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**AN IMPROVED SHIPPING CONTAINER
FOR FISSILE MATERIAL**

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AN IMPROVED SHIPPING CONTAINER FOR FISSILE MATERIAL

Abstract

Based on an ORNL design, an improved shipping container for fissile materials has been developed. This container has passed the normal and accident tests proposed in the current revision of AEC Safety Standards. Further, a criticality analysis by the LLL Criticality Safety Advisory Group has established

quantitative limits for shipping solid forms of enriched uranium and plutonium according to AEC criteria for Class I, Class II, and Class III categories.

Tests made on simulated quantities of fissile material indicate the degree of internal heat buildup that can be expected in this container.

Introduction

During the past few years, to judge by symposia on the subject,^{1,2} considerable efforts have been made to develop containers for shipping radioactive and fissile materials safely. Two kinds of containers have been developed: heavy, shielded units for radioactive materials that emit gamma rays; and lighter containers for fissile materials, which are essentially alpha

emitters. The Materials Management Section of the Lawrence Livermore Laboratory is particularly interested in items in the latter category. They therefore asked the Hazards Control Department to provide a suitable container; they suggested that an ORNL design, reported in Ref. 1, page 161, might be used as a starting point.

1. AEC Symposium on Packaging and Regulatory Standards for Shipping Radioactive Material, Germantown, Md., 1962, AEC report TID-7651 (1962).

2. Proceedings, International Symposium for Packaging and Transportation of Radioactive Materials, Albuquerque, New Mexico, 1965, Sandia Corporation, Albuquerque, New Mexico, Rept. SC-RR-65-98 (1965).

Container Criteria and Design

The Oak Ridge design consists of a shortened 55-gallon drum (22-1/2 in. in diameter by 21-5/16 in. high, 16-gauge metal), lined with a 1/16-in. layer of polyvinyl acetate, insulated with about 5-1/2 in. of borosilicate-foamed glass (Foamglas), and further lined with about 1/8 in. of polyvinyl acetate. The interior cavity is a cylinder 10 in. in diameter by 10 in. high. This package successfully passed tests for normal and accident conditions of transport. These tests, which were subsequently formalized in USAEC Manual, Chapter 0529, "Safety Standards for the Preparation of Radioactive and Fissile Materials for Transportation," will be enumerated later in this report.

The Oak Ridge package satisfies most of LLL's requirements for shipping enriched uranium. However, there is also need for a package having a larger internal capacity for shipping plutonium in secondary, inner leaktight containers. We therefore modified the ORNL design as follows (see Fig. 1):

1. We obtained larger drums from Rheem Manufacturing Company in both 14- and 16-gauge steel. The dimensions of both are 28-3/4 in. in diameter by 26 in. high inside. The locking rings, made of 10-gauge steel, are secured by a 5/8-in. ring bolt. The bolt ring is of forged steel.

2. For the internal container, we used a 25-qt aluminum sterilizer (pressure cooker) approximately 12 in. i.d. by 12 in. high inside. The overall height is about 15-3/4 in. The top of the sterilizer

mates the body with a wedged metal-to-metal fit. The locking bolts on the body are Bakelite, containing brass-threaded inserts and lock washers.

These changes allow us to retain at least 5 in. of Foamglas insulation between the cavity and the drum surface. We have also made the following changes, which we believe are improvements:

1. The entire drum (both inside and out) and the lid are coated with Bisomite silicone enamel (G6-53). Previous experience³ has demonstrated that such coating withstands radiant temperatures to at least 1238°F (670°C).

2. The primary lining of the drum wall and bottom consists of two 1/16-in. layers of asbestos paper, secured with stripes of Foster's cement.

3. The lining of the cavity is 0.020-in. aluminum sheet, coated internally with a fire-retardant, epoxy-polyamide white paint (Glidden's Nu-Pon Cote), and secured to the Foamglas insulation with Keene's cement. The aluminum protects the glass insulation against damage in normal use. The coating provides a tough, glossy surface that can be decontaminated with acids, alkalis, and solvents.

4. The top plug for the cavity is a truncated cone of Foamglas, covered top and bottom with glass cloth, and encased on the side with 0.020-in. aluminum sheet.

3. J. R. Gaskill, Fire-Retardant Coatings, Lawrence Livermore Laboratory Rept. UCRL-6697, Pt. 1 (1961).

Lifting straps of tinned, flexible ground-
ing strap are attached to this sheet; this
feature eliminates the finger holes in the
OFNL design and hence provides slightly
more top insulation. The top of the plug

is coated with QF-150 Fiberfrax coating
cement. Subsequently the exterior plug
surfaces are overcoated with Glidden's
Nu-Pon Cote. Figure 2 shows the design
of the new container.

Fig. 1. LLL-SS material shipping container.

All external surfaces of plug and internal surfaces of aluminum liner coated with white Nu-Pon Cote epoxy enamel.

Fig. 2. Details of the LLL-SS material shipping container.

Test Procedures

Two drum assemblies (Fig. 3), 14- and 16-gauge, respectively, each containing dummy loads of fissile material, were made up and subjected sequentially to the tests described below. The dummy loads were canned, encased in vinyl bags, and placed in the sterilizers with or without paper packing material. The sterilizers were then closed and sealed.

Two of the normal tests—dropping a steel rod onto a drum and the water spray test—were not performed because two of

the accident tests were considerably more stringent. Tests performed were:

1. Compression Test

An empty drum with the top and ring in place was subjected to a compression of 2 psi (based on top area) for 24 hr. To accomplish this, we placed a plywood disk, 1.5 in. thick, just inside the rim on top of the drum, and a pallet loaded with scrap lead on top of the disk (total

Fig. 3. Assembled shipping containers - before testing.

weight 1320 lb). Calculated loading was 2.1 psi.

2. Operational Drop Test

A loaded drum was dropped from 4 ft onto a blacktop surface at a 45-deg angle so that the drum impacted on the closing ring. (See Fig. 4).

