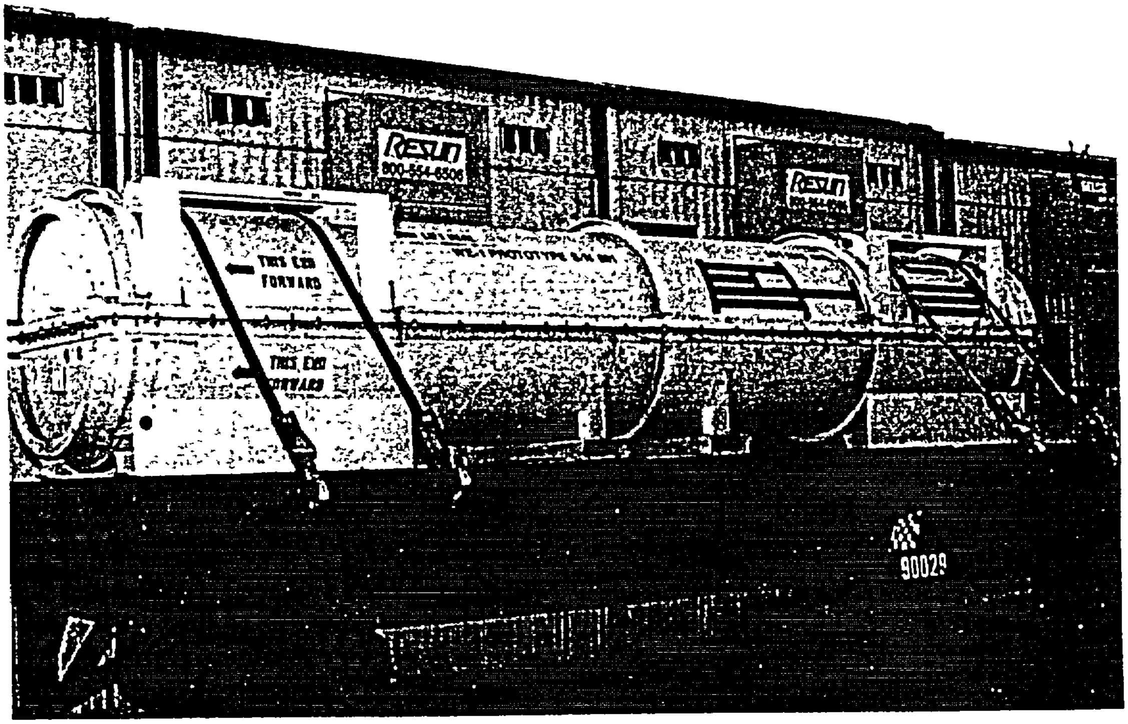


Figure 2-1-2 Inner Container with Fuel Assembly Covered with Insulation

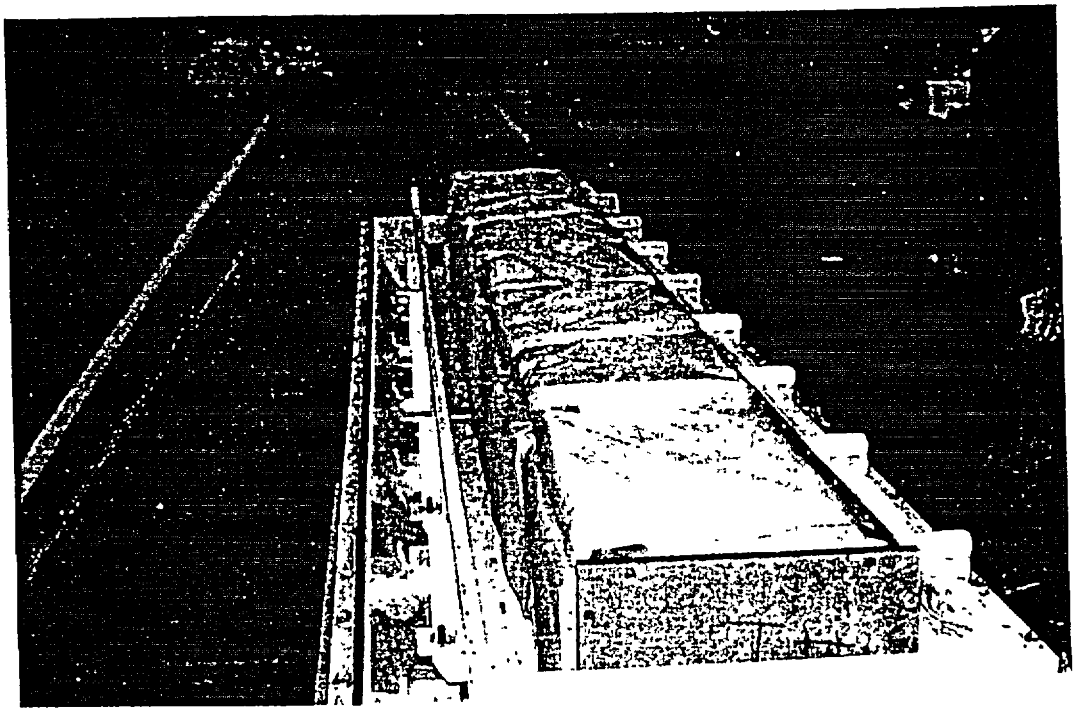


Figure 2-1-3 View of Clamps, Fuel Assembly and Insulation

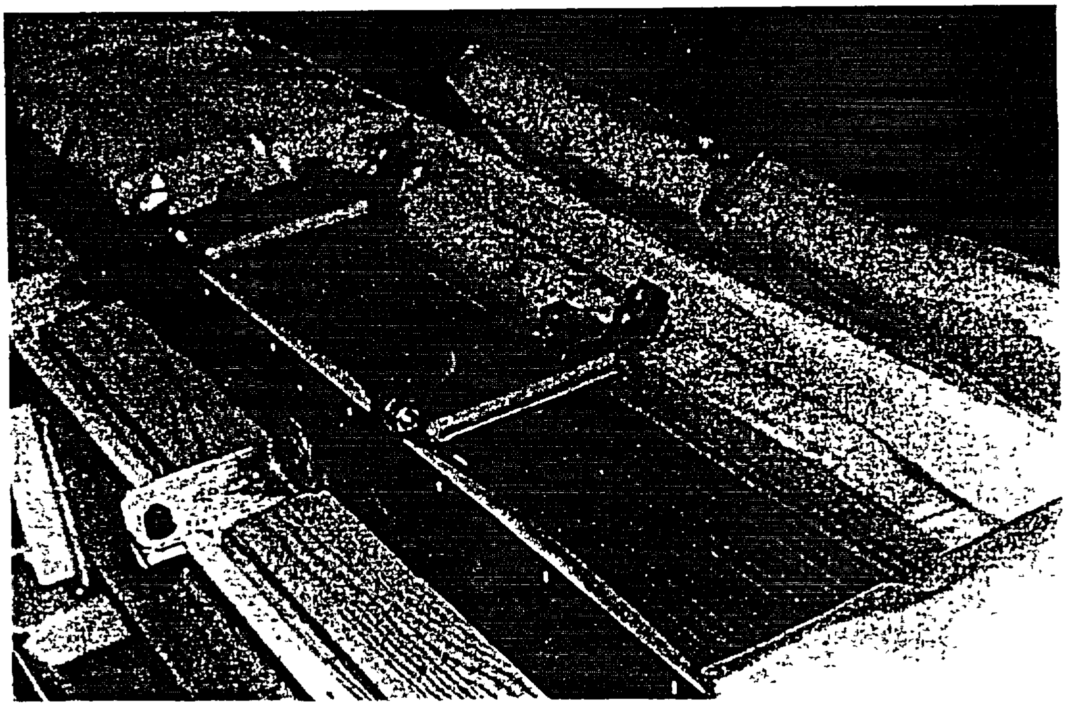


Figure 2-1-4 Inner Container with Fuel Assembly Covered with Insulation

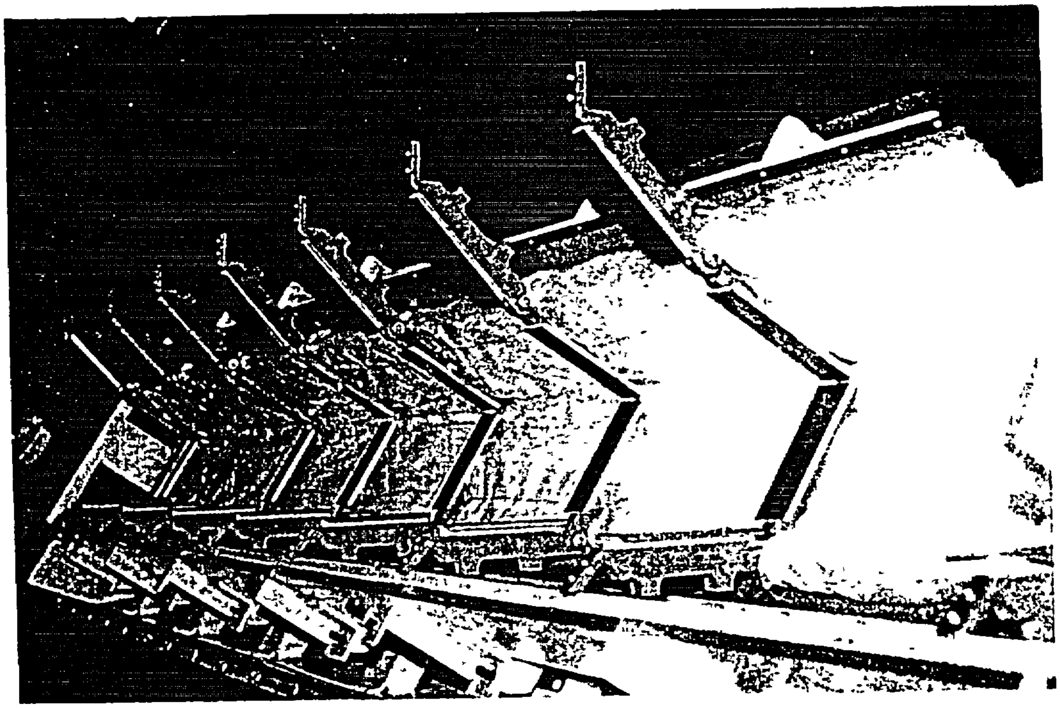
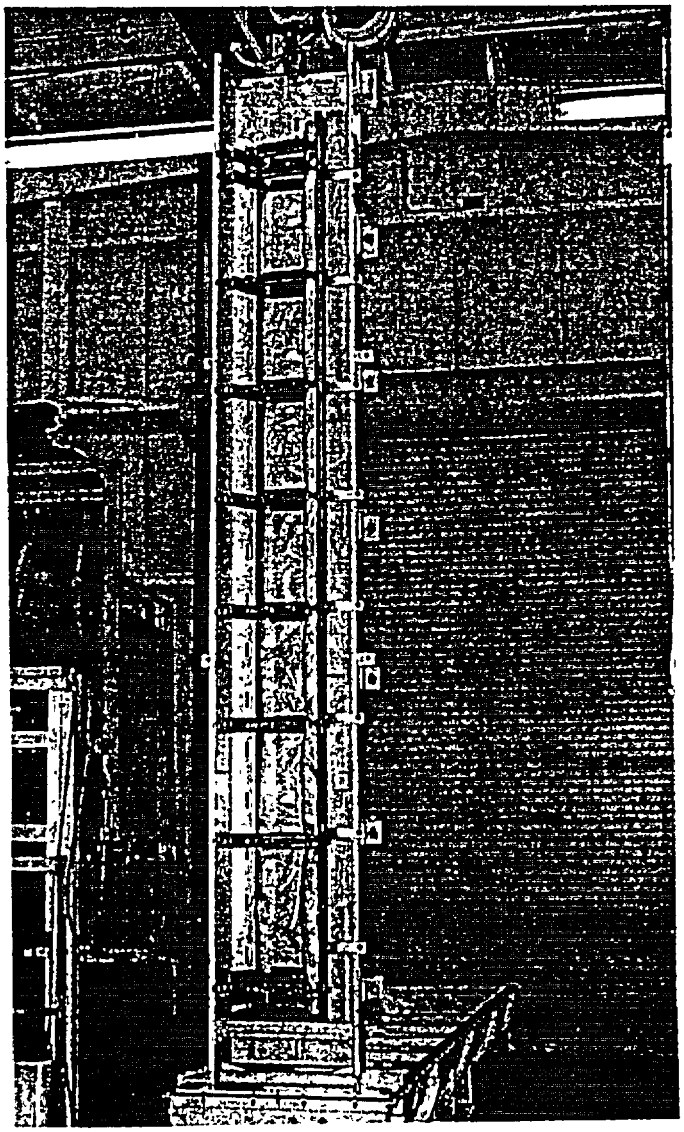


Figure 2-1-5 Strongback in Position for Fuel Assembly Loading



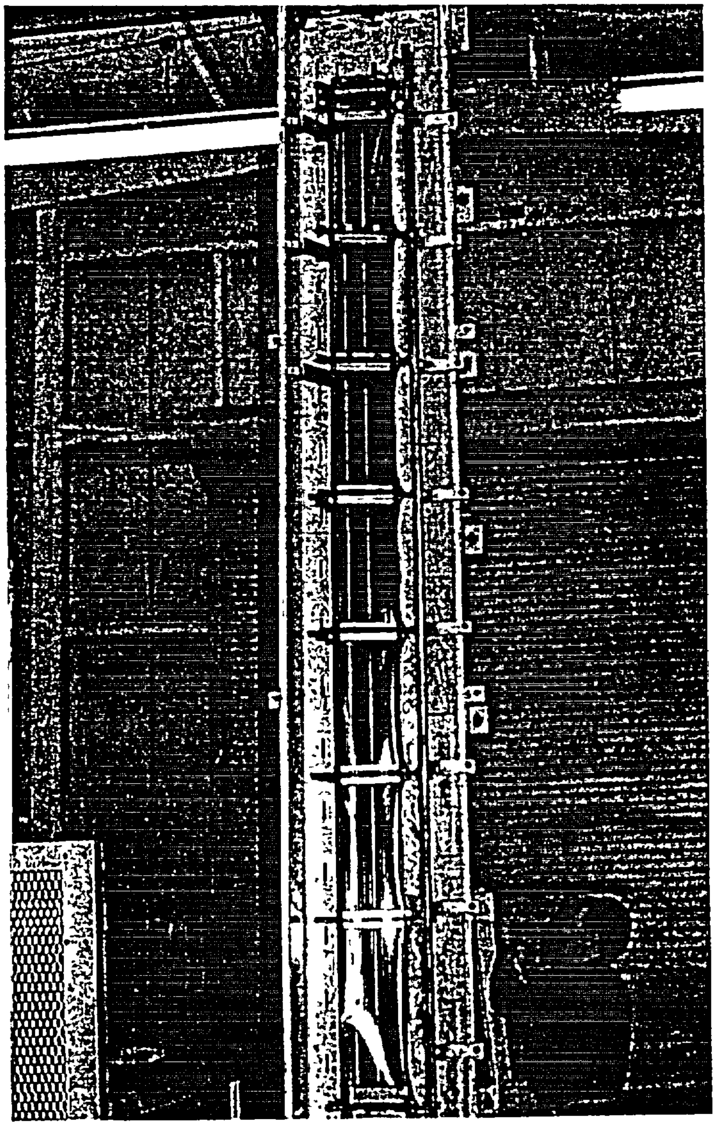
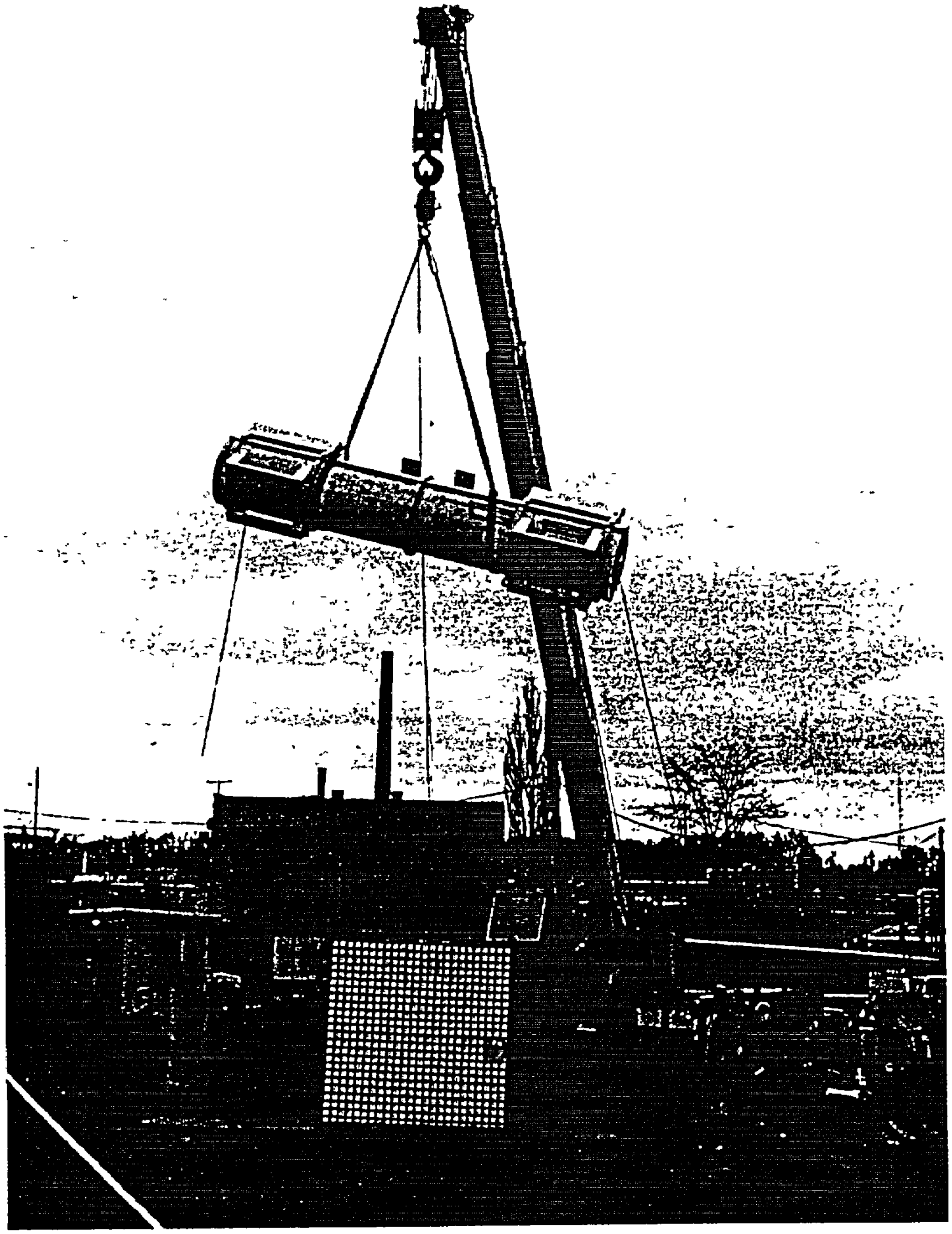


Figure 2-1-6 Strongback Position with Fuel Assembly

WE-1 CONTAINER 30 FT. DROP TEST

Figure 2-1-7 General View - 30-foot Drop Test Setup

4641 48



6

Figure 2-1-8 Close-up View - 30-foot Drop Test Setup

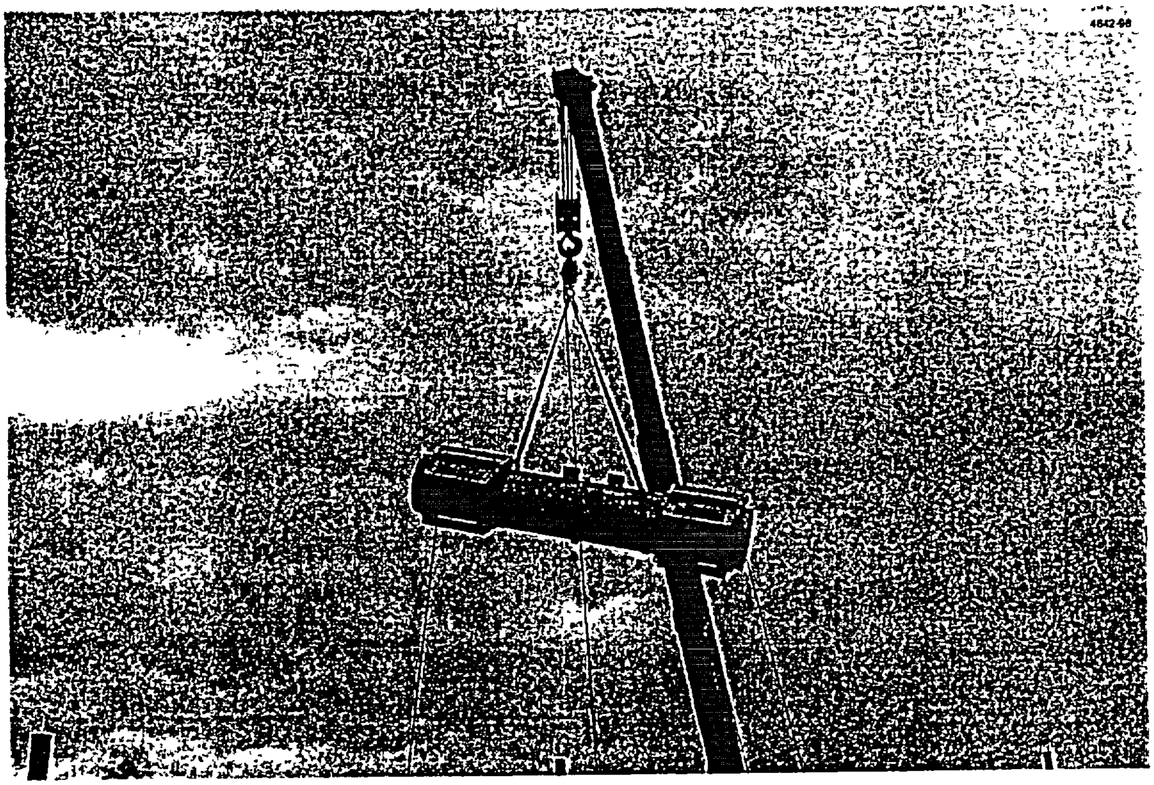


Figure 2-1-9 WE-1 30-foot Drop Test - Free-fall

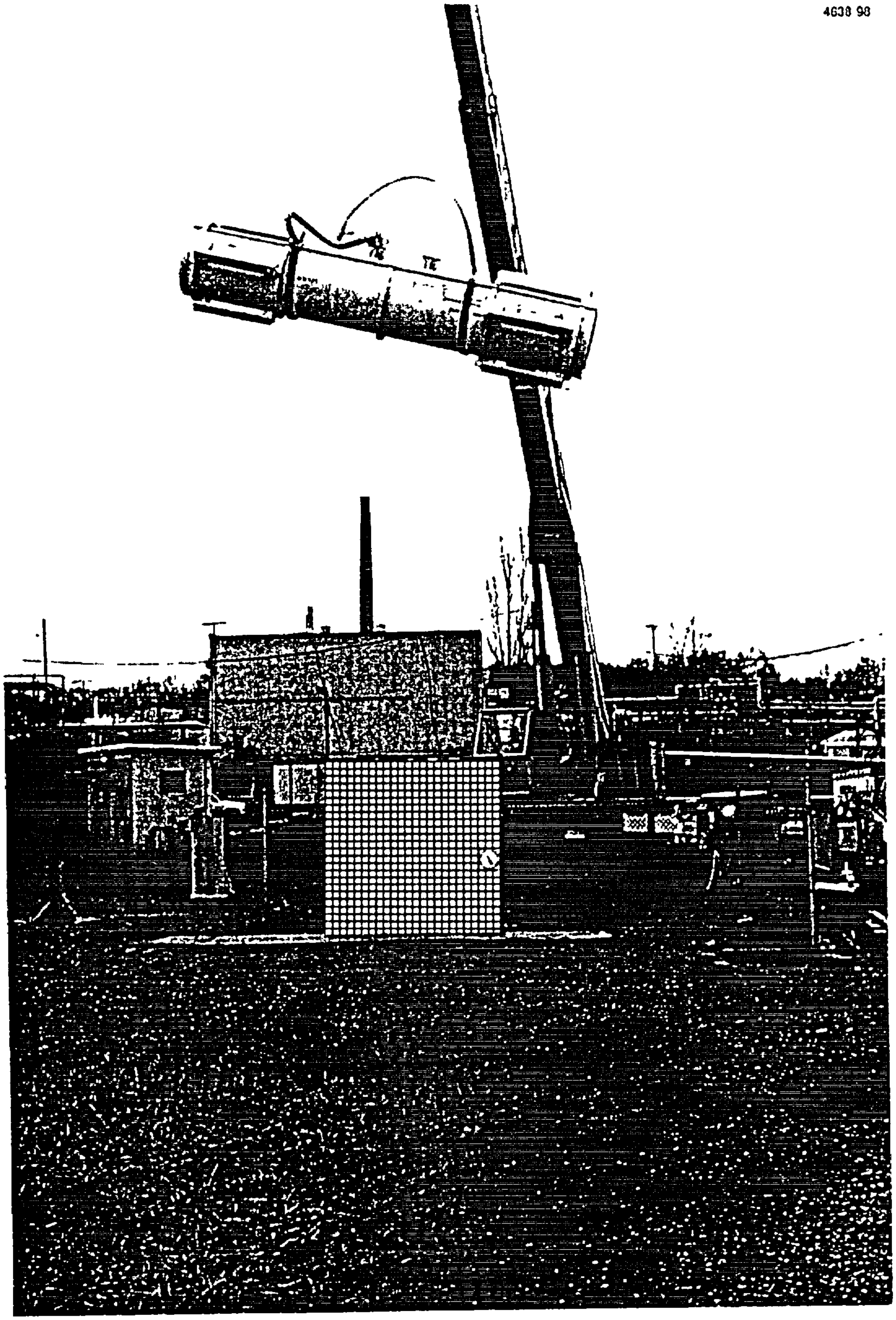
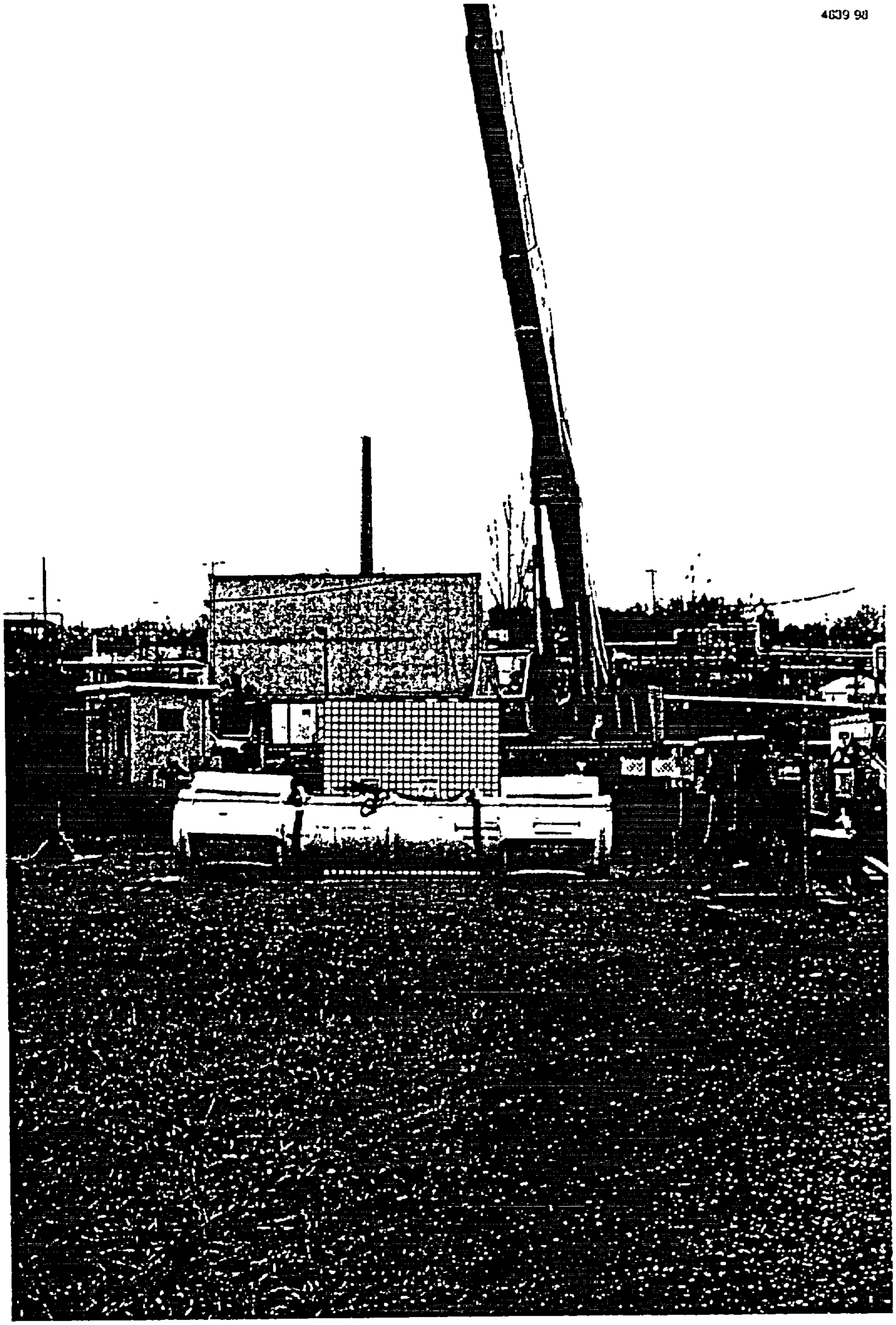


