ENGINEERING CHANGE NOTICE

1. ECN 647522

Proj. ECN

2. ECN Category (mark one)	3. Originator's Name, Organization, MSIN, and Telephone No.	4. USQ Required?	5. Date
Supplemental [ ] Direct Revision [x] Change ECN [ ] Temporary [ ] Standby [ ] Supersedure [ ] Cancel/Void [ ]	S. F. Kessler, Nuclear Safety, R3-26 376-2768	[ ] Yes [x] No	10/11/99
	6. Project Title/No./Work Order No. Spent Nuclear Fuel Project	7. Bldg./Sys./Fac. No. SNF	8. Approval Designator S^N
	9. Document Numbers Changed by this ECN (includes sheet no. and rev.) HNF-SD-SNF-CSER-005, Rev. ~~1~~ 5	10. Related ECN No(s). 647502	11. Related PO No. N/A

12a. Modification Work	12b. Work Package No.	12c. Modification Work Complete	12d. Restored to Original Condition (Temp. or Standby ECN only)
[ ] Yes (fill out Blk. 12b) [x] No (NA Blks. 12b, 12c, 12d)	N/A	N/A Design Authority/Cog. Engineer Signature & Date	N/A Design Authority/Cog. Engineer Signature & Date

13a. Description of Change

13b. Design Baseline Document? [x] Yes [ ] No

This report was revised to incorporate analyses performed in response to review comments for the CVD and CSB FSARs.

No USQ required because this ECN doesn't change the facility or its procedures.

14a. Justification (mark one)

Criteria Change	[ ]	Design Improvement	[x]	Environmental	[ ]	Facility Deactivation	[ ]
As-Found	[ ]	Facilitate Const	[ ]	Const. Error/Omission	[ ]	Design Error/Omission	[ ]

14b. Justification Details

Both the MCO and the fuel and scrap basket designs were changed and new criticality analyses were required to demonstrate acceptability.

15. Distribution (include name, MSIN, and no. of copies)

See attached distribution coversheet.

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DATE: OCT 20 1999 HANFORD RELEASE STA: 4 ID: 2

ENGINEERING CHANGE NOTICE

1. ECN (use no. from pg. 1): 647522

16. Design Verification Required	17. Cost Impact				18. Schedule Impact (days)	
	ENGINEERING		CONSTRUCTION			
[ ] Yes	Additional	[ ] N/A	Additional	[ ]	Improvement	[ ] N/A
[x] No	Savings	[ ]	Savings	[ ]	Delay	[ ]

19. Change Impact Review: Indicate the related documents (other than the engineering documents identified on Side 1) that will be affected by the change described in Block 13. Enter the affected document number in Block 20.

SDD/DD	[] N/A	Seismic/Stress Analysis	[]	Test Calibration Manual	[]
Functional Design Criteria	[]	Stress/Design Report	[]	Health Physics Procedure	[]
Operating Specification	[]	Interface Control Drawing	[]	Spares Multiple Unit Listing	[]
Criticality Specification	[]	Calibration Procedure	[]	Test Procedures/Specification	[]
Conceptual Design Report	[]	Installation Procedure	[]	Component Index	[]
Equipment Spec.	[]	Maintenance Procedure	[]	ASME Coded Item	[]
Const. Spec.	[]	Engineering Procedure	[]	Human Factor Consideration	[]
Procurement Spec.	[]	Operating Instruction	[]	Computer Software	[]
Vendor Information	[]	Operating Procedure	[]	Electric Circuit Schedule	[]
OM Manual	[]	Operational Safety Requirement	[]	ICRS Procedure	[]
FSAR/SAR	[]	IHPD Drawing	[]	Process Control Manual/Plan	[]
Safety Equipment List	[]	Cell Arrangement Drawing	[]	Process Flow Chart	[]
Radiation Work Permit	[]	Essential Material Specification	[]	Purchase Requisition	[]
Environmental Impact Statement	[]	Fac. Proc. Samp. Schedule	[]	Tickler File	[]
Environmental Report	[]	Inspection Plan	[]		[]
Environmental Permit	[]	Inventory Adjustment Request	[]		[]

20. Other Affected Documents: (NOTE: Documents listed below will not be revised by this ECN.) Signatures below indicate that the signing organization has been notified of other affected documents listed below.

Document Number/Revision	Document Number/Revision	Document Number Revision
	N/A	

21. Approvals

	Signature	Date		Signature	Date
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			Signature or a Control Number that tracks the Approval Signature		
			ADDITIONAL		

ENGINEERING CHANGE NOTICE

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	ENGINEERING		CONSTRUCTION			
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SDD/DD	[] N/A	Seismic/Stress Analysis	[]	Tank Calibration Manual	[]
Functional Design Criteria	[]	Stress/Design Report	[]	Health Physics Procedure	[]
Operating Specification	[]	Interface Control Drawing	[]	Spares Multiple Unit Listing	[]
Criticality Specification	[]	Calibration Procedure	[]	Test Procedures/Specification	[]
Conceptual Design Report	[]	Installation Procedure	[]	Component Index	[]
Equipment Spec.	[]	Maintenance Procedure	[]	ASME Coded Item	[]
Const. Spec.	[]	Engineering Procedure	[]	Human Factor Consideration	[]
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	N/A	

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Design Authority L. H. Goldmann	L. H. GOLDMAN PTC	10/13/99		
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Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
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Criticality Safety Evaluation Report for the Multi-Canister Overpack

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U.S. Department of Energy Contract DE-AC06-96RL13200

ECN: 647522 UC: 940
Org Code: 403 Charge Code: 105531/CB80
B&R Code: EW31354040 Total Pages: ~~170~~ 182
10-20-98

Key Words: Low enriched spent nuclear fuel shipping container, criticality, Monte Carlo, Deterministic transport

Abstract: This criticality evaluation is for Spent N Reactor fuel unloaded from the existing canisters in both KE and KW Basins, and loaded into multiple canister overpack (MCO) containers with specially built baskets containing a maximum of either 54 Mark IV or 48 Mark IA fuel assemblies. The criticality evaluations include loading baskets into the cask-MCO, operation at the Cold Vacuum Drying Facility, and storage in the Canister Storage Building. Many conservatisms have been built into this analysis, the primary one being the selection of the K_{eff} = 0.95 criticality safety limit. This revision incorporates the analyses for the sampling/weld station in the Canister Storage Building and additional analysis of the MCO during the draining at CVDF. Additional discussion of the scrap basket model was added to show why the addition of copper divider plates was not included in the models.

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Release Approval 10/19/99 Date

DATE: HANFORD RELEASE ID: 2
STA: 4
OCT 20 1999
Release Stamp

Approved for Public Release

RECORD OF REVISION	(1) Document Number HNF-SD-SNF-CSER-005, Rev. 5	Page 1
(2) Title Criticality Safety Evaluation Report for the Multi-Canister Overpack		

CHANGE CONTROL RECORD			
(3) Revision	(4) Description of Change - Replace, Add, and Delete Pages	Authorized for Release	
		(5) Cog. Engr. Date	(6) Cog. Mgr. Date
	(7)		
0	**EDT: 616568**		
1	**ECN: 605703** *Addition of CVDF criticality analysis.*		
2	**ECN: 605707** *Incorporation of DOE RCR comments.*		
3	**ECN: 605711** *Incorporation of RCR comments.*		
4	**ECN: 647502** *Revised to incorporate the latest MCO basket design changes and the incorporate additional analyses performed in response to review comments for the MCO Topical Report.*		
5 RS	**ECN: 647522** *Revised to incorporate the CSB sampling/weld station analysis, additional analysis for the draining operation at CVDF, and justification for not modeling the copper dividers in the scrap baskets.*	S. F. Kessler JRE for SF Kessler.	R. L. Garrett

CRITICALITY SAFETY EVALUATION REPORT FOR THE MULTI-CANISTER OVERPACK

October 1999

Prepared for the U.S. Department of Energy
Office of Environmental Restoration and Waste Management

DE&S Hanford, Incorporated
Fluor Daniel Northwest
Richland, Washington 99352

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ACRONYMS AND ABBREVIATIONS

CSB	Canister Storage Building
CSER	criticality safety evaluation report
CVDF	Cold Vacuum Drying Facility
MCNP	Monte Carlo N-Particle Transport Code
MCO	multi-canister overpack
MHM	multi-canister overpack handling machine
SNF	spent nuclear fuel
SPR	single pass reactor

CRITICALITY SAFETY EVALUATION REPORT FOR THE MULTI-CANISTER OVERPACK

1.0 INTRODUCTION AND SUMMARY OF LIMIT AND CONTROLS

This criticality safety evaluation report (CSER) addresses the criticality analysis for spent nuclear fuel (SNF) inside a multi-canister overpack (MCO). The results reported in this revision of the CSER have been upgraded to incorporate the basket designs from HNF-S-0426, *Performance Specification for Spent Nuclear Fuel Multi-Canister Overpack* (Goldmann 1998).

1.1 OVERVIEW

SNF will be removed from existing canisters in both the K East and K West Basins, washed, sorted, loaded into baskets, and the baskets loaded into MCOs. Since the majority of the SNF consists of spent N Reactor fuel, the basket designs are based on the Mark IV and Mark IA fuel assemblies.

A fraction of the fuel inventory is damaged or corroded and does not closely resemble fuel elements. This fissionable material is referred to as scrap. Scrap materials, and any additional scrap that may be generated during the fuel retrieval process, will be loaded into scrap baskets. Normally, Mark IV fuel scrap will be placed in Mark IV scrap baskets and Mark IA fuel scrap in Mark IA scrap baskets. Some single pass reactor (SPR) fuel also is stored in canisters in the K Basins. This fuel will be loaded into modified Mark IA baskets and loaded into an MCO that contains no other fuel type.

Baskets containing fuel or scrap are loaded into the MCO by the MCO loading system in the K Basins. An MCO can contain either six Mark IA baskets or five Mark IV baskets. Mark IA and Mark IV baskets are not mixed in the same MCO. Each MCO may be loaded with all fuel baskets, one scrap basket with the rest of the baskets being fuel baskets, or two scrap baskets with the rest being fuel baskets. By design, a Mark IA fuel basket may contain a maximum of 48 fuel assemblies, and a Mark IV basket may contain a maximum of 54 fuel assemblies.

Once the MCO has been loaded with baskets of fuel and scrap, it is sealed and the cask–MCO removed from the K Basin pool, the lid installed on the shipping cask, and the cask–MCO secured to a transporter. The cask–MCO is then taken to the Cold Vacuum Drying Facility (CVDF) where the water inside the MCO is removed. The dry cask–MCO is taken to the Canister Storage Building (CSB), and the MCO is removed from the cask. A cover cap is welded into place on top of the MCO, and the sealed MCO is then inserted into a tube in the CSB vault for interim storage. Some MCOs are monitored and will not have a welded cover cap installed until the monitoring campaign has been completed.

The fissile materials in the K Basins that are to be put into the MCO baskets exist in different forms. These forms include whole fuel assemblies, parts of fuel assemblies (scrap), and oxides of corroded fuel. The terms used in this report to describe each modeling category are defined below.

- Fuel is any of the various forms of fuel located in the K Basins.
- Scrap is any fissile material and inseparable debris loaded into MCO scrap baskets. The enrichment of the scrap is defined as the maximum enrichment of any of the material contained in the scrap. This material is treated as optimally sized and spaced uranium rods.
- An assembly is N Reactor fuel consisting of both an inner and an outer element.
- Elements are individual inner or outer fuel elements.
- Rubble is compressed and fractured fuel assemblies that may result from an accident, such as a cask drop. Its enrichment is the average of the intact fuel that was rubblized.
- Unirradiated fuel is fuel with nominal ^{235}U enrichment.

Of the forms defined above, it should be noted that for equal volumes, the scrap is the most reactive form. Scrap models used in this report are optimally configured and therefore bound all forms of N Reactor and SPR uranium scrap.

1.2 LIMITS, CONTROLS, AND ENGINEERED FEATURES

This CSER shows that for all normal and accident conditions, the MCO loaded with fissile material will meet the acceptance criteria when the following limits and operational guidelines are met. Basket loading limits are specified in HNF-SD-SNF-CSER-010, *Criticality Safety Evaluation Report for the K Basin Fuel Retrieval Subproject* (Kessler and Peck 1999).

Limit 1 A maximum of two baskets of scrap, one in the top and one in the bottom, may be loaded into an MCO.

Basis: Scrap has been modeled as optimally sized rods at optimal water moderation. Placing scrap at both ends of the stack of baskets in the MCO limits the k_{eff} to less than 0.95 for all credible accidents. The limit of two scrap baskets and their locations is based on heat removal from the MCO and is specified in HNF-SD-SNF-OCD-001, *Spent Nuclear Fuel Project Product Specification* (Pajunen 1998).

The features of the MCO and Mark IA baskets engineered to be safety class as a geometry control to ensure safety (Goldmann 1998) include:

- The MCO shell
- The filter guard plate
- The shield plug
- The Mark IA fuel and scrap basket base plate
- The Mark IA fuel and scrap basket center post
- The Mark IA fuel and scrap basket outer trapezoidal bars.

In addition, the maximum allowable radial deflection of the center post during a design basis accident is 2 in. The maximum inner diameter of the MCO shell during a design basis accident is 23.25 in.

1.3 DIMENSIONS REQUIRING QUALITY CONTROL VERIFICATION

The following dimensions require quality control verification during fabrication:

- The inner diameter of the MCO can be 23.025 ± 0.01 in.
- The Mark IA base plate nominal thickness is 1.23 in. to 1.25 in.

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2.0 DESCRIPTION OF FACILITY AND OPERATIONS

SNF is to be removed from existing canisters in both the K East and K West Basins. The intact fuel assemblies, fuel pieces, or scrap will be loaded into fuel and scrap baskets, and the baskets loaded into MCOs. The loaded MCOs will be transported to the CVDF for draining and drying and then to the CSB for long-term interim storage. This chapter briefly describes the SNF, the MCOs into which it will be loaded, the CVDF, and the CSB.

2.1 SPENT NUCLEAR FUEL

WHC-SD-NR-CSER-009, *Criticality Safety Evaluation K Basin Storage Rack Seismic Qualification* (Wittekind 1993), and UNI-3894, *Procedures, Methods and Models for Neutronic Analysis of N Reactor* (Burnside et al. 1987), provide the essential specifications for the intact fuel assemblies to be loaded into the MCO. Unless otherwise stated, this CSER uses the longest fuel assembly length for the Mark IV fuel assemblies because they contain the most fissile material and tend to be the most reactive. The Mark IA intact fuel is modeled as 20.9 in. long, the most common length. Twelve Mark IA assemblies are 26.1 in. long and, because of their length, cannot be loaded into a Mark IA basket. They have been analyzed to allow them to be loaded into a Mark IV fuel basket. A small amount of Mark IA fuel is stored in the K East Basin. This material will be loaded in Mark IV baskets in accordance with the limits in HNF-SD-SNF-CSER-010 (Kessler and Peck 1999).

2.1.1 N Reactor Fuel

The vast majority of the 2,100 metric tons of irradiated fuel in the K Basins is from the N Reactor. There are two basic fuel assembly types, designated Mark IV and Mark IA. Figure 2-1 illustrates a typical Mark IV N Reactor fuel assembly (Mark IA assemblies are similar). The N Reactor fuel has a tube-within-a-tube design.

Mark IV fuel assemblies have a pre-irradiation enrichment of 0.95 wt% ^{235}U in both elements and a maximum weight of 51.6 lb. They have an outside diameter of 2.42 in. and lengths of 17.4 in. to 26.1 in. Other types of N Reactor fuel stored at the K Basins are Mark IB, IC, IVB, and IVC. Mark IB and IVB have preirradiation enrichments of 0.71 wt% ^{235}U and Mark IC has a preirradiation enrichment of 0.95 wt% ^{235}U. These fuel types are handled as Mark IV fuel. The Mark IVC fuel has a preirradiation enrichment of 1.15 wt% ^{235}U in the outer element and 0.95 wt% ^{235}U in the inner element. No Mark IVC fuel is currently stored in the K Basins. Mark IA assemblies have a pre-irradiation enrichment of 1.25 wt% ^{235}U in the outer element, 0.95 wt% ^{235}U in the inner element, and a maximum weight of 36.6 lb. They have an outside diameter of 2.40 in. and lengths of 14.9 in. to 26.1 in. Only 12 Mark IA assemblies are 26.1 in. long. Table 2-1 provides a detailed listing of the N Reactor fuel dimensions and weights. The majority of the Mark IA material is stored in the K West Basin. Only a very small amount of Mark IA material is stored in the K East Basin.

Table 2-1. Nominal Dimensions and Weights for N Reactor Fuel Assemblies.

	Mark IV fuel assembly		Mark IA fuel assembly	
Outer tube diameters:	(cm)	(in.)	(cm)	(in.)
Zirconium cladding, outer diameter	6.160	2.425	6.106	2.404
Uranium, outer diameter	6.032	2.375	5.979	2.354
Uranium, inner diameter	4.422	1.741	4.592	1.808
Zirconium cladding, inner diameter	4.321	1.701	4.481	1.764
Outer tube enrichment:	(wt%)		(wt%)	
^{235}U	0.94700[a]		1.2500	
^{236}U	0.03920		0.0392	
^{238}U	99.0138		98.7108	
Inner tube diameters:	(cm)	(in.)	(cm)	(in.)
Zirconium cladding, outer diameter	3.249	1.279	3.165	1.246
Uranium, outer diameter	3.096	1.219	2.962	1.166
Uranium, inner diameter	1.321	0.520	1.245	0.490
Zirconium cladding, inner diameter	1.219	0.480	1.118	0.440
Inner tube enrichment:	(wt%)		(wt%)	
^{235}U	0.94700[a]		0.94700	
^{236}U	0.03920		0.03920	
^{238}U	99.0138		99.0138	
Fuel assembly dimensions:	(cm)	(in.)	(cm)	(in.)
Maximum length	66.294	26.10	53.035[b]	20.88[b]
End cap thickness	0.483	0.19	0.483	0.19
Fuel assembly weight:	(kg)	(lb)	(kg)	(lb)
Maximum weight	23.4	51.6	16.6	36.6

[a]Mark IVB fuel consists of natural uranium (0.71 wt % ^{235}U) in both the outer and inner tubes, which correspond to Mark IV tube diameters and assembly lengths of 19.9, 23.2, and 26.1 in.

[b]There are twelve Mark IA assemblies that are 26.1-in. long.

A significant portion of the N Reactor fuel stored in the K East Basin has undergone corrosion as a result of cladding damage during fuel handling. The fuel in many cases has swollen from the uranium corrosion, causing further damage to the cladding, and leading to further corrosion. The fuel stored in the K West Basin was encapsulated in water-filled canisters with an added corrosion inhibitor. Analyses performed on samples of fuel from these canisters have shown that this fuel is significantly less corroded than the fuel in the K East Basin (Makenas 1998). For this CSER, the corrosion rates of the fuel in both basins were assumed to be the same. In addition, some of the K West Basin canisters show evidence of leakage.

2.1.2 Single Pass Reactor Fuel

The K Basins also contain an estimated 3.9 metric tons (0.16% of the total inventory) of irradiated fuel from Hanford Site SPRs. The inventory lists 183 kg of 0.95 wt% ^{235}U fuel and 98 kg of fuel of unknown enrichment. The rest of the SPR fuel is either natural or depleted uranium metal with a ^{235}U weight fraction of up to 0.72%.

SPR fuel has a machined uranium core with aluminum alloy cladding. Initial enrichment levels for unirradiated SPR fuel range from 0.114 wt% to 2.1 wt% ^{235}U. While the enrichment of the unidentified fuel is not expected to exceed 1.25 wt% ^{235}U, the analyses for this CSER assumed it was 2.1 wt% ^{235}U enriched. A sketch of typical SPR fuel elements appears in Figure 2-2. The SPR fuel diameter varies from 1.35 in. to 1.88 in., while fuel length varies from 5.55 in. to 8.98 in. Weight varies from 2.08 kg to 6.75 kg (4.58 to 14.9 lb) per fuel element.

The majority of the SPR fuel was depleted to 0.06 wt% ^{235}U with a high fraction of the plutonium in the fuel, 27 wt%, being ^{240}Pu. This highly depleted fuel has an individual assembly weight of 3.57 kg (7.87 lb), an outer diameter of 1.51 in., and a length of 8.65 in. Table 2-2 provides a detailed listing of the dimensions and weights of SPR fuel stored in the K Basins.

The majority of the SPR fuel is assumed to be in good condition with minimal cladding damage. However, some SPR fuel has been damaged by handling or by galvanic reactions between its cladding and incompatible metals.

2.2 MULTI-CANISTER OVERPACKS

The MCO is a single-use container that consists of a cylindrical shell, five to six baskets, a shield plug, and features necessary for maintaining the structural integrity of the MCO while providing criticality control and fuel drying capability. The safety basis of the MCO requires it to maintain the SNF in a critically safe configuration (Goldmann 1998).

Table 2-2. Maximum and Minimum Dimensions and Weights of Single Pass Reactor Fuel Assemblies in the K Basins.

	Maximum		Minimum	
Diameters:	(cm)	(in.)	(cm)	(in.)
Aluminum cladding, outer diameter	5.04	1.98	3.67	1.44
Uranium, outer diameter	4.78	1.88	3.44	1.35
Uranium, inner diameter	1.38	0.543	1.08	0.424
Aluminum cladding, inner diameter	1.10	0.433	0.787	0.310
Enrichments:	(wt%)		(wt%)	
^{235}U	2.1		0.114	
Fuel assembly dimensions:	(cm)	(in.)	(cm)	(in.)
Length	22.8	8.98	14.1	5.55
End cap thickness	0.635	.250	0.635	.250
Fuel assembly weight:	(kg)	(lb)	(kg)	(lb)
Uranium core	6.75	14.9	2.08	4.58

The MCO shell is a stainless steel cylindrical vessel that is closed with a stainless steel shield plug. The shell is fabricated from 24-in. diameter, schedule 80S pipe with a nominal wall thickness of 0.5 in.; it has an overall length of 166 in. with the cover cap installed. The maximum diameter of the MCO's internal cavity is 23.25 in. (Goldmann 1998), and it is approximately 145 in. long. The MCO has a bottom end plate that has a constant thickness of 2.0 in. except in the center region, where it is 1.13 in. thick. A stainless steel closure shield plug assembly is used to seal the MCO after loading. This assembly contains internal high-efficiency particulate air (HEPA) filters to prevent contamination of the process ports. Ports for MCO processing are provided in the top part of the shield plug assembly. The filter guard plate on the bottom of the assembly protects the HEPA filters. The vessel holds baskets, which contain fuel or scrap, and incidental equipment. Incidental equipment includes a support tube nesting feature on the filter guard plate and bottom plate, two process tubes connected to shield plug process ports, and sealing features.

All MCO baskets are stainless steel, annular, open-top containers with a maximum outer dimension of 22.6 in. Each fuel basket has six rods that support the fuel basket above. At the minimum, approximately 0.3 in. of clearance exists between the top of the fuel assemblies and the lower surface of the basket above. All baskets incorporate a center support tube for axial support during lifting.

The fuel baskets are designed to support fuel assemblies vertically in individual sockets bored into the 2.5-in.-thick fuel rack that is installed above the basket baseplate. An outer skirt provides additional lateral support and confinement for smaller sections of fuel assemblies. Only those portions of a combined fuel assembly (i.e., an outer and an inner element) that will fit in the basket's fuel rack are loaded into a fuel basket. Solo outer or inner elements may be combined to make up a complete fuel assembly or placed in the basket as single elements. Those portions of the fuel assemblies that are greater than 0.25 in. in diameter but less than approximately 3 in. in length, or are too broken up to stand upright in the fuel basket, or will not fit in the fuel rack because of swelling caused by damage or corrosion also are placed in a scrap basket.

Each scrap basket has a fines compartment around the center pipe (center post for the Mark IA baskets) into which the smaller particles of scrap are placed. The size of the fines compartment is intentionally set to limit the amount of fine particles allowed within any one scrap basket. A fine particle is defined as any piece of fuel scrap larger than 0.25 in. in diameter but smaller than approximately 1 in. in diameter. Particles smaller than 0.25 in. in diameter are handled by the water treatment system installed in the K Basins.

Because of their higher initial enrichment, Mark IA fuel assemblies and scrap are normally segregated from Mark IV assemblies and scrap. The Mark IA fuel is limited to 48 fuel assemblies per basket. A 6.6-in.-outer-diameter center post with a 1.75-in-diameter bore is inserted in the center of both the fuel and scrap baskets to physically exclude fuel and scrap from the center region of the baskets. The insert is designed to allow less than a 2-in. offset from center in the MCO in the event of a worst-case drop accident (Goldmann 1998). Six Mark IA baskets will fit inside an MCO.

Mark IV fuel assemblies have a lower initial enrichment than Mark IA fuel assemblies, allowing 54 Mark IV fuel assemblies to be loaded per fuel basket. Both the Mark IV fuel and scrap baskets contain a small center pipe to allow the insertion of the long process tube for draining but do not need a center post for criticality control. Because Mark IV fuel assemblies are longer than the Mark IA assemblies, five Mark IV baskets will fill an MCO.

The fuel is unloaded from the canisters and loaded into the baskets remotely underwater in the basin pools. The baskets are queued and then loaded into the MCO, which is also underwater in the load-out pit. The analyses performed in this CSER allow the loading of a maximum of two scrap baskets in an MCO, one on the bottom and one on the top. Loading an MCO with a single scrap basket or only fuel baskets also is allowed.

The MCO is housed in a shipping cask and surrounded by an immersion pail that provides a clean water housing during loading. Once the MCO is loaded, the shield plug is installed, the cask and MCO are lifted out of the pool, and the shield plug is secured with the locking ring. The lid is placed on the cask, the cask–MCO is loaded on a transporter, and the unit is moved to the CVDF.

The CVDF has four processing bays that can each house a loaded transporter and a fifth spare bay that could be modified for use if required. A typical processing bay layout is shown in Figure 2-3. After the transporter has been placed in a bay, the cask lid is removed, a process

hood installed, and process lines connected to the shield plug assembly. The water inside the MCO is pumped to a receiver tank in the process water conditioning system, and the interior of the MCO is dried. Temperatures inside the MCO are controlled by circulating water in the annulus between the MCO and the shipping cask. When the MCO has been determined to be sufficiently dry, the cask annulus water is drained and the MCO and cask are prepared for shipping to the CSB.

The CSB has three storage vaults. Vault 1, which will contain the MCOs, has 220 storage tubes arranged in a 10 by 22 array. The vaults are surrounded by vertical concrete walls that neutronically isolate the fissionable material in each vault from adjacent vaults. When the transporter arrives at the CSB, the MCO is removed from the shipping cask, placed in a storage tube, or sealed with a welded cover cap and then placed in a storage tube. Two MCOs are placed in each storage tube in a vertical column. Impact absorbers are placed at the bottom of each tube and between the MCOs to limit the impact forces on an MCO should the MCO drop into the storage tube.

Figure 2-1. N Reactor Mark IV Fuel Assembly.

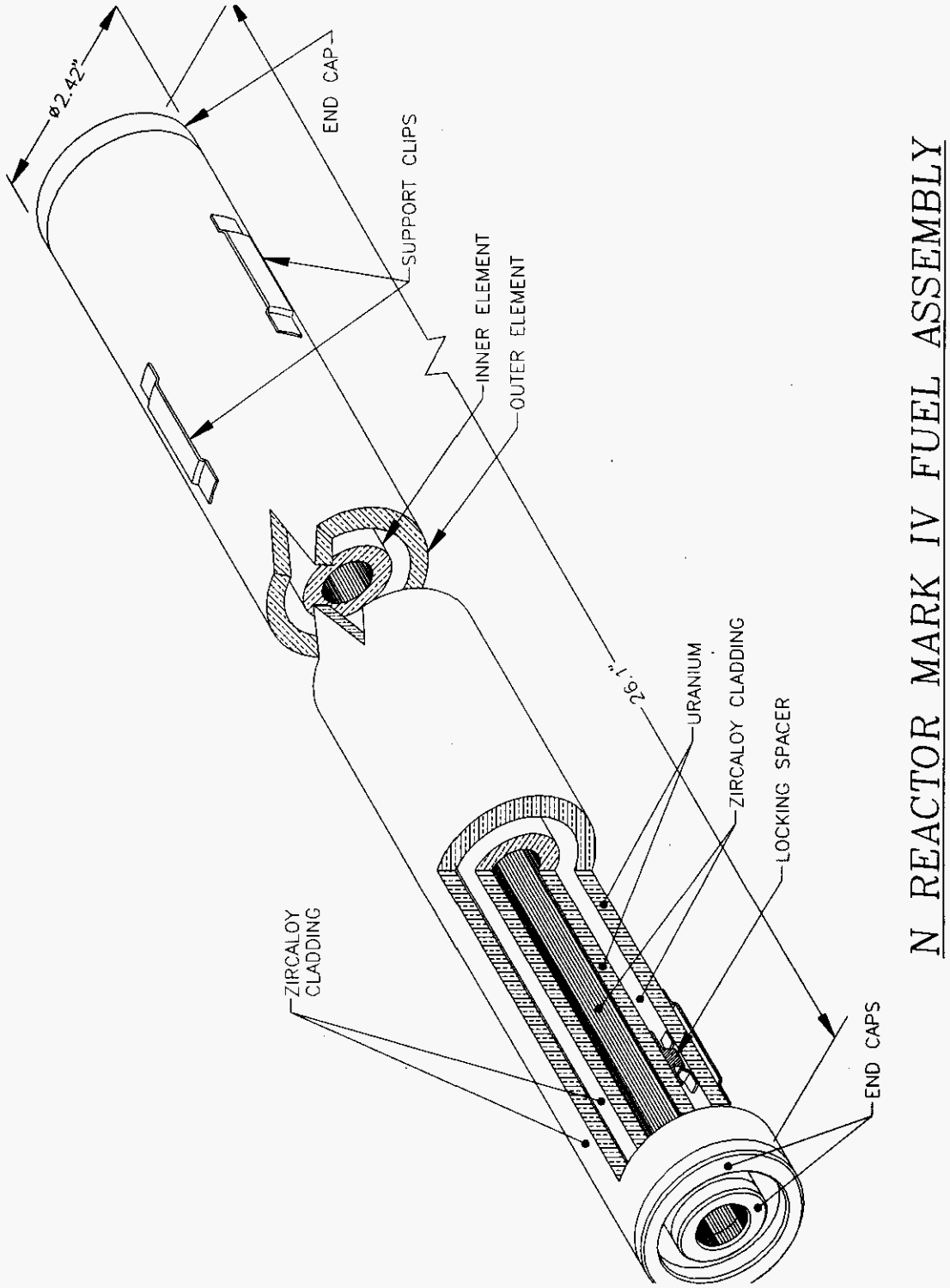


Figure 2-2. Single Pass Reactor Fuel.

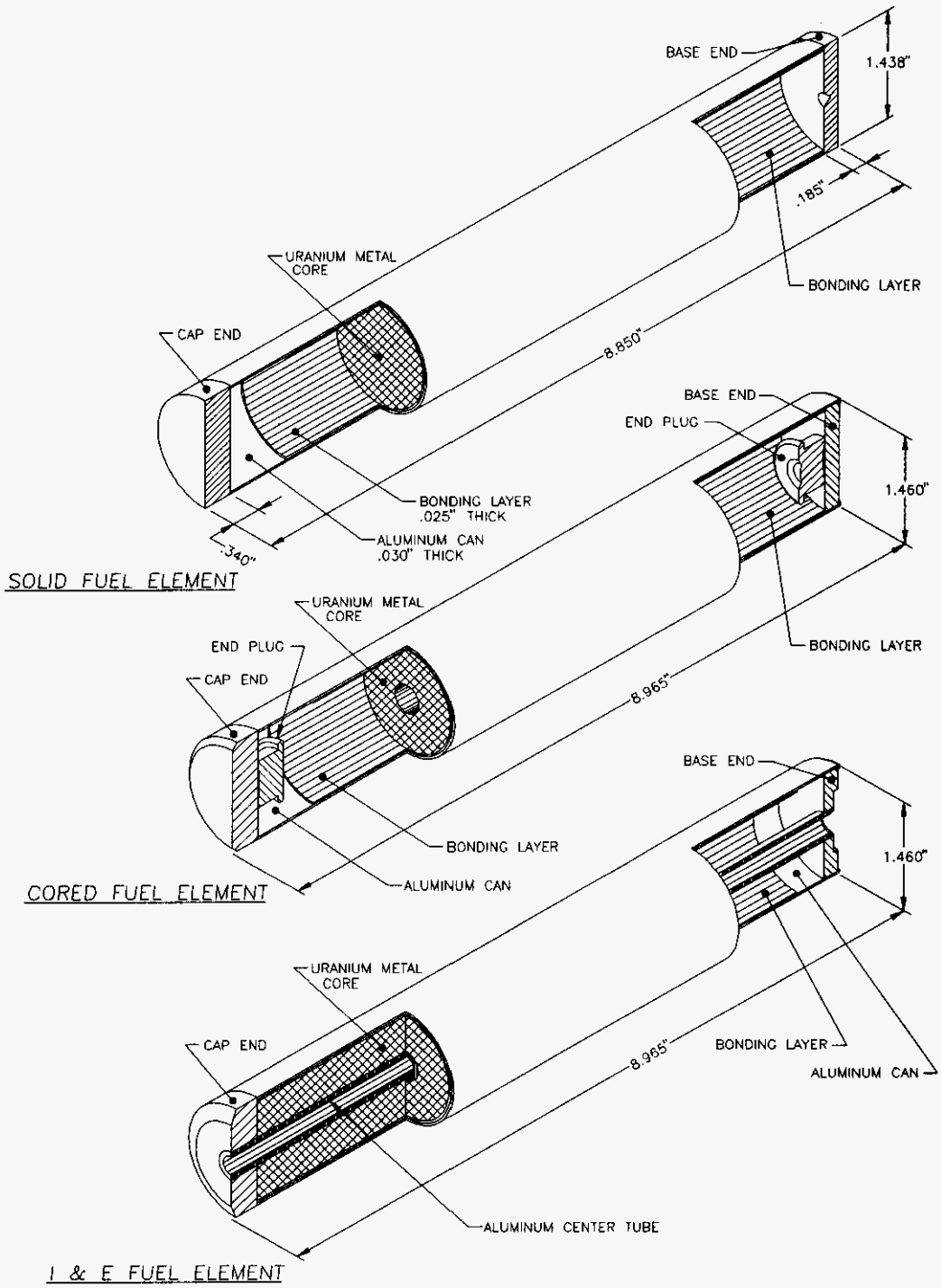
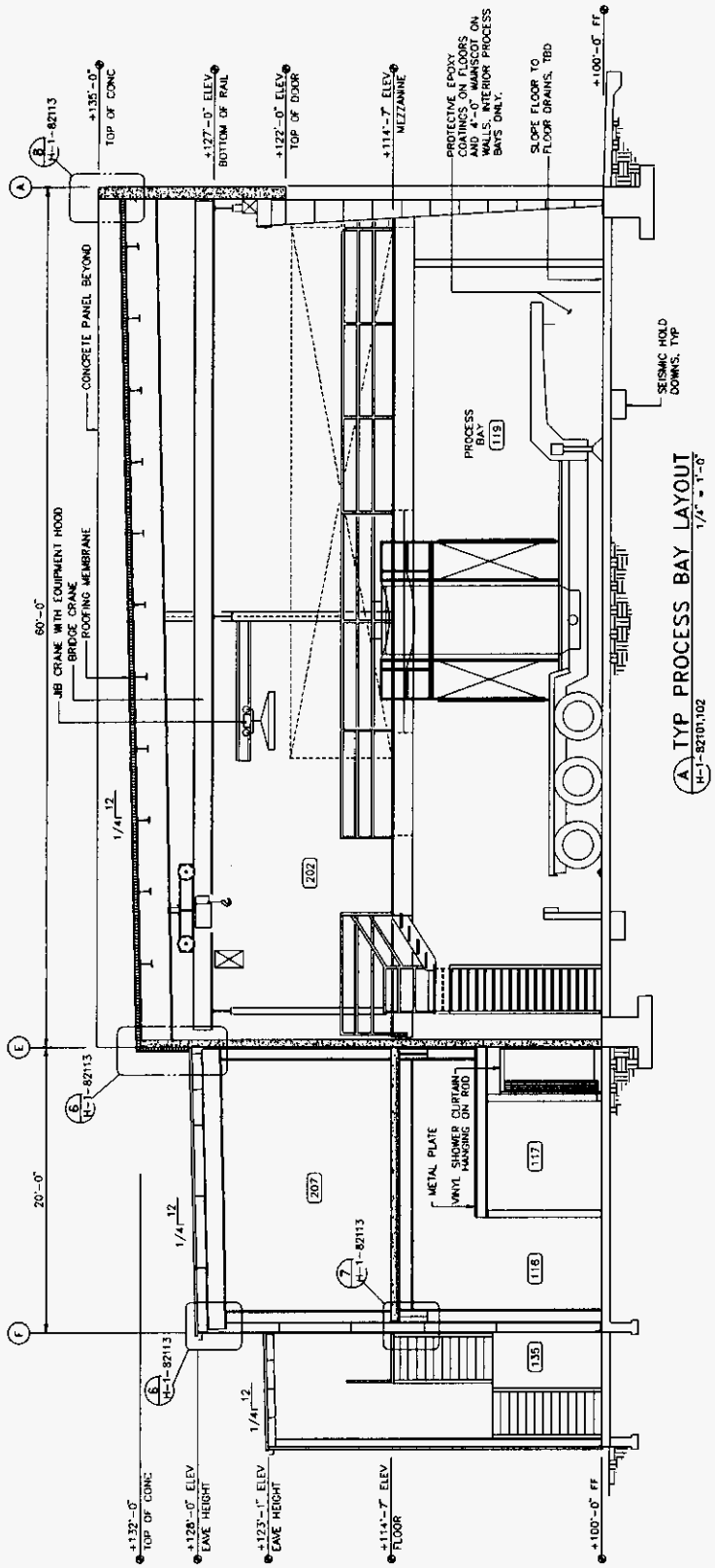


Figure 2-3. Cold Vacuum Drying Facility.



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3.0 REQUIREMENTS AND EXEMPTIONS

This analysis must meet the requirements of HNF-PRO-539, *Criticality Safety Evaluations*. No exemptions from these requirements apply to this evaluation.

3.1 CRITICALITY SAFETY CRITERION FOR CALCULATION OF MULTI-CANISTER OVERPACK LOADINGS

The criticality safety criterion for MCO loading, transport from the K Basins to the CVDF, operations in the CVDF, transport from the CVDF to the CSB, and operations in the CSB requires that k_{eff} be less than 0.95 (Garvin 1997), which meets the requirements of HNF-PRO-537, *Criticality Safety Control of Fissionable Material*, including the double contingency principle. The double contingency principle requires that process designs incorporate sufficient factors of safety that at least two unlikely, independent, and concurrent changes in process conditions occur before a criticality accident is possible. The analysis in this CSER must demonstrate compliance with the double contingency principle by showing that allowed fuel and scrap configurations will not exceed a k_{eff} of 0.95 for violation of any single contingency. Contingencies include MCO drops, misloadings, and flooding while in storage.

3.2 CRITERIA FOR ACCEPTABLE CRITICALITY DETERMINATIONS

The criticality safety criterion, used to judge the acceptability of a calculated neutron multiplication factor (k_{eff}) for fissile configuration, must account for the bias inherent in the code and cross sections used, any uncertainties in the physical problem being analyzed, and the uncertainties in both the bias determination (the experimental basis) and the calculational methods. This may be stated as follows:

$$k_{eff} = k_{calc} - \Delta k_{bias} + (\sigma_b^2 + \sigma_c^2 + \sigma_d^2 + \sigma_e^2 + \sigma_T^2)^{1/2} < k_{limit}$$

where

k_{limit} = criticality prevention criterion (0.95)
k_{calc} = calculated result
Δk_{bias} = methods bias
σ_b = bias uncertainty
σ_c = calculational uncertainty
σ_d = uncertainty in dimensional tolerances
σ_e = uncertainty in enrichment tolerances
σ_T = uncertainty in temperature change.

The calculated k_{eff} must be at the 95% confidence level. Thus, inserting the values into the formula and applying the one-tailed test to the standard deviation gives

$$k_{eff} = k_{calc} - \Delta k_{bias} + [(2\sigma_b)^2 + 1.645^2 (\sigma_c^2 + \sigma_d^2 + \sigma_e^2 + \sigma_T^2)]^{1/2} < 0.95$$

where

Δk_{bias} = -0.0004 (Schmittroth 1996)
σ_b = 0.005 (Schmittroth 1996)
σ_c = calculational standard deviation (varies with each calculation)
σ_d = 0.000546 (Appendix B)
σ_e = 0.001840 (Appendix B)
σ_T = 0.000810 (Appendix B).

The equation above then simplifies to

$$k_{eff} = k_{calc} + 0.0004 + [\,0.01^2 + 1.645^2(\sigma_c^2 + 0.002083^2)]^{1/2} < 0.95\ .$$

No uncertainty is calculated for variations in the position of the scrap basket in the MCO. This is because the scrap basket is modeled such that the scrap is as close as possible to the bottom of the fuel basket, and the scrap basket sides are expanded as widely as possible to conserve mass. The dimensions used exceed the manufacturing tolerances for the basket. The effect on k_{eff} of the height of the scrap in the basket is shown by cases mk4r.0 and mk4r0.1 in Table 4-2. In the case mk4r.0, the scrap is modeled up to the bottom of the fuel basket above it, while in case mk4r0.1, the basket sides are removed, and the scrap is modeled to the inner side of the MCO with a small gap above the top of the scrap. The highest k_{eff} is calculated for the first case and no specific uncertainty for the scrap basket is required.

4.0 METHOD OF ANALYSIS AND RESULTS

4.1 SUMMARY AND CONCLUSIONS

This section of the analysis describes the normal conditions of the MCO in the K Basins, the CVDF, and the CSB. Analysis has shown that the k_{eff} of the contents of the loaded shipping cask under normal conditions will be below 0.95 by a substantial degree. Loaded shipping casks containing MCOs flooded with water and loaded with intact N Reactor fuel assemblies will have values for k_{eff} less than 0.93. Loaded shipping casks containing dry MCOs loaded with intact N Reactor fuel assemblies will have values for k_{eff} less than 0.33. MCOs in arrays of 10 by 22 by 2 in the CSB tubes, when dry, have values for k_{eff} of less than 0.36 for any density water between the tubes.

An MCO containing dry fuel or scrap material cannot be made critical under any conditions. Criticality is a concern in situations in which there is water moderation internal to the MCO. MCOs containing Mark IV or Mark IA fuel have values of $k_{eff} < 0.85$ for flooded intact fuel loadings under normal conditions. Loading scrap into the top and bottom baskets with intact fuel in the other baskets results in a k_{eff} less than 0.91 for a flooded Mark IA MCO and less than 0.93 for a flooded Mark IV MCO.

Placing Mark IV fuel assemblies, components, or scrap together in baskets designed for Mark IA fuel (which contain the center post for geometry control) is allowed because of the lower unit reactivity of Mark IV fuel. However, with the exceptions described in HNF-SD-SNF-CSER-010 (Kessler and Peck 1999), no assemblies, components, or scrap with uranium enrichment greater than 0.95 wt% ^{235}U may be loaded into fuel baskets that do not contain the center post without additional analysis. Separate criticality analyses have been performed to allow the loading of the 12 long Mark IA assemblies from the K West Basin into a Mark IV basket containing Mark IV fuel. A small amount of Mark IA fuel and scrap also is stored in the K East Basin. The fuel assemblies are stored in single fuel element containers and the scrap is stored in remnant return canisters, which are limited to one per barrel of a canister. Each single fuel element container or remnant return canister may contain no more than 52.5 kg of material (Kessler and Peck 1999) for a total of 105 kg per canister. This fuel and scrap also may be loaded into a Mark IV basket in accordance with the limits in HNF-SD-SNF-CSER-010 (Kessler and Peck 1999) and into an MCO.

The inside diameter of the MCO limits the maximum diameter of the fuel to 23.25 in. None of the components of the Mark IV baskets are required to control the geometry of the Mark IV fuel for criticality safety. Both the base plate and center post of the Mark IA basket are required to maintain the favorable geometry of the Mark IA fuel by preventing fuel from accumulating in the center of the basket.

An MCO may be loaded in one of three ways: all fuel baskets, one scrap basket and the rest fuel baskets, or two scrap baskets and the rest fuel baskets. There are no minimum loading requirements for either the fuel or scrap baskets. Analysis has shown that the most reactive state

for the Mark IA MCOs is with two scrap baskets and partially loaded fuel baskets containing 47 fuel assemblies with one empty location in a middle row location. The most reactive configuration for the Mark IV MCO is with two scrap baskets and fuel baskets that each contain 53 assemblies with one inner element only loaded in an outer row location. Section 4.5.1 describes this analysis in detail and these are the configurations designated as the base cases unless otherwise stated in the analysis.

The model for the MCO at the CVDF is flooded, loaded with partially loaded fuel baskets as described above, and two scrap baskets — one at the top and one at the bottom — and in a cask with a flooded annulus. Since the MCO is always in a cask at the CVDF and each cask is in a separate processing bay, each MCO is isolated neutronically from other MCOs and is analyzed alone.

The normal condition in the CSB is for the vault to have a 10 by 22 by 2 array of normally loaded MCOs containing less than 0.0051 g/cm^3 of water (3 kg). With a conservative water density between the tubes of 0.0012 g/cm^3, the upper limit of the neutron multiplication factor is approximately 0.36, although with optimal interspersed water moderation between storage tubes, this value may increase to 0.42, as shown in Chapter 5.0. This is less than half the allowable limit of 0.95.

The effects of fuel length, cask–MCO gap, and the migration of uranium corrosion products from the upper fuel elements to the lower baskets have been addressed in a sensitivity analysis (see Appendix B). The results show only insignificant changes in reactivity.

4.1.1 Conservatisms in the Analysis

Many conservatisms have been built into this analysis.

- The safety limit is 0.95. The margin of safety provided by using the 0.95 limit for the low-enriched uranium metal fuel in the K Basins is far greater than the margin of safety provided by using the same limit for the greater enrichment of commercial fuels on which the limit is based.

- It is assumed that the baskets completely fail in an accident.

- The reduction of reactivity resulting from fuel burnup, fission products in the spent fuel, and other nonfissionable material introduced as contaminants in the K Basin sludge and fuel debris, is not included in the analyses (although burnup effects are discussed in Appendix D).

