GENERAL ATOMIC

CONSOLIDATED SAFETY ANALYSIS FOR FSV-3 SHIPPING CONTAINER

FEBRUARY 1982

1. INTRODUCTION

This document describes the shipping container FSV-3, designed to package nuclear reactor fuel elements of the type intended to be used first in the reactor at Fort St. Vrain (FSV), Colorado. The container employs well-known standard materials established by prior experience to be suitable for use in the transportation of Type A quantities of fissile radioactive material.

The fuel in these containers will be shipped as either Fissile Class II or Fissile Class III. The maximum number of loaded FSV-3 containers in any Class II shipment will be 38, with each loaded container bearing a transport index of 1.3. The maximum number of loaded FSV-3 containers in a Class III shipment will be 100.

Since Special Permit No. 6347 was first issued for the use of FSV-3 containers, nearly 2000 fuel elements have been shipped in these containers without accident or damage.

2. PACKAGE DESCRIPTION

The shipping container FSV-3 consists of inner and outer steel drums, vermiculite, a plywood disk, a plastic or paper bag(s), and drum lids with bolted locking rings. The bolt associated with the outer drum locking ring is drilled to accommodate a metal seal.

The inner and outer containers are DOT Specification 6J drums, or equal. They together with the material in their annular space and in the other space not occupied by a fuel element are regarded as a unit to be the containment vessel. The inner container is a 18.5-in. inside diameter by 34-in. high, 18-gauge steel drum with 16-gauge steel top and bottom heads. The upper head of the inner drum has a 2-in.-wide, 1/4-in.-thick steel reinforcing ring welded around the periphery adjacent to the head edge. The inner container is centered and supported in a 22.5-in. inside diameter by 38.25-in.-high, 16-gauge steel drum. Each fuel element will be placed in a plastic or paper bag(s) prior to loading. A 1/4-in. plywood disk will be placed atop the fuel element within the inner container.

Void spaces between the fuel element and the inner and outer container are all filled with vermiculite. The vermiculite is disposed with approximately 2 in. in the bottom of the outer container, 2 in. in the bottom of the inner container, 1 in. between the apices of the fuel element and the inner surface of the inner container, and 2 in. between the fuel element flats and the inner surface, measured horizontally. All interspaces will be packed firmly with vermiculite prior to affixing lids, clamp rings, and bolts on both the inner and outer containers.

The total gross weight of the package, including contents, will be a maximum of 500 lb.

The package is constructed in accordance with General Atomic Company Dwg. No. FFE-613, Issue D, included at the end of Section 2.

2.1. OPERATIONAL FEATURES

There are no valves, sampling ports, or tie-down devices that are integral parts of the FSV-3 packaging. The lifting fixtures shown in some of the photographs in Section 3 of the hypothetical accident tests were used only for handling in the tests and are not regarded as part of the packaging.

There are no structural or mechanical means for transfer or dissipation of heat nor are any materials used particularly as coolants, since only unirradiated fuel not requiring such precautions is normally transported in FSV-3 containers.

Materials used as nonfissile neutron absorbers are the steel drums themselves and vermiculite of a density no less than 4 lb/ft^3.

2.2. CONTENTS OF PACKAGING

Each FSV-3 will contain a fuel element consisting of a graphite body that is hexagonal in transverse cross section, approximately 14.2 in. across the flats, and 31.2 in. high. Disposed in columns within the fuel element body are fuel rods containing in total a maximum of 1.41 kg U-235 plus U-238 and Th-232. The U-235:U-238:Th-232 ratio will be approximately 1:0.07:8.4. The atomic ratio of carbon to U-235 is in the range of 1800 to 1. Uranium-233 may be substituted for U-235 in the ratio of (g U-235/1) = (g U-233/ 1.6).

The weight of one fuel element containing not more than 1.41 kg of U-235 will not be more than 320 lb.

FIGURE WITHHELD UNDER 10 CFR 2.390

LTR	DATE	ISSUE DESCRIPTION	DR	CHK.	DES.	APPD.	APPD.
D	1-2282	UPDATED & RE-DRAWN	DCK				

ITEM	PART NO.	DESCRIPTION	MAT'L

REQD/ASSEMBLY

LIST OF MATERIAL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES.
TOLERANCES:
DECIMALS .XXX± .XX±
FRACTIONS ± 1/16
ANGLES ±
ALL MACHINED SURFACES √

SCALE 1/4 & NOTED

SHIPPING CONTAINER
F.S.V. - 3

GENERAL ATOMIC COMPANY
SAN DIEGO, CALIFORNIA

DRAWING NUMBER: FFE613
ISSUE: D

3. PACKAGE EVALUATION

3.1. STRUCTURAL AND THERMAL

Neither the packaging materials nor the fuel elements, which were described in Section 2, cause any significant chemical, galvanic, or other reaction by their use. Closure devices are the familiar lock rings and bolts. There are no lifting devices or other structural parts of the package used as lifting devices that impact the design and testing of the package.

The inner and outer containers are DOT Specification 6J drums or equivalent, which have already been established as acceptable for use in transport of Type A radioactive material in normal transport conditions; therefore, repetitious evaluation of the FSV-3 container to survive the conditions expressed in 10 CFR Part 71, Appendix A is not undertaken here. The nuclear analysis of the fissile material hazard is presented in Section 5.

Sample containers were prepared and subjected to hypothetical accident conditions while loaded with a simulated fuel element. The weight of the simulated element exceeded that of an actual element by approximately 60 lb, but the dimensions were identical to those of an actual element. Drop, puncture, thermal, and water immersion tests were conducted with a package utilizing a 19-gauge inner drum; consequently, the results of these tests could be considered conservative with regard to the DOT Specification 6J 18-gauge inner drum actually being used.

3.2. TESTS AND RESULTS

3.2.1. Free Drop

The container was dropped from 30 ft onto its lid edge, striking a steel-reinforced slab at a 45 deg angle. The damage sustained was a 3-in. deformation over approximately 18 in. of the circumference of the outer drum. Minimum buckling at the point of contact occurred, showing a 1/4-in. gap at each terminus of the deformation. The lid of the inner drum was only slightly bent, with no buckling and no gapping. (The condition of the inner drum was not determined until after all four tests were performed.) (See photographs following Section 3 showing the test configuration and the damage.)

3.2.2. Puncture

The container was dropped on its side from 40 in. onto a 6-in.-diameter, 8-in.-long, mild steel bar. Damage was restricted to a semicircular depression approximately 3/4-in. deep, with no breaks in the metal. (See photographs following Section 3 showing the test configuration and the damage.) (Note: The impact from both of the drop tests failed to dislodge or displace the simulated fuel element and inner drum from their centered positions within their respective containers.)

3.2.3. Thermal

The container was placed in an electric Sunbeam radiant heat furnace at 1475°F for 30 minutes; it was removed and allowed to cool normally. No immediate apparent damage was observed other than the loss of the black surface paint.

Temperature-indicating material (TEMPILSTIK) had been placed on the outside surface of the inner drum and on the surface of the simulated fuel element. The indicating material revealed that a temperature between 600° and 800°F existed on the surface of the inner drum and between 200° and 400°F existed on the surface of the simulated fuel element. These data indicate that thermal decomposition of the fuel element or the packing materials could not occur under these sets of circumstances. The 1/4-in. plywood disk showed no evidence of heat damage.

3.2.4. Water Immersion

The container was submerged on its side for 24 hours in a tank with a minimum depth of 3 ft of water above the top surface of the container. Bubbling was observed as water replaced the air through the gap between the outer drum and its lid.

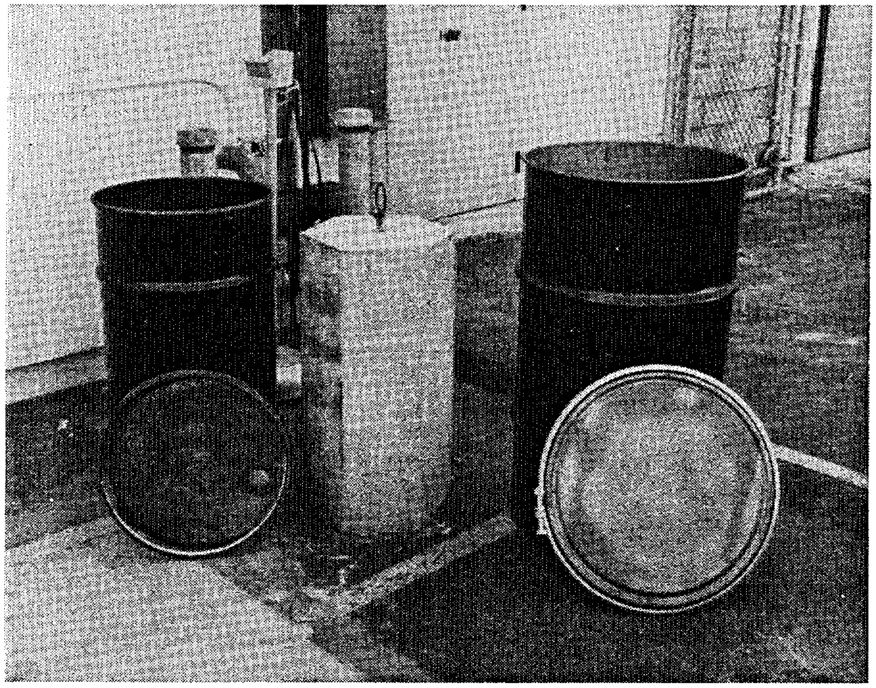
When the container was removed from the water tank and the outer drum lid removed, it was observed that the vermiculite was completely saturated with water as was anticipated. However, removal of the lid on the inner drum revealed that the contents were dry. Additionally, the 1/4-in. plywood disk was only cracked at the impact area.

Photographs showing the tests and their effects are included at the end of Section 3.

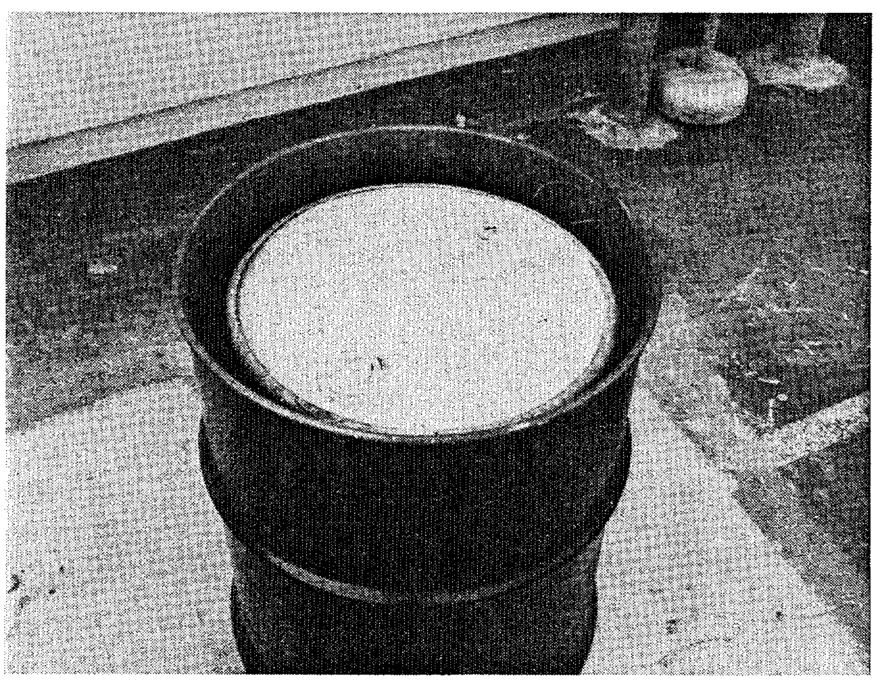
3.3. CONTAINMENT

The primary containment of radioactive material within the FSV-3 container is its impregnation within the matrix of the fuel rods themselves, which are, in turn, confined within the graphite fuel element through the use of graphite plugs. The element is likewise contained within the inner drum (with closures), which is, in turn, contained within the outer drum (with closures) and held in position by vermiculite material to assure that under both normal and accident conditions of transport the inner container will remain positioned as originally placed within the outer container. As shown in the photographs at the end of Section 3, tests have demonstrated that both the simulated fuel element within the inner container and the inner container itself remained in essentially the same positions as those in which they were originally placed in preparation for the test environments.

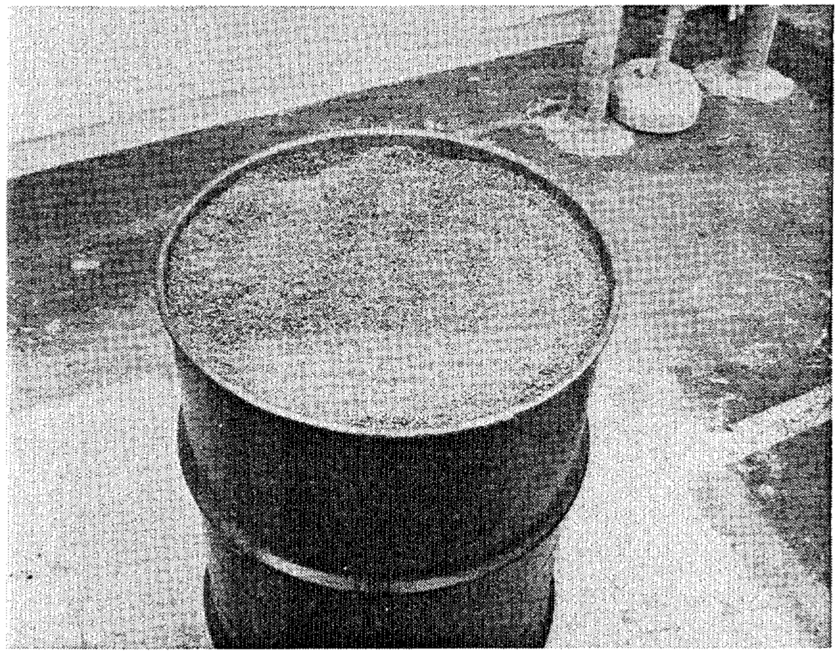
As stated in Section 2, each fuel element will be placed in a plastic or paper bag(s). Each upper drum head may additionally have a gasket seal. The bag(s) and gasket(s) may be exposed freely to heat and water and destroyed entirely by their action without detriment to safety since neither plays any part in criticality considerations. In addition, even if gasses resulting from their burning were sufficient to rupture the containers, the massive form of the fuel element would assure that it could not escape through the anticipated small openings.