Figure 2-1-10 WE-1 30-foot Drop Test - Post-Impact

4039 98



WE-1 CONTAINER DAMAGE AFTER 30 FT. DROP TEST

Figure 2-1-11 Outer Container Deformation after 30-foot Drop - End View

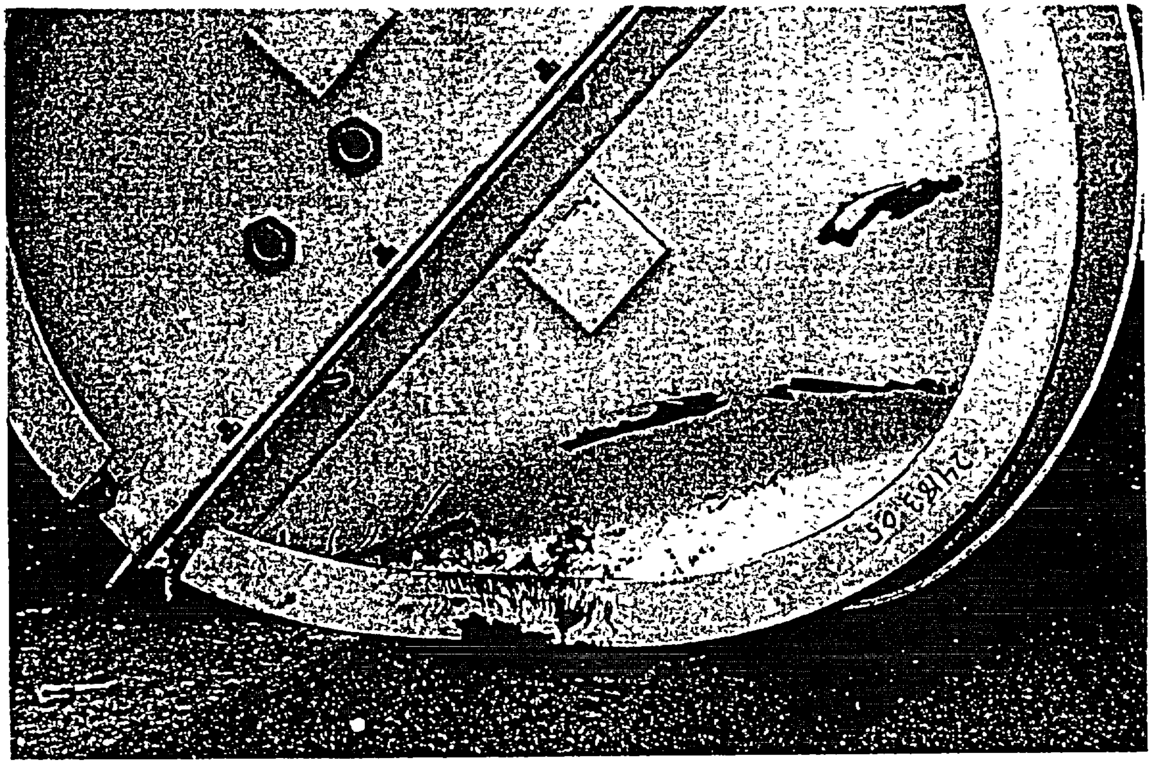


Figure 2-1-12 Outer Container Deformation, Slapdown End, after 30-foot Drop - Side View

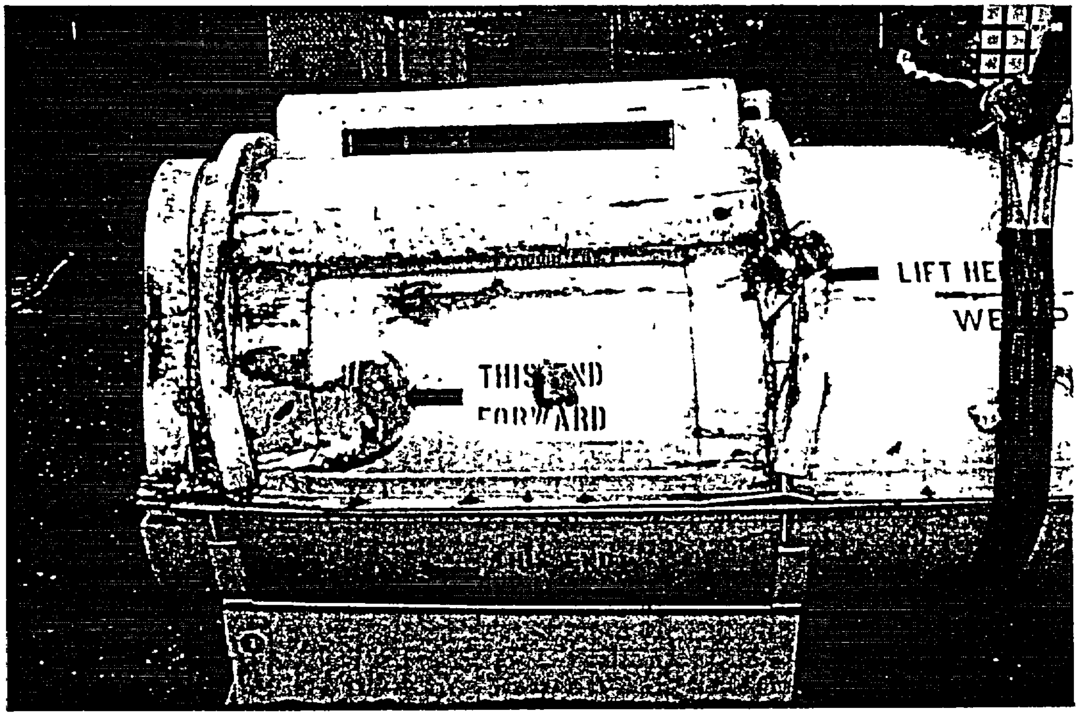


Figure 2-1-13 Outer Container and Skid after 30-foot Drop

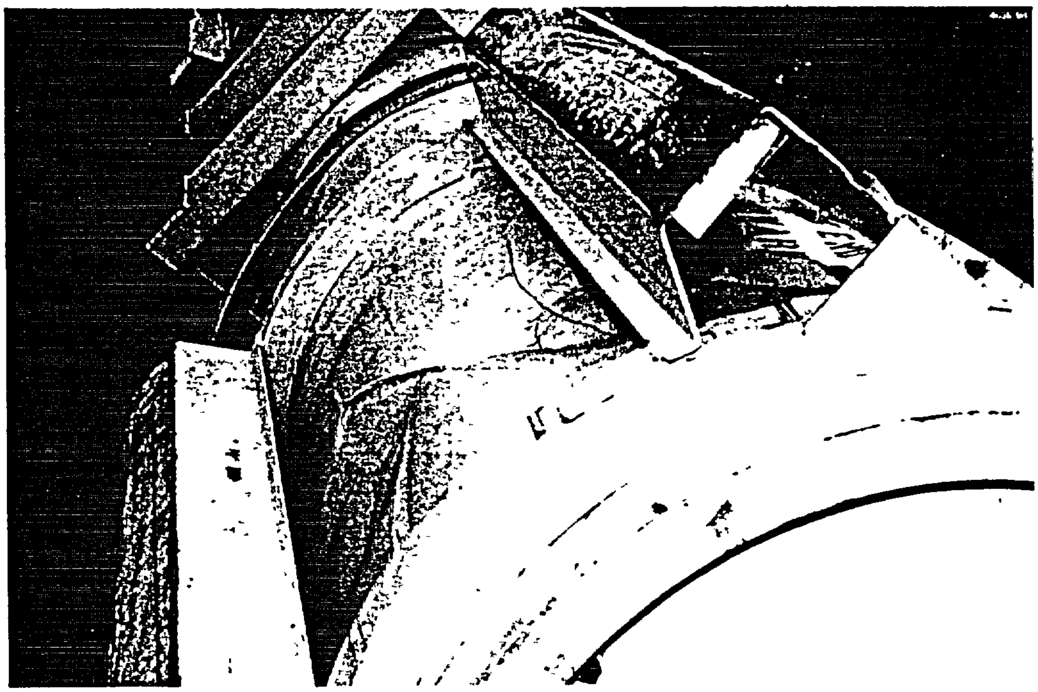


Figure 2-1-14 Outer Container Stacking Bracket and Rollover Ring Deformation after 30-foot Drop

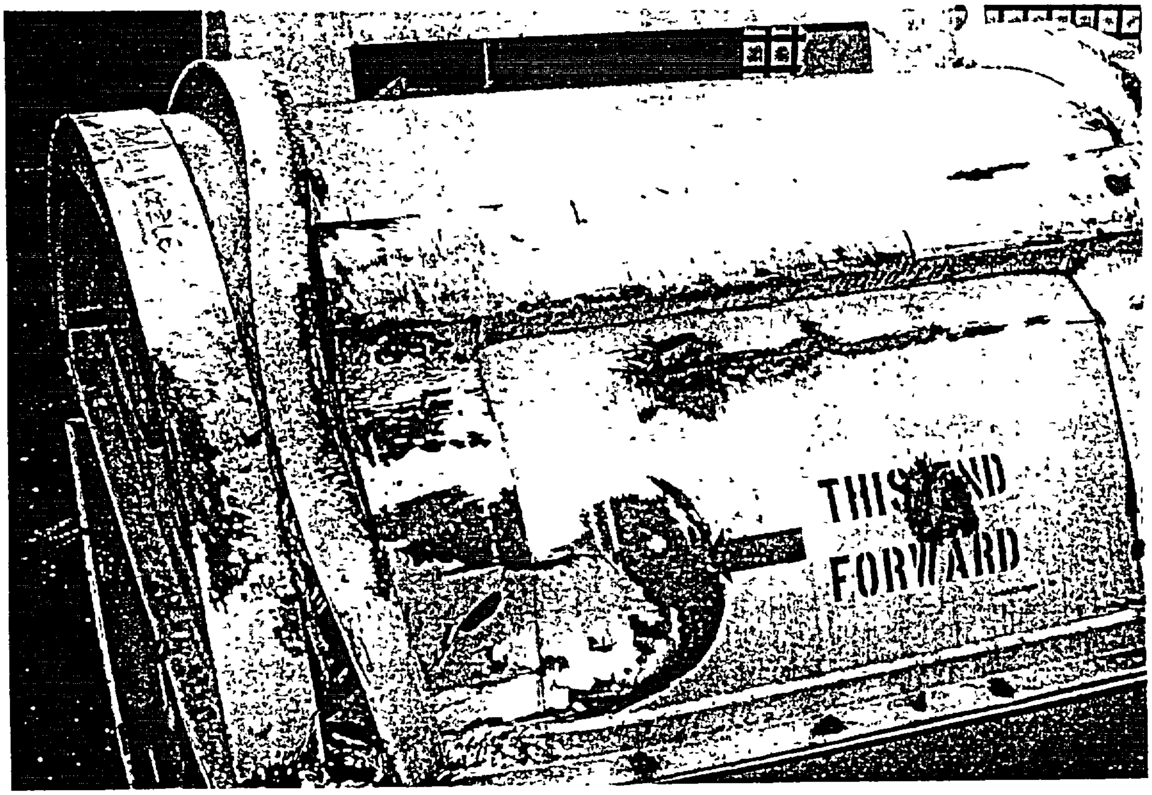


Figure 2-1-15 Outer Container Stacking Bracket Deformation after 30-foot Drop

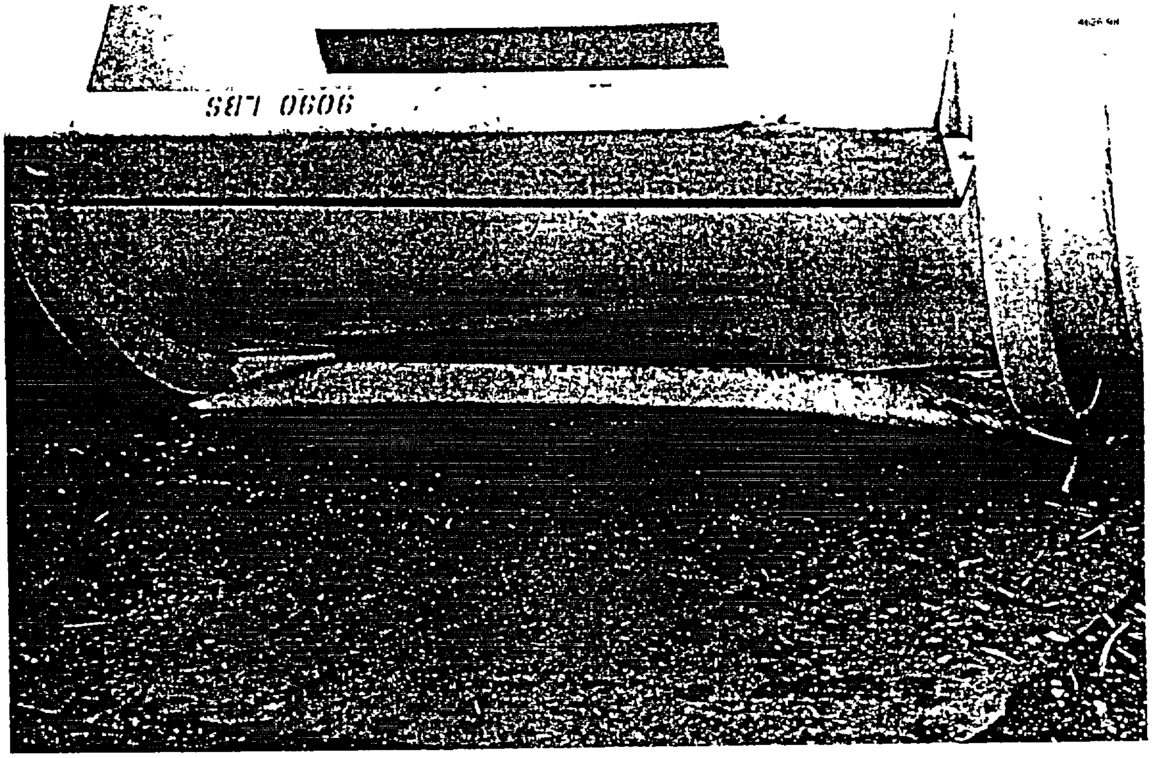


Figure 2-1-16 Outer Container Deformation after 30-foot Drop

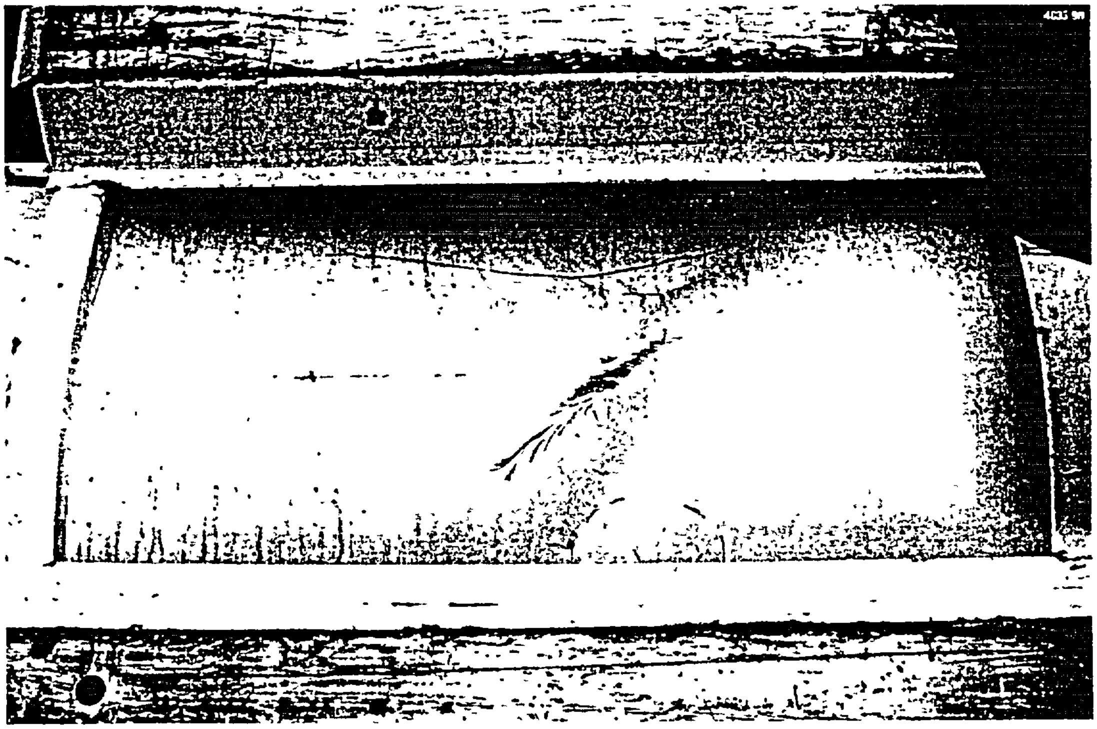


Figure 2-1-17 Package after 30-foot Drop - Side View

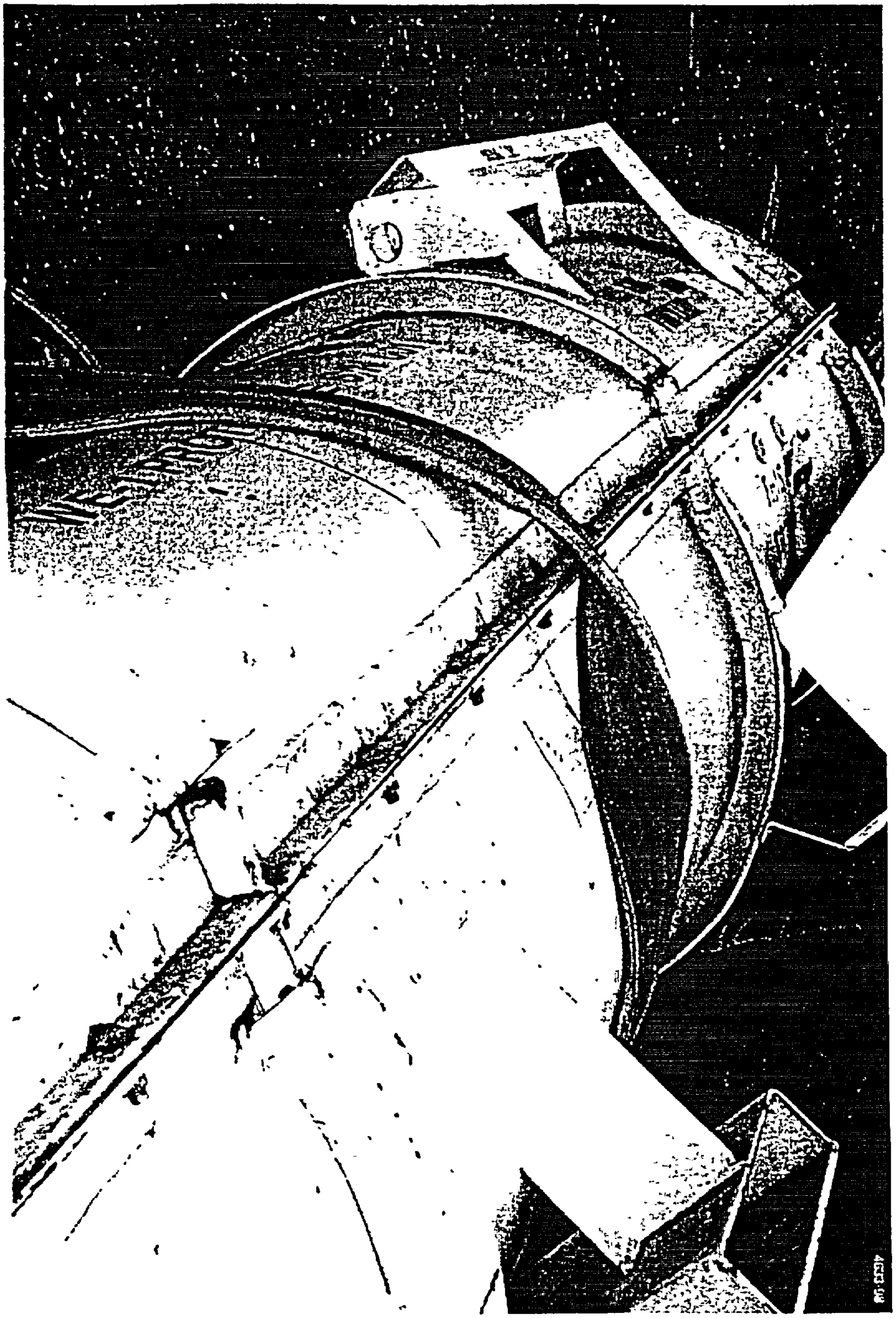
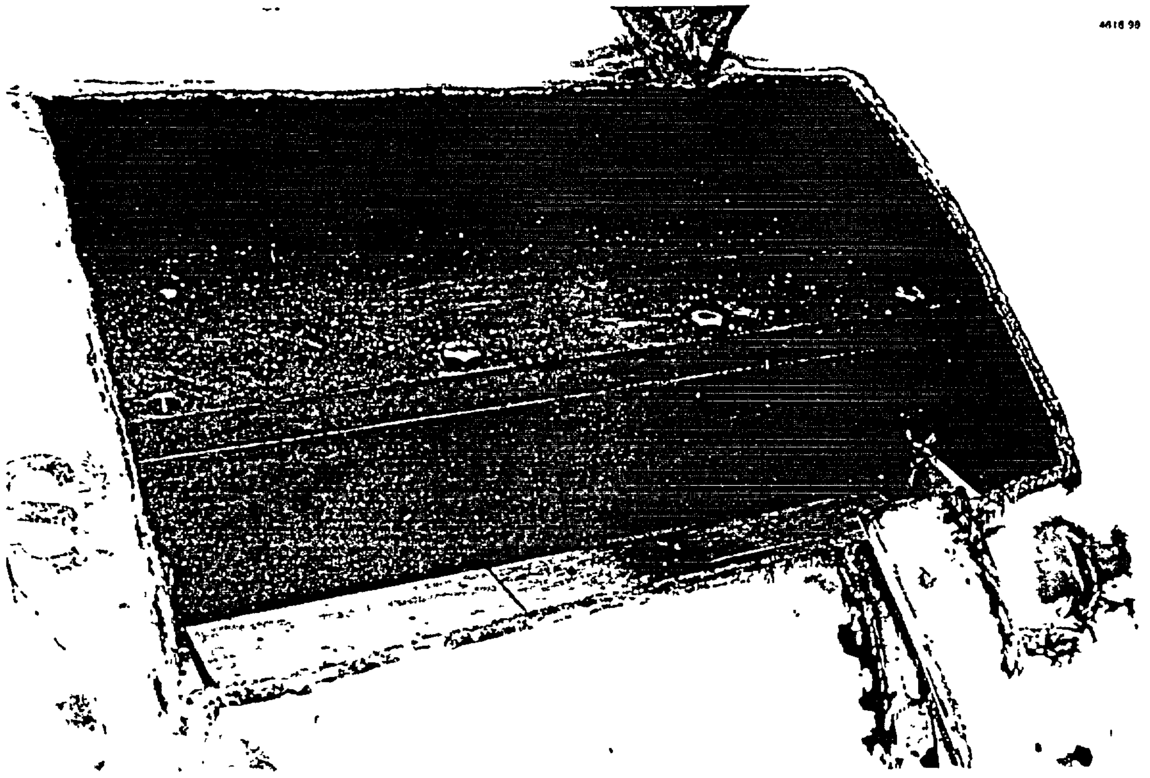


Figure 2-1-18 Outer Container Cutout - To Target Pin Puncture Test on Inner Container



WE-1 CONTAINER PUNCTURE TEST

Figure 2-1-19 Welding of Pin Fixture to Test Bed

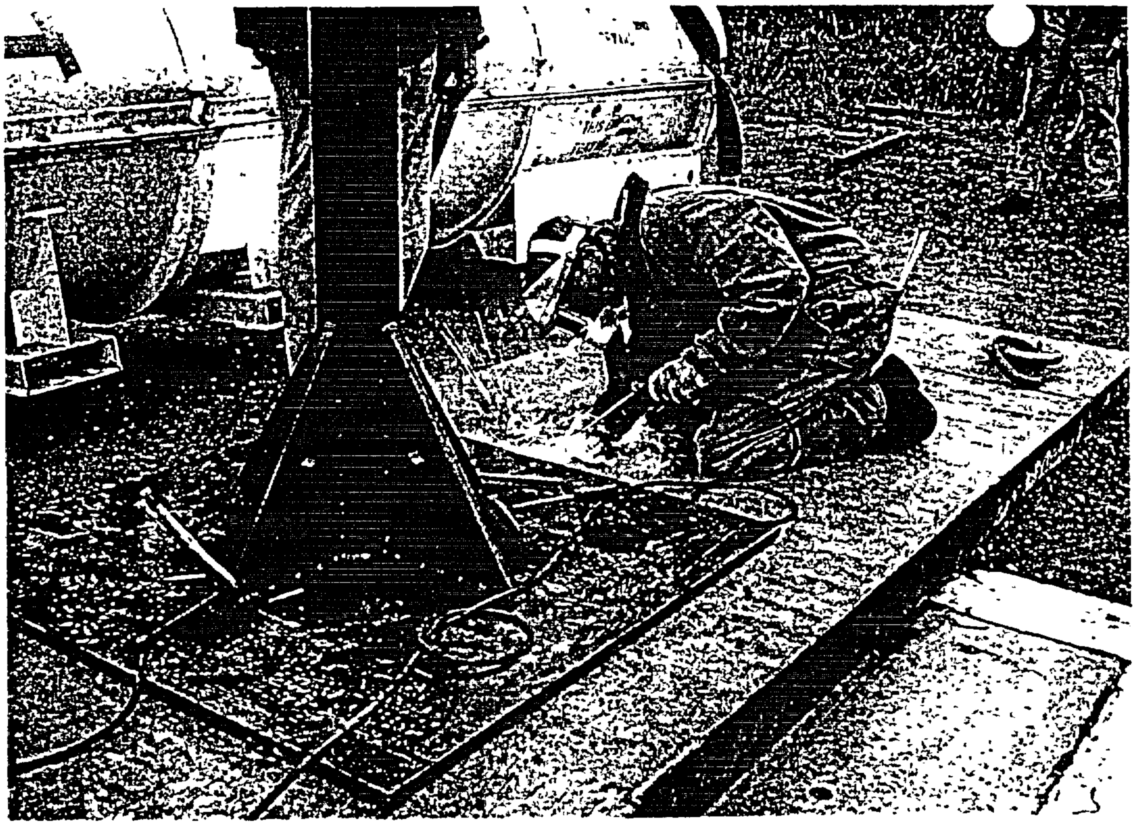


Figure 2-1-20 Pin Puncture Setup - Side View

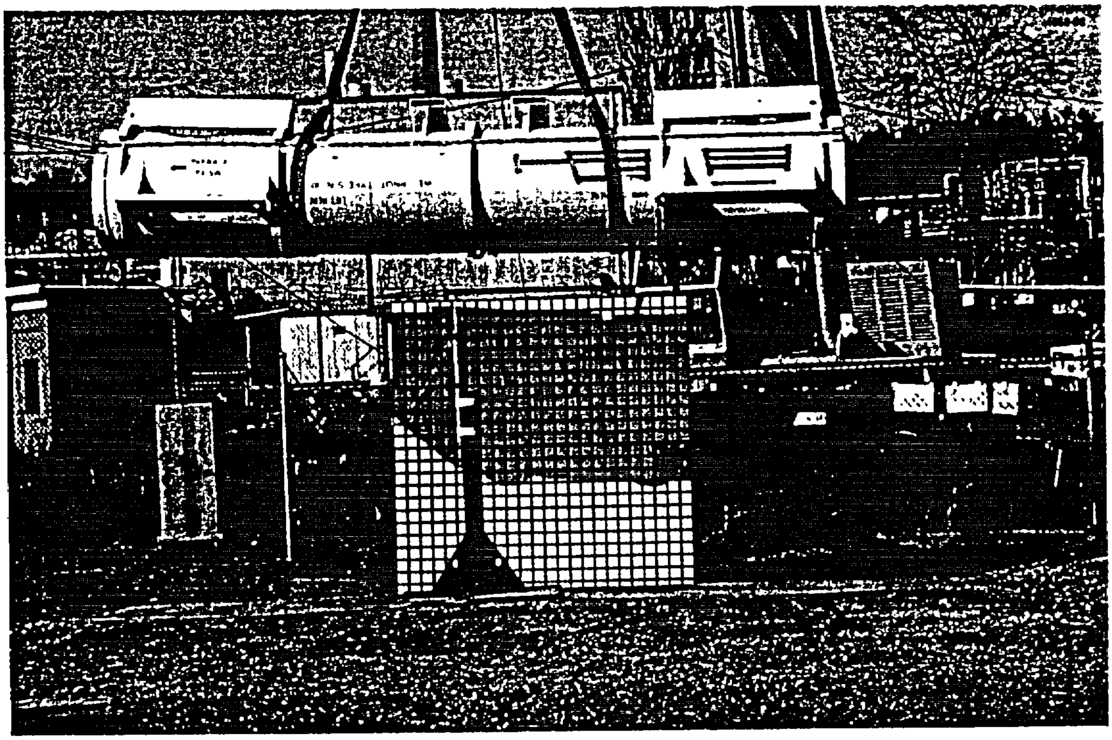


Figure 2-1-21 Pin Puncture Setup - End View

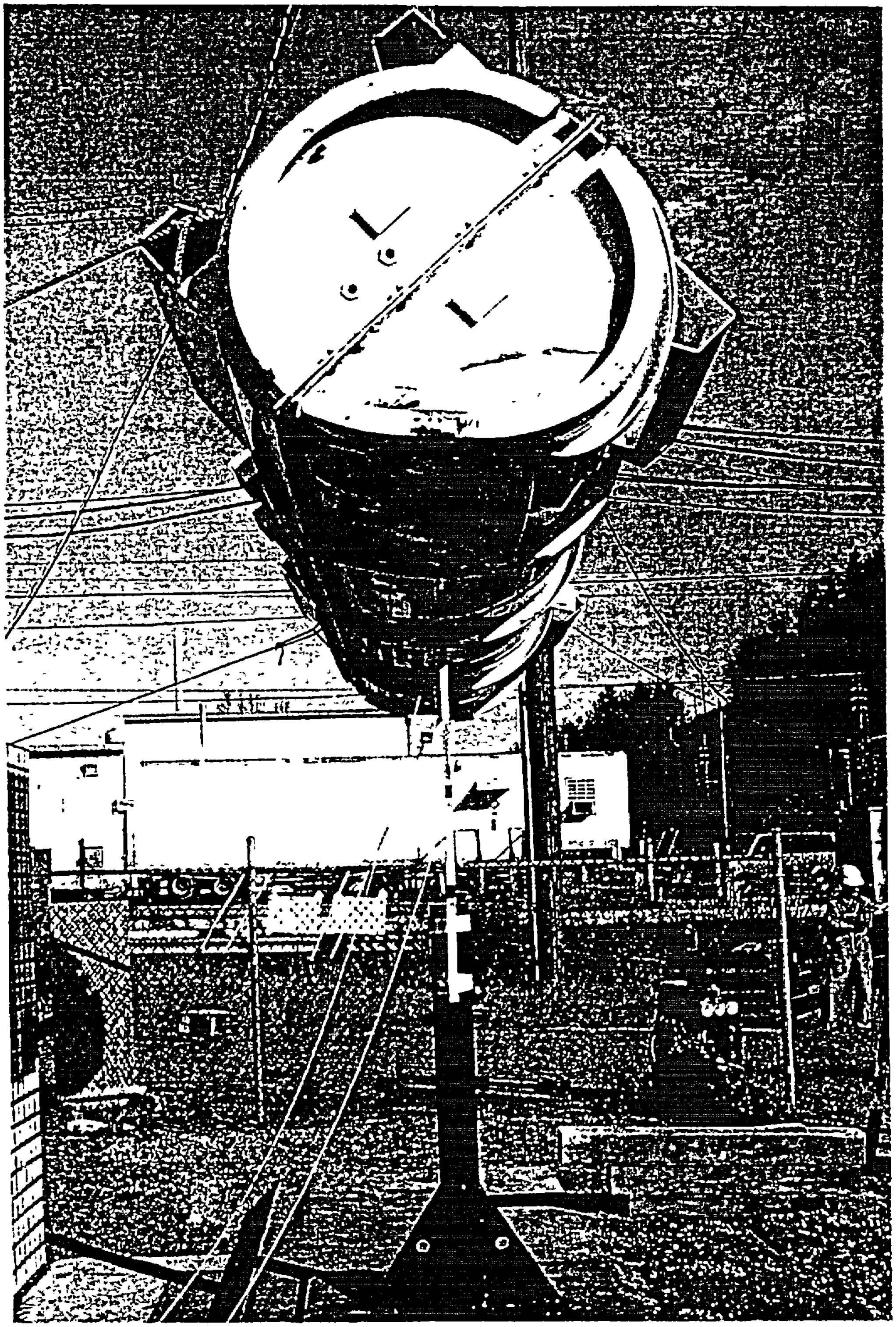


Figure 2-1-22 Drop Orientation Just Prior to Impact with Pin

Figure 2-1-23 Resting Position after Pin Puncture Impact

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

Figure 2-1-24 Top View (1) of Pin Showing Impact Line Where Inner Container Corner Hit