3. Accident Drop Test

The drum was dropped from 30 ft onto the blacktop in a fashion similar to that in Test 2. (See Fig. 5.)

4. Impact Test

The drum was dropped vertically from 40 in. onto a fixed, solid steel cylinder, 6 in. in diameter, so that impact occurred on the bottom approximately in the center of the drum. (See Fig. 6.)

5. Fire Test

The drum was placed in a preheated 187-kW electric furnace maintained at 800°C (1475°F) for 1/2 hr. (See Fig. 7.) (This test is proposed in the latest AEC Manual revision; it is less stringent than the existing requirement of exposure for 1 hr at 1600-1700°F.)

6. Water Immersion Test

After removal from the furnace and cooling, the drum was immersed under 3 ft of water for 24 hr. (See Fig. 8).

Fig. 4. Operational drop test of shipping container.

Fig. 5. Accident drop test of shipping container.

Fig. 6. Accident puncture test.

Fig. 7. Heat-resistance test.

Fig. 8. Appearance of cooled drums after furnace test and prior to immersion test.

Test Results

Results of the tests are reported below.

1. Compression (no photograph.)

The drum showed no adverse effects whatsoever from this test.

2. Operational Drop (see Fig. 9)

The rim of the 16-gauge drum was dented slightly; marring of the 14-gauge drum rim was barely noticeable.

3. Accident Drop (see Fig. 10)

The rings and rims of both drums

were noticeably flattened or dented.

Additionally, the locking ring of the 16-gauge drum popped off. However, the ring had not been tightened sufficiently before the test. It was properly replaced, and functioned well during the remaining tests.

4. Impact (see Fig. 6)

The bottoms of both drums were dented slightly. No penetration of the metal skin occurred.

Fig. 9. Appearance of drums after operational drop test.

Fig. 10. Appearance of drums after accident drop test.

5. Fire (see Figs. 7 and 8)

As each drum was lowered into the furnace, copious amounts of smoke began to evolve from under the locking ring. Later inspection indicated that this was caused by pyrolysis of the white paint on the top surface of the plug and drum insulation. A few minutes later in each case, the thermocouple leads burned off, so that it was impossible to determine the temperatures at the various locations within the drum during the test. However, the undamaged final condition of the contents speaks for itself. (See par. 7.)

Smoke continued to evolve from the furnace vent pipe during most of the test times. However, in the second test—that with the 14-gauge container, which had no rubber ring gasket—the smoke subsided after about 15 min and a light-colored, smokeless flame appeared at the vent opening. This flare continued for the balance of the test. We judged this to be an H_2S flame, since the glass is foamed with this gas.

After the drums were removed from the furnace and cooled, examination indi-

cated that the exterior coating, although somewhat blistered, was generally intact. We believe that excessive coating (about 5 mils maximum) and metal contraction caused these bubbles.

6. Immersion (see Fig. 11)

Water immersion caused some flaking of the exterior coating, especially where it had been blistered, but did not appear to affect the sound coating. When the drums were opened, water was found inside the drum and the sterilizer cavity, but, with the exception noted below, not inside the sterilizers.

7. Final Examination (see Figs. 11 and 12)

After the tests were completed, we opened the drums and sterilizers and examined the interiors and dummy packages.

We found that the Foamglas had been dented in the 30-ft drop test, and that the top surfaces of the plug and drum insulation had been charred. However, the sides of the internal cavity were not charred. One sterilizer had lost some of its original

Fig. 11. Appearance of shipping containers and contents after all tests.

Fig. 12. Appearance of sterilizer interiors, dummy loads, and packing material after all tests.

external sheen, but was otherwise undamaged. Water had entered the drum along the sides where some of the insulation had been burned away and had also partially filled the cavities containing the sterilizers.

Water had seeped slightly into one sterilizer, apparently through a faulty thermocouple seal; the other sterilizer was dry inside. The "leaking" sterilizer was the one in which we had sprinkled fluorescent powder over the package before sealing. After the tests, we examined this sterilizer and internal package under ultraviolet light and found the following:

1. No evidence of powder on the outside of the sterilizer, including the neck under the rim.
2. No smearing of the powder on the plastic envelope, which would have indicated wetting.
3. No evidence that the powder had been affected by heat.

Thus it appears that no gross leakage had occurred in this sterilizer.

The dummy packages and packing material were in the same condition after the tests as they were originally. Laboratory tests on these materials indicate the following heat deterioration temperatures:

Material	Deterioration temperature (°C)	Remarks
Fluorescent powder	280 +	melted
Newspaper	260	turned brown
Vinyl film	110	start of melt
Vinyl tape	190	became sticky
Wrapping paper	240	browned

From these data and the appearance of the vinyl film bags used to package the loads, the temperature inside the sterilizer obviously did not exceed approximately 100°C. Since the aluminum sterilizer is a good heat conductor, the central portion of the drum cavity also could not have been much hotter.

Discussion

Clearly the containers withstood the mechanical "accident" tests satisfactorily. Further, the appearances of the drum, drum cavity, sterilizer, and contents show that the system passes the tentative fire test. This confirms the soundness of ORNL design on which ours is based. Although water entered the drum in the immersion test, it did not enter the sterilizer. (We dismiss the leak in the faulty thermocouple seal as being non-pertinent.) Both these facts were considered in the criticality calculations* to determine the quantities of plutonium or enriched uranium that may be shipped in this package under AEC Regulation 0529. These calculations have been completed and the results and the test data are to be submitted to the Commission and to the Bureau of Explosives with a request for a Shipping Permit for the package.

* See Appendix A.

