SAFETY ANALYSIS REPORT
FOR THE
MODEL MST-30 PROTECTIVE SHIPPING PACKAGE
FOR 30-INCH UF_6 CYLINDERS

(Revision 6, March 2020)

submitted by :

Mitsubishi Nuclear Fuel Co., LTD

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1.0 GENERAL INFORMATION

1.1 Introduction

The MST-30 Protective Shipping Package (MST-30) is a Type A, Fissile Material and Uranium Hexafluoride(UF_6) Package used for the shipment of 30-inch cylinders containing solid Uranium Hexafluoride (UF_6) enriched up to 5wt% ^{235}U. The package is designed to conform to the technical and regulatory requirements as specified in the Japanese Safe Transport Regulations pursuant to the IAEA Regulations for Safe Transport of Radioactive Materials, 2012 Edition (SSR-6). The package is intended to be used for transport from, to, or through foreign countries, including the USA.

The MST-30 package was approved by the Japanese Authority (Nuclear Regulation Authority: hereinafter referred to as “NRA”) and certified as a Type A Fissile UF_6 Package on March 5, 2020 (NRA Certificate number J/159/AF-96(Rev.3)). A copy of the NRA certificate in English dated on March 24, 2020 is provided in Appendix 1.3.1.

The maximum transport index (TI) expected from the calculation reported in this safety analysis report (SAR) is 0.5 (Para. 523 of SSR-6). The criticality safety index (CSI) is 0 (zero), since an unlimited number of packages is subcritical (Para. 686 of SSR-6).

The MST-30 has been rigorously tested according to the regulatory requirements to assure water leak-tightness of the UF_6 cylinder. UF_6 is not only a radioactive material, but is also a toxic and corrosive material, classified into Class 6/Division 6.1 and Class 8 of the United Nations (UN) Recommendations on the Transport of Dangerous Goods (Para.110 of SSR-6). Additionally, inleakage of water may compromise criticality control; thus, the ability of the MST-30 package to exclude water under all conditions of transport is an indispensable and the most essential design feature. Therefore, the primary goal for the design of the MST-30 was to assure water leak-tightness of package under the severest of conditions. The exacting and comprehensive test program completely confirms that the design of the MST-30 maintains water leak-tightness of the cylinder under all regulatory conditions.

1.2 Package Description

1.2.1 Packaging

Drawings of the MST-30 overpack including the ring plate are provided in Appendix 1.3.2. A drawing of the 30B UF_6 cylinder is provided in Appendix 1.3.3. The MST-30 is an overpack used to protect a 30-inch cylinder containing enriched uranium hexafluoride during transport. The packaging is approximately 1.2m (approx. 47inch) in diameter by 2.4m (approx. 95inch) long.

The annulus between outer shell and inner shell of the overpack is filled with polyurethane and phenolic foam. Three layers of polyurethane foam plates are used at the ends of the overpack for shock-absorption and fire-resistance. Phenolic foam is used in the annular areas of overpack for fire-resistance. Figure 1-1 provides an illustration of the overpack construction.

The ring plate is a stainless steel plate in a circular ring form. It is inserted in the gap on the plug side between the overpack and the cylinder when the cylinder is loaded in the overpack in order to prevent excessive deformation of the inner shell of the overpack.

1.2.1.1 Gross Weights

The maximum weights of the MST-30 are provided in Table 1-1.

1.2.1.2 Materials and Construction

The overpack is a right circular container which is composed of the top (upper) and bottom (lower) halves and is constructed of two stainless steel shells, i.e. outer shell and inner shell. The steel used is JIS SUS-304 (Japanese Industrial Standard) and is equivalent to ASTM SS-304. The outer and inner shell end plates are 6mm (0.24in) thick, and the outer and inner cylindrical shell plates are 3mm (0.12in) thick.

The annulus between the MST's inner shell and outer shell is filled with two (2) kinds of shock-absorbing and/or fire-resistant materials: closed-cell polyurethane foam, and phenolic foam. The polyurethane foam is used in the ends of the package for extra impact resistance and has densities of 0.37 g/cm^3 (approximately 23 lb/ft.^{3}) and 0.48 g/cm^3 (approximately 30 lb/ft.^{3}). The phenolic foam is used in the MST's annular area. The phenolic foam used has a very low free chloride content. The specifications for the Phenolic and Polyurethane foams used to fabricate the MST are provided in Appendix 1.3.4.

The ring plate is a circular ring form with an outer diameter of 770 mm (30.3in), an inner diameter of 624 mm (24.6in) and a thickness of 6 mm (0.24in). This plate is made of JIS SUS-304.

The 30B cylinder, valve and plug are constructed in accordance with ANSI N14.1 or ISO 7195. They are defined to be the containment boundary of the packaging. In the case of the MST-30 package, the type of plug allowed is a socket head plug only. A hex head plug is not available. A 30B cylinder which does not have any plug and plug-coupling may be used.

1.2.1.3 Outer and Inner Protrusions

There are no inner protrusions on MST-30 overpack. Outer protrusions on the MST-30 overpack consist of lifting and tie-down point and fastening devices. And there is no protrusion on the ring plate.

1.2.1.4 Lifting and Tie Down Device

1.2.1.4.1 Lifting Devices

The top half of the package is lifted using the two (2) lift lugs welded on the outer shell of the overpack (see the drawings provided in Appendix 1.3.2). These lift lugs are intended to support the weight of the top half of the packaging only. Therefore, in order to prevent misuse, they are marked, “LIFT TOP HALF OF PACKAGE ONLY,” using 1" high black lettering near each lug.

The MST-30 package may be lifted as intended using either a fork-truck or a crane. When using a fork-truck, the fork-truck tines are supported by angle reinforcements at the base of the package. Normally, when using a crane, the package is lifted directly using slings. Alternatively, the package also may be crane lifted with the four (4) shackles fitted in to shackle lugs welded on the outer shell on the bottom half of the overpack (see the drawings provided in Appendix 1.3.2). The shackles used for lifting consist of shackle bodies and pins fabricated from JIS SUS-304 stainless steel (equivalent to ASTM SS304) and have a 24 mm diameter (approx. 15/16 inch). In order to prevent misuse, these shackles are removed from the package during transport, and each shackle lug is marked, “REMOVE SHACKLES WHEN NOT IN USE” and “SHACKLES & LUGS FOR LIFTING ONLY,” using 1" high black letters near each shackle lug.

1.2.1.4.2 Tie-down Devices

The bottom half of the overpack is fitted with 14 mm (approx. 9/16 inch) thick tie-down legs used to bolt the package to the floor of the carrier vehicle using eight 18-mm (approx. 3/4 inch) bolts.

1.2.1.5 Shielding

Shielding is not required for contents of the 30B cylinder.

1.2.1.6 Pressure Relief System

Other than the vent ports used to vent the gas from foams under the fire event, there is no pressure relief system in the package.

1.2.1.7 Closures

A stepped horizontal joint permits the top half of the overpack to be removed from the bottom half. This joint is covered with stainless steel, and a 13 mm thick (1/2 inch) silicone rubber seal is used to keep dust and debris out of the interior.

The top and bottom halves of overpack are secured with ten (10) fastening devices. The fastening devices utilize a swing-lever system that assures positive capture of the fasteners. Each device is equipped with a M20 size JIS SUS-316 (equivalent to ASTM SS-316) stainless steel bolt to assure that the halves of the overpack are not inadvertently opened by vibration or shock during transport of the package.

1.2.1.8 Containment

The containment boundary is defined as the Model 30B UF_6 cylinder, valve and plug. The cylinder is constructed and maintained in accordance with USEC-651 and ANSI N14.1 or ISO 7195.

1.2.2 Operational Features

The principal design features of MST-30 overpack and ring plate are as follows:

- Valve Pocket - sufficient space is provided around the valve to prevent direct contact of the valve with any other component of the packaging for Normal and Hypothetical Accident Conditions (HAC) without the need for a valve protection device (VPD);

- Misalignment Protection – the overpack is designed to assure that the cylinder valve is properly aligned in the valve pocket. If the cylinder is not properly aligned, the positioners provided in the bottom half of the overpack prevent closure of the package. Additionally, a pin is inserted into the hole of cylinder skirt (the 3-inch diameter hole is provided in the cylinder skirt for lifting in accordance with the ANSI N14.1) to prevent the cylinder from rotating along the circumference of the inner shell. If the pin is not inserted properly, the halves of overpack cannot close.

- Cylinder-Skirt Protection – the overpack structure is designed to protect the cylinder-skirt, within the proximity of valve, from excessive deformation, thereby preventing damage to the valve as a result of HAC. Heavy steel reinforcement with the valve pocket is welded along the semi-circumferential radius of the inner shell of the end wall of top half.

- Vent-Ports – several vent ports are located on the outer shell of the package to facilitate the discharge of gases generated by the phenolic and polyurethane foams during a fire event. The vent ports are also designed to eliminate the possibility of water ingress into the annulus.

- Impact Limiters – Closed-cell, high-density polyurethane foam is used in both end walls of the overpack to maintain appropriate energy absorption and impact resistance to protect the valve or plug from damage.

- Ring Plate – A ring plate is inserted in the gap on the plug side between the overpack and the 30B cylinder. The ring plate is used to prevent the internal end plate on plug side of the overpack from excessively deforming in the HAC. In the case of a 30B cylinder with no plug, use of a ring plate is optional.

1.2.3 Contents of Packaging

The MST-30 is used for the safe transport of unirradiated uranium hexafluoride (UF_6) with a maximum enrichment of 5.0 wt% of uranium-235 and a total radionuclide content not to exceed

a Type A quantity as defined by the JPN Regulations, IAEA Regulations and United States Code of Federal Regulations. A maximum of 2,277 kg (5,020 lb) of UF_6 is allowed per package.

The specification of the maximum quantity of radionuclides for the UF_6 is as follows;

^{232}U	0.0001 μg/gU
^{234}U	11.0 x 10^3 μg/g^{235}U
^{235}U	5.0 wt%
^{236}U	5000 μg/g^{235}U
^{238}U	balance of total uranium content
^{99}Tc	0.01 μg/gU

(Note) Above listed values of ^{232}U, ^{234}U and ^{99}Tc are quoted from the radionuclides specification for Enriched Commercial Grade Uranium Hexafluoride (ECGU) in ASTM C996 (2010). Value of ^{236}U is complied with the definition of unirradiated uranium in SSR-6.

1.3 Appendices

1.3.1 Copies of the Japanese Authority Certificate for the MST-30

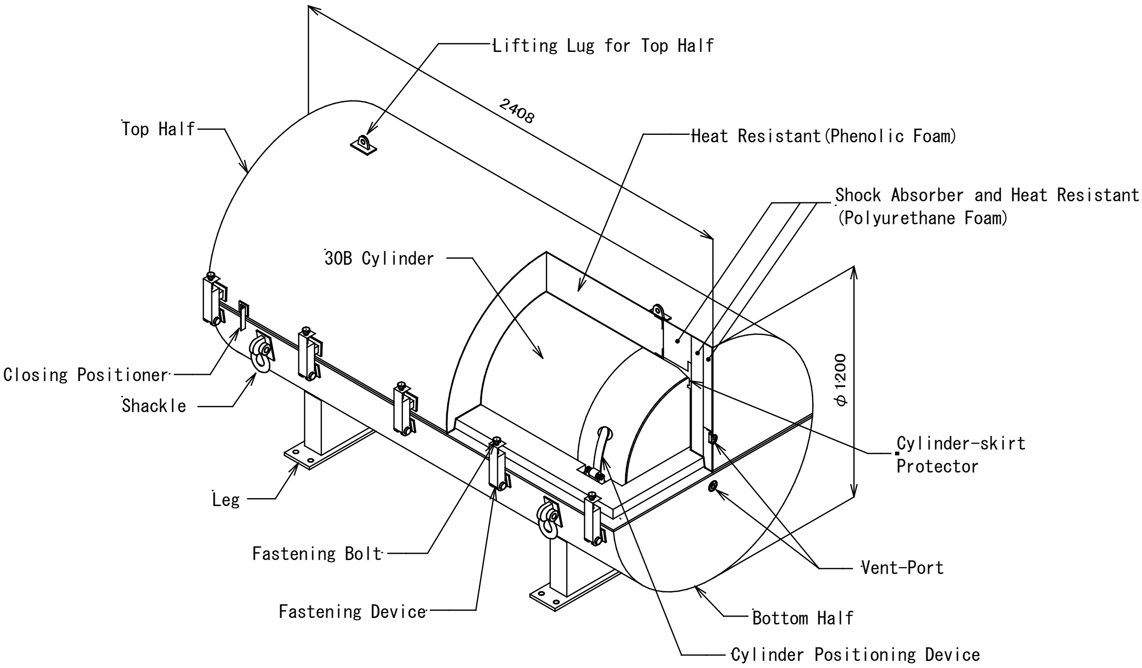
1.3.2 Drawing of Model MST-30 Protective Shipping Package

1.3.3 Drawing of 30B Cylinder

1.3.4 Phenolic and Polyurethane Foam

Table 1-1 MST-30 Maximum Weights

Component	Weight (kg)	Weight (lb)
MST-30 Overpack	1,228	2,707
30B Cylinder	655	1,444
UF_6 Maximum load	2,277	5,020
Ring Plate	10	22
Gross Weight of Loaded Package	4,170	9,193



Unit : mm

Figure 1- 1 Illustration of MST-30 Overpack and 30B Cylinder

Appendix 1.3.1

Copies of the Japanese Authority Certificate for the MST-30

IDENTIFICATION MARK
J/159/AF-96 (Rev. 3)

COMPETENT AUTHORITY
OF
JAPAN

CERTIFICATE FOR APPROVAL OF PACKAGE DESIGN FOR THE TRANSPORT OF RADIOACTIVE MATERIALS

ISSUED BY

NUCLEAR REGULATION AUTHORITY
1-9-9, ROPPONGI MINATO-KU
TOKYO, JAPAN

CERTIFICATE FOR APPROVAL OF PACKAGE DESIGN
FOR THE TRANSPORT OF RADIOACTIVE MATERIALS

This is to certify, in response to the application by MITSUBISHI NUCLEAR FUEL CO., LTD., that the package design described herein complies with the design requirements for a package containing fissile uranium hexafluoride, specified in the 2012 Edition of the Regulations for the Safe Transport of Radioactive Material (International Atomic Energy Agency, Safety Standards Series No.SSR-6) and the Japanese rules based on the Act on Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors.
This certificate does not relieve the consignor from compliance with any requirement of the government of any country through or into which the package will be transported.

COMPETENT AUTHORITY
IDENTIFICATION MARK: J/159/AF-96 (Rev. 3)

Mar. 24, 2020.
Date

K. Hasegawa
Hasegawa Kiyomitsu

Director, Division of Licensing for
Nuclear Fuel Facilities

Secretariat of Nuclear Regulation Authority
Competent Authority of JAPAN
for Package Design Approval

1. The Competent Authority Identification Mark : J/159/AF-96 (Rev.3)

2. Name of Package : MST-30

3. Type of Package : Type A, Fissile Material and Uranium Hexafluoride Package

4. Specification of Package
   (1) Materials of Packaging : See the attached Table-1
   (2) Total Weight of Packaging : 1,893 kg or less
   (3) Outer Dimensions of Packaging :
      (i) Length : Approximately 2.4 m
      (ii) Width : Approximately 1.3 m
      (iii) Height : Approximately 1.4 m
   (4) Total Weight of Package : 4,170 kg or less
   (5) Illustration of Package : See the attached Figure-1 (Bird's-eye view)

5. Specification of Radioactive Contents : See the attached Table-2

6. Description of Containment System
   Containment system consists of 30B cylinder, valve and plug.
   Teflon rubber is used for valve gaskets. The type of plug is limited to a socket head plug.

7. For Package containing Fissile Materials,
   (1) Restrictions on Package
      (i) Restriction Number "N" : No restriction
      (ii) Array of Package : No restriction
      (iii) Criticality Safety Index (CSI) : 0
   (2) Description of Confinement System
      Confinement system consists of a mass of uranium hexafluoride and 30B cylinder.
   (3) Assumptions of Leakage of Water into Package
      No water will leak into or out of any void spaces of 30B cylinder not only during routine transport but also under normal and accident conditions even if the protective overpack is fractured and deformed.
   (4) Special Features in Criticality Assessment
      Quality control of 30B cylinder including its valve and plug should be performed so as to prevent any leakage of water thereinto.

8. For Type B(M) Packages, a statement regarding prescriptions of Type B(U) Package that do not apply to this Package

This is not applicable to this type MST-30 package.

9. Assumed Ambient Conditions

(1) Ambient Temperature Range : −20℃～38℃

(2) Insolation Data : Table 12 of IAEA Regulation

10. Handling, Inspection and Maintenance

Execute a handling, the periodic inspection and maintenance of the packaging used for the transportation of this package by the method indicated in safety analysis report of this package.

In particular, the acceptance criterion for the wall thickness of cylinder in the five year periodic inspection shall be 11.3 mm or more, which is decided based on 11 mm of the wall thickness required for subcriticality of this package and 0.3 mm of the wall thickness reduction assumed for five years.

11. Issue Date and Expiry Date

(1) Issue Date : March 5, 2020

(2) Expiry Date : March 4, 2025

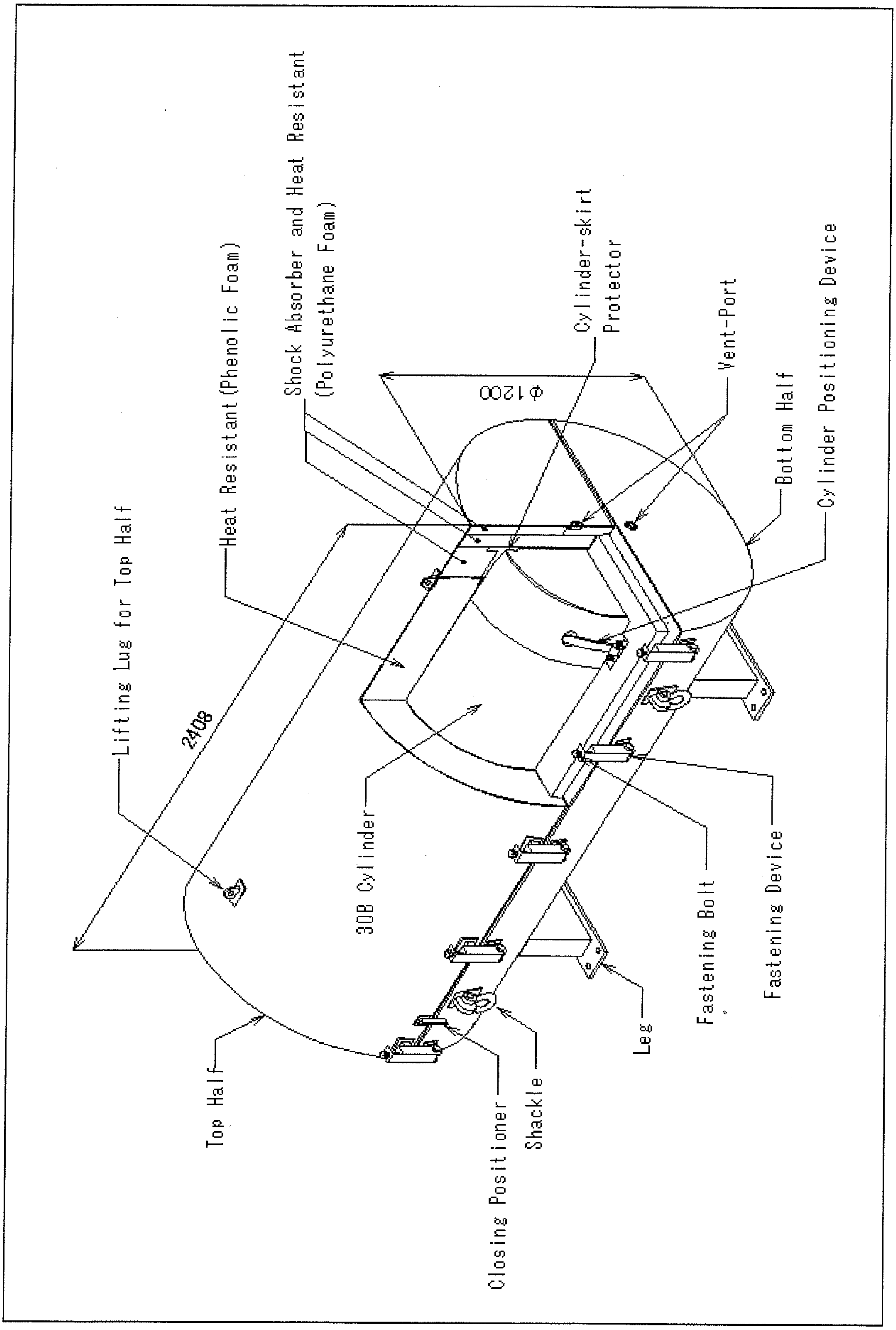


Figure-1 MST-30 Type Transport Package External Appearance

Table-1 Materials of Packaging

Construction		Material
Protective Packaging	External Shell	Stainless Steel (SUS304)
	Internal Shell	
	Heat Insulator	Phenolic Foam
	Support	Polyurethane Foam
	Pad	Neoprene and Neoprene Sponge
Cylinder	Shell	Pressure Vessel Plates, Carbon Steel, for Moderate–and Lower–Temperature Service (ASTM A516)
	Heads	
	Skirt	Pressure Vessel Plates, Carbon Steel, for Moderate–and Lower–Temperature Service (ASTM A516) or Structural Steel (ASTM A36)
	Valve	Aluminum Bronze (UNS C63600)
	Plug	Aluminum Bronze (ASTM B150 or ASTM B171)
Ring Plate		Stainless Steel (SUS304)

Table-2 Specification of Content

Material of Nuclear Fuel		Uranium Hexafluoride (UF_6)		
Physical State		Solid (Block and Powder)		
Total Weight of Nuclear Fuel		2,277 kg -UF_6 or less		
Activity (Bq/package)	Total	265 GBq or less		
	Principle Radionuclides (breakdown)	Isotope	Without progeny nuclides	With progeny nuclides
		^{232}U	1.22×10^{8} Bq	8.87×10^{8} Bq
		^{234}U	1.96×10^{11} Bq	1.96×10^{11} Bq
		^{235}U	6.16×10^{9} Bq	1.24×10^{10} Bq
		^{236}U	9.22×10^{8} Bq	9.22×10^{8} Bq
		^{238}U	1.82×10^{10} Bq	5.46×10^{10} Bq
		^{99}Tc	9.66×10^{6} Bq	9.66×10^{6} Bq
		Total	2.22×10^{11} Bq	2.65×10^{11} Bq
Enrichment		5% or less		
Moderation Control, i.e. H/U Atomic Ratio		0.088 or less (The purity of UF_6 shall be 99.5% or more.)		
Radionuclide Concentrations		^{232}U	$\leqq$ 0.0001 μg/g U	
		^{234}U	$\leqq$ 11.0×10^{3} μg/g ^{235}U	
		^{236}U	$\leqq$ 5,000 μg/g ^{235}U	
		^{99}Tc	$\leqq$ 0.01 μg/g U	
		If the ^{236}U measurement result is less than 125 μg/g U, then measurement of ^{232}U and ^{99}Tc is not required .		

