June 9, 1992
July 10, 1992 (Rev. 1)

APPLICATION FOR REVALIDATION OF CERTIFICATES OF COMPLIANCE AND COMPETENT AUTHORITY CERTIFICATIONS (USA/9034/AF AND USA/9037/AF) FOR TRIGA 1 AND TRIGA 2 SHIPPING PACKAGES

1. INTRODUCTION

This document describes the TRIGA fuel element shipping container packages (TRIGA-1 and TRIGA-2) as they relate to the safe transportation of the various TRIGA reactor fuels. The shipping containers have been used for the past 17 years for the several types of fuel elements normally used in fueling TRIGA reactors which General Atomics (GA) builds and markets throughout the world.

The shipping containers will be constructed using specifications applicable to the DOT 6L container. The specific characteristics of the TRIGA fuels are such that DOT 6L hydrogen/uranium ratio phraseology preempts its use unless a specific criticality analysis is performed. A criticality analysis shows the safety of shipping TRIGA fuels which, because of their various uranium loadings, have H/U^{235} ratios ranging from approximately 30 to 250. The shipping containers described therefore will be considered to meet the conditions required for safe packaging and transport of the TRIGA fuels.

The fuels in these containers will be shipped as fissile Class I. Shipments of these packages can be via air, highway, rail or water.

This document is intended to provide the information necessary to demonstrate compliance of the shipping containers with the applicable requirements of the 1973 Edition of IAEA Safety Series 6 for Type A fissile radioactive packaging and follows the general outline of the IAEA document.

2.0 PACKAGE

2.1 Description

The TRIGA fuel element shipping containers consist of an outer metal drum, an inner steel tube, supporting spacers, an inner tube cap, a drum lid and a bolted locking ring with provision for a tamper-proof seal. The package is constructed to DOT 6L specifications.

The TRIGA-1 container has outer dimensions of approximately 22.5 inches (572 mm) in diameter by 36 inches (914 mm) high. The inner vessel is a 5-inch (127 mm) pipe approximately 31 inches (787 mm) in height. The loaded weight is about 235 lbs (107 kg).

The TRIGA-2 container has outer dimensions of approximately 22.5 inches (572 mm) in diameter and 55 inches (1397 mm) in height. The inner 5-inch (127 mm) pipe is approximately 50 inches (1270 mm) high. The loaded weight is about 330 lbs (150 kg).

The outer packaging is fabricated to DOT Specification 6J requirements. The outer metal drum is made of 18 gauge carbon steel side body and bottom. The side body incorporates two formed rolling hoops. The drum top is made of 16 gauge steel with a rolled edge to permit closure. The closure device for the outer package is a 12 gauge rolled steel ring with drop forged lugs. One of the lugs will accommodate a 5/8 inch threaded bolt. The closure shall have provision for a tamper-proof seal.

The inner container will meet the minimum standards of DOT Specification 2R. It consists of a schedule 40 carbon steel pipe (1/4" wall x 5" i.d.) whose bottom (1/4" thick) is welded closed. The top closure is a threaded carbon steel pipe cap containing U.S.-Standard pipe threads with an engagement of at least 5 threads, luted with a non-hardening compound capable of withstanding 250°F.

The inner container support mechanism consists of a series of braces and rods made of carbon steel. These braces and rods are welded to the inner container. The spacing, sizing, and weldments of the spacers will be accomplished in accordance with 49 CFR 178.103-3(c)(i). In addition, eight spacers are provided near the top of the package.

The space between the inner container and outer barrel is filled with tamped vermiculite (expanded mica) with a minimum density of 0.072 gm/cc (4.5 lbs/cu.ft.).

The details of package dimension, inner cavity materials, etc., are shown on the respective package drawings. No special coolants, shields, neutron absorbers, etc., are employed. The package weight and size eliminates the need for tie downs or lifting devices. The details of the TRIGA-1 package are shown on attached drawing TOS396C160. Details of the TRIGA-2 package are shown on attached drawing TOS396C161.

Packaging of the fuel elements within the inner container is accomplished as follows:

1) The appropriate number of fuel elements with their individual protective packaging are placed in the inner container.

2) The inner container cavity is filled with empty cardboard tubes to retain spacing where less than full load is desired.

3) A sheet of styrofoam or the like will be placed under the closed lid to assure tight packaging with no movement in normal transport. Details of a typical individual protective package are shown in the attached Figures 1 and 2.

2.2 Operational Features Meeting General Design Requirements

The TRIGA-1 and TRIGA-2 shipping container packages are designed to be easily handled and properly secured during transport. The TRIGA-1 with contents weighs about 235 lbs (107 kg) and the TRIGA-2 about 330 lbs (150 kg). These weights are significantly less than the allowable limit of 480 lbs (218 kg) for 6L containers over 55 gallons but less than 110 gallons. They have the shape of an oil drum and are handled in much the same way.

Handling is normally done with barrel dollies, and lifting with lift gates. Several containers can be secured to a pallet for handling by a forklift. There are no lifting attachments on the shipping container packages.

The outer layer of packaging is designed to avoid the collection and retention of water and is designed for relatively easy decontamination.

2.3 Operational Features Meeting Requirements for Type A Packages

2.3.1 The smallest overall external dimension of the packaging is 572 mm, much greater than the 100 mm minimum requirement.

2.3.2 The lid portion of the shipping container package is held in place with a closure ring containing drop-forged lugs for a 5/8th inch steel bolt and lock nut to hold the closure ring tightly closed. A seal, which is not readily breakable (such as a cup seal or a keyless padlock), is placed through a hole near the end of the steel bolt to provide evidence that the package has not been opened.

2.3.3 There are no protruding features on the external packaging aside from the minor protrusion of the bolt and lock nut on the closure ring.

2.3.4 The design of the shipping container package, constructed of welded steel and filled with tamped vermiculite, is such that it will be essentially unaffected by temperature changes in the range of -40°C to 70°C, including any problems with brittle fracture.

2.3.5 The design, fabrication and manufacturing techniques for welded joints contained in the shipping container package are in accordance with national standards (ASME).

2.3.6 The welded steel shipping container package is capable of withstanding the effects of any acceleration, vibration or vibration resonance which may arise during normal transport. The fact that the outer barrel is filled with tamped vermiculite drastically reduces any potential for vibration. The steel screw-cap on the steel inner 2R container has an engagement of at least 5 threads and is tightened to a firmly secure position. The closure ring is fastened securely with a steel bolt and steel lock nut which is tightened to a firmly secure position. The bolt and lock nut are inspected before each use and replaced if not in good working condition.

2.3.7 The shipping container package is designed with an inner containment system of schedule 40 steel pipe with a welded end and a screw cap on the other end. The steel screw cap has an engagement of at least 5 threads, is securely tightened to its closed position and cannot be unintentionally opened. There are no means for generating pressure within the package which would cause the containment to open.

2.3.8 The TRIGA fuel shipped in these shipping container packages is an indispersible solid material and is sealed in a stainless steel or Incoloy 800 clad, which is welded to stainless steel or inconel end fittings, all of which meets the structural definition of "special form radioactive material".

2.3.9 The containment system is a separate unit of the packaging in that it has its own separate, securely fastened, positive closure device, independent of any other part of the packaging (described in 2.3.7). This inner container (meeting DOT specification 2R) is welded to other parts of the packaging system.

2.3.10 The welded steel components of the shipping container package, along with the contained tamped vermiculite are all physically and chemically compatible with each other and with the contents (TRIGA fuel elements), including any foreseeable conditions under irradiation.

2.3.11 There are no liquids to undergo radiolytic decomposition, or other vulnerable materials and no gases to be generated by chemical reaction or radiolysis which must be taken into account in the design of the containment system.

2.3.12 The schedule 40 steel pipe (meeting DOT specification 2R) which is used as the containment system in the shipping container package will retain its contents under a reduction of ambient pressure to 0.25 kg/cm². The stress resulting from such a pressure change would be:

S = P r/t, where

P = pressure = 1.03 kg/cm² inside-0.25 kg/cm² outside

r = radius of containment (2.5 in. = 6.35 cm)

t = thickness of containment (0.25 in = 0.635 cm)

$$= 0.78 \text{ kg/cm}^2 \times \frac{6.35 \text{ cm}}{0.635 \text{ cm}}, \approx 7.8 \text{ kg/cm}^2 \text{ (111 lbs/in}^2\text{)}$$

which is very small compared to the yield (3500 kg/cm² [50,000 psi]) and tensile (6300 kg/cm² [90,000 psi]) strength of the steel.

2.3.13 There are no valves in or on the shipping container package.

2.3.14 There is no specific radiation shield included as part of the containment system or any other part of the shipping container package. The contents of the package are to be unirradiated fuels which have radiation levels less than 0.5 mR/hr at surface contact, before being placed in the shipping container package.

2.3.15 There are no specific tie-down attachments as part of the shipping container package.

2.3.16 This Type A packaging is so designed that, if it were subjected to the tests specified in the IAEA safety series 6, 1973 edition (Section VII), it would still prevent loss or dispersal of the radioactive contents and any measurable increase in the maximum radiation level at the external surface compared to that measured before the test. (See section 7.)

2.3.17 This package is not designed for liquids.

2.3.18 This package is not designed for compressed or uncompressed gases.

2.4 Package Contents

The authorized contents are TRIGA fuel elements of UZrH which may include various burnable poisons such as erbium. The UZrH fuel meat, with applicable burnable poison, is a uniform solid eutectic having a melting point on the order of 1800°C.[1] The UZrH fuel has a maximum H/Zr ratio of 1.65 (nominal value of 1.60) and, depending upon the uranium loading, H/U^{235} ratios ranging from about 30 - 250. Also contained in the larger diameter elements are graphite end pieces which serve as a lumped moderator/reflector in the reactor.