Although the package passed the tests satisfactorily, we propose to incorporate some minor improvements in the production unit. These improvements are:

1. The thickness of the aluminum coating will be reduced from 5 mils to 2-3 mils. This should result in a tighter seal, less subject to heat and water damage.
2. The top of the plug and drum insulation will be protected from heat by securing a 1/8-in. layer of Fiberfrax paper (970-J) to the inside of the drum lid.
3. Heat-resistant silicone rubber foam (GE-RTV-757) will be used as a gasket for the lid. The closed cell structure of this foam will provide a soft, watertight seal. When exposed to a propane torch, this rubber forms a tough, dense char. This should be a good heat insulator, and it may also provide a reasonable water seal.

Acknowledgment

We thank Clarence Tunistra of the Mechanical Shops Department for his skill in fabricating and assembling the containers, and for the useful ideas he contributed.

Appendix A: Criticality Safety
No. 33, Rev. II Memorandum

October 4, 1971

LLL Shipping Container For Fissile Metal or Oxide Mass Limits
For AEC Classes I, II, and III Transportation Rules

This memorandum summarizes the results of a study to reevaluate fissile mass limits for LLL shipping container

No. 5848, with allowance for an increase in the amount of nonfissile materials permitted inside the container.

SUMMARY OF RESULTS

Table A-I. Fissile Class I limits^a for LLL container No. 5848.

Fissile material	Maximum container loading (kg)	Maximum M/X ratio
U(93.5) ^b	1.28	10
²³⁹ Pu ^c	1.20	10
U(93.5) ^b	2.8	0.4
²³⁹ Pu ^c	1.5	0.4

^aM/X is calculated by taking the ratio of nonfissile atoms, M, that are contained within the outer surface of the fissile part to the number of fissile atoms within the same volume. If the fissile part is irregular in shape, has concave surfaces, or consists of several pieces, the volume used in the calculation of M/X is that contained within an envelope containing the fissile part or parts. Materials external to the part or its envelope are reflectors and are not included in the calculation.

^bThe U(93.5) limits apply to mixtures of ²³⁴U, ²³⁵U, ²³⁶U, and ²³⁸U, with ²³⁵U < 93.5%, provided that all isotopes except ²³⁸U are considered to be ²³⁵U in computing mass.

^cThese limits may be applied to isotopic mixtures of plutonium, provided that the concentration of ²⁴⁰Pu exceeds that of ²⁴¹Pu, all plutonium isotopes are considered to be ²³⁹Pu in computing mass, and no more than 1% ²³⁸Pu is present.

Table A-II. Class II mass limits for $^{239}\text{Pu}^a$ for LLL container No. 5848.

M/Pu	Maximum container loading (kg) ^b					²³⁸ U
	Reflector material					
	H ₂ O ^c	Be	BeO	C	CH ₂ ^d	
0 - 0.4	4.5	2.1	2.3	3.5	3.6	3.6
0.4 - 3.0	2.9	1.3	1.6	2.2	2.3	2.3
3.0 - 6.0	3.8	1.7	1.9	3.0	3.0	3.0
6.0 - 10.0	3.3	1.5	1.7	2.6	2.7	2.7

Unit mass (kg)	Transport index
----------------	-----------------

2	0.1
3	0.2
4	0.3
5	0.8
6	3.0
6.5	6.0

^aThese limits may be applied to isotopic mixtures of plutonium, provided that the concentration of ^{240}Pu exceeds that of ^{241}Pu , all plutonium isotopes are considered to be ^{239}Pu in computing mass, and no more than 1% ^{238}Pu is present.

^bThese limits must not be exceeded unless, by reason of geometry or poisons, the single package is safely subcritical. M/Pu is calculated by taking the ratio of nonfissile atoms, M, that are contained within the outer surface of the fissile part to the number of fissile atoms within the same volume. If the fissile part is irregular in shape, has concave surfaces, or consists of several pieces, the volume used in the calculation of M/Pu is that contained within an envelope containing the fissile part or parts. Materials external to the part or its envelope are reflectors and are not included in the calculation.

^cThe H_2O limits also apply to iron, aluminum, oil, carbon tetrachloride, and trichloroethylene reflectors.

^dThe CH_2 limits also apply to paper packing material.

Table A-III. Class II mass limits for U(93.5)^a for LLL container No. 5848.

M/U	Maximum container loading (kg) ^b					
	Reflector material					
	H ₂ O ^c	Be	BeO	C	CH ₂ ^d	²³⁸ U
0 - 0.4	18.5	6.1	6.5	13.5	17.5	13.1
0.4 - 3.0	9.0	3.0	3.1	6.6	8.5	6.3
3.0 - 6.0	7.2	2.3	2.5	5.3	6.8	5.1
6.0 - 10.0	5.3	1.7	1.8	3.9	5.0	3.7

Unit mass (kg)	Transport index
10	0.1
15	0.2
20	1.0
26	4.0

^aThe U(93.5) limits apply to mixtures of ²³⁴U, ²³⁵U, ²³⁶U, and ²³⁸U, with ²³⁵U < 93.5%, provided that all isotopes except ²³⁸U are considered to be ²³⁵U in computing mass.

^bThese limits must not be exceeded unless, by reason of geometry or poisons, the single package is safely subcritical. M/U is calculated by taking the ratio of moderator atoms, M, that are contained within the outer surface of the fissile part to the number of fissile atoms within the same volume. If the fissile part is irregular in shape, has concave surfaces, or consists of several pieces, the volume used in the calculation of M/U is that contained within an envelope containing the fissile part or parts. Materials external to the part or its envelope are reflectors and are not included in the calculation.

^cThe H₂O limits also apply to iron, aluminum, oil, carbon tetrachloride, and tri-chloroethylene reflectors.

^dThe CH₂ limits also apply to paper packing material.

Table A-IV. Class III mass limits for LLL container No. 5848.

²³⁹ Pu		U(93.5)	
Unit mass (kg) ^a	Number of containers	Unit mass (kg) ^b	Number of containers
2	1000	10	1000
3	500	15	500
4	330	20	100
5	125	26	25
6	33		
6.5	16		

^aThe container limits of Table A-II and the footnotes apply here.

^bThe container limits of Table A-III and the footnotes apply here.