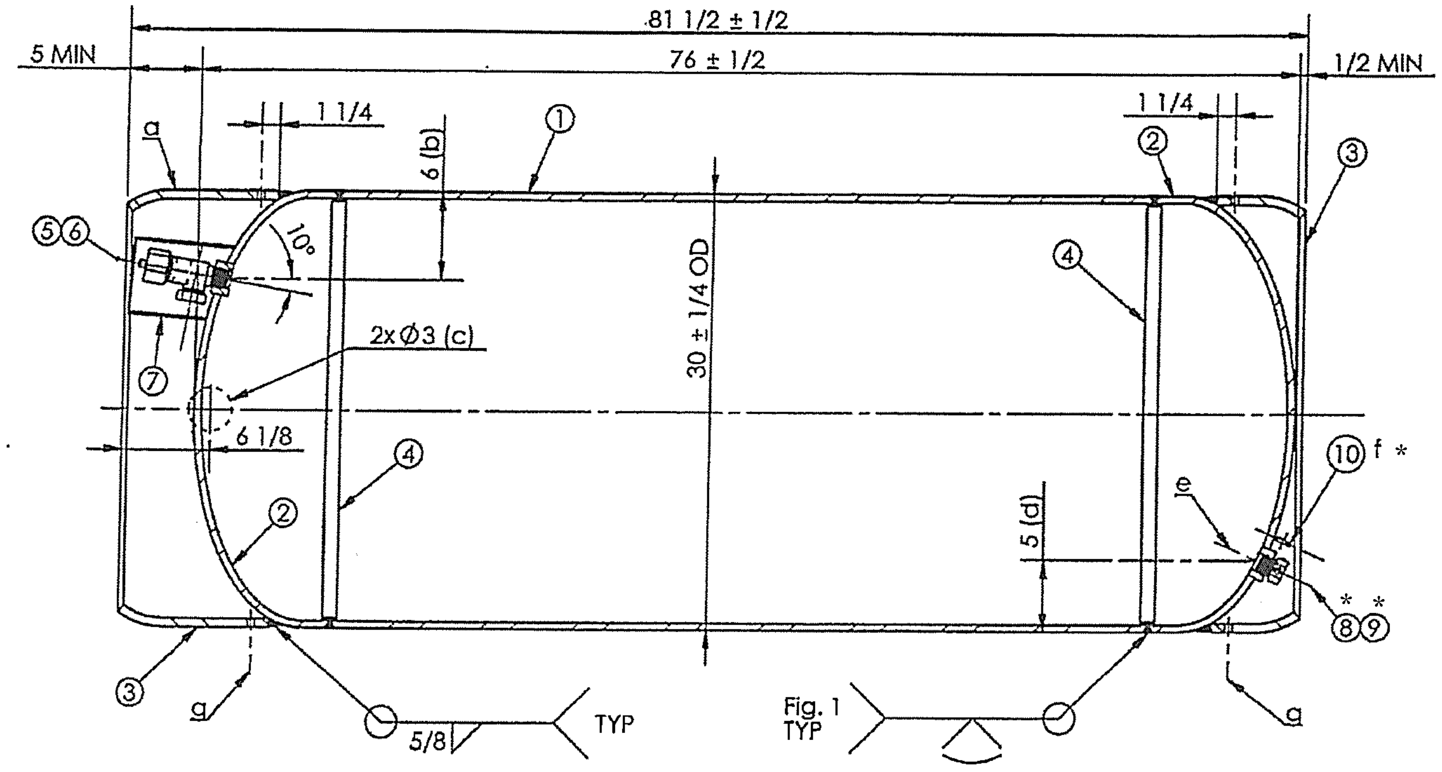
Appendix 1.3.2

Drawing of Model MST-30 Protective Shipping Package

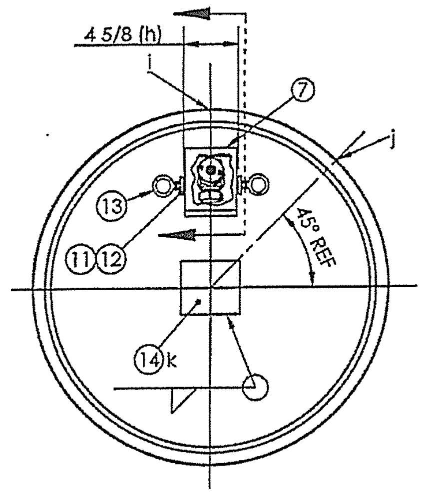
Drawings have been withheld as Sensitive Unclassified Non-Safeguards Information-Security-Related Information

Appendix 1.3.3

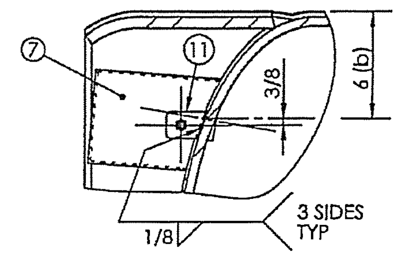
Drawing of 30B Cylinder



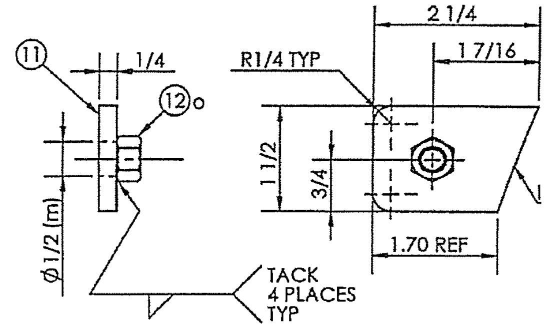
a) Cylinder longitudinal section



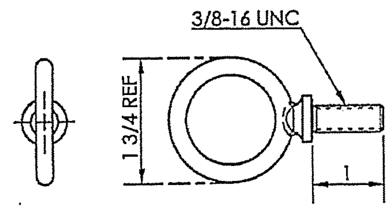
b) Valve end view



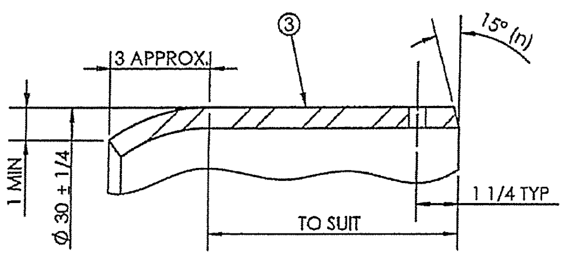
c) Part 11 - location (TYP)



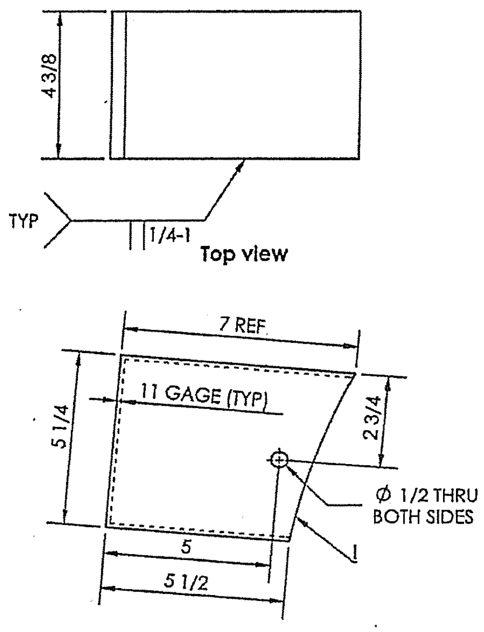
d) Part 11- Right side item detail



e) Part 13 - detail (2 reqd)



e) Typical skirt ring detail



f) Part 7 - detail

PARTS

1. Shell, plate, 1/2 nominal. Shells fabricated using a spiral weld seam shall have the weld start 2 below the horizontal ℄ .
2. Head, 30 OD ellipsoidal (2:1), 1/2 nominal (7/16 min), 2 (min) straight flange.
3. Skirt, plate, 5/8 nominal (see Figure 8e).
4. Backing bar (optional, see Figure 1).
5. Coupling, valve (see Figure 14 for detail).
6. Cylinder valve 51 (see Figure 16).
7. Valve protector, approx 11 gage (see Figure 8 f).
8. Coupling, plug (optional, see Figure 14).
9. Plug (optional, see Figure 17).
10. Seal loop, rod (use in conjunction with use of parts 9 and 10 at plug end, optional at valve end, see Figure 14).
11. Valve protector mounting lug, plate, 1/4 nominal (2 reqd).
12. Nut, SS, 3/8-16 UNC (2 reqd).
13. Eyebolt, shoulder, SS (2 reqd).
14. Nameplate (see Figure 2a for detail).

NOTES

Other than pressure envelope thickness, dimensional tolerances are ± 1/16 unless otherwise indicated. Angular tolerances are ± 2°.

- a Cylinder serial number stamped on valve end skirt. Use approx. 3/8 V-notch stamps.
- b Dimension intersects coupling ℄ at head outer surface.
- c Drill thru skirt on opp sides at horizontal ℄ .
- d Dimension intersects coupling ℄ at head inner surface.
- e Installation of plug and coupling is optional (if used see Fig.14)
- f Weld to head (each leg, see Fig. 14)).
- g Weep holes, 4xØ1/2 drill thru skirt, equally spaced and on vertical and horizontal ℄ 's.
- h Dimesion to inside faces of mounting lugs, lugs shall be parallel and accurately located prior to welding to the head. The valve protector may be used as a locating jig.
- i Longitudinal shell weld, locate on vertical ℄ at top. Locate valve under this weld and align outlet on vertical ℄ .
- j Position of longitudinal skirt weld.
- k Optionally, a nameplate backing plate may be welded to the head and have the nameplate welded to the backing plate. A supplemental nameplate (see Fig. 2c) may be added below the nameplate shown.
- l To suit contour of head.
- m Drill thru part 11 only, before tack-welding. Weld nut on opp. side shown for left side (facing head) lug.
- n Suggested edge prep angle.
- o Nut may be welded on outside of mounting lug or inside valve protector.

Unit: inch
Reference: ANSI N14.1-2012

* Cylinders without plug, plug-coupling and ring for seal may be used for MST-30.

Appendix 1.3.4

Phenolic and Polyurethane Foam

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Phenolic and Polyurethane Foam

Both phenolic and polyurethane foams are used in the MST-30 Overpack. Phenolic foam is used as a thermal insulator, and polyurethane foam is used as a thermal insulator and shock absorber. Figure 1.3.4-1 illustrates the location of the different types of foam used in the MST-30.

1 Phenolic Foam

The phenolic foam used in the MST-30 is based on SP-9 Rev.1; however, equivalent materials have been substituted as necessary. The raw materials and the nominal mixture ratios, as well as the SP-9 values, are shown in Table 1.3.4-1.

1.1 Chemical Composition of Phenolic Foam

Tests performed on phenolic samples confirm that the cured foam has a chemical composition equivalent to that of the mixture of raw materials. Table 1.3.4-2 provides the nominal chemical composition for the cured phenolic foams used in the MST-30, as well as the SP-9-Rev.1 specification.

1.2 Chlorine Content

The Phenolic Resin (BRL-2760) used to produce the MST-30 foam does not include chlorine compounds such as hydrochloric acid in the neutralization process; therefore, the chlorine content for the cured product is very small. The foam is also subject to a free chlorine limitation of 0.05wt%(500ppm), consistent with the Japanese competent authority's approval of the packaging. As a part of the foaming process, samples are taken from each batch for testing. The results of these analyses are provided in Table 1.3.4-3 for the overpacks produced to date. As shown in Table 1.3.4-3, the free chlorine content is less than 0.01w%(100ppm), well below the maximum allowable.

2 Polyurethane Foam

The raw materials and nominal mixing ratios used to produce the polyurethane foam for the MST-30 overpack are provided in Table 1.3.4-4. The polyurethane foam produced for the MST-30 uses a phenolic-based resin. The reaction mechanism for production of the polyurethane foam is shown in Figure 1.3.4-2.

2.1 Chemical Composition

The theoretical chemical composition for the polyurethane foam used in the MST-30 is shown in Table 1.3.4-5.

2.2 Chlorine Content

The polyurethane specified for use in the MST-30 uses HCFC-141b or HFC-365mfc as a foaming (blowing) agent. The molecular formula of HCFC-141b is $CCl_2F\text{-}CH_3$; thus, the cured foam contains a large amount of stable chlorides which come from HCFC-141b. However, as those chlorides are not leachable, they do not become free chlorine, and most of the HCFC-141b is trapped within the closed-cell foam. Samples of a similar polyurethane foam were tested for free chlorine and the results showed that the amount of free chlorine is on the order of 0.007wt%(7ppm). Therefore, the polyurethane foam used is not expected to cause pitting corrosion on the shell of the overpack.

In addition, the molecular formula of HFC-365mfc, which is another foaming agent used for polyurethane foam instead of HCFC-141b, is $CF_3\text{-}CH_2\text{-}CF_2\text{-}CH_3$ which does not contain chlorine.

2.3 Closed-Cell Content

Tests were completed on foam samples using ASTM D 2856 "Standard Test Method for Open-Cell of Rigid Cellular Plastic by Air Pycnometer." The closed-cell ratio measured for the foam was greater than 98%.

2.4 Fire Resistance

As stated previously, the polyurethane foam utilized in the MST-30 uses a phenolic-based resin. The benzene ring in the molecule creates favorable carbide under high temperature conditions, providing a foam that is capable of withstanding high temperatures without decomposing.

The polyurethane foam has been tested for weight loss over a range of temperatures. As shown in Figure 1.3.4-3, significant weight loss does not occur until a temperature of approximately $300^{o}C$. Figure 1.3.4-3 also shows the weight loss curve for a polyurethane foam based on a other types of resins made using normal polyol (not phenolic-based resin) for comparison.

Table 1.3.4-1 Materials and Proportions of Phenolic Foam

Material	Vender-Trade Name	Component wt% (Note 1)
Phenolic Resin	Showa Highpolymer CO.,LTD. BRL-2760	67.1±0.2 (66.2±0.2)
Surfactant	Nippon Unicar CO.,LTD or Dow Corning Toray Co.,LTD. L-7002	2.0±0.1 (2.0±0.1)
Refrigerant	HCFC-141b or HFC-365mfc	4.7±0.1 (5.9±0.1)
Boric Anhydride (B_2O_3), Powder	BORAX BOLIC OXIDE	8.4±0.2 (8.3±0.1)
Oxalic Acid	JIS K 1357, or equivalent	8.4±0.1 (8.3±0.1)
Fiberglass	JIS R3419, or equivalent	9.4±0.1 (9.3±0.1)

(Note 1) Non-parenthetical values show components value in case HCFC-141b is used as foaming agent, and parenthetical values show in case HFC-365mfc is used.

Table 1.3.4-2 Chemical Composition of Phenolic Foam

wt%

	C	H	B	Si	Cl
SP-9	41.0	4.5	3.2	2.2	0.5
M1	55.3	5.4	2.5	1.8	0.03
M2	45.36	5.25	3.81	2.27	1.6
M3	53.06	5.33	2.3	4.84	0.22
M4	53.05	5.34	2.38	3.59	0.46
J1	58.15	5.6	2.41	3.25	0.031
J2	55.73	5.35	2.33	5.48	0.15
J3	56.79	5.56	2.55	2.7	0.14
A1	48.04	5.61	1.5	1.2	$<5x10^{-4}$

(Note) M1~M4 and J1~J3 are sampling results of Phenolic foam using HCFC-141b as foaming agent, and A1 is for HFC-365mfc used as a foaming agent.

Table 1.3.4-3 Free Chlorine Content of Phenolic Foam

Phenolic Foam using HCFC141b wt%

No.	Free Chlorine	No.	Free Chlorine	No.	Free Chlorine
00-1	0.0046	00-16	0.0020	00-31	0.0012
00-2	0.0093	00-17	0.0023	00-32	0.0012
00-3	0.0040	00-18	0.0017	00-33	0.0013
00-4	0.0032	00-19	< 0.0005	00-34	0.0006
00-5	0.0032	00-20	< 0.0005	00-35	0.0006
00-6	0.0035	00-21	< 0.0005	00-36	< 0.0005
00-7	0.0034	00-22	< 0.0005	00-37	0.0009
00-8	0.0049	00-23	< 0.0005	00-38	0.0007
00-9	0.0044	00-24	< 0.0005	01-1	0.0010
00-10	0.0037	00-25	< 0.0005	01-2	0.0011
00-11	0.0037	00-26	< 0.0005	01-3	0.0008
00-12	0.0030	00-27	< 0.0005	01-4	0.0008
00-13	0.0041	00-28	< 0.0005	01-5	0.0010

Phenolic Foam using HFC-365mfc wt%

No.	Free Chlorine	No.	Free Chlorine
05-1	< 0.0005	08-1	< 0.0005
05-2	< 0.0005	08-2	< 0.0005
05-3	< 0.0005		
06-1	< 0.0005		
06-2	< 0.0005		

Table 1.3.4-4 Materials and Proportions of Polyurethane Foam

Material	Vender-Trade Name	Component wt%
Polyol	Showa Highpolymer CO.,LTD. R-210 or R-211	43.2
Isocyanete	Showa Highpolymer CO.,LTD. I-210	52.3
Specified Reagent	Showa Highpolymer CO.,LTD. G210/H210, or equal	4.5

Table 1.3.4-5 Calculated Chemical Composition of Polyurethane Foam

wt%

	C	H	N	O	P	F	Cl	Al
Polyurethane Foam	66.7 (69.1)	6.7 (6.1)	5.7 (5.7)	18.5 (18.0)	0 (0.1)	0.3 (0.2)	1.3 (-)	0.8 (0.8)

(Note 1) Non-parenthetical values show composition values in case R-210 is used as polyol, and parenthetical values show in case R-211.