TRIGA reactors utilize special fuel elements such as fuel follower control rods, instrumented elements, etc. These special elements are typically longer than the standard element. A similar, but longer package, TRIGA-2, is required to ship these elements.

The authorized contents for each type packaging is as follows:

	TRIGA-1	TRIGA-2
Maximum U^{235}/package		
Enrichment $<20\%$	1.39 kg	1.39 kg
Enrichment $\geq 20\%$[2]	1.30 kg	1.30 kg

[1] for U-Zr. Before reaching a melting temperature, the hydrogen becomes unbound (~1200 - 1300°C) and is not a structural part of the material.

[2] to meet activity limits of Section 4. Not a requirement based on reactivity or criticality.

	TRIGA-1	TRIGA-2
Number of elements	7/ea 1.5 in or 25/ea 0.5 in.	7/ea 1.5 in. or 25/ea 0.5 in.
Element Length (max.)	30.3 in.	49.5 in.
U^{235} Enrichment %	93.5 max.	93.5 max.
Material form	Contained in UZrH mixture	Contained in UZrH mixture

3.0 ITEMS EXEMPT FROM SPECIFIED PRESCRIPTIONS

The contents of this package do not meet the requirements for exemption from specified prescriptions.

4.0 ACTIVITY LIMITS

There are activity limits for Type A packages which depend upon the contents being either (A1) special form radioactive material, or (A2) any other radioactive material (non-special form). While TRIGA fuel elements meet the structural definition for special form radioactive material, in that the fuel is an indispersible solid radioactive material and is also seal-welded in a capsule (stainless steel or incoloy 800 clad and stainless steel or inconel end fittings) that can only be opened by destroying the capsule, it has not been tested to document the results of impact, percussion, bending and heat tests that are required for formal classification as special form material.

From Table VII of the 1973 Edition of IAEA Safety Series 6, the activity limits for uranium, the only radioactive material in the TRIGA fuel, in other than special form material are:

Enrichment < 20% - unlimited

Enrichment ≥ 20% - 0.1 Ci

The criticality analysis described in Section 6 documents the maximum allowable contents of each shipping container package to be 1.39 kg of U^{235} in the form of U with a maximum enrichment of 93%. For 93% enriched U, Table VIII of the 1973 Edition of IAEA Safety Series 6 gives a specific activity of 70 μCi/gm. The 1.39 kg maximum allowed quantity of U^{235}, based on the criticality analysis, would have an activity of $1.39 \times 10^3/0.93$ gm x 70×10^{-6} Ci/gm = 0.1046 Ci, which is greater than that allowable for other than special form material. Thus, to meet the activity limits, the maximum allowed quantity of U^{235} will be as follows:

Enrichment < 20% - 1.39 kg
Enrichment ≥ 20% - 1.30 kg

5.0 CONTROLS FOR TRANSPORT AND STORAGE IN TRANSIT

5.1 Packing

The TRIGA shipping container package shall contain only TRIGA fuel elements and their packaging as described in this document.

5.2 Category

The TRIGA shipping container package, being a Fissile Class I package, is classed as:

Category I - WHITE

5.3 Labelling and Marking

Each TRIGA shipping container package will be labelled and marked in accordance with the requirements of the 1973 Edition of IAEA Safety Series 6 for Category I - WHITE packages.

6.0 FISSILE CLASS I PROVISIONS

TRIGA shipping container packages meet the definition of Fissile Class I in that they are packages which are nuclearly safe in any number and in any arrangement under all foreseeable circumstances of transport.

6.1 Structural Design Requirements

The TRIGA shipping container package is so designed that, if it were subjected to the tests referenced in Section 7:

a) water could leak into the package, as optimum water flooding was assumed in assessing criticality and the allowable number of containers per shipment;

b) the configuration of the contents and the geometry of the containment system would not be altered so as to increase reactivity significantly.

6.2 Nuclear Safety Criteria

A specific criticality analysis and evaluation was performed for groupings of a very large number of TRIGA shipping container packages - much greater than the maximum anticipated single shipment.

Conditions of heavy damage to the packages were evaluated in the analysis, where optimum water moderation and reflection were assumed, in conjunction with a crushing or compression of the packages to a 20% reduction in shipment volume. The most reactive configurations for the several conditions evaluated were all substantially sub-critical ($k < 0.65$). Some of the conservatisms used in the analysis included spherical geometry and use of cross sections with no disadvantage factors to account for thermal neutron flux depression in the fuel elements.

This analysis demonstrates that using a structurally accepted DOT specification 6L shipping container design (2R tube inside a 6J barrel) and the most reactive TRIGA fuel element likely to be manufactured (0.5 in. o.d., 22 in. high containing 45 wt-% U [20% enriched] in $ZrH_{1.65}$) allows any number of undamaged or more than 250 damaged containers to be grouped in a shipment and still be highly sub-critical, thus meeting Fissile Class I standards.

The maximum fuel loading in any one container would be the U^{235} contained in 25 TRIGA fuel elements of the most reactive type. This maximum fuel loading is 1.39 kg of U^{235} in a single container.

The approach for this Criticality Evaluation was to demonstrate that a very large number of shipping containers containing the most reactive TRIGA fuel[3] elements can be shipped together and remain highly subcritical even under conditions of heavy damage.

Results of the analysis give a calculated reactivity of 0.618 for 5000 shipping containers (containing the most reactive TRIGA fuel) in a close-packed spherical array with infinite (20 cm) water reflection. As an upper limit projection for an infinite number of barrels, an additional calculation was performed with a spherical (conservative) infinite cell model of the shipping barrel which gave a calculated reactivity of 0.949. This model assumed a packing fraction for the barrels of 1.0 vs an actual maximum value of 0.907. For the analysis on damaged containers, a calculated reactivity of 0.628 was obtained on an infinitely water reflected spherical array of 2000 containers, each with the fuel-containing central tube (the 2R tube) water flooded, the annulus between the central tube and the barrel containing only 50% water, and each container "cell" (container plus allowance for packing fraction) reduced to 80% of its normal size as a result of the crushing together of the barrels. The 20% "crush factor" was considered conservative in that it is more than twice the packing fraction residual (1-packing fraction =

[3]Uranium-zirconium-hydride or erbium-zirconium-hydride with U-235 content equal to or less than 1.39 kg per shipping container.

1-0.907 = 0.093). Thus, it allows for the barrels to be crushed together so that no empty space remains between barrels, plus an additional reduction of the space between the inner tube and outer barrel of about the same size (~10%). For the postulated case where the crushed barrels are lifted out of the water and the central tube remains flooded but the water drains out of the rest of the barrel, the analysis results give a reactivity of 0.827 for 200 barrels and 0.950 for 500 barrels, where the group of barrels is still infinitely water reflected.

Calculations show that any moderator material in the annulus between the central tube and the barrel rapidly decreases the reactivity of the configuration because neutrons are thermalized in a region where they are most likely to be captured by structural materials rather than fuel. Moderator material inside the central 2R container increases the reactivity of the configuration. Thus, for the calculations on the damaged containers, the very conservative assumption was made that all central tubes (containing fuel) were water-filled and the annulus between the central tube and the outer barrel of each container was only 50 vol-% water homogenized over the entire region. This region normally contains vermiculite, which is very porous, and will essentially instantaneously absorb more than 50 vol-% water in the region in which it is present.

The criticality analysis is documented in Appendix A.

7.0 TEST AND INSPECTION PROCEDURES

7.1 Demonstration of Compliance with Test Requirements

Demonstration of compliance with test requirements may be accomplished by reference to previous satisfactory demonstrations of a sufficiently similar nature.

The shipping containers described herein, which are fabricated to the specifications of DOT 6L, were previously issued Certificates of Competent Authority certifying that the design met the regulatory requirements for packaging for fissile radioactive materials as prescribed in IAEA Safety Series 6, 1967 Edition. As the test requirements for the 1973 Edition are essentially identical to those for the 1967 Edition, compliance with the 1973 Edition test requirements (Section VII) has already been established. At the time of applying for the original shipping container licenses and certificates of Competent Authority, the test data documentation for sufficiently similar containers was not required as part of the application as it was already in residence at the NRC (Docket No. HM-111, published 12-31-74) and was alluded to in the NRC Safety Evaluation by the Transportation Branch.

8.0 OPERATING PROCEDURES

8.1 Procedures for Loading the Package

1. Verify package model number, identify number and serial number.

2. Verify package integrity visually. Visually inspect for

   a) Broken welds
   b) Damaged inner container threads
   c) Damaged bolts and threads
   d) General physical condition
   e) Inner container cleanlienss and dryness

3. Load package with up to seven each 1-1/2 inch diameter fuel elements in their individual protective covers or 25 each 0.5 diameter fuel elements in their individual covers. Special clusters of the above may be also loaded, but not to exceed the equivalent of 7 or 25 elements respectively.