LLL CONTAINER DESCRIPTION

The LLL shipping container (see Fig. 1 on p. 3) consists of a cylindrical 73.6-gal drum, with internal dimensions of $R = 14.25$ in. and $H = 26.62$ in., made of 14-gauge steel (approximately 0.075 in.); a cylindrical can with equivalent dimensions of $R = 7.2$ in. and $H = 20.0$ in., made of 0.02-in. aluminum; and an inner cylindrical container (pressure cooker) with equivalent outer dimensions of $R = 6.25$ in. and $H = 12.5$ in., made of 0.25 in. aluminum (see Fig. A-1).

The void between the can and the drum is filled with Foamglas (a closed bubble foam which consists of a type of borosilicate glass, having a density of ~ 9 lb/ft³).

The space between the can and the inner container is a small void which, under accident conditions, could possibly be filled with a very thin layer of water which would not exceed $1/8$ in. Thus, it is neglected in these calculations.

The rolled rings and rim of the drum provide a 1.38-in. radial clearance and a 1.6-in. axial clearance between containers under normal stacking conditions. In an accident situation, where the array is submersed, this void would be filled with water.

SHIPPING CRITERIA¹

Class I

The following is the definition of a Fissile Class I Shipment:

"Fissile Class I: Packages which may be transported in unlimited

1. All definitions and package specifications for Classes I, II, and III are contained in AEC Manual, Chap. 0529, "Safety Standards on the Packaging of Radioactive and Fissile Materials," revised February 15, 1969,

numbers and in any arrangement, and which require no nuclear criticality safety controls during transportation. For purposes of nuclear criticality safety control, a transport index is not assigned to Fissile Class I packages. However, the external radiation levels may require a transport index number."

The following are Specific Standards for a Fissile Class I Package:

"A Fissile Class I package shall be so designed and constructed and its contents so limited that:

1. Any number of such undamaged packages would be subcritical in any arrangement, and with optimum interspersed hydrogenous moderation unless there is a greater amount of interspersed moderation in the packaging, in which case that greater amount may be considered; and
2. Two hundred and fifty such packages would be subcritical in any arrangement, if each package were subjected to the hypothetical accident conditions specified in annex 2, below, as the Free Drop, Thermal, and Water Immersion conditions, in the sequence listed in annex 2, with close reflection by water on all sides of the array and with optimum interspersed moderation unless there is a greater amount of interspersed moderation in packaging, in which case that greater amount may be considered. The condition of the package shall be assumed to be as described in G., above."

MORSE² calculations were performed for dry infinite arrays. The dry array was considered as the most reactive situation since hydrogenous material dispersed in the array would slow down the neutrons which would be captured by the boron in the foam. Calculations were also made which verify this assumption

2. T. P. Wilcox, MORSE-C, A Special Version of the MORSE Program Designed to Solve Criticality Problems, MORSE Note No. 2 (MOR-2), April 27, 1971.

Fig. A-1. Internal container (pressure cooker) for LLL shipping container.

for H/X ratios as high as 10. In any case, an additional safety factor was applied. This is discussed as follows: Since the revised 0529 requirements do not specify a safety factor, the former 0529 safety factor of limiting the contents of each container to 80% of the unit mass in an infinite critical array is retained.

Results of the MORSE calculations are summarized in Table A-V.

Final results of the Fissile Class I determination are presented in Table A-I, where the 80% safety factor has been applied to the critical data in determining container limits. Since hydrogen is seen to actually reduce array reactivity, the $H/X < 0.4$ limits pertain as long as the fissile material is a single piece with no concave surfaces which would permit entry of water or other hydrogenous material.

The atomic densities used in the calculation are included in Table A-VI. The container geometry was simplified, as shown in Fig. A-2.

Table A-V. Results of MORSE calculations for infinite arrays of LLL containers.

Homogeneous mixtures of metal and hydrogen			
k_{eff}			
H/X	1.6 kg U(93.5) uniformly distributed inside container	1.55 kg ^{239}Pu uniformly distributed inside container	
0	0.99 ± 0.019	0.99 ± 0.016	
3	0.90 ± 0.01	0.94 ± 0.009	
10	0.75 ± 0.009	0.84 ± 0.007	
Solid metal spheres			
Fissile material		Critical unit mass (kg)	
U(93.5)		3.55	
^{239}Pu		1.90	

Table A-VI. Isotopic composition of materials considered in neutronic analysis.

Material	Density (g/cm ³)	Atomic composition (10 ²⁴ atoms/cm ³)
U(93.5)	18.78	N(235) = 0.04466 N(238) = 0.00322
α -Plutonium	19.6	N(239) = 0.04938
Water	1.0	N(H) = 0.067 N(O) = 0.0335
Borosilicate foam	0.144	N(Si) = 0.0009232 N(O) = 0.002309 N(Na) = 0.0002184 N(Mg) = 0.0000321 N(Ca) = 0.0000649 N(Al) = 0.0000899 N(B) = 0.0000882 ^a

^a Natural boron.

Fig. A-2. Neutronic mockup cylinder of LLL container for MORSE calculations.

Class II

The following is the definition of a Fissile Class II shipment of fissile materials:

"Fissile Class II: Packages which may be transported together in any arrangement but in numbers which do not exceed a transport index of 50. For purposes of nuclear criticality safety control, individual packages may have a transport index of not less than 0.1 and not more than 10. However, the external radiation levels may require a higher transport index number but not to exceed 10. Such shipments require no nuclear criticality safety control by the shipper during transportation."

The following are specific standards for a Fissile Class II package.

- "1. A Fissile Class II package shall be so designed and constructed and its contents so limited, and the number of such packages

which may be transported together so limited, that:

- a. Five times that number of such undamaged packages would be subcritical in any arrangement if closely reflected by water; and
- b. Twice that number of such packages would be subcritical in any arrangement if each package were subjected to the hypothetical accident conditions specified in annex 2, below, as the Free Drop, Thermal, and Water Immersion conditions, in the sequence listed in annex 2, with close reflection by water on all sides of the array and with optimum interspersed hydrogenous moderation unless there is a greater amount of interspersed moderation in the packaging, in which case that greater amount may be considered. The condition of the package shall be assumed to be as described in G., above.