Table 1.3.4-6 Closed Cell Ratio of Polyurethane Foam

Polyurethane Foam Density g/cm^3	Closed Cell Ratio %
0.37	98.5
0.48	98.8

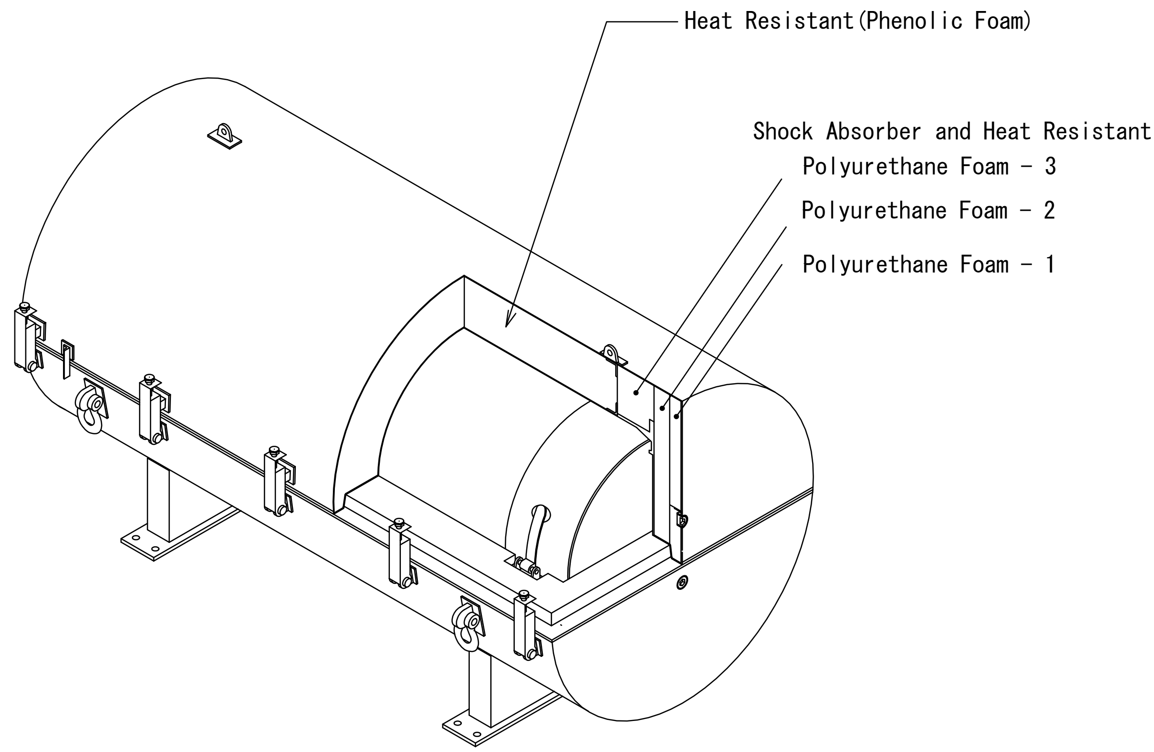

Figure 1.3.4-1 Phenolic and Polyurethane Foam

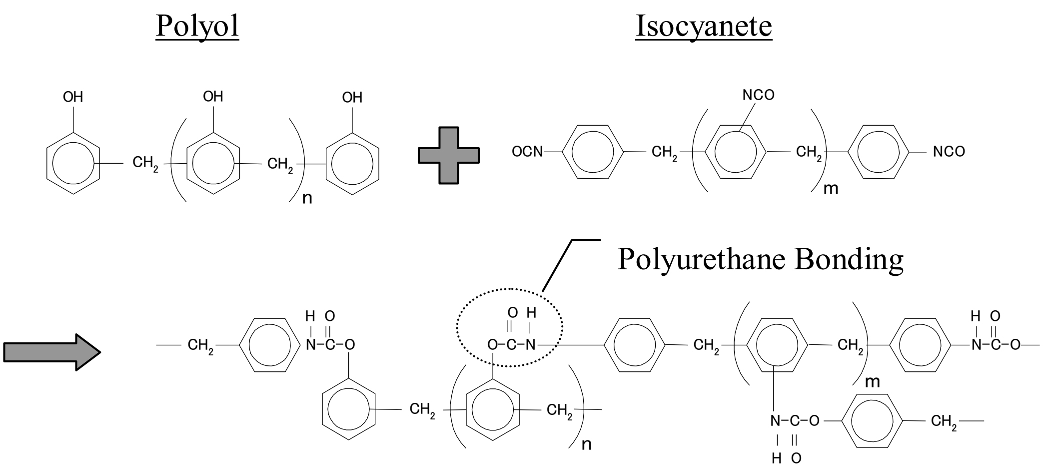

Figure 1.3.4-2 Reaction Mechanism of Polyurethane Foam

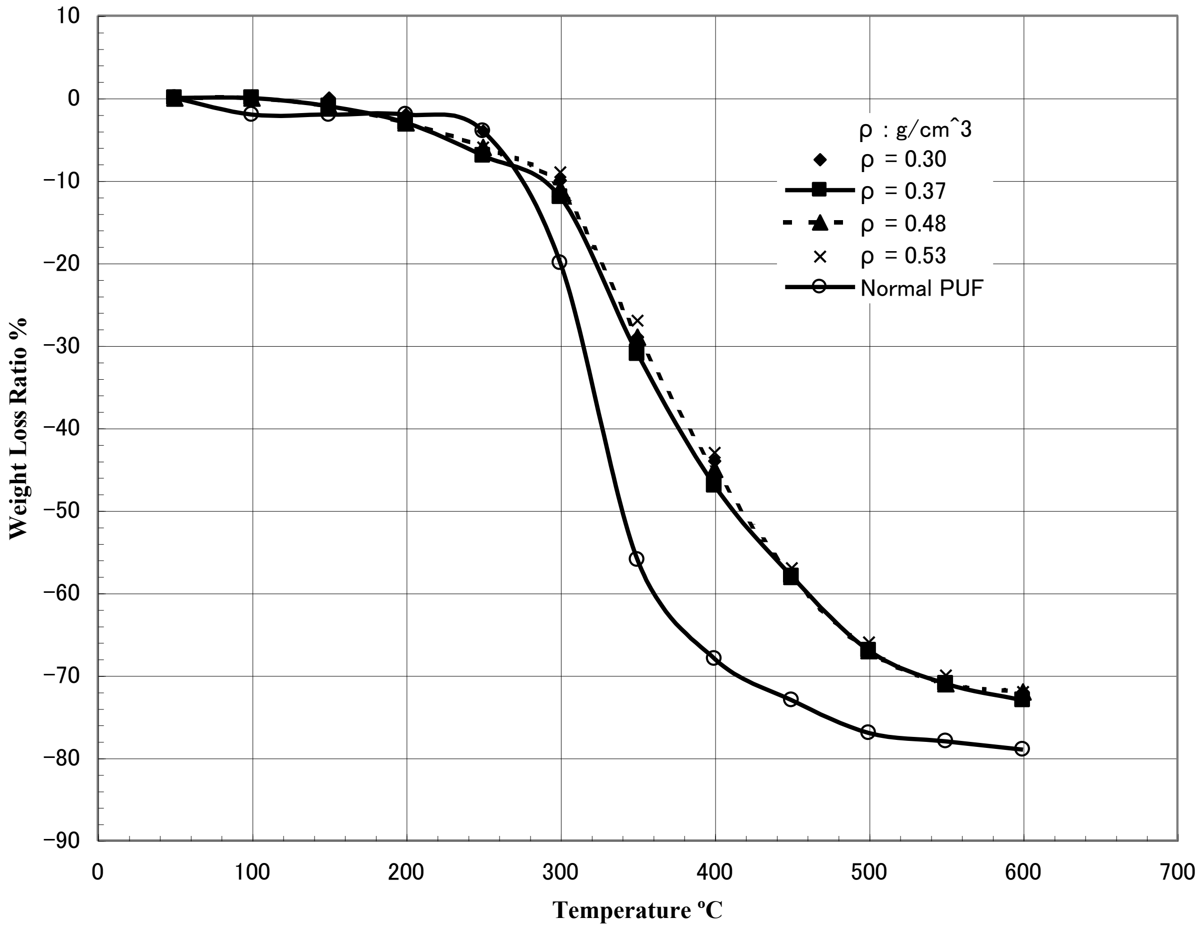

Figure 1.3.4-3 Curve of weight loss on heating of Polyurethane Foam

SECTION 2 STRUCTURAL EVALUATION

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2.0 STRUCTURAL EVALUATION

2.1 Structural Design

2.1.1 Discussion

The MST-30 Protective Shipping Package (MST-30) is a Type A Fissile package used for the shipment of 30-inch cylinders containing Uranium Hexafluoride (UF_6) enriched up to 5wt% U-235. Drawings of the MST-30 overpack including the ring plate are provided in Appendix 1.3.2. A drawing of the 30B UF_6 cylinder is provided in Appendix 1.3.3.

The MST-30 is approximately 1.2m (approx. 47 inches) in diameter by 2.4m (approx. 95 inches) long. The MST-30 package consists of the overpack, the ring plate and the 30B cylinder. The overpack consists of steel inner and outer shells filled with polyurethane and phenolic foam. The overpack is split axially with a stepped joint, creating upper and lower sections to allow loading of the UF_6 cylinder. Three layers of polyurethane foam plates are provided in the ends of the overpack for shock-absorption and fire-resistance. Phenolic foam is used in the annular areas of overpack for fire-resistance. The ring plate is inserted in the gap on the plug side between the overpack and the 30B cylinder. The MST-30 has been rigorously tested according to the regulatory requirements to assure water leak-tightness of the UF_6 cylinder, since it is absolutely required that water be excluded from the cylinder for moderation control of enriched UF_6.

2.1.2 Design Criteria

The MST-30 is designed to conform to the technical and regulatory requirements of a Type A, Fissile UF_6 Package as specified in the Japanese Safe Transport Regulations pursuant to SSR-6. The package is intended to be used for transport from, to, or through foreign countries, including the USA. The MST-30 package is also designed in compliance with the current 10CFR Part 71 and 49CFR Part 173 Subpart I.

2.2 Weights and Center of Gravity

The maximum weights and Center of Gravity of MST-30 Overpack are shown in Table 2-1 and Figure 2-1.

2.3 Mechanical Properties of Materials

The Yield and Tensile strength of the metal used is provided in Table 2-2. The compressive strength and density of the insulation used is provided in Table 2-3.

2.4 General Standards for All Packages

2.4.1 Minimum Package Size

The MST-30 packaging meets the minimum size requirement specified in Para. 636 of SSR-6 and 10CFR § 71.43(a).

2.4.2 Tamper Proof Feature

Each UF_6 cylinder must be secured for shipment with a numbered tamper-indicating device (TID). The TID is attached to each cylinder-valve in the manner shown in USEC-651, Rev.10. Furthermore, four (4) stainless steel semi-circular rings are welded at the overpack closure joint to provide a tamper-indicating device for the overpack. Thus, the package is in compliance with Para. 637 of SSR-6 and 10 CFR § 71.43(b).

2.4.3 Positive Closure

The top and bottom halves of overpack are securely closed with ten (10) fastening devices in accordance with Paras. 613 and 641 of SSR-6 and 10 CFR § 71.43 (c). The fastening devices utilize a swing-lever system that assures positive capture of the fasteners. Each device is equipped with a M20 size JIS SUS-316 (equivalent to ASTM SS-316) stainless steel bolt to assure that the halves of the overpack are not inadvertently opened by vibration or shock during transport of the packages.

2.4.4 Chemical and Galvanic Reactions

The MST-30 materials of construction, stainless steel, carbon steel, Monel, aluminum bronze, polyurethane foam, phenolic foam, neoprene, silicone rubber, are such that no significant chemical or galvanic reactions occur between the package components and/or the package contents in accordance with Para. 614 of SSR-6 and 10 CFR § 71.43 (d).

2.5 Lifting and Tie-down Devices for All Packages

2.5.1 Lifting Devices

The MST-30 package may be lifted as intended using either a fork-truck or a crane. In case of using a fork-truck, the fork-truck tines are supported by angle reinforcements at the base of the package. Normally, when using a crane, the package is lifted directly using slings. Alternatively, the package also may be lifted by crane using shackles (see the drawings provided in Appendix 1.3.2).

For lifting with shackles, the package is lifted with four (4) shackles fitted into the shackle fixtures welded on the outer shell of bottom half using a four-point lifting sling. The shackles are made of JIS SUS304 24- and 30-mm diameter stock and each shackle has a minimum proof load of 70.60kN (15,872lbf).

The package is normally lifted with each steel rope of the sling at a lifting angle of more than 60° (from horizontal). The lower the lifting angle, the severer the load on the shackle becomes. The maximum load on each shackle (i.e. at a lifting angle of 60°) is:

$$[(4170 \text{ kg})\ (g)\ /\ 4]\ [1/\sin 60^{o}] = 1.181 \times 10^{4} \text{ N} \quad (2{,}654 \text{ lbf}).$$

Therefore, the margin of safety (M.S.) is:

$$\text{M.S.} = (7.060 \times 10^{4} \text{ N} / 1.181 \times 10^{4} \text{ N}) - 1 = 4.9.$$

Using the geometry for the shackle support fixture shown in Figure 2-2 and applying the stress concentration factor [Reference 2.11.2] also shown in Figure 2-2, the maximum stress on each shackle support fixture is:

$$\sigma_{max} = \alpha \cdot \sigma_0 = 2.22\ (11.25 \text{ N/mm}^2) = 24.98 \text{ N/mm}^2\ (3{,}620 \text{ psi}).$$

where;

α	Stress Concentration Factor = 2.22 (See Figure 2-2)
a	Radius of the Hole of the Shackle Support Fixture = 16 mm
b	Width of the Shackle Support Fixture = 37 mm
h	Thickness = 25 mm
P	Tensile Load = 1.181×10^4 N
a/b	0.4324
σ_o	Mean Stress on the Cross Section, where:

$$\sigma_0 = \frac{P}{2(b-a)h} = \frac{1.181 \times 10^4\ N}{2 \times (37\ mm - 16\ mm) \times 25\ mm} = 11.25\ \text{N/mm}^2\ \ (1{,}631\ \text{psi}).$$

Therefore, the margin of safety for shackle support fixture can be obtained as:

$$\text{M.S.} = (205\ \text{N/mm}^2\ /\ 24.98\ \text{N/mm}^2) - 1 = 7.2.$$

Thus, the lifting shackles and shackle support fixtures exceed the minimum safety factor of three against yielding required by regulation when the package is lifted in the intended manner.

Para. 608 of SSR-6 requires that each lifting device that is a structural part of the package be designed so that failure of the device under excessive loading would not impair the ability of the package to meet other requirements in the regulation. If the MST-30 is lifted improperly, the lifting shackles could fail under excessive loads. The worst-case result of lifting shackle failure is a drop of the package. Free drop tests under normal and hypothetical accident conditions as prescribed in the regulations were performed using full-scale prototypes of the MST-30 package, and the test results demonstrate that the package integrity is maintained (See Sections 2.6.7 and 2.7.1, and Appendix 2.10.1). Therefore, in the event of shackle failure due to improper lifting and excessive loading, the ability of the package to meet the other requirements of IAEA regulations or Subpart E of 10CFR Part 71 would not be impaired.

2.5.2 Tie-down Devices

MST-30 package is tied down to the carrier vehicle at eight bolted locations in the foot plate using M18 bolts. When subjected to the acceleration loads specified in 10CFR § 71.45, the combined horizontal load on the bolts is the square root sum of the squares of the 10g acceleration along the direction of vehicle travel and the 5g transverse acceleration:

$$\text{Combined Horizontal Load} = \sqrt{10^2 + 5^2}\; g\,(4170\; kg) = 4.573 \times 10^5\, N \;\; (103{,}000 \text{ lbf}).$$

For the eight bolts used, the shearing stress on each bolt is:

$$\tau = \frac{4.573 \times 10^5\, N}{8 \times \frac{\pi}{4} \times (17.57\, mm)^2} = 235.8\; N/mm^2 \;(34{,}200 \text{ psi}).$$

Assuming that the allowable shear stress is 0.6 of the yield strength ($0.6\sigma_y$) of the bolt material, the margin of safety against shearing the tie down bolts is:

$$\text{M.S.} = \frac{0.6 \times 940\; N/mm^2}{235.8\; N/mm^2} - 1 \;= 1.39.$$

With the package loaded side way on a carrier, the 10g longitudinal load creates a coupling moment about the center of gravity, placing a vertical load, V_1, on the 4 bolts along one side of the package. The 5g transverse load creates a similar vertical load, V_2, on the 4 bolts at one end of the package. The magnitude of V_1 and V_2 are:

$$V_1 = 10\,(4170\, g)(700/1016) = 2.818 \times 10^5\, N \;(63{,}400 \text{ lbf})$$

$$V_2 = 5\,(4170\, g)(700/1474) = 9.711 \times 10^4\, N \;(21{,}800 \text{ lbf}).$$

The 2g vertical load (V_3) on 8 bolts is:

$$V_3 = 2\,(4170\, g) = 8.179 \times 10^4\, N \;\; (18{,}400 \text{ lbf}).$$

The maximum total vertical load on a bolt (V) is:

$$V = (2.818 \times 10^5 / 4\,bolts) + (9.711 \times 10^4 / 4\,bolts) + (8.179 \times 10^4 / 8\,bolts)$$

$$= 1.050 \text{ x } 10^5 \text{ N } (23{,}600 \text{ lbf}).$$

Thus, the maximum tensile stress applied to a bolt due to the acceleration loads specified by regulation is:

$$\sigma = \frac{1.050 \times 10^5\ N}{\frac{\pi}{4} \times (17.57\ mm)^2} = 433.1\ \text{N/mm}^2\ (62{,}950\ \text{psi}).$$

The allowable stress for the bolt is assumed to be the lesser of $(1.4\sigma_y - 1.6\tau)$ or (σ_y), where σ_y is the yield strength of the bolt material and τ is the shearing stress on the bolt [Reference 2.11.3]. Since,

$$\sigma_y = 940\ \text{N/mm}^2\ (136{,}300\ \text{psi})\ \text{and}$$

$$1.4\sigma_y - 1.6\tau = 938.7\ \text{N/mm}^2\ (136{,}100\ \text{psi}),$$

the allowable bolt stress is 938.7 N/mm^2.

Therefore, for a bolt stressed by the regulatory specified accelerations, the least margin of safety is:

$$\text{M.S.} = (938.7\ \text{N/mm}^2 / 433.1\ \text{N/mm}^2) - 1 = 1.16,$$

and the stress resulting due to the regulatory specified accelerations is well below the yield strength of the bolt material.

2.6 Normal Conditions of Transport

2.6.1 Heat

The maximum temperature of the package and contents is 60°C (140°F) for Normal Conditions of transport (see Section 3). The maximum pressure of the contents is 123 kPa (18 psia) for Normal Conditions of Transport (see Section 3). Therefore, the maximum internal pressure of cylinder is well below the design pressure of cylinder specified in ANSI N14.1 and ISO 7195.

2.6.2 Cold

The minimum temperature of the package and contents is limited to –20°C (–4°F) for Cold conditions of transport as specified in the Japanese design certificate of MST-30 (see Appendix 1.3.1).

On the other hand, the cylinder is fabricated in accordance with ANSI N14.1 or ISO 7195 which specify the minimum transport temperature is -40°C. The JIS SUS304 stainless steel used in MST-30 overpack has no possibility of the ductile to brittle transition since it is

austenitic stainless steel.

Therefore, it will not have adverse effect on package materials even if an ambient temperature lowers to -20°C or -40°C during transportation.

2.6.3 Reduced External Pressure

Assuming that the cylinder's internal pressure is at the minimum (0 psia), the net pressure on cylinder resulting from a reduced ambient pressure of 60kPa (8.7psia) (Para. 645 of SSR-6) is 60kPaG (8.7psig), applied as an external pressure. The 30B cylinder is designed for an external pressure of 172kPa (25 psig) as specified in ANSI N14.1 and ISO 7195; therefore, the net external pressure of 60kPaG is well within the capabilities of the cylinder.

Alternatively assuming that the cylinder's internal pressure is at the maximum (123kPa (18psia)), the net pressure on the cylinder resulting from the 60kPa external pressure is 63kPaG (9.1psig) applied as an internal pressure. The 30B cylinder is designed for an internal pressure of 1.38MPa (200 psig) as specified in ANSI N14.1 and ISO 7195; therefore, the net internal pressure of 63kPaG (9.1psig) is well within the capabilities of the cylinder.

2.6.4 Increased External Pressure

Conservatively assuming a minimum cylinder internal pressure of 0kPa (0 psia), an increased external pressure of 140kPa (20 psia) in accordance with 10CFR results in a net external pressure of 140kPaG (20 psig). The 30B cylinder is designed for an external pressure of 172kPaG (25 psig) as specified in ANSI N14.1 and ISO 7195; therefore, the net external pressure of 140kPaG (20 psig) is well within the capabilities of the cylinder.

2.6.5 Vibration

Vibration incident to normal transport has a negligible effect on the MST-30 package. Neoprene pads on the inner surface of the overpack firmly hold the 30B cylinder to prevent movement during transport. A "HELI-SERT" is used in the fastening device to avoid bolt loosening.

Assuming that MST-30 package is mass-spring system of which the leg is a spring as shown in Figure 2-3, the natural frequency of the MST-30 [Reference 2.11.4] is:

Natural frequency in the longitudinal direction, T_1:

$$T_1 = 2\pi\sqrt{\frac{W}{K_1 \cdot g}} = 2\pi\sqrt{\frac{2.045\times10^4 N}{2.344\times10^5 N/mm \times 9806.65\,mm/s^2}} = 1.88\times10^{-2} s$$

Natural frequency in the side direction, T_2:

$$T_2 = 2\pi\sqrt{\frac{W}{K_2 \cdot g}} = 2\pi\sqrt{\frac{2.045\times10^4\, N}{1.061\times10^6\, N/mm \times 9806.65\, mm/s^2}} = 8.81\times10^{-3}\, s$$

where,

W is the load on a leg, 1/2 x 4170kg x 9.80665m/s^2 =2.045 x 10^4 N

g is the acceleration of gravity, 9806.65 mm/s^2

K_1 is the Spring Constant in the longitudinal direction [N/mm]

K_2 is the Spring Constant in the side direction [N/mm]

and

$$K_1 = \frac{1}{\frac{h^3}{12EI_y} + \frac{h}{GA_{s1}}} = \frac{1}{\frac{299^3}{12\times194000\times5.078\times10^6} + \frac{299}{74600\times2000}} = 2.344\times10^5\, N/mm$$

$$K_2 = \frac{1}{\frac{h^2(3H-h)}{6EI_x} + \frac{(H-h)h(H-h/2)}{EI_x} + \frac{h}{GA_{s2}}}$$

$$= \frac{1}{\frac{299^2\times(3\times700-299)}{6\times194000\times9.639\times10^8} + \frac{(700-299)\times299\times(700-299/2)}{194000\times9.639\times10^8} + \frac{299}{74600\times9000}}$$

$$= 1.061\times10^6\, N/mm$$

where,

h is the height of the Legs to the body, 299 mm

H is the height to the center of gravity, 700 mm

E is the Modulus of longitudinal elasticity, 194,000 N/mm^2

G is the Modulus of transverse elasticity, 74,600 N/mm^2

I_x is the Moment of inertia of area for the leg in the longitudinal direction, 9.639 x 10^8 mm^4

I_y is the Moment of inertia of area for the leg in the side direction, 5.078 x 10^8 mm^4

A_{S1} is the Effective cross sectional area of leg for the longitudinal direction, 2,000 mm^2

A_{S2} is the Effective cross sectional area of leg for the side direction, 9,000 mm^2

Thus, the natural frequency of the package is approximately 53 Hz in the longitudinal direction and approximately 113 Hz in the side direction.

On the other hand, the frequency of vibration generated by the transport vehicle (truck-trailer or

truck) ranges from 0 to 10 Hz during routine, normal conditions of transport according to the MNF's road survey using vibro-meter. Therefore, the package does not resonate, because the natural frequency of the package is out of the frequency range of vibration of the vehicle.

2.6.6 Water Spray

The package's curved surfaces inhibit the collection of rainwater and/or seawater when the packaging is closed. Additionally, the outer shell is constructed from stainless steel that does not allow water to penetrate. The step-joint at the closure is sealed with silicone rubber gaskets to prevent water ingress during normal conditions of transport. Thus, a one-hour water spray at a rate of 5cm/hr (2 in/hr) would have no effect on the MST-30.

2.6.7 Free Drop

In accordance with the relevant regulations (Para. 722 of SSR-6), the packaging must be drop tested in the position for which the most damage is expected through a distance of 1.2 m (4 ft).

Drop testing was conducted using three full-scale prototypes of the MST-30. The test results are summarized in Table 2-4. A complete description of the tests completed is provided in Appendix 2.10.1. The MST-30s were tested in a variety of orientations at 0.3 and 1.2 m. The packaging maintained its integrity throughout and following the series of tests.

2.6.8 Corner Drop

Since the MST-30 package weighs more than 100kg (220lb), this drop is not required for the MST-30 according to 10CFR. However, a 0.3m (1ft) corner free drop prior to the 1.2m corner free drop was performed in compliance with the Japanese regulations in effect at the time of the test.

2.6.9 Compression

Regulations require that the top and bottom of the package be subjected to a compressive load equal to five times the mass of the package or 13 kPa (2lbf/in^2) multiplied by the vertically projected area of the package, whichever is greater, for a period of 24 hours.

In the case of the MST-30, the equivalent of five times the mass of the actual package provides the higher loading.

$$W_1 = 5\ (4170\ \text{kg})\ g = 2.045 \times 10^5\ \text{N}\ (45{,}970\ \text{lbf})$$

Assuming that outer shell of MST-30 is a beam supported at two point as shown Figure-2-4 , the maximum moment acting on the outer shell [Reference 2.11.2] is :

$$M = \frac{(2.045 \times 10^5 N) \times (2408 mm)}{2} \left(\frac{1}{4} - \frac{467 mm}{2408 mm} \right) = 1.381 \times 10^7 N\text{-}mm$$

The bending stress acting on the outer shell is:

$$\sigma = \frac{M}{Z} = \frac{1.381 \times 10^7 \ N - mm}{3.384 \times 10^6 mm^3} = 4.081 \ N/mm^2 \ (592 \text{ psi})$$

where,

Z is the section modulus of outer shell [mm^3]

$$Z = \frac{\pi}{32} \frac{(1200 mm)^4 - (1194 mm)^4}{1194 mm} = 3.384 \times 10^6 mm^3$$

Since the yield stress of outer shell is 205 N/mm^2 (29,700 psi), the margin of safety against failure of the outer shell is:

$$\text{M.S.} = \frac{205}{4.081} - 1 = 49.2$$

Therefore, the outer shell is capable of maintaining the structural integrity of the packaging under the compression loading.

2.6.10 Penetration

Dropping a 6 kg (13 lb) rod onto the MST-30 as described in Para. 724 of SSR-6 has a negligible effect on the 3mm (0.12 in) stainless steel shell.