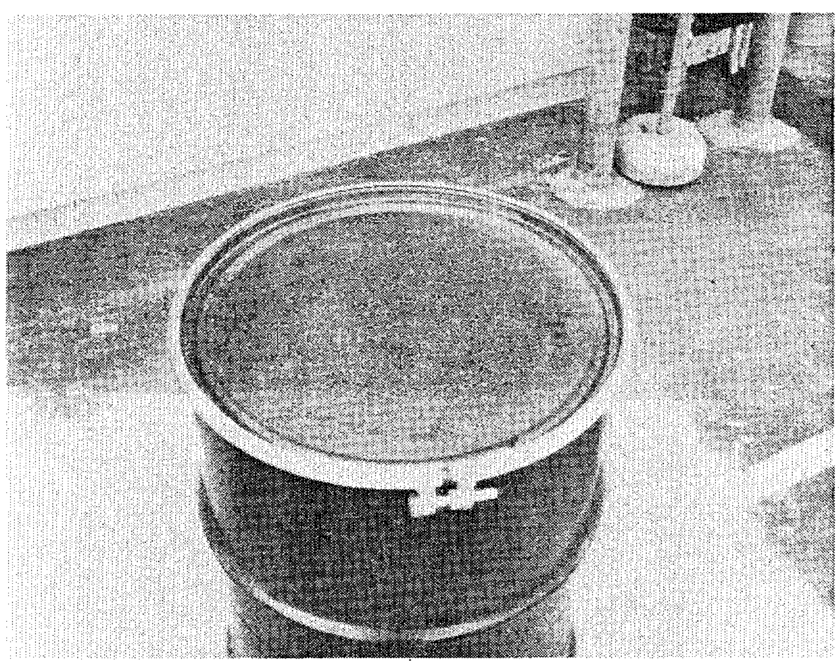
CONTAINER PRE–ASSEMBLY. SIMULATED CONCRETE FUEL ELEMENT WITH INNER AND OUTER CONTAINERS.



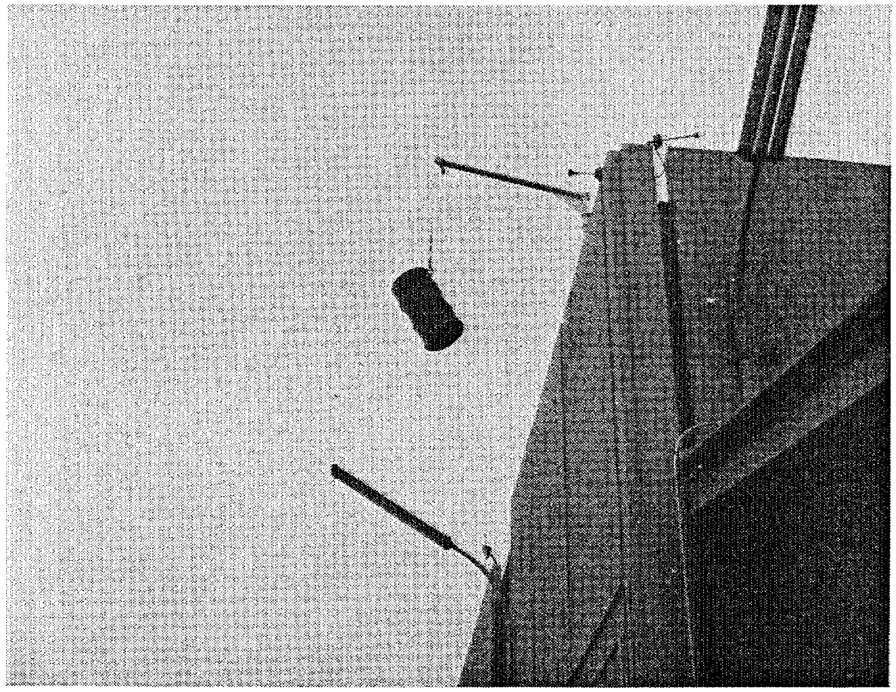
SIMULATED CONCRETE FUEL ELEMENT INSIDE INNER CONTAINER PLACED IN OUTER CONTAINER. INNER CONTAINER PACKED WITH VERMICULITE.



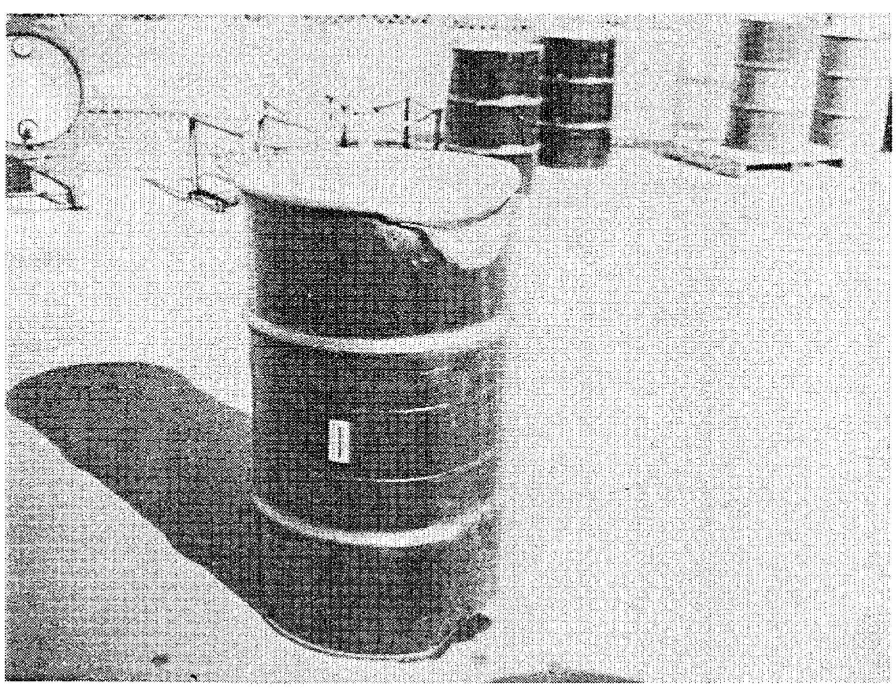
OUTER CONTAINER PACKED WITH VERMICULITE.



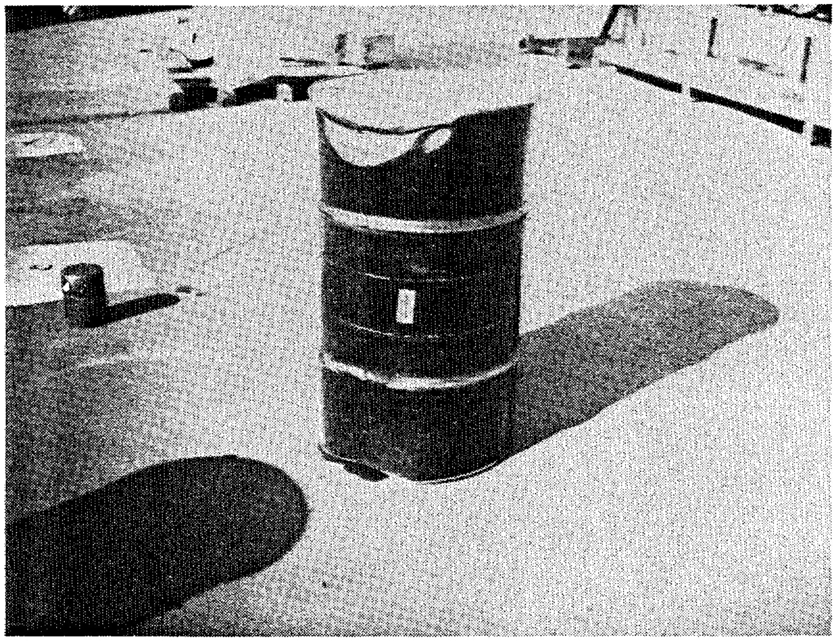
OUTER CONTAINER CLOSED AND READY FOR
HYPOTHETICAL ACCIDENT TESTING.



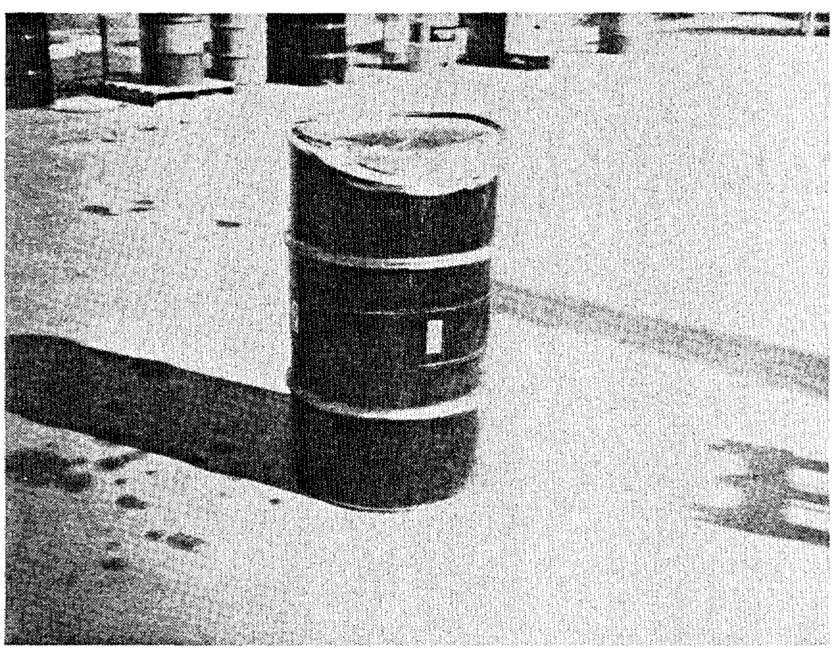
CONTAINER SUSPENDED FOR 30 FOOT FREE DROP
AT 45° ANGLE ONTO THE LID EDGE.



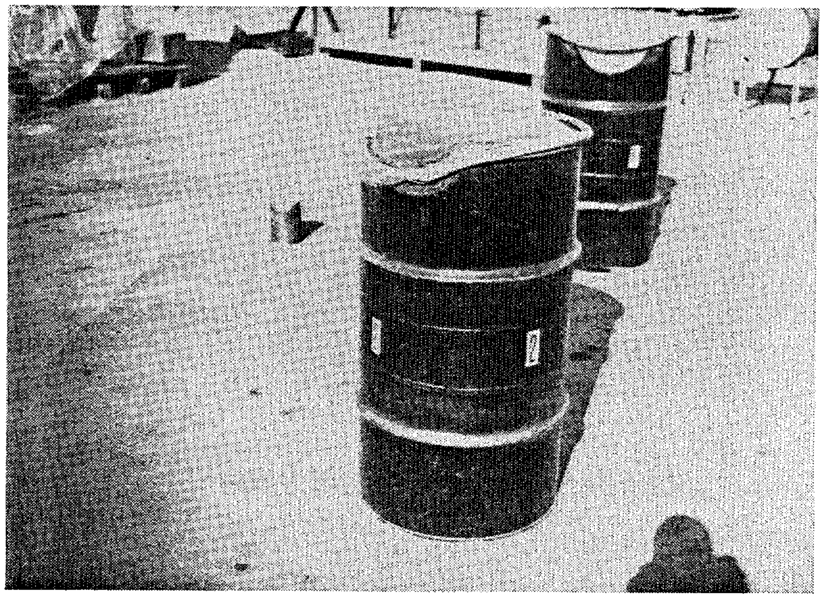
CONTAINER NO. 1 DAMAGE AFTER 30 FOOT FREE DROP.



CONTAINER NO. 1 DAMAGE AFTER 30 FOOT FREE DROP.

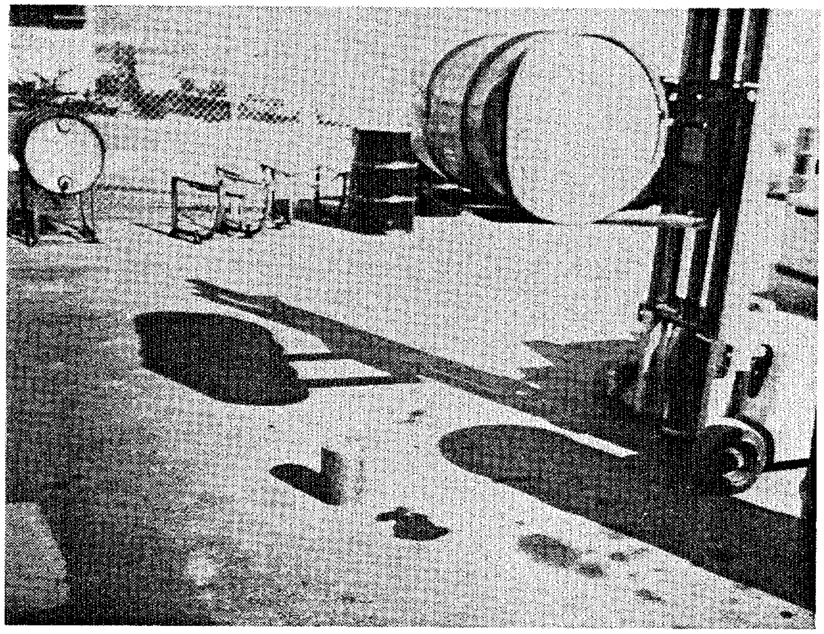


CONTAINER NO. 2 DAMAGE AFTER 30 FOOT FREE DROP.