4. Fill any void spaces with empty cardboard protective covers.

5. Place appropriate styrofoam or equivalent spacer pad in the inner cavity on top of the elements.

6. Lubricate threads on screwed cap.

7. Screw cap onto inner containment pipe and tighten to effect seal.

8. Fill barrel with vermiculite tamped to required density.

9. Place outer drum lid in position.

10. Affix the closure ring to drum and lid.

11. Insert 5/8 inch bolt and tighten firmly while tapping slightly on the ring exterior. Affix the lock nut.

12. Wipe drum surface. Analyze to verify absence of surface contamination.

13. Affix appropriate labels showing contents and fissile class I.

14. Witness the placement of tamperproof wire and seal or keyless padlock.

8.2 Procedure for Unloading the Package

1. Wipe drum surface. Analyze to verify absence of surface contamination.

2. Verify package model number, identity number and serial number.

3. Verify contents on label with invoice or receiver papers.

4. Verify integrity of tampersafe seal.

5. Open drum closure ring, remove 5/8 inch bolt.

6. Remove vermiculite to below the cap on the inner containment pipe.

7. Remove screw cap from inner containment pipe.

8. Remove fuel element assemblies one at a time. Inspect and move to intermediate storage.

9. Remove all contents from inner pipe. Verify absence of contamination and foreign matter.

10. Replace screw cap.

11. Place outer drum lid in position.

12. Affix the closure ring to drum and lid.

13. Insert 5/8 inch bolt and tighten.

14. Wipe drum surface. Analyze to verify absence of surface contamination.

15. Remove, cover or otherwise obliterate the fissile class and transport index labels used during shipment.

8.3 Preparation of An Empty Package for Transport

1. Verify 1 through 15 in 8.2 above have been accomplished.

2. Repeat step 14 of 8.2 above.

3. Move package to shipping for delivery to carrier.

9.0 ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

The acceptance tests shall be performed to verify and document the proper use of materials, construction technique and quality of workmanship. The maintenance program is restricted to the cleaning, lubrication and repair of bolt threaded components.

9.1 Acceptance Tests

9.1.1 Visual Inspection

a) Visually inspect all welds for workmanship and good practice.

b) Visually and dimensionally inspect materials and components against those values specified on appropriate drawing.

c) Inspect for proper bolt and thread size on inner cavity lid and drum closure ring.

d) Inspect lid for smoothness and flatness.

9.1.2 Structural and Pressure Test

The structural tests and pressure tests are considered to be met by reference to DOT spec. evaluation.

9.1.3 Leak Tests

Perform leak test per 49 CFR 178.120-3 or verify its performance by manufacturer.

9.1.4 Component Tests

a) Verify fit of screw cap on inner container.

b) No other component tests are applicable.

9.2 Maintenance Program

a) Lubricate bolt and assure freedom of action. Replace worn bolt and clean threads with appropriate tap as required.

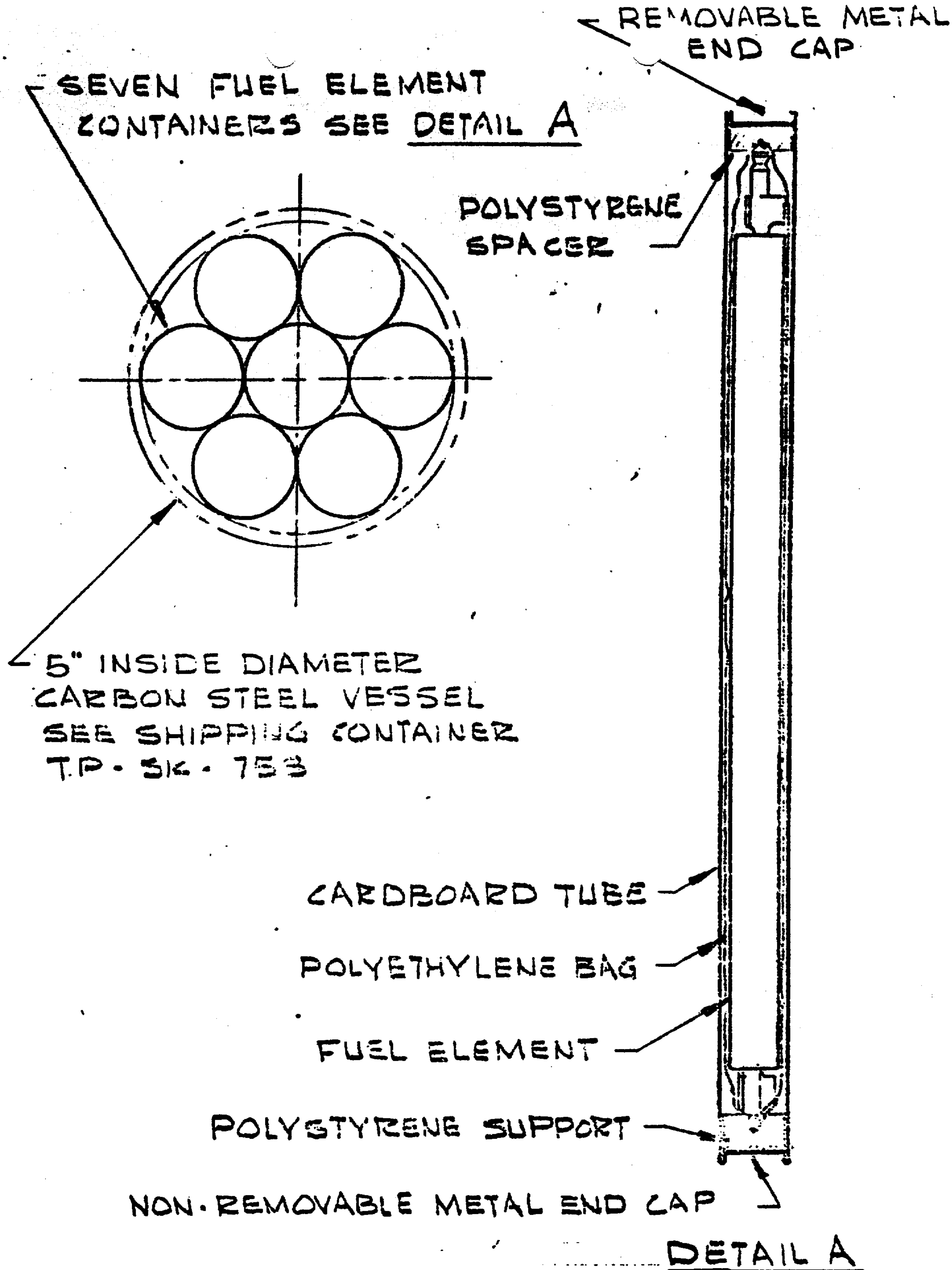

FIGURE 1

TYPICAL 1 1/2" ⌀ FUEL ELEMENT ARRANGEMENT

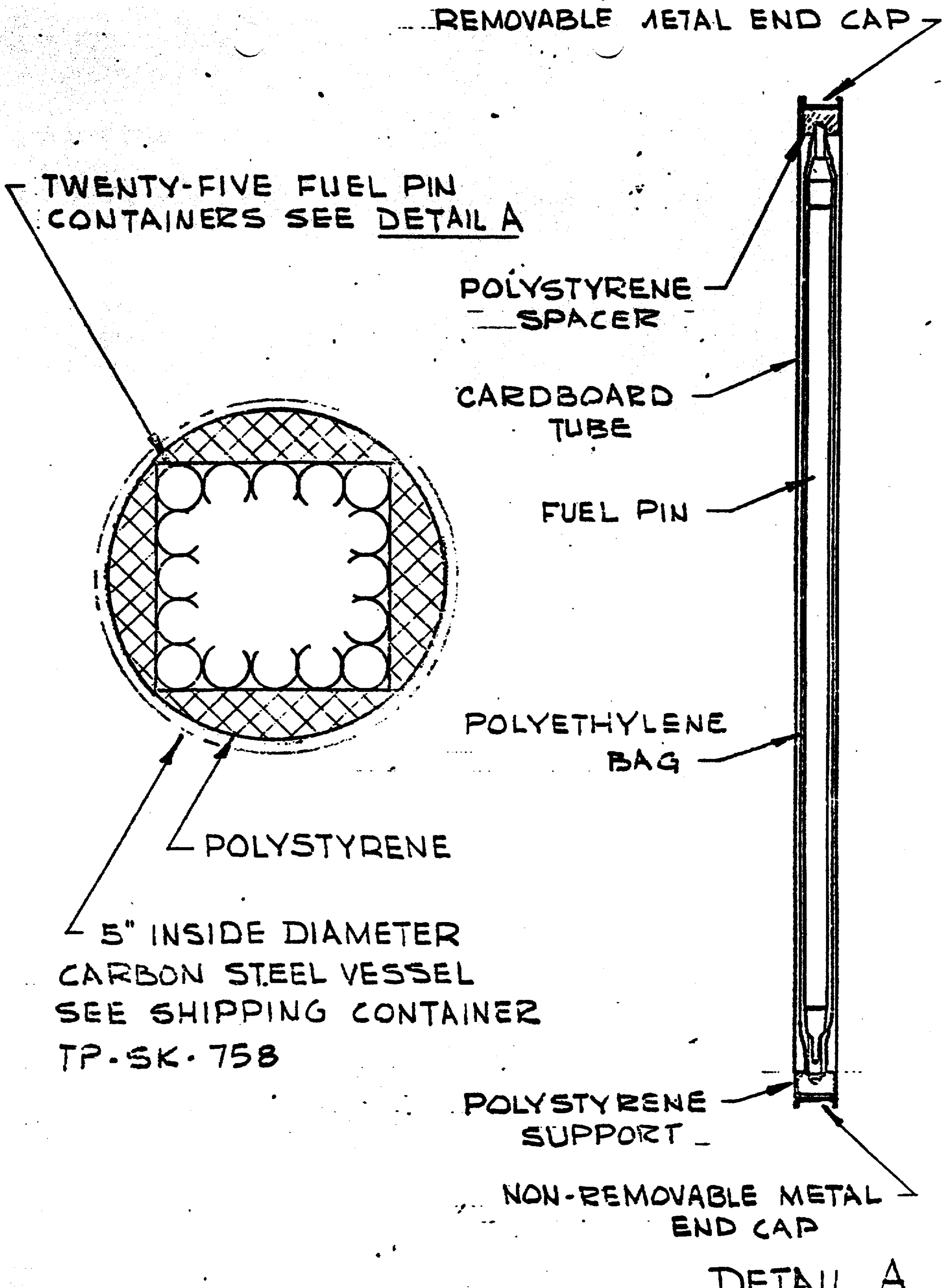

FIGURE 2

TYPICAL ½" ϕ FUEL ELEMENT ARRANGEMENT

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FIGURE WITHHELD UNDER 10 CFR 2.390

SPECIFICATION CONTROL DRAWING

QTY REQD	PART NO	DESCRIPTION	MAT'L/SPEC	ITEM NO

PARTS LIST

PART DASH NO	NEXT ASSY	USED ON
	APPLICATION	

GA PROPRIETARY INFORMATION

PROJECT

CUSTOMER

CONTRACT NO.