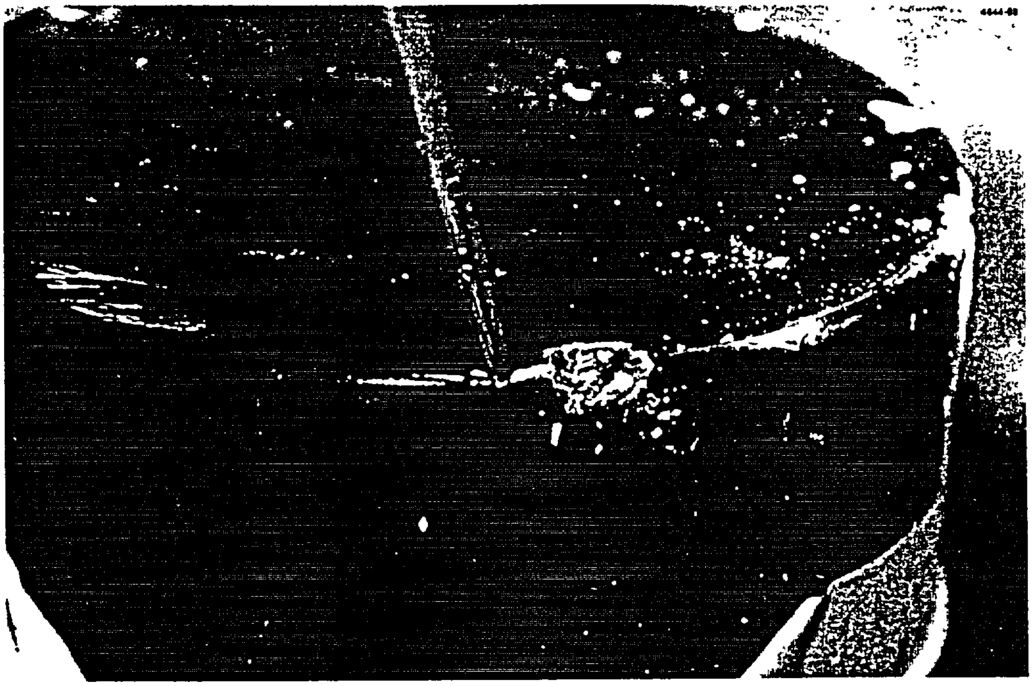


Figure 2-1-25 Top View (2) of Pin Showing Impact Line Where Inner Container Corner Hit

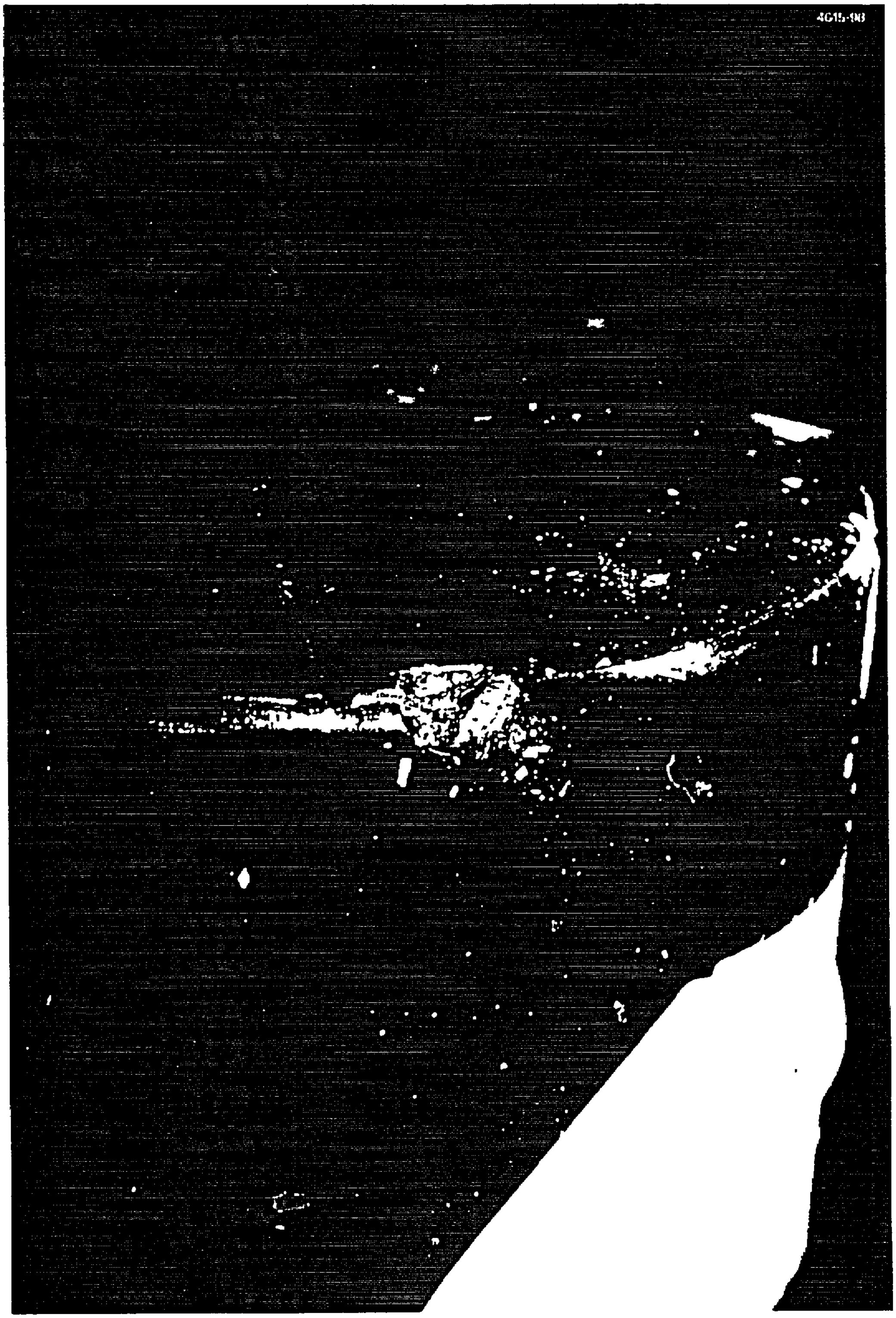
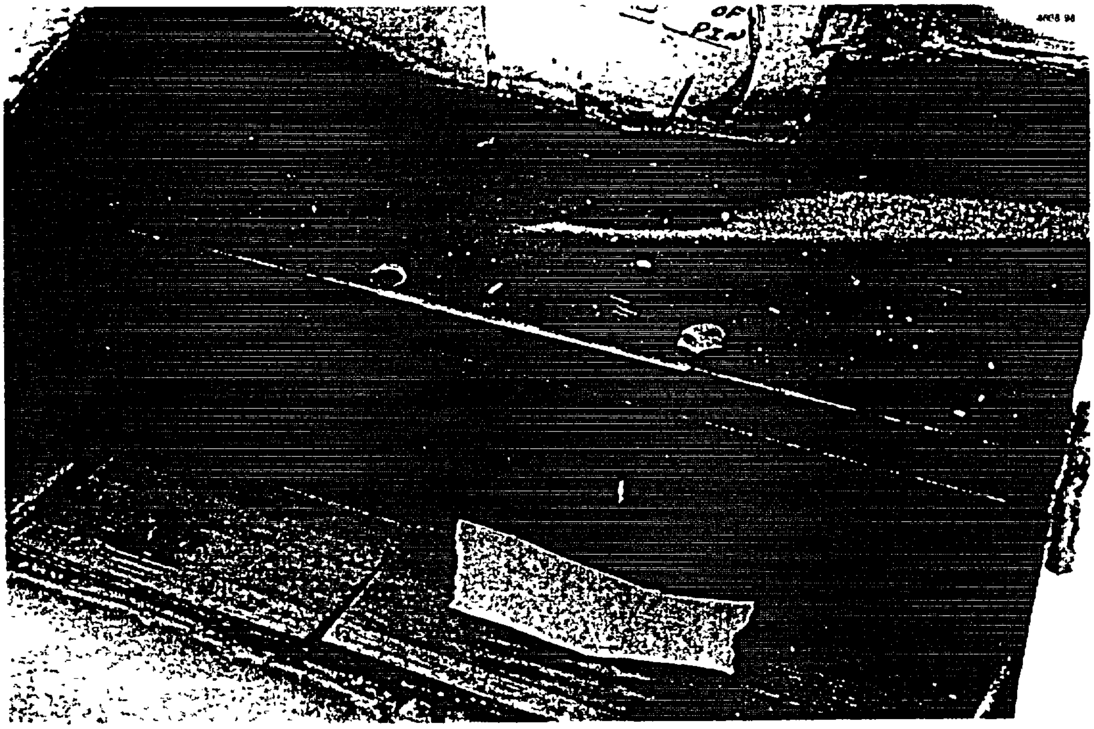


Figure 2-1-26 View Inner Container Through Cutout Window of Outer Container

Figure 2-1-27 View of Inner Container Showing Pin Impact Area



WE-1 CONTAINER DAMAGE ASSESSMENT AT LMF

Figure 2-1-28 Post-Testing Removal of Inner Container Lid

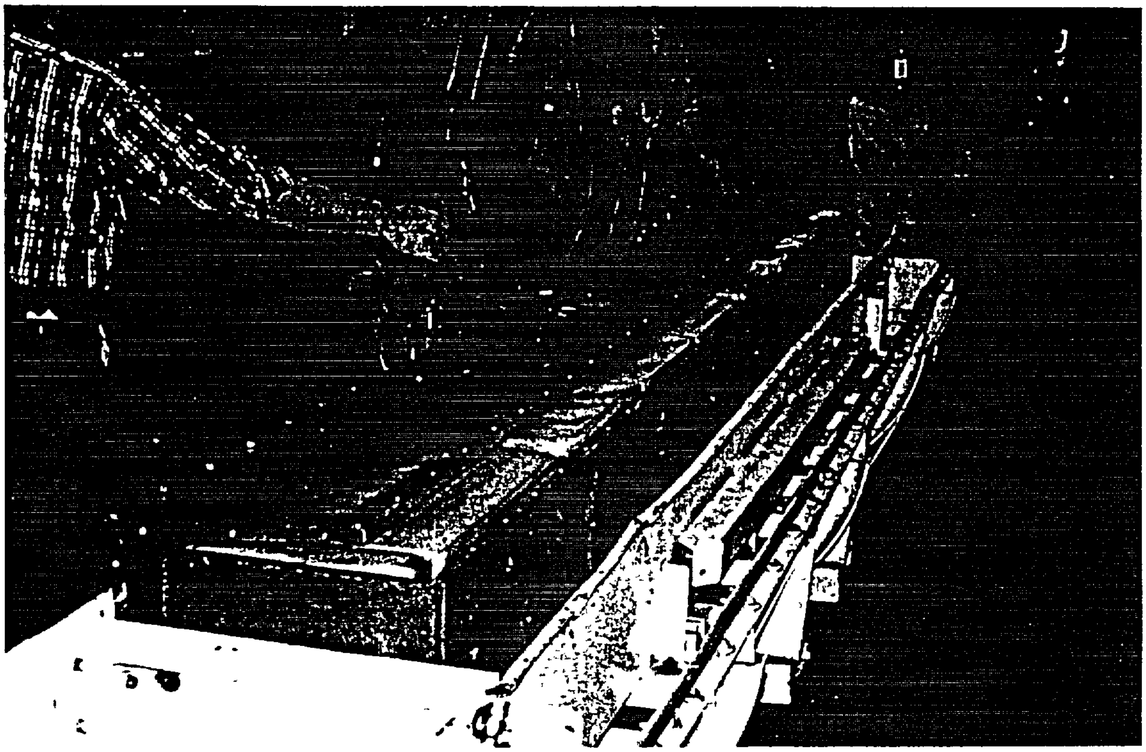


Figure 2-1-29 Post-Testing View of Inner Container and Assembly - End View

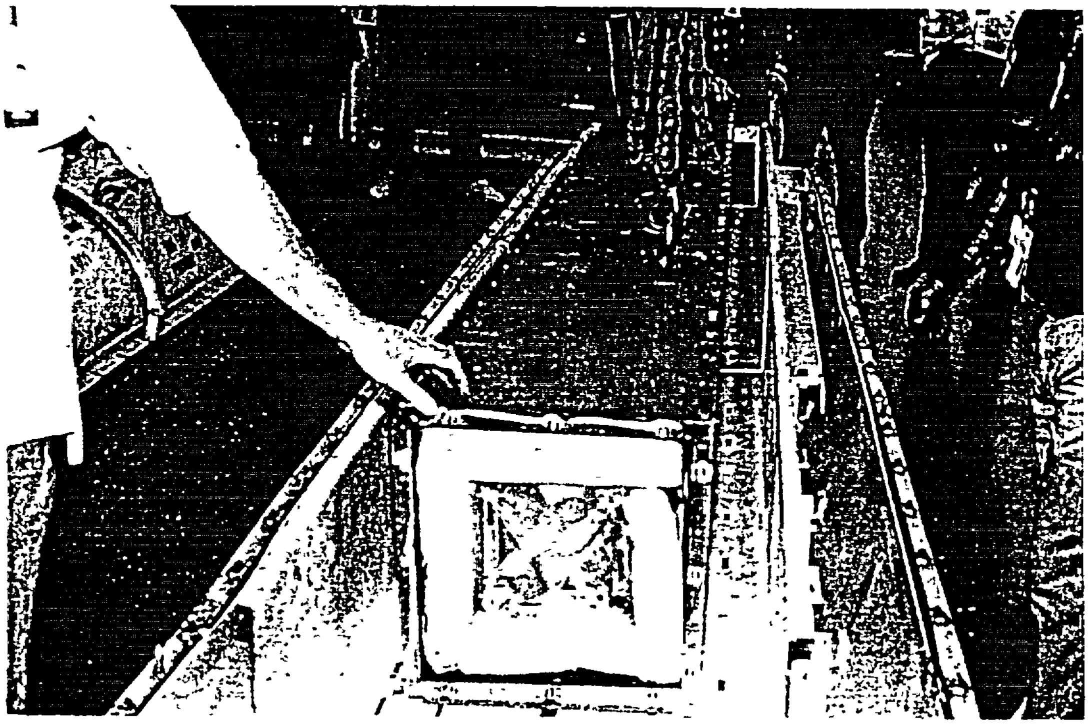


Figure 2-1-30 Post-Testing View of Fuel Assembly, Clamps, and Insulation

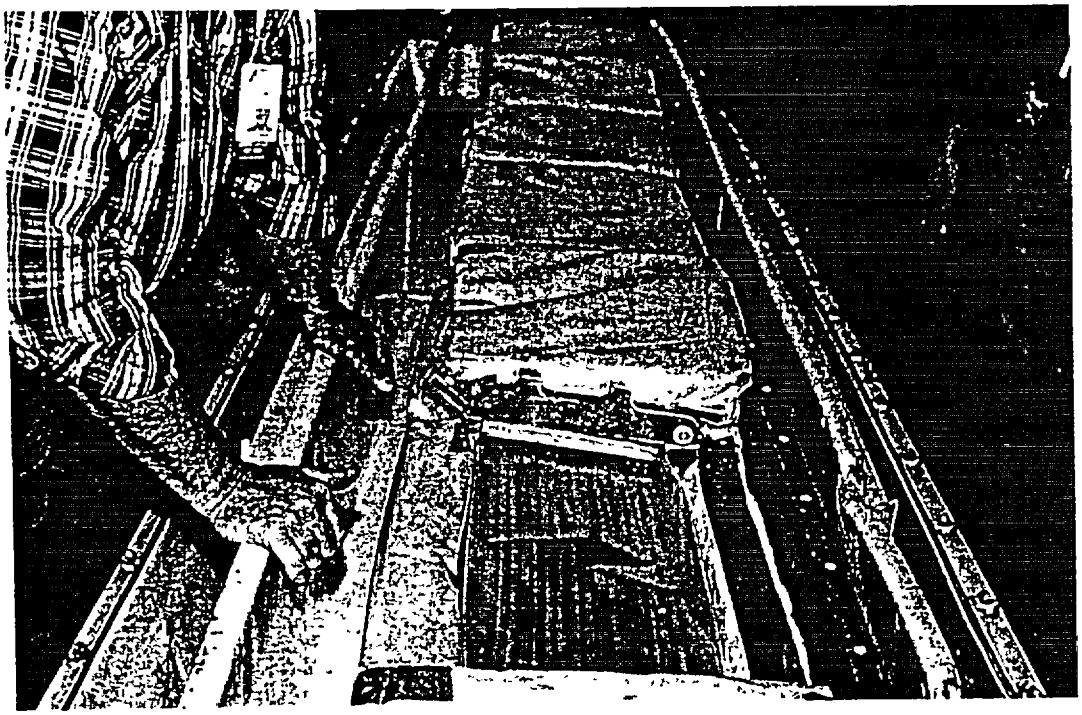


Figure 2-1-31 Post-Testing View of Inner Container and Strongback

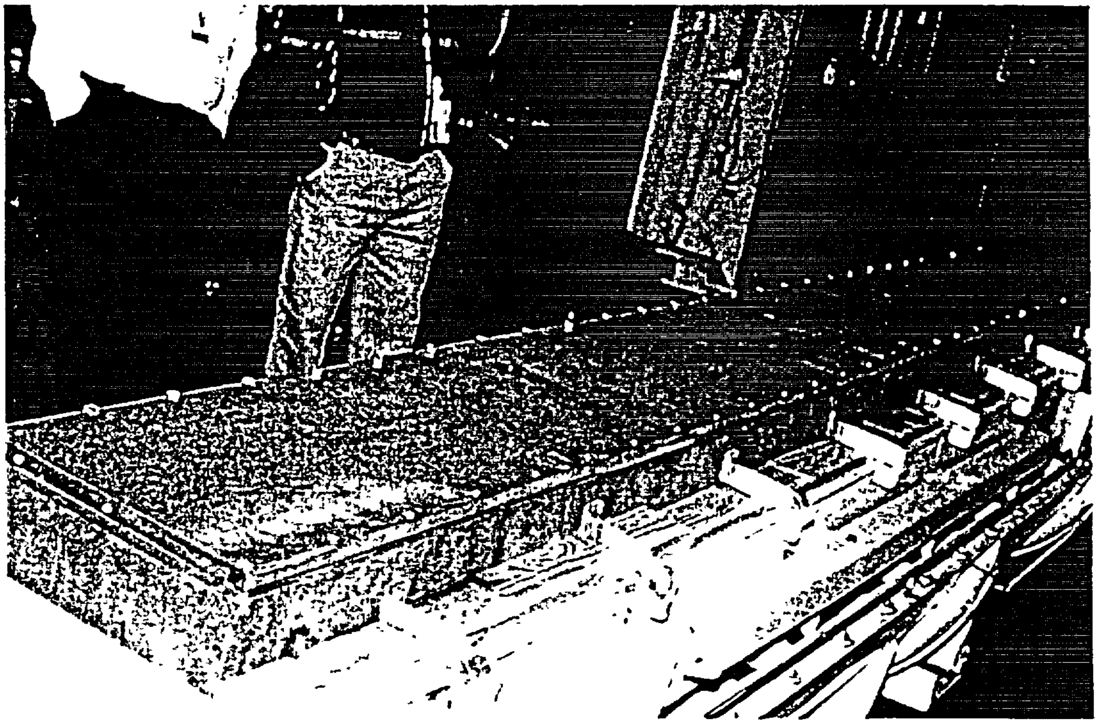


Figure 2-1-32 Post-Testing View of Inner Container and Strongback - Close-up

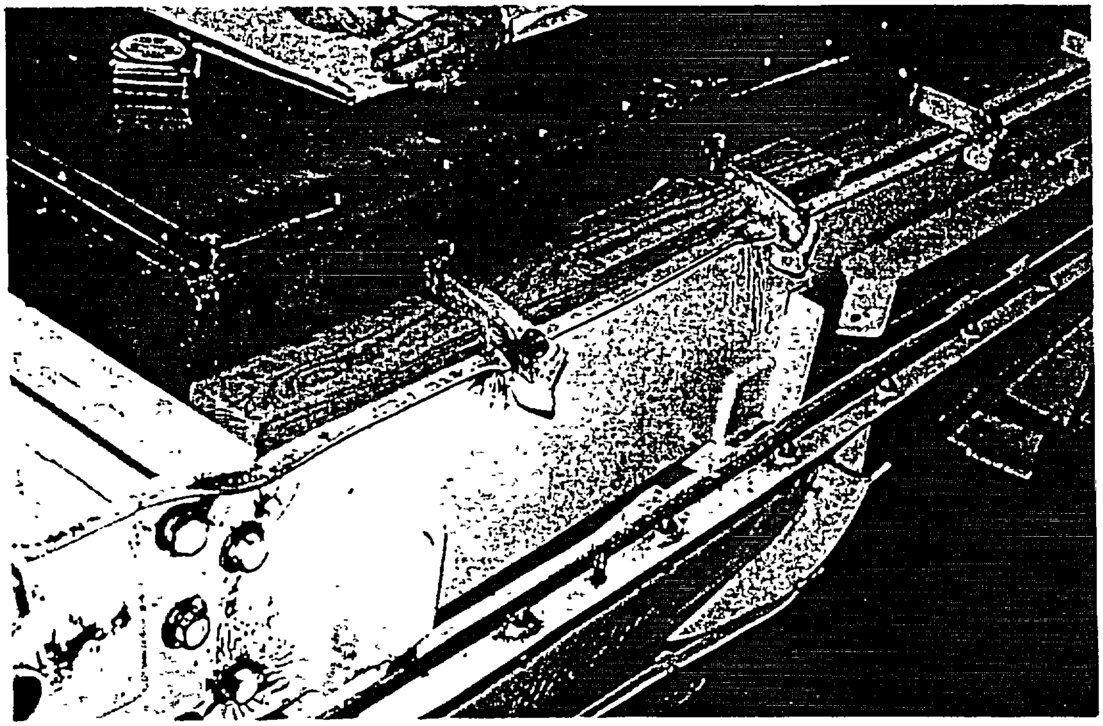
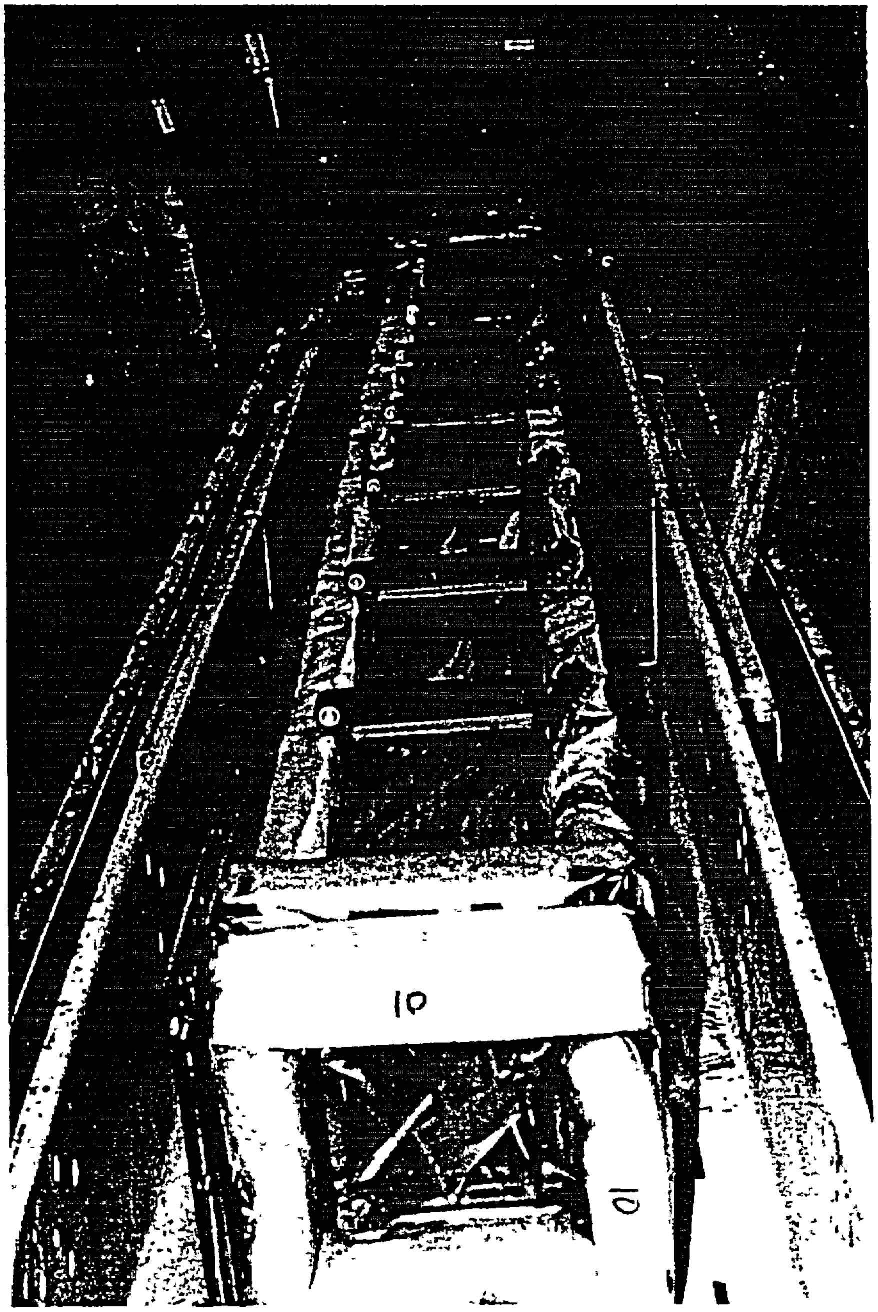


Figure 2-1-33 Post-Testing View of Fuel Assembly, Inner Container, and Strongback



3✓

Figure 2-1-34 Post-Testing View of Fuel Assembly Spacer Grid and Clamp (1) - Close-up

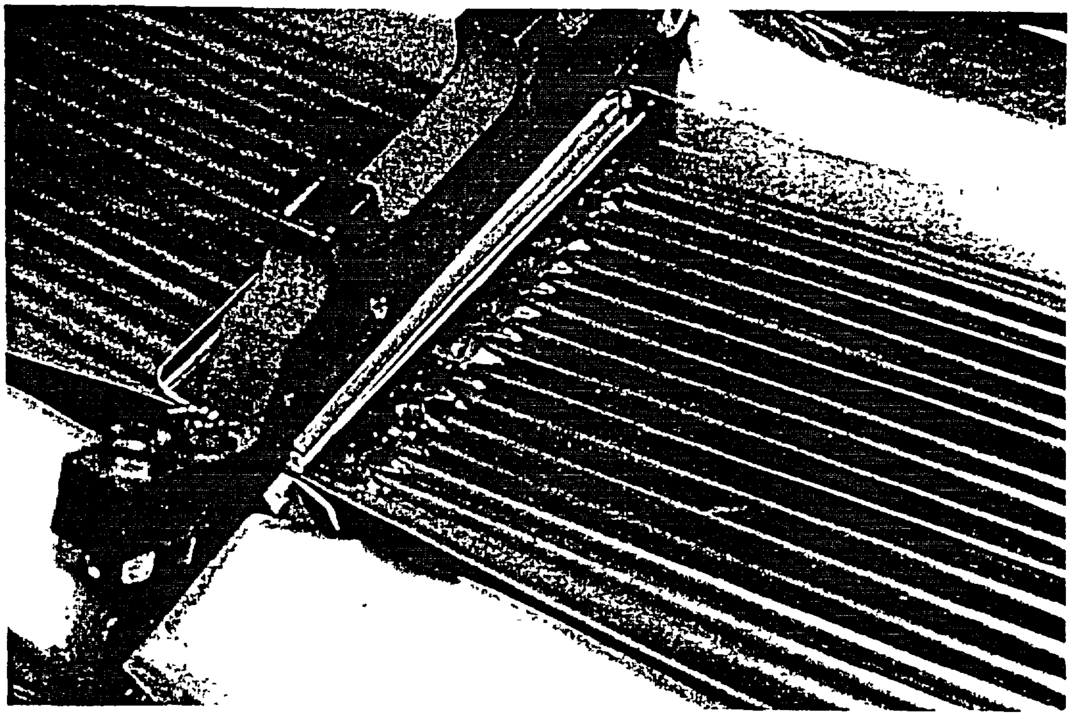


Figure 2-1-35 Post-Testing View of Fuel Assembly Spacer Grid and Clamp (2) - Close-up

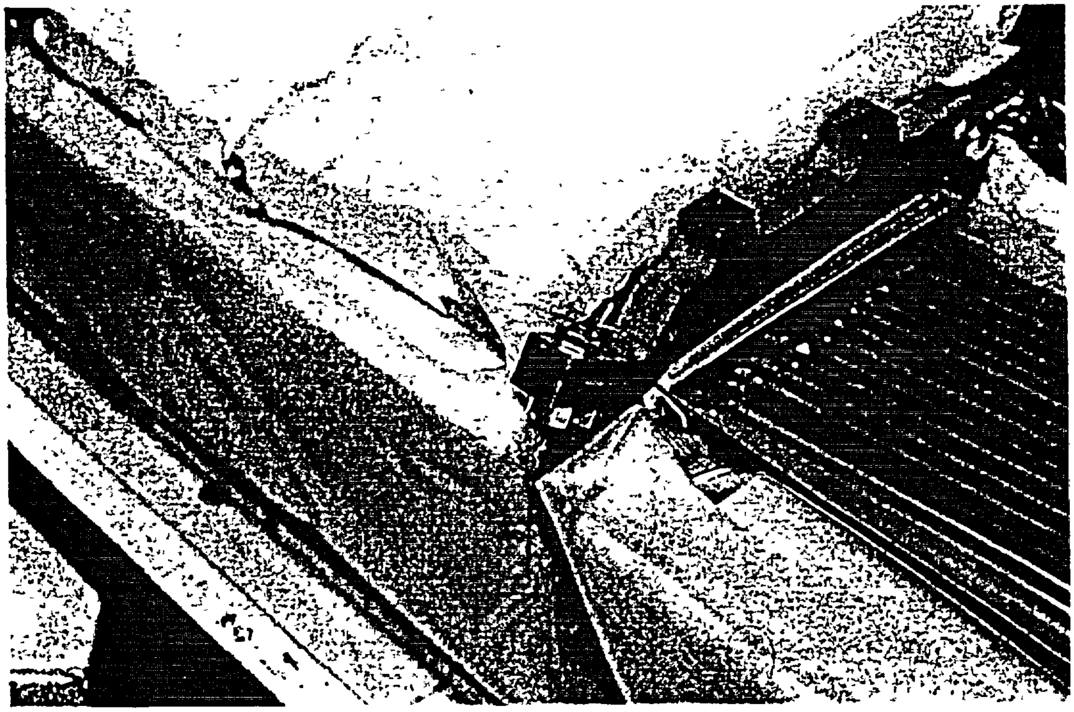


Figure 2-1-36 Post-Testing View of Fuel Assembly Spacer Grid Deformation at Clamp Location