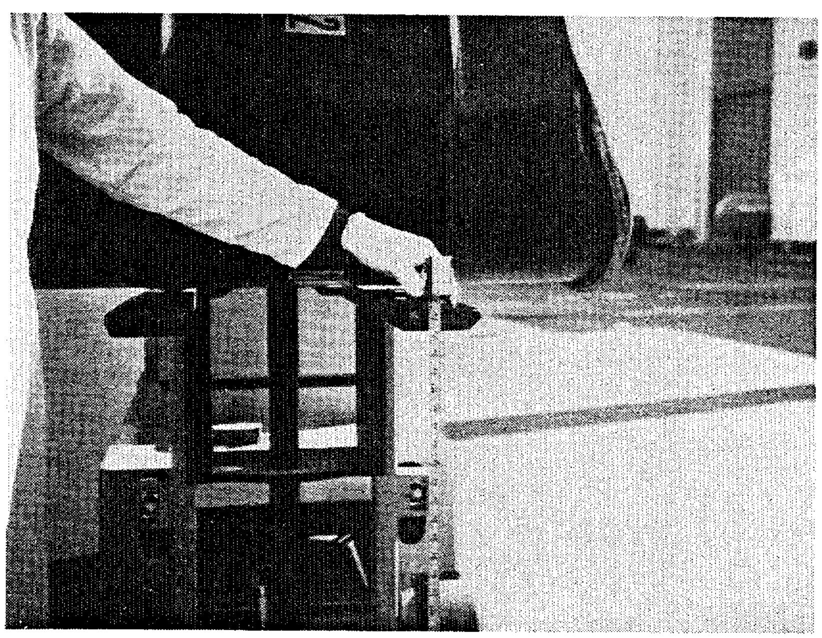


CONTAINER NO. 2 DAMAGE AFTER 30 FOOT FREE DROP.

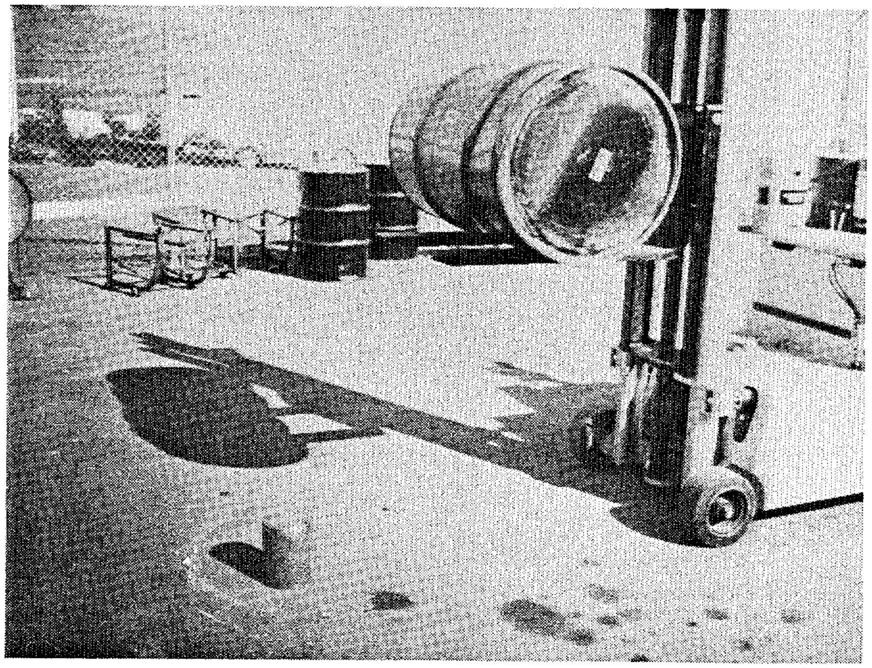
CHECKING HEIGHT OF CONTAINER NO. 1 FOR 40 INCH PUNCTURE TEST ONTO AN 8–INCH HIGH, 6–INCH DIAMETER MILD STEEL BAR.



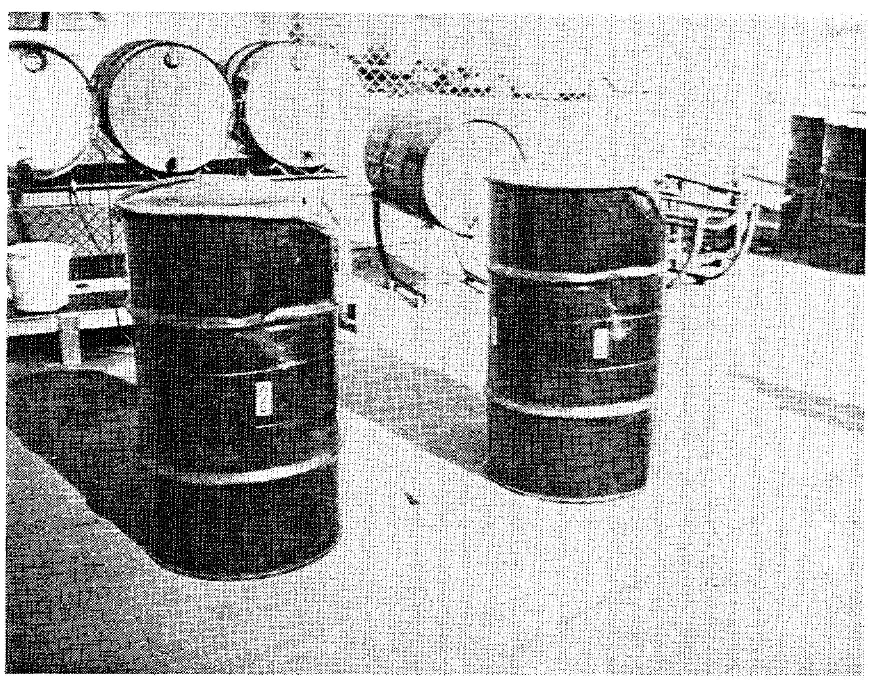
CONTAINER NO. 1 AND MILD STEEL BAR PRIOR TO PUNCTURE TEST.



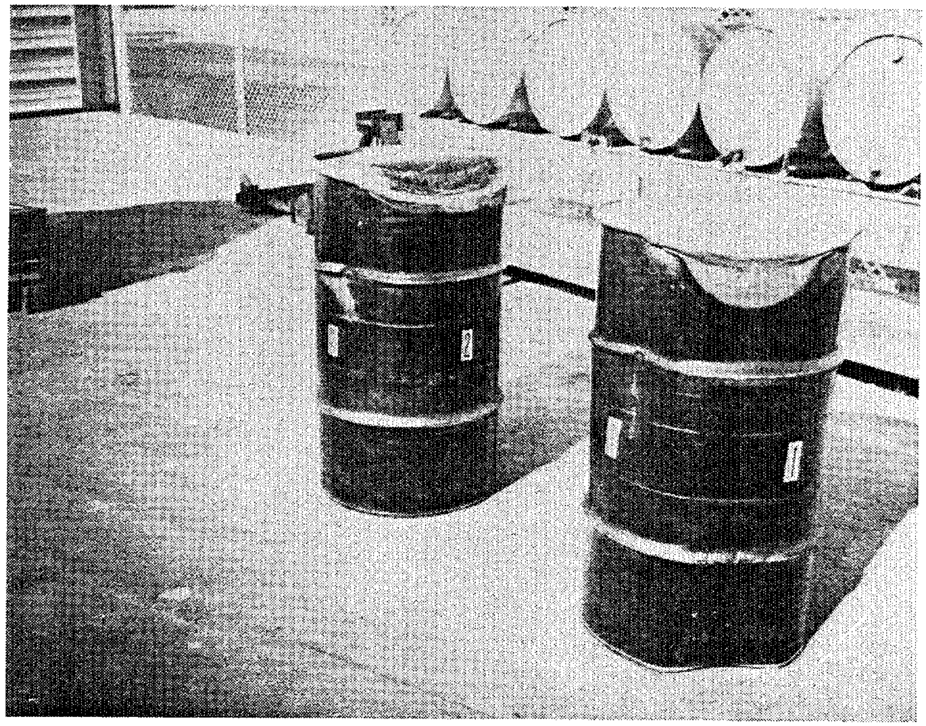
CHECKING HEIGHT OF CONTAINER NO. 2 FOR 40 INCH PUNCTURE TEST ONTO AN 8–INCH HIGH, 6–INCH DIAMETER MILD STEEL BAR.



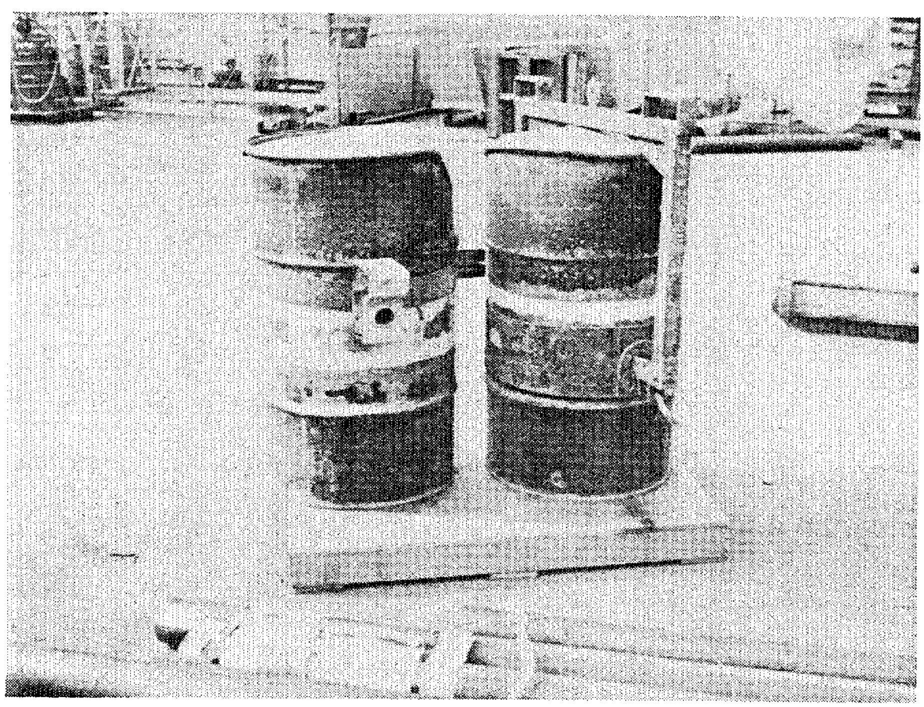
CONTAINER NO. 2 AND MILD STEEL BAR PRIOR TO PUNCTURE TEST



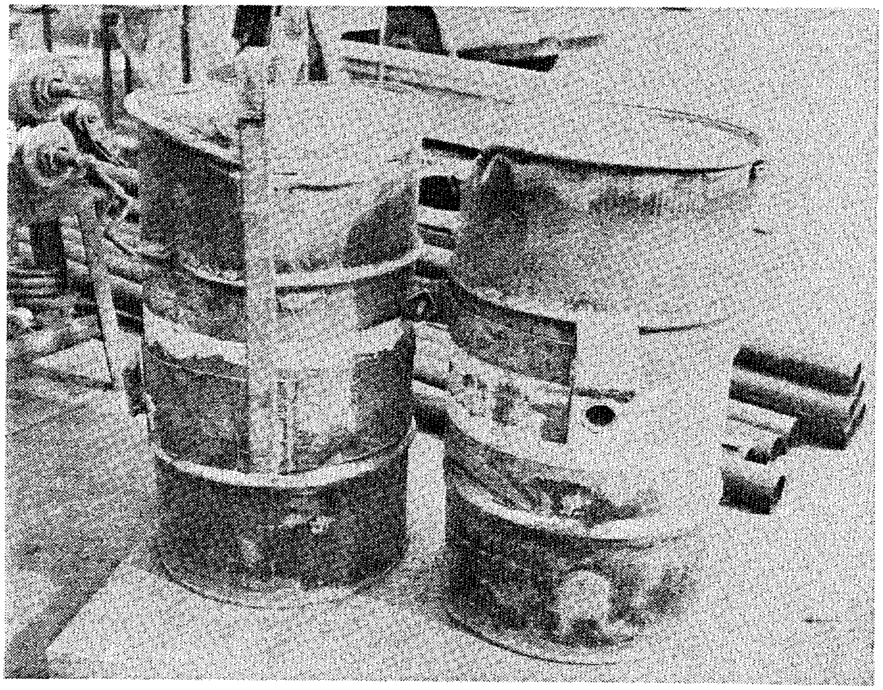
CONTAINERS NO. 1 AND NO. 2 AFTER PUNCTURE TEST.