PLANT LOCATION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCES ARE

ALL MACHINED SURFACES √

CALC UP

DO NOT SCALE DRAWING

GENERAL ATOMICS

SAN DIEGO, CALIFORNIA

TITLE FUEL SHIPPING CONTAINER TRIGA I

SIZE	FSCM NO	DWG NO	REV
G	32334	TOS396C160	F

SCALE NONE

SHEET 1 OF 1

FIGURE WITHHELD UNDER 10 CFR 2.390

SPECIFICATION CONTROL DRAWING

PARTS LIST

GENERAL ATOMICS

SAN DIEGO, CALIFORNIA

TITLE: FUEL SHIPPING CONTAINER TRIGA II

SIZE	FSCM NO	DWG NO	REV
C	32334	TOS396C161	C

SCALE: NONE

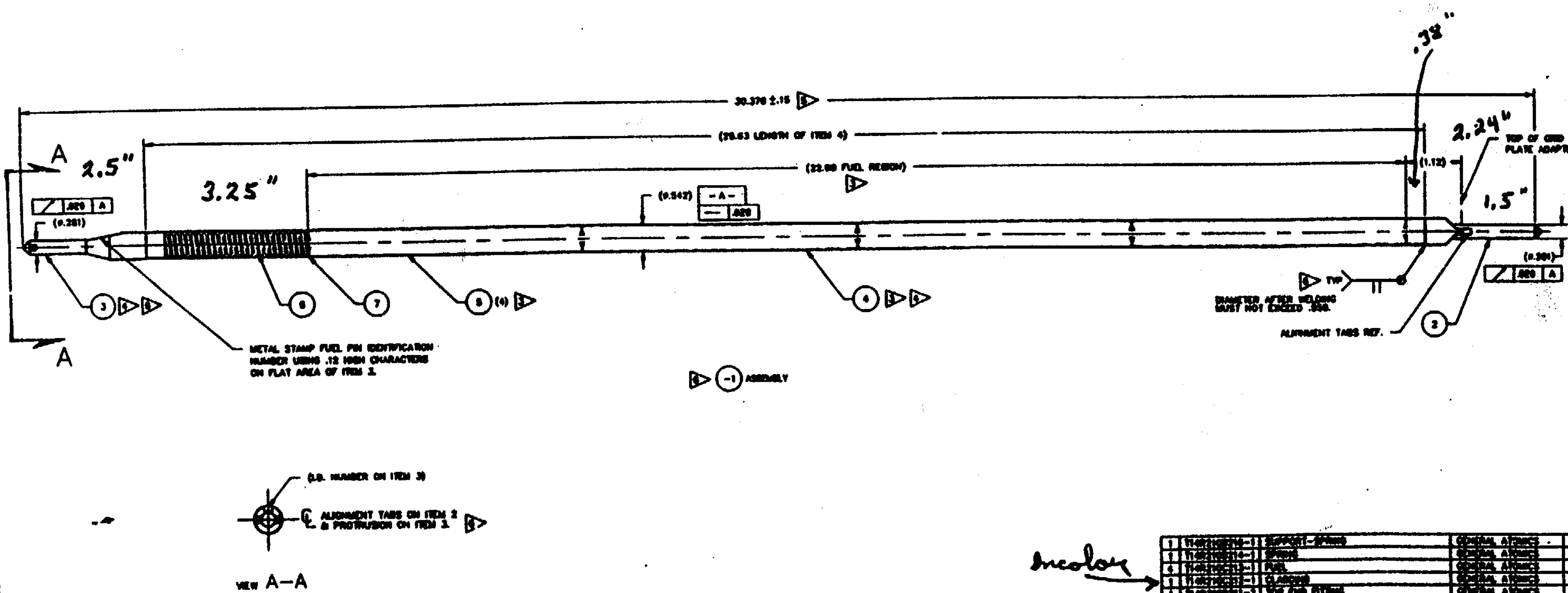
SHEET 1 OF 1

APPLICATION

NOTES:

1. FABRICATE IN ACCORDANCE WITH CURRENT TRIGA FUEL FABRICATION & OPERATING PROCEDURE.
2. INSPECTION OF 14MW TRIGA FUEL ELEMENT FABRICATION PER DOCUMENT QDI-32-4.
3. SELECTIVE ASSEMBLY OF ITEMS 4 & 5 IS REQUIRED TO MAINTAIN DIAMETRICAL CLEARANCE OF .00010 - .0025. STACK HEIGHT MUST BE 22.00 ±.06 INCHES.
4. BACK-FILL ITEM 4 WITH HELIUM BEFORE WELDING TO ITEM 3.
5. DIMENSION INDICATED MUST BE MEASURED & RECORDED AT TIME OF FABRICATION.
6. ALIGNMENT TABS ON ITEM 2 & PROTRUSIONS ON ITEM 3 MUST BE ON THE SAME CENTER LINE WITHIN 5° - SEE VIEW A-A.

Top fitting 53.5 gm Inconel
Bottom " 43.5 gm "
Spring 21 gm "



Incoloy →

1	[illegible]-1	SUPPORT-SPRING	GENERAL ATOMICS	7
1	[illegible]-1	SPRING	GENERAL ATOMICS	6
4	[illegible]-1	FUEL	GENERAL ATOMICS	5
1	[illegible]-1	CLADDING	GENERAL ATOMICS	4
1	[illegible]-2	TOP END FITTING	GENERAL ATOMICS	3
1	[illegible]-1	BOTTOM END FITTING	GENERAL ATOMICS	2
1	-1	ASSEMBLY	GENERAL ATOMICS	1
	PART NO	DESCRIPTION		

PARTS LIST

GENERAL ATOMICS

FUEL PIN ASSEMBLY

D 38334 T14R2100210

APPLICATION

June 9, 1992

TRIGA FUEL SHIPPING CONTAINER

APPENDIX A

CRITICALITY ANALYSIS

This analysis demonstrates that using a structurally accepted DOT specification 6L shipping container design (2R tube inside a 6J barrel) and the most reactive TRIGA fuel element likely to be manufactured [0.5 in. o.d., 22 in. high containing 45 wt-% U (20% enriched) in $ZrH_{1.6}$] allows any number of undamaged or more than 250 damaged containers to be grouped in a shipment and still be highly sub-critical, thus meeting Fissile Class I standards. This analysis used the same methodology as the previous analysis and the previous analysis primary reactivity values were reproduced as part of the validation of this current analysis.

A.1 Discussion and Results

TRIGA reactor fuel currently includes the compositions and dimensions as shown in Table A.1-1. Also shown in Table A.1.-1 are the composition and dimensions of the fuel element used for the Criticality Evaluation for Fissile Class I shipment of TRIGA fuel in the structurally accepted shipping container composed of a 2R pipe inside a 6J barrel. The shipping container upon which the Criticality Evaluation was based is shown in Fig. A.1-1. The 5.00 inch i.d. of the 2R pipe will accommodate 7 standard TRIGA fuel elements (1.475 inch o.d.) each inside a protective cardboard cylinder. A 3.5 inch square 14 MW TRIGA fuel cluster (25 fuel rods) will also fit inside the 5.00 inch i.d. 2R pipe. However, it is not intended to ship the fuel cluster as an assembled unit, but to ship the 25 fuel pins, with protective covers, in a single shipping container. Table A.1-2 shows the number of elements or pins and the resultant quantity of fuel (U-235) and burnable poison (Er-167) for each type of TRIGA fuel in a single shipping container.