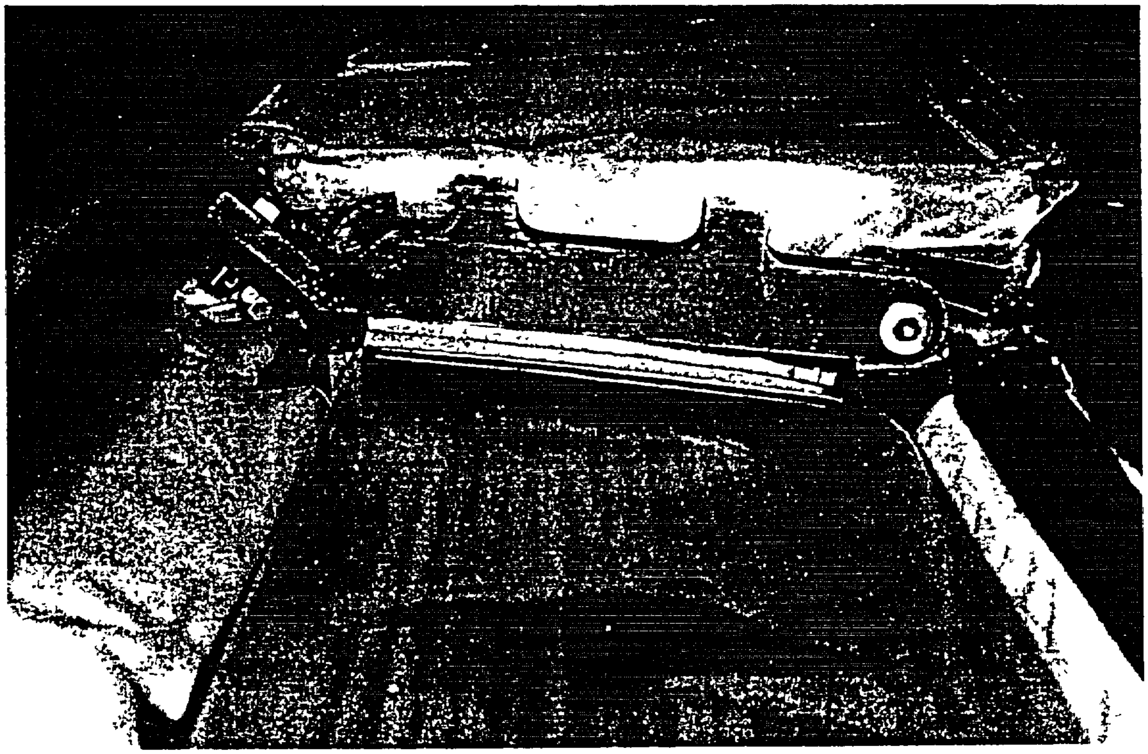


Figure 2-1-37 Deformation of Fuel Rods at Slapdown End of Container

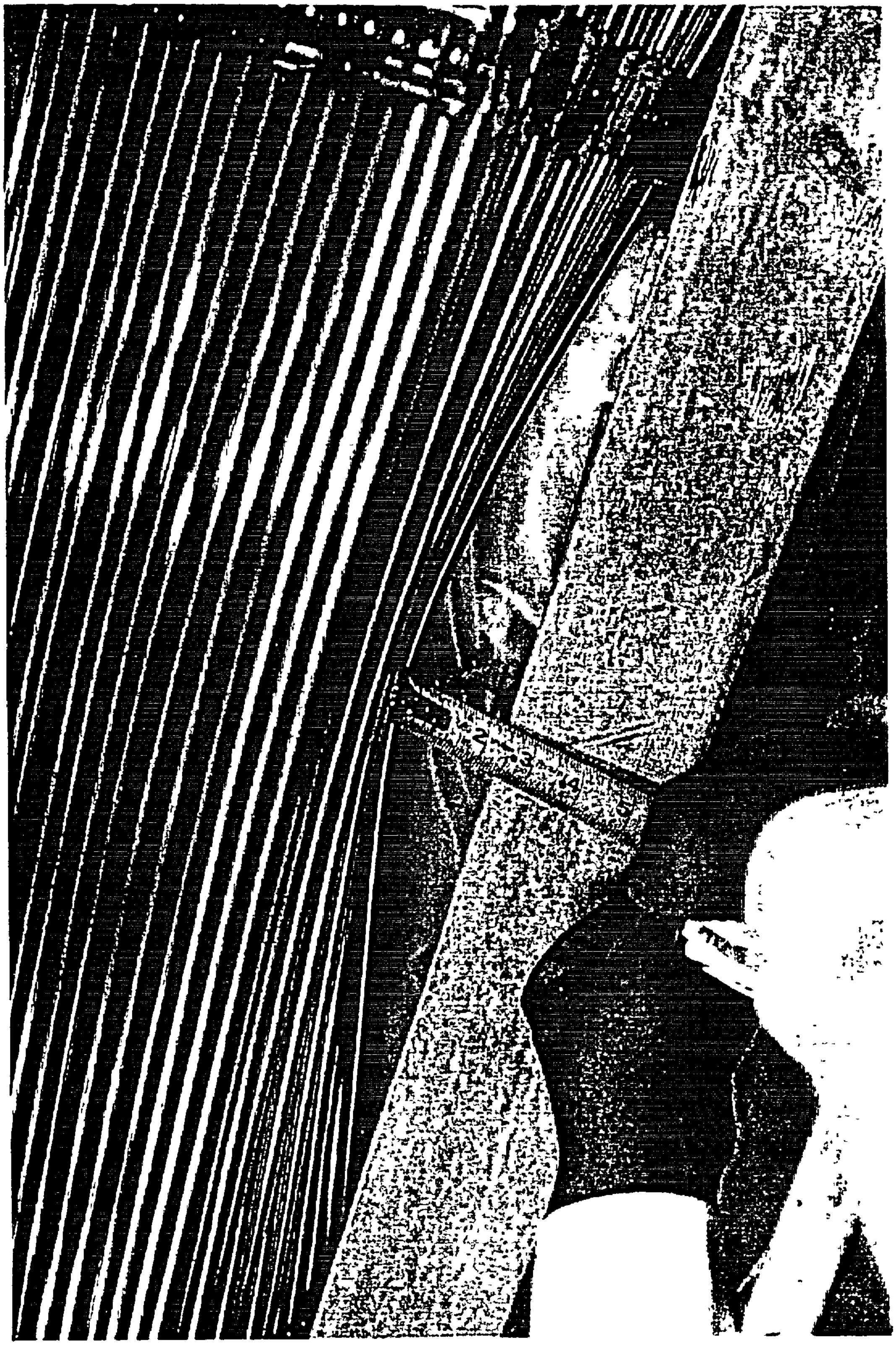
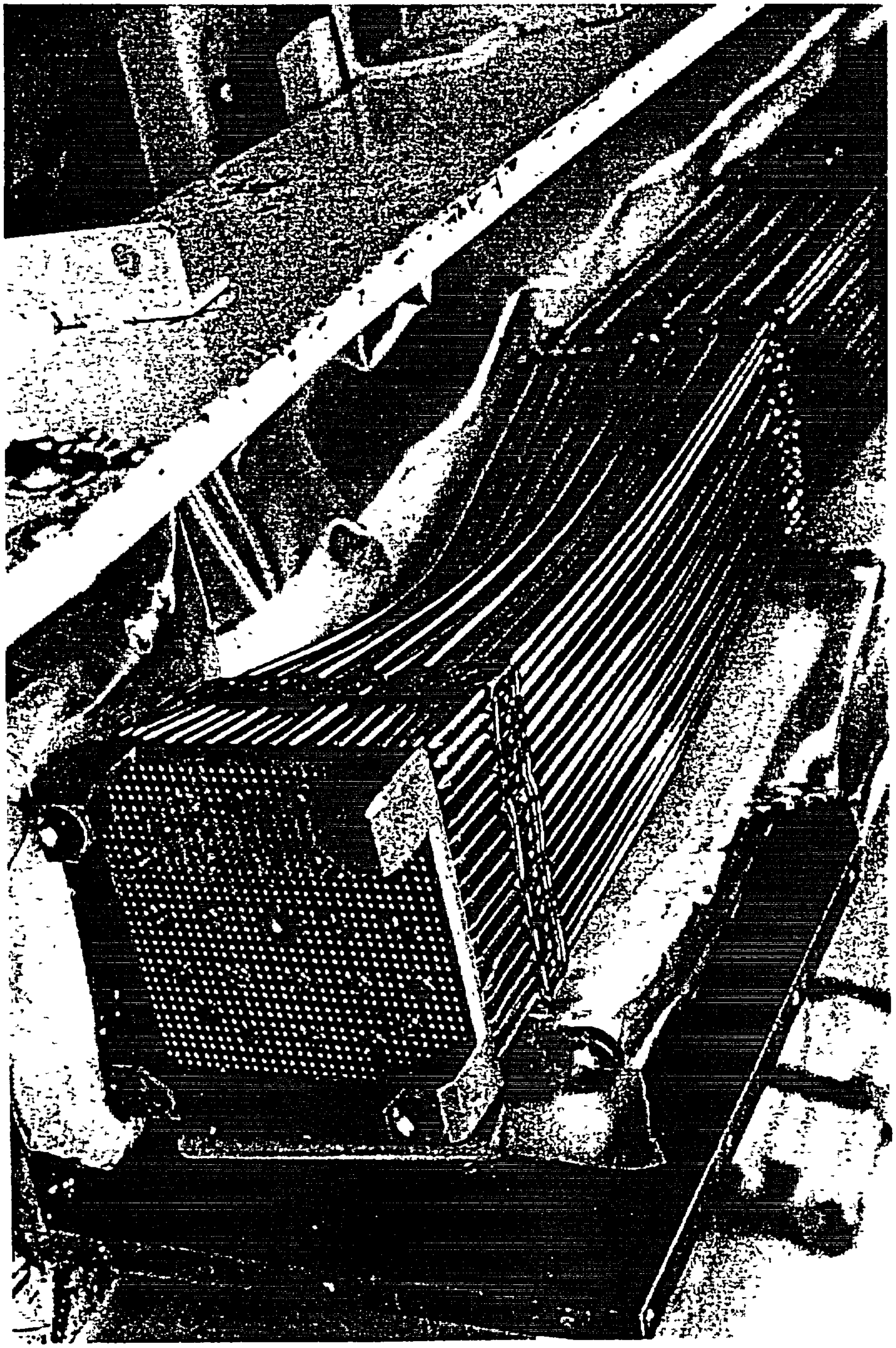


Figure 2-1-38 Lower End of Fuel Assembly Showing Fuel Rod Deformation at Slapdown End of Container



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)[3].

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:

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

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

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

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

---

[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:

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

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:

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

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

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

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

and, for horizontal heated surfaces facing downward:

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

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

$$\mathrm{Gr} = \frac{g\beta\Delta T L^3}{\nu^2}$$

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 3-2: ANSYS® INPUT FILES

3-2.1 ANSYS® FINITE ELEMENT MODEL, GEOMETRY AND MESH

```
! CREATE 10" Section of WE-1 PACKAGE
!  INNER CONTAINER, INSULATION AND
!  SUPPORT BRACKET, DECEMBER 1998

fini
/cle
/prep7

! set up toolbar abbreviations
/NOPR
*ABBR,ANSYSWEB
*ABB,HIDLINE,Fnc_Pl_Hidden
*ABB,BLOWAREA,ALLS,BELOW,AREA
*ABB,KNUMON,/PNUM,kp,1
*ABB,kNUMOFF,/PNUM,kp,0
*ABB,LNUMON,/PNUM,LINE,1
*ABB,LNUMOFF,/PNUM,LINE,0
*ABB,COL_NUM,/NUMB,0
*ABB,COL_ONLY,/NUMB,1
*ABB,NUMB_ONLY,/NUMB,2
*ABB,NO_COLR,/NUMB,-1
*ABB,REPLOT,/REPLOT
/GO

/PNUM,KP,0
/PNUM,LINE,0
/PNUM,AREA,0
/PNUM,VOLU,0
/PNUM,NODE,0
/PNUM,SVAL,0
/NUM,1
/PNUM,MAT,1

! set element types
et,1,55,3,,1
et,2,55,3,,1
et,3,55,3,,1
et,4,55,3,,1
et,5,32       ! linear conductors
et,7,50,1     ! radiation superelements
et,14,70,,3

! define mesh keypoints
! inner container meshpoints

k,1,0.0,0.0,0.0
k,2,16.5,0.0,0.0
k,3,16.5,16.5,0.0
k,4,0.0,16.5,0.0
k,5,1.0,1.0
k,6,15.5,1.0
k,7,15.5,15.5
k,8,1.0,15.5
k,11,5.77,1.0
k,12,6.77,1.0
k,13,9.73,1.0
k,14,10.73,1.0
k,15,15.5,5.77
k,16,15.5,6.77
k,17,15.5,9.73
k,18,15.5,10.73
k,19,10.73,15.5
k,20,9.73,15.5
k,21,6.77,15.5
k,22,5.77,15.5
k,23,1.0,10.73
k,24,1.0,9.73
k,25,1.0,6.77
k,26,1.0,5.77
k,31,2.54,2.54
k,32,5.77,2.54
k,33,6.77,2.54
k,34,9.73,2.54
k,35,10.73,2.54
k,36,14.62,2.54
k,37,14.62,5.77
k,38,14.62,6.77
k,39,14.62,9.73
k,40,14.62,10.73
k,41,14.62,11.99
k,42,13.12+.71,12.49+.71
k,43,14.92+.35,14.92-.35
k,44,14.92-.35,14.92+.35
k,45,12.39+.71,13.19+.71
k,46,11.99,14.62
k,47,10.73,14.62
k,48,9.73,14.62
k,49,6.77,14.62
k,50,5.77,14.62
k,51,2.54,14.62
k,52,2.54,10.73
k,53,2.54,9.73
k,54,2.54,6.77
k,55,2.54,5.77
k,71,2.54+1.5,2.54+1.5
k,72,kx(36)-1.5,ky(36)+1.5
k,73,kx(36)-1.5,ky(72)+9.08
k,74,2.54+1.5,ky(73)

! setup gaps
k,111,kx(11),ky(11)+0.005
k,112,kx(12),ky(12)+0.005
k,113,kx(13),ky(13)+0.005
k,114,kx(14),ky(14)+0.005
k,115,kx(15)-0.02,ky(15)
k,116,kx(16)-0.02,ky(16)
k,117,kx(17)-0.02,ky(17)
k,118,kx(18)-0.02,ky(18)
k,119,kx(19),ky(19)-0.02
k,120,kx(20),ky(20)-0.02
k,121,kx(21),ky(21)-0.02
k,122,kx(22),ky(22)-0.02
k,123,kx(23)+0.005,ky(23)
k,124,kx(24)+0.005,ky(24)
k,125,kx(25)+0.005,ky(25)
k,126,kx(26)+0.005,ky(26)

! setup lines
l,1,2
l,2,3
l,3,4
l,4,1
l,5,11
l,11,12
l,12,13
l,13,14
l,14,6
l,6,15
l,15,16
l,16,17
l,17,18
l,18,7
l,7,19
l,19,20
l,20,21
l,21,22
l,22,8
l,8,23
l,23,24
l,24,25
l,25,26
l,26,5
l,31,32
l,32,111
l,111,112
l,112,33
```

```
1,33,34
1,34,113
1,113,114
1,114,35
1,35,36
1,36,37
1,37,115
1,115,116
1,116,38
1,38,39
1,39,117
1,117,118
1,118,40
1,40,41
1,41,42
1,42,43
1,43,44
1,44,45
1,45,46
1,46,47
1,47,119
1,119,120
1,120,48
1,48,49
1,49,121
1,121,122
1,122,50
1,50,51
1,51,52
1,52,123
1,123,124
1,124,53
1,53,54
1,54,125
1,125,126
1,126,55
1,55,31
1,71,72
1,72,73
1,73,74
1,74,71
1,1,5
1,2,6
1,3,7
1,4,8
1,31,71
1,36,72
1,42,73
1,45,73
1,51,74

! define outer shell
!  material 2
!  element type 2
ASEL,U,AREA,,ALL
MAT,2
TYPE,2
FLST,2,8,4
FITEM,2,70
FITEM,2,1
FITEM,2,71
FITEM,2,9
FITEM,2,8
FITEM,2,7
FITEM,2,6
FITEM,2,5
AL,P51X
FLST,2,8,4
FITEM,2,71
FITEM,2,2
FITEM,2,72
FITEM,2,14
FITEM,2,13
FITEM,2,12
FITEM,2,11
FITEM,2,10
AL,P51X
FLST,2,8,4
FITEM,2,3
FITEM,2,73
FITEM,2,19
FITEM,2,18
FITEM,2,17
FITEM,2,16
FITEM,2,15
```

```
FITEM,2,72
AL,P51X
FLST,2,8,4
FITEM,2,4
FITEM,2,70
FITEM,2,24
FITEM,2,23
FITEM,2,22
FITEM,2,21
FITEM,2,20
FITEM,2,73
AL,P51X
AATT,2,,2

! define bracket
! material 3
! element type 3
ASEL,U,AREA,,ALL
MAT,3
TYPE,3
FLST,2,12,4
FITEM,2,25
FITEM,2,26
FITEM,2,27
FITEM,2,28
FITEM,2,29
FITEM,2,30
FITEM,2,31
FITEM,2,32
FITEM,2,33
FITEM,2,75
FITEM,2,66
FITEM,2,74
AL,P51X
FLST,2,13,4
FITEM,2,75
FITEM,2,34
FITEM,2,35
FITEM,2,36
FITEM,2,37
FITEM,2,38
FITEM,2,39
FITEM,2,40
FITEM,2,41
FITEM,2,42
FITEM,2,43
FITEM,2,76
FITEM,2,67
AL,P51X
FLST,2,5,4
FITEM,2,76
FITEM,2,44
FITEM,2,45
FITEM,2,46
FITEM,2,77
AL,P51X
FLST,2,13,4
FITEM,2,68
FITEM,2,77
FITEM,2,47
FITEM,2,48
FITEM,2,49
FITEM,2,50
FITEM,2,51
FITEM,2,52
FITEM,2,53
FITEM,2,54
FITEM,2,55
FITEM,2,56
FITEM,2,78
AL,P51X
FLST,2,12,4
FITEM,2,78
FITEM,2,57
FITEM,2,58
FITEM,2,59
FITEM,2,60
FITEM,2,61
FITEM,2,62
FITEM,2,63
FITEM,2,64
FITEM,2,65
FITEM,2,74
FITEM,2,69
AL,P51X
```

```
AATT,3,,3

! setup the insulation/air layer
!  insulation material 4, air material 5
!  element type 4
ASEL,U,AREA,,ALL
FLST,2,8,3
FITEM,2,26
FITEM,2,126
FITEM,2,55
FITEM,2,31
FITEM,2,32
FITEM,2,111
FITEM,2,11
FITEM,2,5
A,P51X
FLST,2,6,3
FITEM,2,33
FITEM,2,34
FITEM,2,113
FITEM,2,13
FITEM,2,12
FITEM,2,112
A,P51X
FLST,2,8,3
FITEM,2,35
FITEM,2,36
FITEM,2,37
FITEM,2,115
FITEM,2,15
FITEM,2,6
FITEM,2,14
FITEM,2,114
A,P51X
FLST,2,6,3
FITEM,2,38
FITEM,2,39
FITEM,2,117
FITEM,2,17
FITEM,2,16
FITEM,2,116
A,P51X
FLST,2,13,3
FITEM,2,40
FITEM,2,41
FITEM,2,42
FITEM,2,43
FITEM,2,44
FITEM,2,45
FITEM,2,46
FITEM,2,47
FITEM,2,119
FITEM,2,19
FITEM,2,7
FITEM,2,18
FITEM,2,118
A,P51X
FLST,2,6,3
FITEM,2,49
FITEM,2,121
FITEM,2,21
FITEM,2,20
FITEM,2,120
FITEM,2,48
A,P51X
FLST,2,8,3
FITEM,2,50
FITEM,2,51
FITEM,2,52
FITEM,2,123
FITEM,2,23
FITEM,2,8
FITEM,2,22
FITEM,2,122
A,P51X
FLST,2,6,3
FITEM,2,24
FITEM,2,124
FITEM,2,53
FITEM,2,54
FITEM,2,125
FITEM,2,25
FLST,2,4,3
FITEM,2,23
FITEM,2,24
FITEM,2,124
FITEM,2,123
A,P51X
FLST,2,4,3
FITEM,2,25
FITEM,2,26
FITEM,2,126
FITEM,2,125
A,P51X
FLST,2,4,3
FITEM,2,11
FITEM,2,111
FITEM,2,112
FITEM,2,12
A,P51X
FLST,2,4,3
FITEM,2,13
FITEM,2,113
FITEM,2,114
FITEM,2,14
A,P51X
FLST,2,4,3
FITEM,2,18
FITEM,2,118
FITEM,2,117
FITEM,2,17
A,P51X
FLST,2,4,3
FITEM,2,16
FITEM,2,116
FITEM,2,115
FITEM,2,15
A,P51X
FLST,2,4,3
FITEM,2,22
FITEM,2,122
FITEM,2,121
FITEM,2,21
A,P51X
FLST,2,4,3
FITEM,2,20
FITEM,2,120
FITEM,2,119
FITEM,2,19
A,P51X
FLST,2,4,3
FITEM,2,24
FITEM,2,124
FITEM,2,125
FITEM,2,25
A,P51X
FLST,2,4,3
FITEM,2,125
FITEM,2,54
FITEM,2,53
FITEM,2,124
A,P51X
AATT,4,,4
ALLS

! mesh areas
ESHAPE,3
ESIZE,1.0
AMESH,ALL

! extrude areas into volumes
TYPE,14
MAT,2
ESIZE,,1
ASEL,S,AREA,,1,26,1
ASEL,R,TYPE,,2
VEXT,ALL,,,0.0,0.0,-0.5
VATT,2,,2
ALLS

MAT,3
VSEL,U,VOLU,,ALL
ASEL,S,AREA,,1,26,1
ASEL,R,TYPE,,3
VEXT,ALL,,,0.0,0.0,-0.5
VATT,3,,3
ALLS

MAT,5
VSEL,U,VOLU,,ALL
```

```
ASEL,S,AREA,,1,26,1
ASEL,R,TYPE,,4
VEXT,ALL,,,0.0,0.0,-0.5
VATT,5,,4
ALLS

MAT,2
ESIZE,,5
VSEL,U,VOLU,,ALL
ASEL,S,AREA,,1,26,1
ASEL,R,TYPE,,2
VEXT,ALL,,,0.0,0.0,9.5
VATT,2,,2
ALLS

MAT,4
VSEL,U,VOLU,,ALL
ASEL,S,AREA,,1,26,1
ASEL,R,TYPE,,3
VEXT,ALL,,,0.0,0.0,9.5
VATT,3,,3
ALLS

MAT,4
VSEL,U,VOLU,,ALL
ASEL,S,AREA,,1,26,1
ASEL,R,TYPE,,4
VEXT,ALL,,,0.0,0.0,9.5
VATT,4,,4
ALLS

! input material properties from file
/inp,matcrush,inp

! mesh all
ALLS
ACLEAR,ALL

! add bolt elements
MAT,8
REAL,5
! two elements = one bolt
!  half cross-sectional area is 0.19 in2
R,5,0.19635
TYPE,5
E,  474,   658
E,  475,   656
E,  478,   650
E,  479,   648
E,  386,   506
E,  387,   508
E,  390,   514
E,  391,   516

! apply radiation
et,24,57
type,24
mat,2
esurf
n,10000,25.5,25.0,5.0

esel,s,type,,24
nsle,r
nsel,s,loc,x,16.49,16.51
nsel,a,loc,y,16.49,16.51
nsel,a,loc,y,-0.01,0.01
nsel,a,loc,x,-0.01,0.01
esln,r
nsel,a,node,,10000

/aux12
emis,2,0.8
```

```
geom,0
space,10000
vtype,0,20
mprint,1
write,framx82
/prep7
alls

! change air resistance from clamping
!  frame-to-inner container to full
!  contact
esel,s,elem,,636,643
emod,all,mat,3
esel,s,type,,24
edel,all
alls
esel,u,mat,,5
nsle,r
nsel,r,loc,z,-1.0,0.1
esln,r,1
mat,3
type,24
esurf
esel,r,type,,24
nsle,r
nsel,r,loc,z,-1.0,-0.49
esln,r,1
edel,all
alls
esel,s,type,,24
nsle,r
nsel,r,loc,z,-0.01,0.01
esln,r,1
edel,all
alls
esel,s,type,,24
nsle,r
nsel,s,loc,x,16.49,16.51
nsel,a,loc,y,16.49,16.51
nsel,a,loc,y,-0.01,0.01
nsel,a,loc,x,-0.01,0.01
esln,r,1
edel,all
alls
esel,s,type,,24
nsle,r
nsel,s,loc,x,4.03,13.12
nsel,r,loc,y,4.03,13.12
esln,r,1
edel,all
alls
esel,s,type,,24

/aux12
emis,3,0.5
geom,0
vtype,0,20
mprint,1
write,framint2

/prep7
esel,s,type,,24
edel,all
type,7
se,framint
se,framx82

! input convection coefficients
!  from file
/inp,conv,inp

save
```

3-2.2 ANSYS® FINITE ELEMENT MODEL, MATERIAL PROPERTIES (MATCRUSH.INP)

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!     HY-80 Material Properties      !
!     AMSE Material Properties for   !
!     3-1/2Ni, 1-3/4Cr, 1/2Mo, V     !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

mp,dens,2,0.283
mp,emis,2,0.5
```

```
mptemp,1,70,250,450,650,850,1050
mptemp,7,1250,1350,1500
mpdata,kxx,2,1,1.83,1.94,1.93,1.84,1.74,1.62
mpdata,kxx,2,7,1.45,1.31,1.27
mpdata,c,2,1,0.11,0.12,0.13,0.14,0.15,0.17
mpdata,c,2,7,0.22,0.23,0.15

mp,dens,3,0.283
mp,emis,3,0.5
mptemp,1,70,250,450,650,850,1050
mptemp,7,1250,1350,1500
mpdata,kxx,3,1,1.83,1.94,1.93,1.84,1.74,1.62
mpdata,kxx,3,7,1.45,1.31,1.27
mpdata,c,3,1,0.11,0.12,0.13,0.14,0.15,0.17
mpdata,c,3,7,0.22,0.23,0.15

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!     Insulation Properties          !
!     Using ASB-2300, 8 pcf          !
!     Crushed to 2 inch thickness    !
!     using 150% conductivity, while !
!     retaining density, specific    !
!     heat of uncrushed insulation   !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

mp,dens,4,0.0046
mp,emis,0.8
mptemp
mptemp,1,0.,500,1000,1500,2000
mpdata,kxx,4,1,0.0036,.0036,.0080,.0131,.021
mp,c,4,0.28

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!     Air Material Properties        !
!          (A.F. Mills)              !
!     heat transfer coefficient      !
!     for a vertical plate from      !
!      Bayazitoglu and Ozisik        !
!     Elements of Heat Transfer      !
!              p271                  !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

! higher density to ease conversion of transient cases
mp,dens,5,0.001
mptemp
mptemp,1,-40,-20,70,100,200,300
mptemp,7,400,500,600,700,800,900
mpdata,kxx,5,1,0.0011,0.0011,0.0012,0.0013,0.0015,0.0017
mpdata,kxx,5,7,0.0018,0.0020,0.0021,0.0023,0.0024,0.0026
mptemp
mptemp,1,0,50,100,150,200,250
mptemp,7,300,500,700,1375

! vertical surface heat transfer coefficient
mpdata,hf,5,1,0.0000013,0.0048,0.0058,0.0064,0.0068,0.0072
mpdata,hf,5,7,0.0074,.0078,.0083,.0086

! horizontal surface heat transfer coefficient, hot facing up
mpdata,hf,15,1,0.0000013,.0058,.0070,.0078,.0083,.0087
mpdata,hf,15,7,.0090,.0096,.0100,.0103

! horizontal surface heat transfer coefficient, hot facing down
mpdata,hf,25,1,0.0000013,.0016,.0018,.0020,.0021,.0022
mpdata,hf,25,7,.0023,.0025,.0026,.0028

mp,c,5,0.242

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!   Series 300 Stainless Steel       !
!   Used for Bolting Material        !
!   From ASME B&PV Code              !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

mp,dens,8,0.289
mp,emis,8,0.5
mptemp
mptemp,1,-20,70,100,200,400,600
mpdata,kxx,8,1,.692,.717,.725,.775,.867,.942
mptemp
mptemp,1,0.0,200.,400.,600.,800.,1500.
mpdata,c,8,1,.111,.124,.13,.134,.140,0.158
```

3-2.3 ANSYS® FINITE ELEMENT MODEL, CONVECTION COEFFICIENTS (CONV.INP)

```
fini
/solu
! set up convection coefficients
!  for fire case
ALLS
NSEL,S,LOC,Y,-0.001,0.001
NSEL,A,LOC,Y,16.499,16.501
NSEL,A,LOC,X,-0.001,0.001
NSEL,A,LOC,X,16.499,16.501
SF,ALL,CONV,0.018,1475.0

ALLS
D,10000,TEMP,1425.0
TUNIF,122.0

! set up run parameters for fire case
AUTOTS,ON
NSUBST,1,0,0,OFF
DELTIM,1.0E-02,1.0E-03,1.0E-01,ON
KBC,1
KUSE,0
MODE,0,1
TIME,0.5
DMPRAT,0.0
TIMINT,ON,THER
TINTP,R5.0,5.0E-03,,,
TINTP,R5.0,0.5,0.5,0.2
CNVTOL,HEAT,-1
CNVTOL,TEMP,-1
CRPLIM,.1
NCNV,1,0.0,0,0.0,0.0
LNSRCH,OFF
NEQIT,50
PRED,OFF,,OFF
ERESX,DEFA
OUTRES,ALL,ALL
ACEL,0.0,0.0,0.0
OMEGA,0.0,0.0,0.0,0
DOMEGA,0.0,0.0,0.0
CGLOC,0.0,0.0,0.0
CGOMEGA,0.0,0.0,0.0
DCGOMG,0.0,0.0,0.0
IRLF,0

LSWRITE,2

! set up convection coefficients
!  for post-fire case
!  top of container
NSEL,S,LOC,Y,-0.001,0.001
SF,ALL,CONV,-15,100.0
ALLS
!  bottom of container
NSEL,S,LOC,Y,16.499,16.501
SF,ALL,CONV,-25,100.0
ALLS
!  sides of container
NSEL,S,LOC,X,-0.001,0.001
NSEL,A,LOC,X,16.499,16.501
SF,ALL,CONV,-5,100.0
ALLS
D,  10000,TEMP,  100.000000    ,
.000000000

! apply solar heat loading
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save
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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	0.99771	0.00021	-	
2,317,158	0.99762	0.00043	0.00009	0.00047
1,000,000	0.99726	0.00067	0.00045	0.00070
480,000	0.99863	0.00095	-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