2.6.11 Summary of Normal Conditions of Transport

Following the1.2m (4ft) Free drop tests, the prototypes remained closed, with no gaps that would admit a 10-cm cube. The gross package dimensions were maintained, and the gross volume of the packaging was reduced by approximately 0.2% in maximum. Therefore, MST-30 is in accordance with Para. 678 of SSR-6 and 10 CFR § 71.55 (d)(4).

2.7 Hypothetical Accident Conditions (HAC)

Three full-scale MST-30 prototypes containing simulated loads were subjected to the regulatory sequence of drop, puncture and fire tests specified by IAEA and 10CFR. A flow chart of the test sequence is provided in Figure 2-5. A summary of the damage accumulated during the tests is provided in Table 2-4.

Each test article consisted of a MST-30 prototype overpack, loaded with a 30B cylinder containing a simulated payload. The prototypes were fabricated to the drawings provided in Appendix 2.10.1 (Figure 2.10.1-2). Prototype A is used for Vertical Drops (End Drops) throughout the testing (including the Normal condition). Prototype B is used for the Corner Drops throughout the testing (including the Normal condition). Prototype C is used for the Horizontal Drops (Side Drops) throughout the testing (including the Normal condition). In order to indicate valve contact with the overpack wall during impact, an aluminum honeycomb was inserted in the valve pocket of Prototype A and B prior to all test series (i.e. prior to Normal Condition drop). These prototype drop tests were conducted without ring plate.

The target for the free drop tests and puncture tests of MST-30 package was constructed to satisfy the guidance specified in the Advisory Material for 1985 IAEA regulations, i.e. IAEA Safety Series No.37.

Following the series of tests, it was confirmed that no water leaks (ingress) into 30B cylinder occurred, and that the overpack remained closed at all times.

In addition to the above-mentioned prototype drop tests, analyses using LS-DYNA code were conducted for the Vertical Drop (End Drop) and Corner Drop configurations in order to confirm that the cylinder valve and plug do not make contact with the overpack in the HAC. As the results, it was confirmed that the valve and plug have no contact with the overpack. The detail of the evaluation using LS-DYNA is provided in Appendix 2.10.6.

2.7.1 Free Drop

The same MST-30 prototype that was subjected to the Normal Condition drop tests was used for the HAC sequence. The package was not opened or repaired prior to the HAC sequence. The package was dropped through a distance of 9m (30 ft) onto an unyielding surface. Three tests were performed on the prototypes: Vertical Drop(End Drop), Horizontal Drop(Side Drop), and Corner Drop. The outlines of the tests are presented in 2.7.1.1 to 2.7.1.5. Details of the tests are provided in Appendix 2.10.1 and a summary of the test results is provided in Table 2-4.

Furthermore, evaluation by LS-DYNA is carried out for the orientations of Vertical Drops and Corner Drops on the valve and plug ends. The outline is presented in 2.7.1.6.

2.7.1.1 End Drop

Following the Normal Condition Drops, the MST-30 Prototype A was subjected to two 9m (30 ft) vertical drops (end drops), one on the valve end, one on the plug end. As a result of the impacts, the prototype was damaged at both the plug end and the valve end, with deformation of 18 and 15 mm (0.6 and 0.7in), respectively. The overpack remained closed following the impact. Some fastening devices (closures) were slightly damaged due to the drop impact, but all devices remained in place and fastened following the drop. Further details are available in Appendix 2.10.1. Table 2-4 tabulates the results of the HAC drop tests.

2.7.1.2 Side Drop

Following the Normal Condition Drops, the MST-30 Prototype C was subjected to a 9m (30 ft) horizontal drop (side drop). As a result of the impact, the prototype was damaged at the impact site, with a maximum deformation of 18 mm (0.7in). The overpack remained closed following the impact. Some fastening devices (closures) were slightly damaged due to the drop impact, but all devices remained in place and fastened following the drop. Further details are available in Appendix 2.10.1. Table 2-4 tabulates the results of the HAC drop tests.

2.7.1.3 Corner Drop

Following the Normal Condition Drops, the MST-30 Prototype B was subjected to a 9m (30 ft) corner drop. The radial axis of the packaging was oriented at an angle of 27 degrees with the horizontal, to align the package's center of gravity over the corner. As a result of the impact, the prototype was damaged at impact site, with deformation of 125 and 252 mm (4.9 and 9.9 in) along the longitudinal and radial axis, respectively. The overpack remained closed following the impact. Some fastening devices (closures) were slightly damaged due to the drop impact, but all devices remained in place and fastened following the drop. Further details are available in Appendix 2.10.1. Table 2-4 tabulates the results of the HAC drop tests.

2.7.1.4 Oblique Drop

Preliminary drop testing and analytical evaluations were performed prior to the compliance tests in order to verify that the MST-30 overpack would perform as designed and to choose the drop angle that would cause the maximum damage to the overpack.

Analytical evaluations identified two orientations producing the maximum damage to the cylinder valve. These two orientations were further evaluated in two series of preliminary drop tests. The first series was a slanting drop (oblique drop) orientation directly toward the cylinder-valve, with the center of gravity over the impact site (15º). The second series was a slanting drop toward the cylinder valve with the center of gravity over the corner (27º). The results of the preliminary tests showed that the 15º drop angle did not cause as much damage as the 27º drop angle, and the 27º drop angle is used in the compliance test program. Further details are available in Appendix 2.10.2.

2.7.1.5 Polyurethane Foam Strength Tolerance Effect on Package Performance

The specification of the MST-30 polyurethane foam provides a range of foam compressive strength to allow for manufacturing variations. In order to bound the effect of the minimum foam compressive strength for the HAC tests, the effects of the fabrication deviation of polyurethane foam compressive strength is evaluated in Appendix 2.10.3. The results of the evaluation show that the allowable variation does not affect the performance of the overpack.

2.7.1.6 Evaluation by LS-DYNA

Analyses by LS-DYNA are conducted in the conditions of drops from 10.2m height taking into account the cumulative effect of the normal conditions of transport. The drop orientations are Vertical Drops and Corner Drops on the valve and plug ends. The calculation results show that the valve and plug have no contact with the overpack. The detail is provided in Appendix 2.10.6.

2.7.1.7 Summary of Results

Following the Normal Condition Drops, the three prototypes were subjected to 9m (30ft) free drops. Some of the fastening devices (closures) were slightly damaged due to the drop impact, but all of the devices remained in place and fastened following the drops. The resulting deformation of the prototypes is summarized in Table 2-4.

Furthermore, evaluation by LS-DYNA was conducted. The results show that the cylinder valve and plug have no contact with the overpack.

2.7.2 Puncture

Following the Normal Condition Drops and the 9m (30 ft) drops, the MST-30 prototypes were subjected to four 1m (40 in) puncture drops (an vertical puncture (end puncture) was performed

on both the plug and valve ends for Prototype A). Prior to puncture testing, the prototypes were not opened or repaired. The test results are summarized in Table 2-5. The details are provided in Appendix 2.10.1.

As described in Appendix 2.10.1, TEST-A (vertical drop) and TEST-B (corner drop) were conducted using specimens with a 40-mm (1.6 in) thick aluminum honeycomb inserted into the valve-pocket (valve-space) to indicate any physical contact between the valve and any other components.

The honeycomb was inspected after the test series was completed (TEST-A after puncture drop and TEST-B after thermal test). No marks were found on the material, indicating that the cylinder valves did not contact the honeycomb during either TEST-A or TEST-B. Therefore, a margin equivalent to at least the thickness of the aluminum honeycomb (40mm) exists for contact between the valve and any other components for HAC.

With regard to the evaluation by LS-DYNA, it was calculated taking into account the cumulative effect of the free drop. The drop orientations are Vertical and Corner Drops on to the valve and plug positions. The calculation results show that valve and plug have no contact with the overpack. The detail is provided in Appendix 2.10.6.

2.7.3 Thermal

The thermal test was performed on a full-scale prototype (Prototype B) following the drop testing. The prototype was not opened or repaired prior to the thermal test. The results of the thermal test are summarized in Table 2-6. Additional details are provided in Appendix 2.10.1.

2.7.3.1 Summary of Pressures and Temperatures

The maximum temperature reached by the overpack's inner shell during the thermal test was 160°C at the inner wall end plate. The maximum temperature reached by the 30B cylinder during the thermal test was 60°C at the cylinder skirt.

In addition to the prototype test results presented, the Thermal Evaluation provided in Section 3.0 provides a conservative analysis of the thermal event. The maximum temperature, evaluated analytically, is 119°C (246°F) for the 30B cylinder and 117°C (243°F) for the content , and the internal pressure calculated for the cylinder is 0.64MPa (0.54MPaG, 93 psia, 78 psig), well below the cylinder's internal design pressure of 1.38MPaG (200 psig).

2.7.3.2 Differential Thermal Expansion

During the thermal test, extreme temperature differentials occurred through the package. A qualitative analysis of the thermal expansion of the parts is provided in Table 2-7.

In order to avoid unacceptable stresses due to thermal expansion, it is necessary to assure that there is no restraint between the inner shell of overpack and the cylinder. There is no possibility that the cylinder is restrained in the radial direction, since the gap between the inner shell and the cylinder in the radius direction is relatively large. The possibility of restraint in the longitudinal direction is evaluated allowing for manufacturing tolerances. The ring plate is also taken into account since in some cases a ring plate may be inserted on the plug side of the cylinder in the overpack.

Conservatively assuming that the initial temperature of 30B cylinder is -40°C (-40°F) and the final temperature is the maximum calculated for the thermal event (119°C, 246°F), the elongation of the cylinder in the longitudinal direction due to thermal expansion is:

$$\delta_c = \alpha_c \cdot L_{c0} \cdot \Delta t = 12.24 \times 10^{-6} \times 2083 \times 159 = 4.1mm \text{ (0.16 in)}$$

where,

- δ_c is the elongation of cylinder (mm)
- α_c is the thermal expansion coefficient of cylinder at 121°C (250°F), 12.24×10^{-6} mm/mm/°C
- L_{c0} is the longitudinal length of cylinder with the allowable errors in construction, 2083 mm (81-1/2 in + 1/2 in)
- Δt is the differential temperature, 119 - (-40) = 159 °C

The time of the maximum temperature of the inner cylindrical shell part of the overpack differs from that of the cylinder body. Then, assuming conservatively the temperature of the inner cylindrical shell part to be 60˚C (140°F), which is the initial temperature before the thermal test, the elongation between both endplates of the inner shell is given by the following equation. The bottom half of the overpack has a smaller nominal clearance; thus, the dimensions of the bottom half are used in the evaluation.

$$\delta_i = \alpha_i \cdot L_{i0} \cdot \Delta t = 15.56 \times 10^{-6} \times 2091 \times 100 = 3.2mm \text{ (0.12 in)}$$

where,

- δ_i is the elongation between both endplates of the inner shell (mm)

α_i is the thermal expansion coefficient of the inner shell at 60°C (140°F), 15.56×10^{-6} mm/mm/˚C

L_{i0} is the internal cavity length for the bottom half of the overpack with the manufacturing tolerance,
2096 - 5 = 2091 mm

Δt is the differential temperature,
60 - (-40) = 100 ˚C

Based on the above, the minimum distance from the inner wall end of overpack to the tip of cylinder-skirt (l) for the maximum thermal expansion is:

$$l = L_i - L_c = 2094.2 - 2087.1 = 7.1mm \text{ (0.27 in)}$$

where,

l is the distance from the inner shell to the tip of cylinder-skirt (mm)

L_i is the internal cavity length for the bottom half of the overpack at the evaluation temperature,
2091 + 3.2 = 2094.2 mm

L_c is the longitudinal length of cylinder at the maximum temperature,
2083+ 4.1 = 2087.1 mm

Thus, the minimum clearance between the cylinder ends and the overpack interior is 7.1 mm. Therefore, there is no constraint between the inner shell of the overpack and the cylinder even if a ring plate (6 mm thick) is inserted between them.

2.7.3.3 Stress Calculations

As described in section 2.7.3.2, there is not any thermal stress that would produce a significant stress.

2.7.3.4 Comparison with Allowable Stresses

The maximum internal pressure calculated for the cylinder is 0.64MPa (0.54MPaG, 93 psia, 78 psig) (see Section 3). This pressure is well below the internal design pressure per ANSI N14.1 and ISO 7195 (1.38MPaG, 200 psig).

2.7.4 Immersion – Fissile Material

The criticality analysis presented in Section 6 assumes that water does not enter the 30B

cylinder following HAC.

All seals on the 30B cylinder and in the valve are metal. The valve threads are tinned with solder and then threaded into the cylinder. The tinning material is typically extruded from the threads during the valve installation process. Since there are no elastomeric seals on the cylinder or in the valve, the leakage path into cylinder would be identical to the leakage path out of the cylinder.

The 30B cylinders were completely undamaged following the drop test sequence and the maximum leak rate measured was 2.2×10^{-7} std-cc/s. Since the cylinders were not damaged, they are capable of maintaining the 8.83kPa (1.28 psig) pressure exerted by a 0.9m (3ft) head of water without inleakage, since the external design pressure is 172kPaG (25 psig). This small leak rate indicates that the gas leakage flow regime is molecular flow. Liquids are not able to enter such a fine leak through which a gas might pass under molecular flow [Reference 2.11.5]. Therefore, liquid water will not leak into the 30B cylinder. The amount of water that may pass through the leak in a gaseous state has a negligible impact on the criticality analysis, as demonstrated by the calculation presented in Appendix 4.4.1

2.7.5 Immersion – All Packages

Regulations require that an undamaged 30B cylinder be capable of sustaining leak-free conditions when immersed under a head of water at least 15 m (50 ft) for a period of 8 hours. Since the worst-case occurs when the internal pressure of the cylinder is at a minimum, the pressure of cylinder is conservatively assumed to be zero (0 MPa). The differential pressure acting on the exterior of cylinder is therefore 0.249MPa (36.1 psi)

The cylinder is specifically designed to sustain an external pressure of at least 0.172MPaG (25 psig). Since the worst-case external pressure is approximately 77kPa (11 psi) higher, the cylinder is further evaluated using the technical standards [Reference 2.11.1] corresponding to ASME Section III. The components subject to evaluation are the cylinder-shell and cylinder-head. The minimum required cylinder-shell thickness for the maximum external pressure is:

$$t = \frac{3P_e D_0}{4B} = \frac{3 \times 0.249 \times 762}{4 \times 82} = 1.74mm \ \ (0.07 \text{ in})$$

where,

t is the minimum required thickness (mm) for a thin-walled cylindrical shell (valid for $t < D_o/10$) under an external pressure load.

D_0 is the outside diameter of the cylinder, 762mm (30 in)

P_e is the maximum pressure acting on the exterior of cylinder-shell, 0.249MPa(36.1 psi)

B is 82 (from the External Pressure Chart shown in Figure 2.10.4-1 and -2 of Appendix 2.10.4 if the value (t) is assumed.)

For the semi-elliptical head, the minimum required shell thickness for the maximum external pressure load is:

$$t = \frac{P_e R}{B} = \frac{0.249 \times 685.8}{88} = 1.94 \text{ mm (0.08 in)}$$

where,

t is the minimum required thickness in the calculation (mm)

R is K times outside diameter, 762 x 0.90=685.8

P_e is the maximum pressure acting on the exterior of head, 0.249MPa (36.1 psi)

B is 88 (from the External Pressure Chart shown in Figure 2.10.4-2 of Appendix 2.10.4.), where A is:

$$A = \frac{0.125}{R/t} = \frac{0.125}{685.8/12.7} = 0.0023$$

The margins of safety for the cylinder-shell and cylinder-head are:

Cylinder-shell M.S.= (12.7 mm/ 1.74 mm) – 1 = 6.2.

Cylinder-head M.S.= (12.7 mm/ 1.94 mm) – 1 = 5.5.

2.7.6 Summary of Damage

Evaluations completed by prototype tests demonstrate that the integrity of the package is maintained throughout and following all of the mechanical and thermal hypothetical accident conditions (including the cumulative effects of the normal condition of transport).

Following the series of tests, some fastening devices on the prototypes were deformed and slightly damaged due to the drop impact, but all of the devices remained in place and fastened. Also the conservative thermal evaluation provided in Section 3.0 confirms that the UF_6 temperature does not exceed the triple point (thus maintaining the cylinder pressure well below the design pressure) throughout Normal and HAC. The maximum leak rate of the cylinder-valve measured after the series of tests was 2.2×10^{-7} std-cc/sec. The integrity of the containment system is maintained and containment ability is not affected.

2.8 Special Form

This section is not applicable to the MST-30.

2.9 Fuel Rods

This section is not applicable to the MST-30.

2.10 Appendices

2.10.1 Compliance Test Report for the MST-30 Protective Shipping Package

2.10.2 Summary of Preliminary Drop Testing

2.10.3 Effect of Fabrication Deviation of Polyurethane Foam

2.10.4 Charts for Determining Shell Thickness under External Pressure

2.10.5 Detailed Description of Helium Leak Tests

2.10.6 Evaluation using LS-DYNA code

2.10.7 Summary of analysis code “LS-DYNA”

2.10.8 Explanation of derivation methods for material properties used in LS-DYNA

2.11 References

2.11.1 JSME S NC1-2005/2007 “Codes for Nuclear Power Generation Facilities -Rules on Design and Construction for Nuclear Power Plants.

2.11.2 Japan Society of Mechanical Engineers “JSME Mechanical Engineers’ Handbook – A4: Strength of Materials – ” (1984)

2.11.3 Architectural Institute of Japan, “Design Standard for Steel Structures”(1973).

2.11.4 JEAG4601-1987 “Technical Guidelines for Aseismic Design of Nuclear Power Plants” (1987)

2.11.5 ISO 12807 “Safe transport of radioactive materials – Leakage testing on packages”

2.11.6 JIS B1051,“Mechanical properties of fasteners made of carbon steel and alloy steel - Bolts, screws and studs with specified property classes - Coarse thread and fine pitch thread”(2014).

Table 2-1 Maximum Weight of MST-30 Package

Component	Maximum Weight
Overpack	1,228 kg (2,707 lb)
30 B Cylinder	655 kg (1,444 lb)
Maximum UF_6 Load (Content)	2,277 kg (5,020 lb)
Ring Plate	10 kg (22 lb)
Maximum Package Weight	4,170 kg (9,193 lb)

Table 2-2 Metal Properties[1]

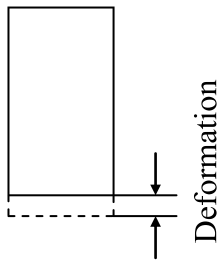
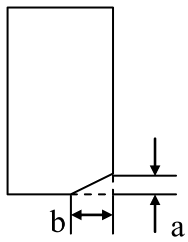
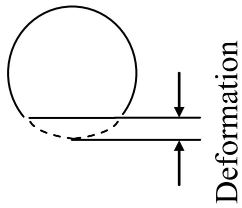
Material Specification	Yield Strength N/mm^2 (psi x 1,000)	Tensile Strength N/mm^2 (psi x 1,000)
JIS G 4305 SUS304 (Cold rolled Stainless Steel Plate) or JIS G4304 SUS304 (Hot rolled Stainless Steel Plate)	205 (29.7)	520 (75.4)
JIS G 4303 SUS304 or JIS SUS316 (Stainless Steel bars)	205 (29.7)	520 (75.4)
JIS B1051, Mechanical properties of steel bolts and screws Class 10.9 or equivalent or more	940 (136.3)	—

1 Material properties were quoted from Reference 2.11.1 and 2.11.6.

Table 2-3 Properties of Polyurethane Foam and Phenolic Foam

Foam Type	**Compressive Stress at 20% strain N/mm^2 (psi x 1,000)**	**Density g/cm^3 (lb/ft^3)**
Polyurethane Type I and III	8.1 – 11.5 (1.17 – 1.67)	0.34 – 0.40 (21.2 – 25.0)
Polyurethane Type II	14.4 – 17.9 (2.09 – 2.60)	0.45 – 0.51 (28.1 – 31.8)
Phenolic	—	approx. 0.1 (approx. 6.2)

Table 2-4 Compliance Test Results of Free Drops

Test Series / Deformed Port'n & Area	TEST-A (Vertical)	TEST-B (Corner)	TEST-C (Horizontal)
Deformed Portion or Area			
0.3 m (1 ft) Corner (Rim) Drop	N/A	$a = 18\,mm$ $b = 35\,mm$ $\begin{pmatrix} a \approx 0.7\,in. \\ b \approx 1.4\,in. \end{pmatrix}$	N/A
1.2 m (4 ft) Free Drop	$2\,mm\,(Valve\,Side)$ $3\,mm\,(Plug\,Side)$ $\begin{pmatrix} 0.08\,in.(Valve\,Side) \\ 0.12\,in.(Plug\,Side) \end{pmatrix}$	$a = 35\,mm$ $b = 67\,mm$ $\begin{pmatrix} a \approx 1.4\,in. \\ b \approx 2.6\,in. \end{pmatrix}$	$5\,mm$ $(0.2\,in.)$
9 m (30 ft) Free Drop	$15\,mm\,(Valve\,Side)$ $18\,mm\,(Plug\,Side)$ $\begin{pmatrix} 0.6\,in.(Valve\,Side) \\ 0.7\,in.(Plug\,Side) \end{pmatrix}$	$a = 125\,mm$ $b = 252\,mm$ $\begin{pmatrix} a \approx 4.9\,in. \\ b \approx 9.9\,in. \end{pmatrix}$	$18\,mm$ $(0.7\,in.)$

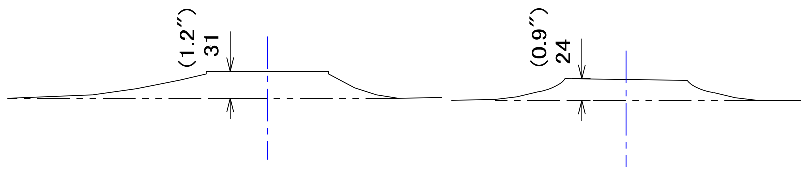
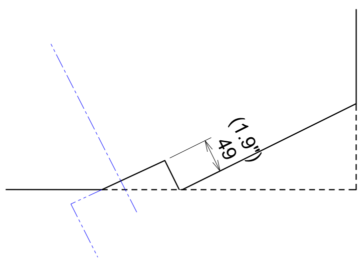
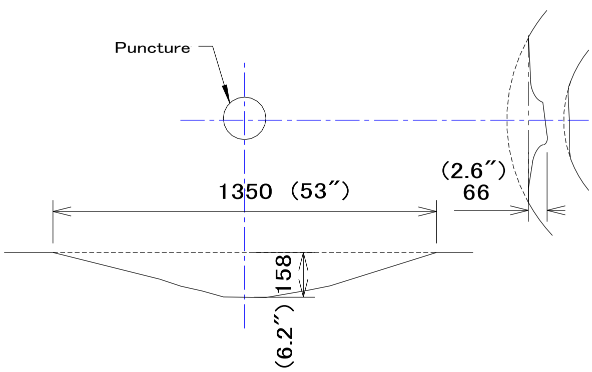
Notes :

(1) Each deformation after the 9 m Vertical Free Drop was that cumulated by both 1.2 m and 9 m free drops.