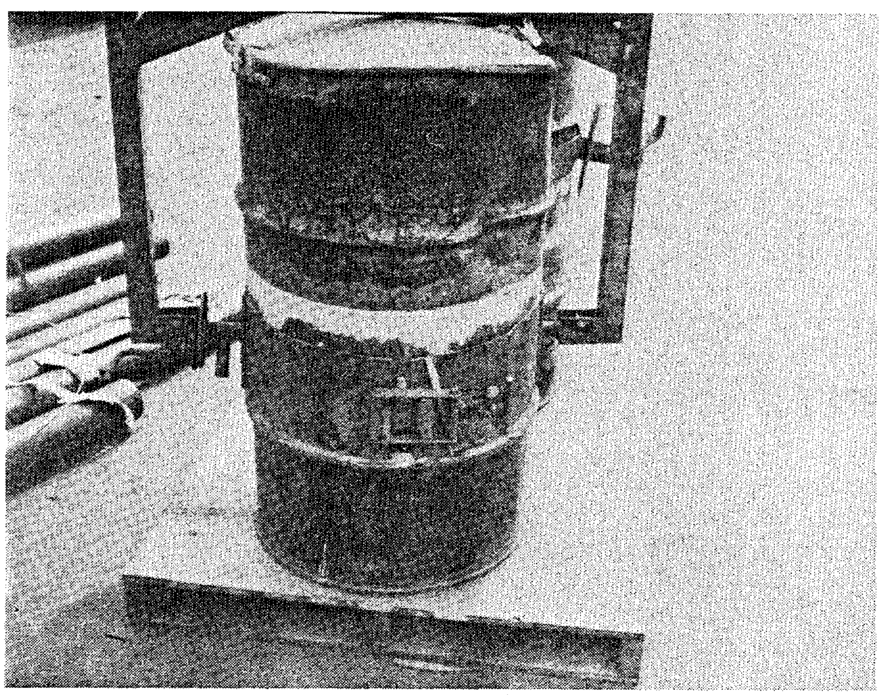
CONTAINERS NO. 1 AND NO. 2 AFTER PUNCTURE TEST



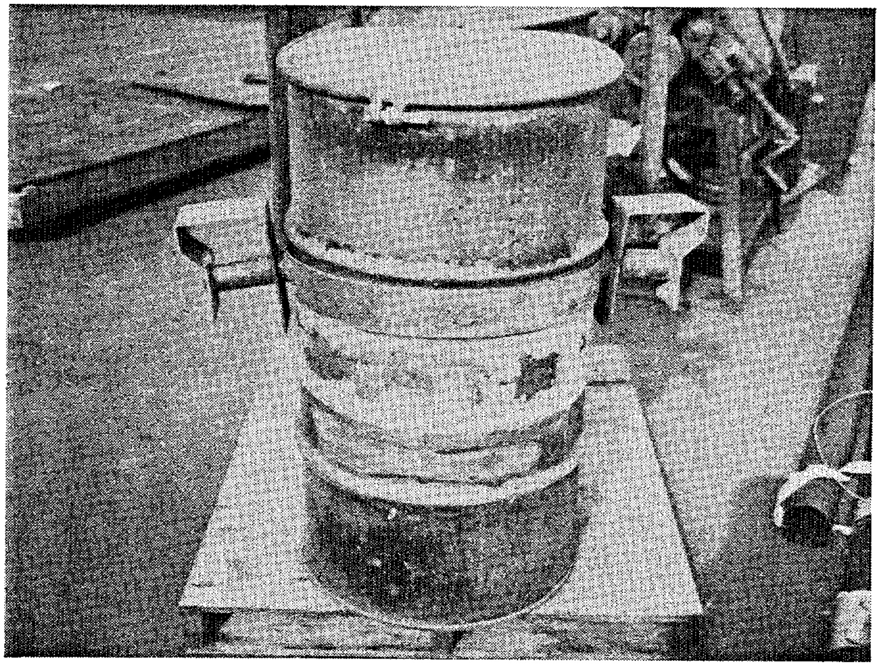
CONTAINERS NO. 1 AND NO. 2 AFTER HEAT TEST.



CONTAINERS NO.1 AND NO. 2 AFTER HEAT TEST

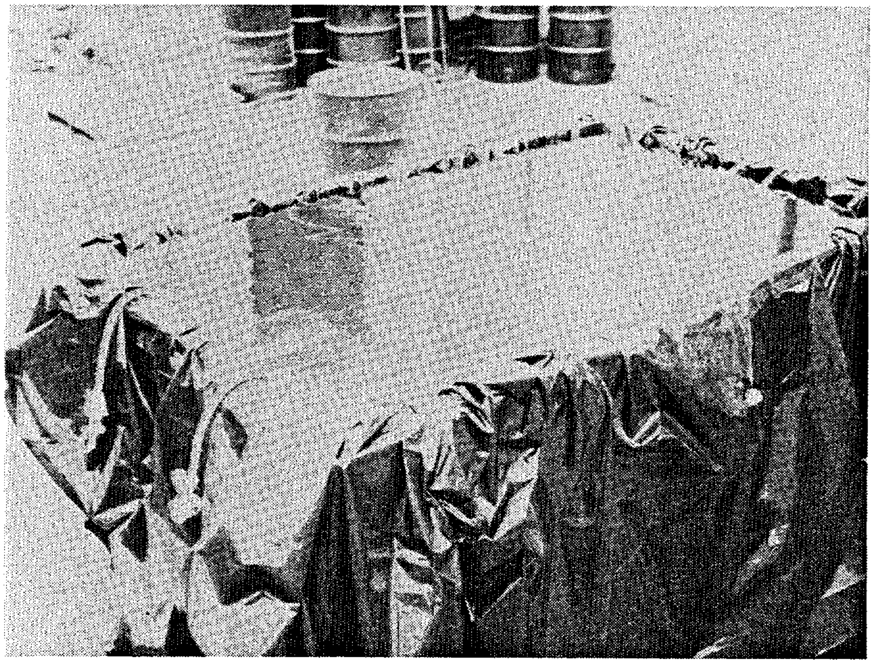


CONTAINER NO. 2 AFTER HEAT TEST (LIFTING FIXTURE ATTACHED).

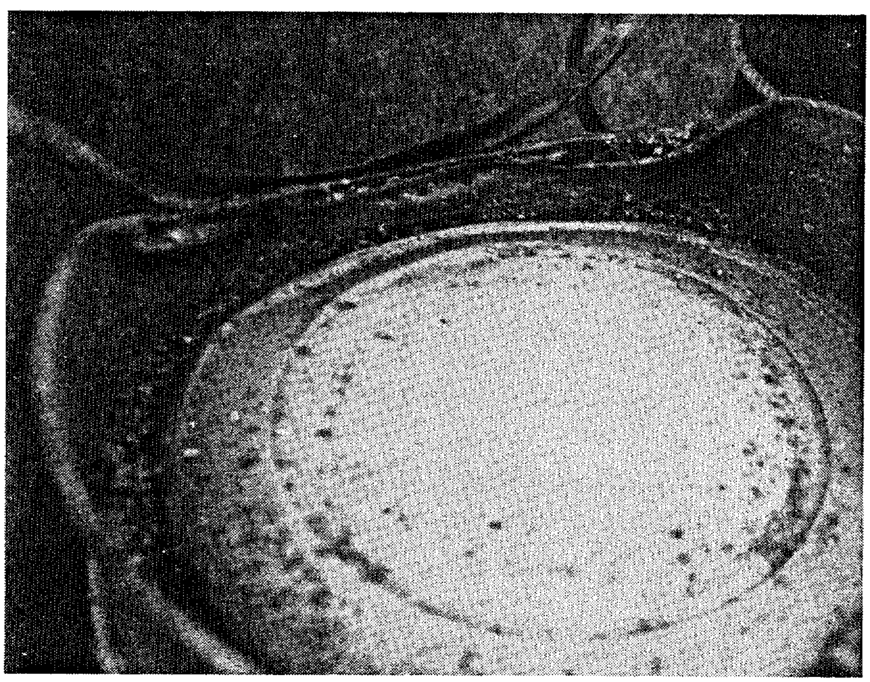


CONTAINER NO. 1 AFTER HEAT TEST (LIFTING FIXTURE ATTACHED)

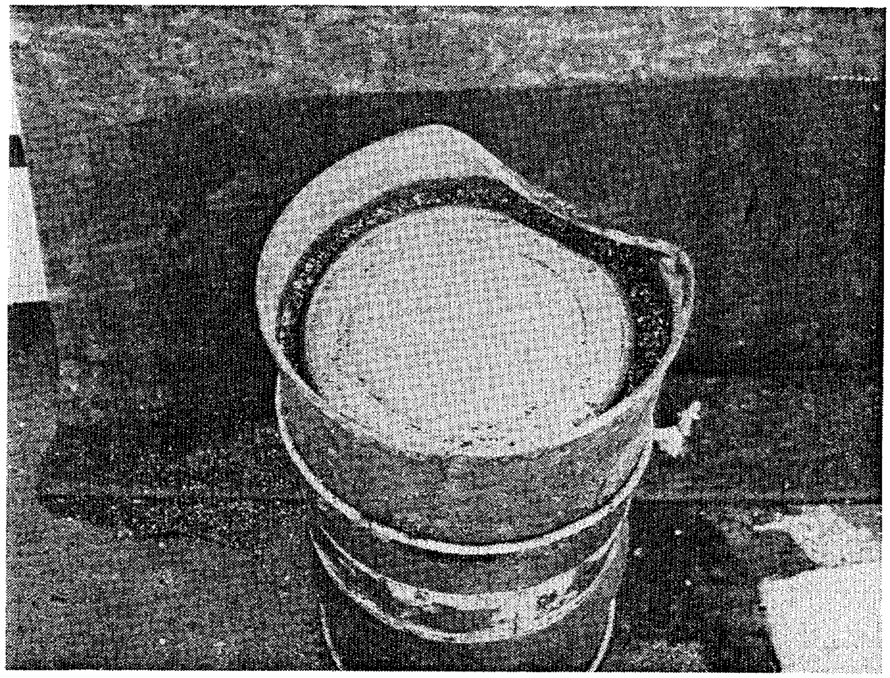
CONTAINERS AFTER PLACEMENT IN WATER TANK (NO WATER).



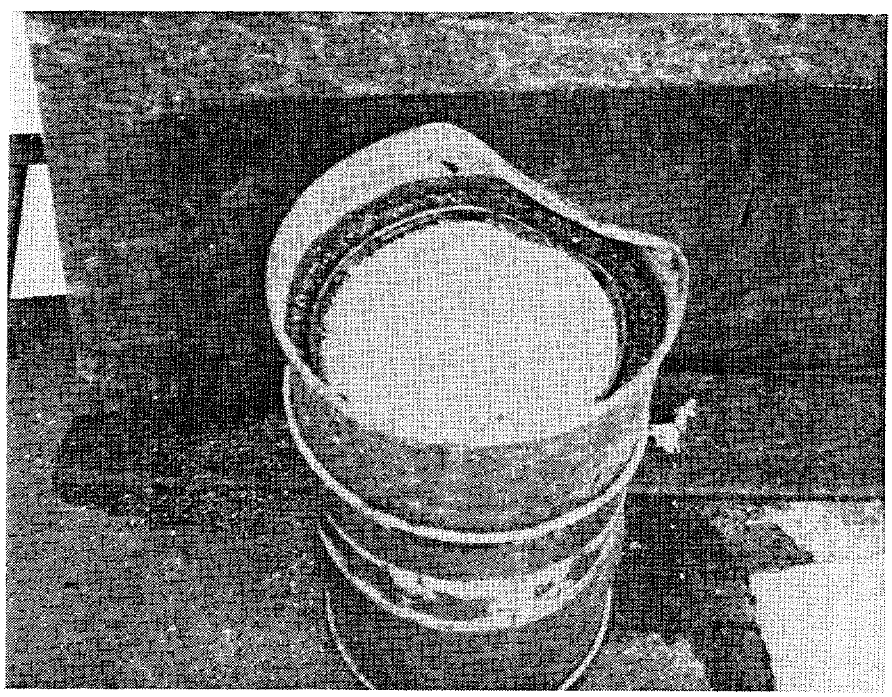
CONTAINERS UNDERGOING WATER IMMERSION TEST
(24 HOURS)



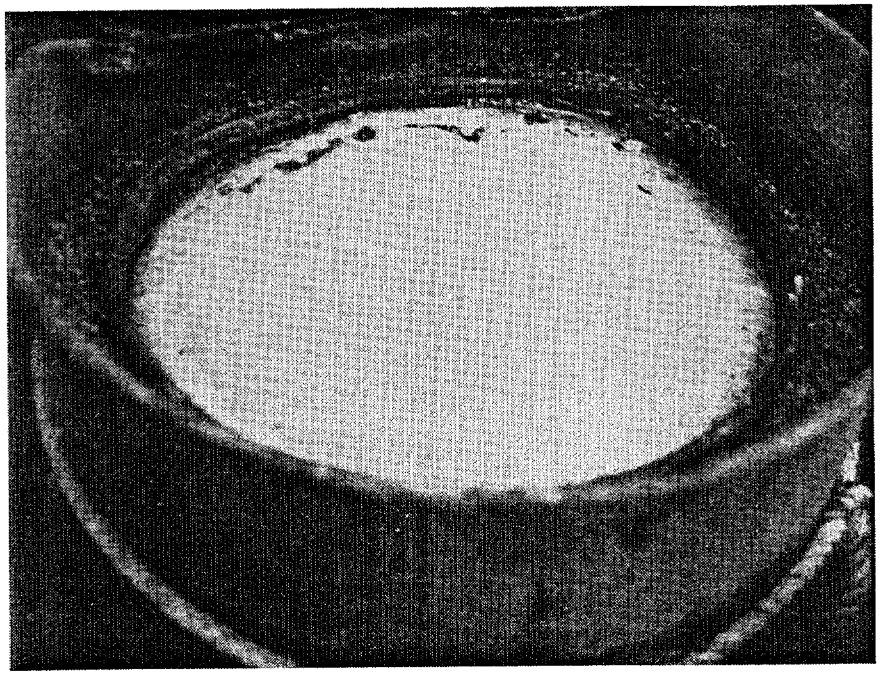
CONTAINER NO. 2 WITH OUTER LID REMOVED.