- The scrap is completely optimized (i.e., optimum particle size and optimum water-to-fuel ratio).

- The fuel rubbilizes to optimized scrap in a drop accident.
- The most reactive loading configuration of the MCO fuel baskets is used.

4.1.2 Analysis Assumptions

The analyses performed to evaluate the acceptability of the normal and accident conditions for the MCO were based on the assumptions defined below.

Assumption 1 The MCO is either always in a cask, loaded into the MHM, in the CSB storage tubes, or in the CSB sampling/weld station when flooded with water. Note that flooded MCOs in the MHM, CSB storage tubes, or CSB sampling/weld station were analyzed as a contingency.

Assumption 2 Mark IA fuel or scrap is normally loaded into Mark IA fuel or scrap baskets, which have the center post that serves as a criticality feature to exclude fissile material from the center of the basket. The only exceptions to this are for the 26.1-in.-long Mark IA fuel assemblies and the Mark IA material stored in the K East Basin, which will be loaded into Mark IV baskets.

Assumption 3 The credible misloading scenario for Mark IA fuel being inadvertently loaded into a Mark IV basket is 14 Mark IA fuel assemblies. For scrap this is equivalent to 155 kg, the mass of 14 Mark IA outer elements, with an enrichment of 1.25 wt% ^{235}U.

Assumption 4 Following the drop of a Mark IV MCO, the basket base plates remain intact. These plates are not safety class; however their mass is conserved in the models.

Assumption 5 The misload model for Mark IV scrap baskets includes the center pipe.

4.2 COMPUTER CODES

The analysis tools used in the preparation of this document are the WIMS-E[1] code (Gubbins et al. 1982) and the GOLF code (Schwinkendorf 1994), which have been used for parametric studies and the calculation of ideal geometry critical dimensions, and the MCNP code (Breismeister 1993, Carter 1996), which has been used for modeling of three-dimensional geometries in detail. The WIMS-E lattice transport code was used to generate infinite neutron

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[1]WIMS is the trademark of Answers, the marketing organization of the United Kingdom Atomic Energy Authority, Winfrith, England.

multiplication factors, k_∞, for lattices and two-group cross sections for use by GOLF, which was used to calculate finite radial dimensions for both cylinders and hemispheres. The MCNP code has been used for all criticality calculations to verify compliance with the 0.95 limit for k_{eff}. Appendix A presents the validation of the criticality computer codes used to demonstrate the acceptability of the MCO k_{eff}. The most recent calculations for this CSER were performed using version 4B to the MCNP code. This version has been verified and validated for use on all computing platforms on the Hanford Site (Hillesland and Schwinkendorf 1998, Schwinkendorf 1998, Erickson 1998).

4.3 SPENT NUCLEAR FUEL FISSILE CHARACTERISTICS

4.3.1 Spent Nuclear Fuel Description

For this CSER, the nominal baseline configuration for the MCO is five baskets of Mark IV fuel assemblies, 270 total assemblies, or six baskets of Mark IA fuel assemblies, 288 total assemblies. The fuel baskets are not required to be fully loaded, and the most reactive configurations are for partially loaded baskets, as described in Section 4.5.1. Two scrap baskets may be loaded into the MCO, one at the top and one at the bottom, replacing baskets loaded with intact fuel.

Scrap baskets may be loaded with fuel scrap or segments of fuel assembly components, with or without cladding. Such scrap material comprises a small fraction of the material stored in the K Basins, and additional scrap may be generated as part of the fuel retrieval process. The weight limits for scrap in the baskets are 980 kg (2,156 lb) of Mark IV scrap and 575 kg (1,265 lb) of Mark IA scrap (Kessler and Peck 1999). These scrap limits are based on spills of the baskets in the K Basins where there is sludge containing fissile material on the floor. For Mark IV scrap at optimum spacing, a full basket would contain less than 980 kg because of the center pipe in the basket used to house the long axial process tube and the basket sides. A basket containing 575 kg of Mark IA scrap at optimum spacing will not be full.

SPR fuel elements will be loaded into modified Mark IA baskets and into MCOs containing no N Reactor fuel (Kessler and Peck 1999).

4.3.2 Spent Nuclear Fuel Reactivity Properties

The spent N Reactor fuel has a burnup range based on ^{240}Pu content — the higher the burnup, the higher the total plutonium content, the higher the percentage of ^{240}Pu in total plutonium, and the higher the fission product concentration. The presence of plutonium isotopes, specifically ^{239}Pu and ^{241}Pu, in the spent fuel tends to compensate for the reactivity loss due to ^{235}U depletion but not enough to increase reactivity beyond that of unirradiated fuel. All values for k_{eff} are conservatively calculated using unirradiated fuel and scrap containing no fission products.

The 8 in. of stainless steel in the cask surrounding the payload provides appreciable neutron reflection, which increases k_{eff} more than would a pure water reflector. When the contents are dry, there is no neutron moderation. Low-enriched uranium metal cannot be made critical without moderation; therefore, the fully loaded MCO cannot go critical when dry, no matter what reflector is present.

Intact Mark IV and Mark IA fuel assemblies do not provide optimal geometry for maximum reactivity in a water-moderated lattice (Schwinkendorf 1995). Scrap pieces of the assembly's component metal could be reconfigured into more reactive clusters, depending on the assumed piece size and average spacing (or packing fraction). The WIMS-E computer code (Gubbins et al. 1982) was used to evaluate k_∞ for various scrap fuel configurations representative of loading scrap in baskets in an MCO to determine the optimal configuration of scrap material — that which produces the highest reactivity per unit mass. These calculations have not been used to establish whether the MCO satisfies the $k_{eff} < 0.95$ criticality safety limit under either normal or accident conditions, but rather to determine the optimal scrap configuration and to guide the modeling of the MCNP calculations. The scrap was represented in the WIMS-E model as unirradiated uranium rods at various diameters and at various lattice pitches (for varying the water-to-fuel volume ratios). Optimization parameters for the scrap material were calculated in HNF-SD-SNF-CSER-010 (Kessler and Peck 1999). These parameters were used in the analysis for this document. The optimization parameters for scrap also were used to model the rubblized fuel.

4.4 MODELING OF THE MULTI-CANISTER OVERPACK, CASK, AND BASKETS

The Monte Carlo code MCNP (Breismeister 1993) was used to evaluate the three-dimensional criticality model of the shipping casks to verify that k_{eff} was less than 0.95. MCOs were modeled as 0.5-in.-thick stainless steel cylinders with an internal diameter of 23.25 in. and a 2-in.-thick base. The shield plug was modeled as a 9-in.-thick plate approximately 10 in. above the top basket. Approximately 1.5 in. above the top basket is a 1.5-in.-thick plate used to protect the internal filters that are contained in the shield plug assembly. The filters were modeled as water for this analysis. Surrounding the MCO is the shipping cask. Figure 4-1 illustrates the loading arrangement for Mark IV baskets in the MCO. The Mark IV fuel assemblies were produced in different lengths, the longest being 26.1 in. For the calculational model, the length of the fuel assemblies was 26.1 in. Whole assemblies were modeled with the inner and outer metal annuli intact and with all the zirconium cladding in place.

Mark IA fuel assemblies were also produced in different lengths, the longest being 26.1 in. Only 12 of the 26.1 in.-long assemblies are stored in the K Basins, so the length of the majority of the assemblies, 20.9 in., was used for the calculational model. Because of their shorter length, MCOs holding Mark IA fuel are loaded with six baskets. These baskets are fitted with a center post to prevent loading more than 48 fuel assemblies per basket.

Both Mark IA and Mark IV scrap were modeled as optimally moderated and sized rods with cladding. Appendix C justifies the used of rods of scrap instead of spheres.

For baskets loaded with Mark IA material, the center post excludes material from the central region during normal and other credible abnormal conditions. Figure 4-2 shows the arrangement for loading Mark IA baskets. Because of their higher enrichment, Mark IA assemblies are not normally loaded into Mark IV baskets. However, loading Mark IV assemblies that are short enough to fit into Mark IA baskets would be acceptable because they would decrease k_{eff}. The 26.1-in.-long Mark IA assemblies in the K West Basin and the Mark IA material stored in the K East Basin may be loaded into Mark IV baskets according to the limits specified in HNF-SD-SNF-CSER-010 (Kessler and Peck 1999).

To improve the heat removal capabilities of the scrap baskets, the sides are made from copper, not stainless steel, and copper plates have been added to the interior of the basket. These plates section the basket into a small region (10% of the basket volume) around the center post and six large sections. No copper was used in the scrap basket models used in the analysis. Adding copper plates to the basket interior both breaks up the optimal geometry of the scrap model and replaces water with copper, which has a higher absorption cross section (3.8 barns versus 0.7 barns [Lamarsh 1992]). Both of these effects will lower the k_{eff}. For conservatism, the original scrap basket model with stainless steel sides and no divider plates was retained.

4.5 RESULTS OF CALCULATIONS FOR NORMAL CONDITIONS

4.5.1 Determination of the Most Reactive Loading Configuration for the Multi-Canister Overpacks

An MCO may be loaded in several different configurations. The maximum loading of the fuel baskets is fixed by design and the loading of the scrap baskets is limited by HNF-SD-SNF-CSER-010 (Kessler and Peck 1999). There are no minimum loading requirements for any baskets. If scrap baskets are to be loaded into an MCO, they are limited to the top and bottom tiers (Pajunen 1998). Thus, an MCO may contain all fuel baskets, one scrap basket in either the top or bottom tier with the fuel baskets in the remaining tiers, or two scrap baskets, one in the top and one in the bottom, and fuel baskets in the remaining tiers. For the Mark IV scrap baskets, two configurations were analyzed: one with no basket sides, which leaves no gap between the scrap and the inside diameter of the MCO and a small gap between the top of the scrap and the bottom of the fuel basket above it; and one with the diameter of the basket adjusted to leave no water gap between the top of the scrap and the bottom of the basket above. The analysis demonstrated that no uncertainty based on basket diameter is required. Tables 4-1 and 4-2 show the results for these loadings for Mark IA MCOs and Mark IV MCOs.

Table 4-1. Calculation Results for Normal Loading of Mark IA Multi-Canister Overpacks.

Case	MCO configuration	k_{calc}	σ_c	k_{eff}*
mk1r.0	Two scrap baskets and four fuel baskets	0.88648	0.00096	0.89757
mk1rf.0	Six fuel baskets	0.82607	0.00105	0.83718
mk1rf.1	Five fuel baskets and a scrap basket in the top tier	0.88558	0.00094	0.89666
mk1rf.2	Five fuel baskets and a scrap basket in the bottom tier	0.88488	0.00108	0.89600

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.

Table 4-2. Calculation Results for Normal Loading of Mark IV Multi-Canister Overpacks.

Case	MCO configuration	k_{calc}	σ_c	k_{eff}*
mk4r.0	Two scrap baskets and three fuel baskets	0.91303	0.00071	0.92407
mk4rf.0	Five fuel baskets	0.83681	0.00087	0.84788
mk4rf.1	Four fuel baskets and a scrap basket in the top tier	0.91146	0.00087	0.92253
mk4rf.2	Four fuel baskets and a scrap basket in the bottom tier	0.91163	0.00092	0.92271
mk4r0.1	No basket sides for the scrap baskets	0.88926	0.00073	0.90030

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.

These results show that an MCO containing two scrap baskets with the fuel baskets has the highest k_{eff}. Therefore, the base loading used to determine the most reactive possible loading for an MCO will include two scrap baskets, and the fuel baskets will be modeled as being partially loaded.

Figure 4-3 shows the MCNP grid used to model the Mark IA fuel baskets in the MCO. This grid is used to determine the location of vacancies and single elements using the row and column numbers. The numbers in the grid represent the fuel assemblies and the water in the basket. Figure 4-3 may also be used for Mark IV fuel baskets by replacing six of the inner water locations with fuel assemblies leaving only the center location as water. To determine the most reactive configuration for the MCO, a single assembly location in each fuel basket was left empty or loaded with either an inner or outer element. After the most reactive configuration for each variation was determined, multiple vacancies, single elements, and mixed vacancies combined with single element cases were analyzed to determine their effect on reactivity. Tables 4-3 through 4-10 show these results.

The results in Tables 4-3 through 4-10 show that the most reactive loading for a Mark IA MCO contains two scrap baskets with four partially loaded fuel baskets, each containing 47 fuel assemblies. Each fuel basket has an empty location in the middle row (location 4,5 in Figure 4-3). Similarly, the most reactive loading for a Mark IV MCO contains two scrap baskets with three partially loaded fuel baskets, each containing 53 fuel assemblies and a single inner fuel element in location 3,6. These loadings were used for all calculations in this document unless noted otherwise. Figures 4-4 and 4-5 show views of the most reactive fuel baskets.

4.5.2 Multi-Canister Overpacks Containing Single Pass Reactor Fuel

SPR fuel will be loaded into scrap baskets and into an MCO that is dedicated solely to SPR fuel. Because SPR fuel is stored in both basins, more than one MCO may be used. The geometry of the SPR fuel was modeled as aluminum-clad uranium cylinders based on representative fuel dimensions at optimum spacing and moderation. The depleted and 0.95 wt% ^{235}U enriched fuels were represented by 0.95 wt% ^{235}U enriched uranium. The 47 unidentified fuel elements are not expected to exceed an enrichment of 1.25 wt% ^{235}U. However, these fuel elements were modeled with uranium corresponding to 2.1 wt% ^{235}U, the highest enrichment used for special SPR fuel irradiations, for all criticality calculations. The mass of the unidentified fuel was modeled as a cylinder in the center of the tier 4 basket, the MCO loading that corresponds to the region of highest neutron importance.

The k_{eff} for spr.1, shown in Table 4-11, is less than 0.85. Comparison of the k_{eff} with that of the most reactive Mark IA MCO loading illustrates that the Mark IA MCO is more limiting than the SPR MCO. Hence, the SPR MCO is bounded by the analyses of the Mark IA MCO.

Table 4-3. Calculation Results for Partial Loadings of Empty Locations in the Mark IA Multi-Canister Overpack.

Case	Empty locations	k_{calc}	σ_c	k_{eff}*
mk1r.0	None	0.88648	0.00096	0.89757
mk1r.1	Row 5, column 5	0.88483	0.00096	0.89592
mk1r.2	Row 4, column 5	0.89017	0.00096	0.90126
mk1r.3	Row 3, column 5	0.88464	0.00098	0.89573
mk1r.4	Row 3, column 6	0.88851	0.00099	0.89961
mk1r.5	Row 4, column 6	0.88768	0.00111	0.89881
mk1r.6	Row 4, column 4	0.88643	0.00102	0.89753
mk1r.10	Row 4, column 5; row 5, column 9; row 7, column 3	0.88808	0.00102	0.89918
mk1r.11	Row 4, column 5; row 7, column 3	0.88635	0.00098	0.89744
mk1r.12	Row 4, column 5; row 5, column 9	0.88557	0.00099	0.89667
mk1r.13	Row 4, column 5; row 5, column 9; row 7, column 3; row 8, column 7	0.88690	0.00102	0.89800

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk1r

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					3	4					
4				6	2,10,11, 12,13	5					
5					1				10,12, 13		
6											
7			10,11, 13								
8							13				
9											
10											
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-4. Calculation Results for Partial Loadings of Locations Containing Single Outer Elements in a Mark IA Multi-Canister Overpack.

Case	Locations containing single outer elements	k_{calc}	σ_c	k_{eff}*
mk1r.0	None	0.88648	0.00096	0.89757
mk1ro.1	Row 5, column 5	0.88618	0.00104	0.89729
mk1ro.2	Row 4, column 5	0.88717	0.00103	0.89828
mk1ro.3	Row 3, column 5	0.88805	0.00109	0.89917
mk1ro.4	Row 3, column 6	0.88443	0.00148	0.89568
mk1ro.5	Row 4, column 6	0.88786	0.00098	0.89895
mk1ro.6	Row 4, column 4	0.88666	0.00106	0.89777
mk1ro.10	Row 3, column 5; row 5, column 3; row 9, column 7	0.88564	0.00099	0.89674
mk1ro.11	Row 3, column 5; row 9, column 7	0.88802	0.00096	0.89911
mk1ro.12	Row 3, column 5; row 5, column 3	0.88552	0.00106	0.89663

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{½}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk1ro

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					3,10, 11,12	4					
4				6	2	5					
5			10,12		1						
6											
7											
8											
9							10,11				
10											
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-5. Calculation Results for Partial Loadings of Locations Containing Single Inner Elements in a Mark IA Multi-Canister Overpack.

Case	Locations containing single inner elements	k_{calc}	σ_c	k_{eff}*
mk1r.0	None	0.88648	0.00096	0.89757
mk1ri.1	Row 5, column 5	0.88598	0.00100	0.89708
mk1ri.2	Row 4, column 5	0.88538	0.00109	0.89650
mk1ri.3	Row 3, column 5	0.88821	0.00095	0.89930
mk1ri.4	Row 3, column 6	0.88815	0.00104	0.89926
mk1ri.5	Row 4, column 6	0.88618	0.00092	0.89726
mk1ri.6	Row 4, column 4	0.88707	0.00093	0.89815
mk1ri.10	Row 3, column 6; row 6, column 3; row 9, column 6	0.88547	0.00106	0.89658
mk1ri.11	Row 3, column 6; row 9, column 6	0.88793	0.00107	0.89905
mk1ri.12	Row 3, column 6; row 6, column 3	0.88605	0.00106	0.89716

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk1ri

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					3	4,10, 11,12					
4				6	2	5					
5					1						
6			10,12								
7											
8											
9						10,11					
10											
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-6. Calculation Results for Partial Loadings of Empty Locations in a Mark IV Multi-Canister Overpack.

Case	Empty locations	k_{calc}	σ_c	k_{eff}^*
mk4r.0	None	0.91303	0.00071	0.92407
mk4r.1	Row 5, column 5	0.91323	0.00094	0.92431
mk4r.2	Row 4, column 5	0.91270	0.00094	0.92378
mk4r.3	Row 3, column 5	0.91438	0.00094	0.92546
mk4r.4	Row 3, column 6	0.91102	0.00090	0.92209
mk4r.5	Row 4, column 6	0.91182	0.00090	0.92289
mk4r.6	Row 4, column 4	0.91376	0.00098	0.92485
mk4r.7	Row 5, column 6	0.91061	0.00098	0.92170
mk4r.8	Row 3, column 5; row 5, column 3	0.91254	0.00088	0.92361
mk4r.9	Row 3, column 5; row 9, column 7	0.91461	0.00088	0.92568
mk4r.10	Row 3, column 5; row 5, column 3; row 9, column 7	0.91408	0.00085	0.92514
mk4r.11	Row 3, column 5; row 5, column 3; row 7, column 9; row 9, column 7	0.91377	0.00085	0.92483

$^*k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk4r

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					3,8,9, 10,11	4					
4				6	2	5					
5			8,10, 11		1	7					
6											
7									11		
8											
9							9,10, 11				
10											
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-7. Calculation Results for Partial Loadings of Locations Containing Single Outer Elements in a Mark IV Multi-Canister Overpack.

Case	Empty locations	k_{calc}	σ_c	k_{eff}^*
mk4r.0	None	0.91303	0.00071	0.92407
mk4ro.1	Row 5, column 5	0.91234	0.00098	0.92343
mk4ro.2	Row 4, column 5	0.91444	0.00089	0.92551
mk4ro.3	Row 3, column 5	0.91359	0.00092	0.92467
mk4ro.4	Row 3, column 6	0.91335	0.00091	0.92443
mk4ro.5	Row 4, column 6	0.91133	0.00087	0.92240
mk4ro.6	Row 4, column 4	0.91289	0.00097	0.92398
mk4ro.7	Row 5, column 6	0.91226	0.00089	0.92333
mk4ro.10	Row 4, column 5; row 5, column 9; row 7, column 3	0.91403	0.00085	0.92509
mk4ro.11	Row 4, column 5; row 7, column 3	0.91382	0.00087	0.92489
mk4ro.12	Row 4, column 5; row 5, column 9	0.91162	0.00076	0.92266
mk4ro.13	Row 4, column 5; row 5, column 9; row 7, column 3; row 8, column 7	0.91249	0.00080	0.92354

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk4ro

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					3	4					
4				6	2,10, 11,12, 13	5					
5					1	7			10,12, 13		
6											
7			10,11, 13								
8							13				
9											
10											
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-8. Calculation Results for Partial Loadings of Locations Containing Single Inner Elements in a Mark IV Multi-Canister Overpack.

Case	Empty locations	k_{calc}	σ_c	k_{eff}*
mk4r.0	None	0.91303	0.00071	0.92407
mk4ri.1	Row 5, column 5	0.91100	0.00086	0.92207
mk4ri.2	Row 4, column 5	0.91409	0.00082	0.92515
mk4ri.3	Row 3, column 5	0.91244	0.00089	0.92351
mk4ri.4	Row 3, column 6	0.91540	0.00084	0.92646
mk4ri.5	Row 4, column 6	0.91312	0.00090	0.92419
mk4ri.6	Row 4, column 4	0.91332	0.00086	0.92439
mk4ri.7	Row 5, column 6	0.91184	0.00090	0.92291
mk4ri.10	Row 3, column 6; row 6, column 3; row 9, column 6	0.91333	0.00086	0.92440
mk4ri.11	Row 3, column 6; row 9, column 6	0.91421	0.00090	0.92528
mk4ri.12	Row 3, column 6; row 6, column 3	0.91243	0.00081	0.92348

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk4ri

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					3	4,10, 11,12					
4				6	2	5					
5					1	7					
6			10,12								
7											
8											
9						10,11					
10											
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-9. Calculation Results for Partial Loadings of Locations Containing Combinations of Single Inner Elements, Single Outer Elements, and Empty Locations in a Mark IA Multi-Canister Overpack.

Case	Configuration analyzed	k_{calc}	σ_c	k_{eff}*
mk1r.0	None	0.88648	0.00096	0.89757
mk1rm.1	Row 3, column 5 inner element; row 4, column 5 empty	0.88725	0.00097	0.89834
mk1rm.2	Row 3, column 5 inner element; row 7, column 8 empty	0.88502	0.00097	0.89611
mk1rm.3	Row 3, column 5 outer element; row 4, column 5 empty	0.88723	0.00095	0.89832
mk1rm.4	Row 3, column 5 outer element; row 7, column 8 empty	0.88592	0.00084	0.89698
mk1rm.5	Row 3, column 5 outer element; row 7, column 8 empty; row 10, column 3 inner element	0.88598	0.00096	0.89707

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk1rm

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					1,2,3, 4,5						
4					1,3						
5											
6											
7								2,4,5			
8											
9											
10			5								
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-10. Calculation Results for Partial Loadings of Locations Containing Combinations of Single Inner Elements, Single Outer Elements, and Empty Locations in a Mark IV Multi-Canister Overpack.

Case	Configuration analyzed	k_{calc}	σ_c	k_{eff}*
mk4r.0	None	0.91303	0.00071	0.92407
mk4rm.1	Row 4, column 5 outer element; row 3, column 5 empty	0.91286	0.00089	0.92393
mk4rm.2	Row 4, column 5 outer element; row 9, column 7 empty	0.91120	0.00091	0.92228
mk4rm.3	Row 3, column 6 inner element; row 3, column 5 empty	0.91414	0.00096	0.92523
mk4rm.4	Row 3, column 6 inner element; row 9, column 7 empty	0.91196	0.00089	0.92303
mk4rm.5	Row 4, column 5 outer element; row 9, column 7 empty; row 3, column 6 inner element	0.91255	0.00098	0.92364
mk4rm.6	Row 4, column 5 outer element; row 9, column 7 empty; row 9, column 3 inner element	0.91364	0.00095	0.92473
mk4rm.7	Row 9, column 7 outer element; and row 6 column 9 outer element; row 3, column 5 empty; row 9, column 3 inner element	0.91325	0.00095	0.92434

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCNP calculation grid: mk4rm

	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3					1,3,7	3,4,5					
4					1,2,5, 6						
5											
6									7		
7											
8											
9			6,7				2,4,5, 6,7				
10											
11											

Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Table 4-11. Single Pass Reactor Fuel in Mark IA Scrap Baskets.

Case	Configuration analyzed	k_{calc}	σ_c	k_{eff}^*
spr.1	All baskets filled with 0.95 wt% ^{235}U scrap with a cylinder of 2.1 ^{235}U scrap in the tier 4 basket	0.83514	0.00296	0.84718
mk1r.2	Most reactive Mark IA configuration	0.89017	0.00096	0.90126

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

4.5.3 Criticality Calculations for the Cold Vacuum Drying Facility

The results of MCNP computer calculations in Tables 4-12 and 4-13 show the reactivities of loaded MCOs containing either Mark IA or Mark IV fuel and scrap under the operating conditions found in the CVDF. Each MCO is in a separate bay at the CVDF and is isolated from the other MCOs. The MCO and the cask annulus are assumed to be flooded, which is the normal condition for the cask–MCO when it is received at the CVDF.

Table 4-12. Mark IA Multi-Canister Overpack Reactivities During Draining.

Case	Configuration analyzed	k_{calc}	σ_c	k_{eff}^*
mk1r.2	Highest k_{eff} base case	0.89017	0.00096	0.90126
cvd1.0	Top scrap basket drained	0.88691	0.00099	0.89801
cvd1.1	Top scrap basket and tier 5 fuel basket drained	0.88788	0.00103	0.89899
cvd1.2	Top scrap basket and tier 4 and 5 fuel baskets drained	0.88832	0.00095	0.89941
cvd1.3	Top scrap basket and tier 3, 4 and 5 fuel baskets drained	0.88618	0.00101	0.89728
cvd1.4	Top scrap basket and all fuel baskets drained	0.88774	0.00107	0.89886
cvd1.9	Bottom scrap basket half full	0.80847	0.00099	0.81957
cvd1.6	Drained MCO with a flooded annulus	0.34606	0.00061	0.35708
cvd1.8	Drained MCO with a drained annulus	0.27991	0.00047	0.29091

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.

Table 4-13. Mark IV Multi-Canister Overpack Reactivities During Draining.

Case	Configuration analyzed	k_{calc}	σ_c	k_{eff}^*
mk4ri.4	Highest k_{eff} base case	0.91540	0.00084	0.92646
cvd4.0	Top scrap basket drained	0.91231	0.00090	0.92338
cvd4.1	Top scrap basket and tier 4 fuel basket drained	0.91372	0.00087	0.92479
cvd4.2	Top scrap basket and tier 3 and 4 fuel baskets drained	0.91351	0.00091	0.92459
cvd4.3	Top scrap basket and all fuel baskets drained	0.91204	0.00083	0.92310
cvd4.9	Bottom scrap basket half full	0.85086	0.00086	0.86193
cvd4.6	Drained MCO with a flooded annulus	0.36980	0.00062	0.38082
cvd4.8	Drained MCO with a drained annulus	0.31643	0.00051	0.32743

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.

The highest reactivity for the Mark IA MCO occurs when it is flooded. Reactivity initially decreases, then increases slightly because of the reflection of neutrons by the drained fuel into the flooded fuel regions of the MCO. The maximum reactivity of approximately 0.9 is still well below the 0.95 limit (see Figure 4-6).

The results for the Mark IV MCO are similar to those for the Mark IA MCO with a maximum k_{eff} of 0.93.

4.5.4 Criticality Calculations for the Canister Storage Building

The CSB is divided into three vaults surrounded by 1-ft-thick vertical concrete walls that neutronically isolate the fissionable material in each vault from surrounding vaults. Reactivity of the CSB may be assessed by analyzing a single vault. Two MCOs are placed in each storage tube in a vertical column in a 10 x 22 storage array. Steel impact absorbers are installed in the bottom of each storage tube and between each MCO. The operations floor at the top of the tubes is modeled as 5-ft-thick concrete. Each tube is a penetration in the operating floor that extends down to the vault floor. The CSB storage tubes are modeled as a hexagonal grid of 54 in. by 56 in. lattice spacing, 54 in. center-to-center spacing in the 10-tube direction (north-south) and 56 in. center-to-center spacing in the 22-tube direction (east-west). The vault walls are closest along the 22-tube side, but over 10 ft distant on the 10-tube side. MCOs are removed from the

casks and moved to the CSB storage tubes using the MCO handling machine (MHM), which was modeled as a 10-in.-thick stainless steel tube. Figure 4-7 depicts the CSB layout plan modeled.

The MCNP results in Table 4-14 present the normal array reactivities and MHM reactivities for Mark IA and Mark IV MCOs at the CSB. These results are for normal dry cases of air in and between the storage tubes with water vapor at 0.0012 g/cm^3, and a conservative estimate of twice the expected residual water in the MCO after drying, 0.0051 g/cm^3 of water (3 kg of water per MCO). At that density, the intertube moderating effect of water vapor has fallen below the maximum, as discussed in Section 5.2.7.

Table 4-14. Multi-Canister Overpack Reactivities in the Canister Storage Building.

Case	Configuration analyzed	k_{calc}	σ_c	k_{eff}*
csb1.0	Mark IA MCOs in the CSB vault	0.32167	0.00029	0.33265
csb4.0	Mark IV MCOs in the CSB vault	0.34860	0.00034	0.35959
mhm1.0	Mark IA MCO in the MHM	0.28439	0.00047	0.29539
mhm1.2	Mark IA MCO lowered 2.5 ft through the floor	0.28706	0.00048	0.29806
mhm1.4	Mark IA MCO lowered 5 ft through the floor	0.31336	0.00057	0.32437
mhm4.0	Mark IV MCO in the MHM	0.31950	0.00052	0.33051
mhm4.2	Mark IV MCO lowered 2.5 ft through the floor	0.32153	0.00056	0.33254
mhm4.4	Mark IV MCO lowered 5 ft through the floor	0.34161	0.00061	0.35263

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.
MHM = multi-canister overpack handling machine.

While it is being removed from or inserted into a storage tube, the MCO is closely surrounded along part of its length by the floor slab. A single MCO has been modeled in the MHM with stainless steel directly around and above it and with the 5-ft-thick concrete floor below it. The most reactive condition occurs when the MCO has been lowered 5 ft and the lower scrap basket is level with the bottom of the floor. In all cases, the values for k_{eff} are less than 0.36. These results show that, under normal conditions, there is a significant reactivity margin for criticality safety when the MCO is being moved.

4.5.5 Loading of the Long-Length Mark IA Assemblies in Mark IV Fuel Baskets

The K West Basin contains 12 Mark IA assemblies and 2 inner elements that are 26.1 in. long that will be handled as Mark IV inner elements. The 12 intact assemblies and 2 inner elements will be loaded into Mark IV fuel baskets. This is not the same situation as misloading Mark IA fuel in a Mark IV fuel basket because misloaded fuel would be a maximum of 20.9 in. long (see Section 5.2.3). For this analysis, 18 26.1-in.-long Mark IA fuel assemblies were loaded either in the center middle or outer row of a Mark IV fuel basket. The results are contained in Tables 4-15, 4-16, and 4-17. These results show that the 12 long-length Mark IA assemblies may be loaded in any fuel basket, in any row.

Table 4-15. Calculation Results for Multi-Canister Overpacks Containing Long-Length Mark IA Fuel Assemblies in the Center of Mark IV Baskets.

Case	Location	k_{calc}	σ_c	k_{eff}[a]
18rc.0[b,d]	Cask–MCO in the K Basins	0.91355	0.00089	0.92462
18rc.1[b,d]	Cask–MCO at the CVDF	0.91312	0.00087	0.92419
18rc.3[c,d]	Cask–MCO in the K Basins	0.91600	0.00089	0.92707
18rc.4[c,d]	Cask–MCO at the CVDF	0.91519	0.00082	0.92625
18rc.6[c,e]	Cask–MCO in the K Basins	0.91412	0.00092	0.92520
18rc.7[c,e]	Cask–MCO at the CVDF	0.91526	0.00092	0.92634
18rc.9[b,e]	Cask–MCO in the K Basins	0.91331	0.00083	0.92437
18rc.16[b,e]	Cask–MCO at the CVDF	0.91313	0.00083	0.92419
18rc.10[b,f]	Cask–MCO in the K Basins	0.91341	0.00099	0.92451
18rc.14[b,f]	Cask–MCO at the CVDF	0.91429	0.00091	0.92537
18rc.11[c,f]	Cask–MCO in the K Basins	0.91536	0.00095	0.92645
18rc.12[c,f]	Cask–MCO at the CVDF	0.91498	0.00094	0.92606

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

[b]Fuel baskets contain an inner element location in position 4,5.

[c]Fuel baskets contain an inner element location in position 3,6.

[d]Mark IA assemblies in the middle fuel basket.

[e]Mark IA assemblies in the lower fuel basket next to the scrap basket.

[f]Mark IA assemblies in the upper fuel basket next to the scrap basket.

Table 4-16. Calculation Results for Multi-Canister Overpacks Containing Long-Length Mark IA Fuel Assemblies in the Middle Row of Mark IV Baskets.

Case	Location	k_{calc}	σ_c	k_{eff}[a]
18rm.0[b,d]	Cask–MCO in the K Basins	0.91407	0.00086	0.92514
18rm.1[b,d]	Cask–MCO at the CVDF	0.91464	0.00093	0.92572
18rm.3[c,d]	Cask–MCO in the K Basins	0.91271	0.00088	0.92378
18rm.4[c,d]	Cask–MCO at the CVDF	0.91189	0.00084	0.92295
18rm.6[c,e]	Cask–MCO in the K Basins	0.91513	0.00091	0.92621
18rm.7[c,e]	Cask–MCO at the CVDF	0.91408	0.00090	0.92515
18rm.9[b,e]	Cask–MCO in the K Basins	0.91271	0.00086	0.92378
18rm.16[b,e]	Cask–MCO at the CVDF	0.91394	0.00103	0.92505
18rm.10[b,f]	Cask–MCO in the K Basins	0.91323	0.00084	0.92429
18rm.14[b,f]	Cask–MCO at the CVDF	0.91208	0.00099	0.92318
18rm.11[c,f]	Cask–MCO in the K Basins	0.91239	0.00079	0.92344
18rm.12[c,f]	Cask–MCO at the CVDF	0.91224	0.00092	0.92332

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

[b]Fuel baskets contain an inner element location in position 4,5.

[c]Fuel baskets contain an inner element location in position 3,6.

[d]Mark IA assemblies in the middle fuel basket.

[e]Mark IA assemblies in the lower fuel basket next to the scrap basket.

[f]Mark IA assemblies in the upper fuel basket next to the scrap basket.

Table 4-17 Calculation Results for Multi-Canister Overpacks Containing Long-Length Mark IA Fuel Assemblies in the Outer Row of Mark IV Baskets.

Case	Location	k_{calc}	σ_c	k_{eff}[a]
18rp.0[b,d]	Cask–MCO in the K Basins	0.91335	0.00089	0.92442
18rp.1[b,d]	Cask–MCO at the CVDF	0.91545	0.00083	0.92651
18rp.3[c,d]	Cask–MCO in the K Basins	0.91462	0.00092	0.92570
18rp.4[c,d]	Cask–MCO at the CVDF	0.91516	0.00087	0.92623
18rp.6[c,e]	Cask–MCO in the K Basins	0.91409	0.00086	0.92516
18rp.7[c,e]	Cask–MCO at the CVDF	0.91410	0.00088	0.92517
18rp.9[b,e]	Cask–MCO in the K Basins	0.91464	0.00088	0.92571
18rp.16[b,e]	Cask–MCO at the CVDF	0.91122	0.00083	0.92228
18rp.10[b,f]	Cask–MCO in the K Basins	0.91409	0.00087	0.92516
18rp.14[b,f]	Cask–MCO at the CVDF	0.91401	0.00087	0.92508
18rp.11[c,f]	Cask–MCO in the K Basins	0.91396	0.00093	0.92504
18rp.12[c,f]	Cask–MCO at the CVDF	0.91464	0.00090	0.92571

[a]$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

[b]Fuel baskets contain an inner element location in position 4,5.

[c]Fuel baskets contain an inner element location in position 3,6.

[d]Mark IA assemblies in the middle fuel basket.

[e]Mark IA assemblies in the lower fuel basket next to the scrap basket.

[f]Mark IA assemblies in the upper fuel basket next to the scrap basket.

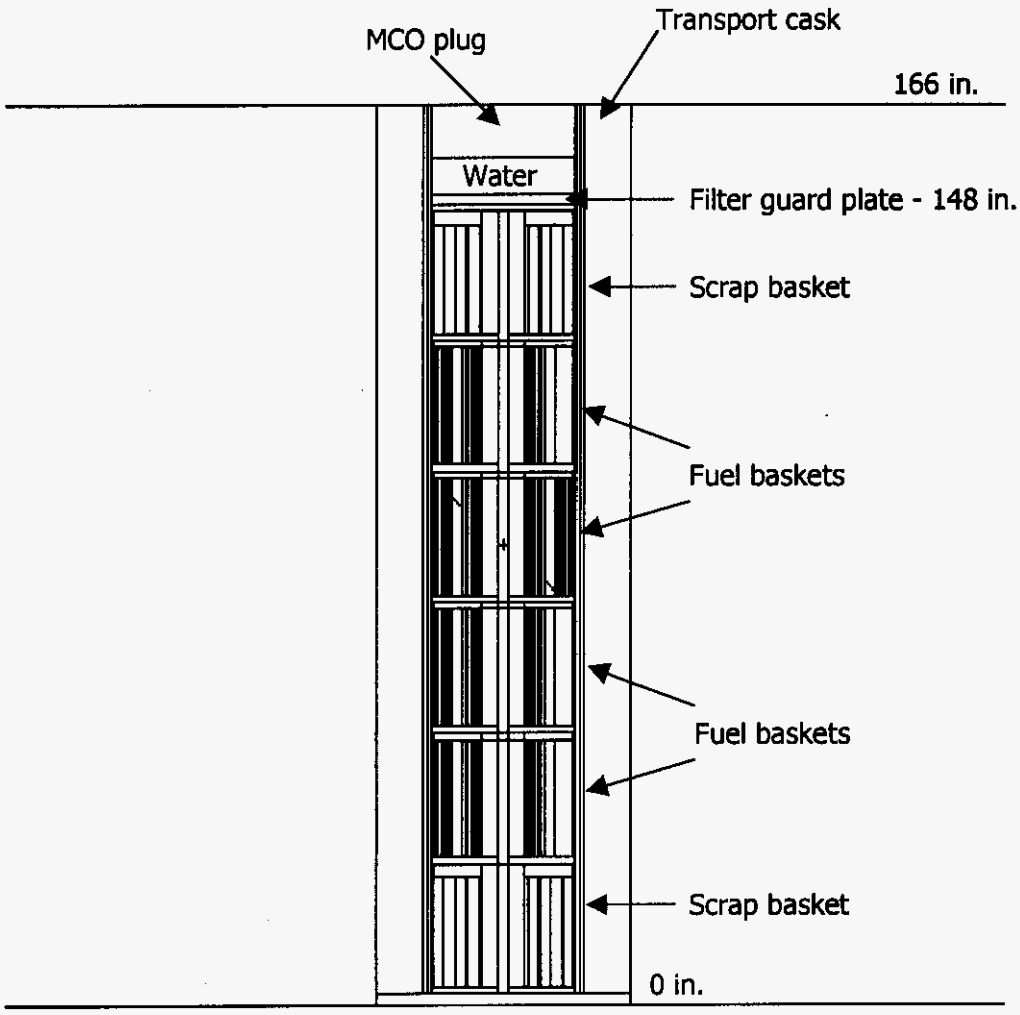
4.5.6 The Effects of Loading Mark IA Outer Elements in Mark IA Fuel Baskets, With No Inner Elements

Loading a Mark IA fuel basket with only Mark IA outer elements may affect the k_{eff} of the MCO. This is because the spacing of the elements in the basket is closer to the optimal spacing for outer elements (Schwinkendorf 1995) and the inner element is replaced by moderator. A series of calculations were performed to show that effect is to lower the k_{eff} because the reduction in ^{235}U mass in the basket containing no inner elements compensates for the increased moderation and the more optimal spacing. Therefore, it is acceptable to load Mark IA fuel baskets with only Mark IA outer elements, and to load these baskets into an MCO either with other fuel baskets containing intact assemblies or with other fuel baskets containing only outer elements. In all cases, the model included two Mark IA scrap baskets and, when fuel baskets containing intact fuel were included, they were partially loaded in accordance with the highest k_{eff} base case.

Table 4-18 Calculation Results for Multi-Canister Overpacks Containing Mark IA Fuel Baskets Loaded with only Mark IA Outer Elements.

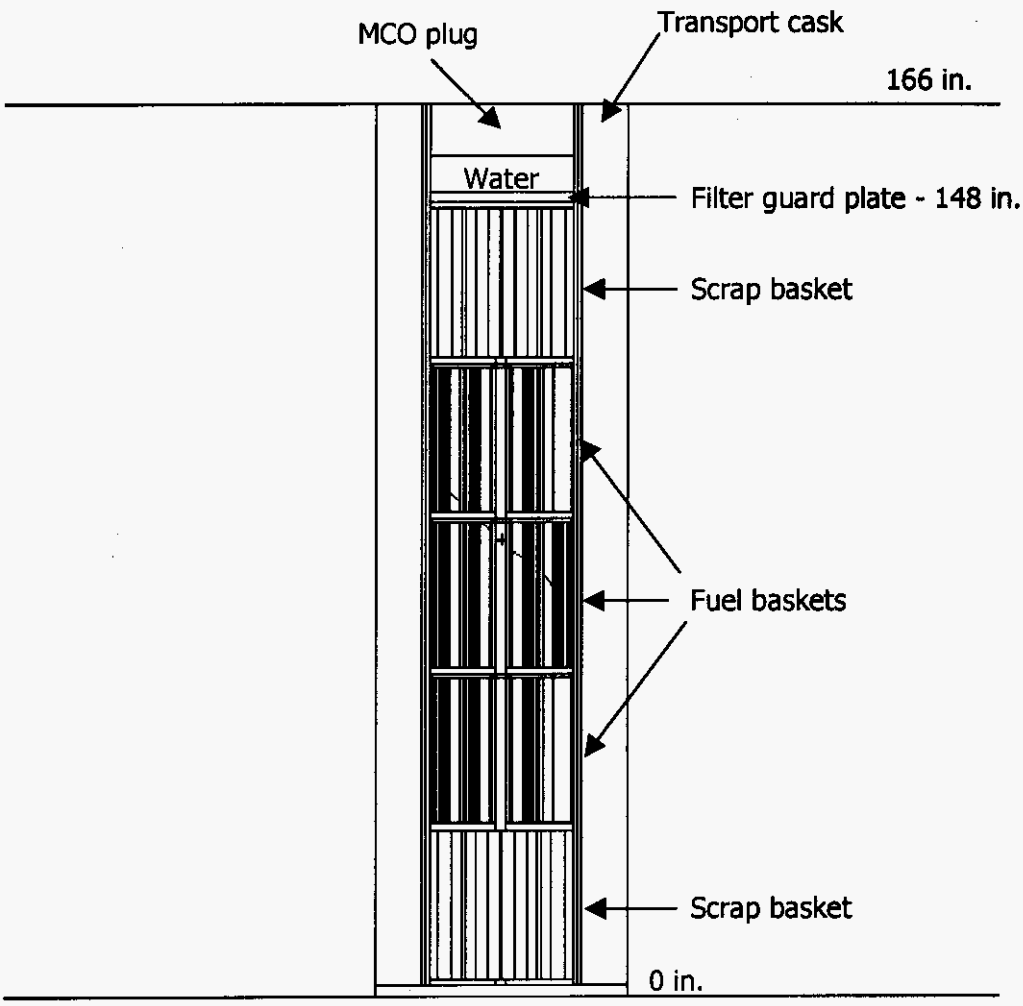
Case	Configuration analyzed	k_{calc}	σ_c	k_{eff}
mk1ro.01	The basket containing outer elements loaded in tier 2 next to the scrap basket	0.88727	0.00096	0.89836
mk1ro.02	The basket containing outer elements loaded in tier 3	0.88668	0.00099	0.89778
mk1ro.03	The basket containing outer elements loaded in tier 4	0.88679	0.00105	0.89790
mk1ro.04	The basket containing outer elements loaded in tier 5 next to the top scrap basket	0.88721	0.00091	0.89829
mk1ro.05	Two baskets containing outer elements loaded adjacent to each other in tiers 2 and 3	0.88737	0.00106	0.89848
mk1ro.06	Two baskets containing outer elements loaded adjacent to each other in tiers 3 and 4	0.88356	0.00101	0.89466
mk1ro.07	Two baskets containing outer elements loaded adjacent to each other in locations 4 and 5	0.88741	0.00101	0.89851
mk1ro.08	Two baskets containing outer elements loaded in tiers 2 and 5	0.88650	0.00103	0.89761
mk1ro.09	Three baskets containing outer elements loaded in tiers 2, 3, and 4	0.88323	0.00111	0.89436
mk1ro.0	Four fuel baskets containing outer elements	0.88750	0.00097	0.89859

Figure 4-1. Input Model for Normal Case – Mark IA.



Mark IA Normal Configuration

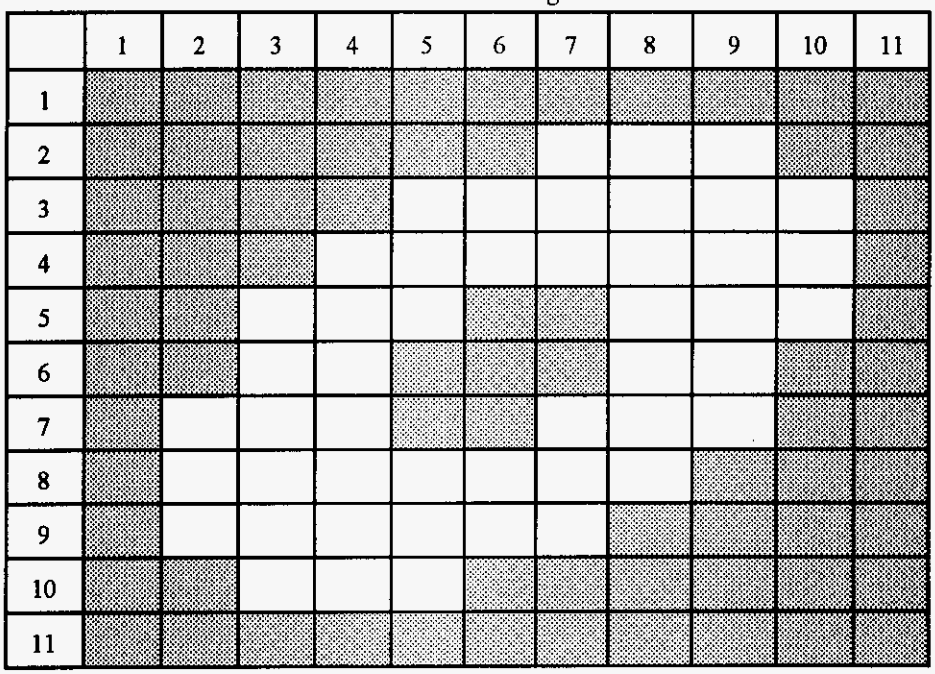
Figure 4-2. Input Model for Normal Case – Mark IV.