(2) Each deformation after the 9 m Corner Free Drop was that cumulated by 0.3 m rim, 1.2 m and 9 m free drops. The 0.3m Corner (rim) Drop was performed in accordance with the Japanese Regulations pursuant to the 1985 IAEA Regulations (SS. No.6) in effect at the time of the compliance test.

(3) The deformation after the 9 m Horizontal Free Drop was that cumulated by both 1.2 m and 9 m free drops.

Table 2-5 Compliance Test Results of 1 m (40 in) Puncture Drops

TEST-A (Vertical)	(Valve Side) (Plug Side)  Unit : mm (inch)
TEST-B (Corner)	(Valve Side)  Unit : mm (inch)
TEST-C (Horizontal)	(Center of Top Half in the longitudinal direction)  Unit : mm (inch)

Notes:

(1) The deformations illustrated were results of the puncture tests only. Deformation due to previous tests (Normal and HAC) are not presented.

(2) The parenthesized values are approximate inches.

Table 2-6 Temperatures Observed During Thermal Testing

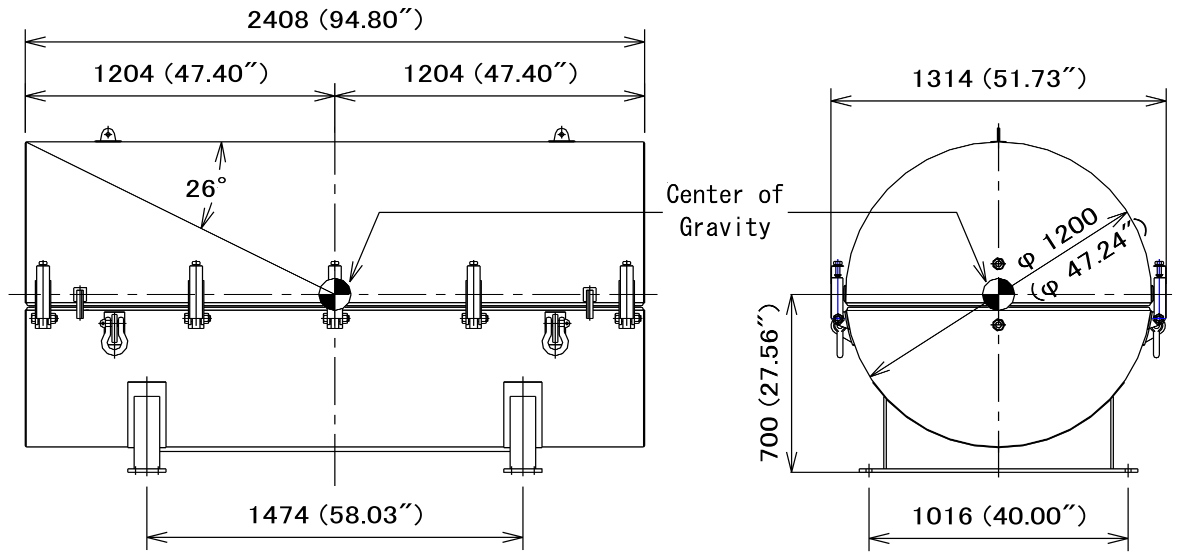
Part	Maximum Temperature and location
Outer Shell	840.6°C (1545.1°F) (at Center of Cylindrical Shell)*
Inner Shell	87.3°C (198.1°F) (at Center of Cylindrical Shell)* 150-160°C (302-320°F) (at Valve Side Wall End) 130-140°C (266-284°F) (at Plug Side Wall End)
Cylinder-body	50.7°C (123.3°F) (at Center of Surface)*
Cylinder-skirt	59.4°C (138.9°F) (at Valve Side)* 55-60°C (131-140°F) (at Plug Side)
Cylinder-head	51.5°C (124.7°F) (at Valve Side)* < 50°C (122°F) (at Plug Side)

Notes:

Values with * is the maximum temperature measured with thermocouples and other data are measured values with thermo-labels.

Table 2-7 Qualitative Evaluation of Thermal Expansion under Thermal Test

<table>
<tr><th>Part</th><th>State of Thermal Extension under Thermal Condition</th></tr>
<tr><td>Outer Shell</td><td>Since outer shell is subjected to the highest temperature, it has large thermal expansion. But it can deform freely, therefore, its thermal expansion is not significant effect.</td></tr>
<tr><td>Polyurethane Foam</td><td rowspan="2">Thermal expansion is produced. Since carbon layer with little strength is produced between outer shell and foams, thermal stress produced by restraint is not significant effect.</td></tr>
<tr><td>Phenolic Foam</td></tr>
<tr><td>Inner Shell</td><td>Thermal stress is produced by non-uniform of temperature since distribution of temperature is not large, it is not significant effect.</td></tr>
<tr><td>Cylinder</td><td>If a cylinder has large elongation caused by thermal expansion, the cylinder is restrained by inner shell. So, it is confirmed by calculation in Section 2.7.3.2 that the elongation of cylinder is not so large as to occur the restraint under the fire event.</td></tr>
<tr><td>Valve threads</td><td rowspan="2">Thermal stress is produced by differing thermal coefficients of expansion. But, since difference of temperature is so small, and valve and plug threads are sealed with solder, no significant effect appears.</td></tr>
<tr><td>Plug threads</td></tr>
</table>



Unit : mm (inch)

Figure 2-1 Center of Gravity of MST-30 Package

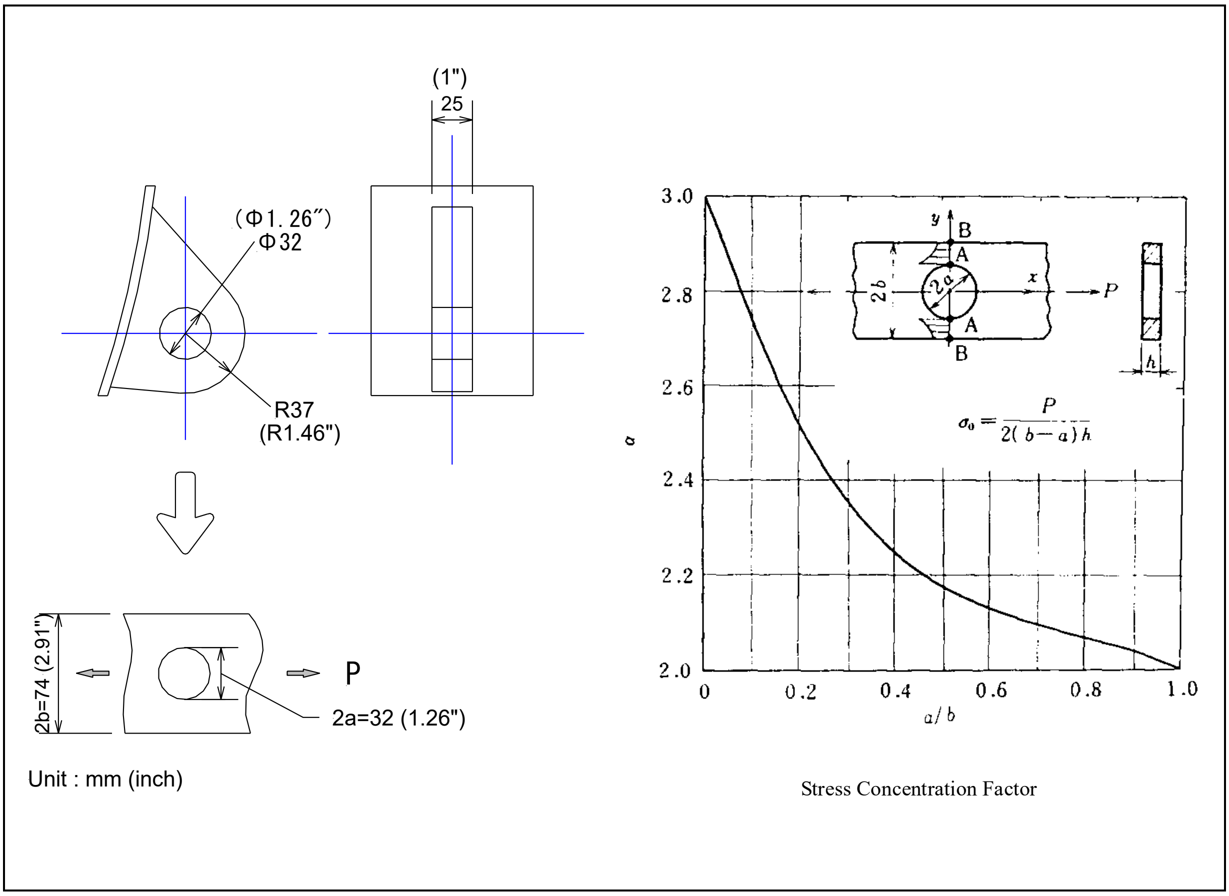
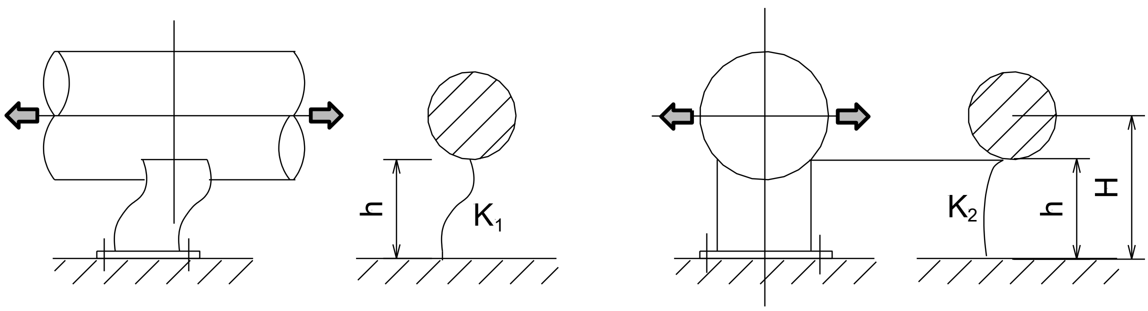


Figure 2-2 Analysis Model of Shackle Support Fixture



Longitudinal Direction

Side Direction

Figure 2-3 Analysis Model for Vibration

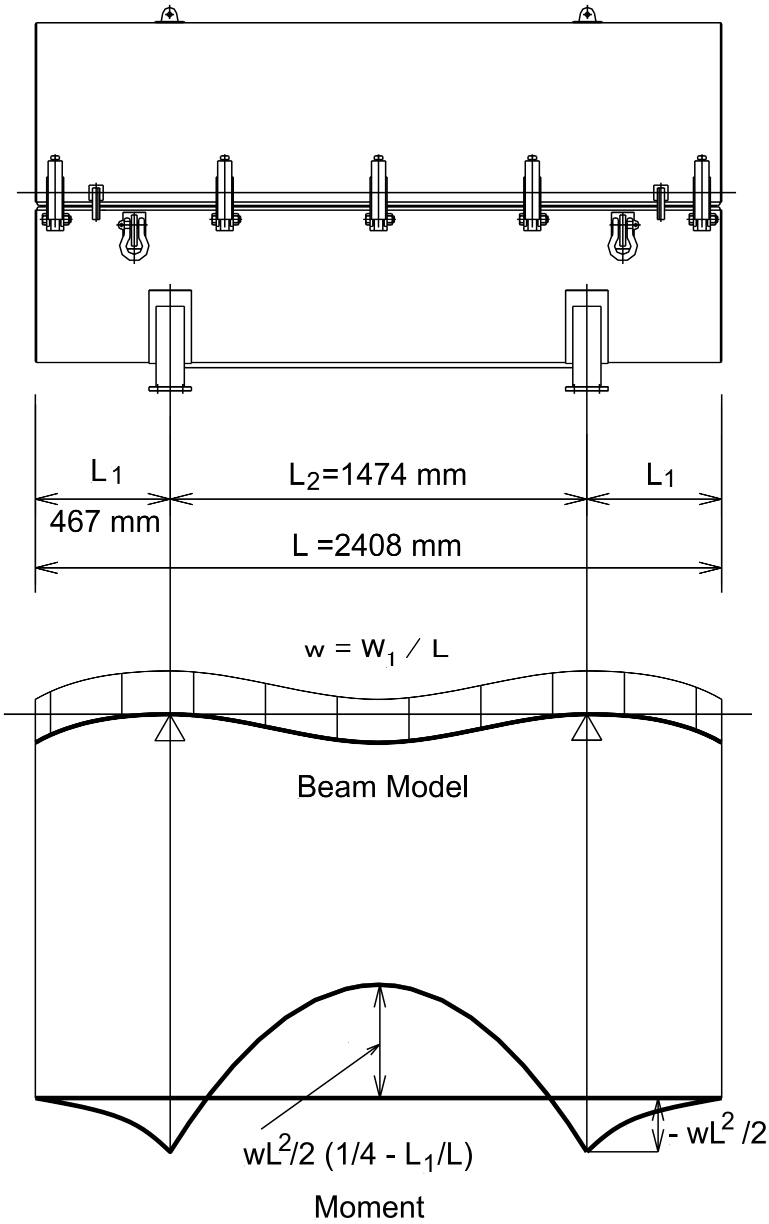
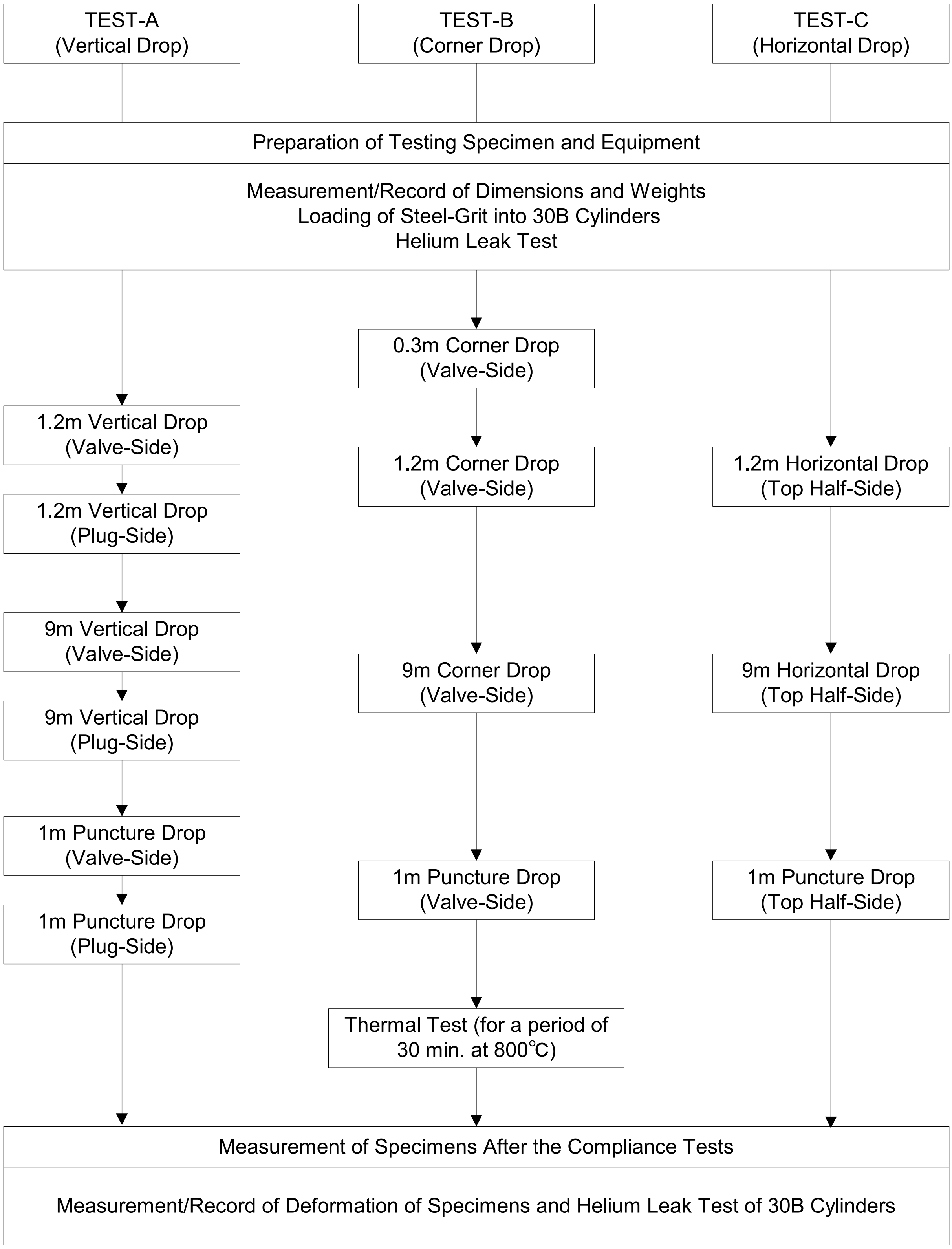


Figure 2-4 Analysis Model for Compression



(Note: The 0.3m Corner (rim) Drop was performed in accordance with the Japanese Regulations pursuant to the 1985 IAEA Regulations (SS. No.6) in effect at the time of the compliance test.)

Figure 2-5 Test Sequence of Compliance Test

Appendix 2.10.1

Compliance Test Report
for the
MST-30 Protective Shipping Package

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Compliance Testing of the MST-30 Protective Overpack for Normal Conditions (NOC) and Hypothetical Accident Conditions (HAC)

1. Introduction

The MST-30 Protective Shipping Package (MST-30) is a Type A Fissile package used for the shipment of 30-inch cylinders containing Uranium Hexafluoride (UF_6) enriched to 5wt% U-235. The package is designed to conform to the technical and regulatory requirements of a Type A Fissile Material Package as specified in the current Japanese Safe Transport Regulations pursuant to the IAEA Regulations for the Safe Transport of Radioactive Material, 1985 Edition, as well as the requirements for UF_6 transport specified in the IAEA Regulations for the Safe Transport of Radioactive Material (ST-1, 1996 edition). Because the current US NRC and US DOT Regulations are almost entirely in accordance with the 1985 IAEA regulations, the MST-30 package is also designed in compliance with the current 10CFR Part 71 and 49CFR Subpart I Part 173. This report details the compliance testing that was performed for the MST-30 in support of its licensing.

The compliance testing includes free drops from varying heights, a puncture drop, and a thirty-minute thermal test. Three full-scale prototypes were constructed for the testing, and each prototype was subjected to a series of Normal Condition and HAC tests. The three test sequences, TEST-A, TEST-B and TEST-C are diagramed in Figure 2.10.1-1. In addition, photographs of compliance testing performance are attached hereto for reference.

2. Purpose of the Compliance Tests

These tests were performed to demonstrate that the design and construction of the MST-30 package conforms to the technical and regulatory requirements of a Type A and Fissile Material Package as described by Japanese, US and international regulations.

3. Testing Combinations and Sequences in the Compliance Tests

Testing combinations and sequences of full-scale prototypes of MST-30 package are diagramed in Figure 2.10.1-1

4. Preparation of Specimens for the Compliance Tests

The weight of each component of the packagings and the overall weight of the test specimens

are shown in Table 2.10.1-1.

4.1 Cylinder

Three (3) new 30B cylinders were prepared for the compliance tests. They were manufactured by Columbiana Boiler Company (CBC), Columbiana, Ohio, U.S.A. in accordance with the specifications specified in the ANSI N14.1, 1995 edition, and QC-released by CBC as per its NRC Approved Quality Assurance Program.

4.2 Protective Overpack

Three (3) full-scale prototypes of the MST-30 overpack designed and constructed by Mitsubishi Materials Corporation were used for the compliance tests. The shape of the MST-30 prototype, including major dimensions, is shown in Figure 2.10.1-2.

4.3 Simulated Payload

Steel grit having a bulk density of 3.3 g/cm^3 (206 lb/ft.^{3}) was used to simulate the maximum UF_6 payload for the compliance tests. The weight of steel grit loaded in each 30B cylinder was determined by subtracting the actual tare weight of each empty 30B cylinder from the maximum allowable gross weight of 30B cylinder.

5. Testing Requirements

5.1 Requirements for Free Drop Test and Puncture Test

5.1.1 Target for Free Drop Test and Puncture Test

The target pad for the free drop tests and puncture tests was constructed to satisfy the guidance specified in the Advisory Material for 1985 IAEA regulations, i.e. IAEA Safety Series No.37. The construction of the target pad is shown in Figure 2.10.1-3.

5.1.2 Drop Orientations (Attitudes) of the Package for Normal (NOC) and Hypothetical Accident Conditions (HAC)

The drop attitudes chosen for the free drop and puncture tests of MST-30 prototypes are shown in Figure 2.10.1-4. Three basic series were performed: Vertical drops, Corner drops, and Horizontal Drops. For the corner drops, a drop angle of twenty-seven degrees (27°)

toward the target was chosen. This angle corresponds to the orientation aligning the center of gravity over the corner to cause the maximum expected damage. This angle was determined by the results of the preliminary drop testing (see Appendix 2.10.2). The corner drop was performed so that the cylinder valve was as near as possible to the impact site. For the vertical and corner puncture tests, the position of the package was adjusted so that the cylinder-valve was positioned just over the puncture bar.

5.1.3 Drop Height of Package for Free Drop and Puncture Drop

Drop heights of the package for each drop test are shown in Table 2.10.1-2. NOC and HAC drops were performed for all three prototypes, using the various package orientations described in Section 5.1.2 above.

5.1.4 Instrumentation of Each Testing Item of the Package

Instrumentation for each test series is shown in Table 2.10.1-3. Measurement of the dynamic strains and accelerations generated were measured on the cylinder only. The accelerations were filtered using a low frequency pulse pass up to 320 Hz. Prototypes A(Vertical) and B (Corner) were fitted with an aluminum honey-comb at the valve-pocket to indicate any contact between the valve and any other components of the packaging during the testing. Alumel-Chromel thermocouples and thermo-labels were used for the purpose of measuring the temperature of the components during the thermal test. The thermo-labels change color depending on their temperatures and have a transition accuracy of ± 2°C. The thermo-labels were used to measure temperatures in the range of 50 to 240 °C (122 to 464 °F). The location of the thermo-couples and thermo-labels on the specimens are shown in Figure 2.10.1-6.