2. The transport index for each Fissile Class II package is calculated by dividing the number 50 by the number of such Fissile Class II packages which may be transported together as determined under the limitations of 1., above. The calculated number shall be rounded up to the first decimal place."

The allowable number of containers per shipment, N_A , determined for administrative control, is a quantity based upon array calculations. Our procedure will be to use tables prepared by Subcommittee 8 on Fissionable Materials Outside Reactors of the Standards Committee of the American Nuclear Society.³ The tables presented in this draft describe water-reflected arrays having computed multiplication factors (k) of 0.93. This

is deemed to be adequately subcritical for storage arrays. For transportation arrays, however, the number allowable in a shipment N_A , according to condition (1.a) above will be taken as:

$$N_A = \frac{N(k = 0.93)}{5}$$

We have already seen in calculations for infinite arrays that the presence of boron in the packaging makes water-moderated arrays of the LLL container less reactive than unmoderated arrays. It is further noted in the ANS draft standard that, if the minimum container wall thickness is 3/16 in. of steel, consideration of optimum moderation is not necessary. A simple comparison of the wall thickness of the LLL container in thermal neutron mean free paths shows the LLL container walls to be six times as thick (0.85 mfp vs 0.14 mfp for 3/16-in. steel).

Drop and water immersion tests⁴ of the container proved that the container remained intact with little loss of volume. However, a hole in the outer container permitted a small amount of water to enter the outer container while the inner container (pressure cooker) remained watertight. Since the internal foam of the container contains boron, this water would slow down the neutrons, permitting them to be captured by the boron. As shown above, this will reduce the array reactivity. Therefore, the presence of the boron and the results of the tests, insure that condition (1.b) above is satisfied by use of the above equation for

3. Proposed American National Standard, Guide for Criticality Safety in the Storage of Fissile Materials, ANS 8.7 Draft (1971).

4. J. R. Gaskill and R. D. Taylor, An Improved Shipping Container for Fissile Material, Lawrence Livermore Laboratory, Rept. UCRL-14903 (1966).

N_A , where $N(k = 0.93)$ is taken from the tables for unmoderated arrays.

As noted above, the container was not distorted during the drop test. Nevertheless, another safety factor was applied by the use of data for 24-in. arrays, whereas the LLL container arrays would be spaced at a minimum center-to-center separation of 28-1/2 in.

An additional condition must be met that is not considered in the tabulated arrays. The loading of an individual container must be limited so that a single container is safely subcritical. For metal systems where the chances of double batching are small, the limit will be set a little below the single-parameter limit of ANSI N16.1-1969.⁵ These are 20.1 kg ^{235}U and 4.9 kg ^{239}Pu . We shall be somewhat more conservative and reduce these values to 18.5 and 4.5 kg, respectively, in accordance with present LLL policy. The following statement is made for metallic units:

"The enrichment limit for uranium and the mass limits given in Table 2 apply to a single piece having no concave surfaces. They may be extended to an assembly of small units provided there is no inter-unit moderation.

The ^{235}U and ^{233}U limits apply to mixtures of either isotope with ^{234}U , ^{236}U , or ^{238}U , provided all isotopes except ^{238}U are considered to be ^{235}U or ^{233}U , respectively, in computing mass. The ^{239}Pu limits apply to isotopic mixtures of plutonium, provided the concentration of ^{240}Pu exceeds that of ^{241}Pu , all plutonium isotopes are considered to be ^{239}Pu in computing mass, and no more than 1% ^{238}Pu is present."

5. American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, ANSI N16.1-1969 (1969).

The metal limits allow for external reflection by an unlimited thickness of water. Therefore, these will apply, regardless of the amount of moderator in the container, provided that there is no mixing of the metal and moderator; i.e., the metal is a single piece having no concave surfaces permitting entry of moderator.

For compounds or mixtures of metal and moderator, it is felt advisable to follow the limits set in the Nuclear Safety Guide.⁶ These include a safety factor which allows for double batching. Results are summarized in Table A-VII.

Table A-VII. Single-package, water-reflected load limits for LLL container No. 5848.

H/X	Container limit (kg)	
	U(93.5)	^{239}Pu
0.4	18.5 ^a	4.5 ^a
3	9.0 ^b	2.9 ^b
6	7.2 ^b	3.8 ^b
10	5.3 ^b	3.3 ^b

^aNo double-batch allowance included.

^bFrom Ref. 5. A safety factor of 2.3 is included.

In order to permit reflection by materials that are better reflectors than water, experimental and calculated data from TID-7028⁷ and RFP-898-A⁸ were used. Critical mass data from these references

6. Nuclear Safety Guide, TID 7016, Rev. 1 (1961).

7. H. C. Paxton, et al., Critical Dimensions of Systems Containing ^{239}U , ^{239}Pu , and ^{233}U , TID-7028 (1964).

8. C. L. Shuske, Research and Development Quarterly Progress Report, November, December, 1966, and January, 1967, Nuclear Safety, The Dow Chemical Company, Rocky Flats Division RFP-898-A (1967).

Table A-VIII. Critical mass data for reflected metal spheres.

Core	Reflector ^{a,b}	Critical mass (M_c) (kg)	M_c
			M_c (H_2O reflected)
^{239}Pu	H_2O	4.95	1.0
	Be	2.3	0.46
	BeO	2.6	0.52
	C	3.9	0.79
	CH_2	4.0	0.81
	^{238}U	4.0	0.81
^{235}U	H_2O	22.8	1.0
	Be	7.5	0.33
	BeO	8.0	0.35
	C	16.7	0.73
	CH_2	21.8	0.95
	^{238}U	16.1	0.70

^aAs much as 10 in. thick. For water this is effectively infinite. This is not necessarily the case for other reflectors.