Mark IV Normal Configuration

Figure 4-3. MCNP Mark IA Fuel Basket Grid.

MCNP calculation grid



Shaded cells represent water in the basket (universe 2 in the MCNP code), and the unshaded cells represent fuel assemblies (universe 3 in the MCNP code).

Figure 4-4. Maximum Reactivity Loading Arrangement for Mark IA Fuel in Multi-Canister Overpack.

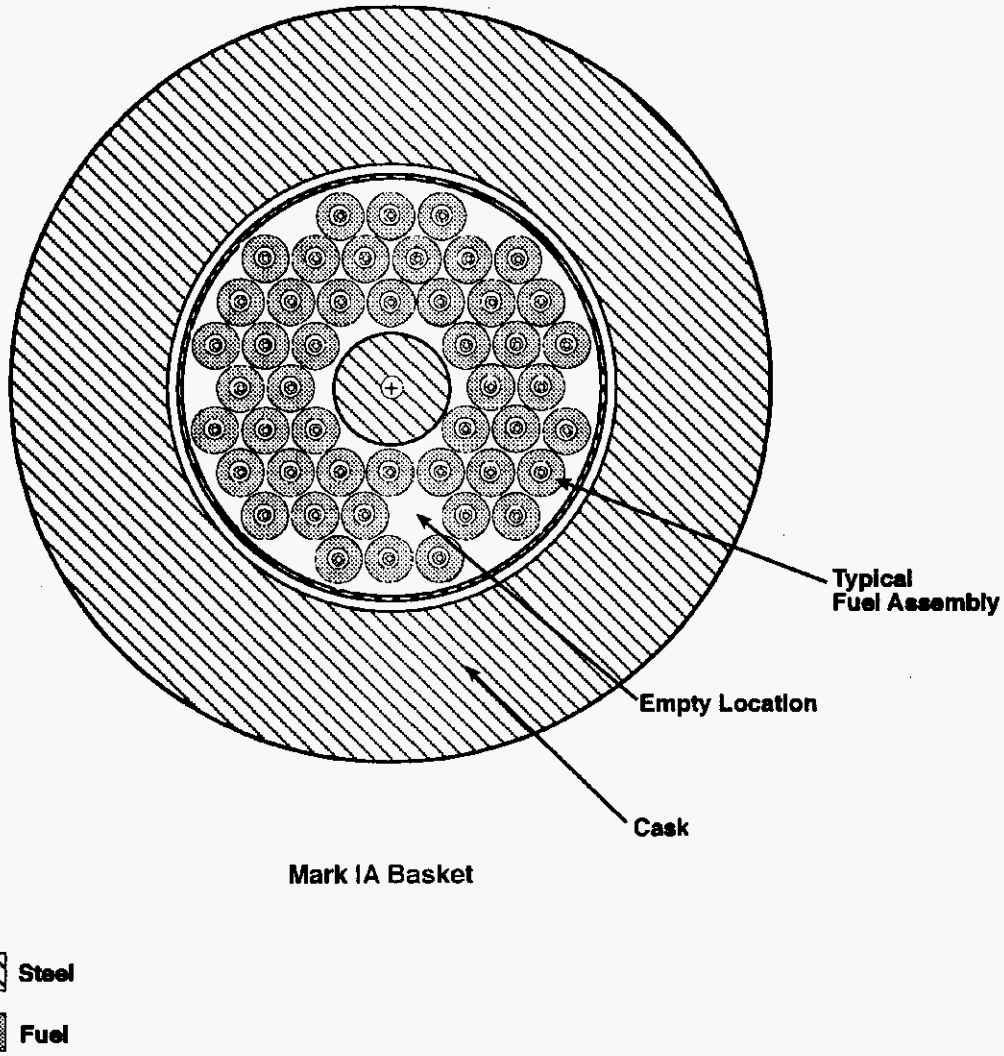


Figure 4-5. Maximum Reactivity Loading Arrangement for Mark IV Fuel in Multi-Canister Overpack.

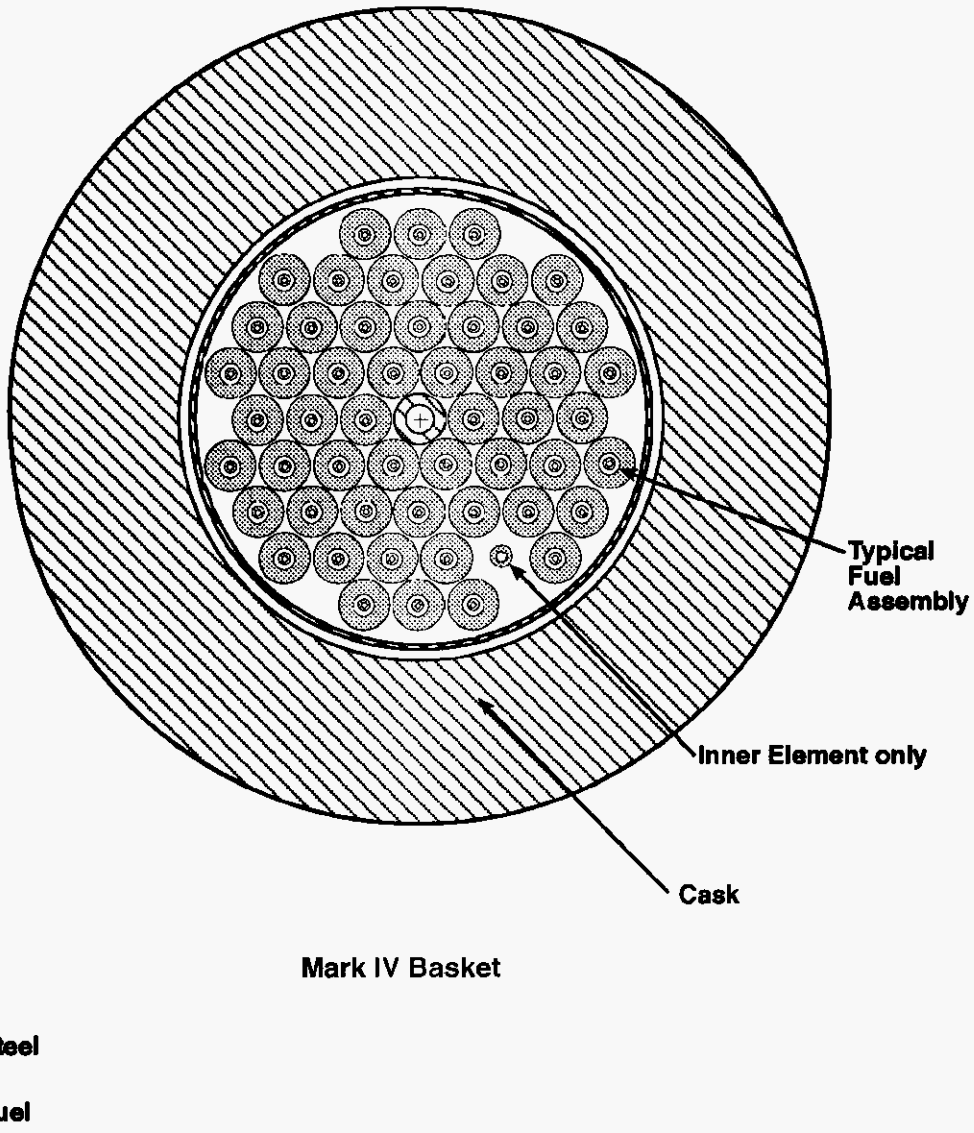


Figure 4-6. K-Effective During Draining of the Multi-Canister Overpack.

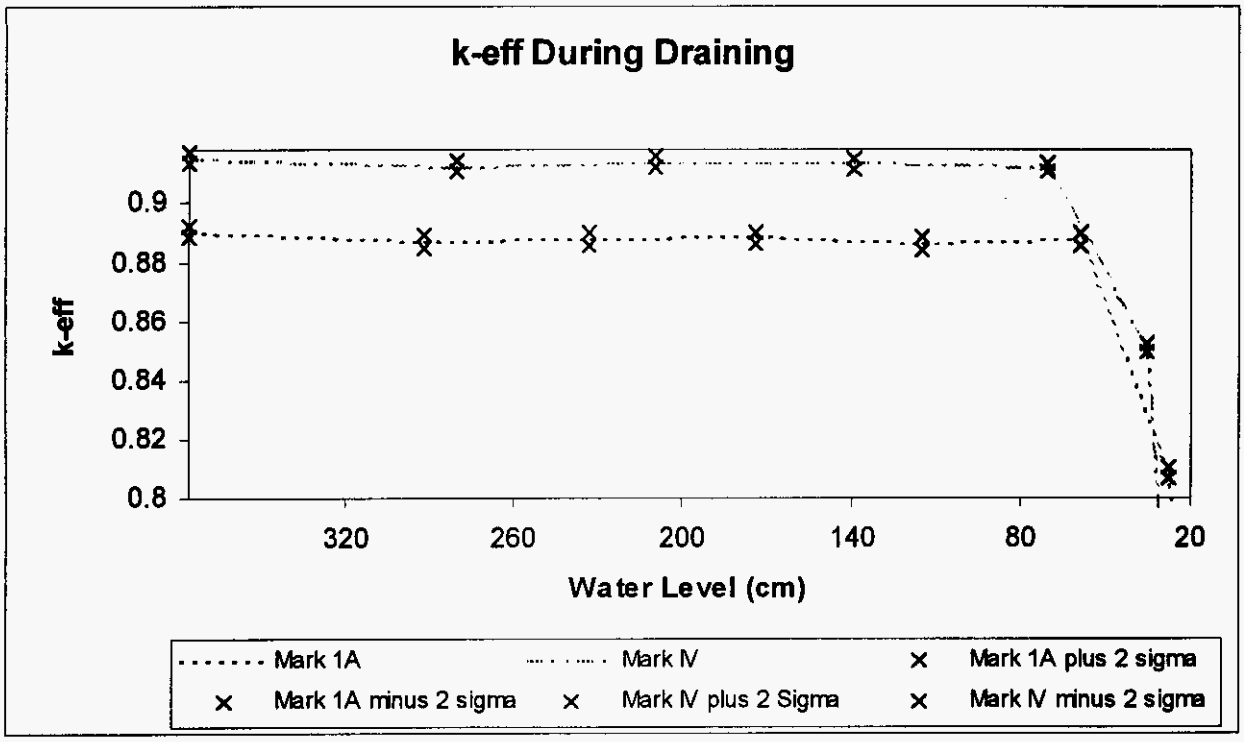
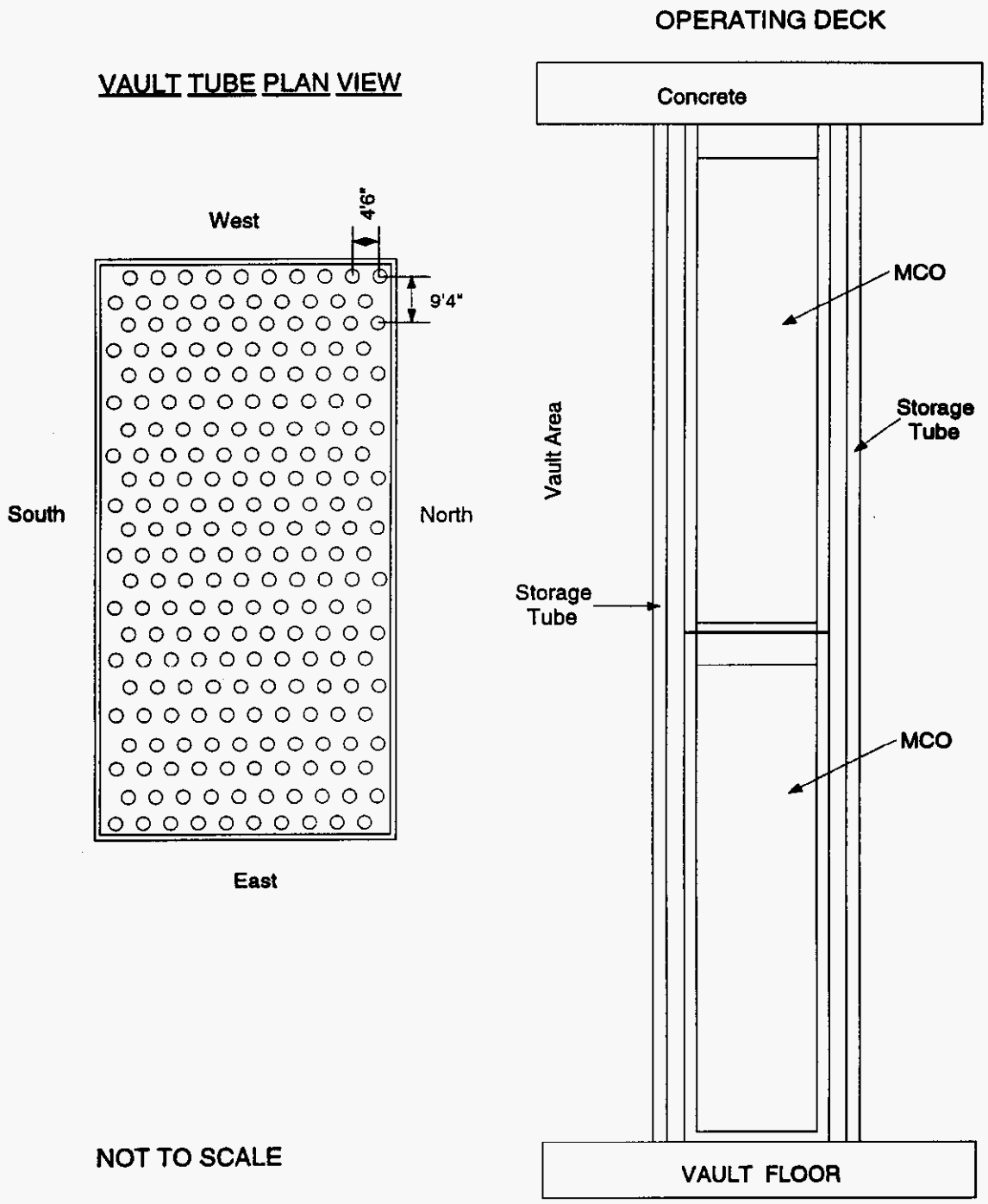


Figure 4-7. Canister Storage Building Array and Storage Tube Layout.



Note: The impact absorber in the bottom of the tube is 36 in. tall, and the intermediate impact absorber is 18 in. tall. The impact absorbers are not shown on this figure.

5.0 CONTINGENCY ANALYSIS

In preparation for performing the analysis for this CSER, significant thought went into trying to determine what normal MCO loadings could be expected; what normal loading range would provide operating flexibility and margin and, consequently, the minimal number of limitations; and what accident conditions were possible.

5.1 POTENTIAL ERROR AND FAILURE SITUATIONS

HNF-PRO-539, Appendix A, "Potential Error/Failure Situations" identifies areas where criticality problems may develop. An evaluation of each of the items on the list is discussed below as it applies to the MCO.

Item 1. Equipment's dimension variation due to

- Fabrication tolerances
- Mechanical disarrangement (e. g., earthquake, drop)
- Chemical attack (corrosion)
- Thermal effect (fire)
- Accidental pressurization effects.

Comment: Appendix B discusses the effects of fabrication tolerances of fuel assemblies on reactivity. The appendix also discusses the effects of fuel corrosion and its products accumulating in the bottom basket of the MCO. Safety-class design features ensure the fuel is maintained in a safe configuration. As the MCO is drained, its internal temperature is controlled, removing heat to the water circulating through the cask annulus. A degradation or loss of cooling could cause a thermal runaway inside the MCO. HNF-SD-SNF-CN-023, *Thermal Analysis of Cold Vacuum Drying of Spent Nuclear Fuel* (Piepho and Crowe 1998), discuses the consequences of a thermal runaway reaction and concludes that the fuel could exceed temperature limits but that safety-class systems and components prevent thermal runaway reactions and thus the reactivity of the MCO is not impacted by this accident scenario. External fires are analyzed in HNF-SD-TP-SARP-017, *Safety Analysis Report for Packaging (Onsite) Multicanister Overpack Cask*, Appendix B, Section 8.5 (Edwards 1997). The analysis shows that the MCO can withstand a fire and not have a thermal runaway of the fuel. At the CVDF, the fuel is always contained in the MCO except for the small amount of particulate released to the process water conditioning system. The amount of fissionable material released is too small to present a criticality hazard (Nelson 1999). At the CSB, there are no combustible materials in the storage vaults and fires are unlikely. Both the CVDF and the CSB are designated as firefighting category B facilities. The only time the MCO is pressurized is during draining at the CVDF. A rupture disk on the MCO prevents overpressurization from the time the MCO is sealed at the K Basins until the drying process has been completed. Since the models assume optimal moderation and flooded conditions, changes in internal MCO pressure will have no affect on criticality.

Item 2. Excesses in mass or volume from errors in

- Segregating materials of different enrichments
- Overbatching
- Analysis error
- Maintaining uniformity of materials
- Loss of control of the number or size of containers.

Comment: HNF-SD-SNF-CSER-010 (Kessler and Peck 1999) and operating procedures (when available) define requirements for correctly loading materials into baskets and loading baskets into the MCO. Loading and handling of the SPR fuel is defined in HNF-SD-SNF-CSER-010 (Kessler and Peck 1999). Over-batching has been analyzed. Limits have been established to control the amount of scrap that can be loaded into an MCO basket. Misloading of the baskets has been analyzed (see Section 5.2.4). Loading the 12 26.1-in.-long Mark IA assemblies in a Mark IV basket has also been analyzed and loading of the Mark IA material in the K East Basin has been evaluated. Since there is no chemical processing, analysis errors are unlikely.

Item 3. Excess of mass in a non-safe geometry vessel resulting from

- Cross connections
- Unauthorized piping changes
- Valve leakage.

Comment: The MCO has been evaluated (see Section 5.2.3) to ensure that excess mass will not lead to inadvertent criticality. In all cases, limits and the need for multiple contingencies to occur provide adequate safety margin. There is no chemical processing and no systems associated with the MCO in which cross connections, leaking valves, and unauthorized piping changes could be a problem.

Item 4. Changes in geometry resulting from

- Spilling or leakage
- Mechanical compacting
- Rubblizing.

Comment: The MCO has been evaluated (see Section 5.2.2) for design basis drop accidents in which spills of fuel or mechanical compacting or settling could occur. The design of the MCO, MCO cover, and Mark IA basket ensure criticality safety is maintained.

Item 5. Changes in reflection from

- Flooding
- Added shielding (dose reduction campaign).

Comment: All MCO loading activities occur under water and have been analyzed assuming optimal moderation and maximum reflection. No additional shielding is planned. Draining the cask–MCO annulus with a flooded MCO is a contingency for CVDF and has been analyzed (see Section 5.2.1). Calculations for the CSB include the contingencies of flooding the storage vaults, the storage tubes, and the MCOs internally. The results of these calculations are presented in Sections 5.2.5 through 5.2.7.

Item 6. Changes in concentration from

- Precipitation
- Accumulation
- Evaporation
- Other process upsets.

Comment: All analyses have been performed assuming the only change in physical form of the fuel is due to corrosion after cleaning and drying. These corrosion products are assumed to fall from the upper baskets and accumulate in the lower baskets. Results of these analyses are discussed in Appendix B. Precipitation and evaporation are not problems because the material is not in solution.

Item 7. Increased interaction from

- Collapse of shelving or spacers
- Material in transit
- Excessive additions to array
- Changes in relative position of units by flooding and floating units
- Spacing error.

Comment: Transport limits are specified in the HNF-SD-TP-SARP-017 (Edwards 1997). Spacing errors and additions to the storage arrays are eliminated by the design of the shipping cask and the design of the CSB storage tubes and the storage arrays. Section 5.2.9 discusses the results of loading two MCOs in a storage tube without an intermediate impact absorber.

Item 8. Changes in moderation from

- Inleakage
- Absorption by hygroscopic material
- Condensation
- Inadequate drying
- Fire fighting activity
- Evaporation
- Precipitation.

Comment: All MCO normal and abnormal conditions have been analyzed assuming fully moderated and optimized conditions. Removing water from the MCO will reduce moderation and k_{eff}. Section 5.2.10 discusses flooding of the CSB sampling/weld station with glycol.

5.2 CONTINGENCY ANALYSIS

Contingencies considered for the MCO include the following:

- Receipt at the CVDF of an MCO in a cask with a drained annulus
- Design basis drops during MCO loading in the K Basins and during CSB operations
- Loading a misloaded basket into an MCO
- Misloading an MCO with an additional scrap basket
- Misloading scrap baskets within the MCO (i.e., loading scrap baskets in the wrong tiers)
- Flooding an MCO at the CSB
- Flooding a CSB storage tube
- Flooding the CSB storage array
- Handling a flooded MCO with the MHM
- Loading an MCO in a storage tube without an intermediate impact absorber
- Flooding the weld or sample station with glycol.

5.2.1 Receipt of a Multi-Canister Overpack in a Cask with a Drained Annulus

The shipping cask is filled with clean water, and the MCO is filled with deionized basin water at the K Basins prior to loading. The cask–MCO is contained in an immersion pail that has seals to maintain the cask and annulus water. The clean water stays in the cask annulus where it is used for temperature control until the MCO is drained at the CVDF. Should the annulus be drained before the cask–MCO is received at the CVDF, the k_{eff} will remain below 0.95. This is shown by cases cvd1.7 and cvd4.7 in Table 5-1. Also included in the table are the results for an MCO containing the long-length Mark IA fuel assemblies in the Mark IV fuel basket.

Table 5-1. Calculation Results for Multi-Canister Overpacks Containing Long-Length Mark IA Fuel Assemblies in Mark IV Baskets with a Drained Annulus. (2 sheets)

Case	MCO configuration	k_{calc}	σ_c	k_{eff}[a]
cvd1.7	2 scrap baskets and 4 partially loaded fuel baskets in a Mark IA MCO	0.90154	0.00096	0.91263
cvd4.7	2 scrap baskets and 3 partially loaded fuel baskets in a Mark IV MCO	0.92152	0.00088	0.93259
18rc.2[b]	Mark IA assemblies in the center of the central basket	0.92155	0.00090	0.93262
18rc.5[c]	Mark IA assemblies in the center of the central basket	0.92091	0.00089	0.93198
18rc.8[c]	Mark IA assemblies in the center of the lower basket	0.92303	0.00079	0.93408
18rc.17[b]	Mark IA assemblies in the center of the upper basket	0.92388	0.00097	0.93497
18rc.15[b]	Mark IA assemblies in the center of the lower basket	0.92453	0.00087	0.93560
18rc.13[c]	Mark IA assemblies in the center of the upper basket	0.92356	0.00091	0.93464
18rm.2[b]	Mark IA assemblies in the middle row of the central basket	0.92123	0.00084	0.93229
18rm.5[c]	Mark IA assemblies in the middle row of the central basket	0.92221	0.00085	0.93327
18rm.8[c]	Mark IA assemblies in the middle row of the lower basket	0.92129	0.00090	0.93236
18rm.15[b]	Mark IA assemblies in the middle row of the lower basket	0.92208	0.00093	0.93316
18rm.17[b]	Mark IA assemblies in the middle row of the upper basket	0.92250	0.00085	0.93356
18rm.13[c]	Mark IA assemblies in the middle row of the upper basket	0.92202	0.00085	0.93308
18rp.2[b]	Mark IA assemblies in the outer row of the central basket	0.92331	0.00091	0.93439
18rp.5[c]	Mark IA assemblies in the outer row of the central basket	0.92257	0.00084	0.93363
18rp.8[c]	Mark IA assemblies in the outer row of the lower basket	0.92000	0.00086	0.93107

Table 5-1. Calculation Results for Multi-Canister Overpacks Containing Long-Length Mark IA Fuel Assemblies in Mark IV Baskets with a Drained Annulus. (2 sheets)

Case	MCO configuration	k_{calc}	σ_c	k_{eff}[a]
18rp.15[b]	Mark IA assemblies in the outer row of the lower basket	0.92059	0.00098	0.93168
18rp.17[b]	Mark IA assemblies in the outer row of the upper basket	0.92208	0.00086	0.93315
18rp.13[c]	Mark IA assemblies in the outer row of the upper basket	0.92094	0.00079	0.93199

[a]$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

[b]Fuel baskets contain an inner element location in position 4,5.

[c]Fuel baskets contain an inner element location in position 3,6.

MCO = multi-canister overpack.

5.2.2 Design Basis Drop Accidents

Drop accidents can occur when the MCO is being moved to the transporter in the K Basins, during transport from the K Basins to the CVDF or from the CVDF to the CSB, or during handling at the CSB. An MCO drop accident cannot occur at the CVDF because the MCO is not lifted off the transporter, and constraints on the shipping cask prevent tipping (Chenault 1998). Drop accidents during transportation are discussed in HNF-SD-TP-SARP-017 (Edwards 1997). After draining and drying, the MCOs are transported from the CVDF to the CSB for interim storage. The only facility where a flooded MCO could be dropped is the K Basins. Once the MCOs have been dried, criticality cannot occur. The CSB is the only facility containing concrete hard enough to displace the center post in the Mark IA baskets. Receipt of a flooded MCO at CSB and dropping an MCO are two independent events thus making the drop of a flooded MCO with displacement of the center post a beyond design basis event. The result is included for information only.

The most severe hypothetical accident considered is the design basis accident drop of a flooded MCO in which all of the intact fuel within the MCO is broken into rubble. During the transient portion of this accident (during the impact and rebound), the fuel debris may space itself optimally in water.

All the material in the MCOs was modeled as optimal scrap with the scrap in the Mark IA fuel baskets at an enrichment of 1.15 wt% ^{235}U, the weight averaged enrichment of a Mark IA fuel assembly. Both the Mark IA and Mark IV fuel baskets are too small to allow a full load of intact assemblies to become optimally spaced as scrap. Therefore, each fuel basket was modeled containing the mass equal to a partial load of assemblies, 45 Mark IA assemblies or 44 Mark IV assemblies. For the Mark IA MCO, four loading variations were analyzed: the normal two scrap basket case, the case with five fuel baskets and a scrap basket in the bottom tier, the case of five

fuel baskets and a scrap basket in the top tier, and the case of six fuel baskets. All scrap baskets contained 575 kg of optimized scrap. Only one loading was analyzed for the Mark IV MCO because there is a single enrichment and, at optimal conditions, the total mass in the MCO is the same regardless of the loading. The safety-class base plates and center post maintain the spacing of the material in the Mark IA MCO. Rearrangement of the material in the MCOs is restricted by the safety-class MCO shell, base, and the filter guard plate on the bottom of the MCO closure plug. The Mark IV basket base plates serve no safety-class function but are essentially identical to the base plates for the Mark IA baskets and are included in the drop models. The results are shown in Table 5-2. Since the MCOs are modeled completely filled with optimum scrap and fuel rubble, no separate analysis was performed for a drop to a horizontal position. Although a drop of a flooded MCO with a displacement of the center post is a beyond design basis event, it was analyzed and the result included in the table. Figures 5-1 and 5-2 show the models used for this analysis.

Table 5-2. Multi-Canister Overpack Drop Analysis for Fuel and Scrap Baskets.

Case	MCO initial configuration	k_{calc}	σ_c	k_{eff}[a]
mk1ad.1	2 scrap baskets and 4 partially loaded fuel baskets in a Mark IA MCO	0.89640	0.00115	0.90754
mk1ad.2	Scrap basket in the bottom tier and 5 partially loaded fuel baskets in a Mark IA MCO	0.89783	0.00091	0.90891
mk1ad.3	Scrap basket in the top tier and 5 partially loaded fuel baskets in a Mark IA MCO	0.90480	0.00093	0.91588
mk1ad.4	6 partially loaded fuel baskets in a Mark IA MCO	0.90572	0.00097	0.91681
mk1ad.5[b]	2 full scrap baskets and 4 rubblized fuel baskets	0.91756	0.00073	0.92860
mk1ad.8[b]	6 partially loaded fuel baskets with the center post offset by 2 in.	0.91337	0.00086	0.92444
mk4d.5	2 scrap baskets and 3 partially loaded fuel baskets in a Mark IA MCO	0.92889	0.00059	0.93991
spr.2	SPR fuel	0.87516	0.00300	0.88723

[a]$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

[b]This case is a beyond design basis accident. k_{eff} does not have to be less than 0.95 for this type of event.

MCO = multi-canister overpack.
SPR = single pass reactor.

The aluminum-clad SPR fuel has not been observed to have its mechanical integrity degraded by cladding failure and corrosion as is the case with N Reactor fuel. Therefore, the fuel has been modeled as representative aluminum-clad uranium cylinders with lattice spacing corresponding to optimum moderation. The inside diameters of the scrap baskets containing the SPR fuel have been expanded to the maximum limit of 23.25 in. The center post has been offset to its limit of 2 in.

Identified SPR fuel in the K Basins contains either depleted, natural, or 0.95 wt% ^{235}U enriched uranium. All identified SPR fuel has been modeled with the limiting 0.95 wt% ^{235}U enrichment. The mass of unidentified SPR fuel has been modeled as a cylinder of 2.1 wt% ^{235}U enriched uranium around the center post of the tier four basket. This location is the highest importance for this fuel. The result of this calculation, shown as spr.2 in Table 5-2, is below 0.95.

The final case is a Mark IA MCO containing completely filled scrap baskets with rubblized fuel baskets. This case bounds all possibilities of the scrap in a partially loaded scrap basket forming an unfavorable geometry in the MCO.

5.2.3 Loading a Misloaded Basket

Loading a Mark IV fuel basket with 14 Mark IA fuel assemblies or a Mark IV scrap basket with the mass equivalent to 14 Mark IA fuel assemblies is a contingency because Mark IV and Mark IA fuel are not normally handled concurrently. The only exceptions to this is the long-length Mark IA assemblies in the K West Basin and the Mark IA material in the K East Basin as discussed in Section 4.5.5 of this report. This section discusses the misloading of a Mark IV basket and loading it into an MCO. Loading Mark IV material into a Mark IA basket is acceptable because of the lower enrichment of the Mark IV fuel.

Several different configurations were analyzed for loading 14 Mark IA fuel assemblies either in the center or in the outer row of a Mark IV fuel basket. For the scrap misload, two configurations were analyzed with the Mark IA fuel around the center pipe of the scrap basket. The mass of the material was 155 kg, equivalent to the mass of 14 1.25 wt% ^{235}U outer elements with the rest of the basket filled with 0.95 wt% ^{235}U scrap. Modeling the scrap this way rather than as a 233 kg cylinder of 1.15 wt% scrap gives the highest k_{eff}. All the scrap was optimized. Table 5-3 lists the results, which show that reactivity stays below 0.95 for every case.

5.2.4 Misloading a Multi-Canister Overpack

Contingency cases in which fuel is misloaded in the flooded MCO and transfer cask are shown in Table 5-4 for both Mark IA and Mark IV MCOs. The cases in Table 5-4 represent situations in which either a scrap basket is loaded adjacent to another scrap basket or the allowed

limit of two scrap baskets per MCO is exceeded by loading a third scrap basket. For both Mark IA and Mark IV fuel, the reactivity is greatest when the misloaded scrap basket is adjacent to an end scrap basket and a fuel basket is loaded in the top tier. These reactivities are below 0.95.

Cases for misloaded MCOs in the CSB were not performed using the new basket designs because the results are more conservative using the original analyses. Results listed in Table 5-5 show that the CSB is significantly subcritical even for loading Mark IA fuel and scrap in the Mark IV fuel and scrap baskets in MCOs stored in the CSB, as long as the MCOs are not flooded. The model used for these cases has a 23.0-in. fuel region diameter.

Table 5-3. Basket Misload Analysis for Mark IV Multi-Canister Overpacks.

Case	MCO configuration	k_{calc}	σ_c	k_{eff}^*
mk4rl.1	14 Mark IA fuel assemblies in the center of the tier 2 fuel basket	0.91313	0.00086	0.92420
mk4rl.2	14 Mark IA fuel assemblies in the center of the tier 3 fuel basket	0.91291	0.00087	0.92398
mk4rl.3	14 Mark IA fuel assemblies in the center of the tier 4 fuel basket	0.91120	0.00076	0.92224
mk4rl.4	14 Mark IA fuel assemblies in the outer row of the tier 2 fuel basket	0.91357	0.00092	0.92465
mk4rl.5	14 Mark IA fuel assemblies in the outer row of the tier 3 fuel basket	0.91227	0.00078	0.92332
mk4rl.6	14 Mark IA fuel assemblies in the outer row of the tier 4 fuel basket	0.91274	0.00098	0.92383
mk4rc.13	Mass of 14 Mark IA outer elements in the center of the lower scrap basket	0.91330	0.00094	0.92438
mk4rc.14	Mass of 14 Mark IA outer elements in the center of the upper scrap basket	0.91485	0.00097	0.92594

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{½}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack

Table 5-4. Misload Analysis for Multi-Canister Overpacks.

Case	MCO configuration	k_{calc}	σ_c	k_{eff}^*
mk1rs.1	Two scrap baskets in the bottom two tiers with a fuel basket in the top	0.89278	0.00097	0.90387
mk1rs.2	Two scrap baskets in the bottom two tiers with a scrap basket in the top	0.89063	0.00098	0.90172
mk1rs.3	Scrap baskets in tiers 1, 3, and 6	0.88738	0.00106	0.89849
mk1rs.4	Scrap baskets in tiers 1, 4, and 6	0.88774	0.00102	0.89884
mk4rs.1	Two scrap baskets in the bottom two tiers with a fuel basket in the top	0.92256	0.00082	0.93362
mk4rs.2	Two scrap baskets in the bottom two tiers with a scrap basket in the top	0.92040	0.00096	0.93149
mk4rs.3	Scrap baskets in tiers 1, 3, and 5	0.91265	0.00090	0.92372

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.

Table 5-5. Calculated Results for Misloaded Multi-Canister Overpack Stored in the Canister Storage Building. (2 sheets)

Case	MCO type	Payload cluster		Water density (g/cm³)		Calculation results		
		Number of baskets	Assemblies per basket	MCO interior	Between storage tubes and outside MCOs	k_{calc}	Standard deviation	k_{eff}
oc3.1b	Mark IV[a]	Top MCO 1 top 3 middle 1 bottom Bottom MCO 2 top 2 middle 1 bottom	Top MCO 0.95 wt% Scrap 54 Mark IV 0.95 wt% Scrap Bottom MCO 0.95 wt% Scrap 54 Mark IV 0.95 wt% Scrap	0.0051	0.008	0.4134	0.0018	0.4248
oc3.1	Mark IV[a]	Top MCO 1 top 3 middle 1 bottom Bottom MCO 2 top 2 middle 1 bottom	Top MCO 0.95 wt% Scrap 54 Mark IV 0.95 wt% Scrap Bottom MCO 0.95 wt% Scrap 54 Mark IV 0.95 wt% Scrap	0.0051	0.0012	0.3939	0.0015	0.4052
oc3.3b	Mark Iv[a]	Top MCO 1 top 3 middle 1 bottom Bottom MCO 1 top 3 middle 1 bottom	Top MCO 0.95 wt% scrap 54 Mark IV 0.95 wt% scrap Bottom MCO 0.95 wt% scrap mixed with 1 canister of 1.25 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.008	0.4131	0.0017	0.4244

Table 5-5. Calculated Results for Misloaded Multi-Canister Overpack Stored in the Canister Storage Building. (2 sheets)

Case	MCO type	Payload cluster		Water density (g/cm³)		Calculation results		
		Number of baskets	Assemblies per basket	MCO interior	Between storage tubes and outside MCOs	k_{calc}	Standard deviation	k_{eff}
oc3.3	Mark IV[a]	Top MCO 1 top 3 middle 1 bottom Bottom MCO 1 top 3 middle 1 bottom	Top MCO 0.95 wt% scrap 54 Mark IV 0.95 wt% scrap Bottom MCO 0.95 wt% scrap mixed with 1 canister of 1.25 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.0012	0.3973	0.0019	0.4087

[a]Infinite square array.

MCO = multi-canister overpack.

The single contingency case of loading an MCO with one too many scrap baskets of the correctly enriched material has been analyzed. A third scrap basket is modeled next to the top scrap basket in the bottom MCO in a storage tube. This puts three scrap baskets as close to one another as possible in a storage tube for a single contingency. The value of k_{eff} is 0.4248 for case oc3.1b, which has an intertube optimal water density of 0.008 g/cm^3 (see Table 5-5). The value of k_{eff} is lower, 0.4052 for case oc3.1, which has an intertube water density of 0.0012 g/cm^3.

Another contingency is a canister of Mark IA fuel or scrap that has been misplaced and mislabeled as Mark IV in the K Basins. This one canister is loaded into a Mark IV basket, so a basket intended for 0.95 wt% ^{235}U enriched scrap is loaded with 233 kg of 1.25 wt% ^{235}U enriched scrap, and the rest of the basket is loaded with 0.95 wt% ^{235}U Mark IV scrap. Scrap baskets are more reactive than intact fuel baskets, so this case bounds cases of a canister of Mark IA fuel in Mark IV fuel baskets. The value for k_{eff} is 0.4244, as shown in case oc3.3b, which has an intertube optimal water density of 0.008 g/cm^3 (see Table 5-5). The value of k_{eff} is lower, 0.4087 for case oc3.3, which has an intertube water density of 0.0012 g/cm^3.

These results show that reactivity is well below 0.95 for any single contingency. The conservatisms in the analyses are that all tubes in the array have an extra scrap basket and the array is modeled as an infinite array.

5.2.5 Flooding a Multi-Canister Overpack at the Canister Storage Building

The cases presented in Table 4-14 showed that the storage of dry MCOs in the CSB is significantly subcritical. One occurrence that could significantly raise the reactivity to a level of concern is to flood the MCOs. Putting an optimally dense water mist between the tubes could further optimize the system. The CSB design has excluded a sprinkler system and has no other piped-in water. Flooding the MCOs is not considered credible while in storage, but a flooded MCO may be delivered to the CSB. The effect of flooding on reactivity is calculated to show that even this event is within allowable limits. These calculations were not redone using the revised basket designs.

A flooded MCO delivered to the CSB is considered a contingency. Analyses investigating this contingency, summarized in Table 5-6, show that an infinite array of MCOs could be flooded and still be within acceptable limits. The first two cases, oc2.12 and oc2.12b, have water everywhere outside the MCOs at densities of 0.0012 g/cm^3 and 0.008 g/cm^3, respectively. The results for these two cases are values for k_{eff} of 0.9236 and 0.9135. When full density water is put in the storage tubes, as shown in cases oc2.13 and 2.13b in Table 5-6, the values for k_{eff} are lower, 0.8902 and 0.8967. These results show that for MCOs normally loaded with Mark IV intact fuel and scrap, any degree of flooding of the MCOs or storage tubes can be tolerated without exceeding the criticality limit of 0.95.

Table 5-6. Calculated Results for Multi-Canister Overpack Internal Flooding at Canister Storage Building.

Case	MCO type	Payload cluster		Water density (g/cm³)		Calculation results		
		Number of baskets	Assemblies per basket	MCO interior	Between storage tubes and outside MCOs	k_{calc}	Standard deviation	k_{eff}
oc2.12	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	1.0	0.0012 between storage tubes, 0.0012 outside MCOs	0.9119	0.0025	0.9236
oc2.12b	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	1.0	0.008 between storage tubes, 0.008 outside MCOs	0.9016	0.0027	0.9135
oc2.12c	Mark IV[b]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	1.0	0.008 between storage tubes, 0.008 outside MCOs	0.9027	0.0022	0.9143
oc2.13	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	1.0	0.0012 between storage tubes, 1.0 outside MCOs	0.8782	0.0029	0.8902
oc2.13b	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	1.0	0.008 between storage tubes, 1.0 outside MCOs	0.8849	0.0026	0.8967
oc2.13c	Mark IV[b]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	1.0	0.008 between storage tubes, 1.0 outside MCOs	0.8859	0.0024	0.8976
oc1.15c	Mark IA[c]	1 top 4 middle 1 bottom	1.25 wt% scrap 48 Mark IA 1.25 wt% scrap	1.0	0.008 between storage tubes and outside MCOs	0.8940	0.0009	0.9051
oc1.16c	Mark IV[c]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	1.0	0.008 between storage tubes and outside MCOs	0.8875	0.0014	0.8987

[a]Infinite square array.
[b]Infinite hexagonal array.
[c]Model of actual 10 by 22 by 2 hexagonal array of MCOs in CSB storage tubes with concrete walls, floor, and operating deck.

MCO = multi-canister overpack.

5.2.6 Flooding a Canister Storage Building Storage Tube

Flooding a storage tube is considered a contingency. The floor plugs are vented, but water lines are excluded from the vault operating floor and area. Only a very unusual occurrence would bring water onto the operating floor and into the storage tubes. Flooding the 1.5-in. radial gap between the MCO and the storage tube has no significant effect on the reactivity of dry MCOs in the CSB storage tubes. Comparing cases oc1.3 and oc1.3b in Table 5-7 with oc2.11 and oc2.11b (for full density water in the gap) in Table 5-7, shows all values for k_{eff} are between 0.40 and 0.43. Each pair of cases uses 0.0012 g/cm^3 and 0.008 g/cm^3 of water in the intertube space. Case oc2.14b in Table 5-7 for 0.008 g/cm^3 intertube water density with the gap filled with half density water was also in the 0.40 to 0.43 range for k_{eff}. These cases evaluated an MCO loaded with Mark IV fuel. An MCO loaded with Mark IA fuel is evaluated in cases oc2.10a and oc2.10ba in Table 5-7 with full density water in the gap, and the values for k_{eff} are less, 0.4138 and 0.4125, respectively. These results indicate that for dry MCOs, flooding storage tubes is not a criticality concern. These cases were not reperformed using the revised basket designs.

5.2.7 Flooding at the Canister Storage Building Storage Array

The lack of water lines in the CSB and the fact that the only access to the vault space between the storage tubes is through the two stacks that allow natural convection circulation for cooling precludes flooding of the vault space between the tubes. However, to show the conservative nature of the CSB, the contingency of flooding the vault has been analyzed using the infinite array model. Progressively filling the vault to a quarter full (the bottom MCO is half submerged), and to half full (the bottom MCO is completely submerged), lowers the value of k_{eff} to 0.3877 and 0.3823, as shown for cases oc2.1 and oc2.2, respectively, in Table 5-8. Case oc2.8 in Table 5-8 has an even lower value of 0.3463 for the vault fully flooded (both MCOs submerged). The greater the flooding of the vault, the greater the neutronic isolation of each storage tube. The progressive flooding of a vault decreases the overall reactivity of the array.

The effect of water moderation between the storage tubes also was investigated. An infinite horizontal array model of CSB storage tubes containing two normally loaded MCOs was analyzed with water densities from 0.0005 to 1.0 g/cm^3 between the tubes. Figure 5-3 shows a plot of the data for flooded MCOs, and Figure 5-4 shows a plot of the data for dry MCOs. The peak in reactivity occurs at 0.008 g/cm^3 water density between the storage tubes for dry MCOs. Case ocsb05 in Table 5-8 gives the results of the 10 by 22 by 2 hexagonal array model of normally loaded Mark IV fuel in the MCOs with 0.008 g/cm^3 intertube moisture. The value of k_{eff} was 0.3985. Thus, the actual reactivity for the dry MCO in the CSB storage tube is highly subcritical.

Table 5-7. Calculation Results for Canister Storage Building Storage Tube Flooding.

Case	MCO type	Payload cluster		Water density (g/cm³)		Calculation results		
		No. of baskets	Assemblies per basket	MCO interior	Between storage tubes and outside MCOs	k_{calc}	Standard deviation	k_{eff}
oc1.3	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.0012 (vapor)	0.3997	0.0018	0.4111
oc1.3b	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.008 (vapor)	0.4114	0.0020	0.4229
oc1.3c	Mark IV[b]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.008 (vapor)	0.4105	0.0020	0.4220
oc2.11	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.0012 (vapor) between storage tubes 1.0 outside MCOs	0.4069	0.0018	0.4183
oc2.11b	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark V 0.95 wt% scrap	0.0051	0.008 (vapor) between storage tubes 1.0 outside MCOs	0.4042	0.0026	0.4160
oc2.11c	Mark IV[b]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.008 (vapor) between storage tubes 1.0 outside MCOs	0.4024	0.0023	0.4140
oc2.14b	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.008 (vapor) between storage tubes 0.5 outside MCOs	0.4109	0.0020	0.4224
oc2.10a	Mark IA[a]	1 top 4 middle 1 bottom	1.25 wt% scrap 48 Mark IV 1.25 wt% scrap	0.0051	0.0012 (vapor) between storage tubes 0.5 outside MCOs	0.4021	0.0024	0.4138
oc2.10ba	Mark IA[a]	1 top 4 middle 1 bottom	1.25 wt% scrap 48 Mark IV 1.25 wt% scrap	0.0051	0.008 (vapor) between storage tubes 0.5 outside MCOs	0.4008	0.0024	0.4125

[a]Infinite square array.
[b]Infinite hexagonal array.

MCO = multi-canister overpack.

Table 5-8. Calculation Results for Canister Storage Building Vault Flooding.

Case	MCO type	Payload cluster		Water density (g/cm³)		Calculation results		
		Number of baskets	Assemblies per basket	MCO interior	Between storage tubes and outside MCOs	k_{calc}	Standard deviation	k_{eff}
oc2.1	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	1.00 (vault flooded to one-quarter height)	0.3764	0.0016	0.3877
oc2.1c	Mark IV[b]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	1.00 (vault flooded to one-quarter height, 0.008 outside MCOs)	0.3923	0.0020	0.4038
oc2.2	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	1.00 (vault flooded to half height)	0.3711	0.0014	0.3823
oc2.2c	Mark IV[b]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	1.00 (vault flooded to half height, 0.008 outside MCOs)	0.3808	0.0020	0.3923
oc2.8	Mark IV[a]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	1.00 (vault flooded to full height)	0.3348	0.0020	0.3463
oc2.8c	Mark IV[b]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	1.00 (vault flooded to full height, 0.008 outside MCOs)	0.3349	0.0016	0.3462
ocsb05	Mark IV[c]	1 top 3 middle 1 bottom	0.95 wt% scrap 54 Mark IV 0.95 wt% scrap	0.0051	0.008 (vapor)	0.3874	0.0008	0.3985

[a]Infinite square array.
[b]Infinite hexagonal array.
[c]Modeled using 10 by 22 by 2 array of MCOs in CSB storage tubes with concrete walls, floors, and walls. Fuel density corresponds to the actual 10 by 22 by 2 hexagonal array of CSB.