5.2 Requirements for Thermal Test

5.2.1 Thermal Test Furnace

A furnace that is usually used for heat treatment (shown in Figure 2.10.1-5) was used to provide the environment required for HAC. Oil and air are injected into the furnace through the oil burners and burned. The wall of the furnace is made of firebricks, which reflect radiant heat toward the central area of the furnace so as to maintain the inside temperature uniformly. This furnace, along with a truck, was employed for the thermal test of the prototype MST-30.

The main specifications of the furnace are:

(1) Dimension of the Inside of Furnace: 3.2m Wide, 2.5m High and 9 m Long (approx. 10.5ft. Wide, 8.2ft. High and 30ft. Long)

(2) Maximum Service Temperature: 1,200 °C (approx.2,192°F)

(3) Combustion (Burning) System: kerosene (paraffin oil). The combustion gas is injected together with air and is circulated throughout the interior of the furnace. Air and combustion products are discharged from the lower part of the truck.

(4) Combustion Control: six (6) thermocouples. In order to maintain the inside of the furnace at desired temperature uniformly, six thermocouples are equipped at the locations shown in Figure 2.10.1-5. The temperature of all six thermocouples remained above 800°C (approximately 1472°F) during the thermal test.

5.2.2 Procedures for the Thermal Test

Thermal testing of the prototype MST-30 was conducted in accordance with the following procedures:

(1) The atmospheric temperature in the furnace was stabilized at a temperature greater than 800°C (1472°F).

(2) The truck for placing the specimen of package was withdrawn from the furnace.

(3) The specimen was placed on the truck, and the specimen on the truck was pushed into the center part of the furnace.

(4) The furnace temperature was allowed to re-stabilize at 800°C (1472°F), and then the temperature was maintained over 800°C for a period of thirty (31) minutes.

(5) After 30 minutes had elapsed, the truck on which the specimen was placed was withdrawn from the furnace and the specimen was cooled naturally. Any combustion of the components and/or materials of the specimen was allowed to proceed naturally.

(6) Temperature monitoring of the specimens was discontinued after it was confirmed that the peak temperature of each portion of the specimen had been obtained.

6. Results

The results of the compliance tests are summarized in Tables 2.10.1-4 though 2.10.1-10 and Figures 2.10.1-7 through 2.10.1-13.

6.1 Free Drop Tests and Puncture Test of Package with Different Drop Heights

6.1.1 Deformation of the Outside of Overpack due to the Free Drop and Puncture Test

The measured deformation of the outside of overpack for the TEST-A, TEST-B and TEST-C series of 0.3 m (1 ft) and/or 1.2 m (4 ft) and 9 m (30 ft) free drop tests is shown in Table 2.10.1-4. Deformation resulting from the puncture test for TEST-A, TEST-B and TEST-C is shown in Table 2.10.1-5. There were neither tears nor breaches of the outer skin of the prototypes as a result of the tests.

6.1.2 Deformation of the Inside of Overpack due to Free Drop and Puncture Tests

The measured deformation of the inside of overpack for the TEST-A, TEST-B and TEST-C after the all test series is shown in Table 2.10.1-6. There were neither tears nor breaches of the inner skin of the prototypes as a result of the tests.

6.1.3 Deformation of 30B cylinder due to Free Drop and Puncture Tests

Upon completion of the series of free drop tests for both TEST-A (vertical) and TEST-B (corner), no significant deformation was visible at any portion of 30B cylinder, including the cylinder-skirt.

However, the horizontal orientation puncture test (TEST-C), resulted in a small amount of plastic deformation on the shell of 30B cylinder. The cylinder deformation was a result of the overpack buckling onto the cylinder at the impact site. The horizontal puncture demonstrated the worst case for deformation of the overpack and cylinder away from the valve area, as all of the impact energy was transferred to the package and none was dissipated in rotational motion. Additionally, the foam used in the annular area of the overpack is not as impact-

absorbent as that used in the ends. Despite the buckling observed, there were no breaches or tears of the overpack or cylinder. Figure 2.10.1-7 shows the plastic deformation of 30B cylinder.

6.1.4 Maximum Strain and Acceleration of 30B Cylinder

The maximum strain and acceleration generated at each portion of 30B cylinder due to the impact of the 9 m(30 ft.) free drop test are shown in Table 2.10.1-7 and those generated from the 1 m(40 in.) puncture test are shown in Table 2.10.1-8.

6.2 Thermal Test of Package

Prototype B was chosen for thermal testing, since the damage expected in the area of the cylinder valve and overpack valve pocket provided the highest risk of containment loss. Prototype B was used for progressive corner drops directly over the cylinder valve area, as described in Figures 2.10.1-1 and 2.10.1-4. The damage accumulated due to the corner drop series is provided in Tables 2.10.1-4 through 2.10.1-6.

6.2.1 Temperature of Thermal Test

After stabilizing the atmospheric temperature in the furnace at 810°C (1,490°F), the TEST-B prototype (corner drop specimen) was put into the furnace. Figure 2.10.1-6 shows the locations of the thermocouples and thermo-label on the TEST-B protoype. Several thermo-couples were located in the damaged areas to monitor the temperature of the cylinder in the damage zones. The specimen was kept in the furnace for a period of 31 minutes in an atmospheric temperature ranging from 800°C (1,472°F) up to 847°C (1,557°F). The maximum temperature of the external surface of the specimen reached 841°C (1,545°F). After 31 minutes had elapsed, the specimen was withdrawn from the furnace and allowed to cool naturally. The maximum temperatures reached by the overpack are shown in Figure 2.10.1-8. The maximum temperature of the 30B cylinder is shown in Figure 2.10.1-9.

6.2.2 Combustion State of Polyurethane and Phenolic Foam

During the thermal testing of the MST-30, the foam produced combustible gas as it decomposed. This gas was released from the package shell through the vent holes provided. The released gas produced visible flame while the package was in the furnace, and it continued to burn after removal from the furnace. The level and intensity of the flames observed did not change during or immediately following removal from the furnace, indicating that oxygen starvation did not occur during the test.

Figure 2.10.1-10 is a cross-sectional view showing the combustion state of the specimen following the thermal test. The figure shows the most severely deformed portion of the specimen resulting from the NOC and HAC testing. The shape of the outer shell of the overpack was deformed further by the heating and cooling during the thermal test sequence.

As shown in Figure 2.10.1-10, the polyurethane foam-1 was completely carbonized. The surface of the polyurethane foam-2 seems to have been liquefied by the heat, and then re-solidified after cooling. The region of polyurethane foam-2 that was deformed by the drop testing was comparatively much more carbonized than other region, and the boundary-region between the polyurethane foam-2 and the polyurethane foam-3 at the impact site was partially carbonized. In other areas of the overpack the polyurethane foam-2 was only slightly carbonized. The polyurethane foam-3 was also carbonized in the drop test deformed region. In the other sections of the overpack, the foam-3 was partially carbonized to a uniform depth.

The thermal-insulator made of phenolic foam was carbonized to a uniform depth from the outer shell of the overpack (slightly less than a quarter of the total thickness of the phenolic foam). The phenolic foam was discolored to a uniform depth from the carbonized region (approximately one third of the total thickness of phenolic foam). Photo-18 and Photo-19 provided in the attachment show the foam cross-sections after the thermal test.

Figure 2.10.1-11 provides a graph of the temperatures observed during the MST-30 thermal test. The temperature of the specimen and furnace were measured with thermocouples (T1~T7) continuously for approximately six (6) hours as shown in the upper graph of Figure 2.10.1-11. The lower graph of Figure 2.10.1-11 uses a more finely graduated temperature scale to highlight the temperature of the 30B cylinder (T1 through T6 of the thermocouples attached to 30B cylinder and a part of the overpack) for a period of approximately two (2) hours from the start of the thermal test.

6.3 Inspection of the Honeycomb Impact Indicator

Figure 2.10.1-12 shows the position of the Cylinder-Valve and the Aluminum Honeycomb inserted into the valve-pocket prior to the series of drop tests and puncture test. The original distance “d” between the tip of valve-stem and the tip of cylinder-skirt was 28 mm (approx. 1.1 in.) for the Prototype A of TEST-A and 29 mm (approx.1.1 in.) for Prototype B of TEST-B. Since the honeycomb did not indicate any impacts, it is concluded that there was no contact between any part of the valve and the aluminum honeycomb during any part of the regulatory testing.

6.4 Results of Helium(He) Leakage Tests

All three 30B cylinders from each test prototype (TEST-A, TEST-B and TEST-C) were leak tested using helium gas. Both the cylinder valve and plug were tested. Prototype A and C

were tested following the drop and puncture sequences, and Prototype B was tested following the drop, puncture and thermal sequences. The results of the helium leak tests are provided in Table 2.10.1-9. The maximum leak detected was 2.2 x 10^{-7} std-cc/sec for Prototype B at the cylinder valve. The sensitivity of the helium detector used is 2 x 10^{-11} atm·cc/sec(He).

6.5 Fastening Devices

The position of the fastening devices on the overpack are shown in Figure 2.10.1-13. The damage accumulated as a result of the drop and puncture test is shown in Table 2.10.1-10. Some devices were deformed and slightly damaged due to the drop impact, but all the devices remained in place and fastened following the series of tests.

7. Conclusion

There was no direct contact between the valve of the 30B cylinder and any other component of both overpack and 30B cylinder including its skirt for any of the tests completed. The cylinder valve and plug maintained water leak-tightness throughout and following the testing for all of the tests completed. The overpack remained closed, and there were no gaps large enough to permit the entry of a 10-cm cube. The deformation suffered by the packaging resulted in negligible volume reductions (less than 5 percent of the total volume) and the effective spacing of the packaging was not reduced as a result of the impacts, since the gross dimensions of the packaging were maintained. The maximum temperature attained by the 30B cylinder as a result of the thermal test was 60°C (approx. 140°F). Thus, these tests demonstrate that the design and construction of the MST-30 package conforms to the technical and regulatory requirements of a Type A and Fissile Material Package as described by Japanese, US, and international regulations.

Table 2.10.1-1 Weight of Specimens

Composition	Specimen A	Specimen B	Specimen C
Cylinder	620 kg (1,367 lb)	622 kg (1,371 lb)	625 kg (1,378 lb)
Cylinder + Simulated Content[1]	2,948 kg (6,499 lb)	2,949 kg (6,501 lb)	2,951 kg (6,506 lb)
Overpack	1,271 kg (2,802 lb)	1,257 kg (2,771 lb)	1,265 kg (2,789 lb)
Total Weight	4,219 kg (9,301 lb)	4,206 kg (9,273 lb)	4,216 kg (9,295 lb)

[1] The weight of the 30B test prototypes is less than that specified in Section 2 for the maximum cylinder weight (the maximum cylinder weight is intended to bound all manufacturing tolerances). Additional steel grit was used for the tests to bound the maximum weight of the cylinder.

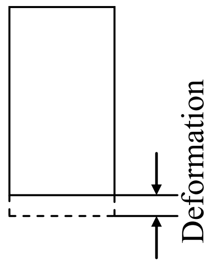
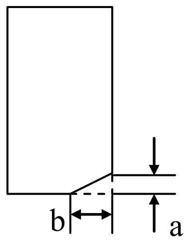
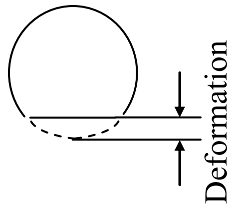
Table 2.10.1-2 Drop Height of Drop Testing for Each Testing Combination

Drop Testing Description	TEST-A	TEST-B	TEST-C
0.3 m Corner Drop (Valve Side)		○	
1.2 m Vertical Drop (Valve Side)	○		
1.2 m Vertical Drop (Plug Side)	○		
1.2 m Corner Drop (Valve Side)		○	
1.2 m Horizontal Drop (Top Half Side)			○
9 m Vertical Drop (Valve Side)	○		
9 m Vertical Drop Plug Side)	○		
9 m Corner Drop (Valve Side)		○	
9 m Horizontal Drop (Top Half Side)			○
1 m Vertical Puncture (Valve Side)	○		
1 m Vertical Puncture (Plug Side)	○		
1 m Corner Puncture (Valve Side)		○	
1 m Horizontal Puncture (Center of Top Half)			○

Table 2.10.1- 3 Test Instrumentation

Testing Sequence & Testing Items	Weight	He Leak	Deformation		Dynamic Strain	Acceleration
			Outer	Inner		
Preparation of Specimen	○	○				
0.3m Corner Drop (Valve Side)			○			
1.2m Vertical Drop (Valve Side)			○			
1.2m Vertical Drop (Plug Side)			○			
1.2m Corner Drop (Valve Side)			○			
1.2m Horizontal Drop (Top Half)			○			
9 m Vertical Drop (Valve Side)			○		○	○
9 m Vertical Drop (Plug Side)			○		○	○
9 m Corner Drop (Valve Side)			○		○	○
9 m Horizontal Drop (Top Half)			○		○	○
1m Vertical Puncture (Valve Side)			○		○	○
1m Vertical Puncture (Plug Side)			○		○	○
1m Corner Puncture (Valve Side)			○		○	○
1m Horizontal Puncture (Center of Top Half)			○		○	○
On Completion of Drop Tests & Thermal Test		○		○		

Table 2.10.1- 4 Cumulative Deformation of Outside of Overpack due to a Series of 0.3 m and/or 1.2 m and 9 m Free Drop Tests

Test Series / Deformed Portion & Area	TEST-A (Vertical)	TEST-B (Corner)	TEST-C (Horizontal)
Deformed Portion or Area			
0.3 m (1 ft) Corner (Rim) Drop	N/A	$a = 18\,mm$ $b = 35\,mm$ $\begin{pmatrix} a \approx 0.7\,in. \\ b \approx 1.4\,in. \end{pmatrix}$	N/A
1.2 m (4 ft) Free Drop	$2\,mm\,(Valve\,Side)$ $3\,mm\,(Plug\,Side)$ $\begin{pmatrix} 0.08\,in.(Valve\,Side) \\ 0.12\,in.(Plug\,Side) \end{pmatrix}$	$a = 35\,mm$ $b = 67\,mm$ $\begin{pmatrix} a \approx 1.4\,in. \\ b \approx 2.6\,in. \end{pmatrix}$	$5\,mm$ $(0.2\,in.)$
9 m (30 ft) Free Drop	$15\,mm\,(Valve)$ $18\,mm\,(Plug)$ $\begin{pmatrix} 0.6\,in.(Valve\,Side) \\ 0.7\,in.(Plug\,Side) \end{pmatrix}$	$a = 125\,mm$ $b = 252\,mm$ $\begin{pmatrix} a \approx 4.9\,in. \\ b \approx 9.9\,in. \end{pmatrix}$	$18\,mm$ $(0.7\,in.)$

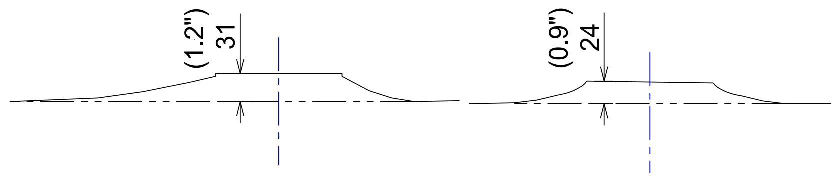
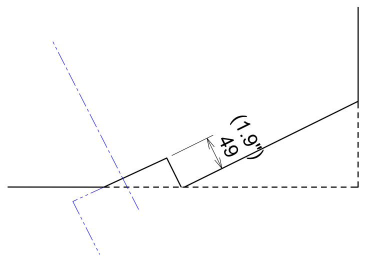
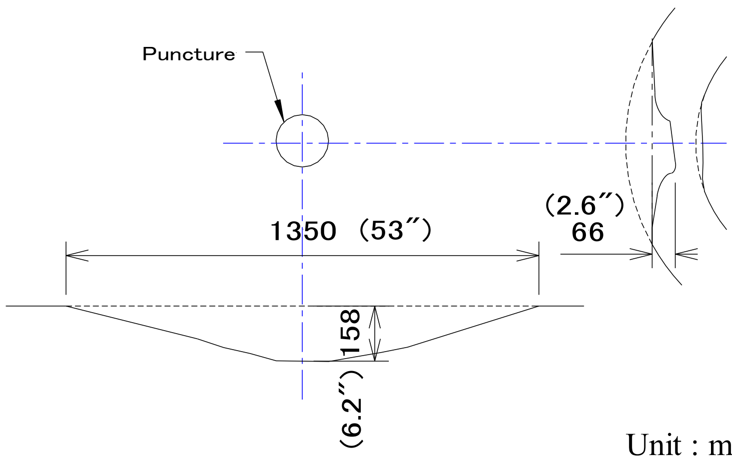
Notes :

(1) Each deformation after the 9 m Vertical Free Drop was that cumulated by both 1.2 m and 9 m free drops.

(2) Each deformation after the 9 m Corner Free Drop was that cumulated by 0.3 m rim, 1.2 m and 9 m free drops.

(3) The deformation after the 9 m Horizontal Free Drop was that cumulated by both 1.2 m and 9 m free drops.

Table 2.10.1- 5 Deformation of Outside of Overpack due to Puncture Test

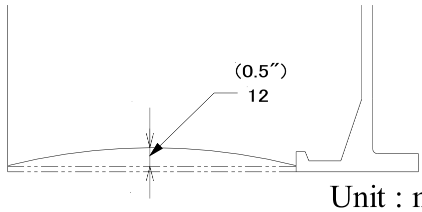
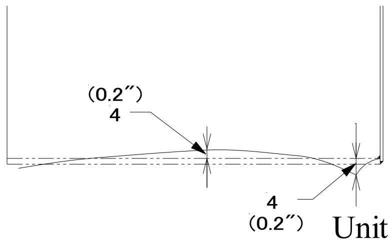
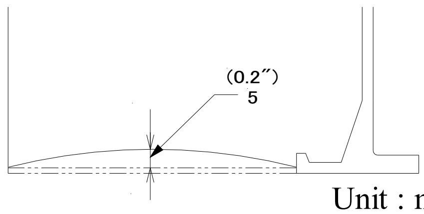
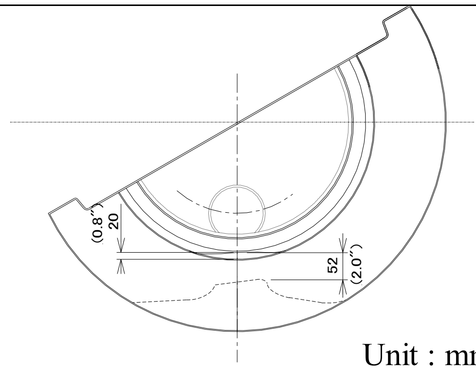
TEST-A **(Vertical)**	(Valve-side) (Plug-side)  Unit : mm (inch)
TEST-B **(Corner)**	(Valve Side)  Unit : mm (inch)
TEST-C **(Horizontal)**	(Center of Top Half in the longitudinal direction)  Unit : mm (inch)

Notes:

(1) The deformations illustrated were results of the puncture tests only. Deformation due to previous tests (Normal and HAC) are not represented.

(2) The parenthesized values are approximate inches.

Table 2.10.1- 6 Deformation of Inside of Overpack due to a Series of Free Drop Tests and Puncture Test with Different Drop Attitudes

TEST-A (Vertical)	**Valve-Side End of Top Half**	 Unit : mm (inch)
	Plug-Side End of Bottom Half	 Unit : mm (inch)
TEST-B (Corner)	**Valve-Side End of Top Half**	 Unit : mm (inch)
TEST-C (Horizontal)	**Center of Top Half in the Longitudinal Direction**	 Unit : mm (inch)

Notes:

(1) The deformation reported is that accumulated during the 0.3 m(1 ft.) rim (for corner drop attitude only), 1.2 m(4 ft.) and 9 m(30 ft.) free drops, and 1 m(40 in.) puncture drop.

(2) As a rule, packages for transporting low enriched UF_6 in a 30B cylinder keep the cylinder valve at the twelve (12) o'clock position. The MST-30 package maintains the valve at the one (1) o'clock position in the overpack in order to position the valve closely over the valve-pocket. Therefore, the valve is always oriented towards the top half of the overpack during transport, and the plug end is always oriented towards the bottom half of the overpack.

Table 2.10.1- 7 Maximum Strain and Acceleration Measured for the 30B Cylinder during 9 m Free Drop Test

Measured Portion/Point		Strain (%)			Acceleration (G)	
TEST-A (Vertical)	Valve-Side	S1	Radial Direction	0.18	A1	440
		S2	Radial Direction	0.16	A2	503
		S3	Radial Direction	0.16		
		S4	Longitudinal Direction.	- 0.35		
		S5	Longitudinal Direction	0.08		
	Plug-Side	S1	Radial Direction	0.11	A1	506
		S2	Circumferential Direction	0.12	A2	531
		S3	Radial Direction	0.10		
		S4	Longitudinal Direction	-0.47		
		S5	Longitudinal Direction	-0.42		
TEST-B (Corner)	S1		Circumferential Direction	0.08	A1	177
	S2		Circumferential Direction	0.09	A2	213
	S3		Circumferential Direction	0.09		
	S4		Longitudinal Direction	-0.22		
	S5		Longitudinal Direction	-0.16		
TEST-C (Horizontal)	S1		Circumferential Direction	0.10	A1	252
	S2		Circumferential Direction	0.08	A2	327
	S3		Circumferential Direction	0.12		
	S4		Longitudinal Direction	0.25		
	S5		Longitudinal Direction	0.26		

Table 2.10.1- 8 Maximum Strain and Acceleration Measured for 30B Cylinder during 1m Puncture Test

Measured Portion/Point			Strain (%)		Acceleration (G)	
TEST-A (Vertical)	Valve-Side	S1	Circumferential Direction	0.012	A1	30
		S2	Radial Direction	0.014	A2	28
		S3	Radial Direction	0.013		
		S4	Longitudinal Direction	-0.098		
		S5	Longitudinal Direction	-0.026		
	Plug-Side	S1	Circumferential Direction	0.016	A1	14
		S2	Circumferential Direction	-0.027	A2	23
		S3	Circumferential Direction	0.021		
		S4	Longitudinal Direction	-0.186		
		S5	Longitudinal Direction	-0.204		
TEST-B (Corner)	S1		Circumferential Direction	0.026	A1	32
	S2		Circumferential Direction	0.021	A2	33
	S3		Circumferential Direction	0.026		
	S4		Longitudinal Direction	-0.052		
	S5		Circumferential Direction	-0.020		
TEST-C (Horizontal)	S1		Circumferential Direction	0.007	A1	23
	S2		Circumferential Direction	0.005	A2	36
	S3		Circumferential Direction	0.006		
	S4		Circumferential Direction	0.403		
	S5		Circumferential Direction	-0.185		

Table 2.10.1-9 Results of Helium (He) Leakage Test of 30B Cylinders for TEST-A, TEST-B and TEST-C

Component and Location Leak Tested		Leak Rate Prior to Test Sequence (std−cc/s)	Leak Rate following the Test Sequence (std−cc/s)
Valve-Side	Cylinder-A	2.2×10^{-8}	1.3×10^{-7}
	Cylinder-B	2.2×10^{-9}	2.2×10^{-7}
	Cylinder-C	3.7×10^{-8}	1.9×10^{-7}
Plug-Side	Cylinder-A	5.9×10^{-10}	5.3×10^{-10}
	Cylinder-B	5.9×10^{-10}	6.0×10^{-10}
	Cylinder-C	1.2×10^{-9}	6.2×10^{-10}

Notes:

(1) The sensitivity of the helium detector is 2×10^{-11} atm·cc/sec. (He)

(2) Cylinder-A and -C were post-test leak tested following the drop and puncture sequence. Cylinder-B was post-test leak tested following the drop, puncture and thermal sequence.