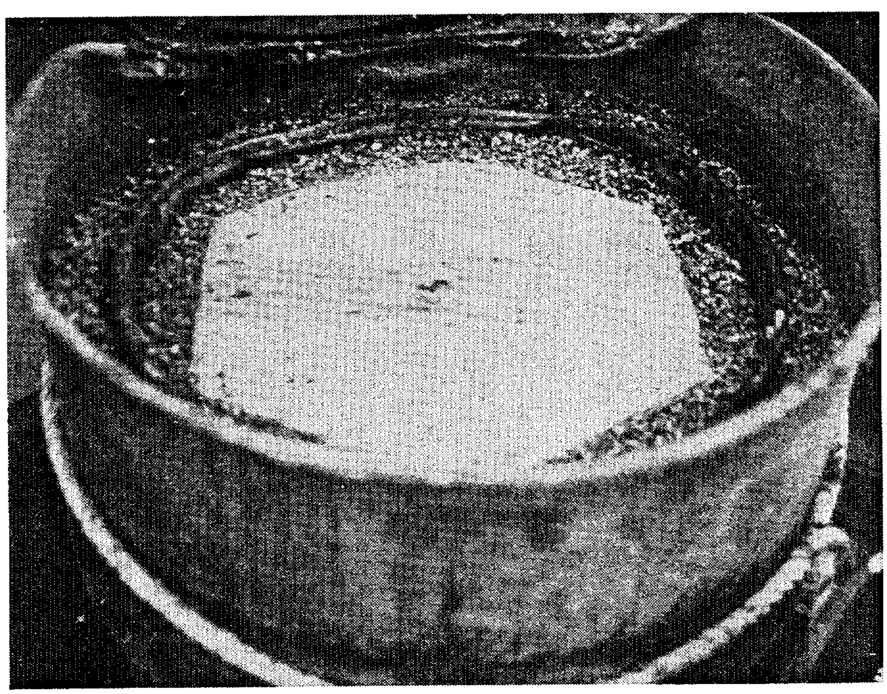
CONTAINER NO. 1 WITH OUTER LID REMOVED.



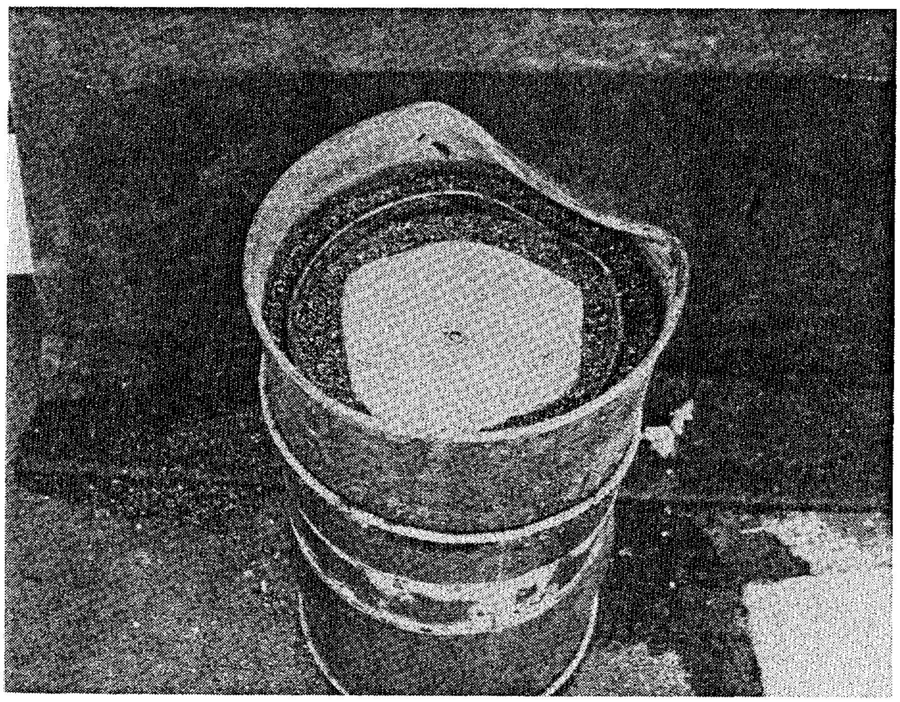
CONTAINER NO. 1 WITH INNER LID REMOVED SHOWING
PLYWOOD DISC.



CONTAINER NO. 2 WITH INNER LID REMOVED SHOWING PLYWOOD DISC.



CONTAINER NO. 2 SHOWING SIMULATED FUEL ELEMENT POSITION AFTER FOUR TEST CRITERIA.



CONTAINER NO. 1 SHOWING SIMULATED FUEL ELEMENT
POSITION AFTER FOUR TEST CRITERIA.

4. SHIELDING

No radiation shielding is required since the contents of FSV-3 packages are normally to be unirradiated fuel elements and radiation levels at the outer surfaces of both the element itself and the package are less than 2 mR/hr, which is significantly below DOT limits.

5. CRITICALITY

5.1. SAFETY SUMMARY

A criticality evaluation of the FSV-3 container under normal conditions of transport and under hypothetical accident conditions was made.

Computer calculations were performed for infinite or semi-infinite arrays of containers using the GAZE-2 diffusion and DTF-IV transport codes. A report on GA's GAZE-2 code (GA-3152) has been supplied to the NRC; DTF-IV is a well-known Los Alamos Scientific Laboratory code. These analyses show the safety of transporting loaded FSV-3 packages in multivehicle shipments under normal and accident conditions.

During normal conditions of transport, the containers would be placed in a two-layer array standing on end atop one another. The analysis indicates that 200 containers in the most reactive ideal array have a calculated multiplication constant of less than 0.80; therefore, no criticality condition will result during normal conditions of transport.

During accident conditions the analysis indicates that only partial water flooding of the inner drum could result in a more reactive system than for containers in the dry condition. The tests of the containers have shown that the inner drum did not absorb water, and so this situation is not presented. Any flooding of the interstices between the containers or between the inner drum and outer drum reduces the multiplication constant compared to the dry condition. The single units become decoupled and absorptions in water, steel, and vermiculite increase rapidly as water is added. Therefore, with partial or complete flooding of the containers, no criticality problem would exist for any number of containers. In addition, undamaged but loaded containers would float in water and thus could not easily be packed into a most reactive array.

The most limiting situation occurs by arranging dry containers in the most reactive configuration. A conservative estimate of this system is that a multiplication constant of less than 0.8 is obtained if 200 dry containers are packed into the most reactive arrangement.

An additional calculation was performed for a doubled Class II maximum shipment under the assumption that each container had sustained a 3-in. deformation along its entire length, rather than only on or near the lid edge. A report of this calculation is given in Section 5.2.6.

5.2. DETAILED CRITICALITY EVALUATION OF FSV-3 SHIPPING CONTAINER ARRAYS

5.2.1. Description of FSV-3 Shipping Container

A standard fuel element 31.2 in. high and 14.2 in. across the flats is surrounded by vermiculite in an 18-gauge low carbon steel container 34 in. high (inner) and having an inner diameter of 18.5 in. There is another layer of vermiculite between the inner barrel and an outer barrel of 16-gauge low carbon steel, which is 38.25 in. high (inner) with an inner diameter of 22.5 in. Figure 5-1 shows a vertical cut view of the container and Fig. 5-2 a horizontal cut view.

5.2.2. Assumptions

Assumptions concerning materials used in all the calculational models were:

1. All U-235 was assumed to be U-233.
2. Every container was assumed to hold the most reactive fuel element anticipated for the FSV reactor. With assumption 1, the fuel element contained 1.4025 kg of U-233, 0.0975 kg of U-238, and 11.8 kg of Th-232.
3. The presence of burnable poisons was ignored.
4. The least dense form of vermiculite available (4 lb/ft^3) was assumed for packaging.
5. Materials within a region were homogenized over that region. In particular, partial flooding of a region was modeled as partial density water flooding it.

Assumptions in the geometry of the models were:

1. The hexagonal block of fuel was cylindricized. In the radial models, the area of the horizontal cross-cut was preserved, which overestimated the ratio of fuel volume (or mass) to nonfuel volume (or mass) by about 20%. For the slab models, the volumes of different regions were considered explicitly so that amounts of all materials were preserved.
2. Closest packing of the containers was used. The barrels then filled up 90.7% of available volume leaving a void volume of 9.3%.

The calculations using the GAZE-2 code with slab geometry contain one further approximation:

1. Disadvantage factors were not used since the radial calculations showed them to be almost one for each material. (These were all unflooded cases.) The non-conservative nature of this approximation was later corrected for by noting the largest possible increase in k_{eff} possible if neutron absorption in the vermiculite and steel was ignored entirely (as if disadvantage factor = 0 had been used for them).

For the cross-section computations, the following assumptions were made:

1. All materials of the dry shipping container were considered to be in a neutron spectrum characteristic of the FSV reactor.
2. For flooded cases, a B1 approximation to the spectrum in an infinite layer of water was used to obtain "thick layer" hydrogen and oxygen cross sections.

5.2.3. Dry Container Analysis

Table 5-1 lists the contents of a dry (unflooded and nonimmersed) shipping container. Region numbers are those shown in Figs. 5-1 and 5-2.

TABLE 5-1
DRY FSV SHIPPING CONTAINER

Element	Density, ρ (g/cm^3)	N (atoms/barn-cm)
	Region 1 – Core	
Carbon	1.247	6.25×10^{-2}
Silicon	5.721×10^{-2}	1.23×10^{-3}
Uranium-233	1.571×10^{-2}	4.058×10^{-5}
Uranium-238	1.115×10^{-3}	2.820×10^{-6}
Thorium-232	1.321×10^{-1}	3.429×10^{-4}
	Regions 2 and 4 – Vermiculite	
Hydrogen	3.7699×10^{-5}	2.2514×10^{-5}
Oxygen	2.9578×10^{-2}	1.1129×10^{-3}
Magnesium	8.7121×10^{-3}	2.1565×10^{-4}
Aluminum	5.0354×10^{-3}	1.1235×10^{-4}
Silicon	1.1503×10^{-2}	2.4653×10^{-4}
Phosphorus	2.7794×10^{-6}	5.4017×10^{-8}
Sulfur	6.3685×10^{-6}	1.1956×10^{-7}
Chlorine	1.7832×10^{-4}	3.0275×10^{-6}
Potassium	4.1449×10^{-3}	6.3816×10^{-5}
Calcium	5.5984×10^{-4}	8.4087×10^{-6}
Chromium	1.2637×10^{-4}	1.4627×10^{-6}
Manganese	5.0460×10^{-5}	5.5291×10^{-7}
Iron	4.1381×10^{-3}	4.4604×10^{-5}
	Regions 3 and 5 – Steel Walls	
Iron	7.80	8.407×10^{-2}

REGION 5
STEELWALL

REGION 2
VERMICULITE

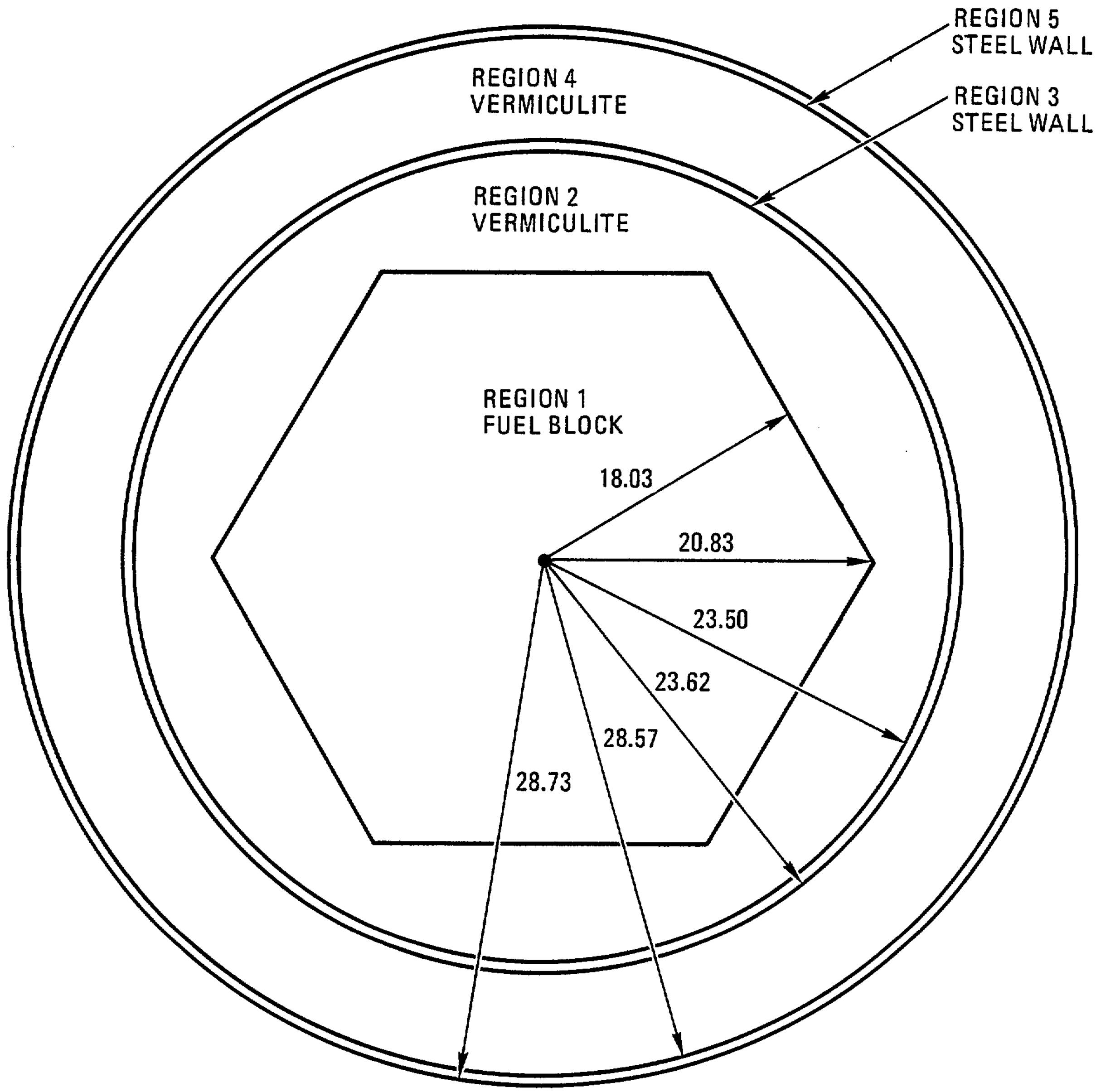
REGION 3
/STEEL WALL

FIGURE WITHHELD UNDER 10 CFR 2.390

DIMENSIONS IN CENTIMETERS; INDICATED DIMENSIONS ARE APPROXIMATE, SUBJECT TO NORMAL MATERIALS AND PACKING VARIATIONS

*RADIUS OF THE CIRCLE PRESERVING AREA OF HEXAGON

Fig. 5-1. Vertical cross-cut of FSV-3 shipping *container*



DIMENSIONS IN CENTIMETERS; INDICATED DIMENSIONS ARE APPROXIMATE, SUBJECT TO NORMAL MATERIALS AND PACKING VARIATIONS

Fig. 5-2. *Horizontal cross-cut of FSV-3 shipping container*

The first calculation, performed in cylindrical geometry with GAZE-2, considered an array of closest-packed containers extending infinitely in all directions. The model used the densities of materials listed in Table 5-1 in radial regions which matched Fig. 5-2, except that the hexagon had been circularized with its area preserved. The relative amount of fuel was thus overestimated, so that the k_{eff} = 1.3981 obtained is possibly somewhat high if compared to the k_{eff} of an infinite array of dry containers.