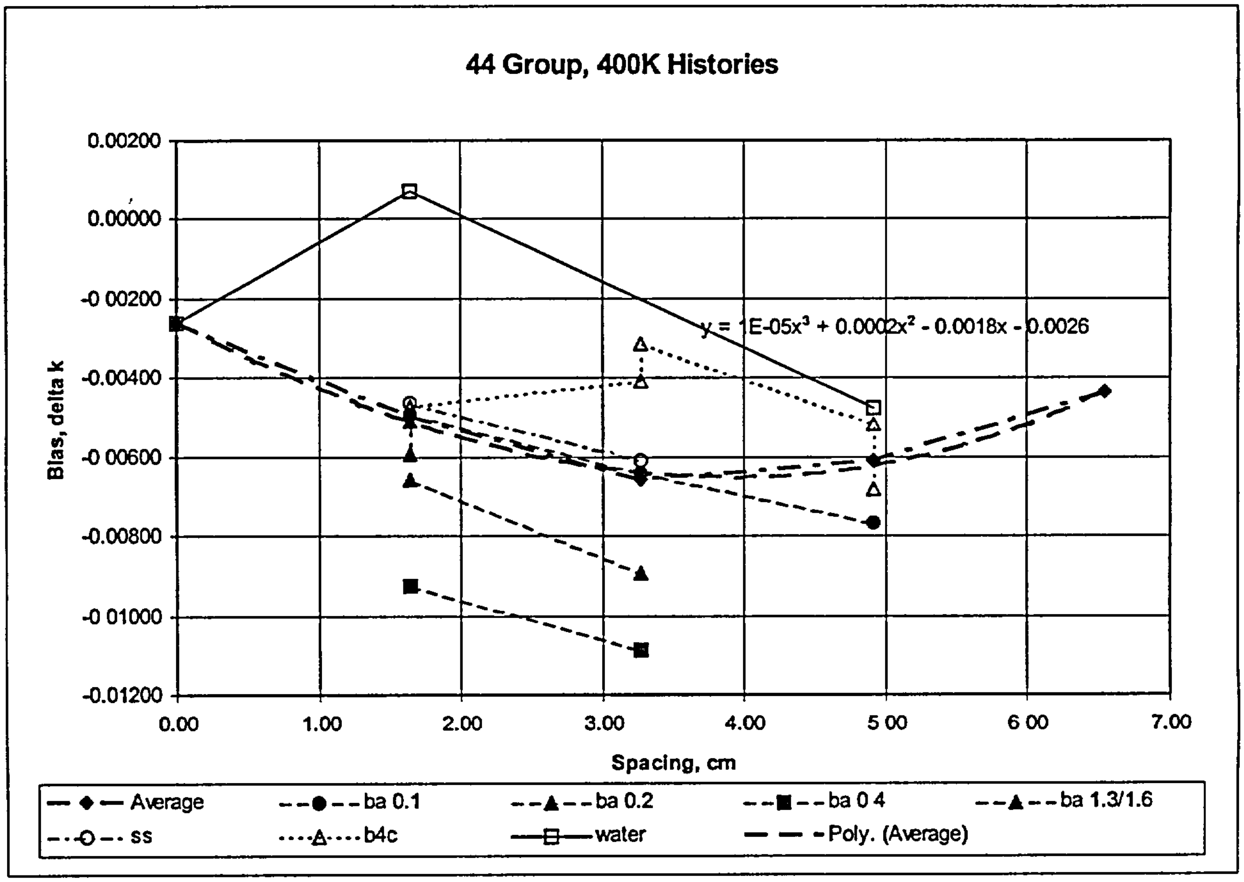


Figure 6-2.2 KENO Va Results for B&W Criticals 1,000,000 Histories

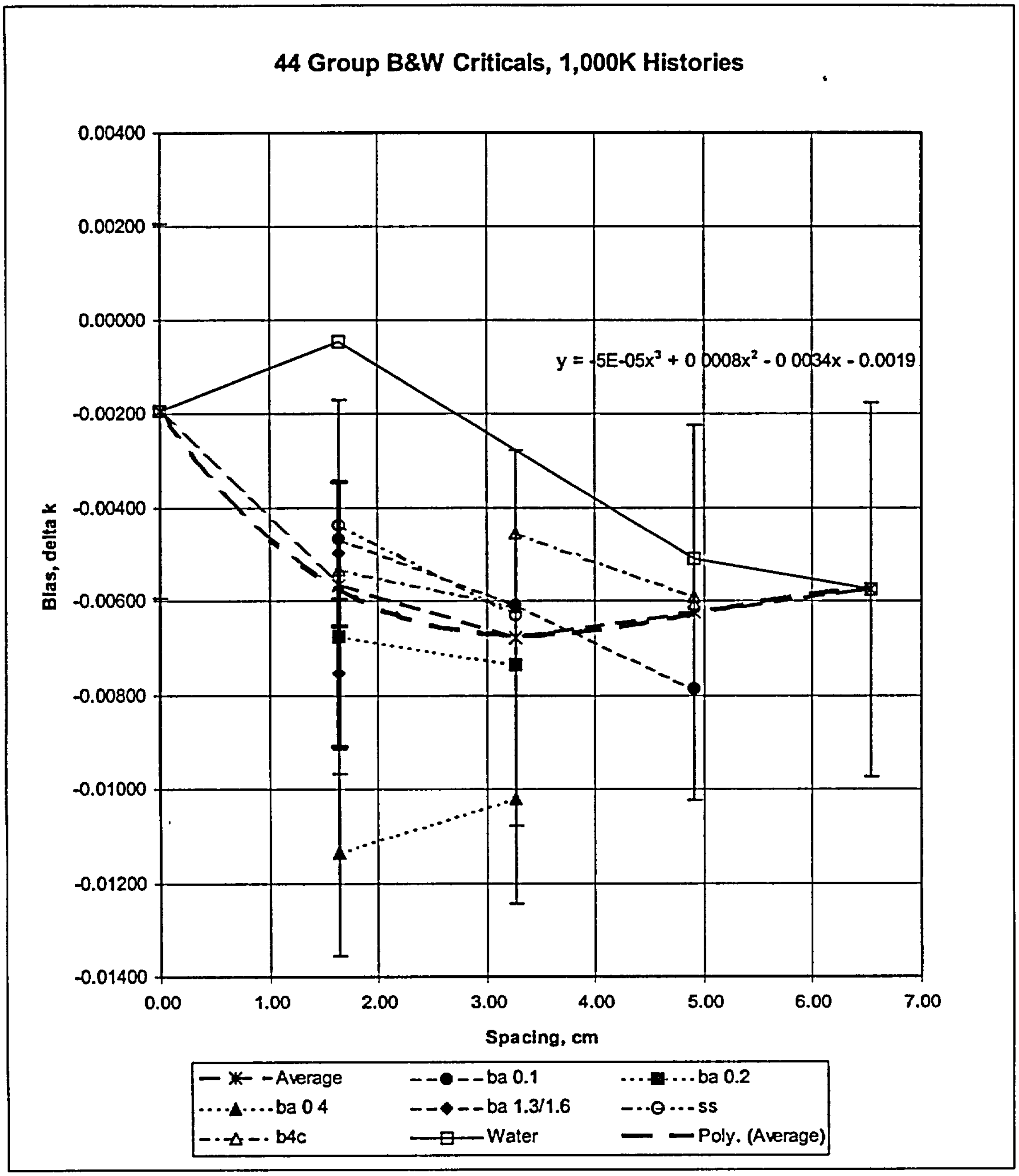


Table 6-2.3 44-group B&W Criticals Results (400K Histories)

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)

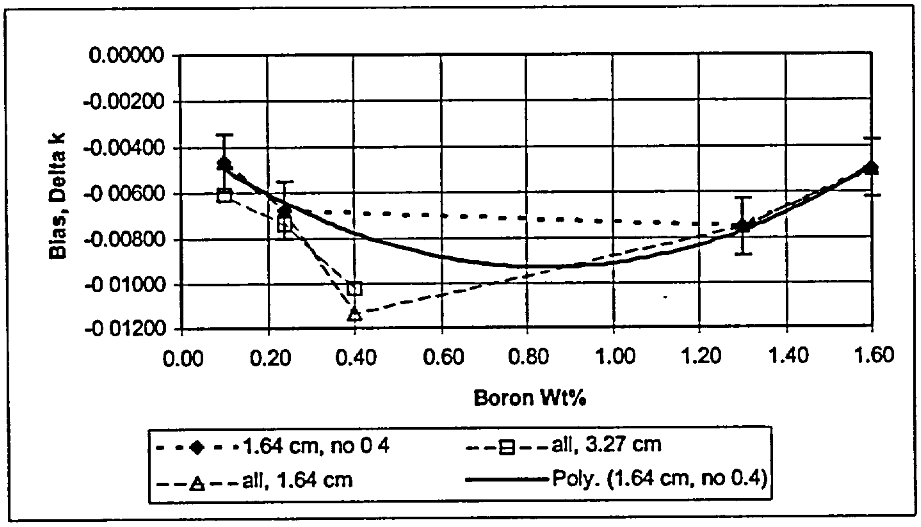
Case	Core	Spacing cm	fiche	Boron ppm	Pins/Plates	Calculated		Experimental		Bias	
						k_{eff}	1σ	k_{eff}	1σ	Δk	1σ
1	i	--	b29229	0	--	0.99655	0.00071	1.00020	0.00050	**-0.00365**	0.00135
2	ii	0.00	b17261	1037	0	0.99816	0.00056	1.00010	0.00050	**-0.00194**	0.00111
3	iii	1.64	b17262	764	0	0.99955	0.00056	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

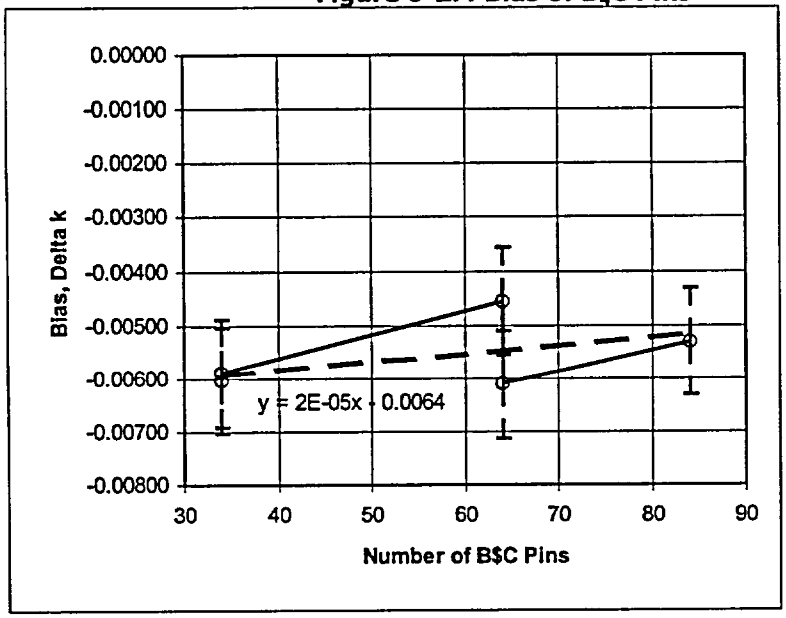


In addition to the borated aluminum plates, several cases with B_4C rods interspersed between the fuel arrays were examined. In these cases the number of rods also varies with the spacing between the fuel arrays. Table 6-2.6 lists the B_4C rod cases that are plotted in Figure 6-2.4 with a linear fit 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.

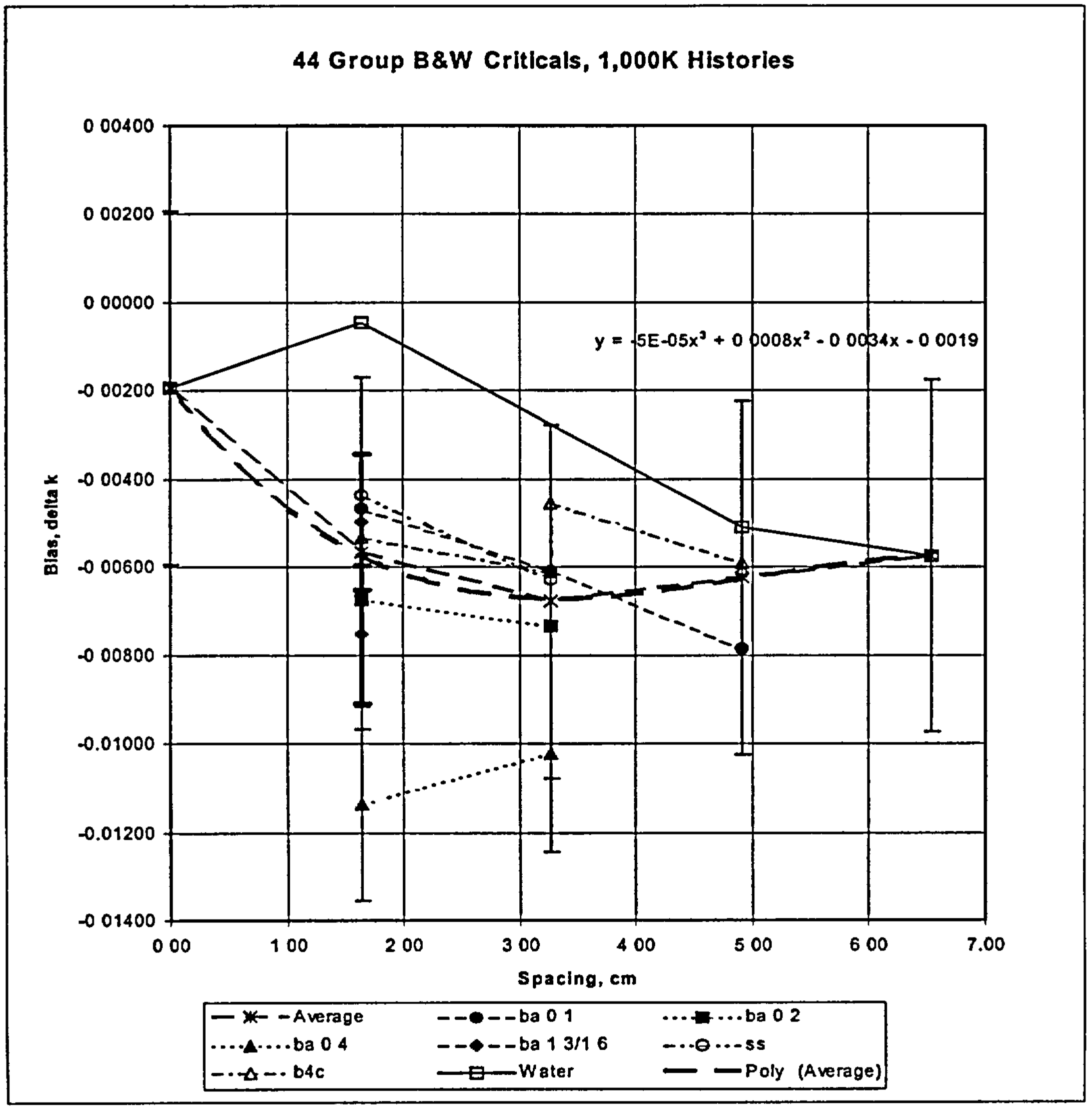
Table 6-2.9 Handbook Critical Experiment Results

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

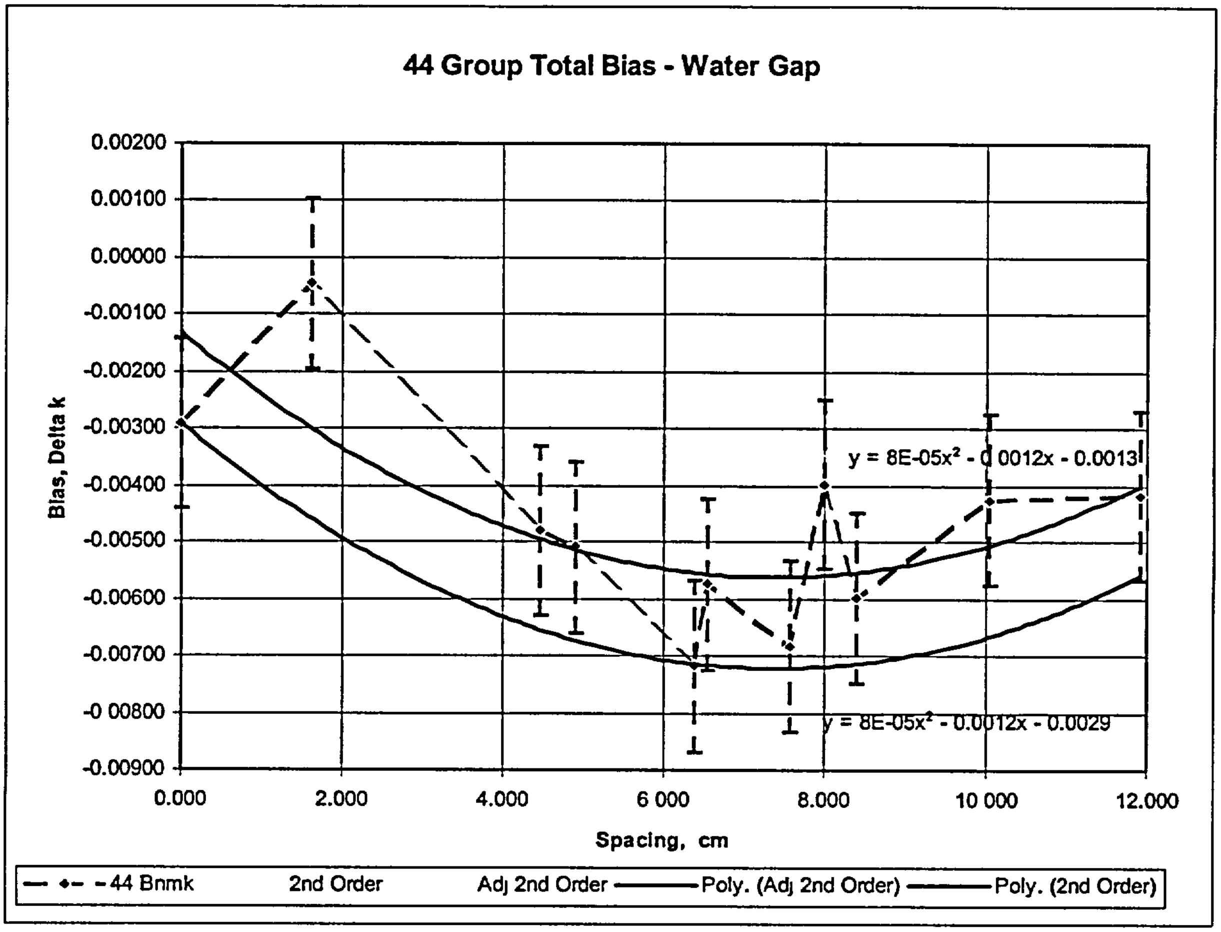
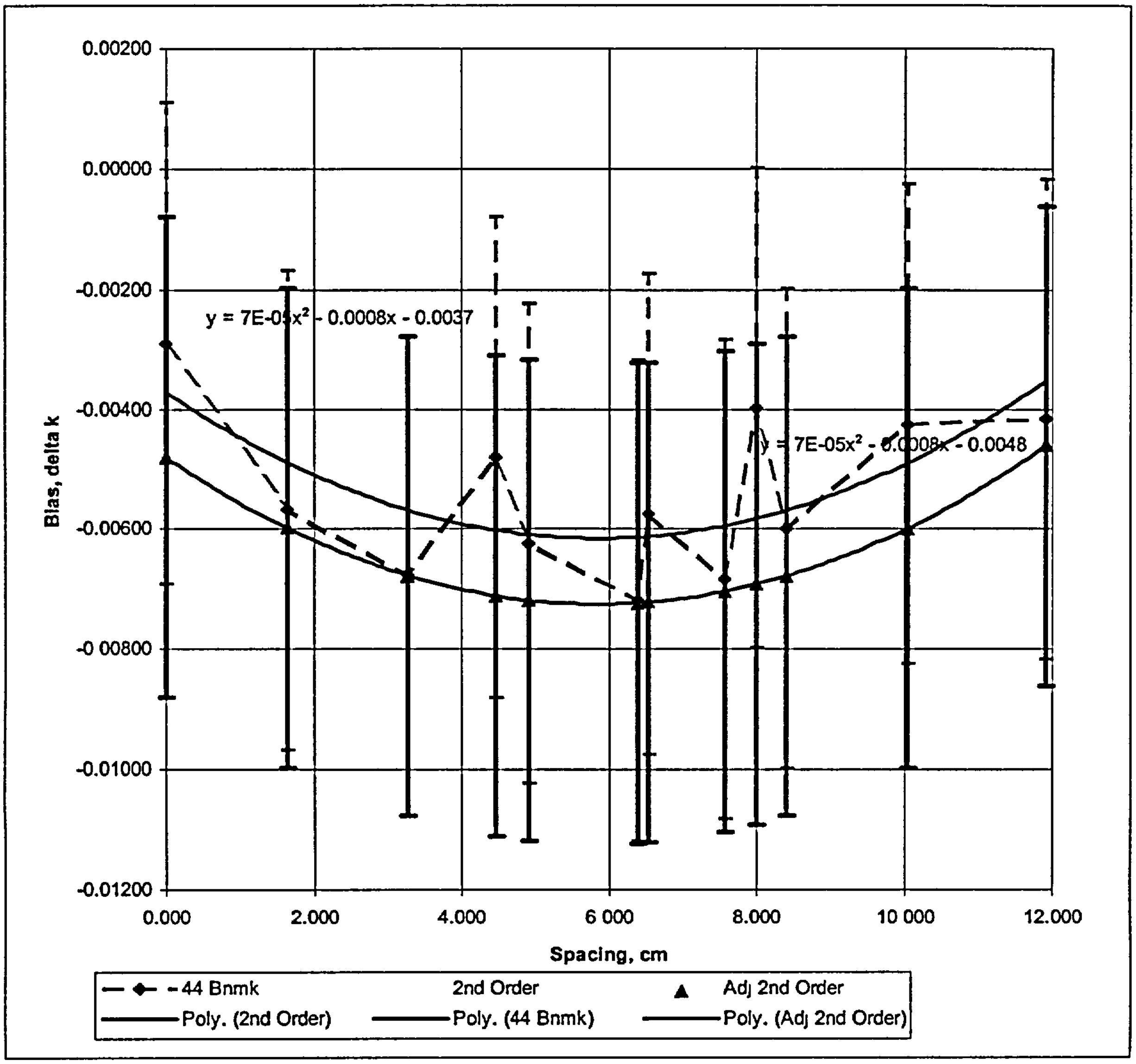


Figure 6-2.7 KENO V.a Bias For 44-group Cross Section Set Total Bias



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]. Due to first-of-a-kind nature of licensing a commercial shipping package in the 5-10wt% ^{235}U range, this document includes significantly more information than would normally be included in the criticality benchmarking section.

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.

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[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.

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 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:

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

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

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 (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

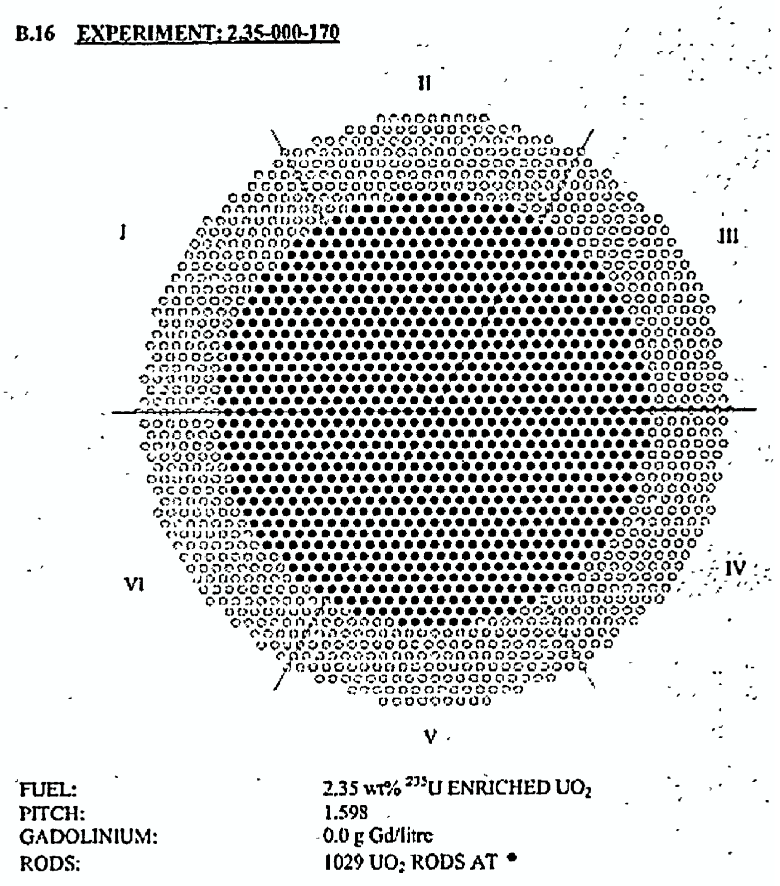
LJU-COMP-TIIHRM-O05

FIGURE WITHHELD UNDER 10 CFR 2.390

figur! 9 M),flfi•cnrKit•i ofr43:l-%.%2'U-Eunnced **UO%**Fl•el Rd

Figure **7.1** **LCT 005** Sketches (cont.)

FIGURE WITHHELD UNDER 10 CFR 2.390



B.16 EXPERIMENT: 2.35-000-170

FUEL:	2.35 wt% ^{235}U ENRICHED UO$_2$
PITCH:	1.598
GADOLINIUM:	0.0 g Gd/litre
RODS:	1029 UO$_2$ RODS AT ●

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

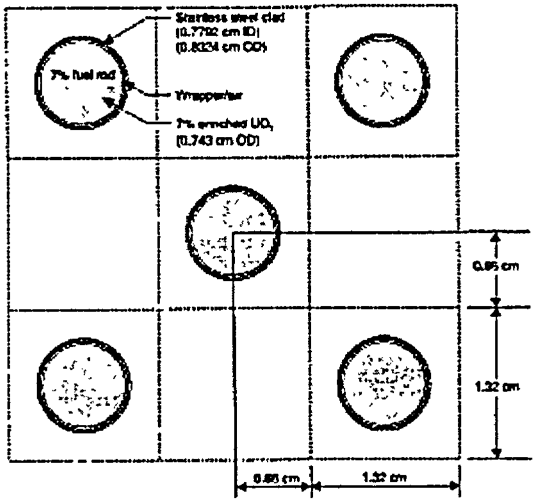


Figure 1. Composite Sectional Plan View of Fuel Rods

FIGURE WITHHELD UNDER 10 CFR 2.390

Figure 2. Composite Setoesi Elevatun View of **Fuel** Rods

Figure 7.2 LCT018 Sketches (cont.)

LEU COMP THERM-018

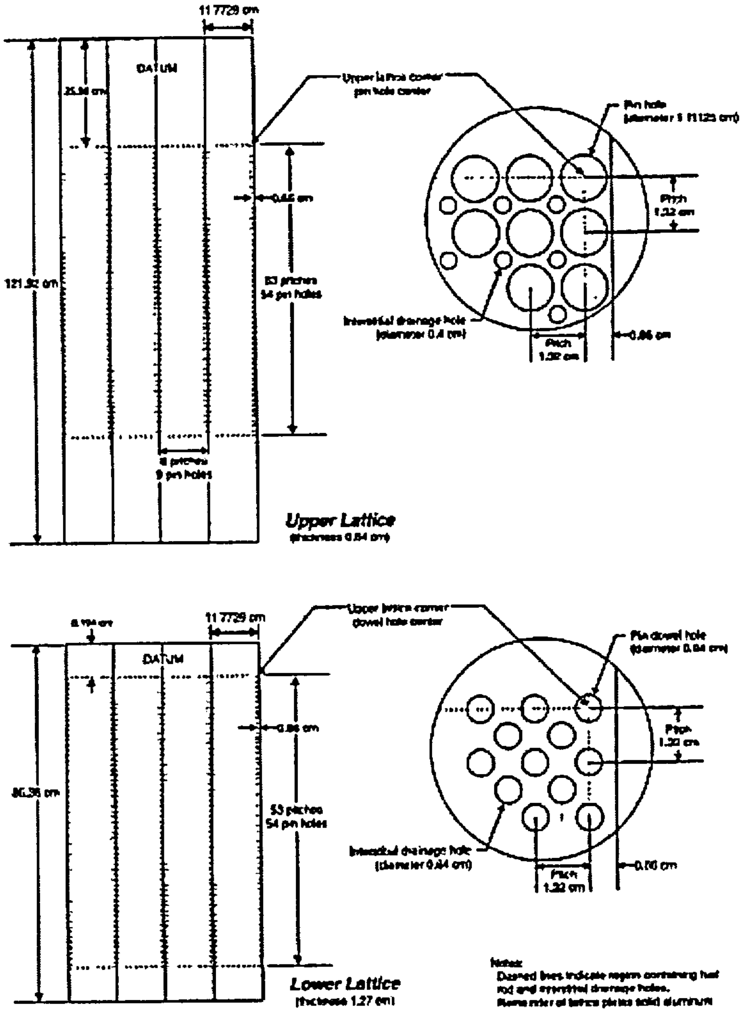


Figure 4 Simplified Plan Views of Upper and Lower Lattice Plates.

Figure 7.2 LCT018 Sketches (cont.)

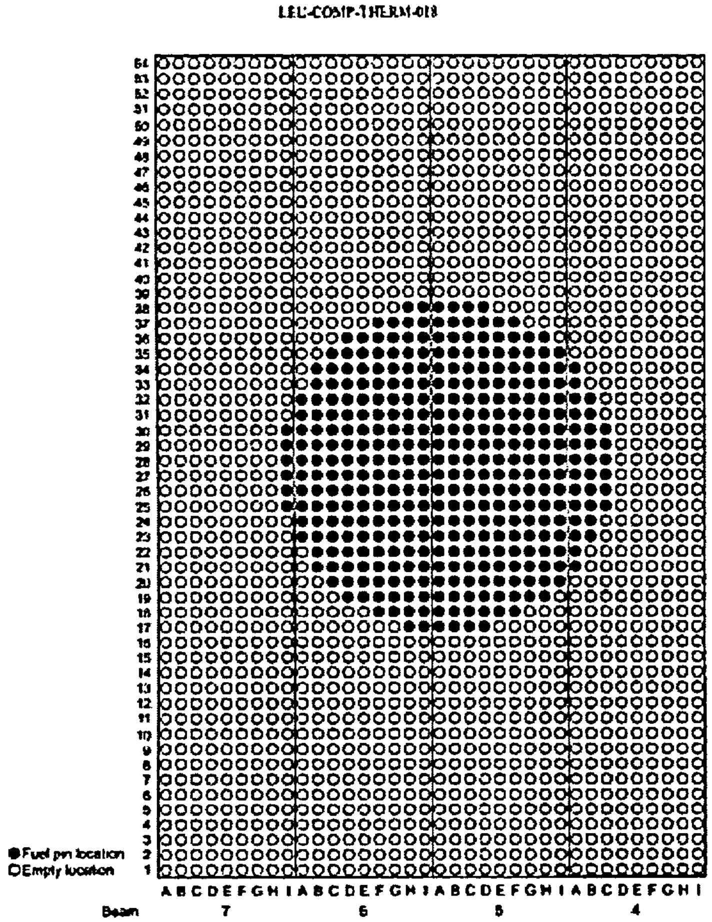


Figure 5. Dimple Experimental Configuration

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

FIGURE WITHHELD UNDER 10 CFR 2.390

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

Hrum1, *11wi~***KOM.kaMeoRFM Vamn sm**

Figure 7.3 LCT019 Sketches (cont.)