^bIron, aluminum, oil ($C_{22}H_{46}$), carbon tetrachloride (CCl_4), and trichloroethylene (C_2HCl_3) are all less effective than water; therefore, water-reflected critical mass data may be conservatively applied to systems with these reflectors.

for reflected metal spheres are presented in Table A-VIII. * Load limits were determined for reflectors other than water by multiplying the data of Table A-VII by the ratio of the critical mass with a given reflector to that with a water reflector, as given in Table A-VIII. This procedure should adequately cover the range of the H/X under consideration, especially when a safety factor of 2.3 has been incorporated. Final results are presented in Table A-IX.

Reference 7 states that diluents other than hydrogen will be less effective as moderators and, in most cases, will increase critical masses. Therefore, it

*These pertain to reflectors up to 10 in. thick. However, there is not sufficient space in the container to permit the average reflector thickness to be this great (see Fig. A-2).

is possible to apply conservatively the container limits established for hydrogen moderation to other diluents. Thus, in our final package limits, summarized in Tables A-I to A-III, we refer to M/X rather than H/X ratios, where M is any nonfissile diluent.

The proper procedure in calculation of M/X requires some explanation, as follows: Any system containing fissile material can be considered as consisting of two regions: (1) A core region consisting of fissile material along with nonfissile materials which may be neutron moderators, diluents or neutron absorbers, and (2) an external reflector material. Such an arrangement is sketched in Fig. A-3.

In some arrays the reflector may also be a material which will moderate neutrons which later enter another core region.

Table A-IX. Single-package load limits for LLL container No. 5848 with various reflectors.

Fissile material	Maximum container loading (kg) ^a						
	Reflector material						
	H/X	H ₂ O ^b	Be	BeO	C	CH ₂	²³⁸ U
²³⁹ Pu	0 - 0.4	4.5	2.3	1.9	3.5	3.6	3.6
	0.4 - 3.0	2.9	1.5	1.2	2.2	2.3	2.3
	3.0 - 6.0	3.8	1.9	1.6	3.0	3.0	3.0
	6.0 - 10.0	3.3	1.7	1.4	2.6	2.7	2.7
U(93.5)	0 - 0.4	18.5	6.1	6.5	13.5	17.5	13.1
	0.4 - 3.0	9.0	3.0	3.1	6.6	8.5	6.3
	3.0 - 6.0	7.2	2.3	2.5	5.3	6.8	5.0
	6.0 - 10.0	5.3	1.7	1.8	3.9	5.0	3.7

^aNo double-batch allowance is made for the H/X < 0.4 system. The remainder of the data include a safety factor of 2.3.

^bWater data may be conservatively applied to iron, aluminum, oil, carbon tetrachloride, and trichloroethylene reflectors.

Fig. A-3. Core and external reflector of a fissile-material system.

another unit of the array. In the present case, however, neutrons that are moderated in the reflector region will be captured by the boron in the container packaging before reaching other units. This

was shown earlier in this report where calculations showed a decrease in k as a result of the addition of moderator between packages. For these reasons, when analyzing the effect of additional reflector materials within a package, we need only insure that the package will remain safely subcritical in the presence of the reflector.

The following procedure is therefore adopted in determining M/X : (1) Determine the number of nonfissile atoms, M , contained within the core region (i.e., within the volume contained by the outer surface of the fissile part) and (2) divide M by X , the number of fissile atoms within the same volume. If the part is irregular in shape, has concave surfaces, or is an assemblage of smaller parts, the volume employed in the calculation should be that of an envelope which would contain the fissile part or parts.

Our final determination of Class II transport indices can be summarized as follows:

- The number of allowable containers per shipment N_A is

$$N_A = \frac{N(k = 0.93)}{5}$$

- Therefore the transport index is:

$$\frac{50}{N_A} = \frac{250}{N(k = 0.93)}$$

- Plots of the transport index vs container loading are presented in Figs. A-4 and A-5. Since it is not convenient to use a continuous curve, we approximate it by a series of convenient steps. These are shown by the dashed lines in Figs. A-4 and A-5 and are tabulated in Tables A-II and A-III. Note that this adds an additional degree of conservatism to the final limits.

Class III

The following is the definition of a Fissile Class III shipment:

"Fissile Class III: Shipments of packages which do not meet the requirements of Fissile Classes I or II and which are controlled in transportation by special arrangements between the shipper and the carrier to provide nuclear criticality safety."

The following are specific standards for a Fissile Class III shipment.

"A package for Fissile Class III shipment shall be so designed and constructed and its contents so limited, and the number of packages in a Fissile Class III shipment shall be so limited that:

1. The undamaged shipment would be subcritical with an identical shipment in contact with it and with the two shipments closely reflected on all sides by water; and

2. The shipment would be subcritical if each package were subjected to the hypothetical accident conditions specified in annex 2, below, as the Free Drop, Thermal, and Water Immersion conditions, in the sequence listed in annex 2, with close reflection by water on all sides of the array and with the packages in the most reactive arrangement and with the most reactive degree of interspersed hydrogenous moderation which would be credible, considering the controls to be exercised over the shipment. The condition of the package shall be assumed to be as described in G., above. Hypothetical accident conditions different from those specified in this subparagraph may be approved by the manager or other designated official if the controls proposed to be exercised by the shipper are demonstrated to be adequate to assure the safety of the shipment."

Since the regulations do not specify a safety factor, it was decided to permit twice the number permitted for Fissile Class II shipments. This is considered very conservative since Woodcock and Paxton⁹ suggest that up to ten times the number of packages in a load are considered safe in the case of controlled shipments which are in nonhydrogenous packages with spacers to ensure isolation during flooding. These results are summarized in Table A-IV.