Table A.1-1

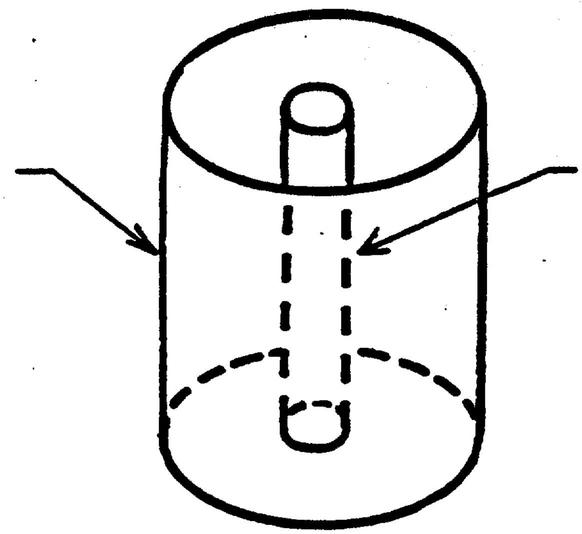
Currently Offered or Existing Compositions and Dimensions of TRIGA Fuel and Clad

Item	U		Nat Er Wt-%	H/Zr	Fuel		Clad		
	Wt-%	Enrich-%			o.d. Inches	Height Inches	Mate-rial	o.d. Inches	Δr Inches
1	8.5	20	0	1.6	1.435	15.0	SS	1.475	0.020
2	8.5	20	0	1.6	1.371	15.0	SS	1.411	0.020
3	8.5	70	1.58	1.6	1.435	15.0	SS	1.475	0.020
4	8.5	70	1.58	1.6	1.371	15.0	SS	1.411	0.020
5	8.5	93	0	1.6	1.435	15.0	SS	1.475	0.020
6	8.5	93	0	1.6	1.415	15.0	alum	1.475	0.030
7	12	20	0	1.6	1.435	15.0	SS	1.475	0.020
8	10	93	2.8	1.6	0.510	22.0	incoloy	0.542	0.016
9	20	20	0.5	1.6	1.435	15.0	SS	1.475	0.020
10	30	20	2.0	1.6	1.435	15.0	SS	1.475	0.020
11	30	20	0.0→1.0	1.6	0.510	22.0	incoloy	0.542	0.016
12*	45	20	0.5→2.0	1.6	0.510	22.0	incoloy	0.542	0.016

* TRIGA fuel element for maximum reactivity (0.0 wt-% Er used for these calculations)

FIGURE A.1-1

SHIPPING CONTAINER MODEL FOR CRITICALITY EVALUATION



	Dimensions (cm)		Vol. (L)	Vol. Fract.
Vol. inside steel tube =	$\pi\ 6.350^2 \times 76.2$	=	9.653	0.0412
Vol. of steel tube =	$\pi\ (6.985^2 - 6.350^2) \times 76.2 + 2\ \pi\ 6.985^2 \times 0.9525$		2.319	0.0099
Vol. of spacer between steel tube and outer barrel =	$\pi\ 28.41625^2 \times 91.1225 - (9653 + 2319)$	=	219.186	0.9344
Vol. of steel barrel =	$\pi\ (28.575^2 - 28.41625^2) \times 91.1225 + 2\pi\ 28.575^2 \times 0.15875$		3.404	0.0145
TOTAL VOLUME -	$\pi\ 28.575^2 \times 91.44$	=	234.562	1.0000

TABLE A.1-2

Number of TRIGA Fuel Elements and Resultant Quantities of Fuel (U-235) and Burnable Poison (Er-167) to be Shipped in a Single Shipping Container

Item	U Wt-%	U Enrich-%	Natural Erbium Wt-%	H/U^{235}	H/Zr	Per Shipping Container: No. of Elements	Grams U-235	Grams Er-167
1	8.5	20	0	215	1.6	7	274	0
2	8.5	20	0	215	1.6	7	250	0
3	8.5	70	1.58	60	1.6	7	959	58.1
4	8.5	70	1.58	60	1.6	7	875	53.2
5	8.5	93	0	46	1.6	7	1219	0
6	8.5	93	0	46	1.6	7	1185	0
7	12	20	0	146	1.6	7	402	0
8	10	93	2.8	37	1.6	25	1029	73.2
9	20	20	0.5	79	1.6	7	693	19.0
10	30	20	0.85	46	1.6	7	1137	37.5
11	30	20	0-1.0	46	1.6	25	775	0-30
12*	45	20	0.5→2.0	23	1.6	25	1376**	17.5-70.2

* TRIGA fuel element for maximum reactivity (0.0 wt-% Er used for these calculations)

** Based on nominal 19.7% enrichment. Calculations for this analysis used upper limit value of 19.9% enrichment which would result in 1.39 Kg U-235 per shippin g container

Clearly, the fuel element used for the Criticality Evaluation contains the greatest quantity of U-235, arbitrarily used no burnable poison and thus is the most reactive element.

The approach for this Criticality Evaluation has been to demonstrate that a very large number of shipping containers containing the most reactive TRIGA fuel[1] elements can be shipped together and remain highly subcritical even under conditions of heavy damage.

Results of the analysis give a calculated reactivity of 0.618 for 5000 shipping containers (containing the most reactive TRIGA fuel) in a close-packed spherical array with infinite (20 cm) water reflection. As an upper limit projection for an infinite number of barrels, an additional calculation was performed with a spherical (conservative) infinite cell model of the shipping barrel which gave a calculated reactivity of 0.949. This model assumed a packing fraction for the barrels of 1.0 vs an actual maximum value of 0.907. For the analysis on damaged containers, a calculated reactivity of 0.628 was obtained on an infinitely water reflected spherical array of 2000 containers, each with the fuel-containing central tube (the 2R tube) water flooded, the annulus between the central tube and the barrel containing only 50% water, and each container "cell" (container plus allowance for packing fraction) reduced to 80% of its normal size as a result of the crushing together of the barrels. For the postulated case where the crushed barrels are lifted out of the water and the central tube remains flooded but the water drains out of the rest of the barrel, the analysis results give a reactivity of 0.827 for 200 barrels and 0.950 for 500 barrels, where the group of barrels is still infinitely water reflected.

Calculations show that any moderator material in the annulus between the central tube and the barrel rapidly <u>decreases</u> the reactivity of the configuration because neutrons are thermalized in a region where they are most likely to be captured by structural materials rather than fuel. Moderator material inside the central 2R container <u>increases</u> the reactivity of the configuration. Thus, for the calculations on the damaged containers, the very conservative assumption was made that all central tubes (containing fuel) were water-filled and the annulus between the central tube and the outer barrel of each container contained only 50 vol-% water homogenized over the entire region. This region normally contains vermiculite, which is very porous, and will essentially instantaneously absorb more than 50 vol-% water in the region in which it is present.

Results from the single length container analysis are used to conclude that a double-length container, with no increase in the contained loading, would not present an increased criticality hazard. Thus, the analysis demonstrates that single or double length containers with TRIGA fuel (U-ZrH or Er-U-ZrH with 1.39 kg or less of U-235 per shipping container) meet the requirements for Fissile Class I shipments.

Table A.1-3 is a summary table for Section A.1.

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[1]Uranium-zirconium-hydride or erbium-zirconium-hydride with U-235 content equal to or less than 1.39 kg per shipping container.

TABLE A.1-3

Summary Table Fissile Class I

NORMAL CONDITIONS

	Analysis
Number of undamaged packages calculated to be subcritical Fissile Class I, any number	Any Number
Package size, cm^3	234.6×10^3

ACCIDENT CONDITIONS

Number of damaged packages calculated to be sub-critical (Fissile Class I must be at least 250)	>500
Optimum interspersed hydrogenous moderation, full water reflection	Yes
Package size, cm^3	206.9×10^3

A.2 Package Fuel Loading

The maximum fuel loading in any one container would be the U-235 contained in 25 TRIGA fuel elements of the most reactive type as shown in Tables A.1-1 and A.1-2. This maximum fuel loading is 1.39 kg of U-235 in a single container.

A.3 Model Specification

A.3.1 Description of Calculational Model

Three calculational models were used for the criticality evaluation. The first model was a one-dimensional radial description of the container shown in Fig. A.1-1. This was a 4 region model, shown in Fig. A.3-1, for doing cell calculations. As noted, the central region contained a homogenized mixture of TRIGA fuel, fuel clad, and various fractions of water in the remaining volume. As a conservative assumption, no disadvantage factors have been applied to the materials in this region. TRIGA reactor design calculations for highly loaded fuel of this type have shown a sizable reduction of the flux in the fuel element when surrounded by water (approximately same volume fractions as for this analysis) - by a factor of ~3 for the lowest thermal group.

The second model, shown in Fig. A.3-2, was a two-region spherical representation of many homogenized fuel containers surrounded by a 20 cm thick water reflector (effectively infinite for neutron reflection). The fueled region in this model had two different sizes: equal to 5000 containers (and accounting for their packing fraction) for calculations of undamaged containers, and equal to 2000 containers for calculations with damaged containers. For the damaged containers, it was assumed that the barrels were crushed together such that the packing fraction was 1.0 and volume between the inner tube and the outer barrel was reduced such that there was a total 20% reduction in the volume external to the central tube containing the fuel. It was also assumed for the damaged container calculations that the inner, fuel containing tube was completely flooded, but only 50 vol-% water (homogenized) occupied the region between the inner tube and outer barrel. This was a very conservative assumption since there is no realistic way for water to fill the inner tube and have water excluded from the space between the inner tube and outer barrel, and results of the cell calculations showed the reactivity of the container increased somewhat as moderator was added to the fuel containing region, but decreased drastically as moderator was added to either both regions or only the region between the central tube and the outer barrel. Two additional calculations for crushed barrels were done for the postulated condition of having all the water drain from the region between the central tube and the outer barrel, but having all the water remain in the inner tube. Calculations were done for both 200 and 500 barrels.

The maximum packing fraction for a single layer array of barrels was assumed for the calculations with undamaged containers. This packing fraction was 0.907 derived for a hexagonal array of touching barrels.

The third model, shown in Fig. A.3-3, was a four-region spherical mock up of the shipping barrel shown in Figure A.1-1. (Region volumes are equal in the two Figures.) This spherical cell model (reflective outer boundary condition) was used to calculate an upper limit projection for an infinite array of undamaged, unflooded barrels. The one-dimensional spherical model was the simplest way to account for the finite dimensions of the fuel and the barrel and to account for the neutron leakage in all directions from the fuel in the central tube. The fuel, clad, inconel end-fittings and internal inconel spring were included in the homogenized fuel rods in the central tube. The 3/8" x 2" internal steel braces in the barrel were homogenized with the vermiculite in the region between the central tube and the outer barrel.