CSB = Canister Storage Building.
MCO = multi-canister overpack.

Figure 5-4 shows that for water densities greater than 0.008 g/cm^3 in the vault, the reactivity drops to that for a single fully water-reflected MCO. Results presented in this section also show that for flooding of the vault space, the reactivity is always below 0.42. For this degree of subcriticality, even at optimum intertube water density, no restriction on fire fighting is necessary for criticality control. For CSB calculations, this water content (0.008 g/cm^3) is used as a conservative assumption in calculations. Figure 5-4 shows that at the lower water densities of normal operations, the reactivity of the storage vault will be lower by about 0.02. These calculations were not reperformed using the revised basket designs nor were similar analyses performed for Mark IA MCOs.

Figure 5-3 shows the k_{eff} for a range of water densities between the CSB storage tubes when they are loaded with flooded MCOs containing Mark IV fuel. The curve rises only marginally, to a maximum k_{eff} less than 0.93 at a water density of 0.002 g/cm^3. This shows the reactivity for an infinite array of fully flooded Mark IV MCOs in the CSB will be below 0.95 for all values of interspersed moderation between the storage tubes. Flooding the CSB vault containing flooded MCOs is a beyond design basis event. Reactivity is not required to stay below 0.95 for an event such as this, and the information is provided for information only.

5.2.8 Handling a Flooded Multi-Canister Overpack with the Multi-Canister Overpack Handling Machine

Should a flooded MCO get to the CSB, it could be loaded into a storage tube. Figure 5-5 shows the configuration of the MCO being lowered by the MHM, and Table 5-9 shows that the reactivity is acceptable for this single contingency event.

5.2.9 Loading a Multi-Canister Overpack in a Tube with no Intermediate Impact Absorber

It is possible to load the second MCO in a storage tube without installing the intermediate impact absorber. For this situation, the CSB array was modeled containing one tube with two MCOs and no intermediate impact absorber. The model used for these calculations was updated to include the lower and intermediate impact absorber, the latest basket and MCO dimensions, correct mass limits for the scrap baskets, and the full length of the MCO. Both the normal array of drained MCOs and the array containing the tube with no impact absorber were analyzed and the results reported in Table 5-10. The results show that the presence of the intermediate impact absorber has no effect on reactivity for drained MCOs. This is because of the space and plug above the top scrap basket, which isolates the top and bottom MCOs from each other.

Table 5-9. Flooded Multi-Canister Overpacks in the Multi-Canister Overpack Handling Machine and Lowered through the Canister Storage Building Floor.

Case	MCO initial configuration	k_{calc}	σ_c	k_{eff}*
mhm1.0	Flooded Mark IA MCO in the MHM	0.89770	0.00101	0.90880
mhm1.2	Flooded Mark IA MCO lowered 2.5 ft through the floor	0.89562	0.00093	0.90670
mhm1.5	Flooded Mark IA MCO lowered 5 ft through the floor	0.89726	0.00096	0.90835
mhm4.1	Flooded Mark IV MCO in the MHM	0.92192	0.00086	0.93299
mhm4.3	Flooded Mark IV MCO lowered 2.5 ft through the floor	0.92048	0.00090	0.93155
mhm4.5	Flooded Mark IV MCO lowered 5 ft through the floor	0.91996	0.00089	0.93103

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.
MHM = multi-canister overpack handling machine.

Table 5-10. Canister Storage Building Array with Single Storage Tube Containing Two Multi-Canister Overpacks and No Intermediate Impact Absorber.

Case	MCO initial configuration	k_{calc}	σ_c	k_{eff}*
csb1.0	10 x 22 x 2 array of dry Mark IA MCOs	0.32167	0.00029	0.33265
csb1.1	10 x 22 x 2 array of dry Mark IA MCOs; one tube contains no intermediate impact absorber	0.32170	0.00028	0.33268
csb4.0	10 x 22 x 2 array of dry Mark IV MCOs	0.34860	0.00034	0.35959
csb4.1	10 x 22 x 2 array of dry Mark IV MCOs; one tube contains no intermediate impact absorber	0.34878	0.00033	0.35976

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.

5.2.10 Flooding the Sampling/Weld Station with Glycol

The temperature of an MCO in the CSB sampling/weld station is controlled by a cooling system containing propylene glycol. The glycol circulates through the upper shield region that surrounds the upper portion of the MCO. For this scenario, it was assumed that the cooling system failed and the void region along the entire lengths of the MCO was flooded. The composition of the coolant was assumed to be 100% propylene glycol ($C_3H_8O_2$). More than 12 in. of concrete separates the stations from each other, neutronically isolating them, so only one station is modeled. The personnel access area around the top of the MCO was assumed to be concrete to provide maximum reflection. Calculations were performed for both flooded and drained MCOs and the results are listed in Table 5-11.

Table 5-11. Canister Storage Building Sampling/Weld Station Flooded with Propylene Glycol and Containing a Multi-Canister Overpack.

Case	Description	Calculation results		
		k_{calc}	σ_c	k_{eff}
gly1.0	Mark IA MCO drained	0.27052	0.00054	0.28153
gly1.1	Mark IA MCO flooded	0.88571	0.00097	0.89680
gly4.0	Mark IV MCO drained	0.30981	0.00073	0.32085
gly4.1	Mark IV MCO flooded	0.91360	0.00094	0.92468

*$k_{eff} = k_{calc} + 0.0004 + ((0.01)^2 + (1.645)^2(\sigma_c^2 + 0.002083^2))^{1/2}$ as defined in Section 3.2. This value should be less than 0.95.

MCO = multi-canister overpack.

These results show that the cooling system containing propylene glycol for the sampling/weld station does not compromise criticality safety. The models of the MCO were updated to incorporate the most recent design changes to the MCO internals and the fuel and scrap baskets.

5.3 CRITICALITY INSTRUMENTATION

This section addresses the need for criticality alarm systems and criticality detection systems. DOE Order 5480.24 references ANSI/ANS-8.3-1997, *Criticality Accident Alarm System*, for requirements relating to nuclear criticality alarm systems. ANSI/ANS-8.3-1997states that neither a criticality alarm system or criticality detection system is required where the probability of a criticality accident is determined to be less than 1×10^{-6} per year. Interpretive guidance on the probability determination (Holten 1993) states: "The use of 10^{-6} does not necessarily mean that a PRA [probabilistic risk assessment] has to be performed. Reasonable grounds shall be presented

on the basis of commonly accepted engineering judgement." Accordingly, the remaining discussion supports the judgement that no criticality alarm or detection systems are required in the CVDF or the CSB.

The MCO is designed to be criticality safe even when fully moderated by water, as it normally is until it is drained at the CVDF. Only one MCO is allowed per process bay at the CVDF. Under normal conditions at the CSB, the MCOs will be dry, and without moderation, the SNF stored at the CSB cannot be made critical. The presence of a significant quantity of water or other neutron moderator in or around the MCOs at the CSB is judged to be an unlikely event. Furthermore, all situations analyzed show that k_{eff} is less than the criticality safety limit of 0.95.

These results show that for single MCOs, at least three contingencies (unlikely, independent, and concurrent events) are necessary before k_{eff} exceeds 0.95. An event is classified as unlikely if its expected frequency is greater than 10^{-4} per year but less than 10^{-2} per year (DOE-STD-3009-94). The probability of three contingencies is then less than $(10^{-2})^3$ per year or 10^{-6} per year. Thus, on the CSB operating deck, where MCOs are handled as single units, the probability of a criticality is less than 10^{-6} per year.

The following discussion provides an analysis of the CSB vault. From results reported earlier in this document, the most reactive single-contingency MCO at the K Basins contains completely rubblized Mark IV fuel. This MCO is also flooded, which is the normal condition there. At the CSB, where MCOs are normally dry, a flooded and rubblized MCO requires two contingencies. Analysis described in Section 5.7.2 shows that the addition of a significant quantity of water to the vault and storage tubes decreases reactivity.

Another two-contingency case unique to the CSB vault involves a scenario in which a normal (drained) MCO is placed in a storage tube on top of a flooded MCO with no intermediate impact absorber between the two. Calculations described in Section 5.2.9 show that the intermediate impact absorber has an insignificant effect on reactivity. Thus, the k_{eff} of an arrangement in which a flooded MCO has a normal MCO directly above or below it would be similar to that of a flooded MCO in a storage tube (see Section 5.2.3).

Thus, any two credible contingencies in the CSB vault will not result in a criticality. A third contingency is required. As with a single MCO on the operating deck, the probability of a criticality in the vault is then judged to be less than 10^{-6} per year. Therefore no criticality alarm system or criticality detection system is required at the CVDF or CSB.

5.4 SUMMARY

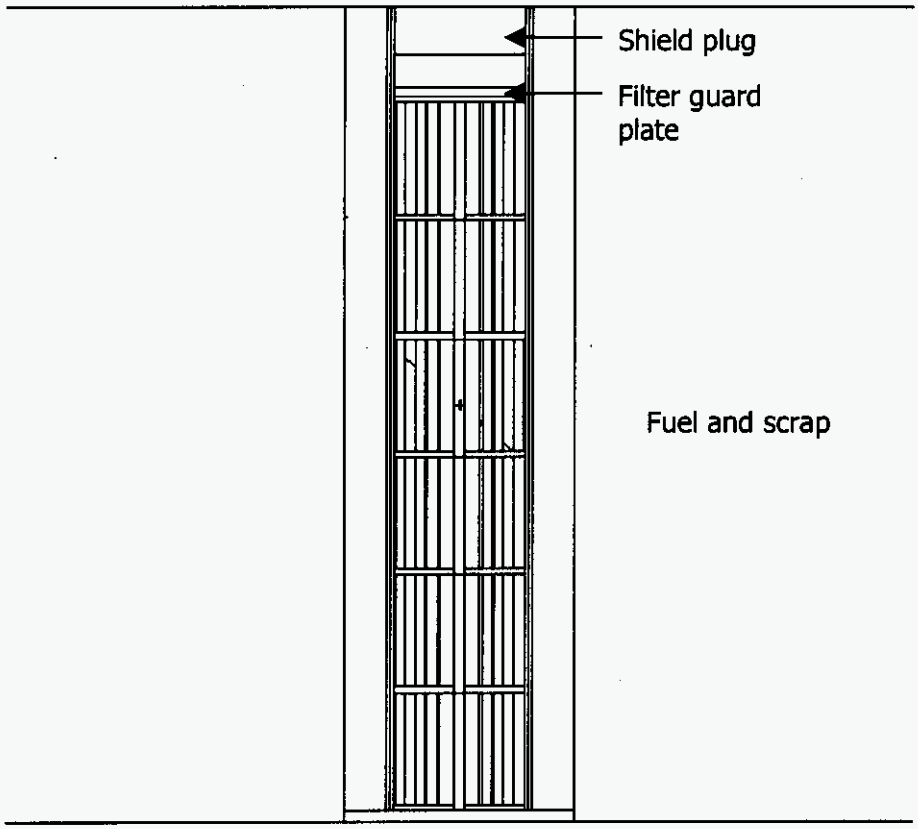
In summary, conservative assumptions have been made for determining worst-case normal and off-normal conditions for the MCO during processing at the CVDF and storage at the CSB. The analyses assumed unirradiated fuel, optimum size scrap rod diameters and optimum water to fuel volume ratios for the scrap and rubble, and appropriate contingencies of misloading scrap or fuel in an MCO. Many of the analyses performed for this CSER have been redone using the

revised designs of the MCO and baskets and incorporate the limits on mass in the scrap baskets established by HNF-SD-SNF-CSER-010 (Kessler and Peck 1999). Some analyses were not redone using revised designs, specifically ones pertaining to drained MCOs in the CSB vault because they were conservative in their assumptions. The results are retained in this revision.

The analyses show that the double contingency principle is met. In many cases, the off-normal conditions have gone beyond the double contingency criteria. Scenarios involving misloading an MCO and shipping a flooded MCO from the CVDF to the CSB require the failure of several administrative controls to occur. Flooding of MCOs in storage at the CSB not only requires failure of administrative controls but also failure of CSB design features. In spite of these assumptions, the scenarios are in compliance with the criticality safety requirements.

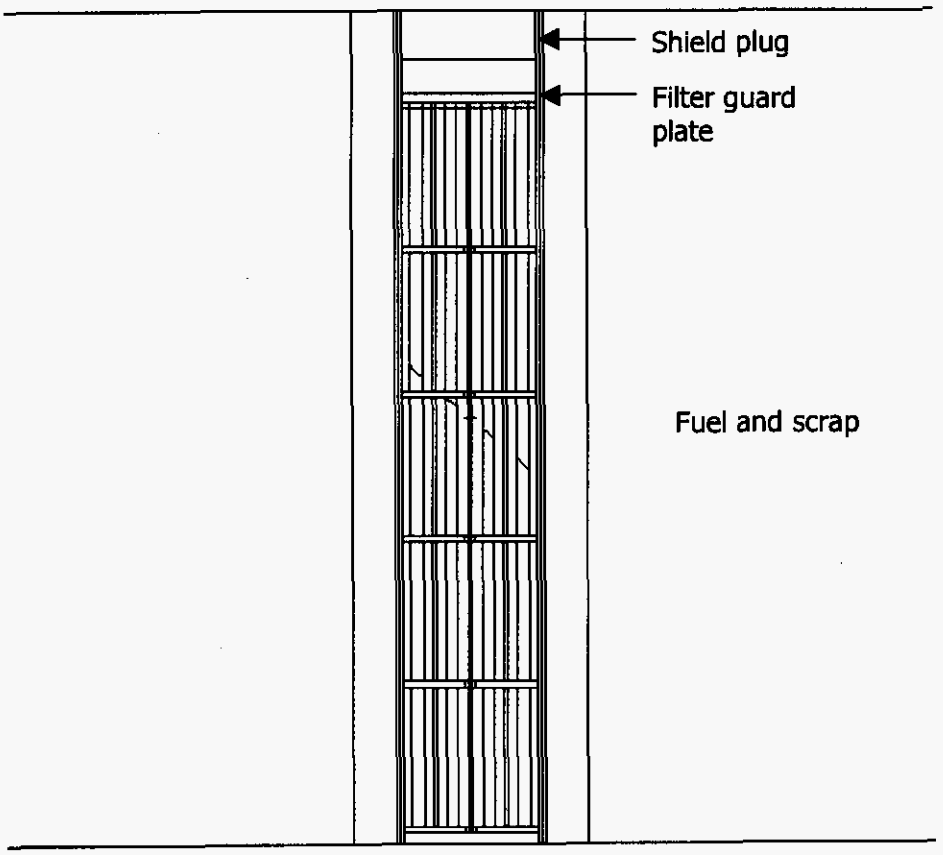
In conclusion, the possibility that the k_{eff} of an MCO or of an array of MCOs could exceed 0.95 requires not only the failure of design features and the failure of administrative controls but also requires that the fissile material form unfavorable configurations that are not credible. This is especially true for the scrap, which is assumed to be optimized for all calculations. The k_{eff} for credible scenarios will be considerably less than 0.95.

Figure 5-1. Drop Analysis Input Model - Mark IA.



Mark IA Drop Model

Figure 5-2. Drop Analysis Input Model - Mark IV.



Mark IV Drop Model

Figure 5-3. Interspersed Moderation for Flooded Mark IV Multi-Canister Overpacks in the Canister Storage Building.

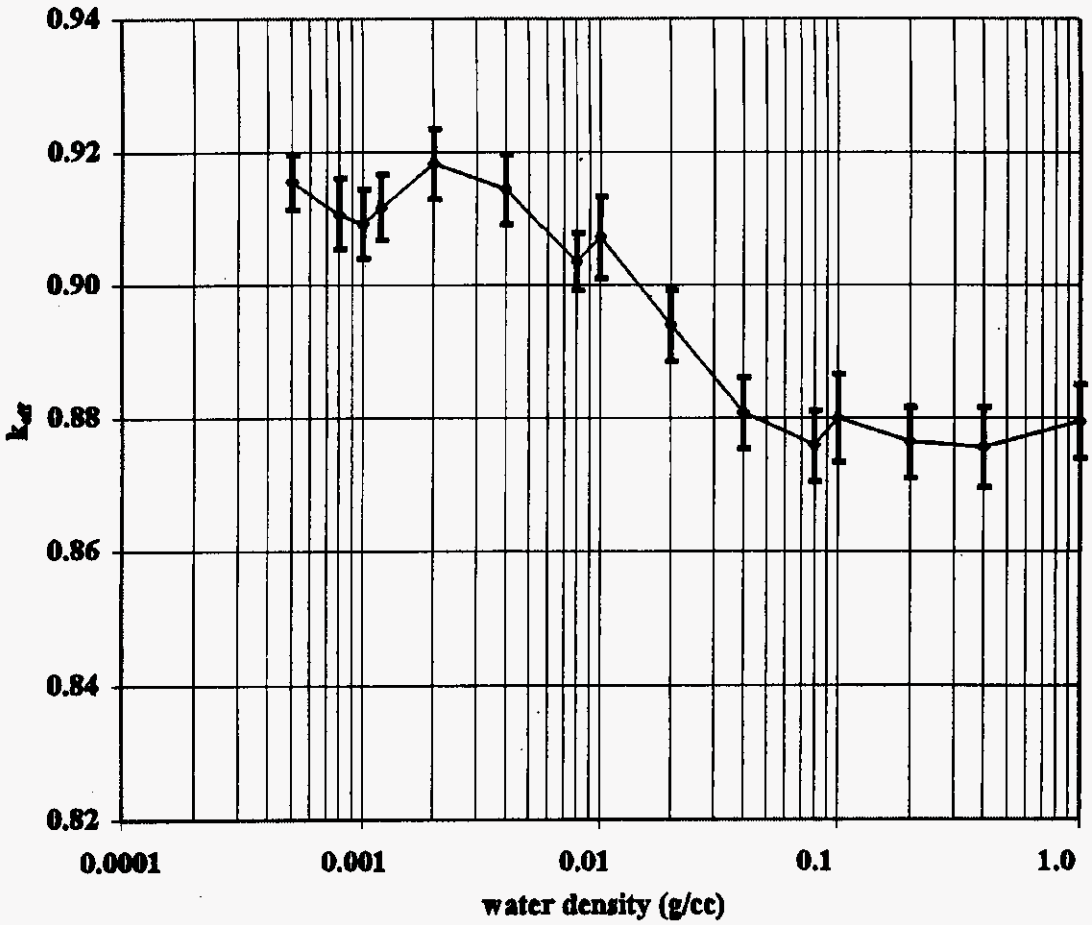


Figure 5-4. Interspersed Moderation for Dry Mark IV Multi-Canister Overpacks in the Canister Storage Building.

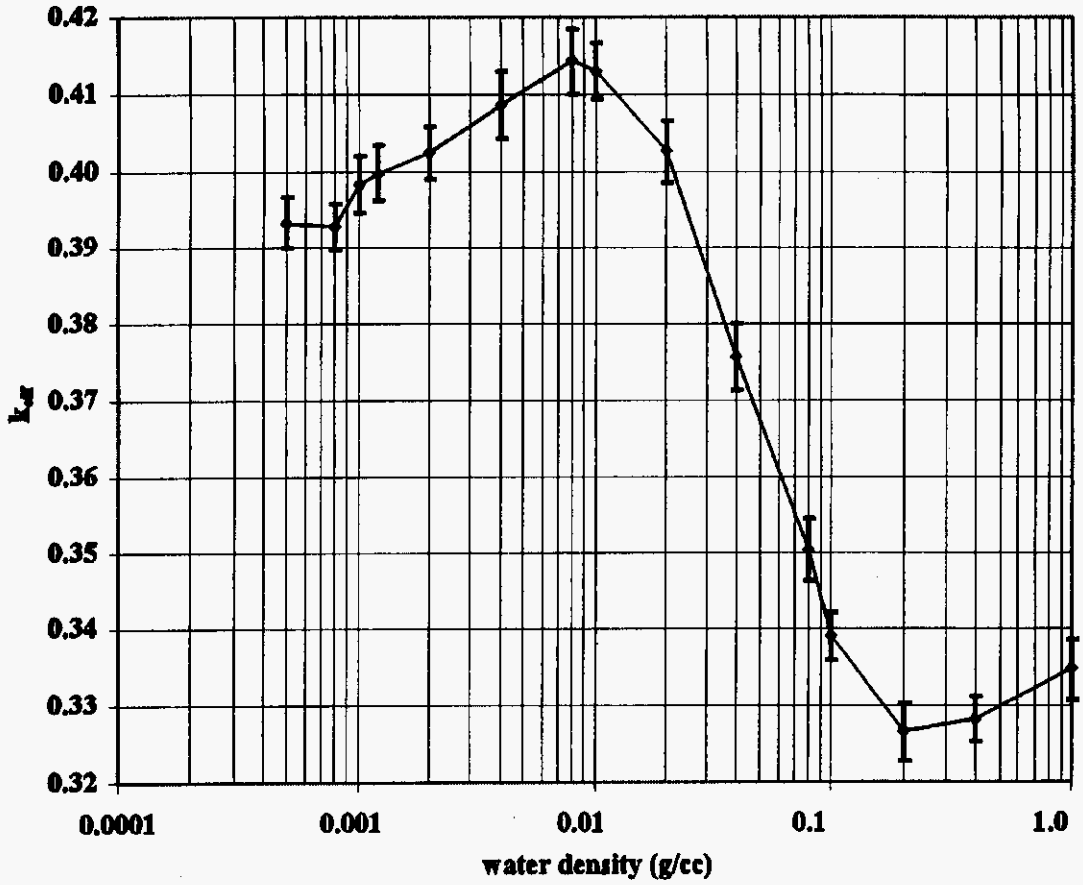
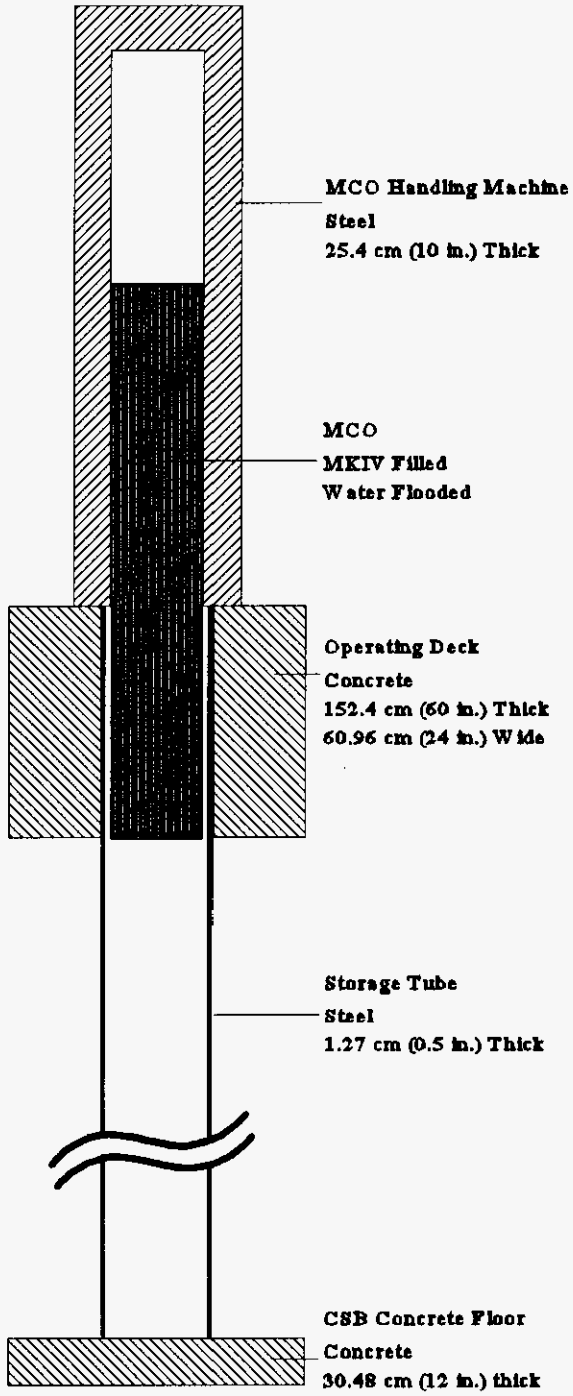


Figure 5-5. Water-Flooded Multi-Canister Overpack Loaded with Mark IV Fuel Being Lowered into a Canister Storage Building Storage Tube.



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6.0 PEER REVIEW

Practice 134 290 1112
Publication Date 01Mar99
Attachment 02 – Sheet 1 of 1

FLUOR DANIEL NORTHWEST

TECHNICAL PEER REVIEWS

CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed: HNF-SD-SNF-CSER-005, Rev. 5
Title: Criticality Safety Evaluation Report for the Multi-Canister Overpack
Author: S. F. Kessler
Date: October 13, 1999
Scope of Review: Changes made and additions to Rev. 4 that resulted in Rev. 5.

Yes	No*	NA	
[x]	[ ]	[ ]	**Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
[x]	[ ]	[ ]	Problem completely defined.
[x]	[ ]	[ ]	Accident scenarios developed in a clear and logical manner.
[x]	[ ]	[ ]	Necessary assumptions explicitly stated and supported.
[x]	[ ]	[ ]	Computer codes and data files documented.
[x]	[ ]	[ ]	Data used in calculations explicitly stated in document.
[x]	[ ]	[ ]	Data checked for consistency with original source information as applicable.
[ ]	[ ]	[x]	Mathematical derivations checked including dimensional consistency of results.
[x]	[ ]	[ ]	Models appropriate and used within range of validity or use outside of range of established validity justified.
[x]	[ ]	[ ]	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
[x]	[ ]	[ ]	Software input correct and consistent with document reviewed.
[x]	[ ]	[ ]	Software output consistent with input and with results reported in document reviewed.
[x]	[ ]	[ ]	Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
[x]	[ ]	[ ]	Safety margins consistent with good engineering practices.
[x]	[ ]	[ ]	Conclusions consistent with analytical results and applicable limits.
[x]	[ ]	[ ]	Results and conclusions address all points required in the problem statement.
[x]	[ ]	[ ]	Format consistent with applicable guides or other standards.
[ ]	[ ]	[x]	**Review calculations, comments, and/or notes are attached.
[x]	[ ]	[ ]	Traceability
[x]	[ ]	[ ]	Document approved (for example, the reviewer affirms the technical accuracy of the document).

Joseph V. Nelson *Joseph V Nelson* — *10/13/99*
Reviewer (printed name and signature) — Date

* All "no" responses must be explained below or on an additional sheet.

** Any calculations, comments, or notes generated as part of this review should be signed, dated, and attached to this checklist. Such material should be labeled and recorded in such a manner as to be intelligible to a technically qualified third party.

Nuclear Engineering

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APPENDIX A

VALIDATION OF CALCULATIONAL METHODS

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APPENDIX A

VALIDATION OF CALCULATIONAL METHODS

A.1 BENCHMARK EXPERIMENTS AND APPLICABILITY

Benchmark experiments are primarily utilized to confirm two aspects of the neutron transport analysis tool:

- That the computer code has a sound treatment of the neutron transport.
- That the nuclear cross section database used in the transport code is in agreement with the relevant integral experiments.

The MCNP computer code (Breismeister 1993, Carter 1996) is used worldwide and has been extensively tested with its ENDF/B-V-based cross sections. The code development group at Los Alamos National Laboratory, where MCNP was developed, also has a set of 25 calculational benchmarks that extensively test various options within the code. These 25 benchmarks are used to confirm that new versions of the code give answers equivalent to those in previous versions, and that executables for users at other sites give exactly the same answer. Hence, the 25 calculational benchmarks supplement additional calculations made on experimental benchmarks.

MCNP validation efforts specifically appropriate for low-enriched uranium metal systems have been made to cover N Reactor fuel elements in water (Wittekind 1991; Wittekind 1992; Wittekind 1993) and low-enriched uranium solutions (Wittekind 1994). The calculational bias has also been determined (Schmittroth and Ruben 1996). The methodology of applying the bias and uncertainty is discussed in Section 3.2.

The WIMS-E code (Gubbins et al. 1982) was used in this analysis to illustrate trends while the detailed three-dimensional criticality calculations were performed using MCNP. WIMS-E also has been extensively validated against critical experimental data. Previous validation efforts have covered low-enriched uranium metal billets (Erickson 1992; Schwinkendorf 1985a; Schwinkendorf 1985b), Mark IA fuel assemblies and uranium metal rods (Schwinkendorf 1992a), and low-enriched uranium solutions (Schwinkendorf 1992b; Wittekind 1992).

A1.1 Details of Benchmark Calculations

MCNP Benchmark Calculations

MCNP has been tested extensively, but the focus here is on a series of benchmark calculational comparisons (Whalen et al. 1991) with experiments that were made at Los Alamos National Laboratory. The first and second series of the comparisons in *MCNP: Neutron Benchmark Problems* (Whalen et al. 1991) were made to confirm agreement with experiments for

fixed source calculations. The third series was for comparison with critical assemblies. These calculations included comparisons for fast neutron systems (Godiva and Jezebel assemblies), for low-enriched uranium systems, for graphite and water-reflected systems, and for interactive (array) units. The powerful geometry features in MCNP were used to model these systems in detail.

WIMS-E Benchmark Calculations

The uranium metal rods validation included critical experimental data from two sources. The first source (Hellens and Honeck 1962) contained data for 1.0 wt% ^{235}U-enriched rods and included measured boron poison effects. The published results were in the form of bucklings, not critical masses or k_{eff}. In order to compare WIMS-E results to the published results, WIMS-E results were output as two-group lattice-averaged cross sections for each experiment, and an analytical formula was used to calculate buckling for each case. WIMS-E results compared very well with experimental results, both as a function of water-to-uranium volume ratio and as a function of amount of poison added. The second source (Kupinski and Toffer 1970) contained data over a range of rod outside diameters (0.444 cm [0.175 in.] outside diameter to 7.62 cm [3.0 in.] outside diameter) and ^{235}U enrichments (3.0 wt% ^{235}U to 4.89 wt% ^{235}U). These results were in the form of critical masses in spherical and cylindrical geometry. Validations for the earlier version of the code, WIMS-D, document comparisons with annular uranium metal tubes over a range of enrichments from 0.947-wt% ^{235}U to 2.1-wt% ^{235}U (Schwinkendorf 1985a).

A1.2 Results of Benchmark Calculations

Agreement between the MCNP code and experiments for k_{eff} was within 1% for all of the critical systems referenced in Whalen et al. (1991). The MCNP N Reactor fuel bias was determined to be -0.4 mk (Schmittroth 1996). This means that MCNP would calculate k_{eff} about 0.4 mk less than experimental measurements would calculate it.

WIMS-E tends to follow critical experimental data more accurately than WIMS-D but is still conservative. Therefore, it has been the practice to neglect the imposition of a bias when using WIMS-E to calculate k_∞, buckling, or cross sections that are input to a diffusion theory code (to calculate idealized, finite dimensions). Inclusion of the bias would reduce the degree of conservatism in the result.

A.2 RESULTS OF ROD AND CYLINDER COMPARISONS

This criticality safety evaluation report treats a random arrangement of scrap as a lattice of uranium rods in water. A series of MCNP calculations have been performed to determine whether a regular lattice in cylindrical geometry will necessarily produce a bounding k_∞ for any arbitrarily shaped chunk of material, whether an explicit spherical lattice will optimize to a higher k_∞ and if it does, then how one would bound irregular lattice geometries. These MCNP calculations compared a hexagonal rod lattice with a three-dimensional lattice based on spheres

arranged in a face-centered-cubic geometry. The fissionable material assumed was uranium metal with an enrichment equal to 0.95 wt% ^{235}U. For both rods and spheres, a double parameter search was made to find the maximum k_∞ (as the spacing was varied) as a function of uranium chunk diameter. The results indicate that even though the maximum k_∞ may occur for slightly different diameters, the maximized value for k_∞ was essentially the same (well within the 1σ uncertainty in the calculation). The use of rod lattices to model scrap is therefore considered to be appropriate.

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APPENDIX B

SENSITIVITY STUDIES

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APPENDIX B

SENSITIVITY STUDIES

A number of design variable uncertainties (i.e., an assortment of fuel assembly lengths, unresolved cask dimensions, and degree of fuel corrosion) affect the reactivity of a multi-canister overpack (MCO). These uncertainties are addressed in this appendix.

Base case calculations discussed in Section 4.5 were performed with conservative assumptions, such as long lengths for Mark IV and Mark IA fuel assemblies, extremes of unresolved design dimensions, and optimum or full moderator densities. The following cases show the relationship of MCO reactivity to several design variables.

B.1 FUEL LENGTH

Both the Mark IA and Mark IV fuel assemblies were manufactured in discrete lengths. The longest Mark IA and Mark IV fuel assemblies are 26.1 in long. Only twelve of the 26.1-in.-long Mark IA assemblies are stored in the K Basins. For this criticality safety evaluation report, the maximum length of a Mark IA assembly is assumed to be 20.88 in. All the cases in Table B-1 represent flooded MCOs loaded with Mark IA fuel assemblies in the four central baskets, with assembly length varied, and Mark IA scrap in the top and bottom baskets. The cases in Table B-2 represent flooded MCOs loaded with Mark IV fuel assemblies in the three central baskets, with assembly length varied, and Mark IV scrap in the top and bottom baskets. The results show a modest sensitivity to the fuel length variations. The maximum k_{eff} for a Mark IA-loaded MCO occurs at a fuel length of 19.6 in. Mark IV fuel reactivity decreased for all lengths shorter than 26.1 in., with a maximum decrease of about 7 mk for the fuel length corresponding to 23.2 in. (1 mk is a 0.001 change in k_{eff}).

B.2 MASS CHANGE CAUSED BY FUEL CORROSION

The next two sets of sensitivity cases involve counteracting situations involving fuel mass lost from the upper baskets because of corrosion and fuel mass added to the lower baskets because of uranium oxide particles dropping from upper baskets. The second set of cases investigates the reactivity effect of fuel mass redistribution, which was modeled as a conservative uniform mass increase in the MCO's central intact fuel baskets.

Fuel mass will be lost from damaged fuel because of corrosion and the removal of that corrosion during cleaning of the fuel in the K Basins before it is loaded into the MCOs. The effect on reactivity of this fuel mass loss is shown in cases ocvd4.11, ocvd4.12, and ocvd4.13 in Table B-3. In these cases, uniform loss of mass in a Mark IV MCO was modeled as density reductions of 10%, 20%, and 30%. The reactivities of these cases show a slight and uncertain effect on reactivity for uniform mass loss at and below 20%. The results show a definite decrease of about 9 mk in reactivity corresponding to a decrease in fuel density of 30%.

Table B-1. Sensitivity Study for Varying Lengths of Mark IA Fuel.

Case	Fuel length (cm)	k_{calc}	σ	k_{eff}
ocvd1.1	53.08	0.8826	0.0031	0.8933
ocvd4.1	49.8	0.8877	0.0036	0.8988
ocvd4.2	37.8	0.8808	0.0031	0.8915

Table B-2. Sensitivity Study for Varying Lengths of Mark IV Fuel.

Case	Fuel length (cm)	k_{calc}	σ	k_{eff}
ocvd1.2	66.3	0.8894	0.0023	0.8995
ocvd4.3	62.5	0.8837	0.0024	0.8939
ocvd4.4	58.9	0.8817	0.0034	0.8926
ocvd4.5	44.2	0.8852	0.0028	0.8956

Table B-3. Sensitivity Study for Mass Reduction.

Case	Mass change	k_{calc}	σ	k_{eff}
ocvd1.2	Normal load	0.8894	0.0023	0.8995
ocvd4.11	Three baskets of intact fuel mass reduced by 10%	0.8891	0.0028	0.8995
ocvd4.12	Three baskets of intact fuel mass reduced by 20%	0.8883	0.0032	0.8991
ocvd4.13	Three baskets of intact fuel mass reduced by 30%	0.8808	0.0029	0.8913
ocvd4.14	Three baskets of intact fuel mass increased by 100 kg UO_2	0.8767	0.0029	0.8872
ocvd4.15	Three baskets of intact fuel mass increased by 200 kg UO_2	0.8624	0.0030	0.8730
ocvd4.16	Three baskets of intact fuel mass increased by 300 kg UO_2	0.8582	0.0027	0.8686

Fuel mass in each of the three baskets of intact fuel was assumed to be increased by uranium oxide dropped from corroded Mark IV fuel and Mark IV fuel scrap in the upper baskets and redistributed in the interstitial regions between the fuel assemblies and in the coolant channels of the fuel assemblies. The effect on reactivity of this fuel mass increase is shown in cases ocvd4.14, ocvd4.15, and ocvd4.16 in Table B-3. In these cases, a uniform mass of 100 kg, 200 kg, and 300 kg of additional UO_2 was modeled as being distributed in the central three fuel baskets. The reactivities of these cases show a progressive decrease in k_{eff} with increasing UO_2 mass when compared with case ocvd1.2.

B.3 SHIPPING CASK ANNULUS THICKNESS

The effect of cask annulus water thickness on reactivity was investigated. The reactivities were determined in cases ocvd4.17 through ocvd4.21 in Table B-4 for a Mark IV MCO. Case ocvd4.17 assumed no cask annulus gap, and cases ocvd4.18 through ocvd4.21 assumed progressive increments of 0.5 in. above the base case thickness of 0.5 in. The results in these cases showed that the reactivity progressively decreased with increasing cask annulus thickness.

Table B-4. Sensitivity Study for Change in Cask Annulus Thickness.

Case	Cask annulus thickness	k_{calc}	σ	k_{eff}
ocvd1.2	Normal annulus	0.8894	0.0023	0.8995
ocvd4.17	0.5-in. decrease of cask annulus region	0.8991	0.0028	0.9095
ocvd4.18	0.5-in. increase of cask annulus region	0.8829	0.0028	0.8933
ocvd4.19	1.0-in. increase of cask annulus region	0.8793	0.0030	0.8899
ocvd4.20	1.5-in. increase of cask annulus region	0.8776	0.0036	0.8887
ocvd4.21	2.0-in. increase of cask annulus region	0.8707	0.0031	0.8814

B.4 WATER LEVEL AND DENSITY

Several calculations have been performed to address changes in water level within the MCO. Both fully flooded and dry cases have been evaluated, as well as intermediate water densities that span the range from fully flooded to dry. As water density decreases inside the MCO, the k_{eff} of the system decreases rapidly, as shown in Figure B-1. In this study, the water density outside the MCO is held constant at 1.0 g/cm^3.

Figure B-2 shows the sensitivity of k_{eff} to changes in water density between MCO containers. As the water between MCO containers is reduced (with water density held constant at 1.0 g/cm^3 inside the MCO), the k_{eff} does not change significantly. These results indicate that

k_{eff} is far more sensitive to water density inside the MCO than to interspersed water density between MCOs. Without internal flooding, the k_{eff} of the MCO will always be less than 0.5.

B.5 PLUTONIUM DISTRIBUTION

Optimal scrap is treated as unexposed fuel pieces with no plutonium buildup. One concern has been that plutonium buildup on the exterior surface of a fuel element might preferentially corrode off the element and contribute to more highly reactive scrap pieces in K Basin sludge. This question was addressed for waste streams sent to the Hanford Site tank farms (Rogers 1996). While enhanced plutonium buildup near the outer surface of nuclear fuel (not just Hanford Site reactor fuel) is well-known, the peaking factor, which may be defined as the plutonium concentration at the surface divided by the average plutonium concentration, is not much greater than a factor of two (see Appendix E).

Enhanced ^{235}U depletion also occurs at the fuel surface. Criticality is affected by both the ^{239}Pu buildup and the ^{235}U depletion. However, fuel corrosion tends to progress axially from damaged ends and not radially inward. Comparison of 1.25 wt% uranium and U–Pu solutions at optimal hydrogen-to-uranium metal atom ratios (H/U) illustrates the U/Pu ratio required for equivalency. For a k_{eff} of 0.98 in hemispherical geometry, the minimum uranium mass required is 2,303 kg for 1.25 wt% enriched uranium solutions (Schwinkendorf 1995).

A parametric study was carried out for solutions of uranium and plutonium with varying H/U and U/Pu ratios (Erickson 1994). Table 2 of HNF-SD-NR-CSER-014, *Criticality Safety Evaluation Report for the 100 KE Basin Sandfilter Backwash Pit* (Erickson 1994), contains calculated minimum masses for a k_{eff} of 0.98 as a function of U/Pu ratio. These results are minimum because the H/U ratio was optimized for each U/Pu ratio. Interpolating between the tabulated data points, the U/Pu ratio required is 193 (minimum mass of 2,303 kg for a k_{eff} of 0.98), at which point the optimal H/U ratio is approximately 7. Therefore, as long as the U/Pu ratio is greater than about 190, the critical mass of optimized uranium–plutonium solution will be greater (and the solution less reactive) than for the optimized 1.25 wt% enriched uranium solution.

The uranium and plutonium isotopic breakdown assumed in HNF-SD-NR-CSER-014 (Erickson 1994) was based on measurements taken from the 100 KE Basin sandfilter backwash pit and is considered representative of actual uranium and plutonium concentrations currently in the fuel storage basins. Furthermore, the measured U/Pu ratio was in excess of 300 and is expected, from N Reactor production tables (Hedengren 1987), to be 450, which also is consistent with WIMS-E burnup results shown in Appendix E. Therefore, treating fuel corrosion product sludge as 1.25 wt% UO_2 solution will bound any real corrosion product sludge arising from exposed fuel assemblies. The measured U/Pu data indicate that plutonium buildup is insufficient to yield reactivity greater than the assumed 1.25 wt% enriched solution model.

B.6 LATTICE SPACING FOR INTACT FUEL ASSEMBLIES

The MCO analyses reported in this criticality safety evaluation report use a center-to-center hexagonal spacing of 2.8 in. for fuel assemblies. The spacing is established by rings on the bottom of the fuel baskets. Previous analyses have shown that the optimal spacing of N Reactor fuel in water is around 3.1 in. Using a larger spacing than 2.8 in. would make loading the MCO containers easier, but this would increase the reactivity of the lattice because the current design is undermoderated.

The effect of fuel assembly spacing was analyzed using the Monte Carlo n-particle transport code (MCNP) (Breismeister 1993, Carter 1996) for the geometric arrangement in Figure B-3, using various lattice spacings from 2.65 in. to 2.90 in. The axial arrangement is as shown in CASE1 (Figure B-4) but with both top and bottom scrap baskets replaced with intact fuel so that the effect is not overshadowed by the more reactive scrap material. A lattice spacing of 2.90 in. is only possible if the outermost 12 assemblies are removed, or they will impact the inner wall of the MCO. This reduced arrangement is shown in Figure B-5. The CASE1 MCNP model assumes an MCO inner diameter of 23.0 in., but the nominal value is only 22.625 in. Assuming this smaller value, the largest possible lattice spacing is just over 2.80 in., which is indicated in Figure B-6. Although an array of intact assemblies with a lattice spacing of 2.85 in. fits inside the MCNP model (with a 23.0-in. inner diameter), it will not fit inside the nominal 22.0625-in. inner diameter. For the 2.90-in. spacing, removal of 12 assemblies is required to fit the array inside the 23.0-in. MCNP model.

The nominal basket diameter is 22.625 in., and the internal diameter of the MCO is 23.25 in. The actual lattice spacing of 2.77 in. is conservatively approximated by 2.8 in. With the spacing of the bottoms of the fuel at 2.77 in., and the unrestrained tops at 2.8 in., the average spacing would be 2.785 in. The change in k_{eff} for this change in lattice spacing (0.015 in.) is only 0.004, derived from examination of the data shown in Figure B-6. This effect of increased fuel element spacing at the unrestrained tops of the intact fuel elements is small and will be neglected. Because decreasing the lattice spacing decreases the k_{eff}, ring spacing of less than 2.80-in. on the fuel bottom plates is covered conservatively by this analysis.

B.7 EFFECT OF UNIFORM CHANGE IN LATTICE SPACING (PARTIAL ASSEMBLIES)

A second set of MCNP calculations was completed to examine the reactivity effect of removing fuel to allow a greater lattice spacing. This set of calculations differs from the set described in the previous section by allowing the unrealistic situation of having partial assemblies in the outer row of the fuel basket. In Section C.6, if a whole assembly did not completely fit into the basket for a given lattice pitch, it was removed from the model. In the calculations described in this section, only that portion of an assembly that would not fit into the basket was removed from the model.

This model is inherently a lower leakage geometry because fuel pieces and partial assemblies exist near the outer boundary where they can intercept neutrons that would otherwise have leaked out. The k_{eff} for the 2.8-in. spacing is therefore somewhat higher (by about 15 mk) than the Mark IA MCO base case, CASE1. Figures B-7 and B-8 illustrate the trend as lattice spacing is changed for the CASE1 and CASE2 geometries (Mark IV MCO), when the Mark IA and Mark IV intact fuel arrangements are replaced with arrangements that have partial assemblies filling the empty spaces seen in Figure B-5) between the outer row of intact assemblies and the basket boundary. These figures clearly show that k_{eff} is not sensitive to lattice spacing (the upper and lower scrap baskets in both of these models are driving the k_{eff} of the system). If the top and bottom scrap baskets also are filled with the intact fuel lattice, the results are as shown in Figures B-9 and B-10.

MCOs loaded with only intact fuel are less reactive than MCOs loaded with the scrap baskets top and bottom. It is significant that even though Figures B-9 and B-10 show some increased reactivity with partially loaded baskets, when scrap baskets are loaded top and bottom, the reactivity of the system appears to be dominated by the scrap baskets. The increased reactivity attributable to partial fuel basket loading does not contribute significantly to the higher reactivity caused by the scrap baskets.