CHECK CALCULATIONS

There are a number of factors that have made the preceding determinations of Class II and III container limits conservative. As a final check, and to demonstrate this conservatism, MORSE calculations were run to check the data

9. E. R. Woodcock and H. C. Paxton, "The Criticality Aspects of Transportation of Fissile Material," Journal of Nuclear Energy, B3, 213 (1962).

Fig. A-4. Transport index as a function of unit mass of ^{239}Pu with $\text{H}/\text{Pu} < 10$.

Fig. A-5. Transport index as a function of unit mass of $\text{U}(93.5\%)$ with $\text{H}/\text{U} < 10$.

of Table A-III, which allow a Class II shipment of 10 kg U(93.5) with a transport index of 0.1. This would mean that 2500 units must be subcritical with external water reflection. A MORSE calculation for a water-reflected $14 \times 14 \times 13$ array (2548 units) with 10 kg U(93.5) distributed uniformly inside each container resulted in the following:

1. $H/U = 0$; $k = 0.45 \pm 0.015$
2. $H/U = 10$; $k = 0.77 \pm 0.02$

Both cases are safely subcritical.

The increase in k from (1) to (2) is not due to an increase in array interaction, but only due to an increase in the reactivity of the single package due to moderation within the container.

A second check of Table A-III is for the 26-kg loading with a transport index of 4.0. This means that a 62.5-unit array must be safely subcritical. A MORSE calculation for a water-reflected $4 \times 4 \times 4$ array (64 units) resulted in the following:

1. $H/U = 0$; $k = 0.29 \pm 0.009$
2. $H/U = 10$; $k = 0.63 \pm 0.014$

Again, the increase from (1) to (2) is only due to the increase in single package reactivity to moderation within the container.

The above results show that a substantial degree of conservatism exists in the Class II and III container limits.

Appendix B: Equilibrium Temperatures Attained by Slugs of Plutonium or Enriched Uranium Shipped in LLL Container.

J. R. Gaskill and R. D. Taylor

INTRODUCTION

As shown in the main body of the report, the shipping container passes the normal and hypothetical accident tests. In Appendix A, it has been shown that the maximum quantities allowed for Fissile Class III shipments are as follows:

Enriched (93.5%) uranium metal or oxide	- 18.5 kg/container
Plutonium metal or oxide	- 4.5 kg/container

The question therefore arises as to the internal equilibrium temperature which will be attained by storage of each of above-noted quantities of material in an LLL shipping container.

The heat generated, H , by the radioactive decay of these materials has been calculated by K. R. Kase* as follows:

(a) For alloy

Specific activity	$= 7.0 \times 10^{-5} \text{ Ci/g}$
Mass	$= 18.5 \times 10^3 \times 0.935$ $= 17.3 \times 10^3 \text{ g}$
α -Particle energy	$= 4.3 \text{ MeV}$

$$\begin{aligned}
 H &= [(1.73 \times 10^4 \text{ g}) (7.0 \times 10^{-5} \text{ Ci/g}) \\
 &\quad \times (3.7 \times 10^{10} \text{ d/sec-Ci}) (4.3 \text{ MeV/d}) \\
 &\quad \times (1.6 \times 10^{-6} \text{ erg/MeV})] \\
 &\quad (10^7 \text{ erg/W-sec}) \\
 &= 3.1 \times 10^{-2} \text{ watt.}
 \end{aligned}$$

(b) For Pu^{239}

Specific activity	$= 6.1 \times 10^{-2} \text{ Ci/g}$
Mass	$= 4.5 \times 10^3 \text{ g}$
α -Particle decay energy	$= 5.1 \text{ MeV}$

$$\begin{aligned}
 H &= [(4.5 \times 10^3 \text{ g}) (6.1 \times 10^{-2} \text{ Ci/g}) \\
 &\quad \times (3.7 \times 10^{10} \text{ d/sec-Ci}) (5.1 \text{ MeV/d}) \\
 &\quad \times (1.6 \times 10^{-6} \text{ erg/MeV})] / (10^7 \text{ erg/W-sec}) \\
 &= 8.3 \text{ watts.}
 \end{aligned}$$

It should be noted that because of isotopic impurities of ^{240}Pu and ^{241}Pu , nominally pure ^{239}Pu could generate up to 25 watts of heat.

The heat generated by enriched uranium is negligible in comparison with that given off by plutonium. Hence, experiments based on 8 and 25 watts of heat were set up.

WORK DONE

For this purpose a steel cylinder, 4.4 in. long by 2.2 in. in diameter was fabricated. A hole $3/8$ in. diam by 2.0 in.

* Former Radiation Safety Section Head, Lawrence Livermore Laboratory.

long was drilled axially in one end to contain an electric heater cartridge. Another hole 1/8 in. diam X 1 in. long

was drilled in the same end, parallel to the first, to contain a thermocouple. (See Fig. B-1.)

Fig. B-1. Cross-sectional schematic view of simulated plutonium equilibrium heat test.

The finished slug (drilled cylinder) had a net volume of 230 cc; this is the volume of 4.5 kg of plutonium metal.

This simulated plutonium slug was wrapped in plastic or aluminum foil (see below) and placed in a covered 3-gal lard can. This in turn was placed in the pressure cooker, which was sealed and then put into the LLL shipping container. Thermocouples were attached to various locations in this assembly and were led out through holes in the lard can and pressure cooker and thence through the annulus in the Foamglas insulating plug to a multipoint temperature recorder. The power wires for the electric heater were led out of the package in similar fashion and were then connected to a dc power supply, which was controlled operationally to yield 8 watts of heat (25 watts in Test No. 4). A schematic diagram of the test setup and a description of the thermocouple stations are shown in Fig. B-1.

Four heat tests were run. Three of these were done, using 8 watts of heat to simulate the radioactive decay of 4.5 kg

of ^{239}Pu . The fourth test employed 25 watts of heat to simulate nominally pure plutonium. The internal packaging of the slug was varied. (See Table B-I.) Before each test was started, temperature-indicating (Temp-Plate) decals of various ranges were adhered to the slug, the side of the lard can, the lid of the lard can, and the annulus of the Foamglas insulating plug. These were used as a check against the thermocouples.