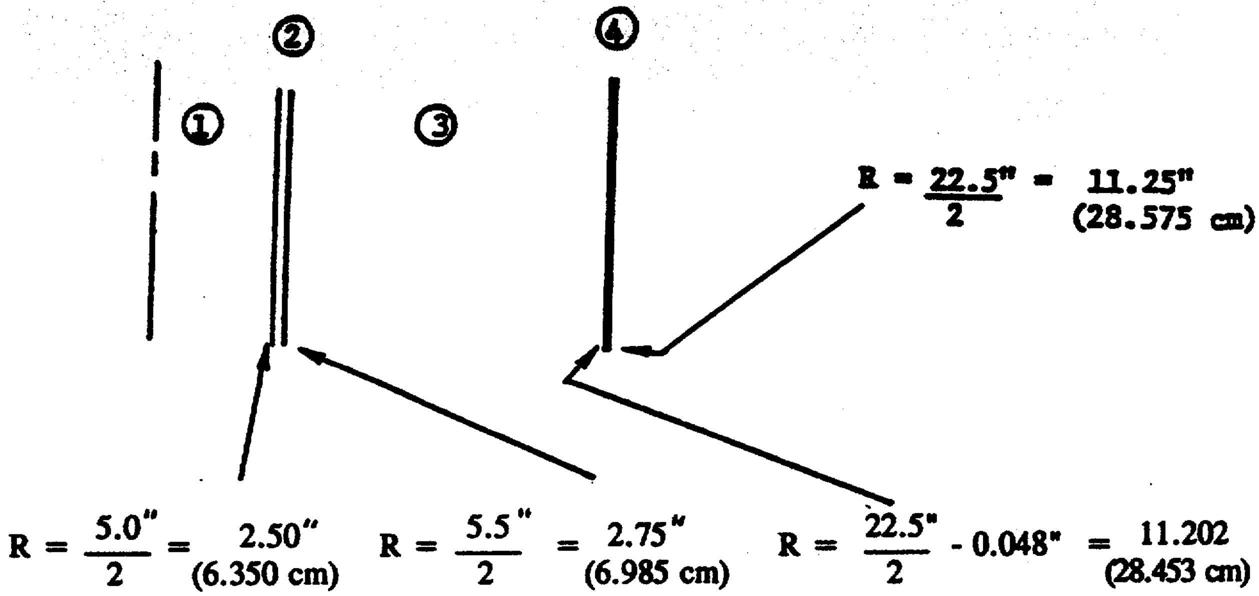
The steel barrel thickness shown in Fig. A.1-1 and forming a part of the homogenized container calculations is greater than that of the actual barrel to be used. This greater thickness was used to approximate the 3/8" round steel braces inside the barrel, and to allow for the barrel top being thicker than the sides. The 3/8" x 2" internal steel braces are not included in this model, nor is the extra thickness and diameter of the screw cap on the 2R internal container.

NOMINAL COMPOSITIONS (%)

	INCOLOY	INCONEL
Mn	1	0.4
Cr	21	16
Ni	32	76
Fe	46	7.6
	8.01 gm/cc	8.43 gm/cc

FIGURE A.3-1

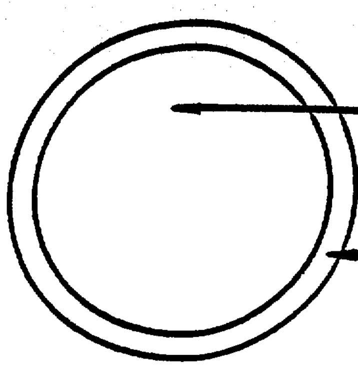
One Dimensional Cell Model Used for Criticality Evaluation



Reg. 1	25 homogenized postulated TRIGA fuel elements with varying fractions of water in the remaining volume
Reg. 2	steel
Reg. 3	Air, vermiculite, or varying fractions of water
Reg. 4	Steel

FIGURE A.3-2

Spherical Geometry of Water Reflected Homogenized Shipping Containers Used for Criticality Evaluation



Radius of Region 1

5000 Homogenized Containers

$$V = 5000 \times \frac{234.562}{0.907} = 1293.1 \times 10^3 L \qquad R = 675.846 \text{ cm}$$

2000 Homogenized Containers of Reduced Volume - Due to Crushing

$$V = 2000 \times 0.8 \times \frac{234.562}{0.907} = 413.78 \times 10^3 L \qquad R = 462.268 \text{ cm}$$

500 Homogenized Containers of Reduced Volume - Due to Crushing

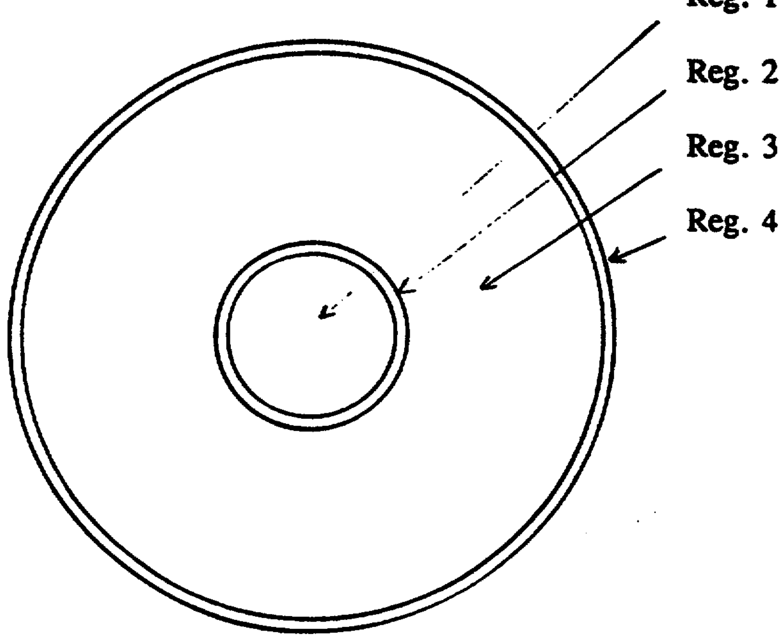
$$V = 103.45 \times 10^3 L \qquad R = 291.211 \text{ cm}$$

200 Homogenized Containers of Reduced Volume - Due to Crushing

$$V = 41.38 \times 10^3 L \qquad R = 214.566 \text{ cm}$$

Figure A.3-3

One Dimensional Spherical Cell Model
Used for Criticality Evaluation



Region volumes are equal to those shown in Fig. A.1-1

Reg. 1	R = 13.209 cm	25 Fuel rods, including total length of Incoloy clad, Inconel end-fittings and Inconel spring
Reg. 2	R = 14.191 cm	steel tube
Reg. 3	R = 38.072 cm	Vermiculite and 3/8" x 2" steel braces
Reg. 4	R = 38.258 cm	Steel barrel, including 3/8" round steel bracing

A.3.2 <u>Package Regional Densities</u>

The composition of the postulated TRIGA fuel material used for the criticality evaluation is described in Table A.3-1. The region compositions for the 4 region cell calculations are given in Table A.3-2. Volume fractions are given in Table A.3-3 for the interior of the 2R internal tube containing 25 TRIGA fuel elements. Table A.3-4 shows the composition of homogenized undamaged shipping containers and Table A.3-5 gives the composition for homogenized damaged containers where the 2R inner tube is water flooded, the space between the inner tube and the outer barrel contains 50 vol-% water, and the barrels have been partially crushed.

TABLE A.3-1

Composition of TRIGA Fuel Material Used for Criticality Evaluation

Description: Nominal 45 wt-% uranium in nominal $ZrH_{1.60}$ with the uranium being 19.9% enriched (specification value is 19.7 ± 0.2% enrichment)

	N - $\frac{\text{atoms}}{\text{barn - cm}}$	ρ - gm/cc
H (ZrH)**	0.04577	0.0766
Zr	0.03016	4.57
U-235	0.001935	.755
U-238	0.007544	2.981

** Hydrogen in zirconium hydride

TABLE A.3-2

Region Compositions for 4 Region One-Dimensional Cell Calculations

Region 1 -

Cylindrical cell (Fig. A.3-1) contains 25, 0.542 inch o.d. fuel elements with 0.016 inch Incoloy clad and varying amounts of water in an area with a 5.00 inch diameter.

			Area Fract.
Area of fuel = $25 \times \pi \times 0.6477^2$	=	32.949 cm^2	0.260
Area of clad = $25 \times \pi \times (0.6883^2 - 0.6477^2)$	=	4.260 cm^2	0.034
Area of air or water = 126.677 - 37.209	=	89.468 cm^2	0.706
Area of Region 1 = $\pi \times 6.350^2$	=	126.677 cm^2	1.000

Spherical cell (Fig. A.3-3) contains 25, 0.542 inch o.d. fuel elements, 30.37 inches long with 25.63 inch clad length, 118 gm of Inconel end fittings and internal spring in a 5.00 inch ID x 30.0 inch IH tube.