B.8 REACTIVITY EFFECT OF FUEL TEMPERATURE

The effect of temperature on reactivity was evaluated for both Mark IV and Mark IA fuel assemblies. The WIMS-E lattice code (Gubbins et al. 1982) was used to calculate lattice k_∞ and change in reactivity for both Mark IV and Mark IA fuel as a function of the temperature coefficient. The temperature coefficient may be approximated between two discrete temperatures using the following relationship:

$$\alpha_T \equiv \left.\frac{\partial\rho}{\partial T}\right|_T \approx \left.\frac{\Delta\rho}{\Delta T}\right|_T = \frac{10^5\ (k_\infty(T+\Delta T)\ -\ k_\infty(T-\Delta T))}{k_\infty(T+\Delta T)k_\infty(T-\Delta T)\ (2\Delta T)}\ \text{pcm/K}$$

The 10^5 multiplier in the equation converts the raw reactivity, $\Delta\rho$, into units of pcm, or percent milli-k. Figure B-11 illustrates the lattice k_∞ and temperature coefficients for both of these fuel types. As expected, both N Reactor fuel types have negative temperature coefficients because they contain large percentages of ^{238}U, which has a large negative Doppler coefficient. Mark IV fuel exhibits a slightly more negative temperature coefficient than Mark IA fuel because the ^{238}U content is greater. At room temperature (MCNP calculations reported here were performed at 300 K), the temperature coefficients are approximately -3 pcm/K. As temperature increases, the magnitude of the temperature coefficients become smaller but they remain negative.

B.9 DIMENSIONAL TOLERANCE

The effect of dimensional tolerance on reactivity was analyzed parametrically by a series of WIMS-E calculations. Table B-5 contains the radial dimension specifications for Mark IV and Mark IA fuel types (Jack 1988).

Table B-5. Radial Dimension Specifications for N Reactor Mark IV and Mark IA Fuel Assemblies.

	Mark IA	Mark IV
Outer element:		
Outer diameter	2.391 in. to 2.416 in.	2.410 in. to 2.435 in.
Inner diameter	1.754 in. to 1.779 in.	1.691 in. to 1.716 in.
Inner element:		
Outer diameter	1.237 in. to 1.256 in.	1.267 in. to 1.286 in.
Inner diameter	0.431 in. to 0.450 in.	0.473 in. to 0.492 in.

Table B-6 shows the variation in lattice k_∞ as the radial fuel dimensions are varied. Either minimum or maximum dimensions were selected to arrive at either minimum or maximum uranium fuel region thicknesses. In all cases, the fuel assemblies were placed in an infinite water lattice at optimal spacing. The sensitivity of reactivity to radial dimension tolerances has been shown to be less than 1 mk.

Table B 6. Sensitivity of Lattice k-Infinity to Radial Dimension Tolerances.

	Mark IA	Mark IV
Minimum uranium thickness	1.131423	1.062878
Nominal uranium thickness	1.132133	1.062349
Maximum uranium thickness	1.132055	1.061646

B.10 ENRICHMENT TOLERANCE

The effect of enrichment tolerance on reactivity was analyzed parametrically by a series of WIMS-E calculations. The enrichment tolerance for N Reactor fuel was equal to 0.006 wt% (Gant and Zilar 1977).

Table B-7 shows the variation in lattice k_∞ as the fuel enrichment was either increased or decreased by 0.006 wt% ^{235}U. In all cases, the fuel assemblies were placed in an infinite water lattice at optimal spacing. The sensitivity of reactivity to enrichment tolerance has been shown to be approximately ±2 mk for a ±0.006 wt% enrichment variation.

Table B-7. Sensitivity of Lattice k-Infinity to Enrichment Tolerances.

	Mark IA	Mark IV
Minimum uranium enrichment	1.130463	1.060261
Nominal uranium enrichment	1.132133	1.062349
Maximum uranium enrichment	1.133780	1.064408

B.11 REACTIVITY EFFECT OF PACKING FRACTION (WATER-TO-FUEL RATIO)

The packing fraction is the volume fraction of fuel in the unit lattice. An optimal packing fraction was used for scrap, with both size and spacing varied to maximize reactivity. The packing fraction varies according to enrichment but is equal to 0.320 for Mark IV scrap and 0.294 for Mark IA scrap.

B.12 MARK IV BASKET BASEPLATE WEIGHT

The baseplates are assumed in the MCNP input model to be solid (the holes are not explicitly modeled). CASE4 was modeled assuming that 0.375-in. stainless steel baseplates formed the bottom of the scrap baskets. Given the diameter of the baseplate, this model includes nearly 50 lb of steel. In reality, the baseplate weighs only 27.13 lb because it is perforated. Therefore, the model was modified by reducing the density of the baseplate material. The results are shown in Table B-8

Table B-8. Sensitivity Study for Baseplate Thickness.

Case	Basket baseplate weight	k_{calc}	σ	k_{eff}
CASE 4	50 lb	0.9344	0.0028	0.9448
CASE 4 modified	27.13 lb	0.9329	0.0027	0.9433

The removal of neutron-absorbing material (reduced steel density in the scrap basket baseplate) from the MCNP model should have increased the k_{eff} of the system. However, this change in the model is so slight that MCNP was not able to discern a statistically significant difference in the neutron multiplication constants between the two cases. The difference between the two k_{eff} values is only one-third of the 1-sigma statistical uncertainty in the two cases. The conclusion is that, within the statistical uncertainty in the MCNP results, there is no statistically significant difference between modeling the scrap basket baseplates at full density (as if they were not perforated) or at reduced density (to account for the perforations).

B.12 REFERENCES

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Figure B-1. Interspersed Moderation: Water Density Variation Inside Multi-Canister Overpack.

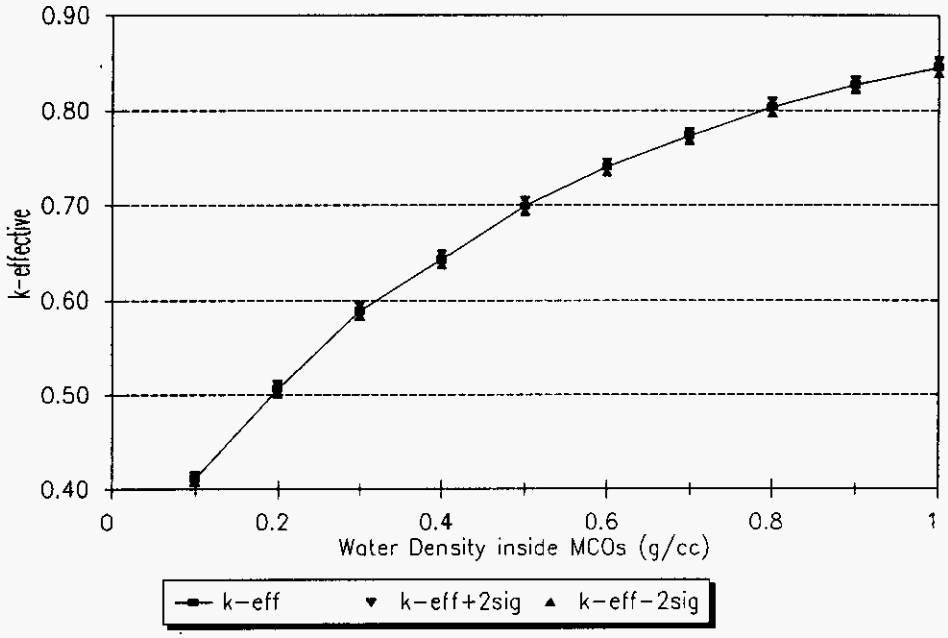


Figure B-2. Interspersed Moderation: Water Density Variation Outside Multi-Canister Overpack.

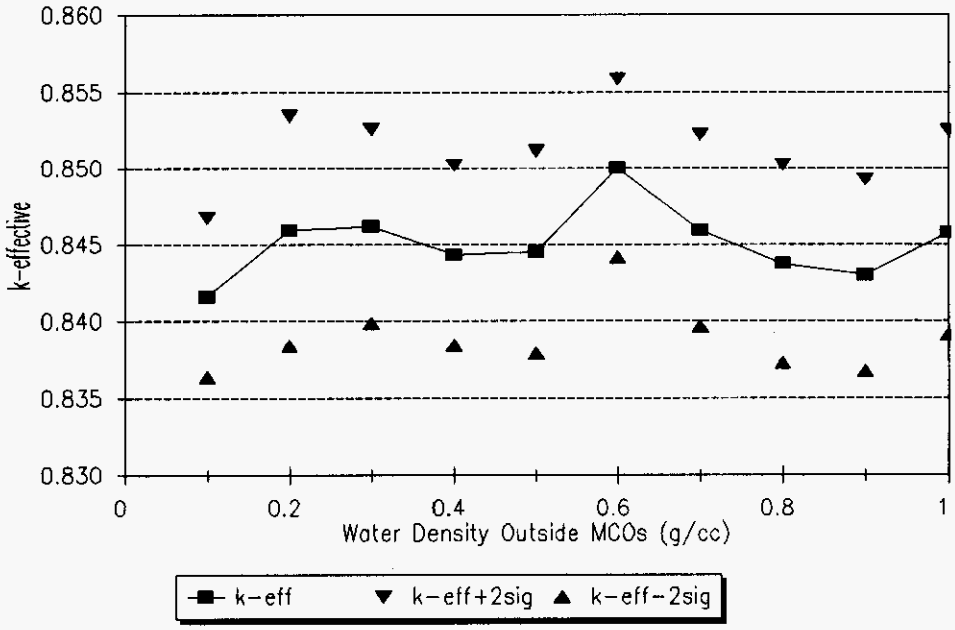


Figure B-3. Loading Arrangement for Mark IA Fuel in Multi-Canister Overpack in Cask.

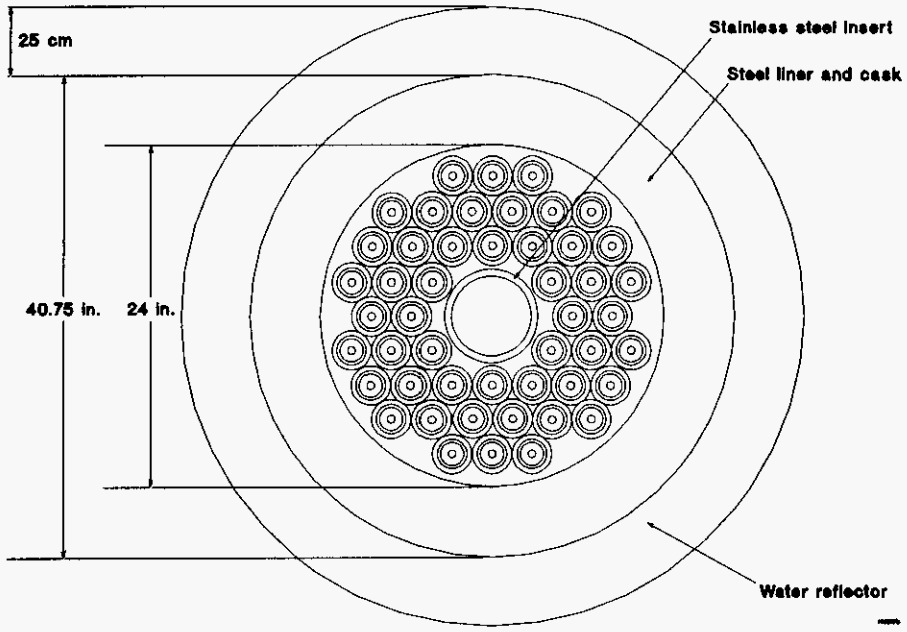


Figure B-4. Input Models CASE 1 and CASE 2: Axial Geometry.

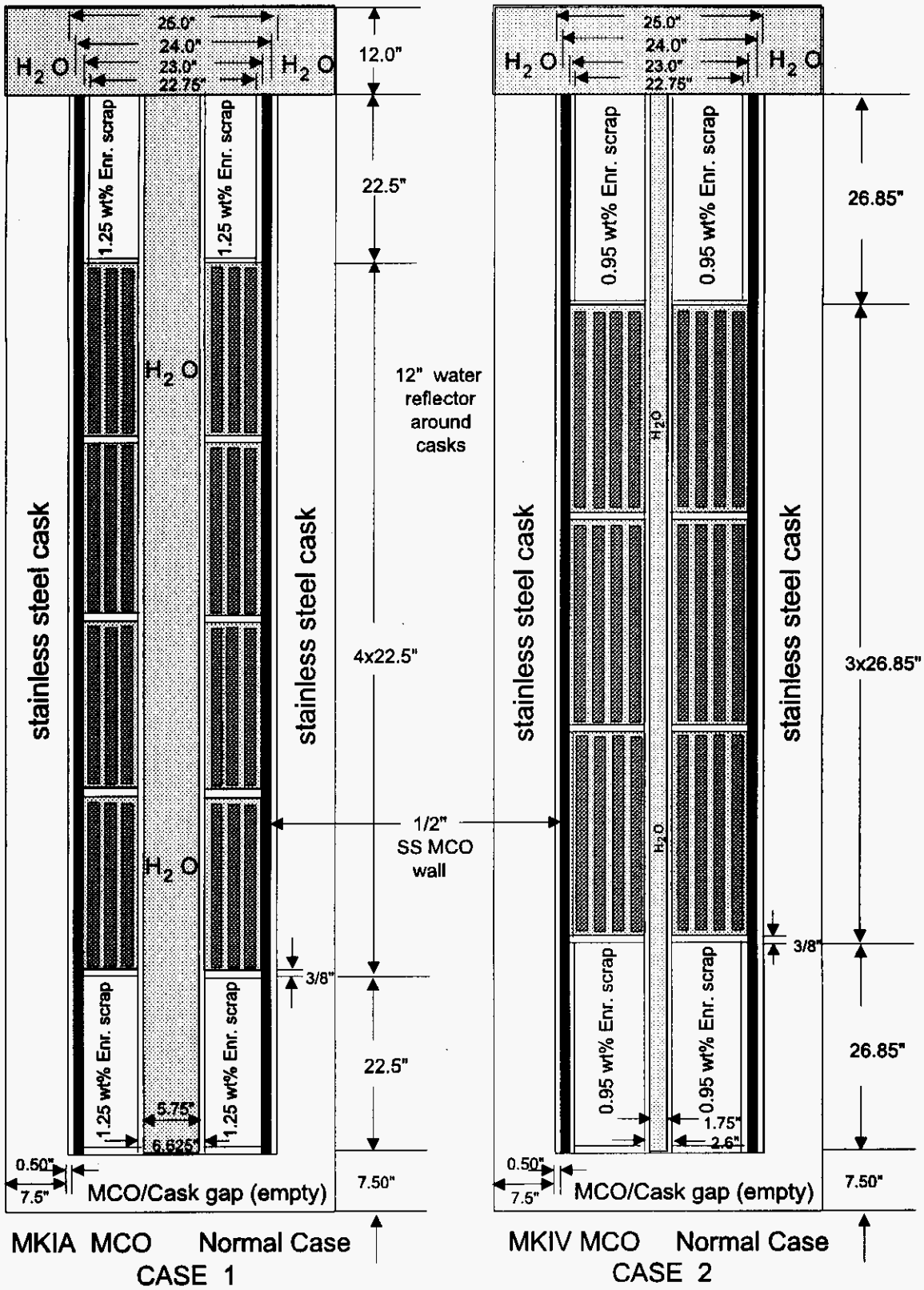


Figure B-5. Reduced Loading for Mark IA Fuel in Multi-Canister Overpack (12 Assemblies Removed).

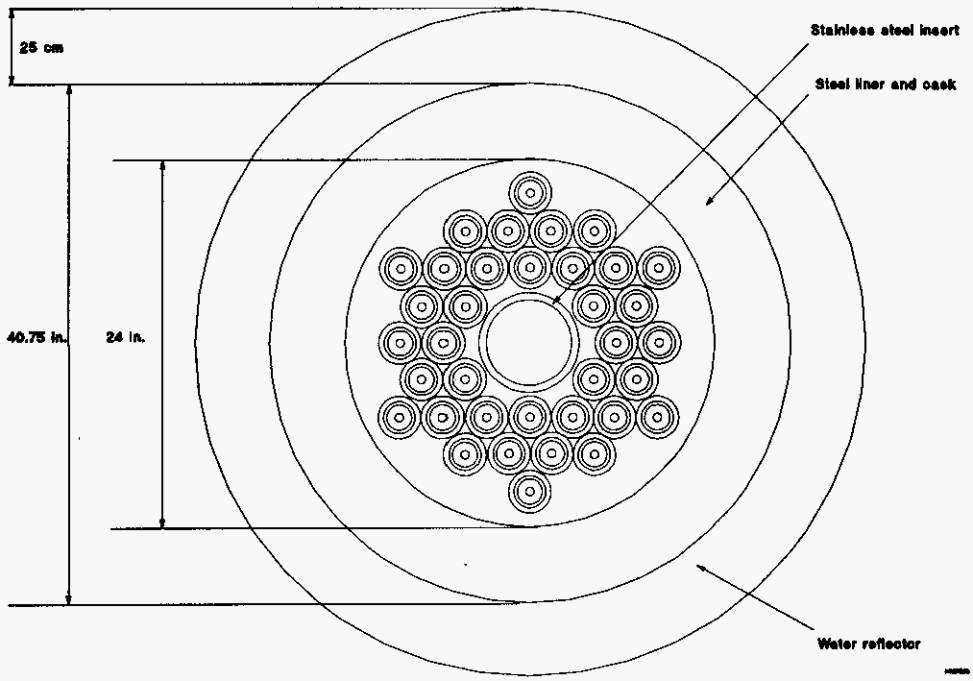
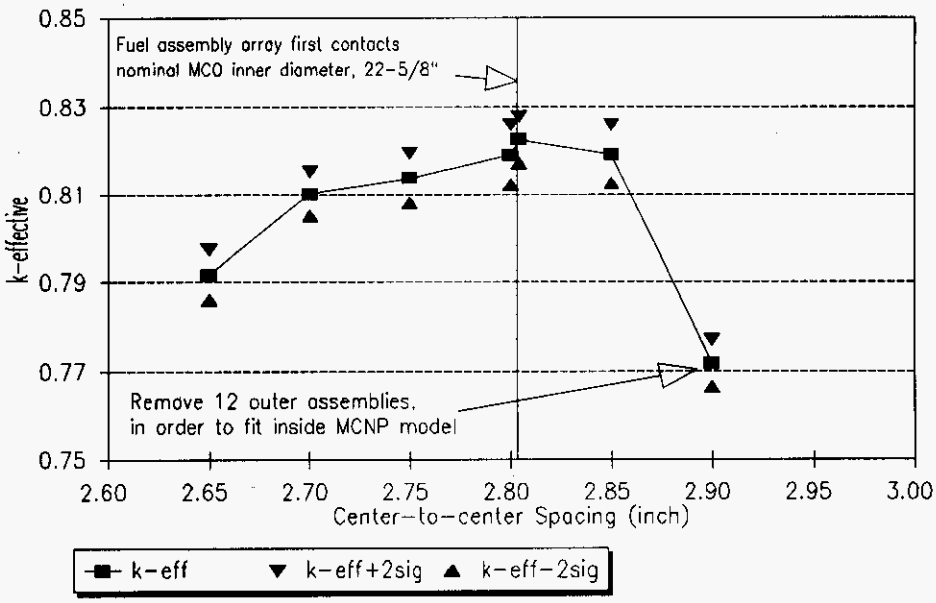


Figure B-6. k-Effective Versus Lattice Spacing for Mark IA Fuel Assemblies.



Note: The fuel assembly array first contacts the basket side at a lattice spacing of 2.8041 in. The k_{eff} for this spacing is 0.82268 with an uncertainty of 0.00264 and for a spacing of 2.80 in. when the k_{eff} is 0.81923 with an uncertainty of 0.00342.

Figure B-7. Uniform Change of Lattice Spacing for Mark IA Assemblies.

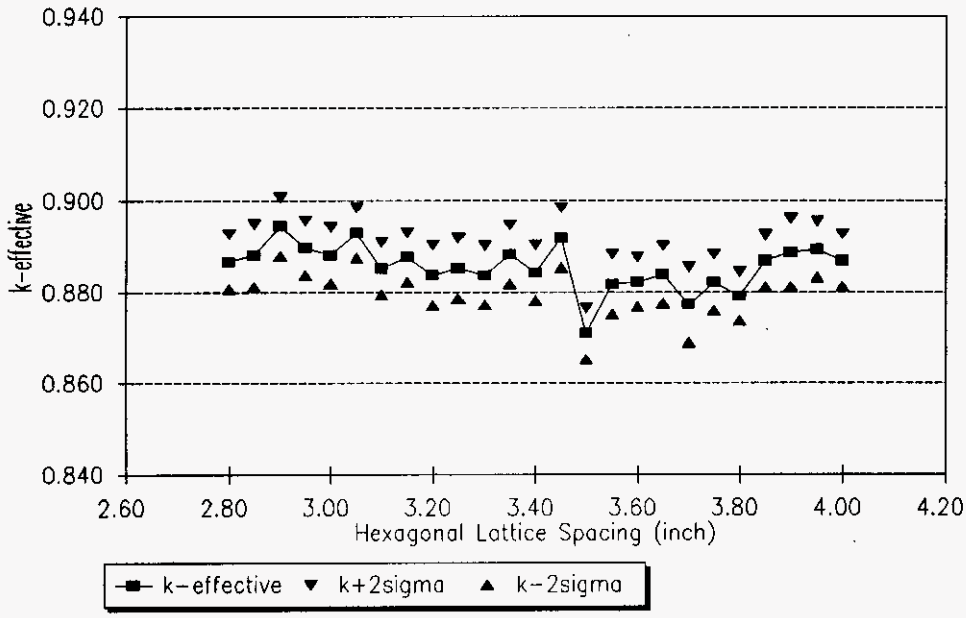


Figure B-8. Uniform Change of Lattice Spacing for Mark IV Assemblies.

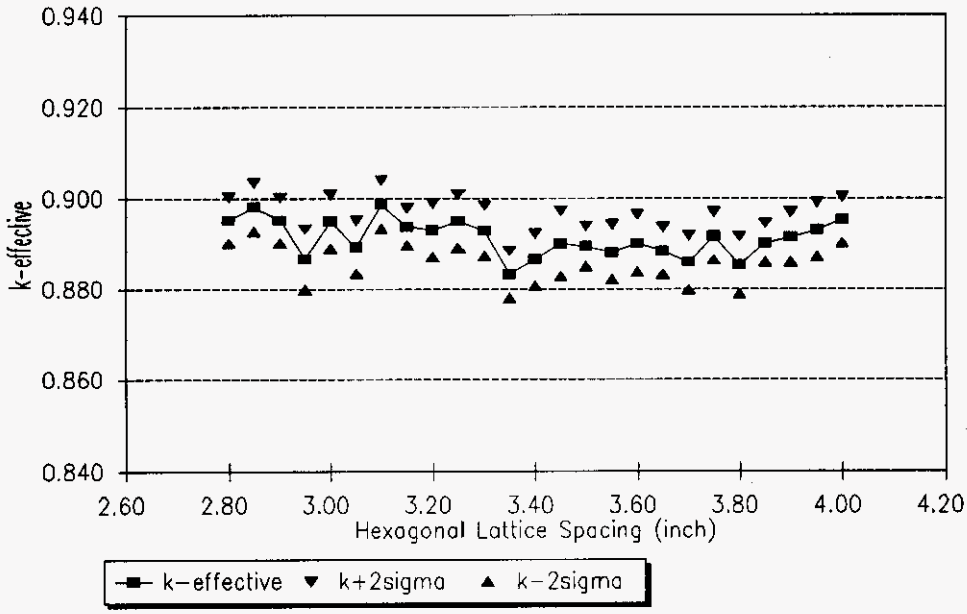


Figure B-9. Uniform Change of Lattice Spacing for Multi-Canister Overpacks Loaded with Mark IA Assemblies and no Scrap Baskets.

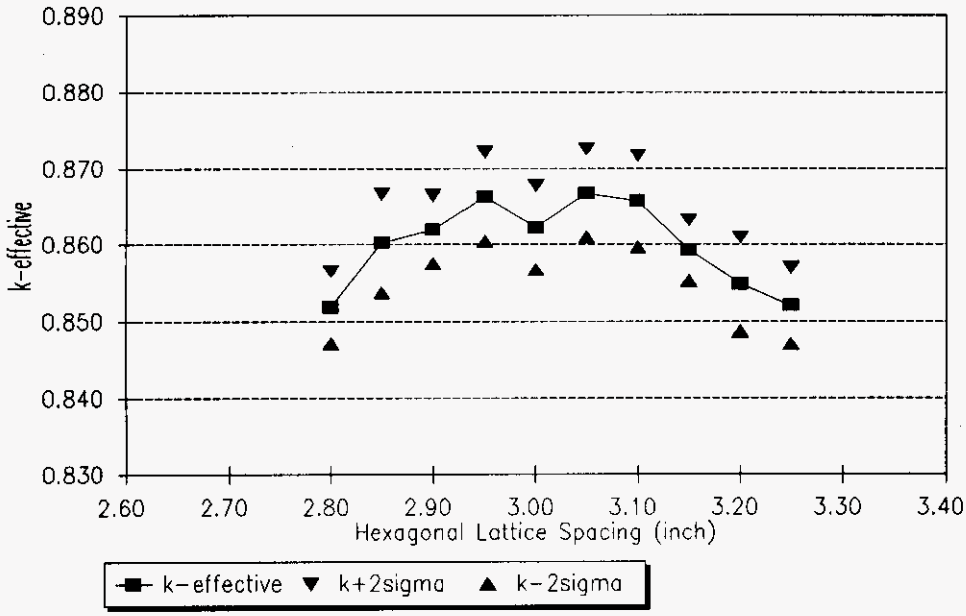


Figure B-10. Uniform Change of Lattice Spacing for Multi-Canister Overpacks Loaded with Mark IV Assemblies and no Scrap Baskets.

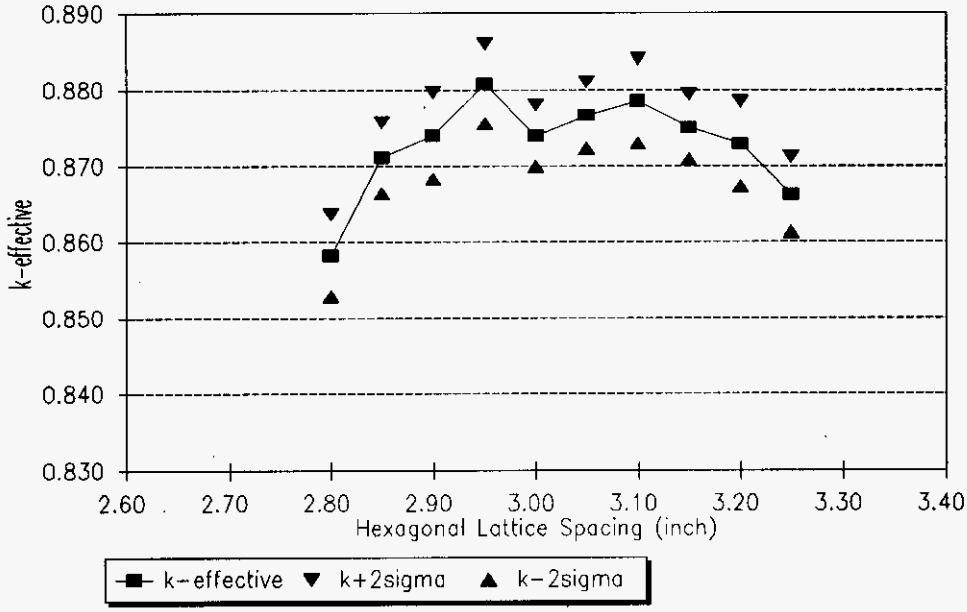
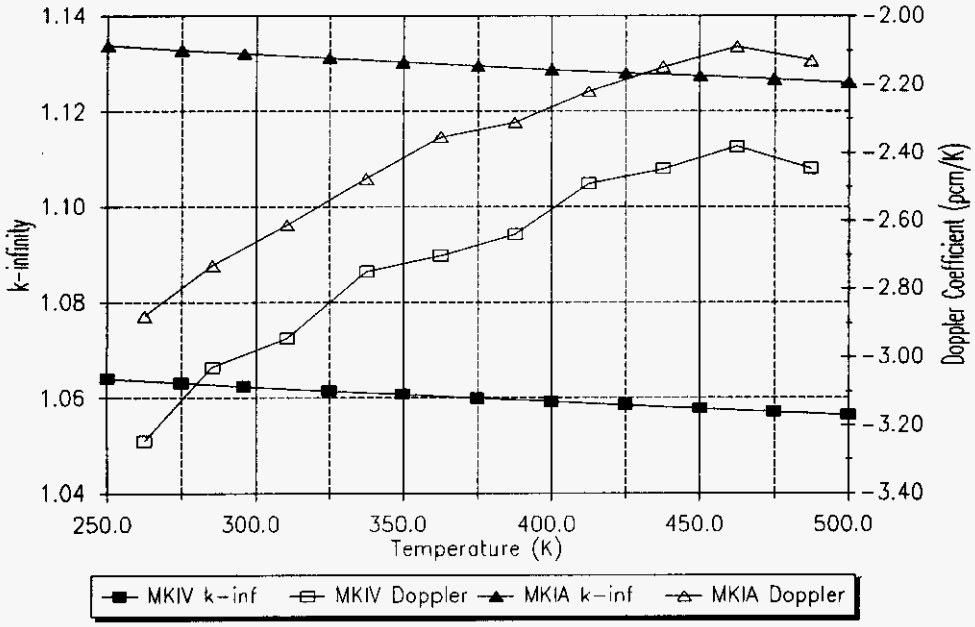


Figure B-11. Lattice k-Infinity and Temperature Coefficients for N Reactor Fuel Assemblies.



APPENDIX C

ROD VERSUS SPHERICAL GEOMETRY FOR SCRAP OR RUBBLE MODEL

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APPENDIX C

ROD VERSUS SPHERICAL GEOMETRY FOR SCRAP OR RUBBLE MODEL

This appendix demonstrates that either spheres or cylinders can be used to find the maximum reactivity of scrap or rubble by optimizing the size and spacing of that shape. By inference, cylinders may then be used to find the maximum reactivity for either rubble or scrap. This demonstrates the applicability of treating a random arrangement of rubble or scrap as a pristine lattice of uranium rods in water. The question to be explored is whether an explicit spherical lattice optimizes to a higher k_∞ than a cylindrical one. A comparison between an optimized array of spheres and cylinders was addressed with a series of calculations using a Monte Carlo n-particle (MCNP) transport code (Breismeister 1993, Carter 1996) calculations, comparing a hexagonal pitch rod lattice with an explicit, three-dimensional, lattice unit based on spheres arranged in a face-centered-cubic geometry. The fissionable material assumed was uranium metal with an enrichment of 0.95 wt% ^{235}U. For both rods and spheres, a double parameter search was made to find the maximum k_∞, as the spacing was varied, as a function of uranium chunk diameter.

Theoretically, the two most important parameters in a heterogeneous lattice cell problem are (1) the degree of self-shielding, and (2) the neutron spectrum, which depends on the degree of neutron moderation. The degree of self-shielding determines the difference between the flux inside and outside the fuel region. Neutrons are born above the ^{238}U resonances and are thermalized by the water to energies below the resonances allowing them to escape much of the ^{238}U resonance parasitic capture in low-enriched uranium metal systems. Lattice calculations of k_∞ are greater for optimal heterogeneous systems because the thermalization of neutrons in the water region where there is an absence of strong absorbers (i.e., ^{238}U) increases the resonance escape probability of neutrons returning into the fuel region. The degree of self-shielding is quantified in neutron transport theory using the concept of the mean chord length. The mean chord length, $\langle R \rangle$, can be thought of as the average distance a neutron travels through a material region. A simple formula for calculating the mean chord length (Duderstadt and Hamilton 1976) is $\langle R \rangle = 4 \times (\text{volume/area})$. For a rod, this becomes

$$\begin{aligned} \langle R \rangle &= \frac{4(\pi R^2 L)}{2\pi R L} \\ &= 2R \\ &= D \end{aligned} \qquad \text{for a cylinder of length L} \qquad (\text{C}\cancel{\text{D}}\text{-1})$$

For a spherical lattice, this becomes

$$
\begin{aligned}
\langle R \rangle &= \frac{4\left(\frac{4}{3}\pi R^3\right)}{4\pi R^2} \\
&= \frac{4}{3}R \qquad \text{for a sphere} \qquad \text{(CD-2)} \\
&= \frac{2}{3}D
\end{aligned}
$$

The mean chord length must be the same for the degree of self-shielding to be the same between cylindrical and spherical lattices. This occurs when the diameter of the cylinder is equal to two-thirds of the diameter of the equivalent sphere. Figure C-1 presents the results of the MCNP calculations. Each MCNP k_{eff} shown in Figure C-1 is a maximum value, out of ten MCNP calculations that varied the spacing between either the rods or spheres. As expected, the shapes of the two curves are different, but the lattice k_∞ that the two curves maximized themselves to is essentially the same (well within the 2σ error of the calculation). The maximum k_∞ for the cylinder lattice is 1.09082 ± 0.00265, and the maximum k_∞ for the spherical lattice is 1.09189 ± 0.00247. Finally, the sphere diameter that produces the maximum is about 1.5 times the diameter that produces a maximum for the rods, as predicted by theory.

The foregoing discussion was intended to establish that treating random, irregularly shaped scrap or rubble as either rods or spheres should make no difference in the calculated value of the maximum reactivity of the material. Experimental evidence exists that supports the assertion that a random arrangement of pieces of fissile material will have a lower reactivity than a uniform lattice of the same size pieces, even if the average moderator-to-fuel volume ratio is the same as for the uniform lattice (Lloyd 1957, Lloyd 1958). This provides another layer of conservatism inherent in the way scrap and rubble calculations have been performed for inclusion in this criticality safety evaluation report.

The rod and sphere comparison is in excellent agreement with certain transport theory predictions, and hence greater confidence may be put in the assumption that the primary factors that have significance in determining unit lattice reactivity are the mean (or effective) chord length and the degree of moderation. These factors are not sensitive to the spatial details of the lattice geometry. Therefore, treating scrap material using parametric calculational results obtained from a cylindrical lattice calculation is valid.

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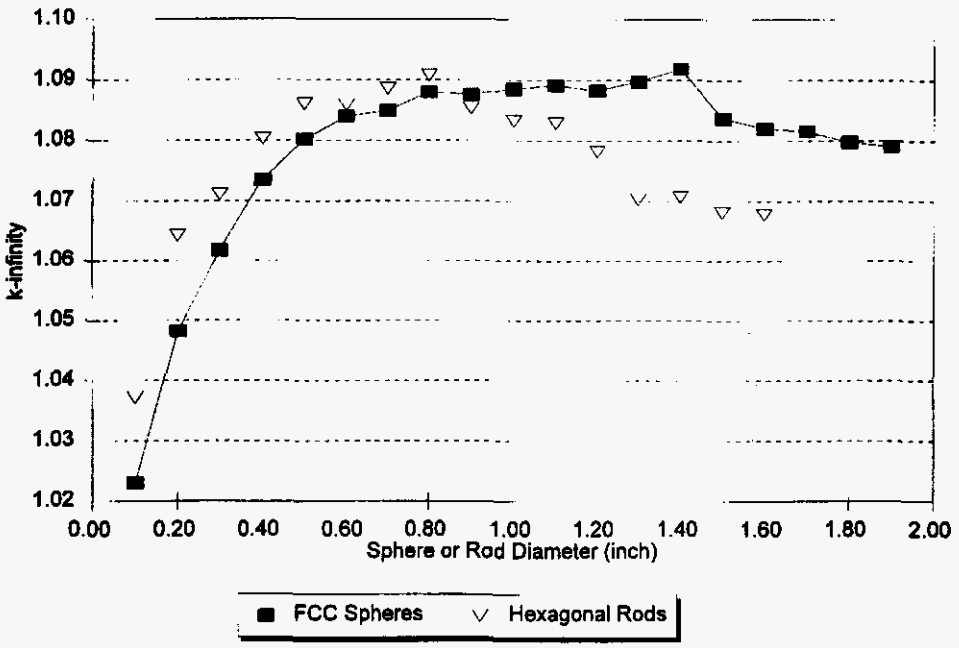
Figure C-1. Maximum k-Infinity Versus Outer Diameter for Face-Centered-Cubic Spherical Lattices and for Hexagonal Rod Lattices.



APPENDIX D

BURNUP EFFECTS ON N REACTOR MARK IV AND MARK IA FUEL

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APPENDIX D

BURNUP EFFECTS ON N REACTOR MARK IV AND MARK IA FUEL

All calculations in this criticality safety evaluation report were based on unirradiated fuel. Fuel burnup credit would provide an additional safety margin. Experimental data exist for Mark IA fuel showing the impact of fuel burnup on nuclear criticality safety parameters. Burnup calculations have been performed for both Mark IV and Mark IA fuel types, using hot operating conditions in the N Reactor lattice.

Figure D-1 shows the reactor lattice k_∞ for both Mark IV and Mark IA fuel. The initial drop in reactivity is due to the buildup of equilibrium xenon poisoning. The subsequent behavior of Mark IA fuel shows that reactivity decreases monotonically with exposure. Mark IV fuel, because of its lower initial enrichment, shows an increase in reactivity because of the buildup of ^{239}Pu. This behavior has been shown in previous analyses using the HAMMER lattice code (Toffer 1975). The minimum spherical critical mass for unirradiated Mark IA fuel is 1,893 kg. This calculation assumes optimal moderation (hexagonal lattice spacing of 3.1 in. center-to-center) and full water reflection. With burnup equal to 92 days, which corresponds to 6 wt% ^{240}Pu in total plutonium, this minimum critical mass increases to 2,419 kg — an increase of 28%. With burnup equal to 162 days, which corresponds to 9 wt% ^{240}Pu in total plutonium, this critical mass increases to 2,946 kg — an increase of 56% over the unirradiated value. These results are consistent with earlier work (Toffer 1975, Figure 11).

Burnup effects were calculated assuming the isotopic concentrations present at each of the exposure points. Because of its short half-life, ^{135}Xe was eliminated. Figure D-2 shows the variation in calculated lattice k_∞ as the spacing in cold water is varied. Figure D-3 shows the corresponding spherical critical mass. As shown in Figures D-2 and D-3, taking credit for burnup to 6 wt% ^{240}Pu for Mark IA fuel gives approximately 20 mk in reactivity and a 28% increase in the minimum critical mass. Figures D-4 and D-5 illustrate these same results for the less reactive Mark IV fuel.

The variations in maximum lattice k_∞ and minimum critical mass are plotted as functions of exposure in Figures D-6 and D-7. In Figure D-7, this evolution is plotted as the minimum critical mass, as exposure increases, divided by the minimum critical mass with no exposure. Figure D-7 may be compared directly with Figure 11 in DUN-7824 (Toffer 1975). The new and the old figures are in reasonably good agreement, but the results shown Figure D-7 were for lower burnup than those shown in DUN-7824 (Toffer 1975). As before, burnup effects were treated by using the isotopics generated with the WIMS-E lattice code (Gubbins et al. 1982) for the hot operating lattice environment of N Reactor. These isotopics (except for ^{135}Xe, which was set to zero) were then used in a cold water lattice model, in which the spacing between fuel assemblies was adjusted to find maximum k_∞ and minimum critical mass. The first points plotted in Figures D-6 and D-7 are for 2 days. The point plotted in Figure D-7 at zero exposure would be exactly equal to 1.0.

There is a significant difference between Figures D-1 and D-6. Figure D-1 shows the change in k_∞ inside the fixed graphite lattice of the N Reactor, using hot operating conditions. These are the k_∞ values produced by WIMS-E as the burnup calculation proceeds. Figure D-6 shows the maximum k_∞ when the fuel is removed from the reactor, ^{135}Xe is allowed to decay away, and the fuel is immersed and optimally spaced in a light water moderator. The relative shapes of the two curves in Figures D-1 and D-6 are quite similar. Results presented in Figures D-1 through D-7 were generated with the old '1986' WIMS-E cross section library.

Figure D-8 illustrates the long-term behavior of the maximum lattice k_∞ in cold water as the fuel is allowed to decay over a 100-year period. This latest burnup evaluation was performed with the new '1994' WIMS-E cross section library, which includes improved treatment of the transuranic burnup chains up through curium. Transuranic isotopic predictions obtained from this new library have been compared to measured N Reactor data (Schwinkendorf et al. 1996). Excellent agreement with measured data is shown for all transuranic isotopes compared. The results indicate a slight reduction in reactivity for both Mark IV and Mark IA fuel as both the fission products and transuranic chains decay. Fission products eventually decay into other isotopes that provide neutron absorption. Figure D-9 depicts only the Mark IV curve shown in Figure D-8, with an expanded vertical scale so that the decrease in reactivity is more easily seen. This curve is, of course, the net result of many isotopes changing simultaneously, but it is worth noting that it closely correlates to the ^{241}Pu half-life of 14.4 years (^{241}Pu is fissile and contributes to the reactivity of the system). Figures D-6 and D-8 are similar but are on different time scales and use different WIMS-E cross section libraries.

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Gubbins, M. E., M. J. Roth, and C. J. Taubman, 1982, *A General Introduction to the Use of the WIMS-E Modular Program*, AEEW-R 1329, Reactor Physics Division, AEE Winfrith, England.

Toffer, H., 1975, *Criticality Safety Analysis Report, Subcritical Measurements in the Hanford N Reactor Fuel Storage Basin*, DUN-7824, Add. 1, Douglas United Nuclear, Richland, Washington.

Schwinkendorf, K. N., S. P. Roblyer, and S. A. Parra, 1996, *Use of the WIMS-E Lattice Code for Prediction of the Transuranic Source Term for Spent Fuel Dose Estimation*, the SPECTRUM 96 International Topical Meeting on Nuclear and Hazardous Waste Management, Seattle, Washington, August 18-23, 1996, Vol. 1, pp. 709-713.

Figure D-1. k-Infinity versus Exposure for N Reactor Hot Operating Conditions.

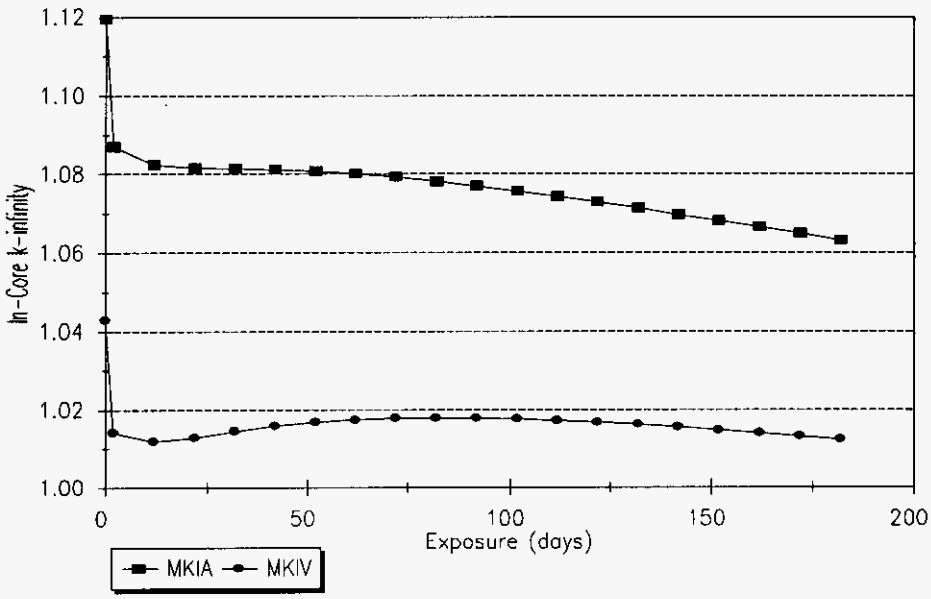


Figure D-2. k-Infinity versus Hexagonal Lattice Spacing for Mark IA Assemblies in Cold Water.

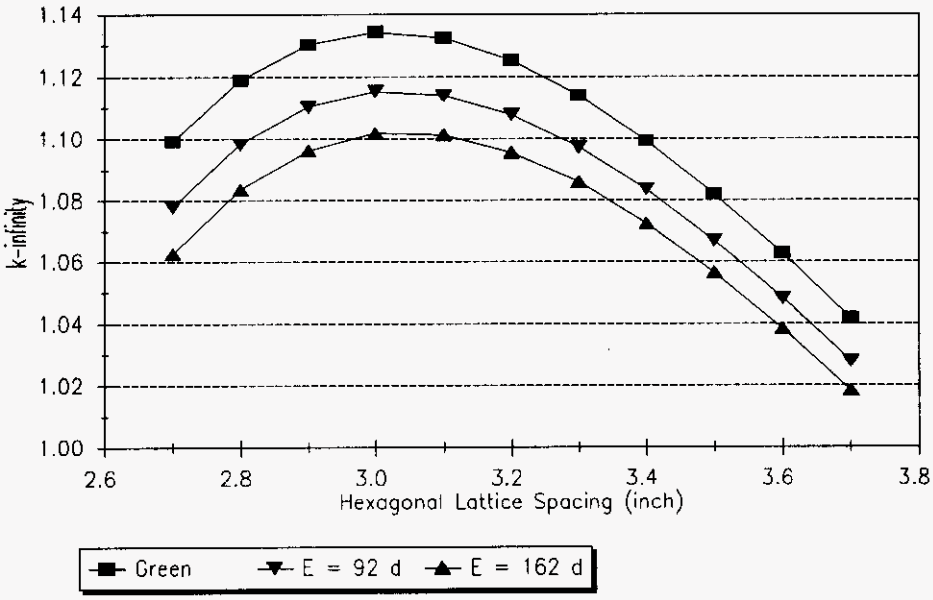


Figure D-3. Critical Mass versus Lattice Spacing for Mark IA Assemblies in Cold Water.

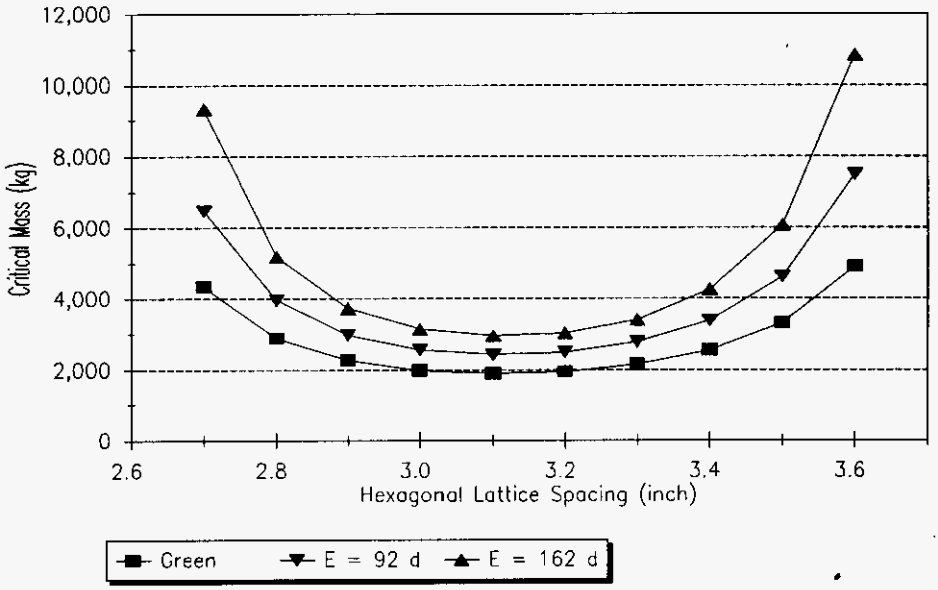


Figure D-4. k-Infinity versus Hexagonal Lattice Spacing for Mark IV Assemblies in Cold Water.