A set of three calculations used GAZE-2 with slab geometry in which the slab extended to infinity of two dimensions. Cases for two, three, and four layers of containers standing on end atop one another (not layers of barrels lying on their sides) were run by varying the slab thickness. Table 5-2 shows the densities of materials in the slab which represented the contents of the shipping containers homogenized over the volume occupied by the containers and associated void volume. The results were k_{eff} = 0.72, 0.98, and 1.10 for two, three, and four layers, respectively (Fig. 5-3).

The disadvantage factors of all materials in the slab calculations above equalled one. The effect of this nonconservative assumption on k_{eff} can be seen by considering the extreme case in which the iron and vermiculite absorb no neutrons. In the two, three, and four layer cases, the iron and vermiculite combined absorbed 9.9%, 8.6%, and 15.4% of the neutrons, respectively. Ignoring these absorptions places upper bounds of 0.82, 1.17, and 1.34 on the k_{eff} for two, three, and four layers. However, these upper bounds are far too conservative, since the ratio of disadvantage factor (iron) to disadvantage factor (fuel) = 0.9831 and the similar ratio for vermiculite to fuel is 0.9835. A reasonable upper bound can be found by reducing absorption in iron and vermiculite by 2%. This leaves k_{eff} = 0.72, 0.98, and 1.10 for two, three, and four layers, respectively.

To check the accuracy of using diffusion calculations, a transport calculation for an array of dry containers extending infinitely in all directions was performed. The result was k_{eff} = 1.4065, higher by 0.0084 than the corresponding diffusion calculation. When this difference is considered, k_{eff} values of 0.73, 0.99, and 1.11 are obtained as reasonable upper bounds for two, three, and four layers of dry containers.

These results show that, for nonaccident conditions, any amount of containers can safely be shipped together if they are only two layers deep (end-on-end). Three or more layers are not safe even under nonaccident conditions (unless the length and breadth of the array of barrels are sufficiently limited).

5.2.4. Effects of Flooding and Immersion

Investigating the effects of flooding and immersion required 29 GAZE-2 programs in addition to the dry-case runs above. Each used cylindrical geometry for a container within an infinite array (in all directions) of like containers (e.g., leakage = 0). Model geometry was that of Fig. 5-2 with two exceptions:

1. The hexagon became a circle of identical area.
2. Immersion in water became a ring of water (called region 6) around region 5 extending to a radius of 30.16 cm. This preserved the proper relative volume of void space outside the barrels.

Densities of materials were those of Table 5-1 except for hydrogen and oxygen densities changed by flooding. Table 5-3 lists the densities of hydrogen and oxygen in each

TABLE 5-2
DENSITIES USED IN HOMOGENIZED SLAB OF FSV SHIPPING CONTAINER

Material	N (atoms/barn-cm)
Vermiculite[a]	6.264×10^{-1}
Carbon	2.210×10^{-2}
Silicon	4.352×10^{-4}
Iron	1.656×10^{-3}
Uranium-233	1.436×10^{-5}
Uranium-238	9.979×10^{-7}
Thorium-232	1.214×10^{-4}

[a]A breakdown into densities of the elements forming vermiculite can be obtained by multiplying the value 0.6264 given here by each of the densities listed for regions 2 and 4 in Table 5-1.

TABLE 5-3
DENSITIES OF HYDROGEN AND OXYGEN IN TOTAL FLOODING

Region	Hydrogen (atoms/barn-cm)	Oxygen (atoms/barn-cm)
1	1.736×10^{-2}	8.681×10^{-3}
2 or 4	6.568×10^{-2}	3.284×10^{-2}
3 or 5	0.00	0.00
6	6.688×10^{-2}	3.344×10^{-2}

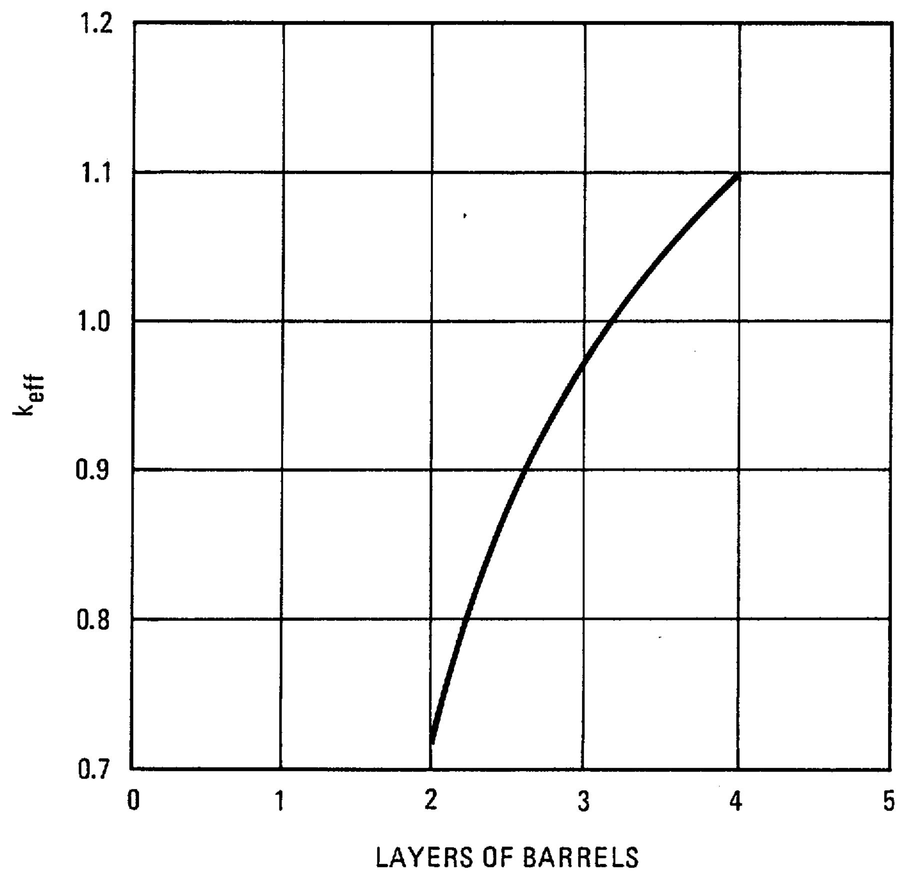


Fig. 5-3. k_{eff} *versus layers of containers for dry FSV-3 shipping containers. (Each layer extends over an infinite plane.)*

region when it is as fully flooded as possible. Densities of hydrogen and oxygen for partial flooding of a region varied linearly between the values in Tables 5-1 and 5-3.

Table 5-4 shows the problems run with their results; the corresponding dry case is also shown. The heading "Fraction of Inner Barrel Flooded" refers to the portion of possible total flooding occurring inside the inner barrel (in regions 1 and 2); "Fraction of Outer Barrel Flooded" refers to the portion of possible total flooding occurring in region 4; and "Fraction of Entire Container Immersed" is the portion of entire container lying under water. Total possible flooding is assumed to occur when only the void spaces in a region are filled; the materials present in the dry case remain in their regions. Accident testing of the container showed this to be a justifiable assumption.

The variation of k_{eff} with different amounts of flooding can be seen in Figs. 5-4 and 5-5. Figure 5-4 shows that, generally, the addition of water to the outer barrel when the container is already immersed in water lowers k_{eff} whether the inner barrel is dry (see left bottom boundary of "carpet") or flooded (right top boundary). This is expected due to the increased absorption in water and steel of neutrons which leak from the core region (region 1). The addition of water to the inner barrel when the outer barrel is already flooded (right bottom boundary) causes k_{eff} to rise. This result is also expected, since adding water to the inner regions (1 and 2) lowers the leakage out of them and also moderates the neutrons in the fuel. The left top boundary is intuitively unexpected - k_{eff} first falls and then rises as water is added. Detailed information and an explanation of this unusual behavior are given in Section 5.2.5.

Figure 5-5 indicates that the contents of the container can be made more reactive than for the dry case only by adding small amounts of water to the inner barrel. Immersion of the containers lowers k_{eff} since the neutrons thermalized in water do not get back to the core because the iron walls serve as a trap to absorb these slow neutrons. The other curve in Fig. 5-5 shows that the dry fuel actually is somewhat undermoderated; adding small amounts of water increases k_{eff} to a maximum of about 0.0042 above that of a totally dry system. Since the dry case is so nearly the most critical, doing the slab calculations for the dry case only is justified. The 0.0042 increase in reactivity can be added to the dry case answers to yield maximum reactivity results with little error.

5.2.5. The Unusual k_{eff} Behavior Set of Cases

In this set of cases, the container is immersed in water, the outer barrel is dry, and flooding of the inner barrel varies. Table 5-5 shows where the neutrons are captured. (Subscript A refers to nonfission absorption and F refers to a fission-producing capture.)

Figures 5-6 and 5-7 clarify what is happening. From Fig. 5-6 it can be seen that the local/average fission shape in the core is qualitatively what intuition suggests; adding water to the inner barrel (core and surrounding vermiculite) causes a larger portion of the fissions to occur near the center of the core. Figure 5-7 shows the not-so-intuitive basis for the observed variations in k_{eff}. The net neutron leakage from the core results primarily from the tradeoff in absorption rates between iron and vermiculite versus water. Small amounts of water in the inner barrel absorb neutrons without decreasing iron and vermiculite absorptions; in fact, the thermalizing effect of the water in region 2 tends to aid absorption by vermiculite. As more water is added, however, the scattering of neutrons by water in the inner barrel effectively shields many of the neutrons from the steel walls and outer vermiculite region. Absorption by iron and vermiculite then drops due to the decreased number of neutrons which leave the core. This explains the rise followed by a drop in leakage out of the core as water is added. The total fission rate

TABLE 5-4
CLOSE-PACKED U-233 LOADED CONTAINERS IN ARRAY EXTENDING INFINITELY IN ALL DIRECTIONS

Fraction of Inner Barrel Flooded	Fraction of Outer Barrel Flooded	Fraction of Entire Container Immersed	k_{eff}
0	0	0	1.398
0.01	0	0	1.402
0.02	0	0	1.401
0.05	0	0	1.377
0.10	0	0	1.331
1/3	0	0	1.163
2/3	0	0	1.035
1	0	0	0.987
0	0	1/2	1.165
0	0	1	0.994
0	1/24	1	0.994
0	1/12	1	0.901
0	1/6	1	0.830
0	1/3	1	0.724
0	2/3	1	0.594
0	1	1	0.526
1/24	0	1	0.957
1/12	0	1	0.933
1/6	0	1	0.905
1/3	0	1	0.886
2/3	0	1	0.899
1	0	1	0.927
1	1/3	1	0.901
1/3	1	1	0.668
2/3	1	1	0.800
1	1	1	0.883
1/3	1/3	1	0.760
1/3	2/3	1	0.698
2/3	1/3	1	0.841
2/3	2/3	1	0.813