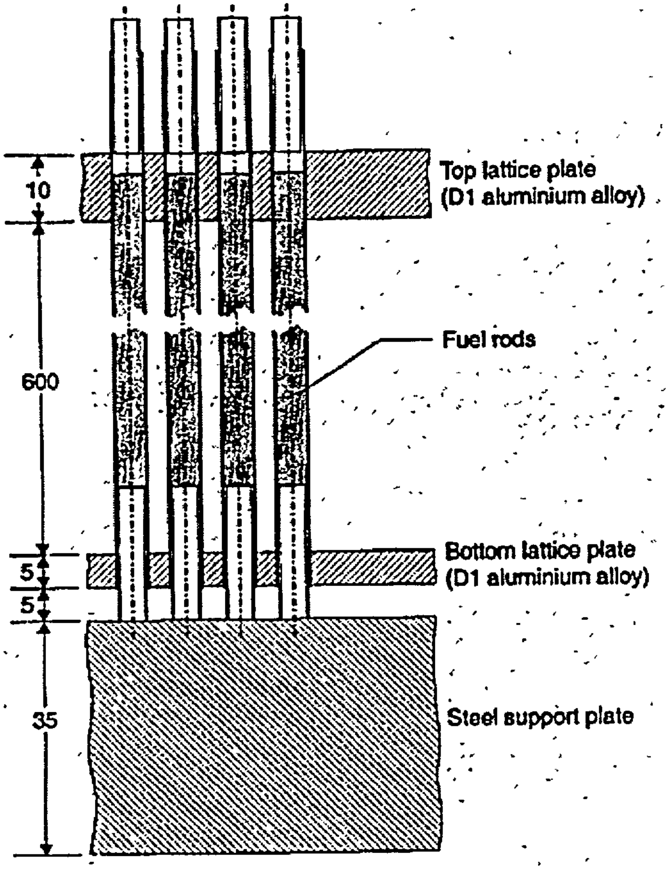


Figure 2. Schematic of the Fuel Rods Placement in the Core.
(dimensions given in mm)

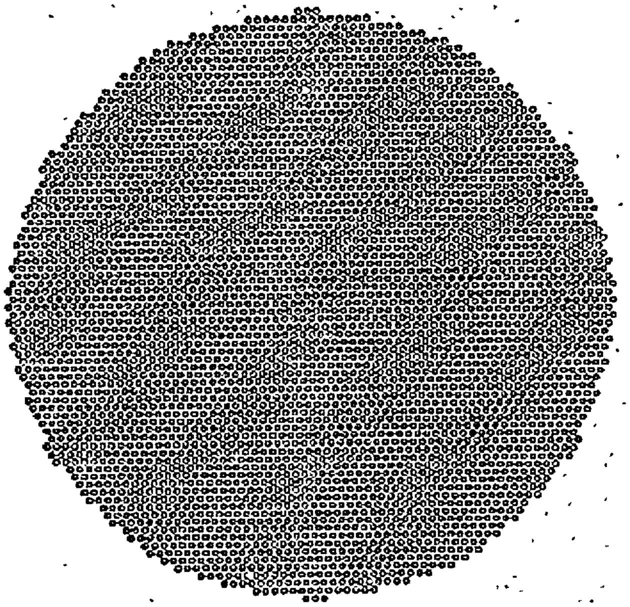


Figure 4. Critical Configuration for Case 1.

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

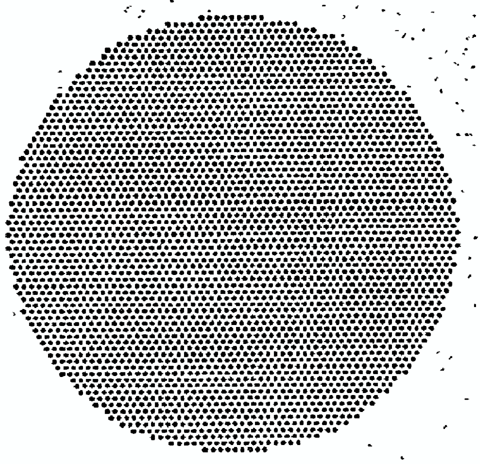


Figure 4. Critical Configuration for Case 1.

FIGURE WITHHELD UNDER 10 CFR 2.390

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

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

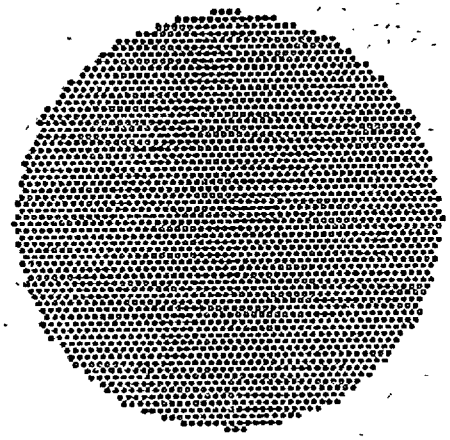


Figure 4. Critical Configuration for Case 1.

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

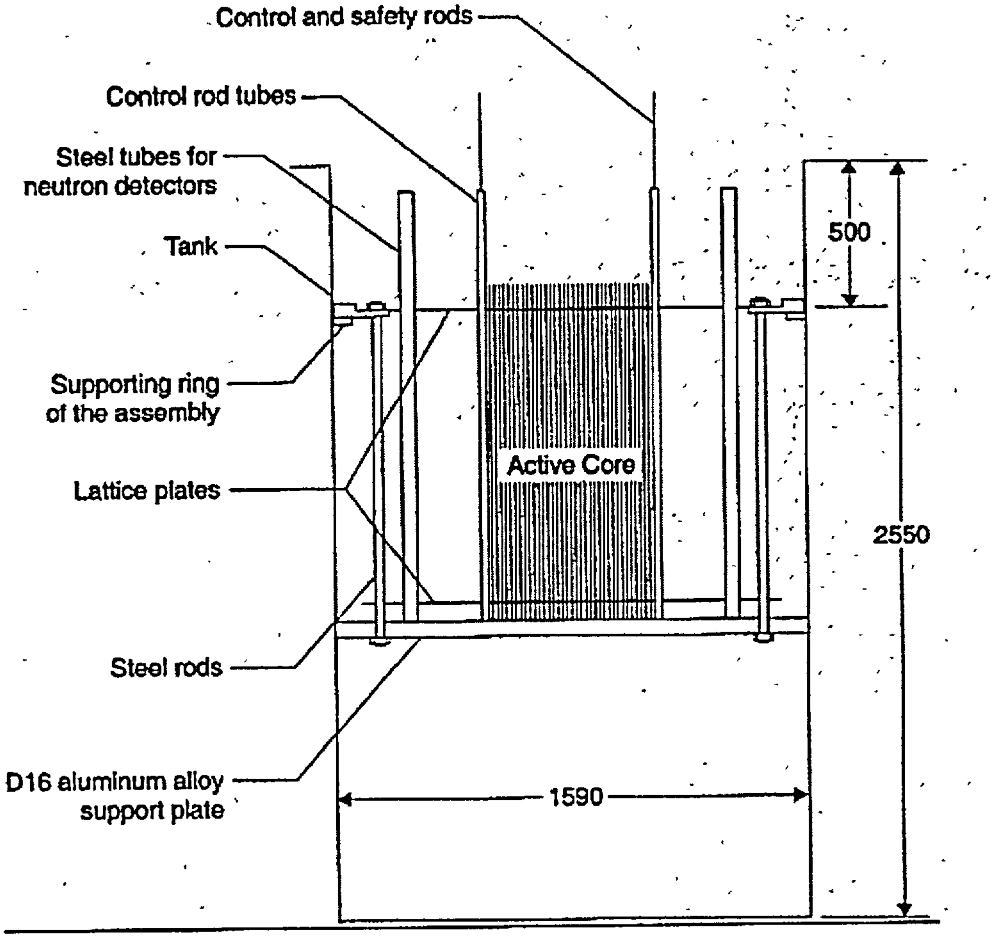


Figure 1. The Placement of Active Core in Tank.
(dimensions given in mm)

Figure 7.6 LCT022 Sketches(cont.)

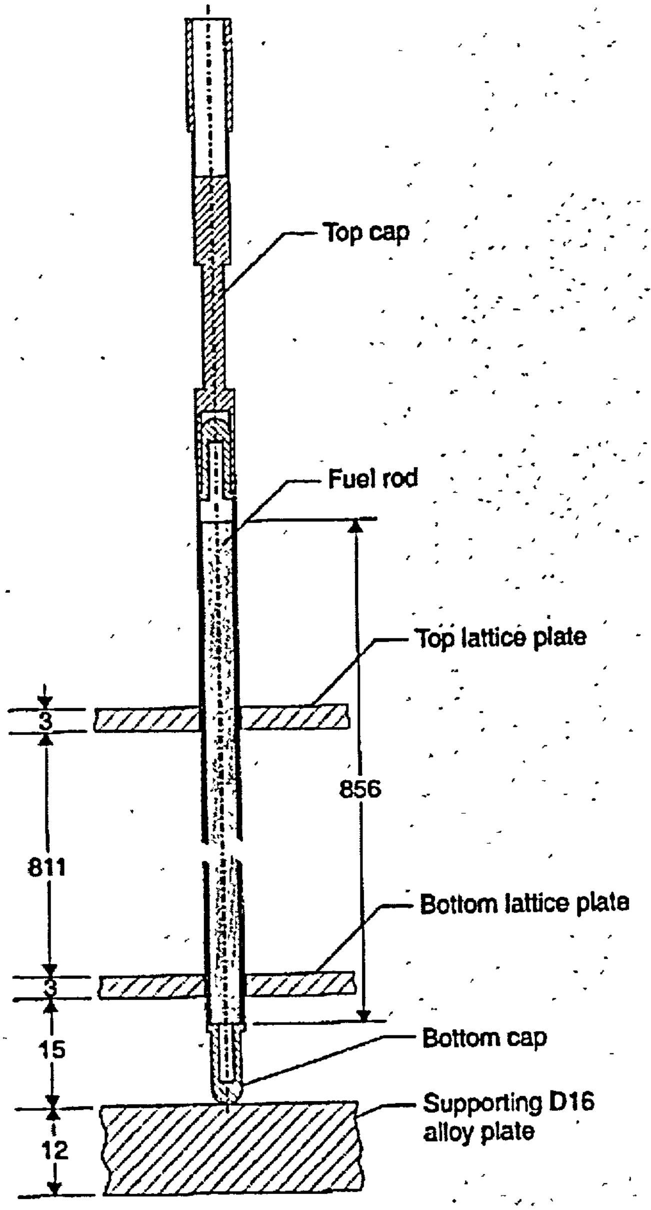
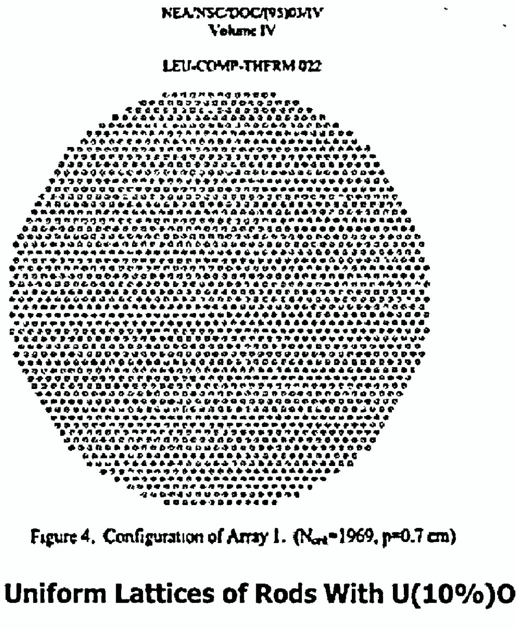


Figure 2. The Placement of Fuel Rod in Active Core.
(dimensions given in mm)

Figure 7.6 LCT022 Sketches(cont.)

FIGURE WITHHELD UNDER 10 CFR 2.390



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Volume IV

LEU-COMP-THERM 022

Figure 4. Configuration of Array 1. (N_{crit}=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

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

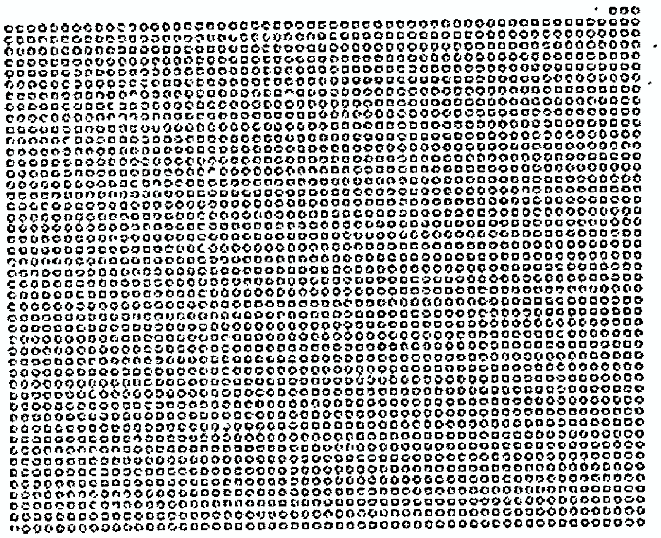


Figure 4. Uniform Lattice of Fuel Rod with Pitch of 0 62 cm (N_{cr}=2625)

FIGURE WITHHELD UNDER 10 CFR 2.390

(fuel)

Figur 6. Model of the Fuel Rod. (dn ensim given in mm)

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

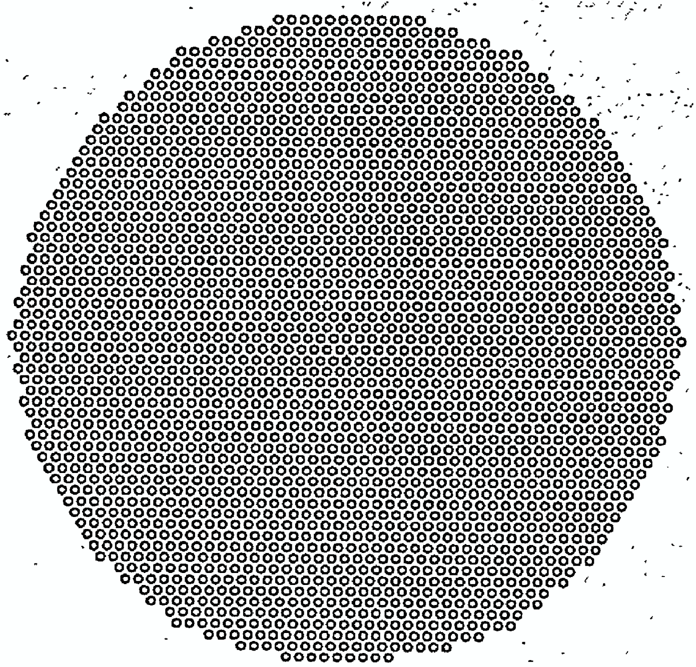


FIGURE WITHHELD UNDER 10 CFR 2.390

Fig=r **8.** Model of thc Fuel Rod- (dimensions given in nun)

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 an were maintained by two 0.8 cm thick steel lattice plates. Criticality for cold (-20^{0}C) and hot (>200'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

Pipm **1.** CofigStrin **ot** die Cncal As-mbly **(dfimmom in mm)**

Figure 7.10 LCT026 Sketches (cont.)

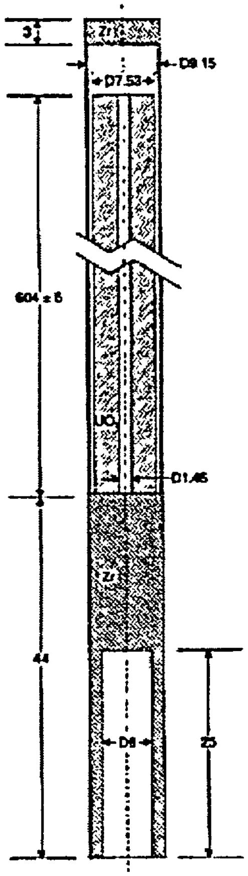


Figure 2 Fuel Rod (dimensions in mm).

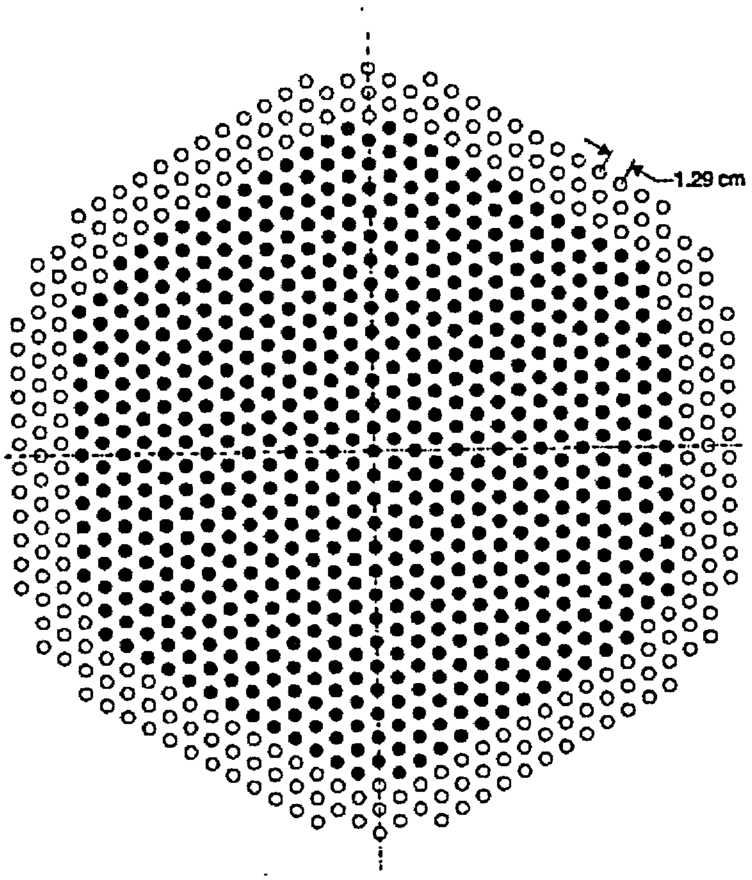


Figure 3. Loading Chart for Case 1 (shaded) and Case 2.

6.2B.7.11 Uniform Water-Moderated Lattices of Rods With U(10%)O$_2$ Fuel Range From 20 °C to 274 °C

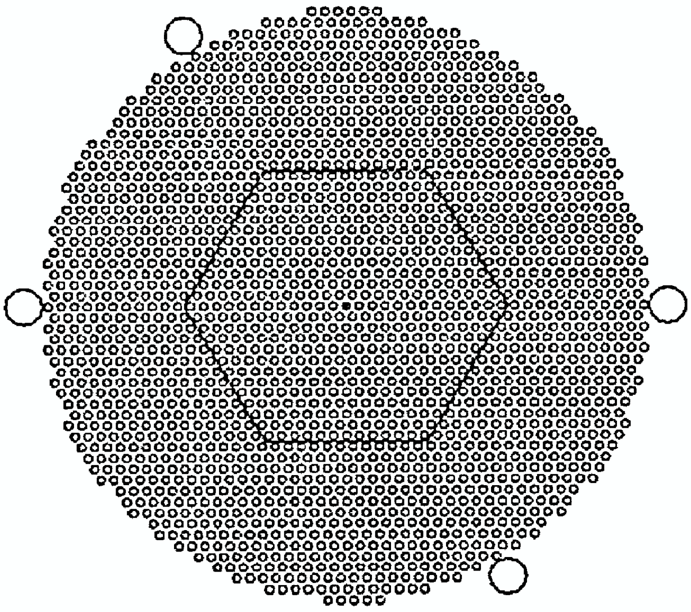
This set of nine experiments was performed at the same facility in the Kurchatov Institute in Russia in two configurations. The room temperature cases used the tank described for experiments LCT-022 listed above. For the high temperature cases the experiments were positioned in a pressure vessel with 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 Active Core. (dimecnsions given in **nun)**

LEU-COMP-THERM-032



Tubes for Safety Rods	
X ,cm	Y,cm
17.4	0
8.7	-15.069
-17.4	0
-8.7	15.069

Figure 6. Configuration of Array 1. (N_{crit}=2002, p=0.7 cm)

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.

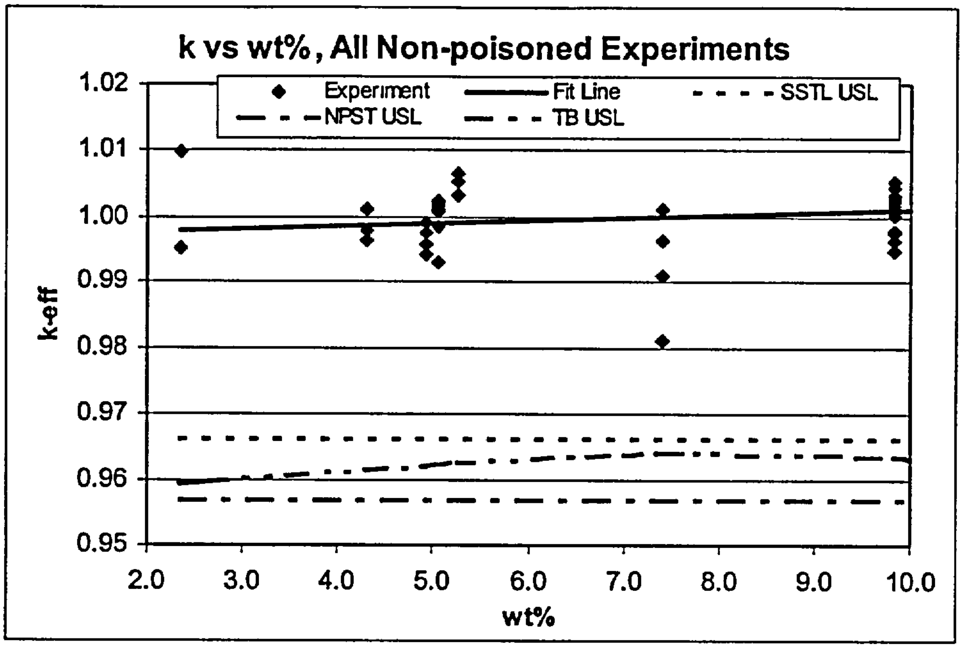


Figure 8.1 k vs enrichment, all experiments wo dissolved absorbers, fit equation: k-eff =0.9968116+(0.0004200326)*wt%.

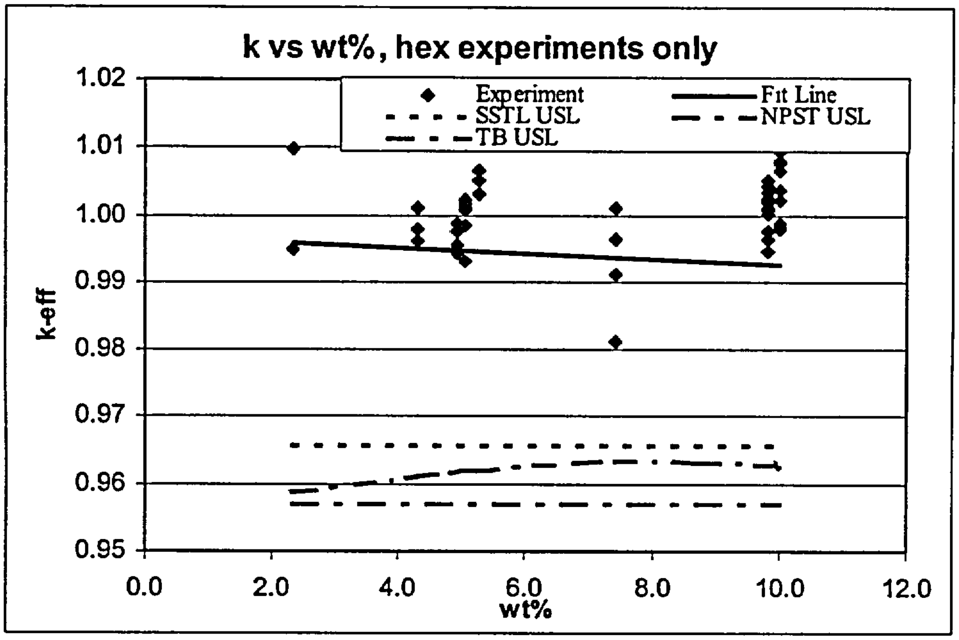


Figure 8.2 k vs enrichment, hex experiments wo dissolved absorbers, fit equation: k-eff = 0.9970209-0.0004211385*wt%.

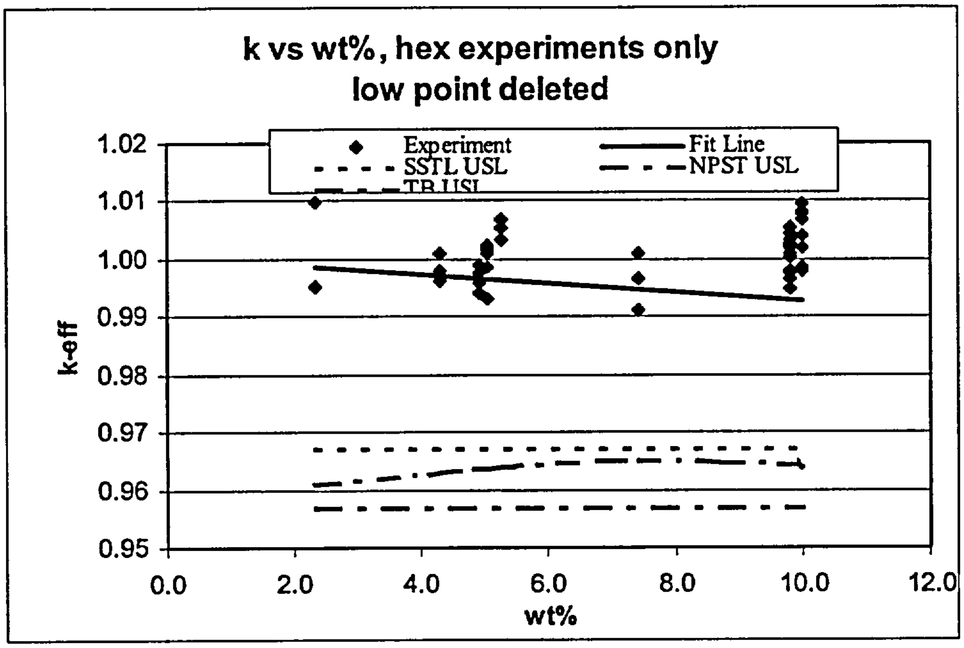


Figure 8.3 k vs enrichment, hex experiments wo dissolved absorbers, low point deleted, fit equation: k-eff =0.9970209-0.0004211385*wt%.

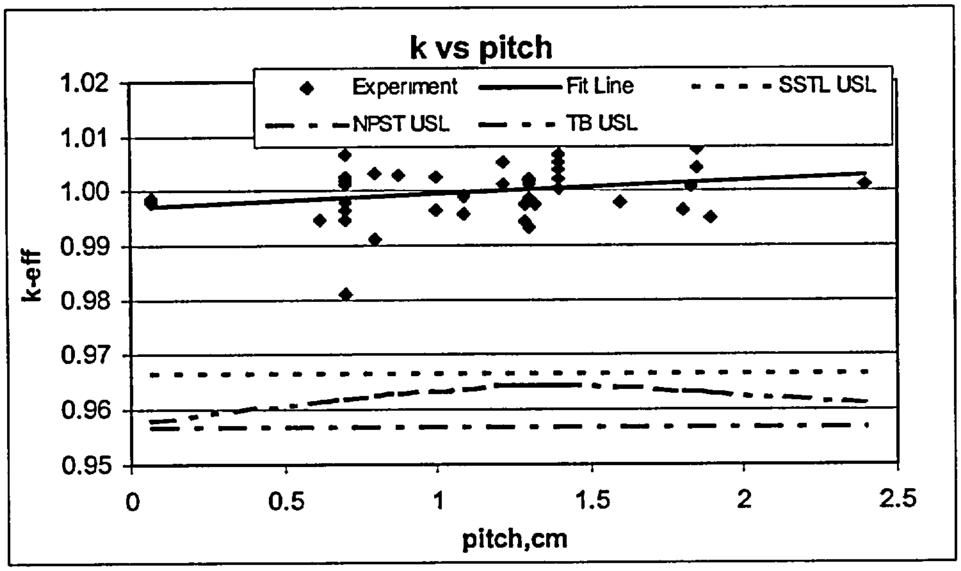


Figure 8.4 k vs pitch, all experiments wo dissolved absorbers, fit equation: k-eff = 0.9968463+(0.002504747)*pitch.

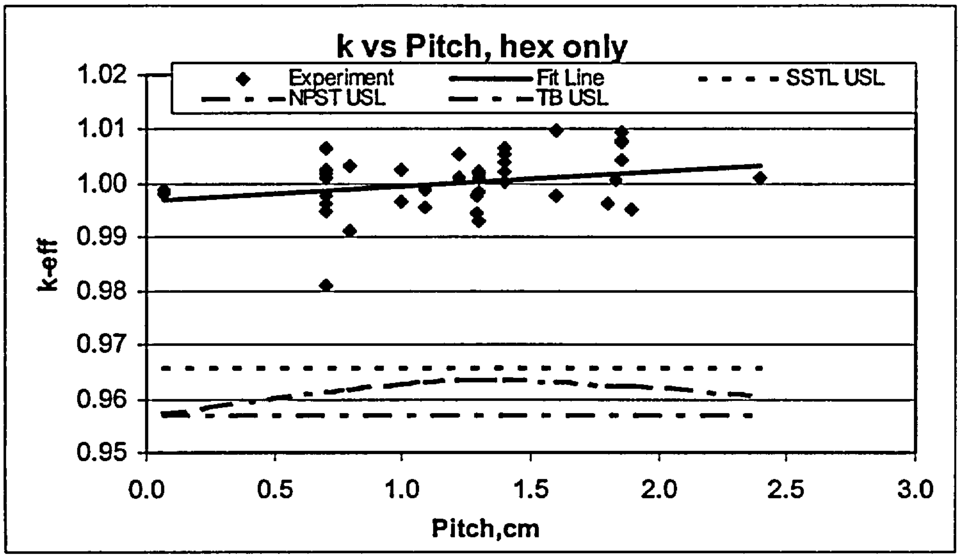


Figure 8.5 k vs pitch, hex experiments wo dissolved absorbers, fit equation: k-eff =0.9969635+(0.002548853)*pitch.