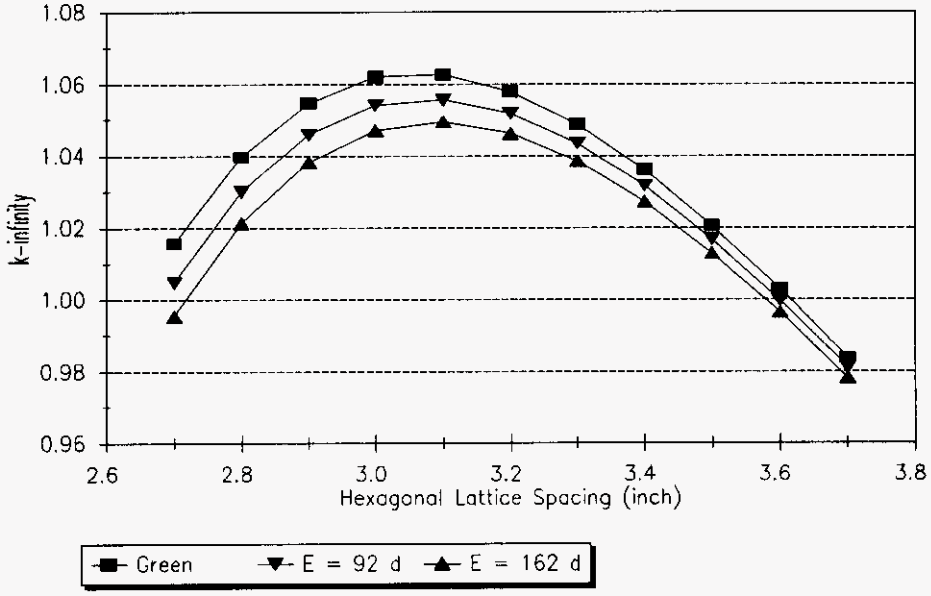


Figure D-5. Critical Mass versus Lattice Spacing for Mark IV Assemblies in Cold Water.

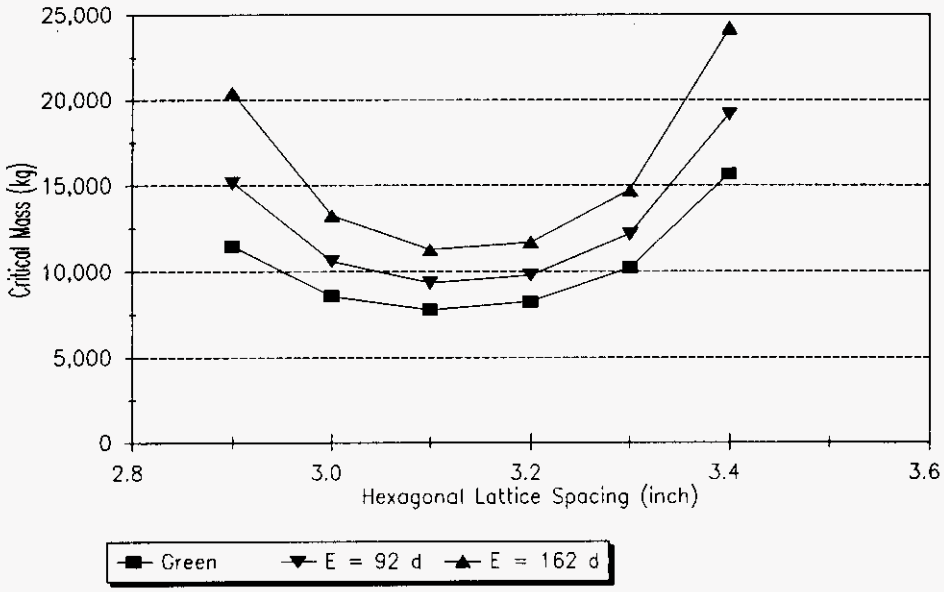


Figure D-6. Maximum Lattice k-Infinity versus Exposure for N Reactor Fuel in Cold Water.

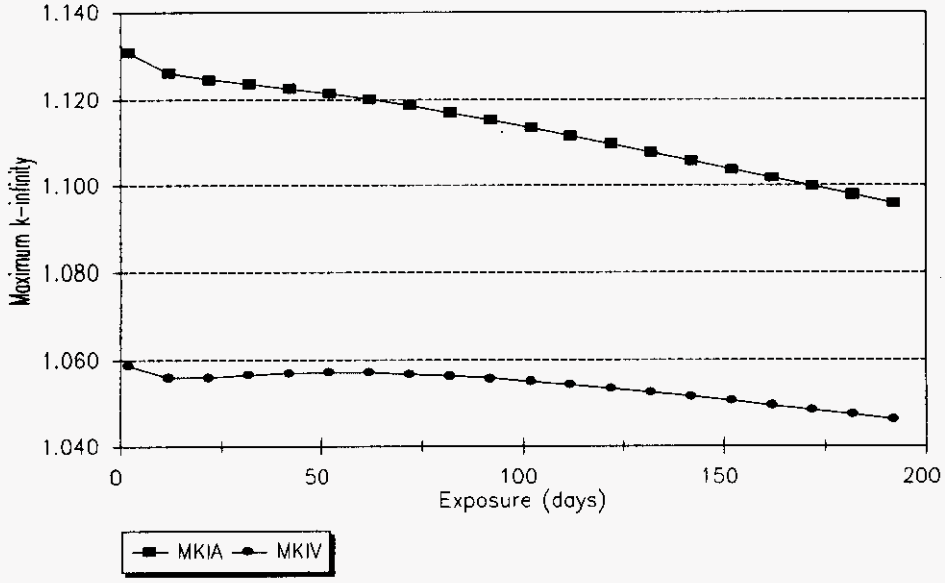


Figure D-7. Minimum Critical Mass Ratio versus Exposure for N Reactor Fuel in Cold Water.

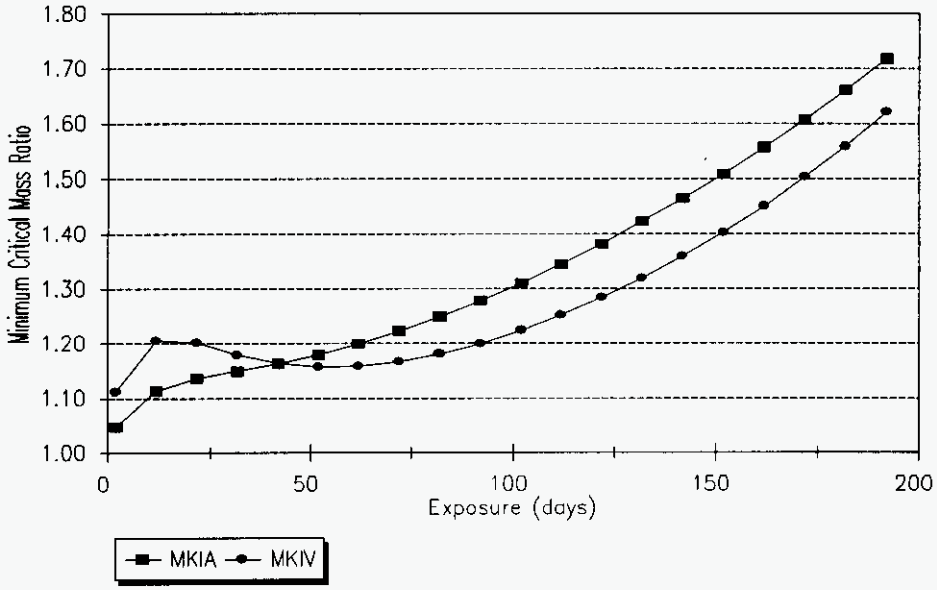


Figure D-8. Maximum Lattice k-Infinity versus One Hundred-Year Decay for N Reactor Fuel.

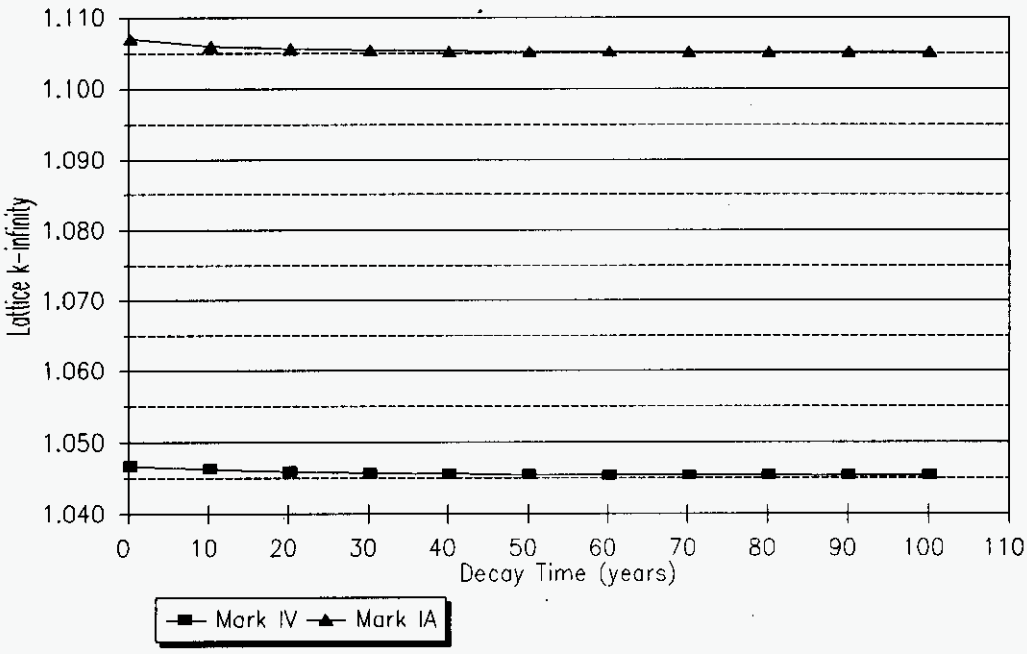
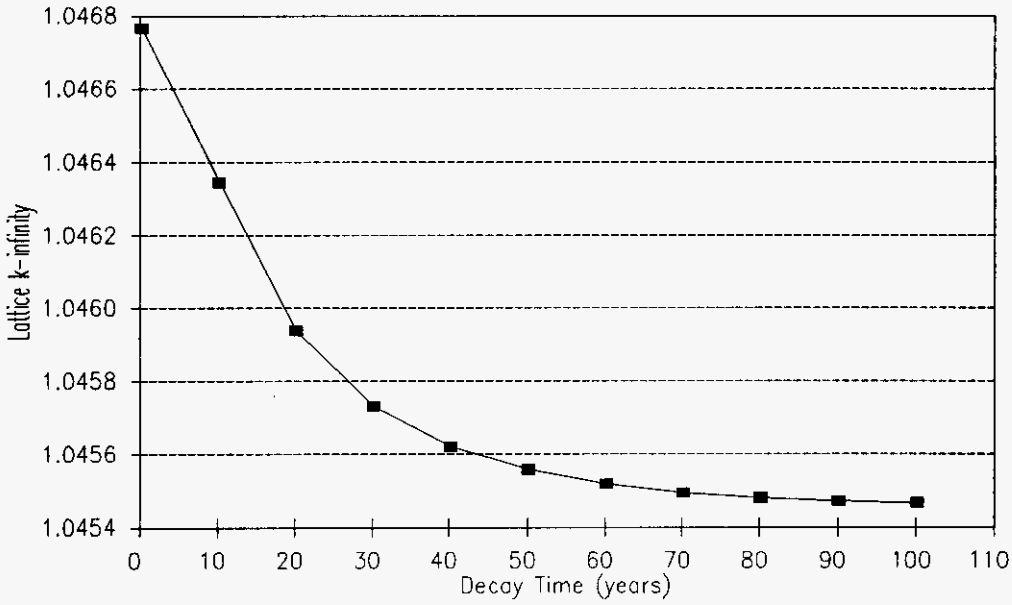


Figure D-9. Maximum Lattice k-Infinity versus One Hundred Year Decay for N Reactor Mark IV Fuel.



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APPENDIX E

RADIAL ISOTOPIC PROFILE EVOLUTION DURING BURNUP

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APPENDIX E

RADIAL ISOTOPIC PROFILE EVOLUTION DURING BURNUP

Uranium and transuranic isotope buildup in nuclear reactor fuel is a function of both the flux and the neutron spectrum. In a heterogeneous reactor lattice, neutrons born from fission in the fuel will escape into the moderator, where they will undergo collisions with the hydrogen in the water molecules and lose energy in the process (i.e., they will become moderated). For low-enriched uranium metal fuel, a heterogeneous lattice will increase reactivity by increasing the probability that a neutron will moderate to thermal energies without being absorbed by one of the many resonances in ^{238}U. This probability is increased by allowing the high energy neutrons to thermalize in the absence of resonance absorbers.

Spatial self-shielding in heterogeneous lattices will produce spatial flux gradients, and the fluxes will have different shapes for different energy ranges throughout the spectrum; the fast, or high energy, flux will have a different spatial shape than will the thermal, or lower energy, neutron flux. This shape function will drive the isotopic burnup equations differently as the radial position within the fuel piece changes. In addition, different nuclear reactions occur at different energies. For example, the depletion of ^{235}U occurs when it absorbs a neutron and either fissions (80% of the time) or emits a gamma ray. The absorption of neutrons in ^{235}U is much greater for thermal neutron energies because of the "1/v behavior" of the absorption cross section. The depletion reaction of ^{235}U is therefore maximized where the thermal neutron flux is maximized. In contrast, the buildup of ^{239}Pu is an indirect result of the absorption of a neutron in ^{238}U. When ^{238}U absorbs a neutron, it is transmuted into ^{239}U, which emits a beta particle to become ^{239}Np, which emits another beta particle to become ^{239}Pu. These beta decays are not a function of the local flux spectra, but the neutron absorption in ^{238}U is. Significant neutron absorption in ^{238}U occurs in the epithermal or resonance range of the spectrum. Plutonium production is therefore expected to be greater where higher-than-thermal neutron energies are maximized.

The early Hanford Site weapons material production reactors (also called single pass reactors [SPRs] because of their lack of a closed primary coolant loop) used both solid (or "slug") uranium metal rods and annular tubes for fuel. The annular tube fuel designs were used in later years because the central coolant region allowed the reactors to operate at higher power. N Reactor used a double tube-in-tube fuel assembly design. Various computer design tools have evolved over the years to analyze the performance of these fuel types, including the DCODE code. The DCODE computer code produced the same engineering results for fuel assemblies of the N Reactor design. DCODE also performed neutronics calculations (which determine the power sharing fractions of inner and outer elements) based on an analytical solution to the four-group P_3 equations.

More modern reactor analysis codes exist for performing these neutronics calculations, such as the British WIMS-E code (Gubbins et al. 1982), which will perform 69-group integral transport theory calculations for any user-defined annular problem geometry. The isotopic burnup chains in WIMS-E are also more detailed than those treated in DCODE. This appendix

presents the results of WIMS-E calculations of the isotopic burnup profiles inside both SPR and N Reactor fuel. Only the annular fuel type (also called the "I&E" fuel) was evaluated for the SPRs, but both Mark IV and Mark IA N Reactor fuel types were evaluated.

Most of the SPR I&E fuel was composed of natural uranium metal. Both the inner and outer elements of the N Reactor Mark IV fuel contained 0.947 wt% enriched uranium metal. The Mark IA fuel used a 0.947 wt% inner and a 1.249 wt% enriched outer tube. The Mark IA fuel, because of its higher reactivity, was used as "spike" fuel to reduce radial peaking factors in the reactor.

For the SPR I&E fuel, hot operating conditions were obtained from archived hardcopy printouts (WIMS-E does not perform heat transport calculations, only reactor physics [Gubbins et al. 1982]). These hot operating conditions were used as input for the material and geometry descriptions for WIMS-E. Hot operating conditions for the N Reactor fuel lattices were obtained from old DCODE results. WIMS-E performed the burnup analysis assuming 20 radial subdivisions in the annular fuel regions; the burnup equations were driven locally for each of the radial intervals by the 69-group neutron flux and spectrum for that particular radial interval. Figure E-1 illustrates the ^{235}U depletion as burnup progresses. Figure E-2 presents the ^{239}Pu buildup. Figure E-3 presents the sum of the two profiles, and is intended to be representative of a "total fissile" profile. Higher fissile transuranics (such as ^{241}Pu) are generated from the WIMS-E burnup chains, but these are not included in Figure E-3. Note the scale in Figure E-3. Even though plutonium buildup is enhanced at the outer periphery of the fuel, fissile uranium depletion partially compensates for this effect. For higher-exposure plutonium, the ^{240}Pu content, which is a thermal-spectrum neutron poison, also increases, as shown in Figure E-4. Figures E-5 through E-8 illustrate the same results for Mark IV fuel from N Reactor, and Figures E-9 through E-12 present the Mark IA results.

The enhancement of plutonium production at the outer periphery of nuclear fuel is documented in the commercial industry (Carlsen and Sah 1980); computer code predictions also are documented (Palmer et al. 1982). In addition to radial profiles generated during irradiation because of neutronic effects, thermochemical migration and vapor transport effects have been considered in mixed oxide fuel (Olander 1976). Because of the co-extrusion process of fuels fabrication of Hanford Site production reactor fuel, the fuel is in intimate contact with the cladding (unlike commercial fuel where there is a fuel-cladding gap). Formation of intermetallic phases of plutonium and cladding, near the fuel-cladding interface, have been suggested as possible concentrating mechanisms for plutonium in Hanford Site production reactors. However, the conclusion has been that formation of intermetallics of this type would not have taken place because of the lower operating temperatures of the fuel. Results reported in this appendix consider only the neutronic factors driving the evolution of radial plutonium profiles.

The N Reactor burnup results indicate a more pronounced ^{239}Pu buildup effect near the outer surfaces of the fuel than do the SPR fuel burnup results. In all cases, there were 20 mesh intervals in the fuel regions. The SPR reactor fuel had thicker fuel annuli; therefore the mesh intervals were also larger. If the SPR burnup calculations had been performed using more radial mesh intervals, the radial plutonium production probably would have more enhancement near the

fuel surface, just like the N Reactor results. The N Reactor results are likely as pronounced as they will get. These profiles look very much like the profiles in Palmer et al. (1982). Palmer et al. (1982) compared two independent codes (WIMS-E and RADAR) for the calculation of these profiles.

In all burnup calculations reported in this appendix, the production of plutonium is enhanced at the outer surfaces of the fuel; there is increased exposure near the surfaces because of self-shielding. However, this effect is at least partially mitigated by the fact that enhanced fissile uranium depletion also occurs near the fuel surfaces. In addition, the increased plutonium production near the surface also has a higher ^{240}Pu content, again, because of the increased exposure at the surface. The number of neutrons produced per fission is higher for ^{239}Pu than for ^{235}U, so the plutonium is worth more than the fissile uranium, but this effect is not large. Scrap material composed of the outer skin of the fuel is more reactive than the average fuel, but not to a significant degree.

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Carlsen, H. and D. N. Sah, 1981, *Radial Concentration and Effect on Temperature of Plutonium Formed in UO_2 During Irradiation*, DK-4000, Risø National Laboratory, Metallurgy Department, Roskilde, Denmark.

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Olander, D. R. 1976, *Fundamental Aspects of Nuclear Reactor Fuel Elements*, TID-26711-P1, Technical Information Center, Energy Research and Development Administration, reprinted by U.S. Department of Energy, pp. 166-169.

Palmer, I. D., K. W. Hesketh, and P. A. Jackson, 1982, *A Model for Predicting the Radial Power Profile in a Fuel Pin*, British Nuclear Fuels Ltd., Springfields Works, Salwick, Preston, United Kingdom.

Figure E-1. Evolution of the Uranium-235 Radial Profile for Annular K Reactor Fuel.

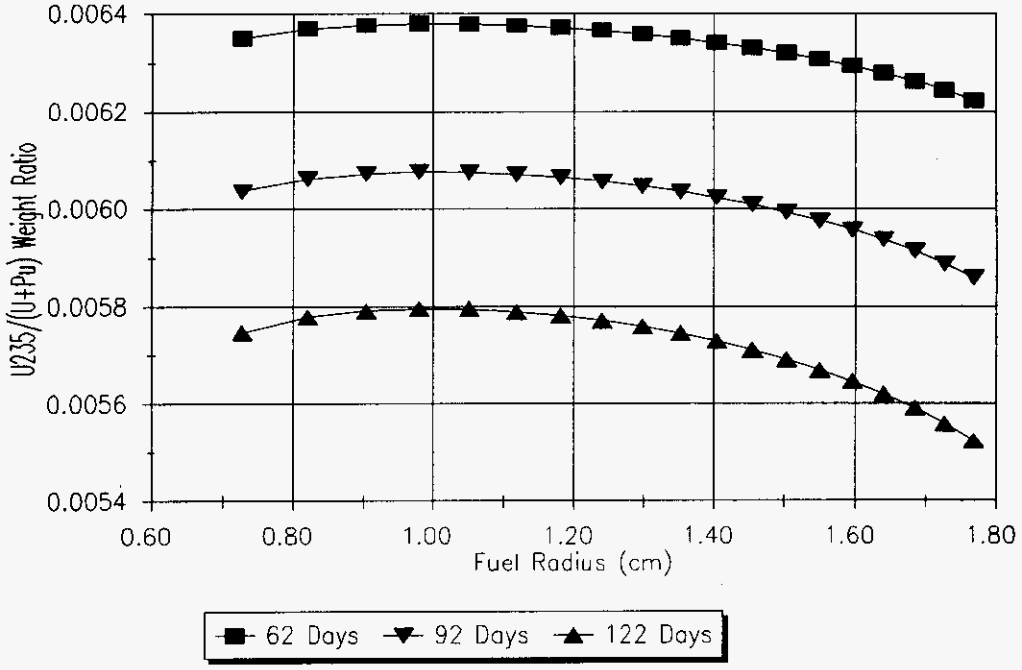


Figure E-2. Evolution of the Plutonium-239 Radial Profile for Annular K Reactor Fuel.

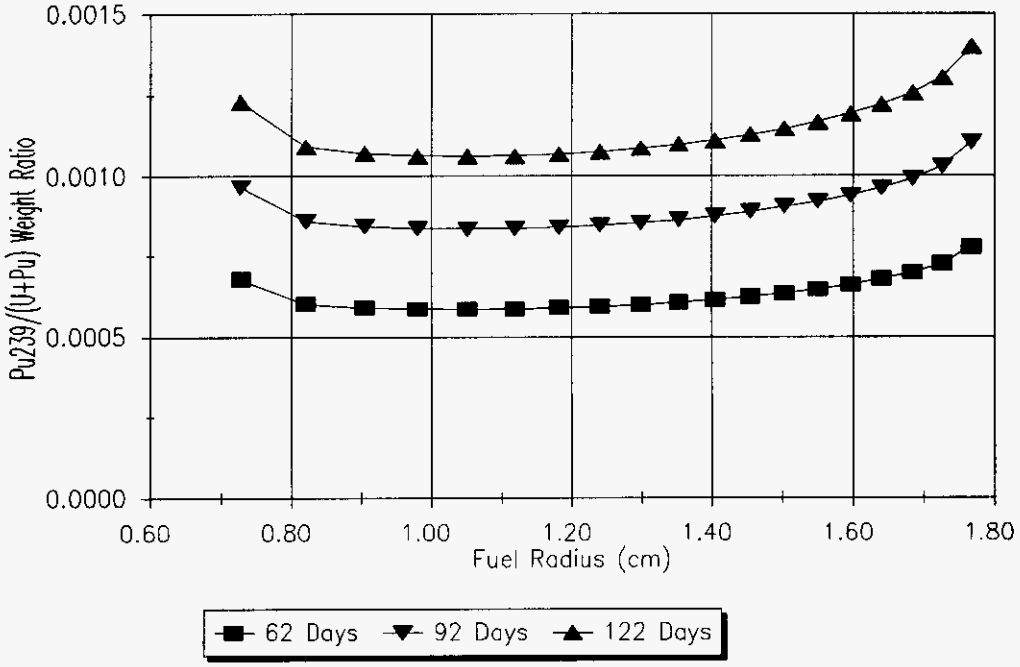


Figure E-3. Evolution of the Uranium-235 Plus Plutonium-239 Radial Profile for Annular K Reactor Fuel.

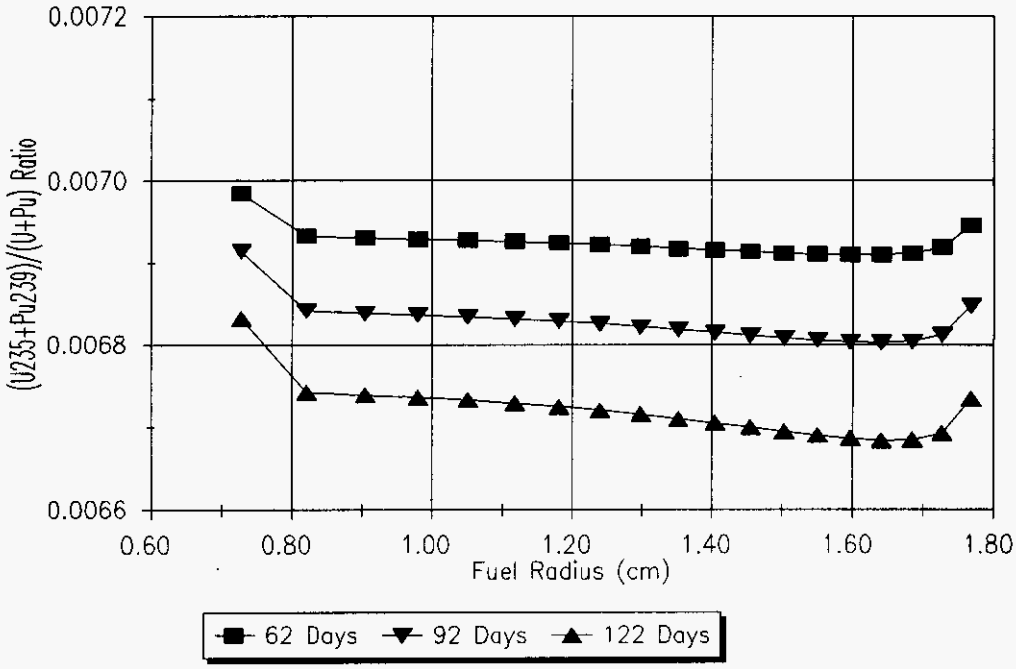


Figure E-4. Evolution of the Weight Percent Plutonium-240 Radial Profile for Annular K Reactor Fuel.

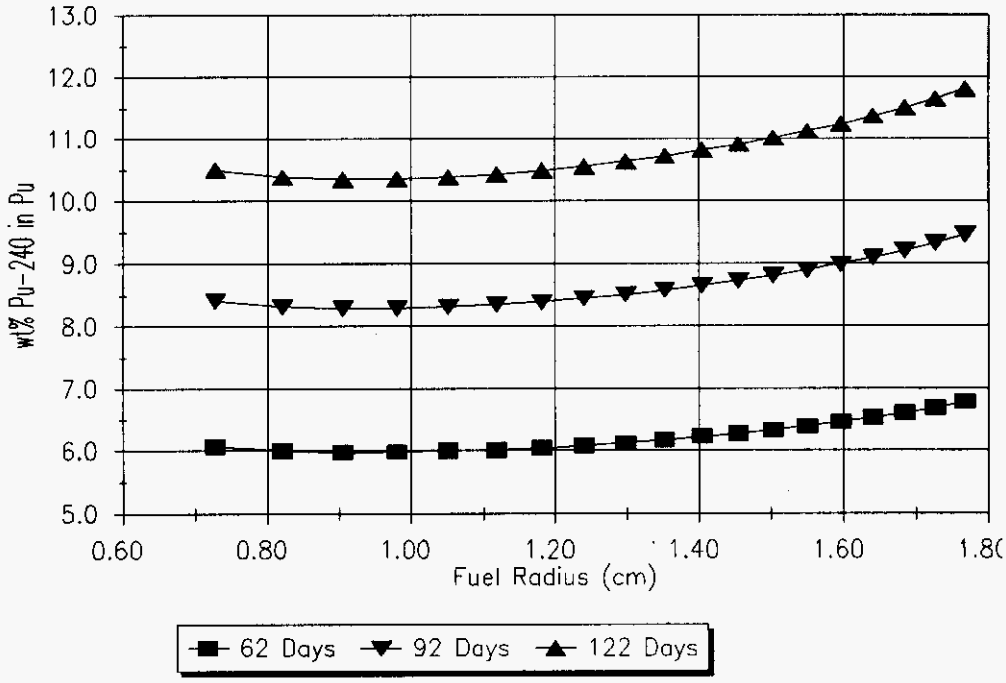


Figure E-5. Evolution of the Uranium-235 Radial Profile for N Reactor Mark IV Fuel.

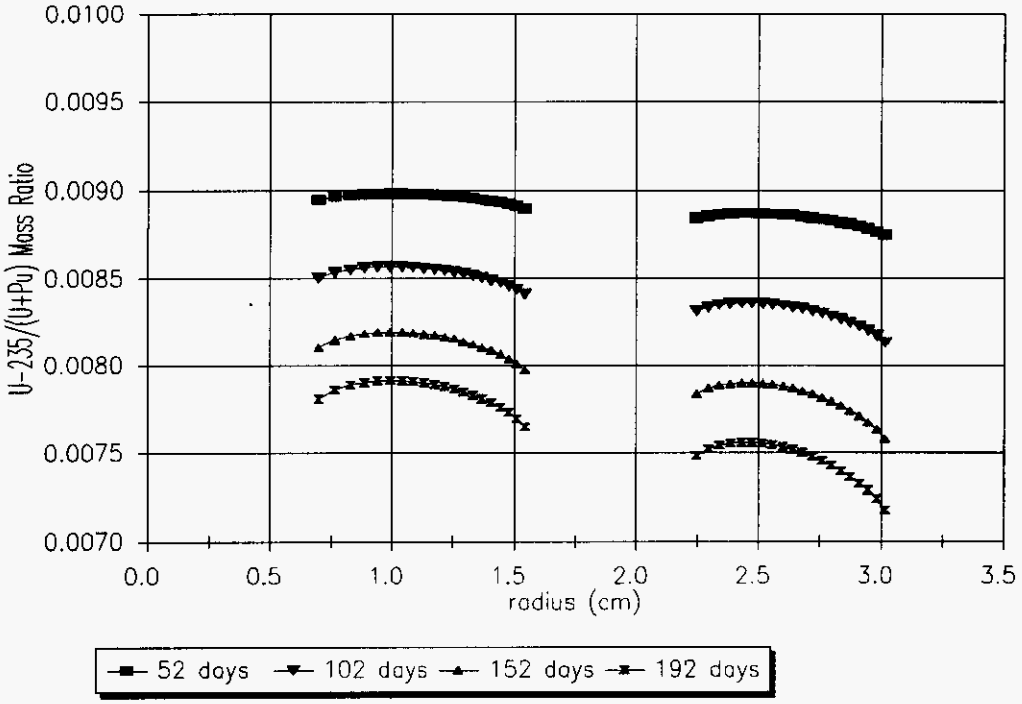


Figure E-6. Evolution of the Plutonium-239 Radial Profile for N Reactor Mark IV Fuel.

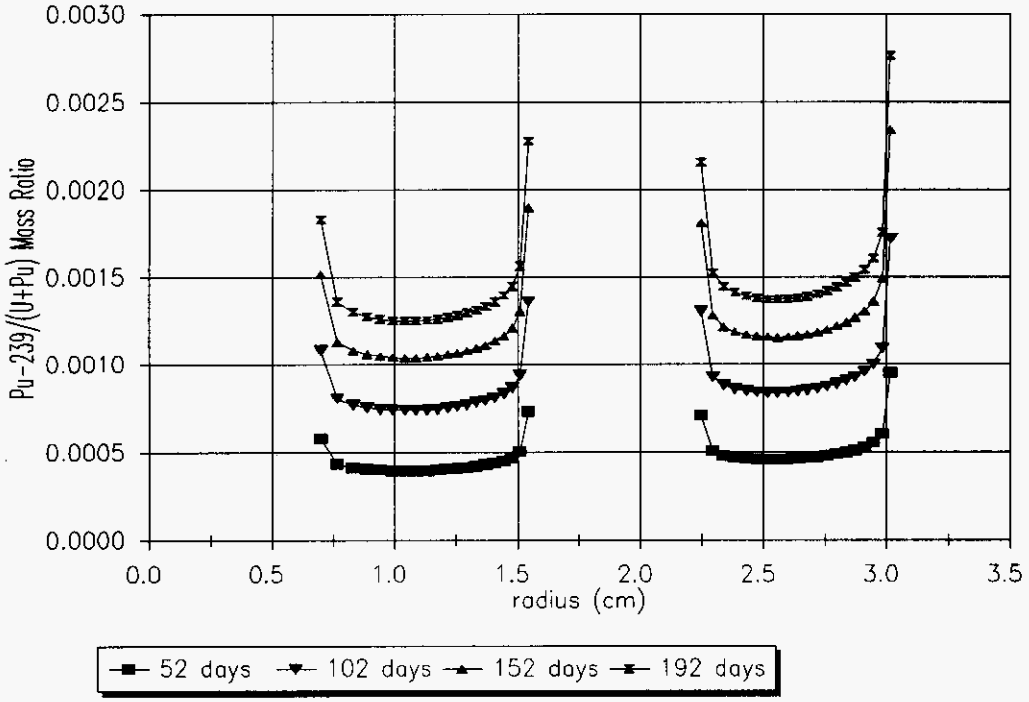


Figure E-7. Evolution of the Uranium-235 Plus Plutonium-239 Radial Profile for N Reactor Mark IV Fuel.

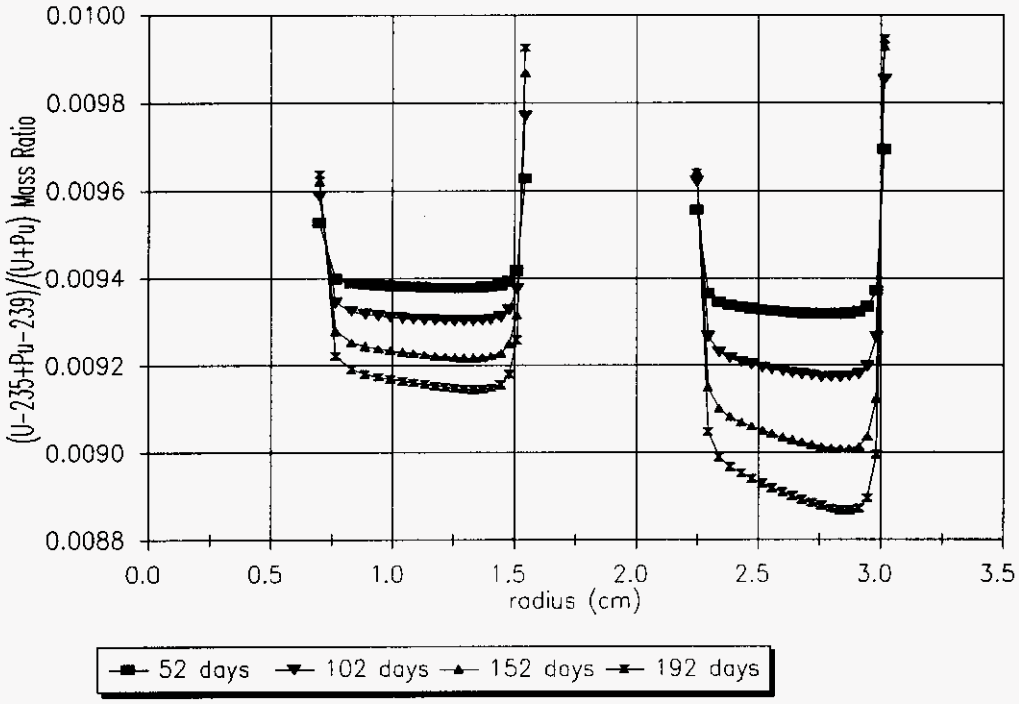


Figure E-8. Evolution of the Weight Percent Plutonium-240 Radial Profile for N Reactor Mark IV Fuel.

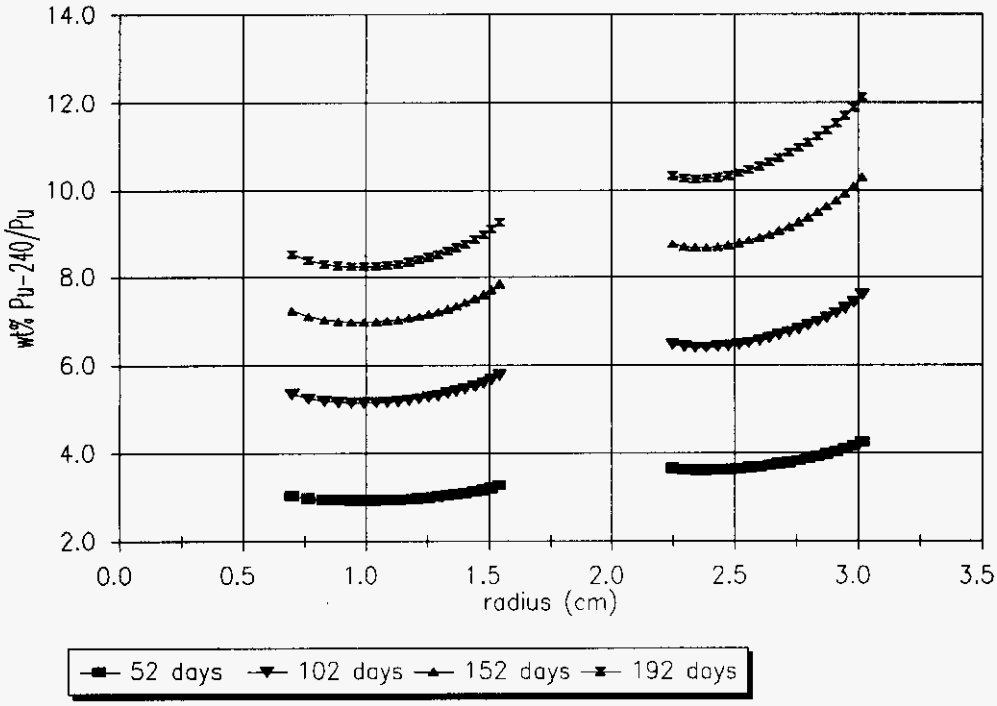


Figure E-9. Evolution of the Uranium-235 Radial Profile for N Reactor Mark IA Fuel.

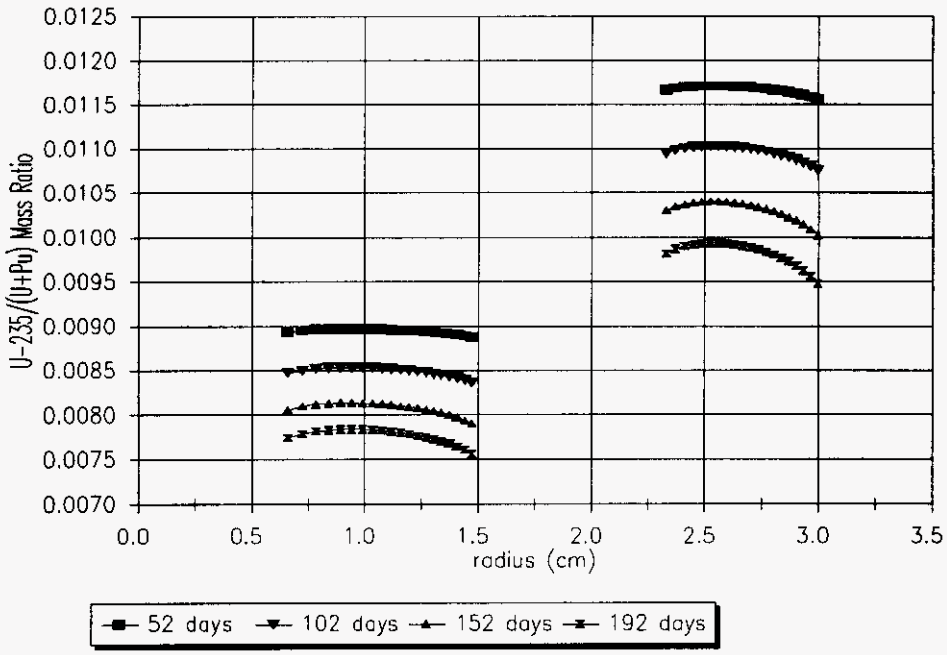


Figure E-10. Evolution of the Plutonium-239 Radial Profile for N Reactor Mark IA Fuel.

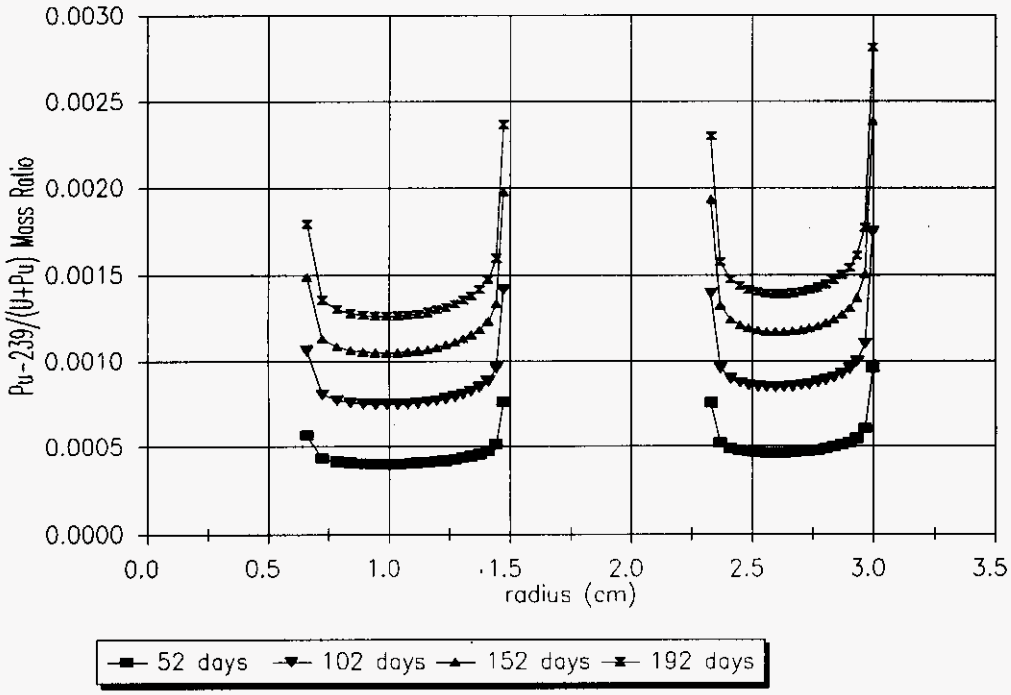


Figure E-11. Evolution of the Uranium-235 Plus Plutonium-239 Radial Profile for N Reactor Mark IA Fuel.

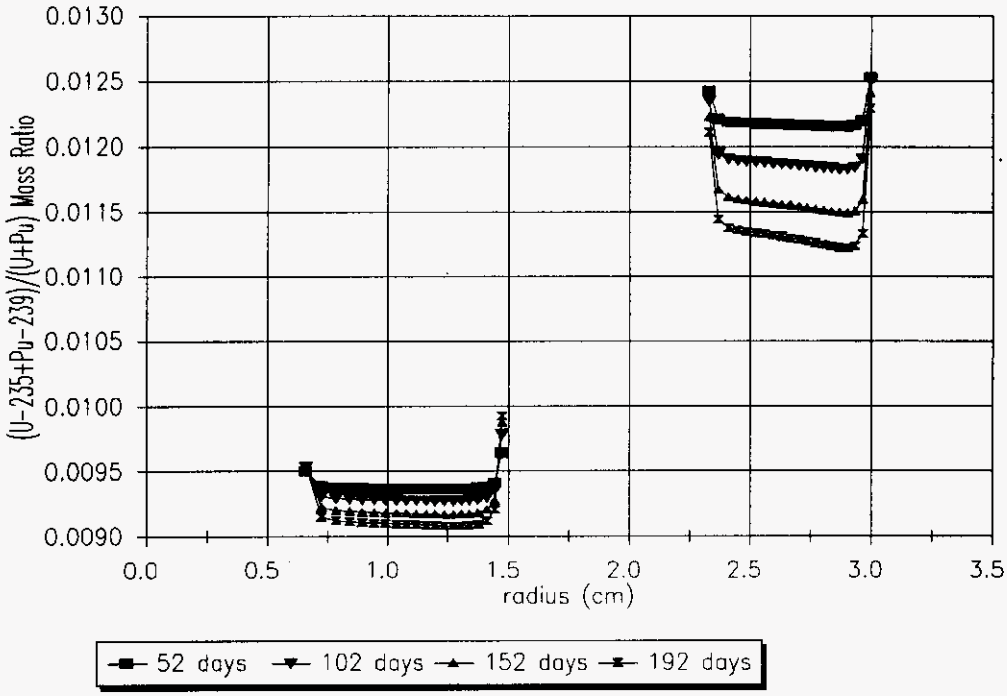
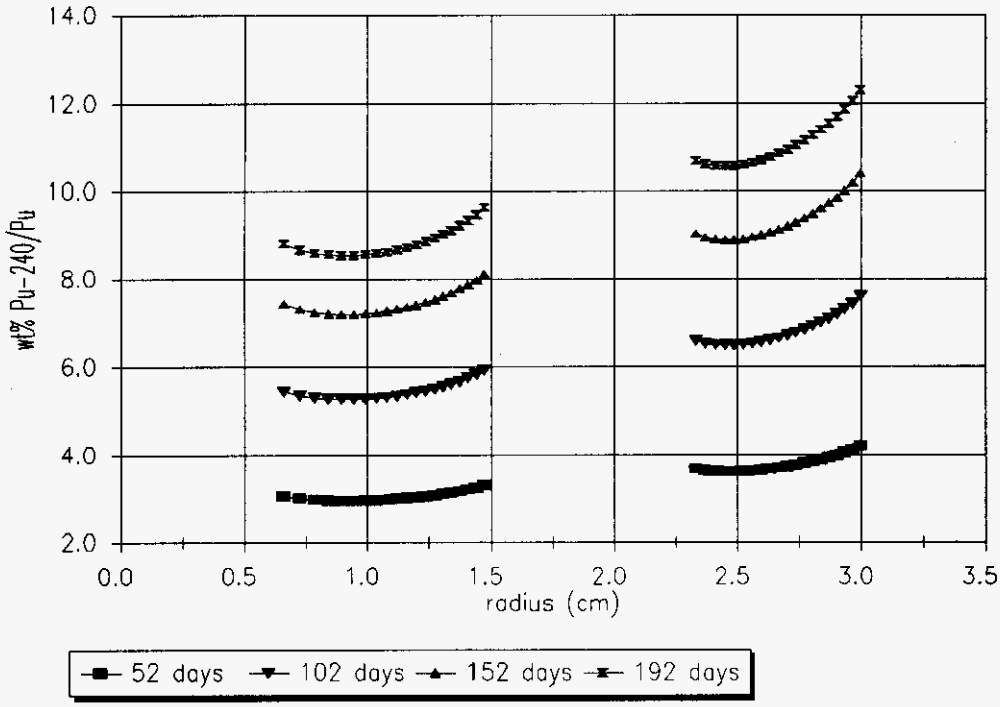


Figure E-12. Evolution of the Weight Percent Plutonium-240 Radial Profile for N Reactor Mark IA Fuel.