			Vol. Fract.
Vol. of fuel = $25 \times \pi \times 0.6477^2 \times 55.88$	=	1841 cc	0.191
Vol. of equiv. Incoloy (clad, end fittings, spring) $25 \times \pi \times (0.6883^2 - 0.6477^2) \times 65.1 + 25 \times 118 \times 1.224^{**}/8.01$	=	725 cc	0.075
Vol. of air = 9653 - 2566	=	7087 cc	0.734
Vol. of Reg. 1 = 126.677 x 76.2	=	9653 cc	1.000

** Σa Inconel/Σa Incoloy

Table A.3-2 (Page 2)

	$N - \frac{atoms}{barn - cm}$	ρ-gm/cc
Cylindrical cell		
H (ZrH) = 0.260 x .04577	0.01190	0.0199
Zr = 0.260 x 0.03016	0.00784	1.19
U-235 = 0.260 x 0.001935	0.000503	0.196
U-238 = 0.260 x 0.007544	0.001961	0.776
Incoloy = 0.034 x 0.0969	0.003295	0.306
For 0% water in remaining areas		0.
H (H_20) = 0.706 x 0.0668 x 0.00 =	0.	
Oxy = 0.706 x 0.0334 x 0.00 =	0.	
For 10% water in remaining area		0.0706
H (H_20) = 0.706 x 0.0668 x 0.10 =	0.00472	
Oxy = 0.706 x 0.0668 x 0.10 =	0.00236	
For 40% water in remaining area		0.2824
H (H_20) = 0.706 x 0.0668 x 0.40 =	0.01886	
Oxy = 0.706 x 0.0334 x 0.40 =	0.00943	
For 70% water in remaining area		0.4942
H (H_20) = 0.706 x 0.0668 x 0.70 =	0.03301	
Oxy = 0.706 x 0.0334 x 0.70 =	0.01651	
For 100% water in remaining area		0.706
H (H_20) = 0.706 x 0.0668 x 1.00 =	0.04716	
Oxy = 0.706 x 0.0334 x 1.00 =	0.02358	
Spherical cell		
H (ZrH) = 0.191 x 04577	0.008742	0.0146
Zr = 0.191 x 0.03016	0.005761	0.873
U-235 = 0.191 x 0.001935	0.000370	0.144
U-238 = 0.191 x 0.007544	0.001441	0.570
Incoloy = 0.075 x 0.0969	0.007268	0.676

Table A.3-2 (Page 3)

Region 2 - Steel (1/4 inch thick, 5.5 inch O.D.)
Mocked up with stainless steel of 80% full density.
The 80% was derived from the ratio of Σa (steel)/Σa (stainless steel)

Steel N = 0.8 x 0.0843 = 0.0674 atoms/barn - cm
= 0.8 x 7.95 = 6.36 gm/cc

Region 3 - Air, vermiculite or water between 22.5 inch O.D. and 5.5 inch I.D.

For air, use oxygen N = 0.00005 atoms/barn - cm
= 0.00133 gm/cc

For vermiculite (ρ = 0.072 gm/cc)
mocked up with correct hydrogen and oxygen density but with additional oxygen replacing all other elements on an atom-for-atom basis. This is conservative in that it increases the moderating effect and decreases the neutron absorptions relative to a more accurate mock up of this material.

For the spherical cell, 0.76 vol-% steel is homogenized with the vermiculite

	N - $\frac{\text{atoms}}{\text{barn - cm}}$	- gm/cc
H	0.0000225	0.0000376
Oxy	0.00181	0.0481
Steel (for spherical model only)	0.000513	0.0483
For Water		
5 vol-%		0.05
H (H_2O) = 0.0668 x 0.05 =	0.00334	
Oxy = 0.0334 x 0.05 =	0.00167	
10 vol-%		0.10
H (H_2O) = 0.0668 x 0.10 =	0.00668	
Oxy = 0.0334 x 0.10 =	0.00334	
15 vol-%		0.15
H (H_2O) = 0.0668 x 0.15 =	0.01002	
Oxy = 0.0334 x 0.15	0.00501	

Table A.3-2 (Page 4)

20 vol-%		0.20
H (H_2O) = 0.0668 x 0.20 =	0.01336	
Oxy = 0.0334 x 0.20 =	0.00668	
25 vol-%		0.25
H (H_2O) = 0.0668 x 0.25 =	0.01670	
Oxy = 0.0334 x 0.25 =	0.00835	
30 vol-%		0.30
H (H_2O) = 0.0668 x 0.30 =	0.02004	
Oxy = 0.0334 x 0.30	0.01002	
50 vol-%		0.50
H (H_2O) = 0.0668 x 0.50 =	0.03340	
Oxy = 0.0334 x 0.50 =	0.01670	
100 vol-%		1.00
H (H_2O) - 0.0668 x 1.00 =	0.0668	
Oxy = 0.0334 x 1.00 =	0.0334	

Region 4 - Steel (0.048 inch thick, 22.5 inch O.D.)
Mocked up with stainless steel of 80% full density.
The 80% was derived from the ratio of Σa (steel)/Σa (stainless steel)

Steel N = 0.8 x 0.0843 = 0.0674 atoms/barn - cm
= 0.8 x 7.95 = 6.36 gm/cc

TABLE A.3-3

Volume Fractions for Interior of 2R Container With 25 TRIGA Fuel Elements

(Used with Table A.3-4)

Each TRIGA element is assumed to be 0.542 inches O.D. by 22.0 inches high with a 0.016 inch incoloy clad (inconel end fixtures have been ignored).

		Vol. Fraction
Vol. of Fuel = 25 x π (0.6477^2) x 55.88 =	1.8412 L	0.1907
Vol. of Incoloy Clad = 25 xπ (0.6883^2 - $0.6477^2/4$) x 55.88 =	0.2381 L	0.0247
Vol. of air or water = 9.653 L - 2.0793 L =	7.5737 L	0.7846
Vol. inside 2R Container = π x 6.3500^2 x 76.2	9.653 L	1.000

TABLE A.3-4

COMPOSITION OF HOMOGENIZED SHIPPING CONTAINERS
FOR SPHERICAL CALCULATIONS WITH UNDAMAGED CONTAINERS
(NO WATER OR VERMICULITE IN CONTAINERS)

<table>
<tr><th rowspan="2">Element</th><th rowspan="2">Pack. Fract. of Barrels</th><th rowspan="2">V. F. of Region in Barrel</th><th rowspan="2">V. F. of Elem. in Region</th><th rowspan="2">Elem. Atom Density</th><th colspan="2">Homog. Elem Atom Dens.</th></tr>
<tr><th>N - $\frac{atoms}{barn - cm}$</th><th>ρ - gm/cc</th></tr>
<tr><td>H (ZrH)</td><td>0.907</td><td>0.0412</td><td>0.1907</td><td>0.04577</td><td>0.000326</td><td>0.000545</td></tr>
<tr><td>Oxy (for air)</td><td>"</td><td>"</td><td>0.7846</td><td>0.000054</td><td rowspan="2">0.000047</td><td rowspan="2">0.00125</td></tr>
<tr><td>"</td><td>"</td><td>0.9344</td><td>1.0</td><td>"</td></tr>
<tr><td>Incoloy</td><td>"</td><td>0.0412</td><td>0.0247</td><td>0.0969</td><td>0.000089</td><td>0.00399</td></tr>
<tr><td>Zr</td><td>"</td><td>"</td><td>0.1907</td><td>0.03016</td><td>0.000215</td><td>0.0326</td></tr>
<tr><td>U-235</td><td>"</td><td>"</td><td>"</td><td>0.001935</td><td>0.0000138</td><td>0.00539</td></tr>
<tr><td>U-238</td><td>"</td><td>"</td><td>"</td><td>0.007544</td><td>0.0000538</td><td>0.0213</td></tr>
<tr><td>Steel</td><td>"</td><td>0.0099</td><td>0.8</td><td>0.0843</td><td rowspan="2">0.001493</td><td rowspan="2">0.141</td></tr>
<tr><td>"</td><td>"</td><td>0.0145</td><td>0.8</td><td>"</td></tr>
</table>

TABLE A.3-5

Composition of Homogenized Shipping Containers for Spherical Calculations with Damaged Containers (no vermiculite, water flooded 2R inside container, 50 vol-% H_20 between inner tube and outer barrel, volume exterior to 2R inside container is reduced to 80% of normal volume due to crushing)

Element	Crush Factor	Pack. Fract. of Barrels	V. F. of Region in Barrel	V. F. of Elem. in Region	Elem. Atom Dens.	Homog. Elem. Atom Dens.	
						N - atoms/barn-cm	ρ - gm/cc
H (ZrH)	1.25	0.907	0.0412	0.1907	0.04577	0.000408	0.000682
H (H_20) (1)	"	"	"	0.7846	0.0668	0.002448	0.00409
H (H_20) (2)	0.8	"	0.9344	0.50	0.0668	0.02265	0.0379
Oxy(H_20)(1)	1.25	"	0.0412	0.7846	0.0334	0.001224	0.0325
Oxy(H_20)(2)	0.8	"	0.9344	0.50	0.0334	0.01133	0.3085
Incoloy	1.25	"	0.0412	0.0247	0.0969	0.000112	0.00502
Zr	"	"	"	0.1907	0.03016	0.000269	0.0407
U-235	"	"	"	"	0.001935	0.0000172	0.00671
U-238	"	"	"	"	0.007544	0.0000672	0.0265
Steel	"	"	0.0099	0.8	0.0843	} 0.001866	0.176
Steel	"	"	0.0145	0.8	0.0843		

1) inside inner tube
2) between inner tube and outer barrel

A.4 CRITICALITY EVALUATION

A.4.1 Calculational Method

Neutron cross sections used in these analyses were generated for seven neutron energy groups. The lethargy and energy for each of the seven broad groups is given in Table A.4-1.