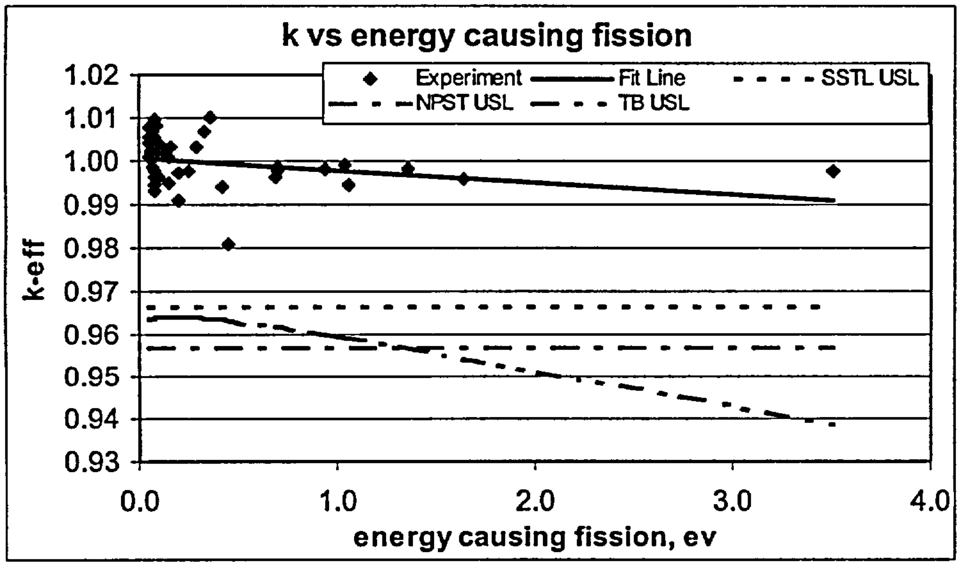


Figure 8.6 k vs energy causing fission, all experiments wo dissolved absorbers, fit equation: k-eff =1.000725+(-0.002837212)*ECF.

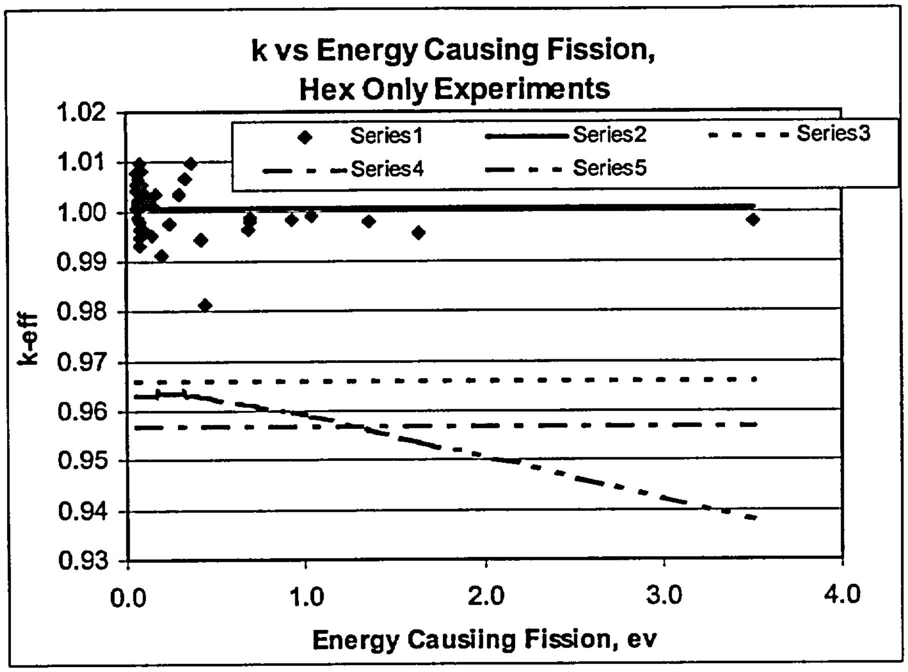


Figure 8.7 k vs energy causing fission, hex experiments wo dissolved absorbers, fit equation: k-eff = 1.000879+(-0.002692876)*ECF.

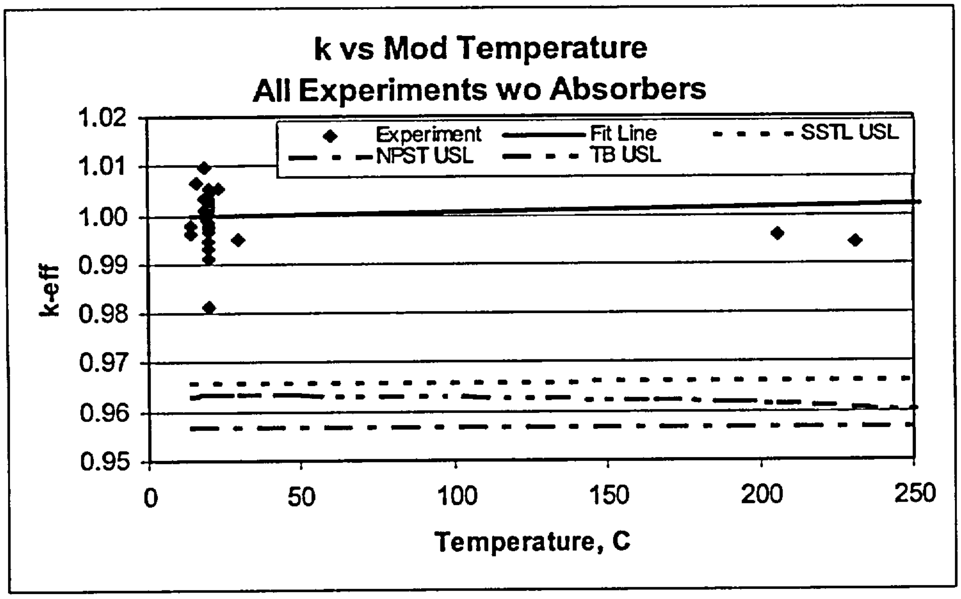


Figure 8.8 k vs temperature, all experiments wo dissolved absorbers, fit equation: k-eff =0.9994713+(0.00001810387)*TEMP.

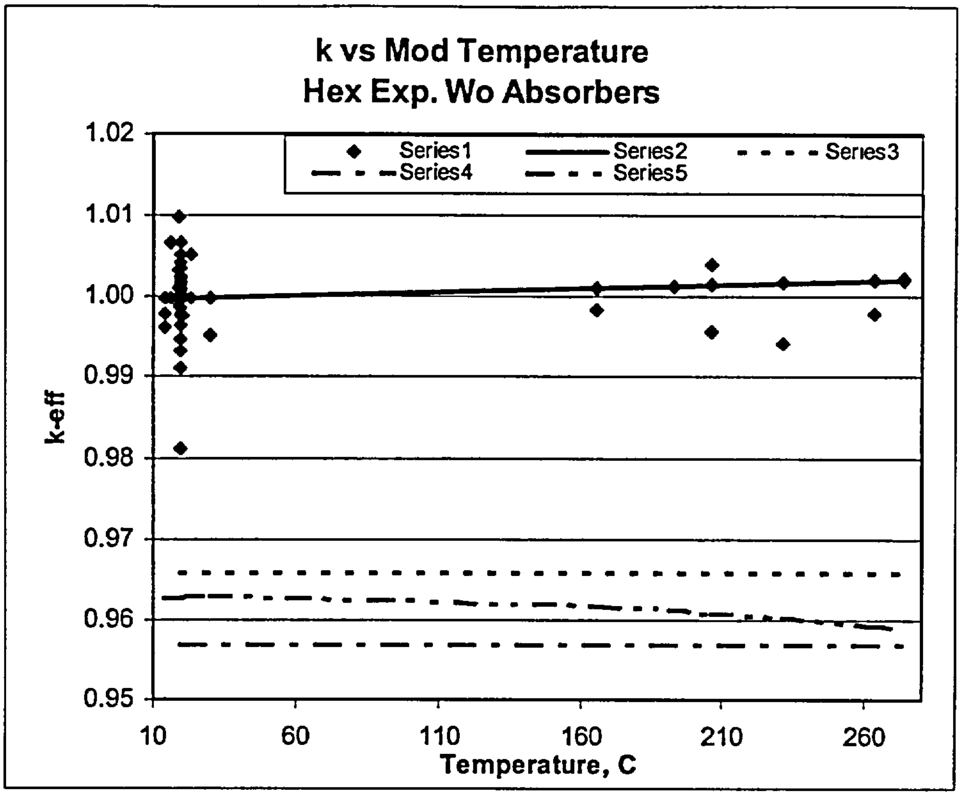


Figure 8.9 k vs temperature, hex experiments wo dissolved absorbers, fit equation: k-eff = 0.9996139+(0.000008789311)*TEMP.

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 ≤ ECF ≤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 $\gamma = (1-p)/2$,
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):

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

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   k-eff    k-eff    k-eff    Sigma    Sigma    Sigma
   Varble x   Expmnt   Calcultd Normalzd Expmnt   Calcultd  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    k-eff    k-eff    k-eff    Sigma    Sigma    Sigma
  Varble x   Expmnt  Calcultd Normalzd  Expmnt  Calcultd   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 B. Pathfinder Fuel

The evaluation for the Pathfinder fuel shipping package used the SCALE 4.4a[6] computer code system with the 238 group 'LAW' library. Validation of this system and determination of an Upper Safety Limit (USL) is provided in this section following the guidance of NUREG/CR-6361[7].

---

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

[7] "Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages," NUREG/CR-6361, ORNL/TM-13211, March 1997.

6-2B.1 Upper Safety Limit for Pathfinder Fuel Package

The validation of SCALE4.4a for this application used data from a set of 43 experiments obtained from the International Handbook of Evaluated Criticality Safety Benchmark Experiments[8]. These experiments were selected as those that most closely reflecting the fuel configuration within the package. The primary parameters considered for the selection were enrichment, fuel configuration, and clad material. These parameters and the results from the KENOV.a for the experimental configurations allowed generation of trend. Following the methodology of 6361, these curves are used to develop an USL for systems with similar parameters, e.g. the Pathfinder fuel package. Based upon evaluations of these curves, a USL of 0.936 was obtained for shipping Pathfinder fuel in the WE-1 shipping container. This USL will ensure the criticality safety of the package if the results of the KENOV.a analysis of the package show that

$$K_{eff} + 2\sigma < 0.936,$$

where k_{eff} is the package calculated effective multiplication factor and σ is the uncertainty of that value.

6-2B.2 Critical Experiments Parameters and Results

The Pathfinder fuel is a hexagonal array of UO_2 fuel rods with a ^{235}U enrichment of 7.51 wt% in an Inconel clad. A review of the International Handbook was made to find benchmark experiments with water moderated low-enriched UO_2 having similar enrichments and cladding material. A total of 53 experiments[9] were identified for use in this validation task. Ten of these experiments were excluded due to soluble poisons in the moderator or aluminum cladding which did not show a conservative trend relative to experiments with either stainless steel or zirconium cladding. The selected 43 experiments used in this evaluation are listed in Table 6.2B.1. The table lists the the significant parameters for each experiment and the k_{eff} and standard deviation for both the experimental configuration and the calculations with KENOVa using the 238-group cross section set. It is noted that the benchmark cases were executed with about one million neutron histories which is the minimum value generally used at Framatome ANP for KENOV.a calculations. The last two columns in the table list the ratio of the calculated to experimental k_{eff} and σ_{total}. The former is designated k_{norm} and normalizes the calculated k_{eff} to the experimental value to account for experimental values that differ from 1.0. The total standard deviation is the square root of the sum of the squares of the calculated and experimental standard deviations. Use of k_{norm} and σ_{total} provides a way to directly factor the experimental uncertainty into the statistical evaluation of the data and the calculation of safety limits. The KENOV.a results listed in the table were obtained from calculations performed at Framatome ANP. The input files for these calculations were either generated at Framatome ANP or obtained externally. Any cases of external origin were carefully examined to ensure consistency both with the experimental description and modeling methods used at Framatome ANP.

The experimental k_{eff} uncertainty values, i.e., either in the critical k_{eff} or σ, were obtained directly from the International Handbook. The values in Handbook were calculated based upon the uncertainty in the experimental measurements, materials, and configurations. These values were calculated with methodologies and/or cross sections that differ from those used in this evaluation and represent reactivity differences from nominal values. It is assumed that these difference calculations are insensitive to either the methodology and/or cross sections and thus can be used

---

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

[9] See item 4 in the reference section for a list of the experiments considered.

in this evaluation without redoing the calculations with KENOV.a and the 238-group cross section set. The range of parameters for this set is shown in Table 7-3. This range of parameters encompasses all those for the Pathfinder fuel, see Table 6.2B.3, except for the pitch. The definition of the pitch for the Pathfinder fuel in the shipping tube is not clear. It could be defined as the pitch between the fuel rods in each assembly, which would then be bounded by the experimental values. Alternately it could be the pitch between assemblies, which for the optimum configuration is outside the bounds of the experiments. Alternate parameters are the $H/^{235}U$ or water/fuel ratio for which the experiments bound the shipping configuration. However, even these are not definitive relative to the pins, assembly, fuel tube, and assembly spacing. The single parameter that includes these interpretations is the ECF (average energy of the lethargy causing fission) or alternately the AFG (average fission group).

6-2B.2 USL Determination

The calculation of the USL will follow that defined in NUREG/CR-6361. The data used for the evaluation will be the trending parameters and the associated k_{norm} and σ_{total} from Table 6.2B.1. This is a slight divergence from the methodology of 6361 that uses the KENOV.a k_{eff} and σ values directly. However, use of k_{norm} and σ_{total} follows NUREG/CR-6698[10] to provide a way of integrating the experimental uncertainties directly into the statistical evaluation. This method takes advantage of the uncertainty information provided in the Handbook for both the critical k and measurement/fabrication uncertainties.

The use of NUREG/CR-6361 requires that the data be normal. The data are shown to be normal based upon the Shaprio-Wilk test for normality discussed in 6698. The method of 6361 requires a least-square fit to the experimental data for each of the trending parameters. A Student-T test is used to ensure that the slopes of the fit equation were not zero, i.e., that a relationship exists between the independent and dependent variables for each fit. This test indicates that a relationship exists for all the trending parameters examined. In summary, the data from the 43 chosen experiments are normal and the trending equations are valid.

The USL was determined with the USLSTATS program described in Appendix C of 6361. The program version dated 7/11/2000 was downloaded from the SCALE website and was verified to be functioning correctly on the Framatome ANP computer system prior to use in this evaluation. In addition to the trending parameter, k_{norm} and σ_{total}, data relative to the desired confidence in the USL are required. These input parameters and the values used are:

P = proportion of population falling above the lower tolerance level = 0.995,
$1-\gamma$ = confidence of fit = 0.95,
α = the confidence on proportion of P = 0.95, and
Δk_m= an administrative margin = 0.05.

The output listing for the evaluation of the trend with pitch is provided in Table 6.2B.8.

Two approaches are provided in 6361 for determining the USL. Method 1 (USL-1) is a confidence band with an administrative margin. This method generally provides the USL for the criticality safety of a system. The second method (USL-2) is a purely statistical method that primarily serves to verify that the USL-1 curve is conservative relative to a statistical approach. Table 6.2B.4 lists the USL-1 equations for the selected trending parameters. The equations are ordered according to the magnitude of the slope of the equations. Based upon the slopes, the trend with

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[10] "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.

pitch seems to provide the most conservative trend. Table 6.2B.5 lists the USL values for the minimum and maximum values of the trending parameters as listed in Table 6.2B.3. This table indicates that the USL could vary from about 0.93 to 0.94 depending on the value of the parameter for the system. Table 6.2B.6 lists the USL-2 equations for the trending parameters. It is seen from this table that the USL values that are obtained from the Table 6.2.B.4 equations will be conservative relative to a statistical evaluation of the data. Figures 6.2B.1 through 6.2.B.7 provide plots of k_{norm}, the least-squares fit through these data, and the curves generated with the USL-2 and USL-1 equations for the seven selected trending parameters. In addition, the values of the parameter(s) for the Pathfinder model are included as the vertical lines in each figures.

6-2B.3 Pathfinder Package USL Determination

The trending parameters for the bounding configurations of the Pathfinder fuel package are listed in Table 6.2B.3. Inserting these values in the USL-1 equations of Table 6.2B.4 enables selection of a bounding USL value for this package. Table 6.2B.7 lists the results of this calculation. The USL values range from 0.9359 to about 0.9390 with the minimum values occurring when the pitch is the trending parameter. However, there is little difference for any of the trending parameters. For conservatism, a USL of 0.936 is chosen for the Pathfinder Fuel Package based upon the data in the table.

6-2B.4 References

The references for the section are listed below in the order of their usage.

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 "Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages," NUREG/CR-6361, ORNL/TM-13211, March 1997.

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

4. Critical benchmark data from: "International Handbook of Evaluated Criticality Safety Benchmark Experiments," Nuclear Energy Agency, NEA/NSC/DOC(95)03, September 2001 Edition:
   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. LEU-COMP-THERM-025, "Water-Moderated Square-Pitched Uniform Lattices of U(7.5 wt%) O_2 Stainless-Steel-Clad Fuel Rods," Kurchatov Institute.

i. 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.

j. LEU-COMP-THERM-032, "Uniform Water-Moderated Lattices of Rods With U(10%)$_{02}$ Fuel in Range From 20 °C to 274 °C," Kurchatov Institute.

5. "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.

Table 6.2B.1 Pathfinder Benchmark Experiment Parameters

No.	Exp. ID	Clad	Lattice	Temp, °C	Pitch	^{235}U wt%	ECF	AFG	H/U	H20/fuel	k_{exp}	σ_{exp}	k_{KENO}	σ_{KENO}	K_{norm}	σ_{total}
1	**lct01901[a]**	ss	Hex	16.00	0.70	5.256	0.3325	193.85	99.87	1.51	1.00000	0.00630	1.00663	0.00082	1.00663	0.00635
2	**lct01902**	ss	Hex	19.00	0.80	5.256	0.1635	202.53	156.76	2.36	1.00000	0.00580	1.00323	0.00091	1.00323	0.00587
3	**lct01903**	ss	Hex	23.00	1.40	5.256	0.0539	215.57	657.47	9.92	1.00000	0.00610	1.00528	0.00073	1.00528	0.00614
4	**lct02201**	ss	Hex	20.00	0.70	9.830	0.7019	184.08	50.08	1.62	1.00000	0.00460	0.99771	0.00097	0.99771	0.00470
5	**lct02202**	ss	Hex	20.00	0.80	9.830	0.2943	195.30	79.64	2.57	1.00000	0.00460	1.00338	0.00084	1.00338	0.00468
6	**lct02203**	ss	Hex	20.00	1.00	9.830	0.1267	205.77	150.59	4.87	1.00000	0.00360	1.00258	0.00089	1.00258	0.00371
7	**lct02204**	ss	Hex	20.00	1.22	9.830	0.0837	210.79	246.83	7.98	1.00000	0.00370	1.00528	0.00110	1.00528	0.00386
8	**lct02205**	ss	Hex	20.00	1.40	9.830	0.0693	213.05	339.77	10.99	1.00000	0.00380	1.00034	0.00088	1.00034	0.00390
9	**lct02206**	ss	Hex	20.00	1.83	9.830	0.0544	215.92	613.49	19.84	1.00000	0.00460	1.00085	0.00083	1.00085	0.00467
10	**lct02207**	ss	Hex	20.00	1.85	9.830	0.0539	216.04	629.47	20.35	1.00000	0.00460	1.00430	0.00075	1.00430	0.00466
11	**lct02301**	ss	Hex	20.00	0.70	9.830	0.0831	210.86	50.07	1.62	1.00000	0.00360	0.99477	0.00084	0.99477	0.00370
12	**lct02302**	ss	Hex	20.00	0.70	9.830	0.0771	211.77	50.07	1.62	1.00000	0.00360	0.99647	0.00080	0.99647	0.00369
13	**lct02303**	ss	Hex	20.00	0.70	9.830	0.0753	212.05	50.07	1.62	1.00000	0.00360	0.99777	0.00072	0.99777	0.00367
14	**lct02304**	ss	Hex	20.00	0.70	9.830	0.0731	212.40	50.07	1.62	1.00000	0.00360	1.00098	0.00081	1.00098	0.00369
15	**lct02305**	ss	Hex	20.00	0.70	9.830	0.0716	212.64	50.07	1.62	1.00000	0.00360	1.00239	0.00088	1.00239	0.00371
16	**lct02306**	ss	Hex	20.00	0.70	9.830	0.0701	212.91	50.07	1.62	1.00000	0.00360	1.00186	0.00070	1.00186	0.00367
17	**lct02501**	ss	Hex	20.00	0.70	7.410	0.4459	190.03	71.97	1.62	1.00000	0.00410	0.98113	0.00096	0.98113	0.00421
18	**lct02502**	ss	Hex	20.00	0.80	7.410	0.2049	199.79	114.46	2.57	1.00000	0.00440	0.99111	0.00082	0.99111	0.00448
19	**lct02503**	ss	Hex	20.00	1.00	7.410	0.0997	208.52	216.42	4.87	1.00000	0.00470	0.99649	0.00086	0.99649	0.00478
20	**lct02504**	ss	Hex	20.00	1.22	7.410	0.0695	212.80	354.76	7.98	1.00000	0.00520	1.00111	0.00086	1.00111	0.00527
21	**lct03201**	ss	Hex	20.00	0.70	9.830	0.7024	184.05	50.08	1.62	1.00000	0.00450	0.99869	0.00083	0.99869	0.00458
22	**lct03202**	ss	Hex	166.00	0.70	9.830	0.9358	181.31	45.64	1.62	1.00000	0.00410	0.99827	0.00097	0.99827	0.00421
23	**lct03203**	ss	Hex	263.00	0.70	9.830	1.3578	176.78	39.71	1.62	1.00000	0.00420	0.99796	0.00084	0.99796	0.00428
24	**lct03204**	ss	Hex	20.00	1.40	9.830	0.0691	213.08	339.77	10.99	1.00000	0.00370	1.00668	0.00086	1.00668	0.00380
25	**lct03205**	ss	Hex	206.00	1.40	9.830	0.1040	210.64	295.32	10.99	1.00000	0.00320	1.00387	0.00093	1.00387	0.00333
26	**lct03206**	ss	Hex	274.00	1.40	9.830	0.1225	209.30	263.31	10.99	1.00000	0.00330	1.00215	0.00091	1.00215	0.00342
27	**lct03207**	ss	Hex	20.00	1.85	9.830	0.0540	216.03	629.45	20.35	1.00000	0.00450	1.00775	0.00072	1.00775	0.00456

Table 6.2B.1 Pathfinder Benchmark Experiment Parameters (cont.)

No.	Exp. ID	Clad	Lattice	TEMP' °C	Pitch	^{235}U wt%	ECF	AFG	H/U	H20/fuel	k_{exp}	σ_{exp}	k_{KENO}	σ_{KENO}	K_{norm}	σ_{total}
28	**lct03208**	ss	Hex	193.00	1.85	9.830	0.0792	213.99	556.27	20.35	1.00000	0.00380	1.00959	0.00081	1.00959	0.00389
29	**lct03209**	ss	Hex	263.00	1.85	9.830	0.0920	212.95	499.07	20.35	1.00000	0.00370	1.00815	0.00098	1.00815	0.00383
30	**lct01801**	ss	square	20.00	1.32	7.000	0.2021	200.33	118.39	2.76	1.00000	0.00200	0.99743	0.00099	0.99743	0.00223
31	**lct02401**	ss	square	20.00	0.62	9.830	1.0574	178.68	40.99	1.33	1.00000	0.00540	0.99451	0.00086	0.99451	0.00547
32	**lct02402**	ss	square	20.00	0.88	9.830	0.1451	204.13	128.46	4.15	1.00000	0.00400	1.00284	0.00090	1.00284	0.00410
33	**lct02001**	Zirc	Hex	20.00	1.30	5.059	0.0795	211.02	450.89	7.05	1.00000	0.00610	0.99320	0.00087	0.99320	0.00616
34	**lct02002**	Zirc	Hex	20.00	1.30	5.059	0.0686	212.76	450.89	7.05	1.00000	0.00610	0.99861	0.00089	0.99861	0.00616
35	**lct02003**	Zirc	Hex	20.00	1.30	5.059	0.0667	213.09	450.89	7.05	1.00000	0.00610	1.00161	0.00095	1.00161	0.00617
36	**lct02004**	Zirc	Hex	20.00	1.30	5.059	0.0657	213.26	450.89	7.05	1.00000	0.00610	1.00103	0.00089	1.00103	0.00616
37	**lct02005**	Zirc	Hex	20.00	1.30	5.059	0.0646	213.45	450.89	7.05	1.00000	0.00610	1.00183	0.00097	1.00183	0.00618
38	**lct02006**	Zirc	Hex	20.00	1.30	5.059	0.0640	213.56	450.89	7.05	1.00000	0.00610	1.00097	0.00085	1.00097	0.00616
39	**lct02007**	Zirc	Hex	20.00	1.30	5.059	0.0619	213.96	450.89	7.05	1.00000	0.00610	1.00226	0.00086	1.00226	0.00616
40	**lct02601**	Zirc	Hex	20.10	1.29	4.920	0.2468	197.78	104.49	1.76	1.00040	0.00330	0.99761	0.00095	0.99721	0.00343
41	**lct02602**	Zirc	Hex	231.40	1.29	4.920	0.4218	193.05	86.61	1.76	1.00000	0.00330	0.99431	0.00107	0.99431	0.00347
42	**lct02603**	Zirc	Hex	19.30	1.09	4.920	1.0372	179.68	49.53	0.83	1.00230	0.00620	0.99892	0.00092	0.99663	0.00627
43	**lct02604**	Zirc	Hex	206.00	1.09	4.920	1.6422	174.88	42.67	0.83	1.00000	0.00620	0.99572	0.00084	0.99572	0.00626

a) lct019xx refers to the International Handbook of Evaluated Criticality Safety Benchmark designation of experiment set LEU-COMP-THERM-**019** and experiment xx of that set. This abbreviation is followed for all values in this table

Table 6.2B.2 Range of Parameters for Benchmark Experiments

Parameter	Minimum Value	Maximum Value
Pitch, cm	0.62	1.85
ECF, eV	0.0539	1.64
Enrichment, wt%	4.9200	9.83
H20/fuel	0.8339	20.35
AFG, group	174.8810	216.0410
H/^{235}U	39.7060	657.4696
Temperature, °C	16.0000	274.0000

Table 6.2B.3 Pathfinder Model Trending Parameter Values

Parameter	48 Flooded	48 Optimum	Homogeneous
Pitch, cm			
Rod	0.7341	0.7341	-
Cell	2.5426	3.8126	-
ECF, eV	0.306251	0.105085	0.104816
Enrichment, wt%	7.51	7.51	7.51
H20/fuel	2.268036	4.951	-
AFG, group number	195.1	208.6	207.3
H/^{235}U	160.8	289.7	189.2
Temperature, °C	20	20	20

Table 6.2B.4 Confidence Band with Administrative Margin (USL-1) Equation

Trending Parameter	Values < Inflection Pt.		Inflection Pt.	Values > Inflection Pt.	
	Intercept	Slope		Intercept	Slope
Pitch, cm	0.9311	6.4986E-03	1.102 cm	0.9383	0.0
ECF, eV	0.9368	0.0	0.301 ev	0.9383	-4.9645E-03
Enrichment, wt%	0.9340	4.9860E-04	7.757 wt%	0.9378	0.0
H20/fuel	0.9354	4.9325E-04	6.056	0.9384	0.0
AFG, group	0.8991	1.9105E-04	203.456 grp	0.9380	0.0
H/^{235}U	0.9353	1.2374E-05	235.57	0.9383	0.0
Temperature, °C	0.9368	6.8658E-06	41.436 °C	0.9371	0.0

Table 6.2B.5 USL-1 Values for the Range of Parameters for Benchmark Experiments

Parameter	Parameter Lower Bound	USL Value at Lower Bound	Parameter Upper Bound	USL Value at Upper Bound
Pitch, cm	0.62	0.9351	1.85	0.9383
ECF, eV	0.0539	0.9368	1.64	**0.9301**
Enrichment, wt%	4.9200	0.9365	9.83	0.9378
H20/fuel	0.8339	0.9358	20.35	**0.9384**
AFG, group	174.8810	0.9325	216.0410	0.9380
H/^{235}U	39.7060	0.9358	657.4696	0.9383
Temperature, °C	16.0000	0.9369	274.0000	0.9371

Table 6.2B.6 Single-Sided Approach (USL-2) Equation

Trending Parameter	Values < Inflection Pt.		Inflection Pt.	Values > Inflection Pt.	
	Intercept	Slope		Intercept	Slope
Pitch, cm	0.9665	6.4986E-03	1.102 cm	0.9737	0.0
ECF, eV	0.9698	0.0	0.301 ev	0.9713	-4.9645E-03
Enrichment, wt%	0.9693	4.9860E-04	7.757 wt%	0.9732	0.0
H20/fuel	0.9709	4.9325E-04	6.056	0.9739	0.0
AFG, group	0.9341	1.9105E-04	203.456 grp	0.9730	0.0
$H/^{235}U$	0.9708	1.2374E-05	235.57	0.9737	0.0
Temperature, °C	0.9704	6.8658E-06	41.436 °C	0.9706	0.0

Table 6.2B.7 USL-1 Values for the Pathfinder Fuel Package

Parameter	48 Flooded		48 Optimum		Homogeneous	
	Parameter	USL	Parameter	USL	Parameter	USL
Pitch, cm					-	-
Rod Cell	0.7341 2.5426	0.9359 0.9383	0.7341 3.8126	0.9359 0.9383	-	-
ECF, eV	0.306251	0.9368	0.105085	0.9378	0.104816	0.9378
Enrichment, wt%	7.51	0.9377	7.51	0.9377	7.51	0.9377
H20/fuel	2.268036	0.9365	4.951	0.9378	-	-
AFG, group	195.1	0.9364	208.6	0.9380	207.3	0.9380
H/U	160.8	0.9373	289.7	0.9383	189.2	0.9376
Temperature, °C	20	0.9369	20	0.9369	20	0.9369
Minimum		**0.9359**		**0.9359**		**0.9369**