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APPENDIX F

REPRESENTATIVE MCNP INPUT FILES

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APPENDIX F

REPRESENTATIVE MCNP INPUT FILES

F.1 MARK 1A HIGHEST k_{eff} BASE CASE

```
Basic model for MCO loaded with 2 scrap baskets and 4 fuel baskets. Each scrap
c basket filled with 575 kg Mk 1A scrap, flooded MCO in water
c fuel baskets full. Revised center post ID
c empty location 4,5
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  3  3  3  3  3  2  $ 3
      2  2  2  3  2  3  3  3  3  3  2  $ 4
      2  2  3  3  3  2  2  3  3  3  2  $ 5
      2  2  3  3  2  2  2  3  3  2  2  $ 6  level 1
      2  3  3  3  2  2  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c  Mark 1A scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   4    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8 236    -1.00000 6                     u=4    $ scrap cell
c  Scrap basket
  9   0    -125  122  128 -148          fill=1  u=9    $ scrap in basket
 10 236    -1.00000  148  -125  128            u=9    $ water above scrap
 11 236    -1.00    -127                   u=9    $ pipe interior
 12  20    -8.03    127  -128  122            u=9    $ pipe wall
 13  20    -8.03    -122  127               u=9    $ basket base
 14  20    -8.03    125  122                u=9    $ basket side
c fictitious water cell for fuel basket lattice
 24 236   -1.00     -144                   u=2    $ fictitious cl
c fuel basket
 25  20   -8.03     -128  127  122  -123        u=7    $ tube wall
 26 236   -1.00     -127  -123              u=7    $ central tube
 27  20   -8.03     -122  127               u=7    $ bottom plate
 28  20   -8.03     -128    127    123        u=7    $ tube wall
 29 236   -1.00     -127  123               u=7    $ central tube
 31 236   -1.00     -125  128     123        u=7    $ above fuel
 32  20  -8.03000 125 122                    u=7    $ fuel basket side
 33   0  -125 122 128 -123              fill=8 u=7    $ fuel in basket
c fuel and scrap basket stack
 51   0         -149            fill=9    u=11   $ bottom scrap basket
 52   0  146  -149 #51        trcl=2  fill=7    u=11   $ fuel basket
```

```
53   0  146  -149 #52        trcl=3 fill=7      u=11  $ fuel basket
54   0  146  -149 #53        trcl=4 fill=7      u=11  $ fuel basket
55   0  146  -149 #54        trcl=5 fill=7      u=11  $ fuel basket
56   0  146  -149 #55        trcl=6 fill=9      u=11   $ top scrap basket
c  MCO and baskets
60  236  -1.000 (-160 146 -152)(-126:-152)  fill=11  u=12   $ interior
61   20  -8.03   160 -161 146                u=12   $ MCO shell
62  236  -1.00   161 -162 146                u=12   $ cask annulus
63   20  -8.03   162     146                u=12   $ cask
64   20  -8.03         -146                 u=12   $ cask bottom
65   20  -8.03  -160  165                   u=12   $ mco top
66   20  -8.03  -160  150  -151             u=12   $ filter guard
67  236  -1.00  -160  151  -165             u=12   $ top gap
68  236  -1.00  -160  -150  152             u=12   $ above top basket
69   0       164  -163  -166          fill=12       $ mco cask
c  Mk1A intact fuel structure
115  236   -1.00          50              u=3   $ between fuels
116   10   -6.49     -50    49            u=3   $ Zr-2 clad
117    4  -18.82     -49    48            u=3   $ 1.250% U-235
118   10   -6.49     -48    47            u=3   $ Zr-2 clad
119  236   -1.00     -47    46            u=3   $ H2O
120   10   -6.49     -46    45            u=3   $ Zr-2 clad
121    5  -18.82     -45    44            u=3   $ 0.947% U-235
122   10   -6.49     -44    43            u=3   $ Zr-2 clad
123  236   -1.00     -43                  u=3   $ H2O
135    2     0.06520 -164 141 -144                $ basin floor
136  236  -1.000  -144  -143  166                 $ water above MCO
137  236  -1.000  -166  163 164 -144                $ surrounding water
139    0  -141 :144 :143                          $ outside world

 5     cz    0.6500000
 6     cz    0.7107000
 11     p    0.8660254   -0.5000000    0.0000000    1.2013000
 12     p    0.8660254   -0.5000000    0.0000000   -1.2013000
 13     p    0.8660254    0.5000000    0.0000000    1.2013000
 14     p    0.8660254    0.5000000    0.0000000   -1.2013000
 15    py    1.2013000
 16    py   -1.2013000
 17    p     0.86602540  -0.5   0.0   3.556
 18    p     0.86602540  -0.5   0.0  -3.556
 19    p     0.86602540   0.5   0.0   3.556
 20    p     0.86602540   0.5   0.0  -3.556
 21    py                      3.556
 22    py                     -3.556
 43    cz    0.5588        $ H2O
 44    cz    0.6223        $ Zr-2 clad
 45    cz    1.4808        $ fuel
 46    cz    1.5824        $ Zr-2 clad
 47    cz    2.2441        $ H2O
 48    cz    2.3076        $ Zr-2 clad
 49    cz    2.9896        $ fuel
 50    cz    3.0531        $ Zr-2 clad
 122    pz    0.0000000
 123    pz    53.086000
```

```
  125     cz    28.416250
  126     cz    28.733750
  127     cz     2.2225000
  128     cz     8.4140000
  141     pz   -113.67300
  143     pz    900.00000
  144     cz    500.00000
  146     pz   -3.1750000
  148     pz    49.719800
  149     pz    55.808880
  150     pz    353.90328
  151     pz    357.71328
  152     pz    350.72828
c MCO
  160     cz   29.2100
  161     cz   30.4800
  162     cz   32.0004
  163     cz   51.0540
  164     pz   -8.2804
  165     pz   375.000
  166     pz   398.1196

tr2   0.00  0.00  58.98388
tr3   0.00  0.00  117.96776
tr4   0.00  0.00  176.95164
tr5   0.00  0.00  235.93552
tr6   0.00  0.00  294.91940
mode  n
m4      92235.50   -0.01250   92238.50   -0.98750        $ outer fuel
m5      92235.50   -0.00947   92238.50   -0.99053        $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n     1.00000     47r        0.00000 $ 5, 139
mt236    lwtr.01t
mt2      lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  200
ksrc   9.7 0. 20.  9.7 9.7 75. -9.7 9.7 130.0
     -9.7 -9.7 185.0  0.0 9.7 250.0  0.0 -9.7 320.0
```

F.2 MARK IV HIGHEST k_{eff} BASE CASE

```
Basic model for MCO loaded with 2 scrap baskets and 3 fuel baskets. Each scrap
c basket filled with Mk 4 scrap, flooded MCO in water, no process tube in the
c scrap baskets. Revised 1.25" basket base plates for all baskets.
c Partially loaded fuel baskets, inner only in location 3,6
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  15  3  3  3  3  2  $ 3
      2  2  2  3  3  3  3  3  3  3  2  $ 4
      2  2  3  3  3  3  3  3  3  3  2  $ 5
      2  2  3  3  3  2  3  3  3  2  2  $ 6  level 1
      2  3  3  3  3  3  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c  Mark 4 scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   5    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8  236   -1.00000 6                     u=4    $ scrap cell
c  Scrap basket
  9   0    -125  122                fill=1  u=9    $ scrap in basket
 11  236   -1.00    -127  -122              u=9    $ pipe interior
 13   20   -8.03    -122  127               u=9    $ basket base
 14   20   -8.03    125  122                u=9    $ basket side
c fictitious water cell for fuel basket lattice
 24  236   -1.00     -144                   u=2    $ fictitious cl
c fuel basket
 25   20   -8.03     -128  127  122  -123        u=7    $ tube wall
 26  236   -1.00     -127  -123              u=7    $ central tube
 27   20   -8.03     -122  127 -130           u=7    $ bottom plate
 28   20   -8.03     -128    127   123        u=7    $ tube wall
 29  236   -1.00     -127  123               u=7    $ central tube
 31  236   -1.00     -129  128     123        u=7    $ above fuel
 32   20  -8.03000 129 122 -130                u=7    $ fuel basket side
 33    0  -129 122 128 -123              fill=8 u=7    $ fuel in basket
 34  236  -1.00  130                        u=7    $ outside fuel basket
c fuel and scrap basket stack
 51   0         -149              fill=9    u=11   $ bottom scrap basket
 52   0  146  -149 #51        trcl=2  fill=7    u=11   $ fuel basket
 53   0  146  -149 #52        trcl=3 fill=7     u=11   $ fuel basket
 54   0  146  -149 #53        trcl=4 fill=7     u=11   $ fuel basket
 55   0  146  -149 #54        trcl=5 fill=9     u=11   $ top scrap basket
 59  236  -1.000      152  #55                u=11   $ above top basket
c  MCO and baskets
 60   0       (-160 146 -150)(-126:-150)  fill=11  u=12   $ interior
 61   20  -8.03   160 -161 146                u=12   $ MCO shell
```

```
 62  236  -1.00   161 -162 146                u=12   $ cask annulus
 63   20  -8.03   162     146                u=12   $ cask
 64   20  -8.03          -146                u=12   $ cask bottom
 65   20  -8.03  -160  165                    u=12   $ mco top
 66   20  -8.03  -160  150 -151               u=12   $ filter guard
 67  236  -1.00  -160  151  -165              u=12   $ top gap
 68    0        164  -163  -166          fill=12      $ mco cask
c  Mk4 inner fuel structure
 80  236   -1.00            46              u=15   $ between fuels
 81   10   -6.49      -46    45              u=15   $ Zr-2 clad
 82    5  -18.82      -45    44              u=15   $ 0.947% U-235
 83   10   -6.49      -44    43              u=15   $ Zr-2 clad
 84  236   -1.00      -43                    u=15   $ H2O
c  Mk4 intact fuel structure
 115  236   -1.00            50              u=3    $ between fuels
 116   10   -6.49      -50    49              u=3    $ Zr-2 clad
 117    5  -18.82      -49    48              u=3    $ 0.947% U-235
 118   10   -6.49      -48    47              u=3    $ Zr-2 clad
 119  236   -1.00      -47    46              u=3    $ H2O
 120   10   -6.49      -46    45              u=3    $ Zr-2 clad
 121    5  -18.82      -45    44              u=3    $ 0.947% U-235
 122   10   -6.49      -44    43              u=3    $ Zr-2 clad
 123  236   -1.00      -43                    u=3    $ H2O
 135    2     0.06520 -164 141 -144                  $ basin floor
 136  236  -1.000  -144  -143  166                   $ water above MCO
 137  236  -1.000  -166  163 164 -144                 $ surrounding water
 139    0  -141 :144 :143                        $ outside world

  5     cz    0.8000000
  6     cz    0.8572000
 11      p    0.8660254   -0.5000000    0.0000000    1.3992000
 12      p    0.8660254   -0.5000000    0.0000000   -1.3992000
 13      p    0.8660254    0.5000000    0.0000000    1.3992000
 14      p    0.8660254    0.5000000    0.0000000   -1.3992000
 15     py    1.3992000
 16     py   -1.3992000
 17      p    0.86602540   -0.5   0.0   3.556
 18      p    0.86602540   -0.5   0.0  -3.556
 19      p    0.86602540    0.5   0.0   3.556
 20      p    0.86602540    0.5   0.0  -3.556
 21     py                     3.556
 22     py                    -3.556
 43     cz    0.6095        $ H2O
 44     cz    0.6605        $ Zr-2 clad
 45     cz    1.5480        $ fuel
 46     cz    1.6245        $ Zr-2 clad
 47     cz    2.1605        $ H2O
 48     cz    2.2110        $ Zr-2 clad
 49     cz    3.0165        $ fuel
 50     cz    3.0800        $ Zr-2 clad
 122     pz    0.0000000
 123     pz    66.294000
c  scrap basket side
 125     cz    28.77001997
```

```
 126     cz    29.08751997
c process tube pipe
 127     cz     2.2225000
 128     cz     3.4925000
c fuel basket side
 129     cz    28.41625
 130     cz    28.73375
 141     pz   -113.67300
 143     pz    900.00000
 144     cz    500.00000
 146     pz   -3.1750000
 149     pz    67.68338
 150     pz    353.83470
 151     pz    357.64470
 152     pz    351.11690
c MCO
 160     cz   29.2100
 161     cz   30.4800
 162     cz   32.0004
 163     cz   51.0540
 164     pz   -8.2804
 165     pz   375.000
 166     pz   398.1196

tr2   0.00  0.00  70.858380
tr3   0.00  0.00  141.71676
tr4   0.00  0.00  212.57514
tr5   0.00  0.00  283.43352
mode  n
m5      92235.50   -0.00947   92238.50   -0.99053          $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n     1.00000     50r         0.00000 $ 5, 139
mt236    lwtr.01t
mt2      lwtr.01t
print   40 60 80 100 110 126
prdmp   j    300
kcode   2000  1. 20  200
ksrc   9.7 0. 20.  -9.7 0.0 85.0 9.7 -9.7 150.0
     -9.7 -9.7 250.0  0.0 -9.7 320.0
```

F.3 SPR FUEL

message:

```
 multiple canister over-pack - RUN 1 - Normal SPR Case
c  2.1 wt% material in the center of the basket
388  4  -1.00  -427                    u=2 imp:n=1 $ inner water
389  2  -2.70   427 -428                u=2 imp:n=1 $ 0.95 clad
390  1 -18.82   428 -429                u=2 imp:n=1 $ 0.95 fuel
391  2  -2.70   429 -430                u=2 imp:n=1 $ 0.95 clad
392  4  -1.00   430                    u=2 imp:n=1 $ lattice water
393  0  -431  432 -435  434 -433  436  lat=2  u=3 fill=2  imp:n=1
394  4  -1.00  -437                    u=4 imp:n=1 $ inner water
395  2  -2.70   437 -438                u=4 imp:n=1 $ 2.1 clad
396  9 -18.82   438 -439                u=4 imp:n=1 $ 2.1 scrap
397  2  -6.55   439 -440                u=4 imp:n=1 $ 2.1 clad
398  4  -1.00   440                    u=4 imp:n=1 $ lattice water
399  0  -441  442 -445  444 -443  446  lat=2  u=5 fill=4  imp:n=1
400  4  -1.00  -404  405 -401                imp:n=1 $ top water reflector
401  0   -398  -405  406  402        fill=3   imp:n=1 $ scrap in basket    #1
402  3  -8.03  -405  407 -402  403            imp:n=1 $ ss insert in basket #1
403  4  -1.00  -405  407 -403                imp:n=1 $ water inside ss insert
404  3  -8.03  -406  407 -398  402            imp:n=1 $ ss plate          #1
405  4  -1.00  -407  408 -398  402            imp:n=1 $ water in gap      #2
406  3  -8.03  -407  408 -402  403            imp:n=1 $ ss insert in gap  #2
407  4  -1.00  -407  408 -403                imp:n=1 $ water inside ss insert
408  0   -398  -408  409  402        fill=3   imp:n=1 $ scrap in basket    #2
409  3  -8.03  -408  409 -402  403            imp:n=1 $ ss insert in basket #2
410  4  -1.00  -408  409 -403                imp:n=1 $ water inside ss insert
411  3  -8.03  -409  410 -398  402            imp:n=1 $ ss plate          #2
412  4  -1.00  -410  411 -398  402            imp:n=1 $ water in gap      #3
413  3  -8.03  -409  411 -402  403            imp:n=1 $ ss insert in gap  #3
414  4  -1.00  -409  411 -403                imp:n=1 $ water inside ss insert
415  0   -398  -411  426  412        fill=3   imp:n=1 $ scrap in basket    #3
416  0   -411  -426  412  402        fill=5   imp:n=1 $ scrap in basket    #3
417  3  -8.03  -411  412 -402  403            imp:n=1 $ ss insert in basket #3
418  4  -1.00  -411  412 -403                imp:n=1 $ water inside ss insert
419  3  -8.03  -412  413 -398  402            imp:n=1 $ ss plate          #3
420  4  -1.00  -413  414 -398  402            imp:n=1 $ water in gap      #4
421  3  -8.03  -412  414 -402  403            imp:n=1 $ ss insert in gap  #4
422  4  -1.00  -412  414 -403                imp:n=1 $ water inside ss insert
423  0   -398  -414  415  402        fill=3   imp:n=1 $ scrap in basket    #4
424  3  -8.03  -414  415 -402  403            imp:n=1 $ ss insert in basket #4
425  4  -1.00  -414  415 -403                imp:n=1 $ water inside ss insert
426  3  -8.03  -415  416 -398  402            imp:n=1 $ ss plate          #4
427  4  -1.00  -416  417 -398  402            imp:n=1 $ water in gap      #5
428  3  -8.03  -415  417 -402  403            imp:n=1 $ ss insert in gap  #5
429  4  -1.00  -415  417 -403                imp:n=1 $ water inside ss insert
430  0   -398  -417  418  402        fill=3   imp:n=1 $ scrap in basket    #5
431  3  -8.03  -417  418 -402  403            imp:n=1 $ ss insert in basket #5
432  4  -1.00  -417  418 -403                imp:n=1 $ water inside ss insert
433  3  -8.03  -418  419 -398  402            imp:n=1 $ ss plate          #5
434  3  -8.03  -418  419 -402  403            imp:n=1 $ ss insert in gap  #5
```

```
435 4 -1.00 -418 419 -403                imp:n=1 $ water inside ss insert
436 0  -398 -419 420 402        fill=3   imp:n=1 $ scrap in basket    #6
437 3 -8.03 -419 421 -402  403           imp:n=1 $ ss insert in basket #6
438 4 -1.00 -419 421 -403                imp:n=1 $ water inside ss insert
439 3 -8.03 -420 421 -424  402           imp:n=1 $ ss plate          #6
440 3 -8.03 -421 422 -400                imp:n=1 $ ss mco bottom end cap
441 3 -8.03  398 -424 -405  407          imp:n=1 $ side of steel basket #1
442 3 -8.03  398 -424 -407  410          imp:n=1 $ side of steel basket #2
443 3 -8.03  398 -424 -410  413          imp:n=1 $ side of steel basket #3
444 3 -8.03  398 -424 -413  416          imp:n=1 $ side of steel basket #4
445 3 -8.03  398 -424 -416  419          imp:n=1 $ side of steel basket #5
446 3 -8.03  398 -424 -419  420          imp:n=1 $ side of steel basket #6
447 3 -8.03  425 -400 -405  421          imp:n=1 $ steel cask outside mco
448 4 -1.00  400 -401 -405  422          imp:n=1 $ water surrounding mco
449 4 -1.00 -422  423 -401               imp:n=1 $ water below ss end cap
450 3 -8.03  424 -399 -405  421          imp:n=1 $ mco liner
451 4 -1.00  399 -425 -405  421          imp:n=1 $ water gap
452 0       404: -423: 401               imp:n=0 $ outside world

398 cz   28.8925          $ basket radius 11.375"
399 cz   30.48            $ mco opening radius 12"
400 cz   50.8             $ outer steel radius 20"
401 cz   81.28            $ water outside mco
402 cz   8.41375          $ ss insert outer radius
403 cz   7.3025           $ ss insert inner radius
404 pz   201.93           $ top of water reflector
405 pz   171.4499         $ top of scrap basket #1
406 pz   115.2525         $ top of ss plate    #1
407 pz   114.3            $ top of water gap   #2
408 pz   111.1377         $ top of intact fuel #2
409 pz   58.1025          $ top of ss plate    #2
410 pz   57.15            $ top of water gap   #3
411 pz   53.9877          $ top of intact fuel #3
412 pz   0.9525           $ top of ss plate    #3
413 pz   0.0              $ top of water gap   #4
414 pz   -3.1623          $ top of intact fuel #4
415 pz   -56.1975         $ top of ss plate    #4
416 pz   -57.15           $ top of water gap   #5
417 pz   -60.3123         $ top of intact fuel #5
418 pz   -113.3475        $ top of ss plate    #5
419 pz   -114.3           $ top of scrap basket #6
420 pz   -170.49749       $ top of ss plate    #6
421 pz   -171.45          $ top of ss end cap
422 pz   -190.5           $ bottom of ss end cap
423 pz   -220.98          $ water below mco
424 cz   29.21            $ mco liner
425 cz   31.75            $ water gap
426 cz   14.73596         $ outer radius of 2.1 scrap
427 cz   0.47333          $ optimum 0.95 spr fuel r1
428 cz   0.6150           $ optimum 0.95 spr fuel r2
429 cz   1.75333          $ optimum 0.95 spr fuel r3
430 cz   1.86833          $ optimum 0.95 spr fuel r4
431 px   2.61886          $ lattice hexagon planes
432 px   -2.61886
```

```
433 p    -0.57735 1.0 0.0 3.02400
434 p     0.57735 1.0 0.0 -3.02400
435 p     0.57735 1.0 0.0 3.02400
436 p    -0.57735 1.0 0.0 -3.02400
437 cz    0.560              $ optimum 2.1 spr fuel r1
438 cz    0.690              $ optimum 2.1 spr fuel r2
439 cz    1.805              $ optimum 2.1 spr fuel r3
440 cz    1.910              $ optimum 2.1 spr fuel r4
441 px    2.76171              $ lattice hexagon planes
442 px   -2.76171
443 p    -0.57735 1.0 0.0 3.18894
444 p     0.57735 1.0 0.0 -3.18894
445 p     0.57735 1.0 0.0 3.18894
446 p    -0.57735 1.0 0.0 -3.18894

mode n
kcode  1000 1.0  10  50
ksrc     9.82784 0.0     143.35125
        -9.82784 0.0     143.35125
         0.0     9.67545   84.6201
         0.0    -9.67545   84.6201
         0.0     9.67545   27.4701
         0.0    -9.67545   27.4701
         0.0     9.67545  -29.6799
         0.0    -9.67545  -29.6799
         0.0     9.67545  -86.8299
         0.0    -9.67545  -86.8299
         9.82784 0.0     -142.39875
        -9.82784 0.0     -142.39875        $ 12 source points
m1    92235.50c  -0.009471 92238.50c  -0.990529 $ mkia inners
m2    40000.50c  -1.000                  $ zr clad
m3     6000.50c  -0.0004                 $ stainless steel 304
     25055.50c  -0.0200                 $ (8.03 g/cc)
     14000.50c  -0.0100
     24000.50c  -0.1900
     28000.50c  -0.0925
     26000.55c  -0.6871
m4     1001.50c  -0.1119   8016.50c  -0.8881   $ water
mt4    lwtr.01t
m9    92235.50c  -0.021   92238.50c  -0.979   $ 2.1 spr fuel
totnu
ctme 350.
print
```

F.4 PARTIALLY DRAINED MCO IN THE CVDF CONTAINING MARK 1A FUEL AND SCRAP

```
Basic model for MCO loaded with 2 scrap baskets and 4 fuel baskets. Each scrap
c basket filled with 575 kg Mk 1A scrap, flooded MCO at CVDF
c fuel baskets full. Revised center post ID
c empty location 4,5
c The top scrap basket and all fuel baskets drained, The bottom
c scrap basket flooded half way.
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  3  3  3  3  3  2  $ 3
      2  2  2  3  2  3  3  3  3  3  2  $ 4
      2  2  3  3  3  2  2  3  3  3  2  $ 5
      2  2  3  3  2  2  2  3  3  2  2  $ 6  level 1
      2  3  3  3  2  2  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c  Mark 1A scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   4    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8 236    -1.00000 6                     u=4    $ scrap cell
c  Scrap basket
  9   0    -125  122  128 -153          fill=1  u=9    $ flooded scrap in basket
 10 237    -0.00510  148  -125  128            u=9    $ water above scrap
 11 236    -1.00    -127 -153               u=9    $ pipe interior
 12  20    -8.03    127  -128  122            u=9    $ pipe wall
 13  20    -8.03    -122  127  -126           u=9    $ basket base
 14  20    -8.03    125  122  -126            u=9    $ basket side
 15 236 -1.000   126 -153                    u=9   $ outside basket flooded reqion
 16   0    -125 153 128 -148            fill=18 u=9   $ drained scrap
 17 237 -0.0051   126  153                   u=9   $ outside basket drained reqion
 18 237 -.005100    -127  153                u=9    $ pipe interior
c fictitious water cell for fuel basket lattice
 24 236   -1.00      -144                   u=2   $ fictitious cl
c fuel basket
 25  20   -8.03      -128  127  122  -123        u=7   $ tube wall
 26 236   -1.00      -127  -123              u=7   $ central tube
 27  20   -8.03      -122  127 -126            u=7   $ bottom plate
 28  20   -8.03      -128    127    123        u=7   $ tube wall
 29 236   -1.00      -127  123               u=7   $ central tube
 31 236   -1.00      -125  128     123         u=7   $ above fuel
 32  20 -8.03000 125 122  -126                 u=7   $ fuel basket side
 33   0 -125 122 128 -123                fill=8 u=7   $ fuel in basket
 34 236 -1.000   126                        u=7   $ outside basket
c fuel and scrap basket stack
```

```
 51   0        -149              fill=9     u=11   $ bottom scrap basket
 52   0      -149          trcl=2  fill=20    u=21   $ fuel basket
 53   0  146  -149 #52        trcl=3 fill=20     u=21   $ fuel basket
 54   0  146  -149 #53        trcl=4 fill=20     u=21   $ fuel basket
 55   0  146  -149 #54        trcl=5 fill=20     u=21   $ fuel basket
 56   0  146  -149 #55        trcl=6 fill=19     u=21   $ top scrap basket
c 57   20 -8.03  -146 127       trcl=2          u=21
c  MCO and baskets
 59   0       -160  149 -152          fill=21  u=12   $ drained volume
 60   0       (-160 146  -149 )       fill=11  u=12   $ interior
 61   20  -8.03   160 -161 146                u=12   $ MCO shell
 62  236  -1.00   161 -162 146                u=12   $ cask annulus
 63   20  -8.03   162     146                u=12   $ cask
 64   20  -8.03         -146                u=12   $ cask bottom
 65   20  -8.03  -160  165                   u=12   $ mco top
 66   20  -8.03  -160  150  -151             u=12   $ filter guard
 67  237  -0.0051 -160  151  -165             u=12   $ top gap
 68  237  -0.0051 -160  -150  152             u=12   $ above top basket
 69   0       164  -163  -166          fill=12       $ flooded mco
c  Mk1A intact fuel structure
 115  236   -1.00          50              u=3   $ between fuels
 116   10   -6.49      -50    49           u=3   $ Zr-2 clad
 117    4  -18.82      -49    48           u=3   $ 1.250% U-235
 118   10   -6.49      -48    47           u=3   $ Zr-2 clad
 119  236   -1.00      -47    46           u=3   $ H2O
 120   10   -6.49      -46    45           u=3   $ Zr-2 clad
 121    5  -18.82      -45    44           u=3   $ 0.947% U-235
 122   10   -6.49      -44    43           u=3   $ Zr-2 clad
 123  236   -1.00      -43                 u=3   $ H2O
 135    2     0.06520 -164 141 -144                $ basin floor
 136  236  -0.0012 -144  -143  166                 $ air above MCO
 137  236  -0.0012 -166  163 164 -144                $ surrounding air
 139    0  -141 :144 :143                        $ outside world
c  drained fuel and scrap baskets
c  fuel basket containing intact fuel assemblies
 202    0  -17  18  -19  20  -21  22     u=16  lat=2
         fill=-5:5  -5:5  0:0
      15  15  15  15  15  15  15  15  15  15  15   $ 1
      15  15  15  15  15  15  13  13  13  15  15   $ 2
      15  15  15  15  13  13  13  13  13  13  15   $ 3
      15  15  15  13  15  13  13  13  13  13  15   $ 4
      15  15  13  13  13  15  15  15  13  13  15   $ 5
      15  15  13  13  15  15  15  13  13  15  15   $ 6  level 1
      15  13  13  13  15  15  13  13  13  15  15   $ 7
      15  13  13  13  13  13  13  13  15  15  15   $ 8
      15  13  13  13  13  13  13  15  15  15  15   $ 9
      15  15  13  13  13  15  15  15  15  15  15   $ 10
      15  15  15  15  15  15  15  15  15  15  15   $ 11
c      1   2   3   4   5   6   7   8   9  10  11
c  drained Mark 1A scrap optimized lattice
 205    0          -11 12 -13 14 -15 16  fill=17 u=18 lat=2  $ scrap hex
 206    4     -18.8200 -5                    u=17    $ scrap pin
 207   10     -6.49000 5 -6                  u=17    $ scrap clad
 208  237      -0.00510 6                    u=17    $ scrap cell
```

```
c  Drained Scrap basket
 209   0    -125  122  128 -148          fill=18 u=19    $ scrap in basket
 210  237   -0.00510  148  -125  128          u=19    $ air above scrap
 211  237   -0.0051  -127                  u=19    $ pipe interior
 212   20   -8.03    127  -128  122          u=19    $ pipe wall
 213   20   -8.03    -122  127  -126         u=19    $ basket base
 214   20   -8.03    125  122  -126          u=19    $ basket side
 215  237  -0.0051  126                     u=19   $ outside basket
c  fictitious air cell for fuel basket lattice
 224  237   -0.0051    -144                  u=15   $ fictitious cl
c  fuel basket
 225   20   -8.03     -128  127  122  -123       u=20   $ tube wall
 226  237   -0.0051    -127  -123             u=20   $ central tube
 227   20   -8.03     -122  127  -126         u=20   $ bottom plate
 228   20   -8.03     -128    127   123       u=20   $ tube wall
 229  237   -0.0051    -127  123              u=20   $ central tube
 231  237   -0.0051    -125  128     123        u=20   $ above fuel
 232   20  -8.03000 125 122  -126               u=20   $ fuel basket side
 233    0  -125 122 128 -123              fill=16 u=20   $ fuel in basket
 234  237  -0.0051  126                     u=20   $ outside basket
c  Mk1A intact drained fuel structure
 315  237   -0.0051          50             u=13   $ between fuels
 316   10   -6.49     -50    49             u=13   $ Zr-2 clad
 317    4  -18.82     -49    48             u=13   $ 1.250% U-235
 318   10   -6.49     -48    47             u=13   $ Zr-2 clad
 319  237   -0.0051    -47    46             u=13   $ air
 320   10   -6.49     -46    45             u=13   $ Zr-2 clad
 321    5  -18.82     -45    44             u=13   $ 0.947% U-235
 322   10   -6.49     -44    43             u=13   $ Zr-2 clad
 323  237   -0.0051    -43                   u=13   $ air

   5     cz    0.6500000
   6     cz    0.7107000
  11      p    0.8660254   -0.5000000    0.0000000    1.2013000
  12      p    0.8660254   -0.5000000    0.0000000   -1.2013000
  13      p    0.8660254    0.5000000    0.0000000    1.2013000
  14      p    0.8660254    0.5000000    0.0000000   -1.2013000
  15     py    1.2013000
  16     py   -1.2013000
  17      p    0.86602540   -0.5   0.0   3.556
  18      p    0.86602540   -0.5   0.0  -3.556
  19      p    0.86602540    0.5   0.0   3.556
  20      p    0.86602540    0.5   0.0  -3.556
  21     py                     3.556
  22     py                    -3.556
  43     cz    0.5588        $ H2O
  44     cz    0.6223        $ Zr-2 clad
  45     cz    1.4808        $ fuel
  46     cz    1.5824        $ Zr-2 clad
  47     cz    2.2441        $ H2O
  48     cz    2.3076        $ Zr-2 clad
  49     cz    2.9896        $ fuel
  50     cz    3.0531        $ Zr-2 clad
 122     pz    0.0000000
```

```
  123     pz    53.086000
  125     cz    28.416250
  126     cz    28.733750
  127     cz     2.2225000
  128     cz     8.4140000
  141     pz   -113.67300
  143     pz    900.00000
  144     cz    500.00000
  146     pz   -3.1750000
  148     pz    49.719800
  149     pz    55.808880
  150     pz    353.90328
  151     pz    357.71328
  152     pz    350.72828
  153     pz     27.49140
c MCO
  160     cz   29.2100
  161     cz   30.4800
  162     cz   32.0004
  163     cz   51.0540
  164     pz   -8.2804
  165     pz   375.000
  166     pz   398.1196
c 167     pz    114.79276

tr2   0.00  0.00  58.98438
tr3   0.00  0.00  117.96776
tr4   0.00  0.00  176.95164
tr5   0.00  0.00  235.93552
tr6   0.00  0.00  294.91940
mode n
m4      92235.50  -0.01250  92238.50  -0.98750        $ outer fuel
m5   -  92235.50  -0.00947  92238.50  -0.99053        $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m237  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n     1.00000     53r   0.00000    1.000 30r $ 5, 139
mt236   lwtr.01t
mt237   lwtr.01t
mt2     lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  200
ksrc   9.7 0. 20.  9.7 9.7 75. -9.7 9.7 130.0
     -9.7 -9.7 185.0  0.0 9.7 250.0  0.0 -9.7 320.0
      1.0 0.0 10.0 2.50 0 10.0 0.0 0.0 0.0
```

F.5 PARTIALLY DRAINED MCO IN THE CVDF CONTAINING MARK IV FUEL AND SCRAP

```
Basic model for MCO loaded with 2 scrap baskets and 3 fuel baskets. Each scrap
c basket filled with Mk 4 scrap, flooded MCO at CVDF, no process tube in the
c scrap baskets. Revised 1.25" basket base plates for all baskets.
c Partially loaded fuel baskets, inner only in location 3,6
c Top scrap and fuel baskets drained. All other baskets flooded.
c flooded fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  25  3  3  3  3  2  $ 3
      2  2  2  3  3  3  3  3  3  3  2  $ 4
      2  2  3  3  3  3  3  3  3  3  2  $ 5
      2  2  3  3  3  2  3  3  3  2  2  $ 6  level 1
      2  3  3  3  3  3  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c  Mark 4 flooded scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   5    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8  236    -1.00000 6                    u=4    $ scrap cell
c  flooded Scrap basket
  9   0    -125  122              fill=1  u=9    $ scrap in basket
 11  236    -1.00    -127  -122            u=9    $ pipe interior
 13   20    -8.03    -122  127             u=9    $ basket base
 14   20    -8.03    125  122              u=9    $ basket side
c fictitious water cell for fuel basket lattice
 24  236   -1.00     -144                  u=2    $ fictitious cl
c flooded fuel basket
 25   20   -8.03     -128  127  122  -123       u=7    $ tube wall
 26  236   -1.00     -127  -123             u=7    $ central tube
 27   20   -8.03     -122  127 -130          u=7    $ bottom plate
 28   20   -8.03     -128    127   123       u=7    $ tube wall
 29  236   -1.00     -127  123              u=7    $ central tube
 31  236   -1.00     -129  128     123       u=7    $ above fuel
 32   20  -8.03000 129 122 -130               u=7    $ fuel basket side
 33    0  -129 122 128 -123              fill=8 u=7    $ fuel in basket
 34  236  -1.00  130                       u=7    $ outside fuel basket
c fuel and scrap basket stack
 51    0         -149            fill=9    u=11    $ bottom scrap basket
 52    0  146  -149 #51        trcl=2  fill=7    u=11    $ fuel basket
 53    0  146  -149 #52        trcl=3 fill=7    u=11    $ fuel basket
 54    0      -149          trcl=4 fill=20    u=21    $ fuel basket
 55    0  146  -152 #54        trcl=5 fill=19    u=21    $ top scrap basket
c  MCO and baskets
 59    0       -160  167  -150          fill=21  u=12   $ drained portion
```

```
 60   0      (-160 146 -167)        fill=11  u=12  $ flooded portion
 61  20 -8.03  160 -161 146                u=12  $ MCO shell
 62 236 -1.00  161 -162 146                u=12  $ cask annulus
 63  20 -8.03  162    146                 u=12  $ cask
 64  20 -8.03        -146                 u=12  $ cask bottom
 65  20 -8.03 -160  165                   u=12  $ mco top
 66  20 -8.03 -160  150 -151              u=12  $ filter guard
 67 237 -0.0051 -160  151  -165           u=12  $ top gap
 68   0      164 -163  -166        fill=12      $ mco cask
c Mk4 inner fuel structure
 80 236  -1.00          46            u=25  $ between fuels
 81  10  -6.49     -46   45           u=25  $ Zr-2 clad
 82   5 -18.82     -45   44           u=25  $ 0.947% U-235
 83  10  -6.49     -44   43           u=25  $ Zr-2 clad
 84 236  -1.00     -43                u=25  $ H2O
c Mk4 intact fuel structure
115 236  -1.00          50            u=3   $ between fuels
116  10  -6.49     -50   49           u=3   $ Zr-2 clad
117   5 -18.82     -49   48           u=3   $ 0.947% U-235
118  10  -6.49     -48   47           u=3   $ Zr-2 clad
119 236  -1.00     -47   46           u=3   $ H2O
120  10  -6.49     -46   45           u=3   $ Zr-2 clad
121   5 -18.82     -45   44           u=3   $ 0.947% U-235
122  10  -6.49     -44   43           u=3   $ Zr-2 clad
123 236  -1.00     -43                u=3   $ H2O
135   2   0.06520 -164 141 -144              $ basin floor
136 236 -0.0012 -144  -143  166                $ space above MCO
137 236 -0.0012 -166  163 164 -144               $ surrounding space
139   0 -141 :144 :143                       $ outside world
c drained fuel and scrap baskets
c fuel basket containing intact fuel assemblies
202   0  -17  18 -19  20 -21  22    u=16  lat=2
        fill=-5:5  -5:5  0:0
     15  15  15  15  15  15  15  15  15  15  15   $ 1
     15  15  15  15  15  15  13  13  13  15  15   $ 2
     15  15  15  15  13  23  13  13  13  13  15   $ 3
     15  15  15  13  13  13  13  13  13  13  15   $ 4
     15  15  13  13  13  13  13  13  13  13  15   $ 5
     15  15  13  13  13  15  13  13  13  15  15   $ 6  level 1
     15  13  13  13  13  13  13  13  13  15  15   $ 7
     15  13  13  13  13  13  13  13  15  15  15   $ 8
     15  13  13  13  13  13  13  15  15  15  15   $ 9
     15  15  13  13  13  15  15  15  15  15  15   $ 10
     15  15  15  15  15  15  15  15  15  15  15   $ 11
c      1   2   3   4   5   6   7   8   9  10  11
c drained Mark IV scrap optimized lattice
205   0          -11 12 -13 14 -15 16  fill=17 u=18 lat=2  $ scrap hex
206   5    -18.8200 -5                   u=17   $ scrap pin
207  10    -6.49000 5 -6                 u=17   $ scrap clad
208 237    -0.00510 6                    u=17   $ scrap cell
c Drained Scrap basket
209   0   -125  122              fill=18 u=19   $ scrap in basket
211 237   -0.0051  -127 -122              u=19   $ pipe interior
213  20   -8.03    -122  127              u=19   $ basket base
```

```
 214   20    -8.03      125  122                u=19    $ basket side
c  fictitious air cell for fuel basket lattice
 224  237    -0.0051    -144                     u=15    $ fictitious cl
c  fuel basket
 225   20    -8.03      -128  127  122  -123        u=20    $ tube wall
 226  237    -0.0051    -127  -123                u=20    $ central tube
 227   20    -8.03      -122  127  -130           u=20    $ bottom plate
 228   20    -8.03      -128    127    123        u=20    $ tube wall
 229  237    -0.0051    -127  123                u=20    $ central tube
 231  237    -0.0051    -129  128     123          u=20    $ above fuel
 232   20  -8.03000 129 122  -130                 u=20    $ fuel basket side
 233    0  -129 122 128 -123                fill=16 u=20   $ fuel in basket
 234  237  -0.0051   130                       u=20    $ outside basket
c  MkIV intact drained fuel structure
 315  237    -0.0051          50               u=13    $ between fuels
 316   10    -6.49      -50    49               u=13    $ Zr-2 clad
 317    5   -18.82      -49    48               u=13    $ 0.947% U-235
 318   10    -6.49      -48    47               u=13    $ Zr-2 clad
 319  237    -0.0051    -47    46               u=13    $ air
 320   10    -6.49      -46    45               u=13    $ Zr-2 clad
 321    5   -18.82      -45    44               u=13    $ 0.947% U-235
 322   10    -6.49      -44    43               u=13    $ Zr-2 clad
 323  237    -0.0051    -43                      u=13    $ air
c  Mk4 drained inner fuel structure
 380  237    -0.0051          46               u=23    $ between fuels
 381   10    -6.49      -46    45               u=23    $ Zr-2 clad
 382    5   -18.82      -45    44               u=23    $ 0.947% U-235
 383   10    -6.49      -44    43               u=23    $ Zr-2 clad
 384  237    -0.0051    -43                      u=23    $ H2O

   5     cz    0.8000000
   6     cz    0.8572000
  11      p    0.8660254   -0.5000000    0.0000000    1.3992000
  12      p    0.8660254   -0.5000000    0.0000000   -1.3992000
  13      p    0.8660254    0.5000000    0.0000000    1.3992000
  14      p    0.8660254    0.5000000    0.0000000   -1.3992000
  15     py    1.3992000
  16     py   -1.3992000
  17      p    0.86602540  -0.5   0.0   3.556
  18      p    0.86602540  -0.5   0.0  -3.556
  19      p    0.86602540   0.5   0.0   3.556
  20      p    0.86602540   0.5   0.0  -3.556
  21     py                      3.556
  22     py                     -3.556
  43     cz    0.6095        $ H2O
  44     cz    0.6605        $ Zr-2 clad
  45     cz    1.5480        $ fuel
  46     cz    1.6245        $ Zr-2 clad
  47     cz    2.1605        $ H2O
  48     cz    2.2110        $ Zr-2 clad
  49     cz    3.0165        $ fuel
  50     cz    3.0800        $ Zr-2 clad
 122      pz    0.0000000
 123      pz    66.294000
```

```
c  scrap basket side
  125      cz     28.77001997
c  process tube pipe
  127      cz      2.2225000
  128      cz      3.4925000
c  fuel basket side
  129      cz     28.41625
  130      cz     28.73375
  141      pz    -113.67300
  143      pz     900.00000
  144      cz     500.00000
  146      pz    -3.1750000
  149      pz     67.68338
  150      pz     353.83470
  151      pz     357.64470
  152      pz     351.11690
c  MCO
  160      cz    29.2100
  161      cz    30.4800
  162      cz    32.0004
  163      cz    51.0540
  164      pz    -8.2804
  165      pz    375.000
  166      pz    398.1196
  167      pz    209.40014

tr2   0.00  0.00  70.858380
tr3   0.00  0.00  141.71676
tr4   0.00  0.00  212.57564
tr5   0.00  0.00  283.43352
mode  n
m5       92235.50   -0.00947   92238.50   -0.99053          $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m237  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n      1.00000     50r          0.00000 1.000 32r  $ 5, 139
mt236    lwtr.01t
mt237    lwtr.01t
mt2      lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  200
ksrc   9.7 0. 20.  -9.7 0.0 85.0 9.7 -9.7 150.0
     -9.7 -9.7 250.0  0.0 -9.7 320.0
       1.0 0.0 10.0 2.50 0 10.0 0.0 0.0 0.0
```