Table 2.10.1-10 Damage States of Fastening Device after Cumulative Free Drop Tests (NOC and HAC)

Name of Specimens	Fitting Positions of Devices	Damaged State of Devices	Fitting Positions of Devices	Damaged State of Devices
TEST-A Specimen (Vertical)	A1	○	B1	△
	A2	○	B2	○
	A3	○	B3	△
	A4	○	B4	△
	A5	○	B5	△
TEST-B Specimen (Corner)	A1	△	B1	△
	A2	△	B2	△
	A3	○	B3	○
	A4	○	B4	○
	A5	○	B5	△
TEST-C Specimen (Horizontal)	A1	○	B1	△
	A2	○	B2	△
	A3	○	B3	△
	A4	○	B4	△
	A5	△	B5	△

Notes

(1) See Figure 2.10.1-13 for the position of each fastening device.

(2) Deformation of Fastening Devices:

○ : No deformation or negligible deformation

△ : Deformed, but the fastening-ability was maintained

× :Breakage (the fastening-ability was lost)

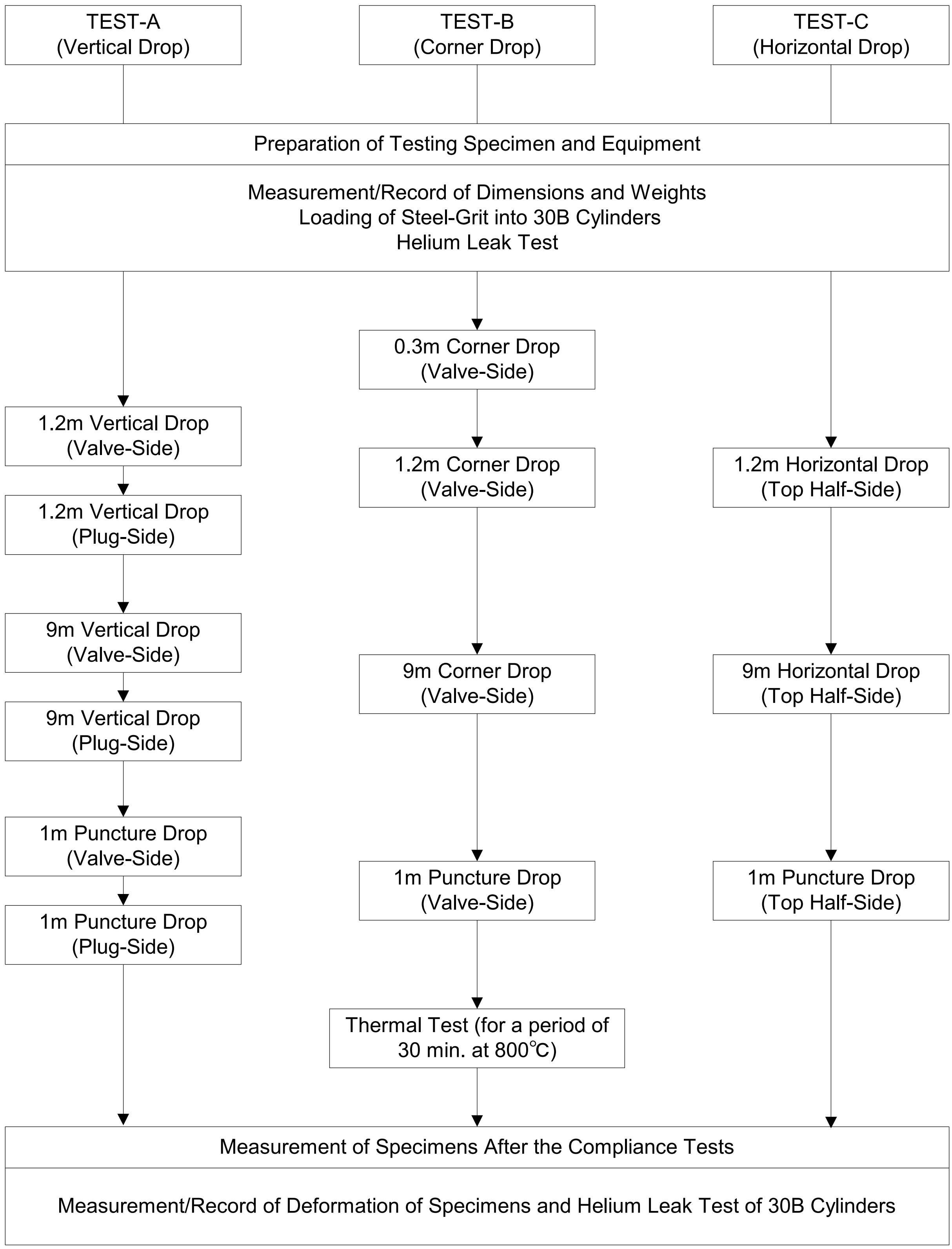


Figure 2.10.1-1 Testing Combinations and Sequences of Full-Scale Prototypes of Model MST-30 Package for Compliance Tests

Figure 2.10.1-2 has been withheld as Sensitive Unclassified Non-Safeguards Information-Security-Related Information

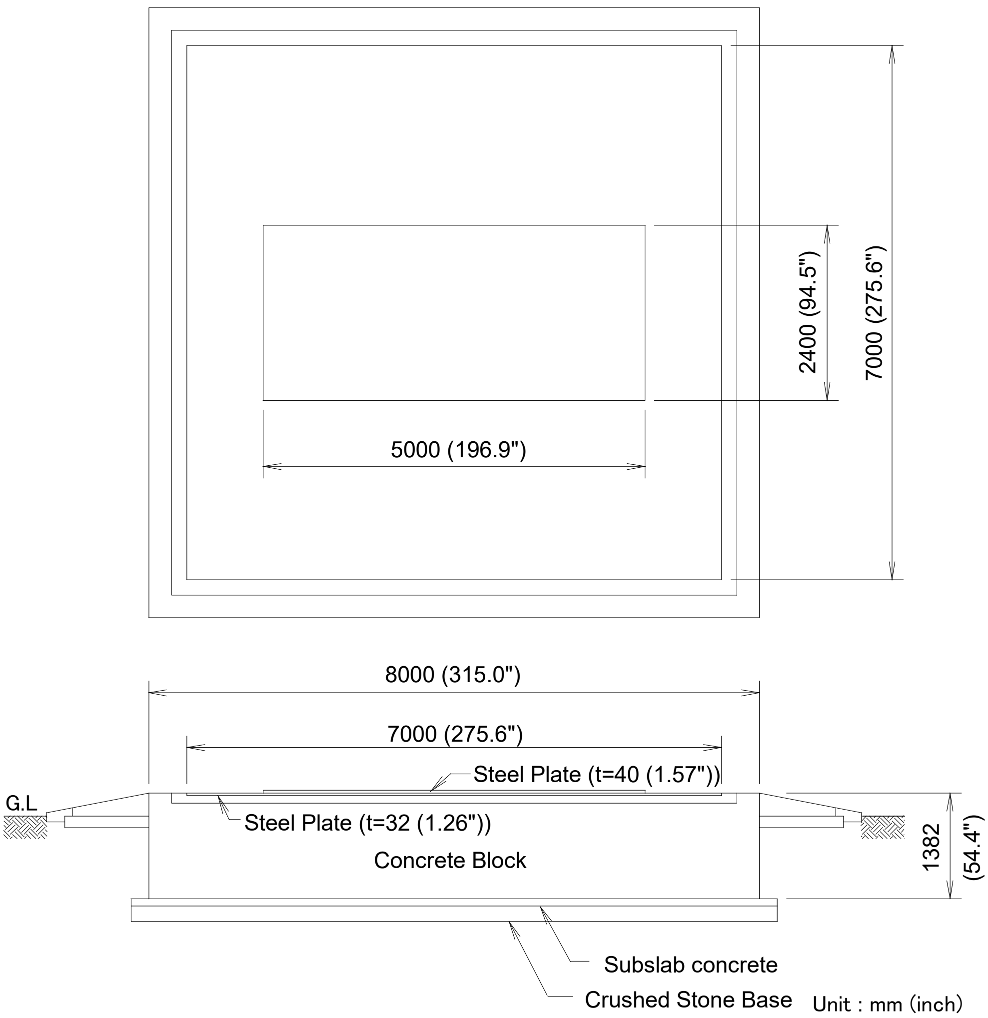


Figure2.10.1-3 Target Pad for Drop Test

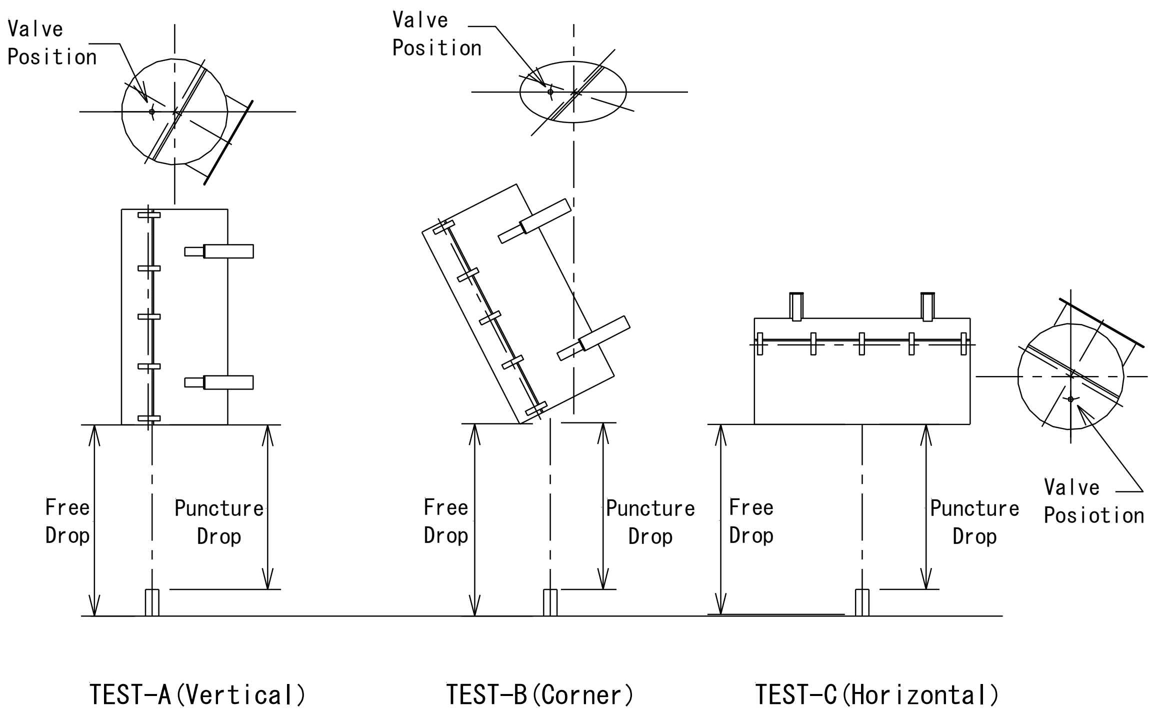
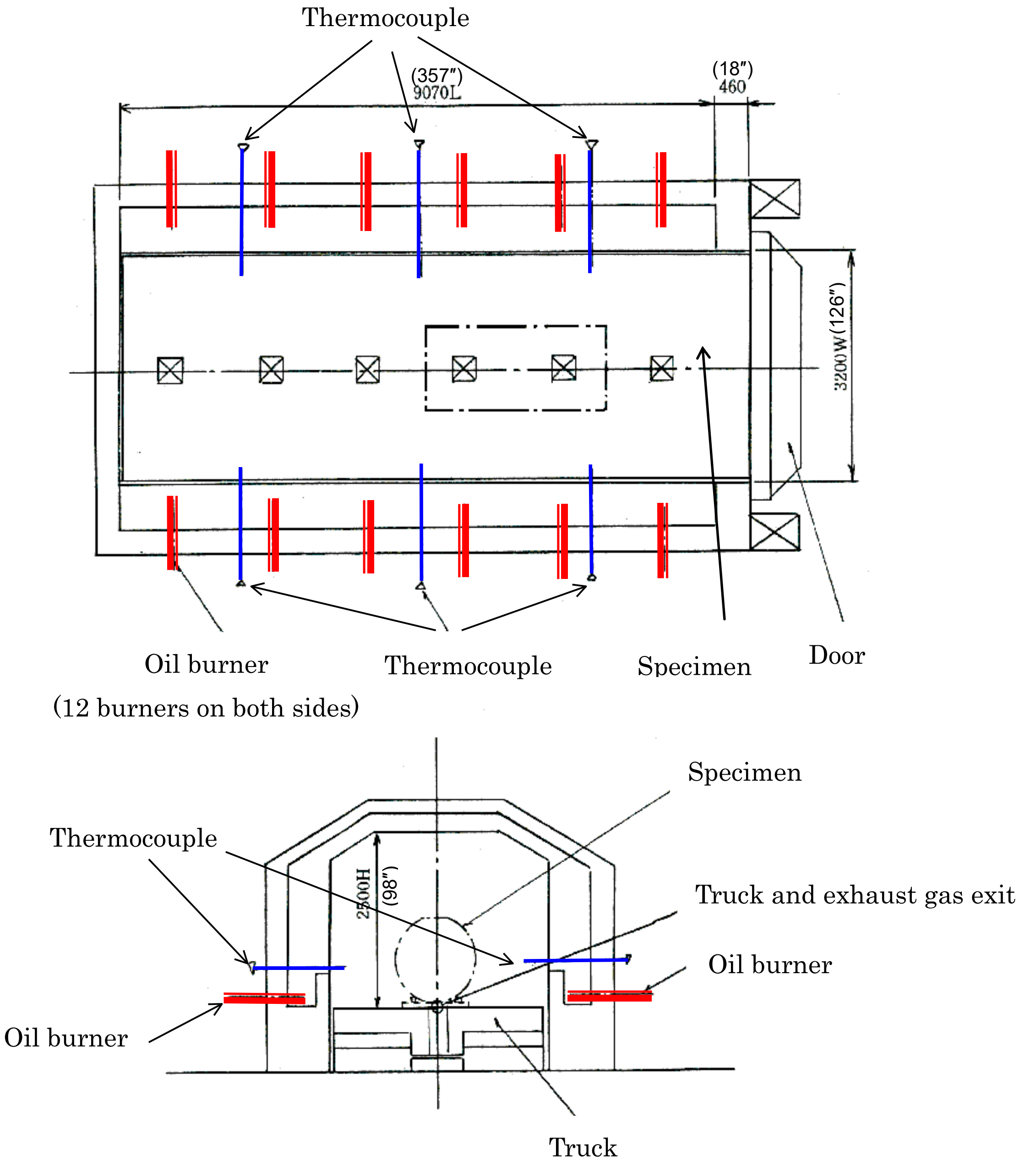


Figure 2.10.1-4 Drop Attitudes of Package for each Series of Free and Puncture Drops under NOC and HAC



Unit : mm(inch)

Figure 2.10.1-5 Furnace used for Thermal Test

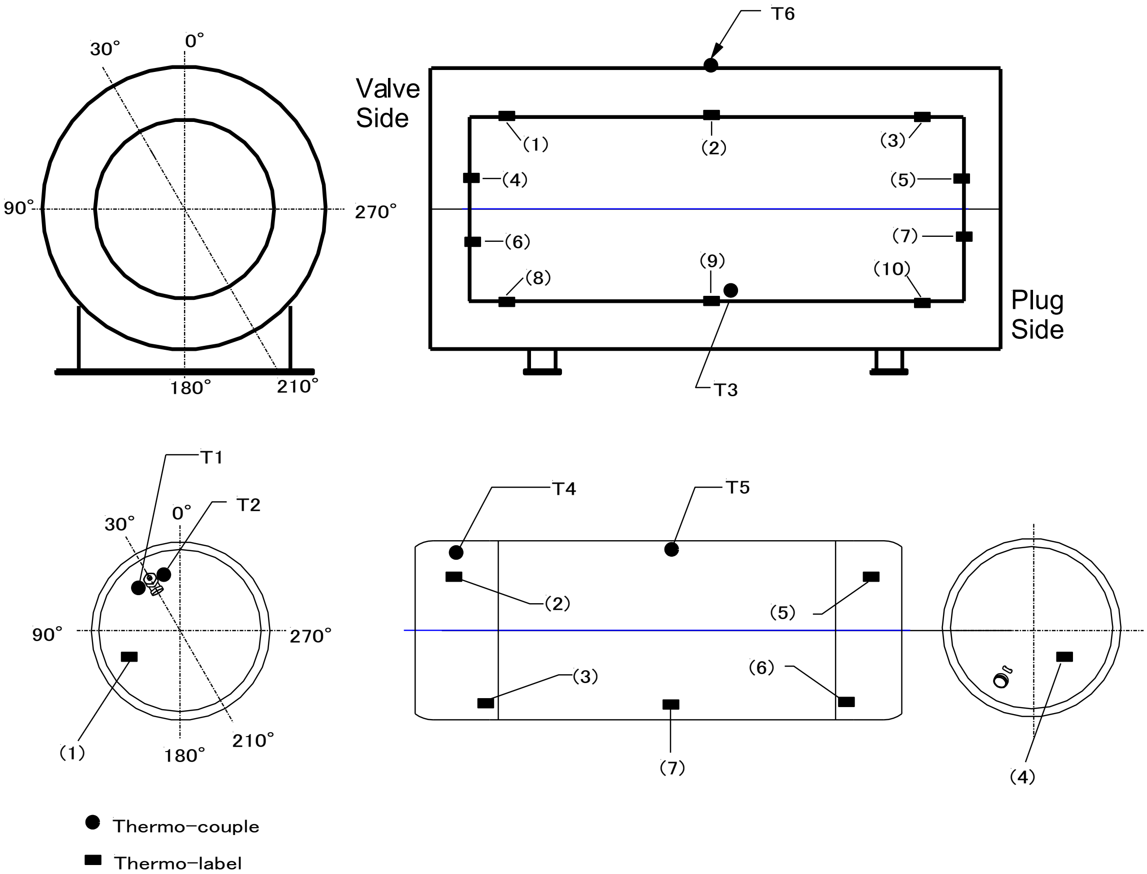
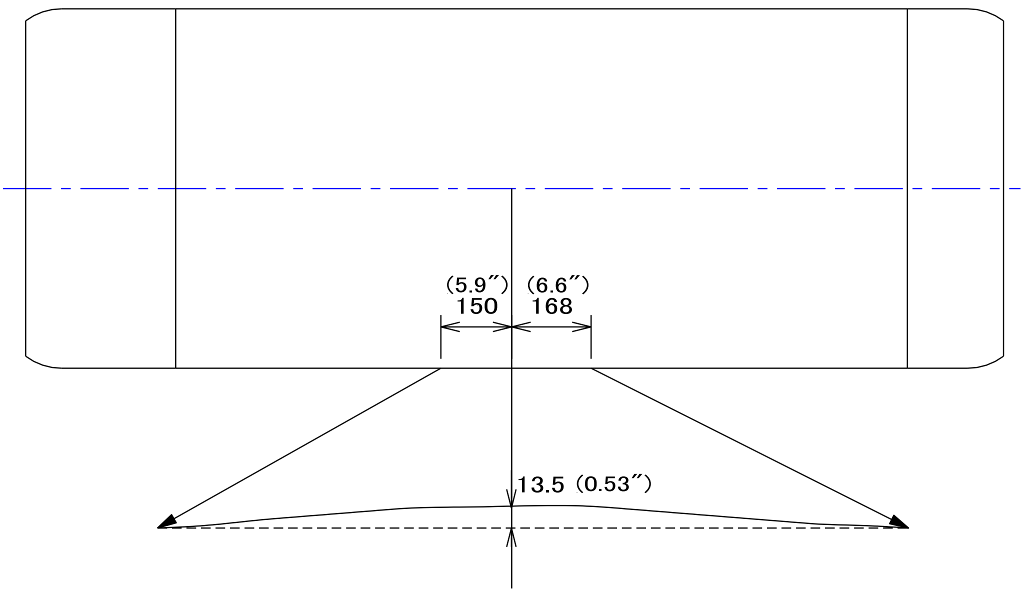
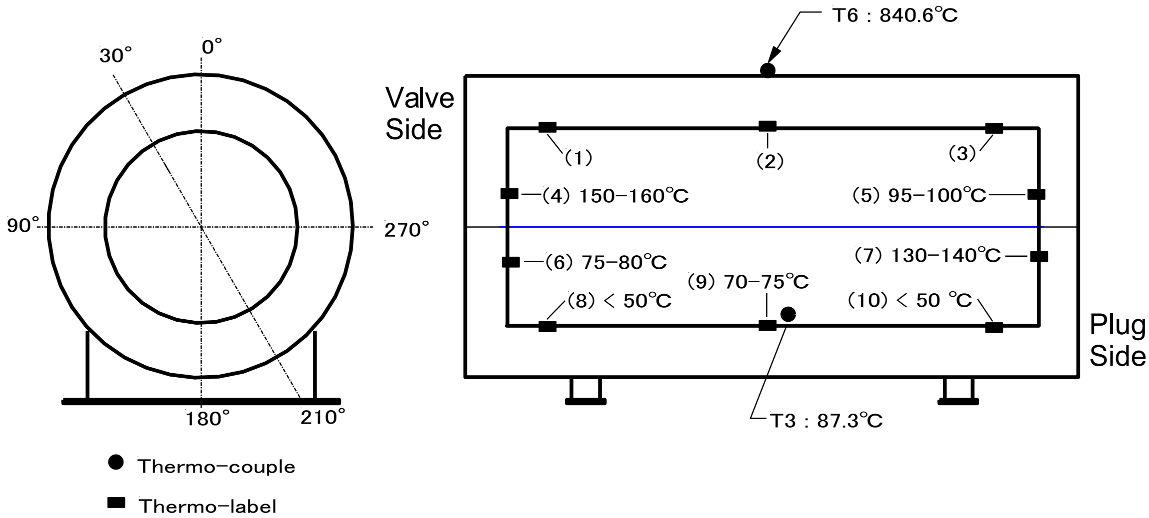