Table 6.2B.8 USLSTATS Output File for Trend k_{eff} Versus Pitch

```
uslstats: a utility to calculate upper subcritical
                        limits for criticality safety applications

  ****************************************************************************
                        Version 1.3.7, May 18, 1999
                         Oak Ridge National Laboratory
  ****************************************************************************


   Input to statistical treatment from file:lecpit

Title:  LEU Cases:238 Gp hex vs Pitch

   Proportion of the population = .995
   Confidence of fit            = .950
   Confidence on proportion     = .950
   Number of observations       =   43
   Minimum value of closed band =     .00
   Maximum value of closed band =     .00
   Administrative margin        =     .05


   independent     dependent       deviation               independent     dependent       deviation
   variable - x    variable - y     in y                   variable - x    variable - y     in y

    7.00000E-01     1.00663E+00     6.35000E-03             7.00000E-01     9.97960E-01     4.28000E-03
    8.00000E-01     1.00323E+00     5.87000E-03             1.40000E+00     1.00668E+00     3.80000E-03
    1.40000E+00     1.00528E+00     6.14000E-03             1.40000E+00     1.00387E+00     3.33000E-03
    7.00000E-01     9.97710E-01     4.70000E-03             1.40000E+00     1.00215E+00     3.42000E-03
    8.00000E-01     1.00338E+00     4.68000E-03             1.85000E+00     1.00775E+00     4.56000E-03
    1.00000E+00     1.00258E+00     3.71000E-03             1.85000E+00     1.00959E+00     3.89000E-03
    1.22000E+00     1.00528E+00     3.86000E-03             1.85000E+00     1.00815E+00     3.83000E-03
    1.40000E+00     1.00034E+00     3.90000E-03             1.32000E+00     9.97430E-01     2.23000E-03
    1.83000E+00     1.00085E+00     4.67000E-03             6.20000E-01     9.94510E-01     5.47000E-03
    1.85000E+00     1.00430E+00     4.66000E-03             8.80000E-01     1.00284E+00     4.10000E-03
    7.00000E-01     9.94770E-01     3.70000E-03             1.30000E+00     9.93200E-01     6.16000E-03
    7.00000E-01     9.96470E-01     3.69000E-03             1.30000E+00     9.98610E-01     6.16000E-03
    7.00000E-01     9.97770E-01     3.67000E-03             1.30000E+00     1.00161E+00     6.17000E-03
    7.00000E-01     1.00098E+00     3.69000E-03             1.30000E+00     1.00103E+00     6.16000E-03
    7.00000E-01     1.00239E+00     3.71000E-03             1.30000E+00     1.00183E+00     6.18000E-03
```

```
    7.00000E-01     1.00186E+00     3.67000E-03           1.30000E+00     1.00097E+00     6.16000E-03
    7.00000E-01     9.81130E-01     4.21000E-03           1.30000E+00     1.00226E+00     6.16000E-03
    8.00000E-01     9.91110E-01     4.48000E-03           1.29000E+00     9.97210E-01     3.43000E-03
    1.00000E+00     9.96490E-01     4.78000E-03           1.29000E+00     9.94310E-01     3.47000E-03
    1.22000E+00     1.00111E+00     5.27000E-03           1.09000E+00     9.96630E-01     6.27000E-03
    7.00000E-01     9.98690E-01     4.58000E-03           1.09000E+00     9.95720E-01     6.26000E-03
    7.00000E-01     9.98270E-01     4.21000E-03

chi =  3.3953 (upper bound = 9.49). The data tests normal.


         Output from statistical treatment

    LEU Cases:238 Gp hex vs Pitch

    Number of data points (n)                        43
    Linear regression, k(X)                          .9928 + ( 6.4986E-03)*X
    Confidence on fit (1-gamma) [input]              95.0%
    Confidence on proportion (alpha) [input]         95.0%
    Proportion of population falling above
    lower tolerance interval (rho) [input]           99.5%
    Minimum value of X                                   .6200
    Maximum value of X                                  1.8500
    Average value of X                                  1.11977
    Average value of k                                1.00011
    Minimum value of k                                 .98113
    Variance of fit, s(k,X)^2                        2.1077E-05
    Within variance, s(w)^2                          2.2762E-05
    Pooled variance, s(p)^2                          4.3839E-05
    Pooled std. deviation, s(p)                      6.6211E-03
    C(alpha,rho)*s(p)                                2.6344E-02
    student-t @ (n-2,1-gamma)                        1.68335E+00
    Confidence band width, W                         1.1744E-02
    Minimum margin of subcriticality, C*s(p)-W       1.4601E-02

    Upper subcritical limits: (  .62000     <= X <=    1.8500     )
    ***** *********** *******

    USL Method 1 (Confidence Band with
    Administrative Margin)          USL1 =  .9311 + ( 6.4986E-03)*X (X <     1.1021    )
                                         =  .9383                   (X >=    1.102)

    USL Method 2 (Single-Sided Uniform
```

```
    Width Closed Interval Approach)    USL2 =  .9665 + ( 6.4986E-03)*X (X <     1.1021   )
                                            =  .9737                   (X >=    1.102)


    USLs Evaluated Over Range of Parameter X:
    **** ********* **** ***** ** ********* **

X:   6.20E-1  7.96E-1  9.71E-1  1.15E+0  1.32E+0  1.50E+0  1.67E+0  1.85E+0
            -------------------------------------------------------------------------
USL-1:       .9351    .9363    .9374    .9383    .9383    .9383    .9383    .9383
USL-2:       .9705    .9717    .9728    .9737    .9737    .9737    .9737    .9737
            -------------------------------------------------------------------------

  ****************************************************************************
                                Thus spake USLSTATS
                                       Finis.
```

Figure 6.2B.1 Plot of K_{eff} Versus Pitch with USL Values

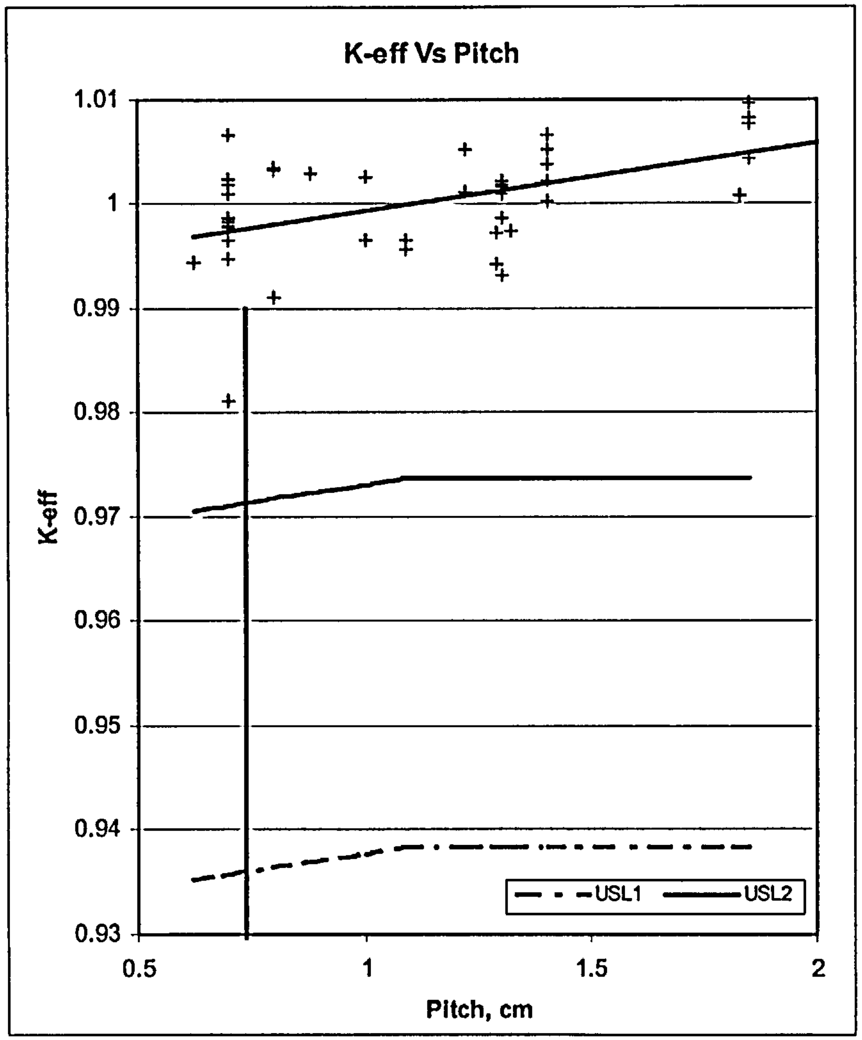


Figure 6.2B.2 Plot of K_{eff} Versus ECF with USL Values

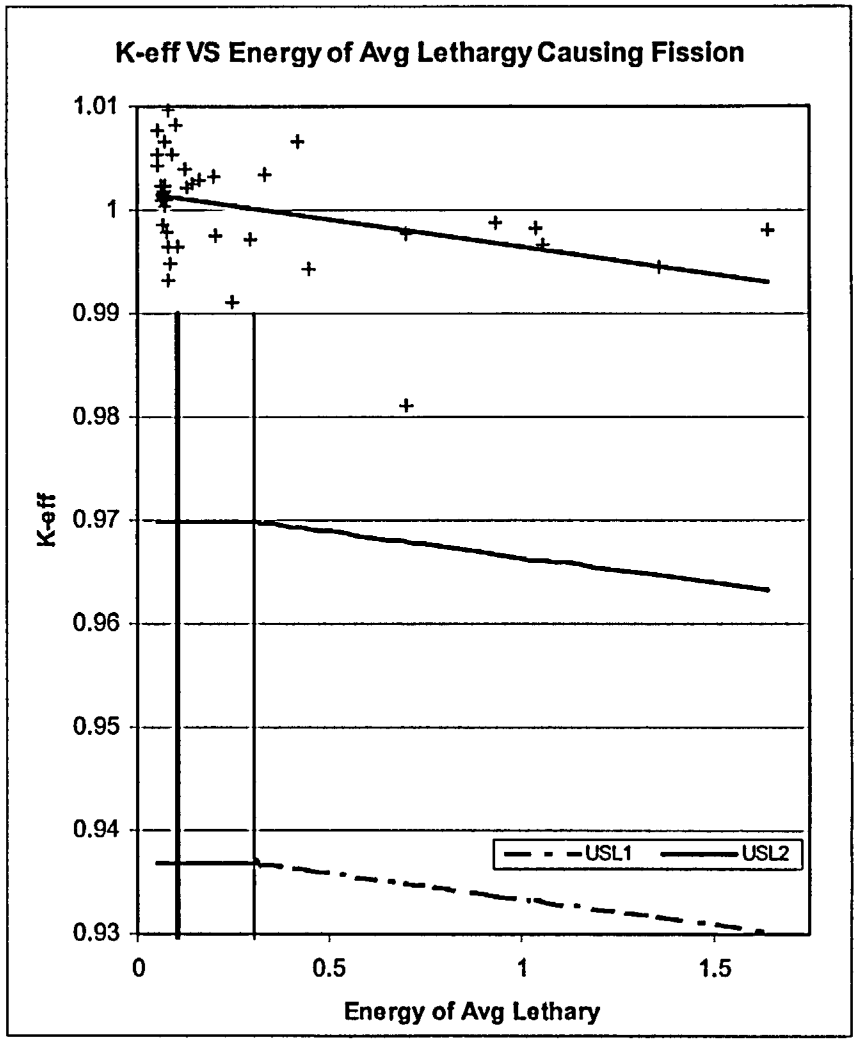


Figure 6.2B.3 Plot of K_{eff} Versus Enrichment with USL Values

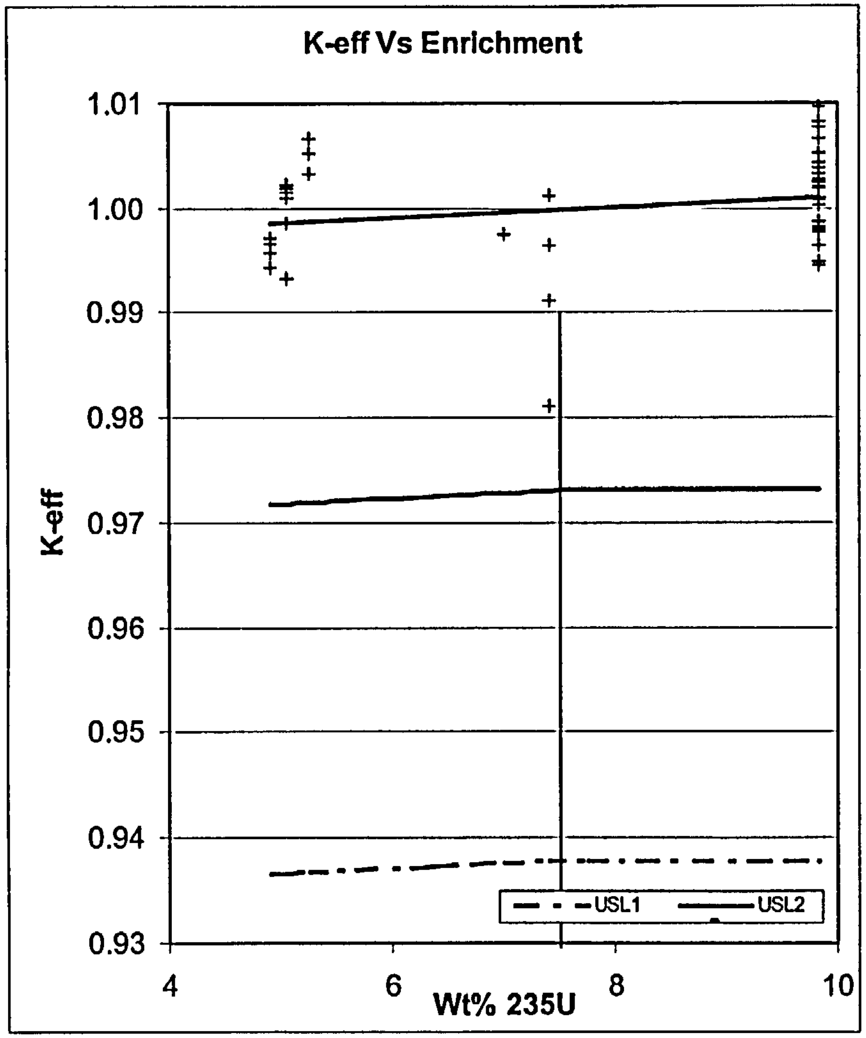


Figure 6.2B.4 Plot of K_{eff} Versus Water/Fuel with USL Values

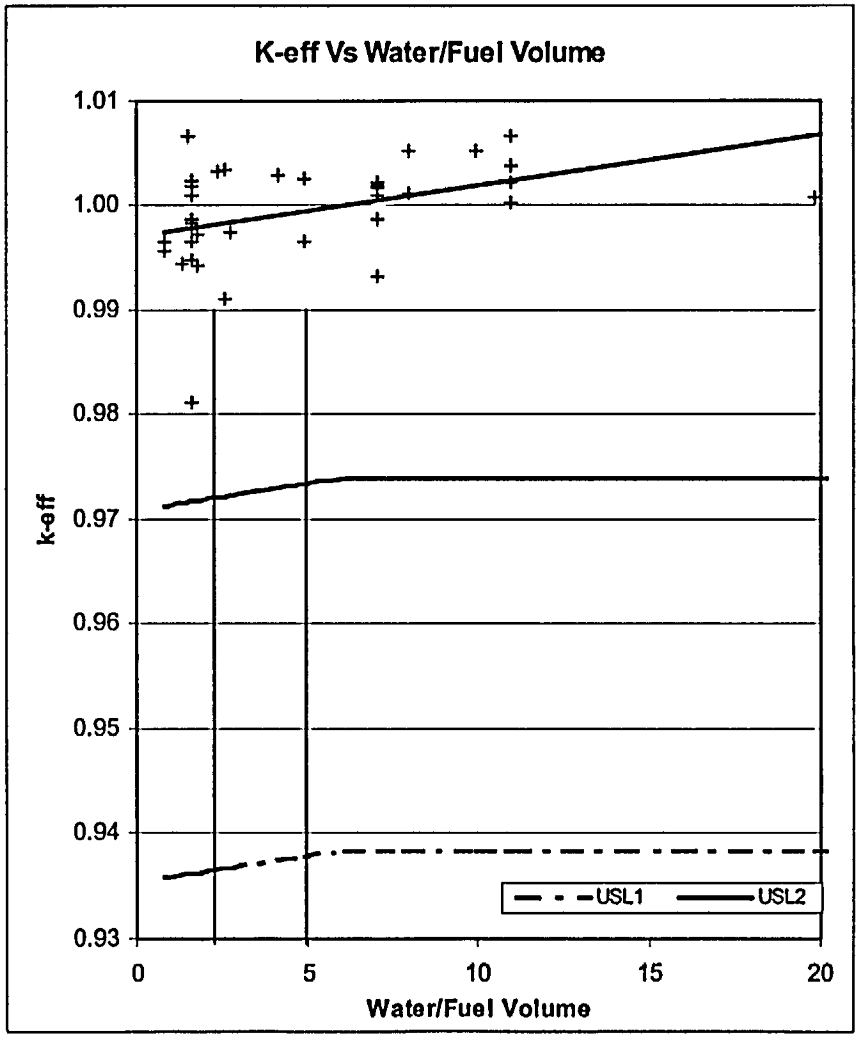


Figure 6.2B.5 Plot of K_{eff} Versus AFG with USL Values

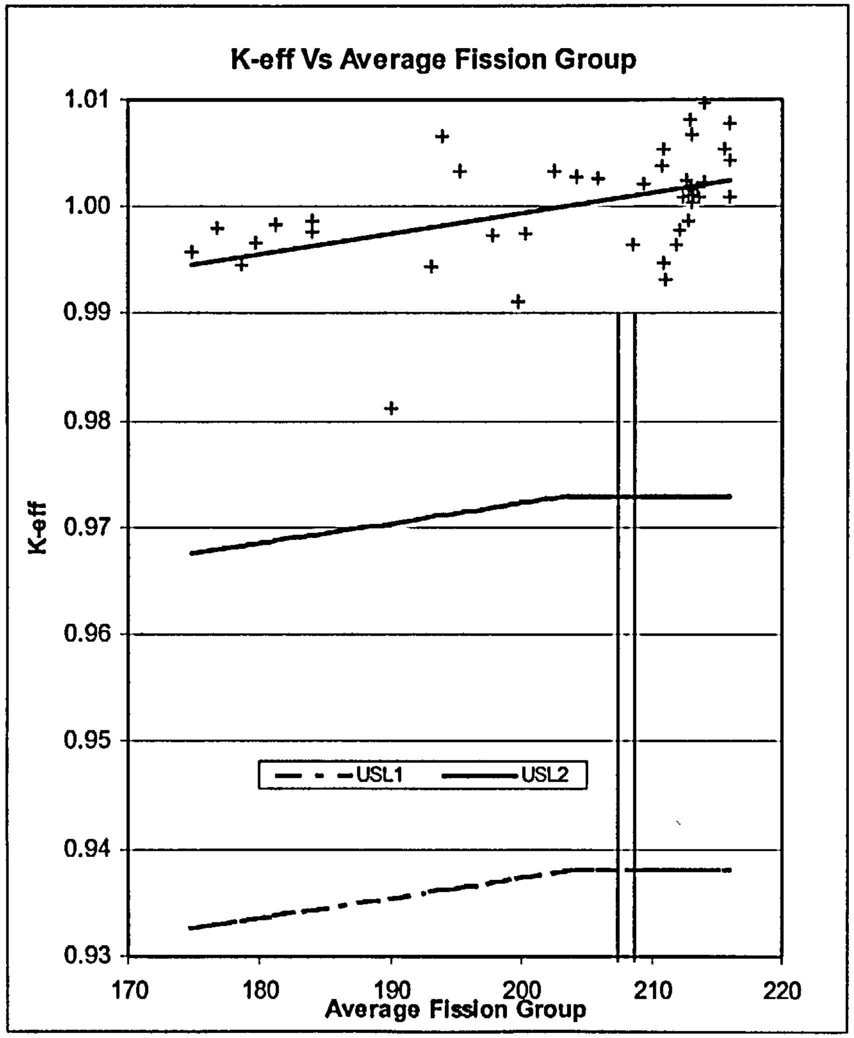


Figure 6.2B.6 Plot of K_{eff} Versus $H/^{235}U$ with USL Values

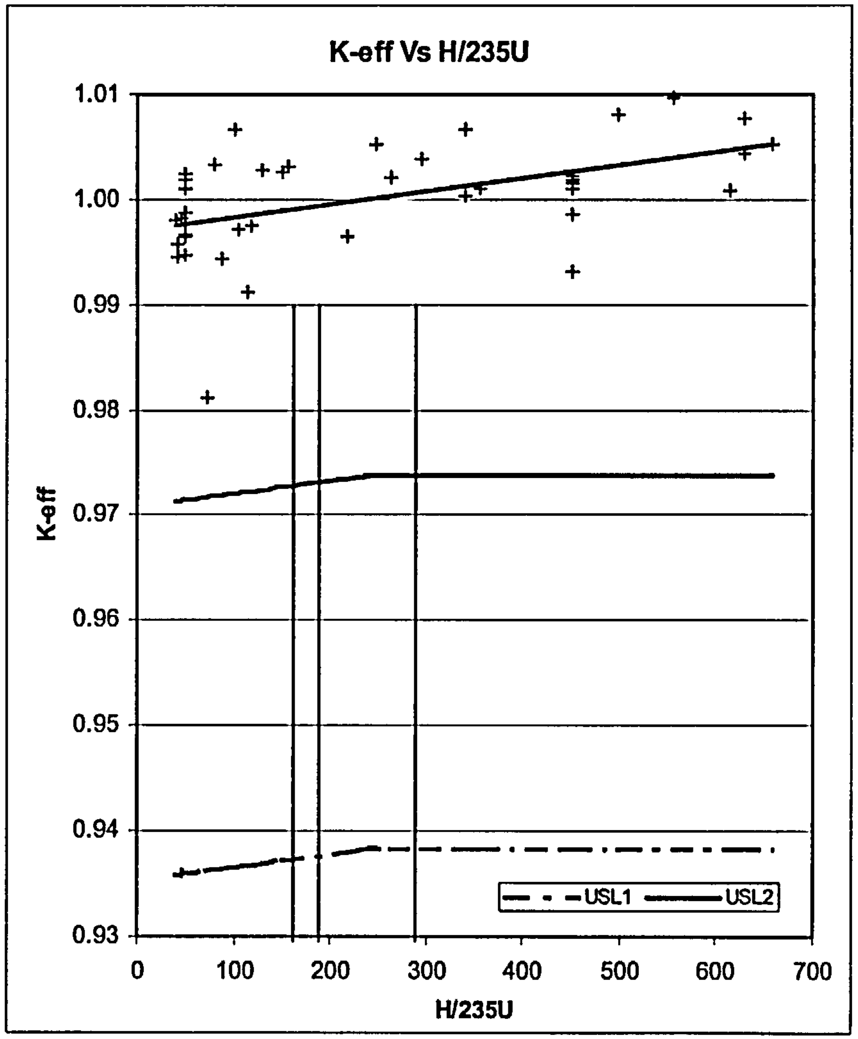
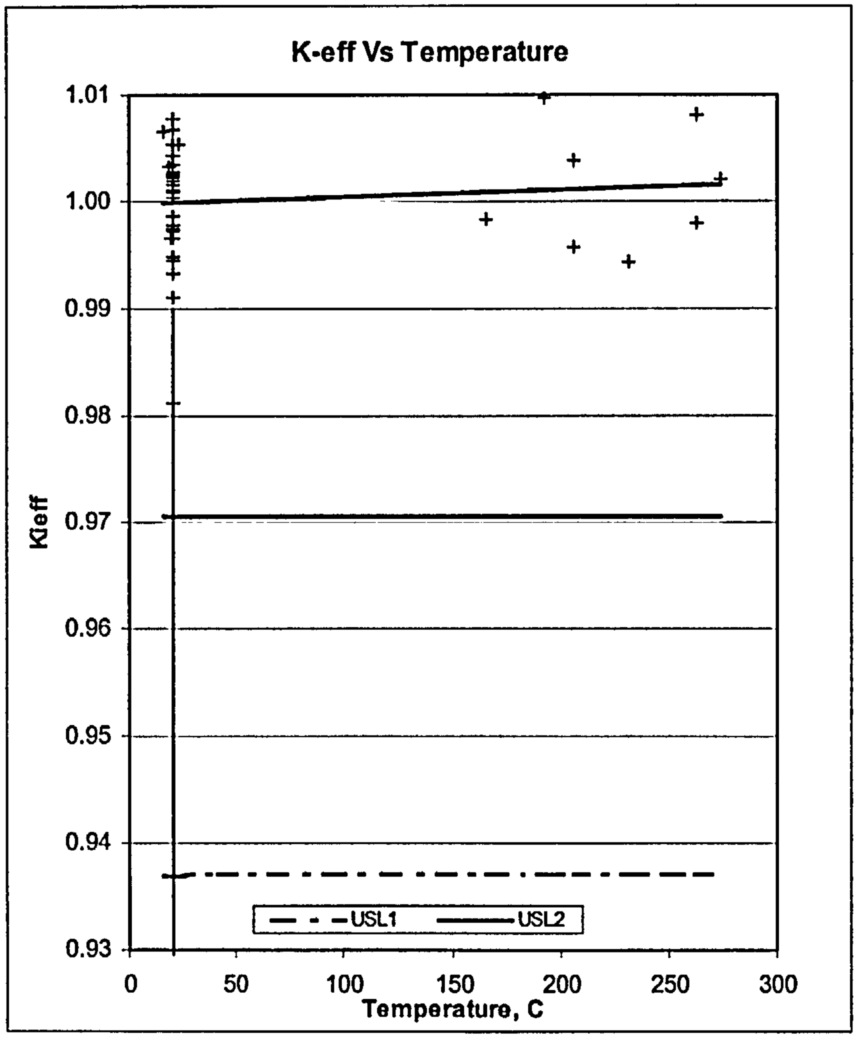


Figure 6.2B.7 Plot of K_{eff} Versus Temperature with USL Values



Enclosure (6)
Change Summary

Chapter	Page Number	Description of Change
Cover Sheet	1	Corrected spelling errors
Table of Contents	All	Addition of Sections/Appendices added in response to RAIs Page number changes related to additional information added to the chapters in response to RAIs
1	All	Footer Changed due to total number of pages
1	1	paragraph 1.1, changed "leak-tight canister" to "Pathfinder Canister"
1	2	added "Transport Index - 100" (Section 1.2.3.1)
1	Table 1-3	modified table to include center-to-center pin pitch, nominal UO2 density, and nominal values with tolerances for pellet diameter and clad outer and inner diameter. Also, corrected assembly k_{eff} value in response to RAI 1-7.
1	5	Added discussion of Quality Assurance Program (Section 1.3)
2	All	Footer Changed due to total number of pages
2	1	Removed reference to Appendix 2-2 (now Section 2.10).
2	3	Added 2nd paragraph to explain the history of the WE-1, and the changes make for this submittal. Changed reference from the 1992 ASME Standard to the 1995 ASME standard, through the 1996 addenda, in bottom paragraph.
2	4	Changed reference from the 1992 ASME Standard to the 1995 ASME standard, through the 1996 addenda, in 2nd paragraph. Added last sentence to last paragraph
2	7	Added 3rd sentence to 1st paragraph. Corrected Aluminum specification (from T6 to T651) Added Rubber Pad specification.
2	8	Corrected 1st value in the "300" column (from 23.5 to 23.4) Corrected Aluminum specification (from T6 to T651) Changed page number in references for "Wood Impact Absorbers" Adjusted crush values in response to RAIs.
2	10	Added discussion of the Rubber to the last paragraph of section 2.4.4.
2	15	Added discussion of the Rubber to the last paragraph of section 2.6.2.
2	16	Removed reference to Appendix 2-2 (now Section 2.10).
2	17	Changed acceleration from 135 g's to 142 g's, and adjusted calculation accordingly.

Enclosure (6)
Change Summary

Chapter	Page Number	Description of Change
2	19	Changed wording in 1st paragraph of Section 2.7.1.2 to clarify impact stiffness discussion.
2	20	Changed wording in 1st paragraph (formerly the last paragraph of p. 19) to clarify discussion. Revised Table 2.7-1.
2	23	Added discussion of WE-1 with Pathfinder Canister to 1st paragraph of section 2.7.1.5. Revised Table 2.7.1.5-1. Revised calculation for "Buckling of Cylinder"
2	25	Removed reference to Appendix 2-2 (now Section 2.10). Added "," to numbers in equations.
2	26	Added "," to numbers in equations. Corrected 10CFR reference in 1st paragraph of section 2.7.6 Removed reference to Appendix 2-2 (now Section 2.10).
2	27	Added "," to numbers in loads listing.
2	28	Reworded paragraph
2	Section 2.10	Moved from Appendix 2-2 to Chapter 2. Revisions from the May 15, 2002 submittal are noted by Revision Bars in the right-hand margin.
3	2	Added discussion of thermal properties between -20 °F and -40 °F in response to RAI 3-4.
3	3	Added data, down to -40 °F, and Alloy 600 to Table 3.2-1 in response to RAI 3-4. Added clarification to note #2.
3	4	Corrected references in Note #1 in response to RAI 3-1.
3	5	Corrected references in Note #2 in response to RAI 3-1. Added clarification to note #2 regarding absoptivity and emissivity in response to RAI 3-2.. Added reference in Table 3.2-4 to Note #1 in response to RAI 3-5.
3	6	Added discussion of ductile-to-brittle transition to Section 3.2 in response to RAI 3-3 and 3-7.
3	7	Corrected units for Stefan-Boltzman constant in response to RAI 3-6.
3	9	Corrected references in Section 3.5.2 in response to RAI 3-1. Corrected units for the convection coefficient in Section 3.5.2 in response to RAI 3-9.
3	10	Added reference to the Section 2.10.1.1 internal pressure calculation in Section 3.5.4 in response to RAI 3-10.

Enclosure (6)
Change Summary

Chapter	Page Number	Description of Change
4	All	Footer Changed due to total number of pages
4	4	Corrected viscosity of air to 0.0185 from 0.00185.
4	8-13	Added "Calculation for Pre-shipment Test of Seals" (Section 4.5) in response to RAIs 7-2, 8-1, and 8-2.
4	13	Changed "Section 4.5 References" to "Section 4.6 References" to facilitate addition of "Calculation for Pre-shipment Test of Seals" (Section 4.5).
6	2	Table 6-1b, Row 4, Column 2; changed "spaced" to "arranged"
6	4 & 4a	Table 6-2b; expanded to include tolerances, additional parameters, and KENO modeled values in Response to RAIs 6-1 and 6-2.
6	4b	Added to maintain page number consistent with current submittal.
6	8	Added dimensions to Figure 6-1b in response to RAI 6-3.
6	17	Corrected k_{eff} value in 2nd paragraph in response to RAI 6-5.
6	18	Clarified wording in bottom paragraph in response to RAI 6-6.
6	21	Section "Pathfinder Fuel Assemblies", paragraph following the number list; added parenthetical statement explaining the 0.001 in. assembly spacing
6	21a	Table 6-10, row 2, column 1; changed 0 to 0.001 to be consistent with previous paragraph
6	24	Added explanation of row and location numbering to the 2nd paragraph.
6	24a	Added discussion of dunnage material and affects on reactivity in response to RAI 6-4.
6	26	Added discussion of accident configurations below Table 6-14 in response to RAIs 2-14 and 6-7.
6	30-31	Section 6.5(b) was rewritten in response to RAIs 6-8 through 6-13.
7	1-3	Changed bullets to paragraph numbering in Section 7.2 in response to RAI 7-1.
7	2	Added description of "visual inspection" to paragraph 3 of Section 7.2.2 in response to RAI 7-1.
7	2	Added reference to the Section 4.5 inner seal region volume and sample calculation in paragraph 7 of Section 7.2.2 in response to RAI 7-2
7	4	Added "end cover plate, and thrust plate" to paragraph 6 of Section 7.6.4.
8	1	Added reference to ANSI N14.5-1997 and details regarding pressure drop test and fabrication leak test to Section 8.1.3 in response to RAI 8-1.

Enclosure (6)
Change Summary

Chapter	Page Number	Description of Change
8	2	Added requirement in Section 8.2.1 to "Inspect closure bolts and replace if damaged."
8	2	Added reference to ANSI N14.5-1997 and details regarding pressure drop test and fabrication leak test to Section 8.2.2 in response to RAI 8-2.
App. 1-1	1 & Drwg.	Revised Drawing No. 5016270 in response to RAI 1-1. Added Drawing No. 5021426 in response to RAI 1-1.
App. 1-2	All	Added appendix to provide additional information regarding the Pathfinder Fuel Assemblies in response to RAI 1-2.
App. 2-1	All	Added figure labels in response to RAI 2-8.
App. 3-1	1	Corrected Reference at the end of the 1st paragraph in response to RAI 3-11. Attached copy of Ref. 1 and 2 to the cover letter in response to RAI 3-12.
App. 3-2	All	Added appendix in response to RAI 3-8.
App. 6-2	All	Footer Changed due to total number of pages
App. 6-2	22-89	Rewrote the appendix to better explain the benchmarking process and methods in response to RAIs 6-8 through 6-13. Discussion has been completely revised. It now reflects the methodology of NUREG/CR-6361 for transportation rather than NUREG/CR-6698.