Each test was started by allowing all components to reach room temperature, assembling the setup, and turning on the heater and thermocouple recorder. The test was continued until the slug had reached an essentially stable temperature.

RESULTS

The results of the tests are detailed on Tables B-II and B-III. The relevant temperature-time curves are shown in Fig. B-2. The equilibrium temperature and times for the slug are summarized in Table B-IV.

Table B-I. Conditions for heat tests.

Test No.	Heat (watts)	Heater wrapping	Heat sink	Heat conductor between lard can and pressure cooker
1	8	Large vinyl plastic bag	None	None
2	8	Aluminum foil	None	Aluminum foil crumpled into annulus
3	8	Large vinyl plastic bag	Three plastic bags of Al shot, 2 kg each	Same as for Test 2
4	25	Aluminum foil	6 kg of bare Al shot poured around slug	Same as for Test 2

Table B-II. Simulated self-heating tests of plutonium slug in LLL fissile material shipping container. Steel cylinder, 2.2-in. diam $\times$ 4.4-in long, with 0.375-in. diam $\times$ 2.0-in. hole containing electric heater was placed in a lard can and the LLL-FM shipping container.

Test No. and description	Heating time (hr)	Temperatures of various locations (°F)					
		1	2	3	4	5	6
		Slug	Can lid	Bottom of pressure cooker	Top of pressure cooker	Side of cavity	Drum insulation
1. Slug wrapped in plastic; 8 watts of heat	0	75	75	75	75	75	75
	8	227	105	95	93	93	77
	16	238	117	106	103	103	79
	24	239	122	110	108	108	80
	32 ^a (Equiv °C)	240 116	123 51	112 45	110 43	110 43	81 27
2. Slug wrapped in Al foil; Al foil "packing" between can and pressure cooker; 8 watts of heat	0	75	75	75	75	75	75
	8	189	102	94	91	90	77
	16	206	115	106	103	103	80
	24	211	121	112	109	108	81
	32	211	122	113	110	110	81
	48 ^a (Equiv °C)	214 101	123 51	115 46	114 46	112 45	81 27
3. Slug wrapped in plastic; 3 plastic bags each containing 2 kg of Al shot folded around slug; Al foil pack- ing as in No. 2; 8 watts of heat	0	75	75	—	75	75	75
	8	165	93	—	85	85	76
	16	179	105	—	96	96	77
	24	187	112	—	102	102	79
	48	196	119	—	108	108	81
	68 ^a (Equiv °C)	198 92	120 49	— —	108 42	108 42	81 27
4. Slug wrapped in Al foil; 6 kg of bare Al shot poured around slug; Al packing as in No. 2; 25 watts of heat	0	75	75	75	75	75	75
	8	325 ^b	140	123	111	112	79
	24	380	185	166	151	157	88
	32 ^a	380	192	174	157	165	90
	(Equiv °C)	193	89	76	70	74	32

^aEquilibrium.

^bAt 3 hr, the temperature of this slug was 275°F (135°C); at 4.5 hr, it was 300°F (149°C).

Table B-III. Final temperatures as indicated by heat-sensitive decals.

Test No.	Slug	Temperature (°C)		
		Can side near top	Side of top insulating plug	Can lid
1	< 115	48-54	37-40	—
2	98-115	54-76	< 43	48-54
3	76-98	54-76	< 43	48-54
4	> 176	76-98	< 54	76-98

Fig. B-2. Temperature of simulated plutonium slugs in LLL fissile metal shipping container with variation in internal wrappings.

Table B-IV. Equilibrium temperatures and times for heat test.

Test No.	Wrapping	Annular heat conductor	Aluminum heat sink	Equilibrium		
				Temp (°F)	Temp (°C)	Time (hr)
1	Plastic	No	No	240	116	24+
2	Aluminum	Yes	No	214	101	48
3	Plastic	Yes	Yes	198	92	48+
4 ^a	Aluminum	Yes	Yes	380	193	24

^a25-watt heating.

DISCUSSION

According to Wilkinson and Murphy,^{*} the phase-change temperatures for plutonium metal are variously given by different authors. From the data, the following extreme values are tabulated:

Lower temp of stability (°C)	Phase	Upper temp of stability (°C)
< 117	α	122
117	β	206
200	γ	319
310	δ	475
450	δ'	476
472	ϵ	640

From these data and the heat test results, it appears that in the worst heat-conducting package (plastic wrap, no heat sink, and no annular heat conductor) a maximum loading (4.5 kg) of α -plutonium-239 will just barely not reach the β transformation temperature. Therefore, to be on the safe side, an internal heat sink and/or a heat conductor should be used.

A crumpled foil plus a metal shot heat sink will provide the necessary heat conduction to the container to keep the

plutonium temperature safely below the transformation point.

In regard to a material shipment with a permissible mass yielding a decay activity equal to 25 watts, the heat sink and heat conductor system are probably necessary if the isotope is to be kept below $\sim 400^\circ\text{F}$ (205°C); even so, this is too hot to handle, and is certainly above the first phase-change temperature.

CONCLUSIONS

1. With an appropriate internal heat sink and heat-conducting packaging, a mass of plutonium metal with a heat generation of up to 8 watts will not exceed the α -to- β transformation temperature if stored indefinitely in the LLL Fissile Material Shipping Container.
2. The internal self-heating of the maximum permissible amount of enriched uranium (93.5%) is negligible by comparison.
3. A permissible shipment of a material with a heat generation rate of 25 watts can be expected to reach an equilibrium temperature approaching 400°F ($\sim 200^\circ\text{C}$) even with an internal heat sink and an internal foil conductor.

^{*}W. D. Wilkinson and W. F. Murphy, Nuclear Reactor Metallurgy, (D. Van Nostrand, Princeton, N. J., 1958), p. 196.

NOTICE

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