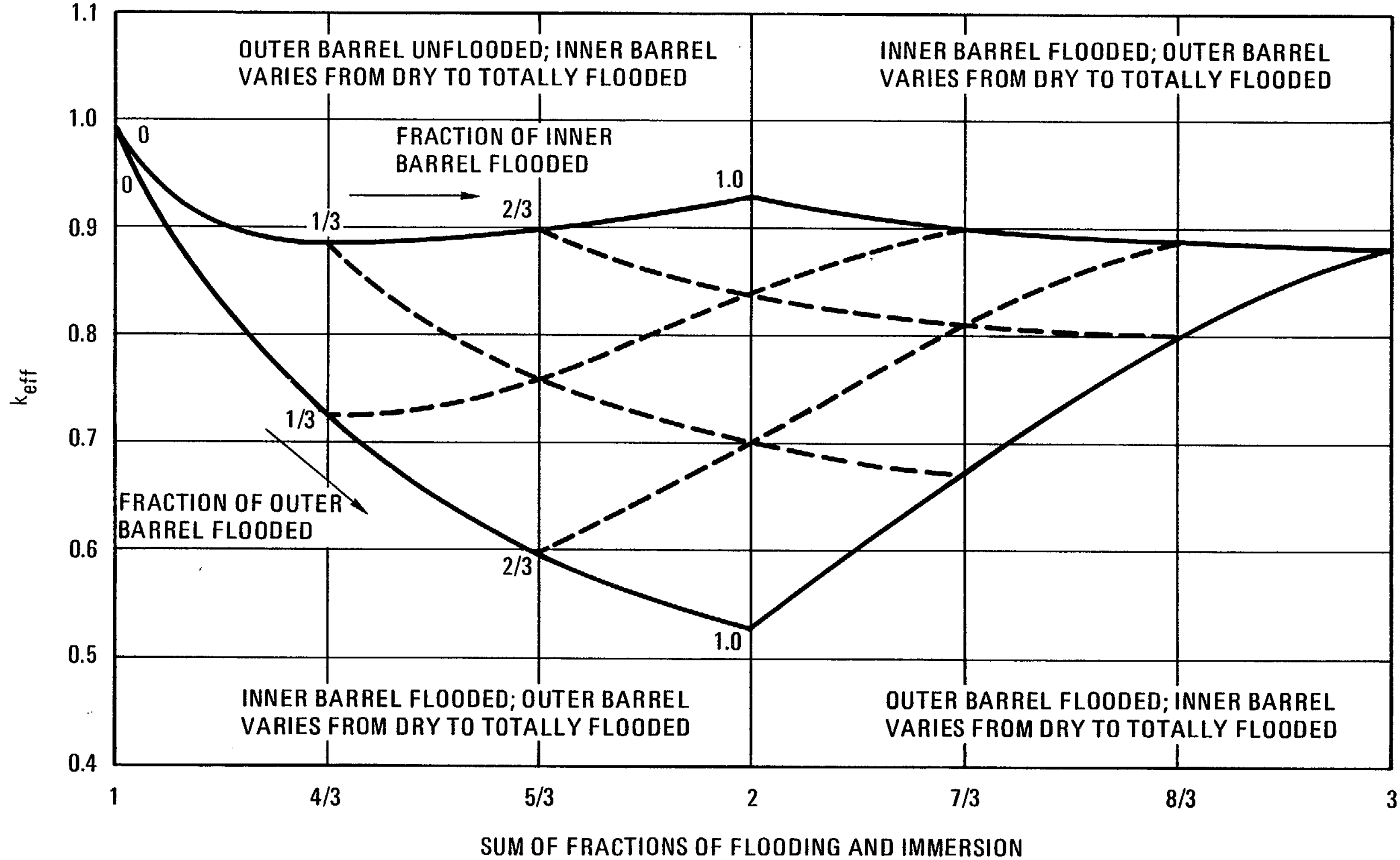


Fig. 5-4. Variation in k_{eff} with different amounts of flooding; FSV-3 container immersed in water

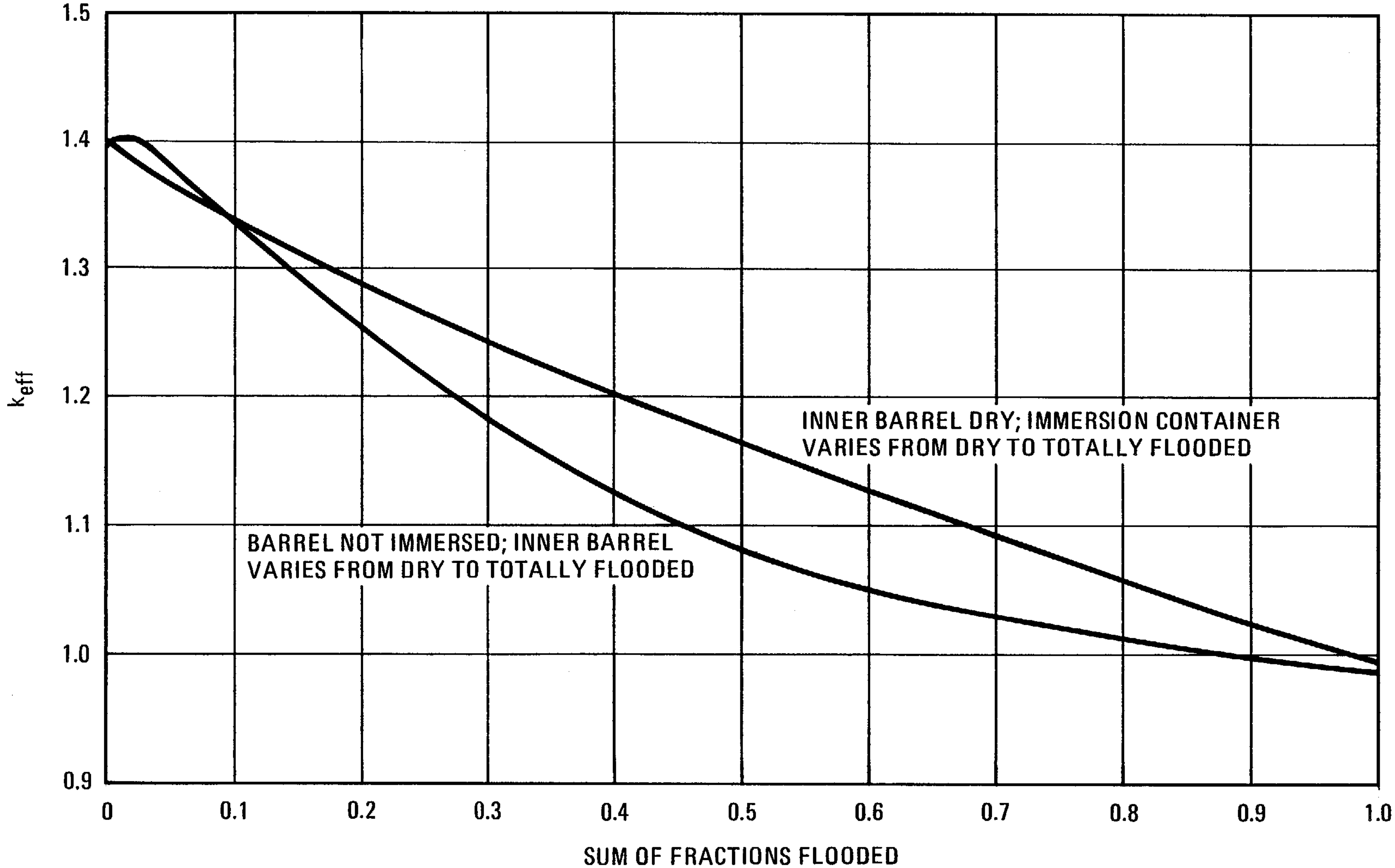


Fig. 5-5. Variation in k_{eff} with different amounts of flooding; FSV-3 container with outer barrel dry

TABLE 5-5
NEUTRON ABSORPTION DEPENDENCY VERSUS VARIOUS FLOODING CASES

	k_{eff} = 0.994 (0,0)[a]	k_{eff} = 0.886 (1/3,0)	k_{eff} = 0.899 (2/3,0)	k_{eff} = 0.927 (1,0)
Σ_A^{1}[b] (vermiculite)	1.55×10^{-2}	1.43×10^{-2}	1.13×10^{-2}	8.53×10^{-2}
Σ_A^2 (C)	3.90×10^{-3}	3.61×10^{-3}	3.75×10^{-3}	3.92×10^{-3}
Σ_A^3 (Si)	3.32×10^{-1}	3.03×10^{-3}	3.13×10^{-3}	3.26×10^{-3}
Σ_A^4 (Fe)	2.43×10^{-1}	2.28×10^{-1}	1.69×10^{-1}	1.18×10^{-1}
Σ_A^5 (U-238)	2.18×10^{-3}	1.46×10^{-3}	1.19×10^{-3}	1.04×10^{-3}
Σ_A^6 (U-233)	4.39×10^{-2}	3.76×10^{-2}	3.71×10^{-2}	3.76×10^{-2}
Σ_A^7 (Th-232)	7.62×10^{-2}	5.91×10^{-2}	5.57×10^{-2}	5.49×10^{-2}
Σ_A^8 (H)	2.12×10^{-1}	2.96×10^{-1}	3.56×10^{-1}	3.98×10^{-1}
Σ_A^9 (O)	1.88×10^{-3}	2.38×10^{-3}	2.59×10^{-3}	2.71×10^{-3}
Σ_A^{TOT}	6.02×10^{-1}	6.45×10^{-1}	6.40×10^{-1}	6.28×10^{-1}
Σ_F^5 (U-238)	1.29×10^{-5}	8.92×10^{-6}	7.28×10^{-6}	6.32×10^{-6}
Σ_F^6 (U-233)	3.97×10^{-1}	3.54×10^{-1}	3.59×10^{-1}	3.70×10^{-1}
Σ_F^7 (Th-232)	4.14×10^{-4}	2.87×10^{-4}	2.34×10^{-4}	2.03×10^{-4}
Σ_F^{TOT}	3.97×10^{-1}	3.54×10^{-1}	3.60×10^{-1}	3.71×10^{-1}

	k_{eff} = 0.957 (1/24,0)[a]	k_{eff} = 0.933 (1/12,0)	k_{eff} = 0.905 (1/6,0)
Σ_A^{1}[b] (vermiculite)	1.57×10^{-2}	1.58×10^{-2}	1.55×10^{-2}
Σ_A^2 (C)	3.77×10^{-3}	3.69×10^{-3}	3.62×10^{-3}
Σ_A^3 (Si)	3.20×10^{-3}	3.13×10^{-3}	3.06×10^{-3}
Σ_A^4 (Fe)	2.51×10^{-1}	2.54×10^{-1}	2.51×10^{-1}
Σ_A^5 (U-238)	2.04×10^{-3}	1.92×10^{-3}	1.72×10^{-3}
Σ_A^6 (U-233)	4.21×10^{-2}	4.08×10^{-2}	3.91×10^{-2}
Σ_A^7 (Th-232)	7.19×10^{-2}	6.86×10^{-2}	6.40×10^{-2}
Σ_A^8 (H)	2.25×10^{-1}	2.36×10^{-1}	2.58×10^{-1}
Σ_A^9 (O)	1.98×10^{-3}	2.06×10^{-3}	2.20×10^{-3}
Σ_A^{TOT}	6.17×10^{-1}	6.26×10^{-1}	6.38×10^{-1}
Σ_F^5 (U-238)	1.21×10^{-5}	1.14×10^{-5}	1.04×10^{-5}
Σ_F^6 (U-233)	3.82×10^{-1}	3.73×10^{-1}	3.61×10^{-1}
Σ_F^7 (Th)	3.89×10^{-4}	3.68×10^{-4}	3.34×10^{-4}
Σ_F^{TOT}	3.83×10^{-1}	3.73×10^{-1}	3.62×10^{-1}

(a) (Fraction inner barrel flooded, fraction outer barrel flooded).

(b) All Σ's are reaction rates: Σ_A = nonfission-producing absorption rate in group i; Σ_F^i = fission-producing capture rate in group i.

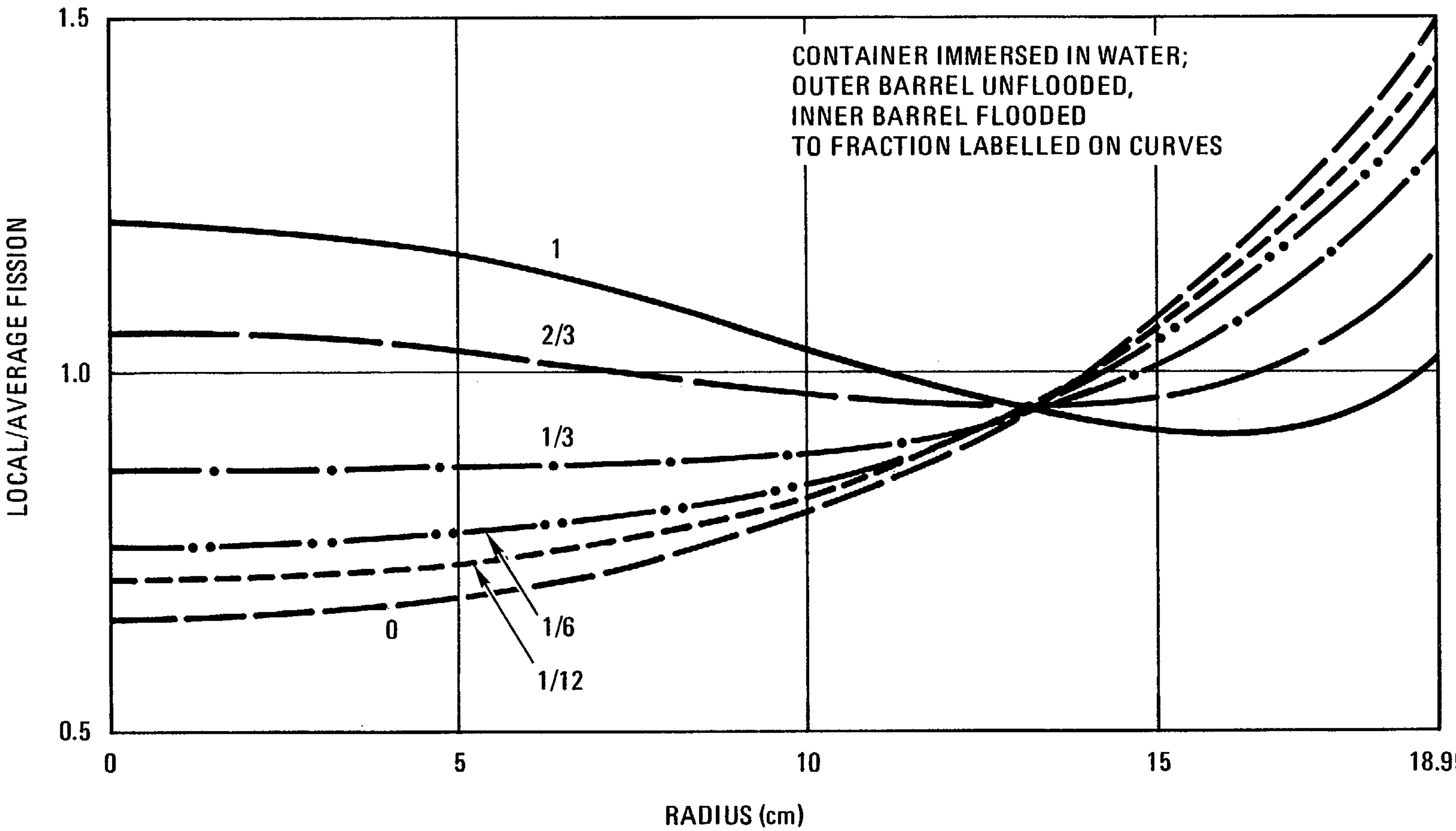


Fig. 5-6. Relative fission distribution within a flooded container for various flooding conditions