TABLE A.4-1

Neutron Energy Group Structure

Group	Lethargy Interval	Energy Interval (eV)
1	-0.4 - 2.8	14.9×10^6 - 6.08×10^5
2	2.8 - 7.0	6.08×10^5 - 9.12×10^3
3	7.0 - 16.0	9.12×10^3 - 1.125
4	16.0 - 16.98	1.125 - 0.420
5	16.98 - 18.08	0.420 - 0.140
6	18.08 - 19.11	0.140 - 0.050
7	19.11 -	0.050 - 0.002

All neutron cross sections were generated using the GGC-5 code (Ref. A.4-1) where for energies above thermal (>1.125 eV) fine group (approximately 100) cross sections, stored on tape for all commonly used isotopes, are averaged over a spatially independent flux derived by solution of the B-1 equations for each discrete reactor region composition. This code, and its related cross-section library, predict the age of each of the common moderating materials to within a few percent of the experimentally determined values and used the resonance integral work of Nordheim (Ref. A.4-2) to generate cross sections for resonance materials.

Thermal cross sections were obtained in essentially the same manner using 58 fine groups. However, scattering kernels were used to describe properly the interaction of the neutrons with the chemically bound moderator atoms. The bound hydrogen kernels for hydrogen in water were generated by the THERMIDOR code (Ref. A.4-3) while those for hydrogen in zirconium hydride were generated by SUMMIT (Ref A.4-4). These scattering models have been used to adequately predict the water and hydride (temperature-dependent) spectra as measured at the General Atomics linear accelerator (Ref. A.4-5).

The reflector cross sections were generated over a water spectrum using the GGC-5 code.

The diffusion theory code used in these analyses is DIF3D (Ref. A.4-6) a multi-dimensional multigroup code which allows scatter-transfer of neutrons between all neutron energy groups.

The transport theory code used is 1DFX (Ref. A.4-7), a one-dimensional, multigroup code which solves the transport equation by the method of discrete originates. In these analyses an S_4 approximation for the flux anisotropy and a P_1 approximation for the scattering anisotropy were used.

The 1DFX code was used for the cell calculations (described by the geometry in Fig. A.3-1 and Fig. A.3-3). The calculations with the cylindrical geometry were done to determine the way in which reactivity varied as a function of water content in the discrete regions, and to generate disadvantage factors (ϕ region/ϕ total) by group for each region of the shipping container ("cell"). The calculations with the spherical geometry were done to determine an upper limit projection of the reactivity for an infinite number of barrels. Only the cell calculations contained discrete air-filled regions, for which transport theory is a suitable means of calculating the relative neutron flux levels.

The D1F3D code was used for the calculations of homogenized shipping containers surrounded by a water reflector. Group dependent disadvantage factors from the appropriate "cell" calculations were used for materials in the homogenized region to reflect the enhanced flux values in the fuel-containing region relative to other regions of the "cell" (shipping container). A given shipment size of 5000 undamaged containers was assumed for this application and no surveys were made of reactivity versus shipment size. Reactivity calculations were also made for several shipment sizes where the assumed shipment size had damaged containers, including partially crushing the outer containers, and thus effectively moving the inner containers closer together.

These codes, with the exception of D1F3D, and the neutron cross section generating procedures, have been used routinely for TRIGA reactor design calculations and analysis of reactor operating characteristics for many years. Comparisons are usually within 1% between measured reactivity and calculated reactivity encompassing the codes and methods described.

The D1F3D code has been used extensively for reactor analysis by many institutions. It has been used at General Atomics for a few years and calculates essentially the same results on comparison TRIGA problems from past analyses using different codes.

A.4.2 Fuel Loading Optimization

The correct fuel loading has been used for the criticality evaluation in that the postulated TRIGA fuel element with maximum reactivity was used, and the maximum number of this type of element (with cardboard covers) that would fit into the inner container was used. The highly loaded fuel elements currently manufactured contain erbium as a burnable poison. As a conservatism, the erbium was left out of the composition for the elements used in this analysis. To demonstrate the poisoning effect of erbium, it is pointed out that the number of fuel elements necessary for criticality would be about the same for fuel composed of either items 1 or 3 of Tables A.1-1 and A.1-2. Thus, about 3.5 times as much U-235 (685 grams) is being compensated by about 250 grams of erbium.

For the cell calculations described by Fig. A.3-1, a one-dimensional radial geometry was used with an assumed infinite height. A reflective boundary condition was used at the inner and outer boundaries of the cell geometry, and a convergence criteria of $\Delta k < 1 \times 10^{-4}$ in three successive reactivity iterations was used.

For the final reactivity calculations using the D1F3D code, a zero current condition was applied at the inner boundary (r = o) and a void boundary was assumed for calculating leakage from the outer boundary. A convergence criteria of $\Delta k < 1 \times 10^{-4}$ in three successive reactivity iterations was used.

A.4.3 Criticality Results

The cell calculations, as summarized in Table A.4-2, show that reactivity rapidly decreases as moderator is added to the empty space between the inner container and the outer barrel. This large region, as it fills with water, serves to isolate the fuel-containing inner container and provide more thermal neutrons for capture in non-fuel materials. These calculations also show that reactivity increases slowly but continuously as water is added to the empty space inside the inner container with 25 fuel elements. However, if water is added equally to both regions, the reactivity again rapidly decreases with an increasing volume fraction of water.

TABLE A.4-2

Results of Cell Calculations with 25 Highest Loaded TRIGA Elements Homogenized in Interior 2R Container

Item	Vol-% H_20 in Vacant Portion of Inner 2R Container	Vol-% H_20 in space Between 2R Container and Outer Barrel	k∞
1	0	0	1.2139
2	0	0*	1.1909
3	0	5	0.8404
4	0	20	0.4489
5	0	100	0.3791
6	10	0	1.2724
7	40	0	1.3870
8	70	0	1.4489
9	100	0	1.4843
10	5	5	0.8513
11	15	15	0.5620
12	25	25	0.4717
13	70	70	0.6253
14	100	100	0.7566
15	100	10	0.9141
16	100	30	0.7307
17	100	50	0.7262

* Vermiculite ($\rho = 4.5$ lbs/ft^3)

For this reason, the conservative assumption was made for damaged containers, that water floods the inner container but the space between the inner container and outer barrel contains only 50 vol-% water. Calculations were also performed for the case where the water has drained from the space between the inner tube and outer barrel but the inner tube itself remains flooded. Already discussed has been the conservative approximation of not using disadvantage factors for the homogenized fuel elements in the cell calculations.

Table A.4-3 summarizes the results of calculated reactivities for homogenized fuel containers with an effectively infinite (20 cm) water reflector. These calculations were done with spherical geometry in order to assume the most compact and reactive container arrangement. Also, the calculations could be done with a one-dimensional geometry without having to make leakage approximations through use of buckling terms.

Results from Table A.4-3 show that a shipment size of 5000 containers gives a reactivity of 0.618 for water reflected undamaged containers. If all the containers were damaged and the central tube was completely water flooded and the region between the inner tube and the outer barrel contained only 50 vol-% water, a water reflected array of 2000 containers would have a reactivity of 0.628 if the array of damaged containers was crushed together so that the empty space exterior to the central tube was reduced to 80% of the original volume. The 20% "crush factor" was considered reasonable in that it is more than twice the packing fraction residual (1-packing fraction = 1-0.907 = 0.093). Thus, it allows for the barrels to be crushed together so that no empty space remains between barrels, plus an additional reduction of the space between the inner tube and outer barrel of about the same size (~10%).

For the case of the damaged and crushed together containers (with flooded inner tube), if the region between the inner tube and the outer barrel contained no water, the calculated reactivity was 0.950 for 500 barrels and 0.827 for 200 barrels.

Results for the spherical cell calculation, represented by the geometry shown in Fig. A.3-3, show a reactivity of 0.949. This is a conservative upper limit for the reactivity of an infinite number of undamaged, unflooded shipping containers.

TABLE A.4-3

Results of Calculations for Water Reflected Spheres of Homogenized Shipping Containers, Each Containing 25 Highest Loaded TRIGA Fuel Elements

Item #		k
1	5000 Undamaged Containers. No internal H_2O or vermiculite Disadvantage factors from cell prob #1	0.618
2	2000 Damaged Containers Water flooded 2R internal container 50 vol-% water between 2R inner tube and outer barrel. Volume exterior to 2R internal container is reduced to 80% of normal volume due to crushing. Disadvantage factors from cell prob #17	0.628
3	500 Damaged Containers Water flooded 2R internal container No water between 2R inner tube and outer barrel Volume exterior to 2R internal container is reduced to 80% of normal volume due to crushing Disadvantage factors from cell prob. #9	0.950
4	200 Damaged Containers same as conditions as #3	0.827

The results shown in Tables A.4-2 and A.4-3 allow the conclusion to be drawn that double length containers, as shown in drawing TOS396C161 could replace the single length containers used for the criticality evaluation without any increase in criticality hazard, as long as the loading limit per container is maintained at the single length container value of 1.39 kg or less of U-235 contained in TRIGA fuel elements. The conclusion that the double length containers do not increase the criticality hazard is based on the fact that the loading limit per container is the same as for the single length container, but the double length container has the effect of separating the fuel in a shipment to a much greater degree than is done with the single length containers.

Use will normally be made of the double length containers for shipping control rods with fuel followers and/or special instrumented fuel elements. Thus, these lesser used containers will normally contain large amounts of poison with the fuel and/or the container will not likely be loaded with the maximum number of fuel elements permitted.

A.5 Criticality Benchmark Experiments

The computer codes (with the exception of D1F3D, as mentioned earlier), cross section generation procedures and analytical techniques used for this criticality evaluation have been used on all TRIGA designs for the past several years. These include all the fuel compositions shown in Tables A.1-1 and A.1-2. As an example of the comparison between the calculated and experimental reactivity, the calculated reactivity for the just-critical TRIGA Mark III at GA (fuel described by item 3 in Tables A.1-1 and A.1-2) was 0.991 (Ref. A.5-1). This is typical of the relationship between calculated and experimental critical masses for TRIGA reactors.

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