F.6 18 MARK 1A 26 IN. LONG FUEL ASSEMBLIES IN A MARK IV FUEL BASKET

```
Basic model for MCO loaded with 2 scrap baskets and 3 fuel baskets. Each scrap
c basket filled with Mk 4 scrap, flooded MCO at CVDF, no process tube in the
c scrap baskets. Revised 1.25" basket base plates for all baskets.
c Partially loaded fuel baskets, inner only in location 3,6
c Central fuel basket contains 18 26.1" Mark 1A fuel assemblies
c flooded annulus
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  15  3  3  3  3  2  $ 3
      2  2  2  3  3  3  3  3  3  3  2  $ 4
      2  2  3  3  3  3  3  3  3  3  2  $ 5
      2  2  3  3  3  2  3  3  3  2  2  $ 6  level 1
      2  3  3  3  3  3  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c     1  2  3  4  5  6  7  8  9  10  11
c fuel basket containing 18 Mk1A assemblies
  3   0  -17  18 -19  20 -21  22     u=21  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  15  3  3  3  3  2  $ 3
      2  2  2  3  3  5  5  3  3  3  2  $ 4
      2  2  3  3  5  5  5  5  3  3  2  $ 5
      2  2  3  5  5  2  5  5  3  2  2  $ 6  level 1
      2  3  3  5  5  5  5  5  3  2  2  $ 7
      2  3  3  3  5  5  5  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c     1  2  3  4  5  6  7  8  9  10  11
c Mark 4 scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   5    -18.8200 -5                  u=4   $ scrap pin
  7  10    -6.49000 5 -6                u=4   $ scrap clad
  8 236    -1.00000 6                   u=4   $ scrap cell
c Scrap basket
  9   0    -125  122              fill=1  u=9   $ scrap in basket
 11 236    -1.00    -127  -122            u=9   $ pipe interior
 13  20    -8.03    -122  127            u=9   $ basket base
 14  20    -8.03    125  122             u=9   $ basket side
c Mk1A intact fuel structure
 15 236    -1.00          30             u=5   $ between fuels
 16  10    -6.49    -30   29             u=5   $ Zr-2 clad
 17   4   -18.82    -29   28             u=5   $ 1.250% U-235
 18  10    -6.49    -28   27             u=5   $ Zr-2 clad
```

```
 19  236   -1.00     -27    26              u=5   $ H2O
 20   10   -6.49     -26    25              u=5   $ Zr-2 clad
 21    5  -18.82     -25    24              u=5   $ 0.947% U-235
 22   10   -6.49     -24    23              u=5   $ Zr-2 clad
 23  236   -1.00     -23                    u=5   $ H2O
c fictitious water cell for fuel basket lattice
 24  236   -1.00     -144                   u=2   $ fictitious cl
c normal fuel basket
 25   20   -8.03     -128  127  122  -123       u=7   $ tube wall
 26  236   -1.00     -127  -123              u=7   $ central tube
 27   20   -8.03     -122  127 -130           u=7   $ bottom plate
 28   20   -8.03     -128    127    123       u=7   $ tube wall
 29  236   -1.00     -127  123               u=7   $ central tube
 31  236   -1.00     -129  128     123        u=7   $ above fuel
 32   20  -8.03000 129 122 -130                u=7   $ fuel basket side
 33    0  -129 122 128 -123              fill=8 u=7   $ fuel in basket
 34  236  -1.00   130                       u=7   $ outside fuel basket
c fuel basket containing Mark 1A assemblies
 35   20   -8.03     -128  127  122  -123       u=22  $ tube wall
 36  236   -1.00     -127  -123              u=22  $ central tube
 37   20   -8.03     -122  127 -130           u=22  $ bottom plate
 38   20   -8.03     -128    127    123       u=22  $ tube wall
 39  236   -1.00     -127  123               u=22  $ central tube
 41  236   -1.00     -129  128     123        u=22  $ above fuel
 42   20  -8.03000 129 122 -130                u=22  $ fuel basket side
 43    0  -129 122 128 -123              fill=21 u=22  $ fuel in basket
 44  236  -1.00   130                       u=22  $ outside fuel basket
c fuel and scrap basket stack
 51    0          -149            fill=9     u=11   $ bottom scrap basket
 52    0   146  -149 #51       trcl=2  fill=7     u=11   $ fuel basket
 53    0   146  -149 #52       trcl=3 fill=22     u=11   $ fuel basket
 54    0   146  -149 #53       trcl=4 fill=7      u=11   $ fuel basket
 55    0   146  -149 #54       trcl=5 fill=9      u=11   $ top scrap basket
 59  236  -1.000     152  #55                u=11   $ above top basket
c MCO and baskets
 60    0       (-160 146 -150)          fill=11  u=12   $ interior
 61   20  -8.03   160 -161 146                u=12   $ MCO shell
 62  236  -1.00   161 -162 146                u=12   $ cask annulus
 63   20  -8.03   162     146                u=12   $ cask
 64   20  -8.03          -146                u=12   $ cask bottom
 65   20  -8.03  -160  165                    u=12   $ mco top
 66   20  -8.03  -160  150 -151               u=12   $ filter guard
 67  236  -1.00  -160  151  -165              u=12   $ top gap
 68    0        164  -163  -166          fill=12      $ mco cask
c Mk4 inner fuel structure
 80  236   -1.00            46              u=15   $ between fuels
 81   10   -6.49     -46    45              u=15   $ Zr-2 clad
 82    5  -18.82     -45    44              u=15   $ 0.947% U-235
 83   10   -6.49     -44    43              u=15   $ Zr-2 clad
 84  236   -1.00     -43                    u=15   $ H2O
c Mk4 intact fuel structure
115  236   -1.00            50              u=3   $ between fuels
116   10   -6.49     -50    49              u=3   $ Zr-2 clad
117    5  -18.82     -49    48              u=3   $ 0.947% U-235
```

```
118  10   -6.49     -48   47              u=3   $ Zr-2 clad
119  236  -1.00     -47   46              u=3   $ H2O
120  10   -6.49     -46   45              u=3   $ Zr-2 clad
121  5   -18.82     -45   44              u=3   $ 0.947% U-235
122  10   -6.49     -44   43              u=3   $ Zr-2 clad
123  236  -1.00     -43                   u=3   $ H2O
135  20  -8.03     -164 141 -144                $ transporter bed
136  236 -0.0012 -144  -143  166                  $ space above MCO
137  236 -0.0012 -166  163 164 -144                 $ surrounding space
139   0  -141 :144 :143                        $ outside world

 5     cz    0.8000000
 6     cz    0.8572000
 11     p    0.8660254   -0.5000000   0.0000000   1.3992000
 12     p    0.8660254   -0.5000000   0.0000000  -1.3992000
 13     p    0.8660254    0.5000000   0.0000000   1.3992000
 14     p    0.8660254    0.5000000   0.0000000  -1.3992000
 15    py    1.3992000
 16    py   -1.3992000
 17     p    0.86602540  -0.5   0.0   3.556
 18     p    0.86602540  -0.5   0.0  -3.556
 19     p    0.86602540   0.5   0.0   3.556
 20     p    0.86602540   0.5   0.0  -3.556
 21    py                    3.556
 22    py                   -3.556
c Mk 1A fuel
 23    cz    0.5588       $ H2O
 24    cz    0.6223       $ Zr-2 clad
 25    cz    1.4808       $ fuel
 26    cz    1.5824       $ Zr-2 clad
 27    cz    2.2441       $ H2O
 28    cz    2.3076       $ Zr-2 clad
 29    cz    2.9896       $ fuel
 30    cz    3.0531       $ Zr-2 clad
c Mk 4 fuel
 43    cz    0.6095       $ H2O
 44    cz    0.6605       $ Zr-2 clad
 45    cz    1.5480       $ fuel
 46    cz    1.6245       $ Zr-2 clad
 47    cz    2.1605       $ H2O
 48    cz    2.2110       $ Zr-2 clad
 49    cz    3.0165       $ fuel
 50    cz    3.0800       $ Zr-2 clad
 122    pz   0.0000000
 123    pz   66.294000
c scrap basket side
 125    cz   28.77001997
c 126   cz   29.08751997
c process tube pipe
 127    cz    2.2225000
 128    cz    3.4925000
c fuel basket side
 129    cz   28.41625
 130    cz   28.73375
```

```
 141     pz   -113.67300
 143     pz    900.00000
 144     cz    500.00000
 146     pz   -3.1750000
 149     pz    67.68338
 150     pz    353.83470
 151     pz    357.64470
 152     pz    351.11690
c MCO
 160     cz   29.2100
 161     cz   30.4800
 162     cz   32.0004
 163     cz   51.0540
 164     pz   -8.2804
 165     pz   375.000
 166     pz   398.1196

tr2   0.00  0.00  70.858380
tr3   0.00  0.00  141.71676
tr4   0.00  0.00  212.57514
tr5   0.00  0.00  283.43352
mode  n
m4      92235.50  -0.01250  92238.50  -0.98750        $ outer fuel
m5      92235.50  -0.00947  92238.50  -0.99053        $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
imp:n     1.00000    69r        0.00000 $ 5, 139
mt236   lwtr.01t
c mt2     lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  200
ksrc   9.7 0. 20.  -9.7 0.0 85.0 9.7 -9.7 150.0
    -9.7 -9.7 250.0  0.0 -9.7 320.0
```

F.7 MARK 1A OUTER FUEL ELEMENTS ONLY LOADED INTO A FUEL BASKET

```
Basic model for MCO loaded with 2 scrap baskets and 4 fuel baskets. Each scrap
c basket filled with 575 kg Mk 1A scrap, flooded MCO in water
c Partially filled fuel baskets. Revised center post ID
c locations 4,6 and 6,4 containing an outer element only.
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  3  3  3  3  3  2  $ 3
      2  2  2  3  15  3  3  3  3  3  2  $ 4
      2  2  3  3  3  2  2  3  3  3  2  $ 5
      2  2  3  15  2  2  2  3  3  2  2  $ 6  level 1
      2  3  3  3  2  2  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c  Mark 1A scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   4    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8 236    -1.00000 6                     u=4    $ scrap cell
c  Scrap basket
  9   0    -125  122  128 -148          fill=1  u=9    $ scrap in basket
 10 236    -1.00000  148  -125  128            u=9    $ water above scrap
 11 236    -1.00    -127                   u=9    $ pipe interior
 12  20    -8.03    127  -128  122            u=9    $ pipe wall
 13  20    -8.03    -122  127               u=9    $ basket base
 14  20    -8.03    125  122                u=9    $ basket side
c fictitious water cell for fuel basket lattice
 24 236    -1.00    -144                   u=2    $ fictitious cl
c fuel basket
 25  20    -8.03    -128  127  122  -123        u=7    $ tube wall
 26 236    -1.00    -127  -123               u=7    $ central tube
 27  20    -8.03    -122  127                u=7    $ bottom plate
 28  20    -8.03    -128    127    123        u=7    $ tube wall
 29 236    -1.00    -127  123                u=7    $ central tube
 31 236    -1.00    -125  128     123        u=7    $ above fuel
 32  20  -8.03000 125 122                    u=7    $ fuel basket side
 33   0  -125 122 128 -123              fill=8 u=7    $ fuel in basket
c fuel and scrap basket stack
 51   0        -149            fill=9    u=11    $ bottom scrap basket
 52   0  146  -149 #51       trcl=2  fill=7    u=11    $ fuel basket
 53   0  146  -149 #52       trcl=3 fill=7    u=11    $ fuel basket
 54   0  146  -149 #53       trcl=4 fill=7    u=11    $ fuel basket
 55   0  146  -149 #54       trcl=5 fill=7    u=11    $ fuel basket
 56   0  146  -149 #55       trcl=6 fill=9    u=11    $ top scrap basket
c  MCO and baskets
 60  236  -1.000 (-160 146 -152)(-126:-152)  fill=11  u=12   $ interior
```

```
61   20  -8.03   160 -161 146                u=12   $ MCO shell
62  236  -1.00   161 -162 146                u=12   $ cask annulus
63   20  -8.03   162     146                u=12   $ cask
64   20  -8.03         -146                 u=12   $ cask bottom
65   20  -8.03  -160  165                   u=12   $ mco top
66   20  -8.03  -160  150  -151             u=12   $ filter guard
67  236  -1.00  -160  151  -165             u=12   $ top gap
68  236  -1.00  -160  -150  152             u=12   $ above top basket
69    0       164  -163  -166        fill=12      $ mco cask
c Mk1A outer fuel structure
80  236   -1.00          50               u=15   $ between fuels
81   10   -6.49     -50   49              u=15   $ Zr-2 clad
82    4  -18.82     -49   48              u=15   $ 1.250% U-235
83   10   -6.49     -48   47              u=15   $ Zr-2 clad
84  236   -1.00     -47                   u=15   $ H2O
c Mk1A intact fuel structure
115  236   -1.00          50              u=3    $ between fuels
116   10   -6.49     -50   49              u=3    $ Zr-2 clad
117    4  -18.82     -49   48              u=3    $ 1.250% U-235
118   10   -6.49     -48   47              u=3    $ Zr-2 clad
119  236   -1.00     -47   46              u=3    $ H2O
120   10   -6.49     -46   45              u=3    $ Zr-2 clad
121    5  -18.82     -45   44              u=3    $ 0.947% U-235
122   10   -6.49     -44   43              u=3    $ Zr-2 clad
123  236   -1.00     -43                   u=3    $ H2O
135    2     0.06520 -164 141 -144                $ basin floor
136  236  -1.000  -144  -143  166                 $ water above MCO
137  236  -1.000  -166  163 164 -144                $ surrounding water
139    0  -141 :144 :143                        $ outside world

 5     cz    0.6500000
 6     cz    0.7107000
 11     p    0.8660254   -0.5000000    0.0000000    1.2013000
 12     p    0.8660254   -0.5000000    0.0000000   -1.2013000
 13     p    0.8660254    0.5000000    0.0000000    1.2013000
 14     p    0.8660254    0.5000000    0.0000000   -1.2013000
 15    py    1.2013000
 16    py   -1.2013000
 17    p     0.86602540  -0.5   0.0   3.556
 18    p     0.86602540  -0.5   0.0  -3.556
 19    p     0.86602540   0.5   0.0   3.556
 20    p     0.86602540   0.5   0.0  -3.556
 21    py                      3.556
 22    py                     -3.556
 43    cz    0.5588        $ H2O
 44    cz    0.6223        $ Zr-2 clad
 45    cz    1.4808        $ fuel
 46    cz    1.5824        $ Zr-2 clad
 47    cz    2.2441        $ H2O
 48    cz    2.3076        $ Zr-2 clad
 49    cz    2.9896        $ fuel
 50    cz    3.0531        $ Zr-2 clad
 122    pz    0.0000000
 123    pz    53.086000
```

```
  125     cz    28.416250
  126     cz    28.733750
  127     cz     2.2225000
  128     cz     8.4140000
  141     pz   -113.67300
  143     pz    900.00000
  144     cz    500.00000
  146     pz   -3.1750000
  148     pz    49.719800
  149     pz    55.808880
  150     pz    353.90328
  151     pz    357.71328
  152     pz    350.72828
c MCO
  160     cz   29.2100
  161     cz   30.4800
  162     cz   32.0004
  163     cz   51.0540
  164     pz   -8.2804
  165     pz   375.000
  166     pz   398.1196

tr2   0.00 0.00 58.98388
tr3   0.00 0.00 117.96776
tr4   0.00 0.00 176.95164
tr5   0.00 0.00 235.93552
tr6   0.00 0.00 294.91940
mode n
m4      92235.50  -0.01250  92238.50  -0.98750        $ outer fuel
m5      92235.50  -0.00947  92238.50  -0.99053        $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n     1.00000    52r        0.00000 $ 5, 139
mt236   lwtr.01t
mt2     lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  200
ksrc   9.7 0. 20.  9.7 9.7 75. -9.7 9.7 130.0
    -9.7 -9.7 185.0  0.0 9.7 250.0  0.0 -9.7 320.0
```

F.8 MARK 1A DROP MODEL

```
Basic model for MCO loaded with 6 fuel baskets in a flooded MCO.
c revised center pipe with 1.75" ID.  Drop model with fuel rubbilized
c and the basket sides destroyed.  Spacing maintained by safety class
c central pipe and basket bases.
c  Mark 1A fuel rubble optimized lattice
  15   0          -11 12 -13 14 -15 16  fill=3 u=8 lat=2  $ scrap hex
  16   6    -18.8200 -5                    u=3    $ scrap pin
  17  10    -6.49000 5 -6                  u=3    $ scrap clad
  18 236    -1.00000 6                     u=3    $ scrap cell
c fuel basket with rubble
  25  20  -8.03     -128  127  122            u=7   $ tube wall
  26 236  -1.00     -127                    u=7   $ central tube
  27  20  -8.03     -122  127               u=7   $ bottom plate
  33   0     122 128                  fill=8 u=7   $ fuel in basket
c fuel and scrap basket stack
  51   0        -149            fill=7     u=11   $ bottom fuel basket
  52   0  146  -149 #51       trcl=2  fill=7     u=11   $ fuel basket
  53   0  146  -149 #52       trcl=3 fill=7      u=11   $ fuel basket
  54   0  146  -149 #53       trcl=4 fill=7      u=11   $ fuel basket
  55   0  146  -149 #54       trcl=5 fill=7      u=11   $ fuel basket
  56   0  146  -149 #55       trcl=6 fill=7      u=11   $ top fuel basket
c  MCO and baskets
  60   0      -160  146 -152          fill=11  u=12   $ interior
  61  20  -8.03   160 -161 146                u=12   $ MCO shell
  62 236  -1.00   161 -162 146                u=12   $ cask annulus
  63  20  -8.03   162     146                u=12   $ cask
  64  20  -8.03          -146                u=12   $ cask bottom
  65  20  -8.03  -160  165                    u=12   $ mco top
  66  20  -8.03  -160  150  -151               u=12   $ filter guard
  67 236  -1.00  -160  151  -165               u=12   $ top gap
  68 236  -1.00  -160  -150  152               u=12   $ above top basket
  69   0       164  -163  -166          fill=12      $ mco cask
 135   2     0.06520 -164 141 -144                   $ basin floor
 136 236  -1.000  -144  -143  166                    $ water above MCO
 137 236  -1.000  -166  163 164 -144                   $ surrounding water
 139   0  -141 :144 :143                          $ outside world

   5     cz    0.6500000
   6     cz    0.7107000
  11      p    0.8660254   -0.5000000    0.0000000    1.2013000
  12      p    0.8660254   -0.5000000    0.0000000   -1.2013000
  13      p    0.8660254    0.5000000    0.0000000    1.2013000
  14      p    0.8660254    0.5000000    0.0000000   -1.2013000
  15     py    1.2013000
  16     py   -1.2013000
 122     pz    0.0000000
 127     cz    2.2225000
 128     cz    8.4140000
 141     pz   -113.67300
 143     pz    900.00000
 144     cz    500.00000
```

```
  146     pz   -3.1750000
  149     pz    55.808880
  150     pz    353.90328
  151     pz    357.71328
  152     pz    350.72828
c MCO
  160     cz   29.2100
  161     cz   30.4800
  162     cz   32.0004
  163     cz   51.0540
  164     pz   -8.2804
  165     pz   375.000
  166     pz   398.1196

tr2   0.00 0.00 58.98388
tr3   0.00 0.00 117.96776
tr4   0.00 0.00 176.95164
tr5   0.00 0.00 235.93552
tr6   0.00 0.00 294.91940
mode n
m4      92235.50  -0.01250  92238.50  -0.98750        $ outer fuel
m6      92235.50  -0.01150  92238.50  -0.98850        $ mixed rubble
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n     1.00000    26r        0.00000 $ 5, 139
mt236   lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  200
ksrc   9.7 0. 20.
```

F.9 MARK IV DROP MODEL

```
Vertical drop model for a mark 4 MCO.
c The MCO is filled with optimized scrap to the filter guard.
c Basket bases included, small pipe region filled with scrap
c  Mark 4 scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   5    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8 236    -1.00000 6                     u=4    $ scrap cell
c  Scrap basket
  9   0        122                 fill=1  u=9    $ scrap in basket
 11   0          -127  -122          fill=1  u=9    $ pipe interior
 13  20   -8.03    -122  127                u=9    $ basket base
c fuel basket containing rubbilized fuel material
 25   0        122                 fill=1  u=7    $ rubble in basket
 27  20  -8.03    -122  127                u=7    $ bottom plate
 28   0          -127  -122          fill=1  u=7    $ pipe interior
c fuel and scrap basket stack
 51   0        -149              fill=9    u=11   $ bottom scrap basket
 52   0  146  -149 #51        trcl=2  fill=7    u=11   $ fuel basket
 53   0  146  -149 #52        trcl=3 fill=7     u=11   $ fuel basket
 54   0  146  -149 #53        trcl=4 fill=7     u=11   $ fuel basket
 55   0  146  -149 #54        trcl=5 fill=9     u=11   $ top scrap basket
 59   0          152  #55          fill=1  u=11   $ top of top basket
c  MCO
 60   0       -160 146 -150          fill=11  u=12   $ interior
 61  20 -8.03  160 -161                  u=12   $ MCO shell
 62 236 -1.00  161 -162                  u=12   $ cask annulus
 63  20 -8.03  162                     u=12   $ cask
 64  20 -8.03  -160    -146              u=12   $ cask bottom
 65  20 -8.03 -160  165                  u=12   $ mco top
 66  20 -8.03 -160  150 -151               u=12   $ filter guard
 67 236 -1.00 -160  151  -165              u=12   $ top gap
 68   0       164  -163  -166          fill=12      $ mco cask
135   2     0.06520 -164 141 -144                  $ basin floor
136 236 -1.000  -144  -143  166                    $ water above MCO
137 236 -1.000  -166  163 164 -144                   $ surrounding water
139   0 -141 :144 :143                         $ outside world

  5     cz    0.8000000
  6     cz    0.8572000
 11      p    0.8660254   -0.5000000    0.0000000    1.3992000
 12      p    0.8660254   -0.5000000    0.0000000   -1.3992000
 13      p    0.8660254    0.5000000    0.0000000    1.3992000
 14      p    0.8660254    0.5000000    0.0000000   -1.3992000
 15     py    1.3992000
 16     py   -1.3992000
122     pz    0.0000000
127     cz    2.2225000
141     pz   -113.67300
143     pz    900.00000
144     cz    500.00000
```

```
  146     pz   -3.1750000
  149     pz    67.68338
  150     pz    353.83470
  151     pz    357.64470
  152     pz    351.11690
c MCO
  160     cz   29.2100
  161     cz   30.4800
  162     cz   32.0004
  163     cz   51.0540
  164     pz   -8.2804
  165     pz   375.000
  166     pz   398.1196

tr2   0.00  0.00  70.858380
tr3   0.00  0.00  141.71676
tr4   0.00  0.00  212.57514
tr5   0.00  0.00  283.43352
mode  n
m5      92235.50  -0.00947  92238.50  -0.99053          $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n     1.00000    27r        0.00000 $ 5, 139
mt236   lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  400
ksrc   9.7 0. 20.
```

F.10 CSB MODEL

```
Basic model for the CSB.  Each MCO loaded with 2 scrap and 4 fuel baskets.
c Each scrap basket filled with Mk 1A scrap.  Vault surrounded by concrete.
c empty location 4,5 in the fuel baskets.  Revised center post ID
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      5  5  5  5  5  5  5  5  5  5  5  $ 1
      5  5  5  5  5  5  3  3  3  5  5  $ 2
      5  5  5  5  3  3  3  3  3  3  5  $ 3
      5  5  5  3  5  3  3  3  3  3  5  $ 4
      5  5  3  3  3  5  5  3  3  3  5  $ 5
      5  5  3  3  5  5  5  3  3  5  5  $ 6  level 1
      5  3  3  3  5  5  3  3  3  5  5  $ 7
      5  3  3  3  3  3  3  3  5  5  5  $ 8
      5  3  3  3  3  3  3  5  5  5  5  $ 9
      5  5  3  3  3  5  5  5  5  5  5  $ 10
      5  5  5  5  5  5  5  5  5  5  5  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c  Mark 1A scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   4    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8 236    -0.00510 6                     u=4    $ scrap cell
c  Scrap basket
  9   0    -125  122  128 -148          fill=1  u=9    $ scrap in basket
 10 236    -0.00510  148  -125  128            u=9    $ vapor above scrap
 11 236    -0.0051  -127                   u=9    $ pipe interior
 12  20    -8.03    127  -128  122          u=9    $ pipe wall
 13  20    -8.03    -122  127  -126         u=9    $ basket base
 14  20    -8.03    125  122  -126          u=9    $ basket side
 15 236    -0.0051   126                   u=9    $ outside basket
c  fictitious cell for fuel basket lattice
 24 236    -0.0051    -144                  u=5    $ fictitious cl
c  fuel basket
 25  20    -8.03     -128  127  122  -123       u=7    $ tube wall
 26 236    -0.0051    -127  -123             u=7    $ central tube
 27  20    -8.03     -122  127  -126         u=7    $ bottom plate
 28  20    -8.03     -128    127    123      u=7    $ tube wall
 29 236    -0.0051    -127  123              u=7    $ central tube
 31 236    -0.0051    -125  128     123        u=7    $ above fuel
 32  20  -8.03000 125 122  -126               u=7    $ fuel basket side
 33   0  -125 122 128 -123              fill=8 u=7    $ fuel in basket
 34 236 -0.0051  126                       u=7    $ outside basket
c  fuel and scrap basket stack
 51   0         -149            fill=9     u=11    $ bottom scrap basket
 52   0  146  -149 #51       trcl=2  fill=7     u=11    $ fuel basket
 53   0  146  -149 #52       trcl=3 fill=7     u=11    $ fuel basket
 54   0  146  -149 #53       trcl=4 fill=7     u=11    $ fuel basket
 55   0  146  -149 #54       trcl=5 fill=7     u=11    $ fuel basket
 56   0  146  -149 #55       trcl=6 fill=9     u=11    $ top scrap basket
c  MCO and baskets
```

```
  60  236  -0.0051 (-160 146 -152)          fill=11  u=12   $ interior
  61   20  -8.03   160     146                u=12   $ MCO shell
  62   20  -8.03          -146                u=12   $ mco bottom
  63   20  -8.03  -160  165                   u=12   $ mco top
  64   20  -8.03  -160  150  -151              u=12   $ filter guard
  65  236  -0.0051 -160  151  -165              u=12   $ top gap
  66  236  -0.0051 -160  -150  152              u=12   $ above top basket
  67    0              -161          fill=12 u=14   $ mco  internals
  68    3  -0.0012         161                u=14   $ outside mco
c  mco storage tube
  70   20  -8.03      -170 -172                u=15   $ tube base
  71   20  -4.01      -170 -164  172            u=15   $ lower impact limiter
  72   20  -4.01    -170 166 -174               u=15   $ middle impact limiter
  73    3  -0.0012  -170 175  #75               u=15   $ air above top mco
  74    0    -170   164  -166            fill=14 u=15   $ bottom mco
  75    0    -170   164  -166  #72 trcl=7    fill=14 u=15   $ top mco
  76   20  -8.03 -171 170                      u=15   $ tube shell
  77    3  -0.0012  171                       u=15   $ dummy air cell
c  fictitious cell for csb lattice
  78    3   -0.0012    -144                    u=2    $ fictitious cl
  79    0   -190 191 -192 193 -194 195      u=16 lat=2       $ tube structure
          fill=-11:12  -12:11   0:0
    2 2 2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2 2 2 $  1
    2 2 2  2  2  2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15 15 2 2 $  2
    2 2 2  2  2  2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15 15 2 2 $  3
    2 2 2  2  2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2 2 2 $  4
    2 2 2  2  2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2 2 2 $  5
    2 2 2  2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2 2 2 $  6
    2 2 2  2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2 2 2 $  7
    2 2 2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2 2 2 $  8
    2 2 2  2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2 2 2 $  9
    2 2 2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2 2 2 $  10
    2 2 2  2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2 2 2 $  11
    2 2 2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2 2 2 $  12
    2 2 2  2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2 2 2 $  13
    2 2 2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2 2 2 $  14
    2 2 2  2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2 2 2 $  15
    2 2 2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2 2 2 $  16
    2 2 2  2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2 2 2 $  17
    2 2 2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2  2 2 2 $  18
    2 2 2  2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2  2 2 2 $  19
    2 2 2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2  2  2 2 2 $  20
    2 2 2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2  2  2 2 2 $  21
    2 2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2  2  2  2 2 2 $  22
    2 2 15 15 15 15 15 15 15 15 15 15  2  2  2  2  2  2  2  2  2  2 2 2 $  23
    2 2 2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2 2 2 $  24
c    1 2 2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22
  80   0  -180 181 -182 183 173 -176            fill=16     $ tube array
c  Mk1A intact fuel structure
  115  236   -0.0051          50              u=3    $ between fuels
  116   10   -6.49      -50    49              u=3    $ Zr-2 clad
  117    4  -18.82      -49    48              u=3    $ 1.250% U-235
  118   10   -6.49      -48    47              u=3    $ Zr-2 clad
  119  236   -0.0051    -47    46              u=3    $ middle channel
```

```
120   10   -6.49      -46    45                u=3   $ Zr-2 clad
121    5  -18.82      -45    44                u=3   $ 0.947% U-235
122   10   -6.49      -44    43                u=3   $ Zr-2 clad
123  236   -0.0051     -43                      u=3   $ inner channel
134    2   -0.06520 (-184 185 -186 187 -176 173)(180:-181:182:
     -183:176:-173)                              $ concrete walls
135    2  -0.06520 -173 141 -144                    $ vault floor
136  236  -0.0012 -144  -143  176                   $ air above vault
137  236  -0.0012 (-176 173 -144)(184:-185:186:-187:176:-173)  $ surrounding air
139    0  -141 :144 :143                            $ outside world

  5     cz    0.6500000
  6     cz    0.7107000
 11      p    0.8660254   -0.5000000    0.0000000    1.2013000
 12      p    0.8660254   -0.5000000    0.0000000   -1.2013000
 13      p    0.8660254    0.5000000    0.0000000    1.2013000
 14      p    0.8660254    0.5000000    0.0000000   -1.2013000
 15     py    1.2013000
 16     py   -1.2013000
 17      p    0.86602540  -0.5   0.0   3.556
 18      p    0.86602540  -0.5   0.0  -3.556
 19      p    0.86602540   0.5   0.0   3.556
 20      p    0.86602540   0.5   0.0  -3.556
 21     py                      3.556
 22     py                     -3.556
 43     cz    0.5588        $ inner channel
 44     cz    0.6223        $ Zr-2 clad
 45     cz    1.4808        $ fuel
 46     cz    1.5824        $ Zr-2 clad
 47     cz    2.2441        $ middle channel
 48     cz    2.3076        $ Zr-2 clad
 49     cz    2.9896        $ fuel
 50     cz    3.0531        $ Zr-2 clad
122      pz    0.0000000
123      pz    53.086000
125      cz    28.416250
126      cz    28.733750
127      cz     2.2225000
128      cz     8.4140000
141      pz   -195.58800
143      pz    2000.00000
144      cz    3000.0000
146      pz   -3.1750000
148      pz    49.719800
149      pz    55.808880
150      pz    353.90328
151      pz    357.71328
152      pz    350.72828
c MCO
160      cz    29.2100
161      cz    30.4800
164      pz   -8.2804
165      pz    375.000
166      pz    398.1196
```

```
c  storage tubes
 170     cz   35.56
 171     cz   36.83
 172     pz   -79.375
 173     pz   -81.915
 174     pz   443.8396
 175     pz   850.2391
 176     pz   1205.230
c tube array boundaries
 180     px   800.000
 181     px   -750.000
 182     py   1400.00
 183     py   -1500.00
c  concrete walls
 184     px   891.44
 185     px   -841.44
 186     py   1491.44
 187     py   -1591.44
c   csb hex element
 190     px    68.0800
 191     px   -68.0800
 192     p     0.5    0.8660254   0.0   71.12
 193     p     0.5    0.8660254   0.0  -71.12
 194     p    -0.5    0.8660254   0.0   71.12
 195     p    -0.5    0.8660254   0.0  -71.12

tr2   0.00  0.00  58.98388
tr3   0.00  0.00  117.96776
tr4   0.00  0.00  176.95164
tr5   0.00  0.00  235.93552
tr6   0.00  0.00  294.91940
tr7   0.00  0.00  452.12000
mode  n
m4      92235.50   -0.01250   92238.50   -0.98750          $ outer fuel
m5      92235.50   -0.00947   92238.50   -0.99053          $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300                    $ water
m10   40000.50c -1.000000                          $ zirc clad
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000  $steel
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500    $ concrete
    20000.50  0.073800 26000.55  0.029900
m3    1001.50c 0.666700 8016.50c 0.333300                    $ air space
imp:n     1.00000     60r         0.00000 $ 5, 139
mt236   lwtr.01t
mt3     lwtr.01t
mt2     lwtr.01t
print   40 60 80 100 110 126
prdmp   j   300
kcode   2000  1. 20  500
ksrc   9.7 0. 20.  9.7 9.7 75. -9.7 9.7 130.0
     -9.7 -9.7 185.0  0.0 9.7 250.0  0.0 -9.7 320.0
     9.7 0. 470.  9.7 9.7 525. -9.7 9.7 580.0
     9.7 -9.7 635.0  0.0 9.7 700.0  0.0 -9.7 770.0
```

F.11 AN MCO IN THE SAMPLING/WELD STATION

```
Basic model for MCO loaded with 2 scrap baskets and 3 fuel baskets. Each scrap
c basket filled with Mk 4 scrap, drained MCO, no process tube in the
c scrap baskets. Revised 1.25" basket base plates for all baskets.
c Partially loaded fuel baskets, inner only in location 4,5
c MCO in the CSB sample or weld pit flooded with glycol
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  3  3  3  3  3  2  $ 3
      2  2  2  3  15  3  3  3  3  3  2  $ 4
      2  2  3  3  3  3  3  3  3  3  2  $ 5
      2  2  3  3  3  2  3  3  3  2  2  $ 6  level 1
      2  3  3  3  3  3  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c Mark 4 scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   5    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8 236    -0.00510 6                     u=4    $ scrap cell
c Scrap basket
  9   0    -125  122                fill=1  u=9    $ scrap in basket
 11 236    -0.0051  -127  -122              u=9    $ pipe interior
 13  20    -8.03    -122  127               u=9    $ basket base
 14  20    -8.03    125  122                u=9    $ basket side
c fictitious water cell for fuel basket lattice
 24 236    -0.0051    -144                   u=2    $ fictitious cl
c fuel basket
 25  20    -8.03    -128  127  122  -123       u=7    $ tube wall
 26 236    -0.0051    -127  -123              u=7    $ central tube
 27  20    -8.03    -122  127 -130            u=7    $ bottom plate
 28  20    -8.03    -128    127   123        u=7    $ tube wall
 29 236    -0.0051    -127  123               u=7    $ central tube
 31 236    -0.0051    -129  128    123        u=7    $ above fuel
 32  20  -8.03000 129 122 -130                u=7    $ fuel basket side
 33   0  -129 122 128 -123              fill=8 u=7    $ fuel in basket
 34 236  -0.0051 130                       u=7    $ outside fuel basket
c fuel and scrap basket stack
 51   0        -149            fill=9    u=11    $ bottom scrap basket
 52   0  146  -149 #51       trcl=2  fill=7    u=11    $ fuel basket
 53   0  146  -149 #52       trcl=3 fill=7    u=11    $ fuel basket
 54   0  146  -149 #53       trcl=4 fill=7    u=11    $ fuel basket
 55   0  146  -149 #54       trcl=5 fill=9    u=11    $ top scrap basket
 59 236  -1.000     152  #55                u=11    $ above top basket
c MCO and baskets
 60   0       (-160 146 -150)          fill=11  u=12    $ interior
```

```
61   20  -8.03   160 -161 146                u=12   $ MCO shell
62  236  -0.0012 161 -162 146                u=12   $ cask annulus
63   20  -8.03   162 -167 146                u=12   $ cask
64   20  -8.03  -167 169  -146               u=12   $ cask bottom
65   20  -8.03  -160  165                   u=12   $ mco top
66   20  -8.03  -160  150 -151               u=12   $ filter guard
67  236  -0.0051 -160  151  -165             u=12   $ top gap
68    0       164  -163  -166          fill=12      $ mco cask
70  240  -1.0327 167 -168  169               u=12   $ cooling cavity
71   20  -8.03   168      169               u=12   $ shield
72   20  -8.03          -169                u=12   $ cell bottom
c Mk4 inner fuel structure
80  236   -0.0051          46               u=15   $ between fuels
81   10   -6.49      -46    45              u=15   $ Zr-2 clad
82    5  -18.82      -45    44              u=15   $ 0.947% U-235
83   10   -6.49      -44    43              u=15   $ Zr-2 clad
84  236   -0.0051    -43                    u=15   $ H2O
c Mk4 intact fuel structure
115 236   -0.0051          50               u=3    $ between fuels
116  10   -6.49      -50    49              u=3    $ Zr-2 clad
117   5  -18.82      -49    48              u=3    $ 0.947% U-235
118  10   -6.49      -48    47              u=3    $ Zr-2 clad
119 236   -0.0051    -47    46              u=3    $ H2O
120  10   -6.49      -46    45              u=3    $ Zr-2 clad
121   5  -18.82      -45    44              u=3    $ 0.947% U-235
122  10   -6.49      -44    43              u=3    $ Zr-2 clad
123 236   -0.0051    -43                    u=3    $ H2O
135   2    0.06520 -164 141 -144                   $ basin floor
136 236  -0.0012 -144  -143  166                   $ space above MCO
137 236  -0.0012 -166  163 164 -144                 $ surrounding space
139   0  -141 :144 :143                      $ outside world

5    cz   0.8000000
6    cz   0.8572000
11    p   0.8660254   -0.5000000   0.0000000   1.3992000
12    p   0.8660254   -0.5000000   0.0000000  -1.3992000
13    p   0.8660254    0.5000000   0.0000000   1.3992000
14    p   0.8660254    0.5000000   0.0000000  -1.3992000
15   py   1.3992000
16   py  -1.3992000
17    p   0.86602540  -0.5   0.0   3.4925
18    p   0.86602540  -0.5   0.0  -3.4925
19    p   0.86602540   0.5   0.0   3.4925
20    p   0.86602540   0.5   0.0  -3.4925
21   py                    3.4925
22   py                   -3.4925
43   cz   0.6095        $ H2O
44   cz   0.6605        $ Zr-2 clad
45   cz   1.5480        $ fuel
46   cz   1.6245        $ Zr-2 clad
47   cz   2.1605        $ H2O
48   cz   2.2110        $ Zr-2 clad
49   cz   3.0165        $ fuel
50   cz   3.0800        $ Zr-2 clad
```

```
 122     pz    0.0000000
 123     pz    66.294000
c scrap basket side
 125     cz    28.77001997
 126     cz    29.08751997
c process tube pipe
 127     cz     2.2225000
 128     cz     3.4925000
c fuel basket side
 129     cz    28.41625
 130     cz    28.73375
 141     pz   -113.67300
 143     pz    900.00000
 144     cz    500.00000
 146     pz   -3.1750000
 149     pz    67.68338
 150     pz    353.83470
 151     pz    357.64470
 152     pz    351.11690
c MCO
 160     cz   29.2100
 161     cz   30.4800
 162     cz   32.0004
 163     cz   51.0540
 164     pz   -8.2804
 165     pz   375.000
 166     pz   398.1196
 167     cz   37.465
 168     cz   41.91
 169     pz  -187.874

tr2   0.00  0.00  70.858380
tr3   0.00  0.00  141.71676
tr4   0.00  0.00  212.57514
tr5   0.00  0.00  283.43352
mode  n
m5      92235.50   -0.00947   92238.50   -0.99053          $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
m240  1001.50c  0.6154 8016.50c 0.1538 6000.50c 0.2308        $ propylene glycol
mt236   lwtr.01t
mt240   lwtr.01t
mt2     lwtr.01t
imp:n     1.00000     53r        0.00000 $ 5, 139
print  40 60 80 100 110 126
prdmp  j   300
kcode  2000  1. 20  120
ksrc   9.7 0. 20.  -9.7 0.0 85.0 9.7 -9.7 150.0
     -9.7 -9.7 250.0  0.0 -9.7 320.0
```

F.12 AN MCO IN THE MHM

```
Basic model for MCO loaded with 2 scrap baskets and 4 fuel baskets. Each scrap
c basket filled with 575 kg Mk 1A scrap, drained MCO in the MHM
c fuel baskets full. Revised center post ID
c empty location 4,5
c flooded fuel and scrap baskets
c fuel basket containing intact fuel assemblies
  2   0  -17  18 -19  20 -21  22     u=8  lat=2
        fill=-5:5  -5:5  0:0
      2  2  2  2  2  2  2  2  2  2  2  $ 1
      2  2  2  2  2  2  3  3  3  2  2  $ 2
      2  2  2  2  3  3  3  3  3  3  2  $ 3
      2  2  2  3  2  3  3  3  3  3  2  $ 4
      2  2  3  3  3  2  2  3  3  3  2  $ 5
      2  2  3  3  2  2  2  3  3  2  2  $ 6  level 1
      2  3  3  3  2  2  3  3  3  2  2  $ 7
      2  3  3  3  3  3  3  3  2  2  2  $ 8
      2  3  3  3  3  3  3  2  2  2  2  $ 9
      2  2  3  3  3  2  2  2  2  2  2  $ 10
      2  2  2  2  2  2  2  2  2  2  2  $ 11
c      1  2  3  4  5  6  7  8  9  10  11
c  Mark 1A scrap optimized lattice
  5   0          -11 12 -13 14 -15 16  fill=4 u=1 lat=2  $ scrap hex
  6   4    -18.8200 -5                    u=4    $ scrap pin
  7  10    -6.49000 5 -6                  u=4    $ scrap clad
  8 236    -0.00510 6                     u=4    $ scrap cell
c  Scrap basket
  9   0    -125  122  128 -148          fill=1  u=9    $ scrap in basket
 10 236    -0.00510  148  -125  128            u=9    $ space above scrap
 11 236    -0.0051   -127                   u=9    $ pipe interior
 12  20    -8.03    127  -128  122           u=9    $ pipe wall
 13  20    -8.03    -122  127 -126           u=9    $ basket base
 14  20    -8.03    125  122 -126            u=9    $ basket side
 15 236    -0.0051   126                    u=9    $ outside basket
c fictitious water cell for fuel basket lattice
 24 236    -0.0051    -144                   u=2    $ fictitious cl
c fuel basket
 25  20   -8.03     -128  127  122  -123       u=7    $ tube wall
 26 236   -0.0051    -127  -123               u=7    $ central tube
 27  20   -8.03     -122  127  -126           u=7    $ bottom plate
 28  20   -8.03     -128    127    123        u=7    $ tube wall
 29 236   -0.0051    -127  123                u=7    $ central tube
 31 236   -0.0051    -125  128     123        u=7    $ above fuel
 32  20  -8.03000 125 122  -126               u=7    $ fuel basket side
 33   0  -125 122 128 -123              fill=8 u=7    $ fuel in basket
 34 236 -0.0051  126                        u=7    $ outside basket
c fuel and scrap basket stack
 51   0        -149            fill=9    u=11   $ bottom scrap basket
 52   0  146  -149 #51       trcl=2  fill=7    u=11   $ fuel basket
 53   0  146  -149 #52       trcl=3 fill=7     u=11   $ fuel basket
 54   0  146  -149 #53       trcl=4 fill=7     u=11   $ fuel basket
 55   0  146  -149 #54       trcl=5 fill=7     u=11   $ fuel basket
```

```
 56   0  146 -149 #55        trcl=6 fill=9     u=11   $ top scrap basket
c  MCO and baskets
 60  236 -0.0051 (-160 146 -152)        fill=11  u=12   $ interior
 61   20 -8.03   160 -161 -166              u=12   $ MCO shell
 62  236 -0.0012 161 -162 -167               u=12   $ MCO/MHM gap
 63   20 -8.03   162                     u=12   $ MHM
 64   20 -8.03   167  -162                u=12   $ MHM top
 65   20 -8.03  -160  165 -166              u=12   $ mco top
 66   20 -8.03  -160  150  -151             u=12   $ filter guard
 67  236 -0.0051 -160  151  -165              u=12   $ top MCO gap
 68  236 -0.0051 -160  -150  152              u=12   $ above top basket
 69   0       164  -163  -168          fill=12      $ filled MHM
 70  236 -0.0012  166 -167  -161              u=12   $ MCO MHM top gap
 71   20 -8.03   -146  -160               u=12   $ dummy cell
c Mk1A intact fuel structure
115  236   -0.0051          50            u=3   $ between fuels
116   10   -6.49      -50    49           u=3   $ Zr-2 clad
117    4  -18.82      -49    48           u=3   $ 1.250% U-235
118   10   -6.49      -48    47           u=3   $ Zr-2 clad
119  236   -0.0051    -47    46            u=3   $ space
120   10   -6.49      -46    45           u=3   $ Zr-2 clad
121    5  -18.82      -45    44           u=3   $ 0.947% U-235
122   10   -6.49      -44    43           u=3   $ Zr-2 clad
123  236   -0.0051     -43               u=3   $ space
135    2     0.06520 -164 141 -144                $ basin floor
136  236  -0.0012 -144  -143  168                 $ air above MCO
137  236  -0.0012 -168  163 164 -144                $ surrounding air
139    0  -141 :144 :143                      $ outside world

  5     cz    0.6500000
  6     cz    0.7107000
 11      p    0.8660254   -0.5000000    0.0000000    1.2013000
 12      p    0.8660254   -0.5000000    0.0000000   -1.2013000
 13      p    0.8660254    0.5000000    0.0000000    1.2013000
 14      p    0.8660254    0.5000000    0.0000000   -1.2013000
 15     py    1.2013000
 16     py   -1.2013000
 17     p     0.86602540  -0.5   0.0   3.556
 18     p     0.86602540  -0.5   0.0  -3.556
 19     p     0.86602540   0.5   0.0   3.556
 20     p     0.86602540   0.5   0.0  -3.556
 21    py                      3.556
 22    py                     -3.556
 43    cz    0.5588        $ H2O
 44    cz    0.6223        $ Zr-2 clad
 45    cz    1.4808        $ fuel
 46    cz    1.5824        $ Zr-2 clad
 47    cz    2.2441        $ H2O
 48    cz    2.3076        $ Zr-2 clad
 49    cz    2.9896        $ fuel
 50    cz    3.0531        $ Zr-2 clad
122     pz    0.0000000
123     pz    53.086000
125     cz    28.416250
```

```
 126     cz    28.733750
 127     cz     2.2225000
 128     cz     8.4140000
 141     pz    -155.5750
 143     pz     900.00000
 144     cz     500.00000
 146     pz    -3.1750000
 148     pz     49.719800
 149     pz     55.808880
 150     pz     353.90328
 151     pz     357.71328
 152     pz     350.72828
c MCO
 160     cz    29.2100
 161     cz    30.4800
 162     cz    32.0004
 163     cz    57.4004
 164     pz    -3.1760
 165     pz    375.000
 166     pz    398.1196
 167     pz    400.6596
 168     pz    426.0596

tr2   0.00 0.00 58.98388
tr3   0.00 0.00 117.96776
tr4   0.00 0.00 176.95164
tr5   0.00 0.00 235.93552
tr6   0.00 0.00 294.91940
mode n
m4      92235.50  -0.01250  92238.50  -0.98750        $ outer fuel
m5      92235.50  -0.00947  92238.50  -0.99053        $ inner fuel
m236  1001.50c 0.666700 8016.50c 0.333300
m10   40000.50c -1.000000
m20   26000.55c 67.970001 24000.50c 20.000000 28000.50c 10.000000
    25055.50c 2.000000 6000.50c 0.030000
m2    1001.50  0.064200 8016.50  0.591600 14000.50  0.240500
    20000.50  0.073800 26000.55  0.029900
imp:n     1.00000    51r   0.00000  $ 5, 139
mt236   lwtr.01t
mt2     lwtr.01t
print  40 60 80 100 110 126
prdmp  j   300
kcode  2000  1. 20  200
ksrc  9.7 0. 20.  9.7 9.7 75. -9.7 9.7 130.0
    -9.7 -9.7 185.0  0.0 9.7 250.0  0.0 -9.7 320.0
```