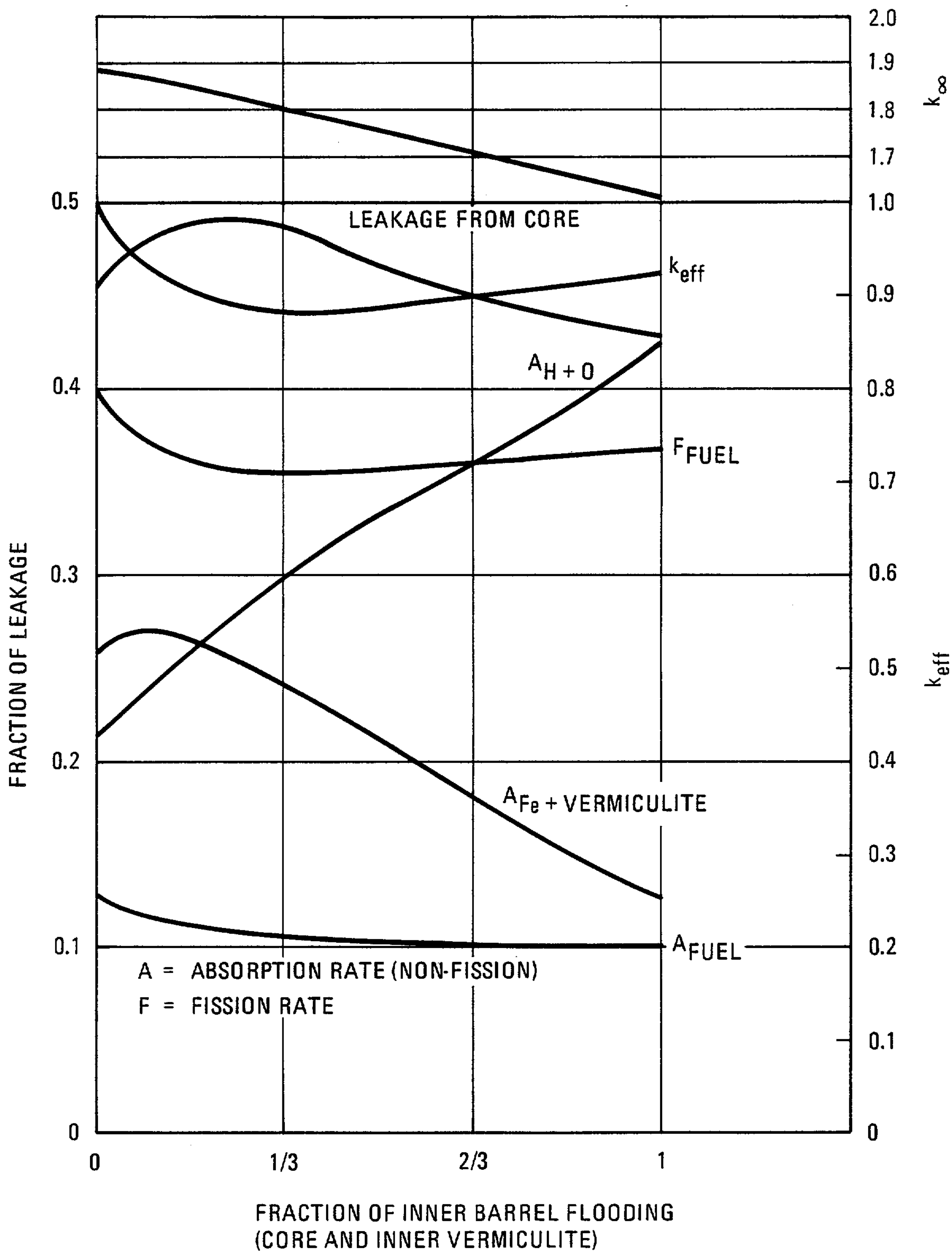


Fig. 5-7. k_{eff} and k_∞ and fractions thereof versus flooding

is inversely proportional (qualitatively) to the leakage from the core and, of course, k_{eff} is roughly proportional to total fission rate. Since the system is overmoderated, k continually decreases as water is added so that it is only the leakage from the core, and thus the tradeoff in absorption rates, that gives the unusual behavior of k_{eff}.

The criticality analysis performed in the foregoing assumes that all fissile material present in the fuel element is U-233. Since this assumption is obviously highly conservative, the criticality evaluation has been summarized using U-235 as the fissile material. The results are summarized in Tables 5-6 and 5-7.

The large differences can easily be explained by the difference in nuclear properties for U-233 and U-235, as summarized in Table 5-8 for the nine neutron energy group structure that was used in the calculations. The neutron spectrum is fairly hard, especially in the unflooded systems, and most of the fissions occur in the upper groups where the η for U-235 is much lower than the η for U-233.

As in the analysis for U-233, the multiplication constant is higher for dry systems. A conservative estimate of the multiplication for various arrangements of dry containers is given in Table 5-9. Even if up to 240 containers are packed in an optimum array, the k_{eff} stays below 0.80.

5.2.6. Criticality of Damaged FSV-3 Fuel Packages

Table 5-10 summarizes the criticality calculations for damaged FSV-3 containers loaded with fresh U-235 fuel. The following assumptions were made in the calculations:

1. Each fuel element contains the most reactive fresh fuel composition anticipated for shipment, i.e., 1.5 kg of 93.15% enriched uranium and 11.8 kg of thorium per element.
2. No neutron absorbing material other than uranium, thorium, and graphite is present in the fuel elements. The presence of burnable poison is neglected.
3. The least dense form of vermiculite (4 lb/ft^3) commercially available is used for packaging.
4. The shipment considered consisted of 100 containers of fresh fuel. This is the maximum number allowable under the Class III license requested and more than twice the number allowable for the Class II license sought.
5. All containers were assumed to be damaged.
6. The damage was such that one side of the container sustained a 3-in. deformation over its entire length; i.e., the outer radius on this side was reduced by 3 in. The tests of sample containers previously reported showed that material is not lost from the container as a result of the 30-ft drop event and that the inner container remains intact and water tight. Since the side impact considered here necessarily distributed the energy over a much greater surface area than the lid-edge drop used to demonstrate maximum impact damage, the test results were assumed to be conservative for these purposes.
7. All damaged containers were assumed to be closely packed in their most reactive configuration.
8. Based on previous criticality analysis of the shipping containers, it was assumed that water flooding, with the inner fuel-bearing container remaining dry, resulted in a decrease of the k_{eff} of the system.

TABLE 5-6
MULTIPLICATION OF INFINITE LAYER OF CONTAINERS

Number of Layers	Fuel U-233	Fuel U-235
2	0.726	0.532
3	0.980	0.731
4	1.10	0.829

TABLE 5-7
CLOSE-PACKED CONTAINERS IN ARRAY EXTENDING INFINITELY IN ALL DIRECTIONS

Fraction of Inner Barrel Flooded	Fraction of Outer Barrel Flooded	Fraction of Entire Container Immersed	k_{eff} U-233 Fuel	k_{eff} U-235 Fuel
1.0	0.0	1.0	0.927	0.851
0.0	1.0	1.0	0.526	0.465
1.0	1.0	1.0	0.883	0.810
0.0	0.0	1.0	0.994	0.887
1/3	0.0	0.0	1.163	1.044
2/3	0.0	0.0	1.035	0.945
1.0	0.0	0.0	0.987	0.908
1/12	0.0	1.0	0.933	0.827
1/6	0.0	1.0	0.905	0.807
1/3	0.0	1.0	0.886	0.797
2/3	0.0	1.0	0.899	0.819
0.0	1/24	1.0	0.944	0.834
0.0	0.0	0.5	1.165	1.008

TABLE 5-8
COMPARISON OF U-233 AND U-235 DATA

Group	Lower Energy (eV)	$\alpha = \sigma_c/\sigma_f$ U-233	$\alpha = \sigma_c/\sigma_f$ U-235	$\eta = \nu/(1 + \alpha)$ U-233	$\eta = \nu/(1 + \alpha)$ U-235
1	1.8×10^5	0.048	0.101	2.49	2.33
2	961	0.168	0.408	2.14	1.73
3	17.6	0.174	0.540	2.13	1.58
4	3.93	0.164	0.907	2.15	1.27
5	2.38	0.239	0.420	2.02	1.71
6	0.414	0.190	0.192	2.10	2.04
7	0.1	0.109	0.197	2.25	2.03
8	0.04	0.091	0.174	2.29	2.07
9	0.0	0.090	0.173	2.29	2.07

TABLE 5-9
CRITICALITY OF DRY SHIPPING CONTAINERS (U-235 FUEL)

Number of Containers per Layer	Number of Containers Stacked	Total Number of Containers	k_{eff}
40	3	120	0.62
50	3	150	0.65
60	3	180	0.67
40	4	160	0.68
50	4	200	0.73
60	4	240	0.75
30	5	150	0.66
40	5	200	0.73
40	6	240	0.77

TABLE 5-10
SUMMARY OF RESULTS OF CRITICALITY ANALYSIS OF DAMAGED FRESH FUEL SHIPPING CONTAINERS

Number of Layers	Containers Per Layer	System k_{eff} Undamaged	System k_{eff} Damaged
1	100	0.294	0.338
2	50	0.532	0.579
3	33.3	0.590	0.629
4	25	0.579	0.613
5	20	0.548	0.581
6	16.6	0.514	0.545

Several close-packed arrays of containers were considered in the analysis. It can be seen from Table 5-10 that the most reactive situation occurs for the 100 containers stacked in three layers.

Criticality of damaged containers was obtained by calculating the change in M^2 and B^2 of the array due to the damage (i.e., densification and reduction in volume) and assuming k_∞ for the system remained unchanged. The value of k_{eff} can be calculated from

$$k_{eff} = \frac{k_\infty}{1 + M^2B^2} \quad .$$

Original values of M^2, B^2, and k_∞ were obtained from the undamaged fuel container calculations.

6. OPERATING PROCEDURES

6.1. LOADING THE PACKAGE

The procedure for loading the package is:

1. Obtain an empty double-barrel shipping assembly and place it in the designated final packaging area.
2. Uniformly distribute the correct amount of vermiculite over the bottom surface of the outer drum and tamp it firmly into place with an approved tamping tool.
3. Center the inner drum within the outer drum and pack the void between the inner and outer drums with vermiculite to a depth of 4 to 6 in. below the top of the inner drum.
4. Uniformly distribute the correct amount of vermiculite over the bottom surface of the inner drum and tamp it firmly into place with an approved tamping tool.
5. Move the prepared double-barrel container to the hoist area.
6. Lift the completed fuel element with an approved lifting tool to enable the Quality Control inspector to perform a complete visual inspection of the element.
7. Enclose the element in a bag(s).
8. Place the inspected and bagged element into the inner drum of the prepared container, taking care to center the element in the drum.
9. Remove the lifting tool from the element.
10. Seal the top(s) of the bag(s) around the element.
11. Pack vermiculite around the sides of the element.
12. Uniformly distribute the correct amount of vermiculite over the top of the element.
13. Insert the plywood disk atop the element.
14. Stencil the inner drum lid with the required information.
15. Install, clamp, and bolt the inner drum lid in place.
16. Distribute vermiculite over the top of the inner drum to fill the remaining void between it and the outer drum.
17. Stencil the outer drum and lid with the required information.
18. Install, clamp, and bolt the outer drum lid in place.
19. Tamper-safe seal the container (two-man rule).

6.2. UNLOADING THE PACKAGE

The procedure for unloading the package is:

1. Remove the tamper-safe seal (two-man rule).
2. Remove the outer drum lid.
3. Remove vermiculite to below inner drum lid.
4. Alternatively remove inner drum and element as a unit or remove the inner drum lid and the plywood disk.
5. Remove vermiculite to below the top of the element.
6. Open the bag(s). Remove any vermiculite dust.
7. Insert the lifting tool and carefully remove the element from the container.

6.3. PREPARATION OF EMPTY PACKAGE FOR TRANSPORT

No specific procedure is needed for the return of the empty packages or package components except for removal or covering of the outer drum warning labels, i.e., transport index, Fissile Class II or III, etc. The packages are typically not contaminated as a result of their use. Individual facility procedures governing materials exiting licensed facilities would control potentially contaminated components.

7. ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

The acceptance tests will be performed to verify and document the proper condition of materials, construction technique, and quality of workmanship.

The maintenance program is restricted to the repainting of, and removal of minor dents from, inner or outer drums before their reuse in the construction of a FSV-3 container.

7.1. ACCEPTANCE TESTS

1. Empty containers
   a. Visual inspection
      (1) Inspect surfaces of inner and outer drums for evidence of residues or foreign material; deterioration such as pitting, creases, or corrosion; and for changes in container shape, contour, height, or diameter.
      (2) Inspect clamp rings for defects or deterioration.
      (3) Verify that a new outer seal ring is used.
      (4) Verify that all prior shipping markings have been removed or obliterated.
   b. Dimensional inspection
      (1) Sample, at random, 5% of the containers scheduled for reuse for dimensional inspection.
      (2) Measure the interior dimensions of both the inner and outer drums and compare the dimensions to the requirements of FFE-613.
   c. Record of inspection

      A record will be made in the Fuel Assembly Inspection Record that the container for the assembled element has been inspected.
2. Completed assemblies and shipping containers
   a. Verify by visual inspection the proper container assembly and use of a new outer drum seal.
   b. Spot check vermiculite packing to confirm that all interspaces are firmly packed and that no visible voids exist.
   c. Verify that required shipping labels and data are on the container.

7.2. MAINTENANCE PROGRAM

1. Repaint inner and outer drums and lids as required prior to reuse.
2. Remove dents from inner and outer drums as required to meet Quality Control inspection requirements.

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