Figure 2.10.1-6 Locations of Thermo-couples and Thermo-labels



Unit : mm (inch)

Figure 2.10.1-7 Plastic Deformation of 30B Cylinder resulting from Horizontal Puncture Drop



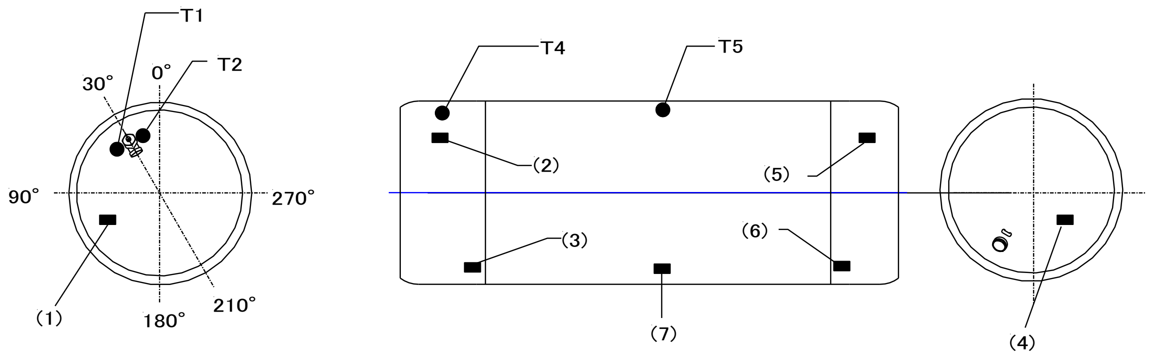
The temperature of each point of the overpack measured with thermo-couple : T3 and T6

T6:	On the external surface of outer shell	840.6°C	(1,545°F)
T3:	On the external surface of inner shell	87.3°C	(189°F)

The temperature of each point of the overpack measured with thermo-label: (1),(2),(3),(4),(5),(6),(7),(8),(9) and (10)

(1):	on the external surface of inner shell	(No.1 could not be identified)	
(2):	on the external surface of inner shell	(No.2 could not be identified)	
(3):	on the external surface of inner shell	(No.3 could not be identified)	
(4):	on the external surface of inner end plate (valve-side)	150~160°C	(302°F~320°F)
(5):	on the external surface of inner end plate (plug-side)	95~100°C	(203°F~212°F)
(6):	on the external surface of inner end plate (valve-side)	75~80°C	(167°F~176°F)
(7):	on the external surface of inner end plate (plug-side)	130~140°C	(266°F~284°F)
(8):	on the external surface of inner shell	lower than 50°C(122°F)	
(9):	on the external surface of inner shell	70~75°C	(158°F~167°F)
(10):	on the external surface of inner shell	lower than 50°C(122°F)	

Figure 2.10.1- 8 Temperature of Each Point of Overpack measured with Thermo-couples and Thermo-labels



The temperature of each point of 30B cylinder measured with thermo-couple: T1,T2,T4 & T5

T1:	on the external surface of cylinder-head (valve-side)	49.8°C	(approx.122°F)
T2:	on the external surface of cylinder-head (valve side)	51.5°C	(approx.125°F)
T4:	on the external surface of cylinder-skirt (valve-side)	59.4°C	(approx.139°F)
T5:	on the external surface of cylinder-body	50.7°C	(approx.123°F)

The temperature of each point of 30B cylinder measured with thermo-label: (1),(2),(3),(4),(5), (6) and (7)

(1):	on the external surface of cylinder-head (valve-side)	lower than 50°C(122°F)	
(2):	on the internal surface of cylinder-skirt (valve-side)	55～60°C	(131°F ~ 140°F)
(3):	on the internal surface of cylinder-body (valve-side)	lower than 50°C(122°F)	
(4):	on the external surface of cylinder-head (plug-side)	lower than 50°C(122°F)	
(5):	on the internal surface of cylinder-skirt (plug-side)	55～60°C	(131°F ~ 140°F)
(6):	on the external surface of cylinder-body (plug-side)	lower than 50°C(122°F)	
(7):	on the external surface of cylinder-body	lower than 50°C(122°F)	

Figure 2.10.1-9 Temperature of Each Point of 30B Cylinder measured with Thermo-couples and Thermo-labels

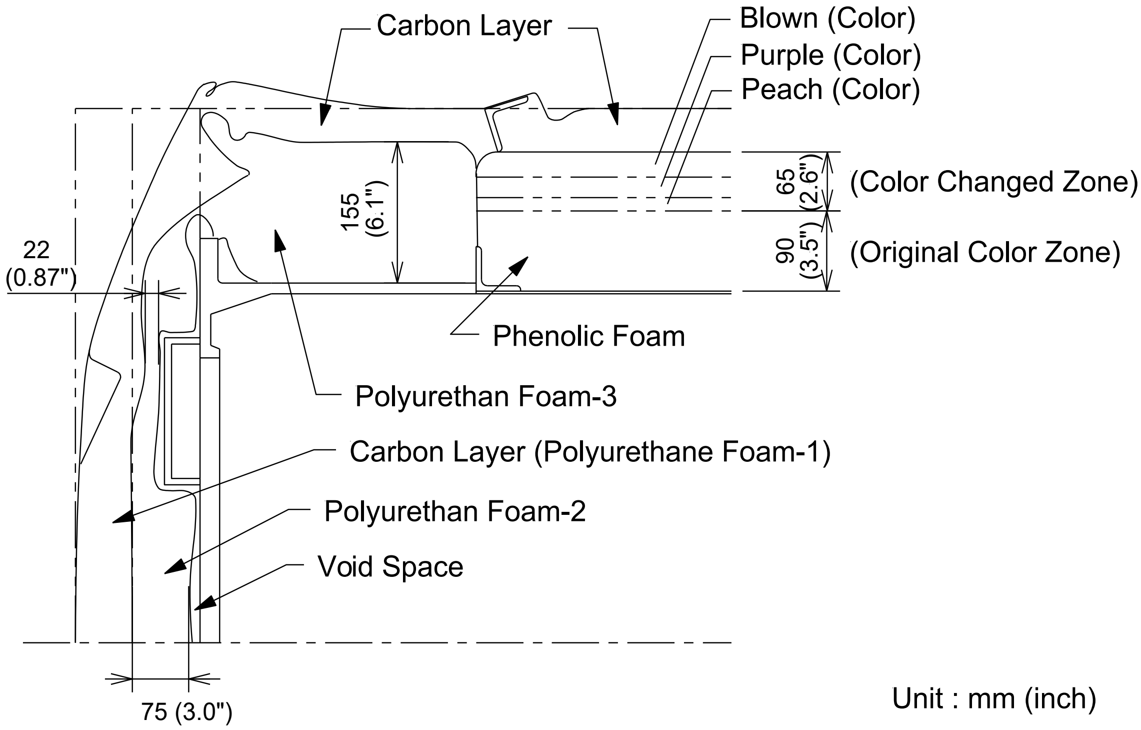
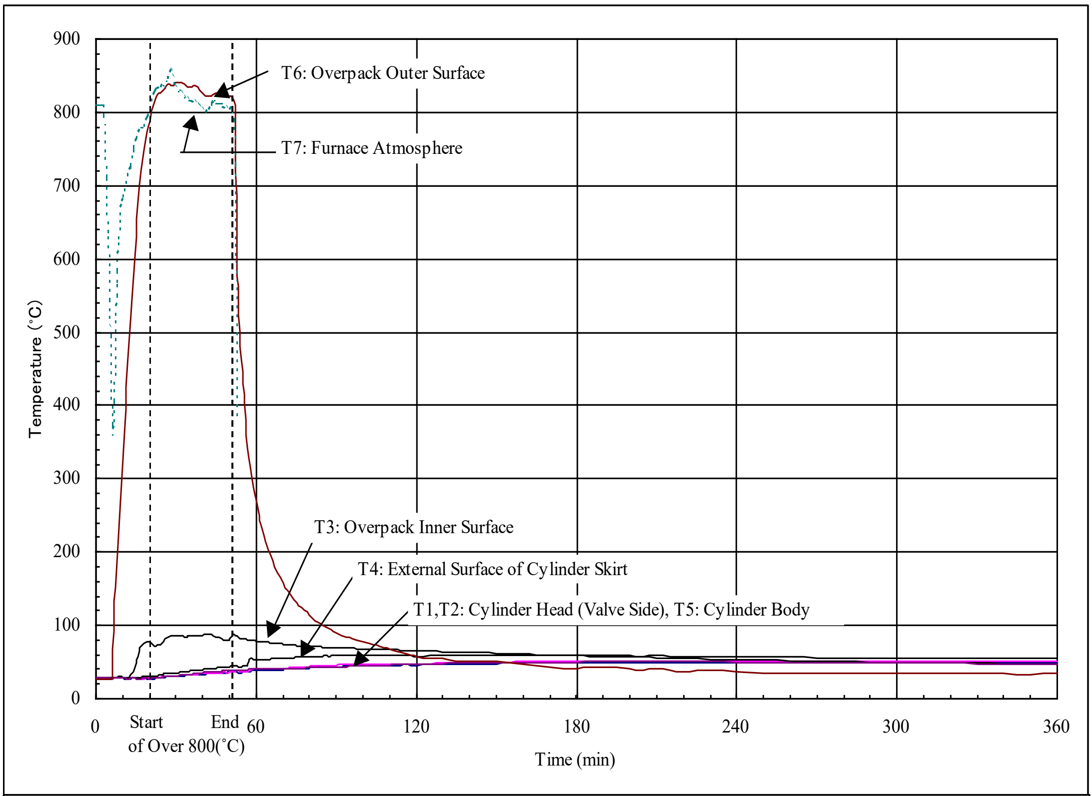
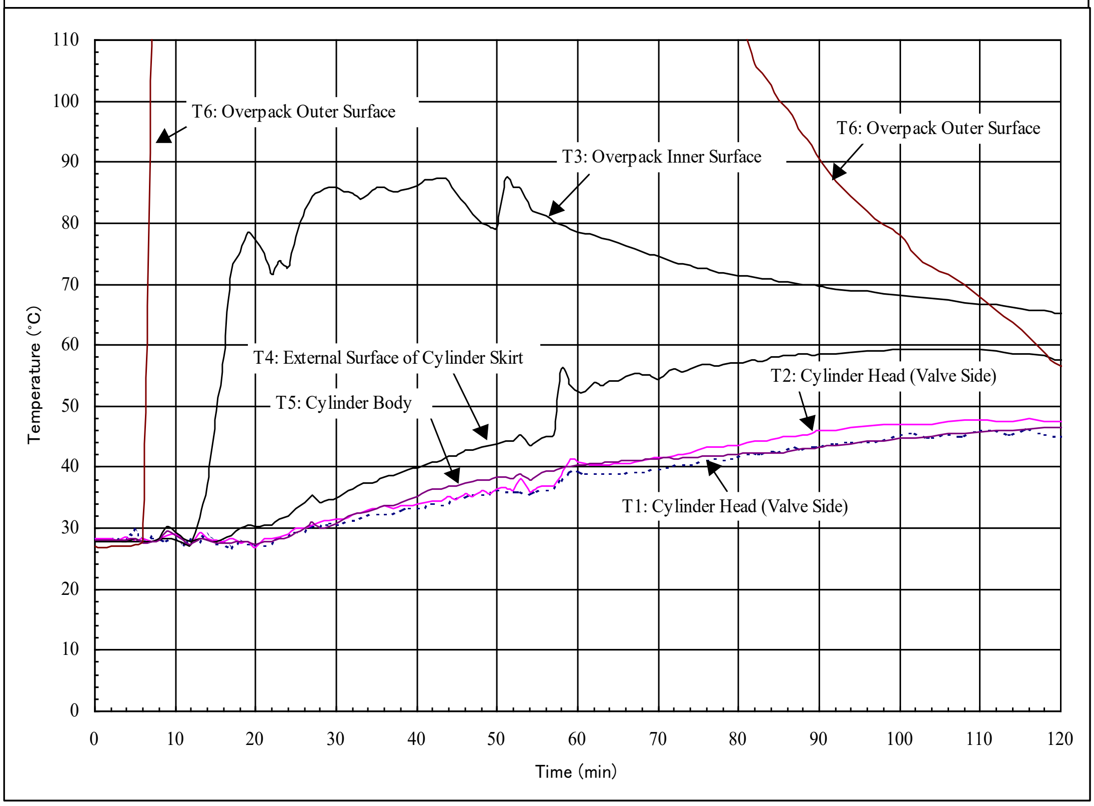


Figure 2.10.1-10 Cross-Section View showing Combustion State of Specimen for TEST-B after Thermal Test





Note: The positions of T1 through T6 are shown in Figure 2.10.1-8 and 9.

Figure 2.10.1-11 Temperatures measured with Thermo-Couples during Thermal Test

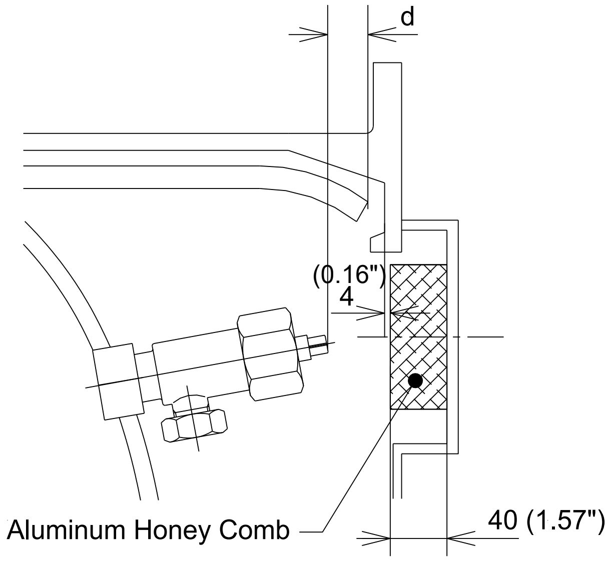
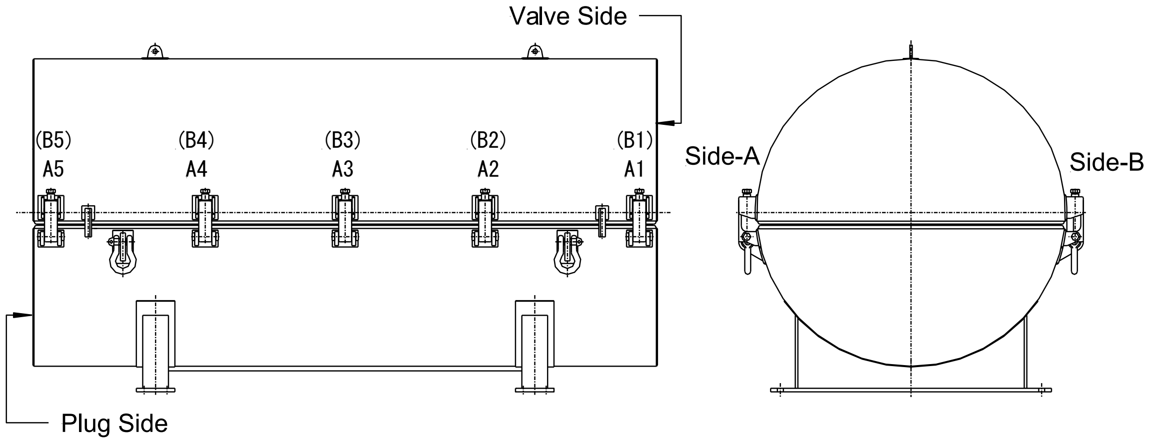


Figure 2.10.1-12 Relative Position of Valve and Aluminum Honey-Comb



Note : The parenthesized numbers (B1 to B5) are fitting position numbers of fastening devices on the opposite side of the overpack.

Figure 2.10.1-13 Position of Fastening Devices

PHOTOGRAPHS OF COMPLIANCE TESTING

DROP TESTS –TEST-A (Vertical Drop)

Photo-1 1.2m Vertical Drop (Valve-Side)

Photo-2 9m Vertical Drop (Valve-Side)

Photo-3 1.2m Vertical Drop (Plug-Side)

Photo-4 9m Vertical Drop (Plug-Side)

Photo-5 Puncture (Valve-Side)

Photo-6 Puncture (Plug-Side)

DROP TEST – TEST-B (Corner Drop to be followed by Thermal Test)

Photo-7 0.3m Rim Corner Drop(Valve-Side) for Fissile Material Package

Photo-8 1.2m Corner Drop (Valve-Side)

Photo-9 9m Corner Drop (Valve-Side)

Photo-10 Puncture (Valve-Side)

DROP TEST – TEST-C (Horizontal Drop)

Photo-11　1.2m Horizontal Drop

Photo-12　9m Horizontal Drop

Photo-13　Horizontal Puncture

Photo-14　Horizontal Puncture

THERMAL TEST

Photo-15 Furnace for Heat Treatment which was used in Thermal Test for MST-30 Package

Photo-16 Immediately after Pulling Out Specimen from Furnace

Photo-17 Specimen after Cooling

Photo-18 State of Polyurethane Foam Carbonization by Thermal Test

Photo-19 State of Phenolic Foam Carbonization by Thermal Test

STATE OF INTERNAL OVERPACK

Photo-20 State of Cylinder(B) after Thermal Test Preceded by a Series of Free Drop & Puncture

Photo-21 Impact Area due to Puncture Bar (Inner Cylindrical Shell of Specimen C)

Photo-22 Area Impacted due to Puncture Bar (Cylinder of Specimen C)

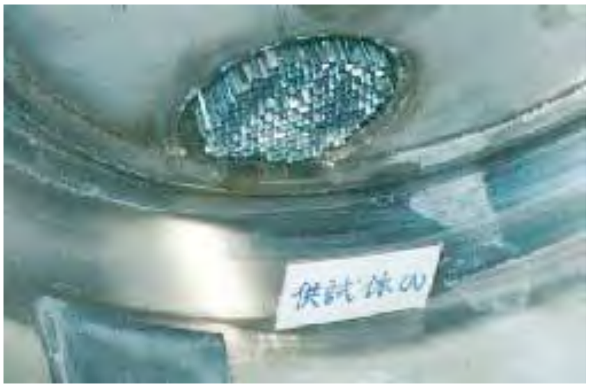


Photo-23 Aluminum Honey Comb (Valve-Pocket of Specimen A)

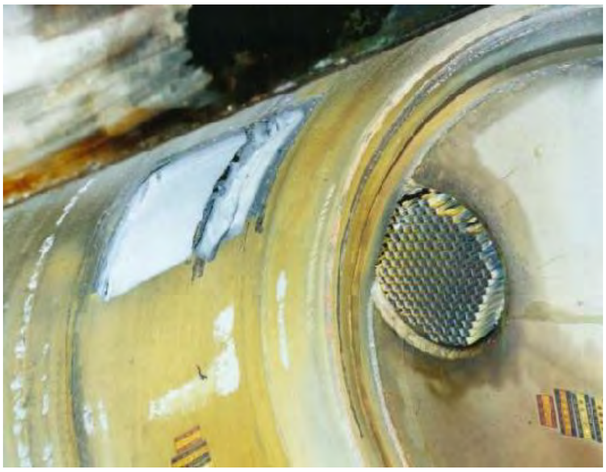


Photo-24 Aluminum Honey Comb (Valve-Pocket of Specimen A)

Photo-25 He Leak Test

Appendix 2.10.2

Summary of Preliminary Drop Testing

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Summary of Preliminary Drop Testing of the Model MST-30 Package Performed by Mitsubishi Materials Corporation

1 Purpose

Preliminary drop testing was performed in order to verify that the MST-30 overpack would perform as designed and also to choose the drop angle that would cause the maximum damage or deformation in the valve region of the overpack. This preliminary drop testing was performed prior to the compliance tests using full-scale prototype packagings. The flow chart provided in Figure 2.10.2-1 illustrates the sequence of tests performed.

2 Testing Dates and Test Facility

Test Dates: November 26 and 27, 1996

Test Facility: Drop Testing Facility at Naka Energy Laboratory, Mitsubishi Materials Corporation. 1002-14, Mukouyama, Naka-Machi Naka-Gun Ibaraki-Prefecture, JAPAN

3 Description of Specimens for Preliminary Drop Testing

3.1 Specimens for Originally Designed Overpack

The preliminary test program utilized a full-size cylinder and overpack. The package was almost constructed according to the drawings provided in Appendix 1.3.2 and 1.3.3, with the mainly following exceptions: the foam insulation was provided only at the valve end of the overpack, as shown in Figure 2.10.2-2; the fastening devices on the exterior of the overpack were replaced by less complex fasteners; and the outer wall end plate was 4mm thick (rather than the 6mm thick final design). The gross weight of the package was completely simulated, using dummy weights to make up the weight equivalent to the omitted components. Two (2) specimens (A and B) were used in the preliminary drop testing.

3.2 Cylinder Specimens and Simulated Payload

Two 30B cylinders were used in the testing. In order to simulate the 30B cylinder containing UF_6 equivalent to the authorized maximum loading quantity, cylinder A for Test-Series No.1 (15°) was filled with 2,304.5 kg (5,080.5 lb) steel grit and cylinder B for Test-Series No.2 (27°) 2,303.5 kg (5,078.3 lb) steel grit.

4 Drop Orientations

Two different test-series were performed for the preliminary drop testing as follows:

- Test-Series No.1 : a slanting Drop Orientation directly toward the cylinder-valve, with the center of gravity over the impact site (15°).
- Test-Series No.2 : a slanting drop toward the cylinder valve with the center of gravity over the corner (27°).

Figure 2.10.2-3 illustrates the orientation of the package for the drop tests.

5 Summary of Testing Results

Photographs of the preliminary drop testing are shown in Figure 2.10.2-4 and 2.10.2-5. Deformation of the two specimens for overpack due to Drop-I (9m Free Drop) and deformation of the specimens due to Drop-II (1m Puncture Test) are shown in Figure 2.10.2-6. The preliminary drop testing showed:

- Very few deformation of the cylinder-skirt for either drop orientation.
- No contact of the cylinder-valve with the inner wall end plate of overpack (i.e. the space between the valve and the inner wall end was sufficiently maintained), although some distortion was visible on the inner wall end plate for both drop orientations.
- Negligible deformation of the circumferential corner of inner shell.

6 Discussion of Test Results

As a result of the preliminary drop testing, the overpack was proven to have a sufficient capability of protecting the cylinder-valve as designed, even at a drop orientation that were predicted to cause the maximum damage for the valve.

The 15° drop angle did not cause as much damage as the 27° drop angle. This is consistent with predictions, as the 27° drop angle imparts almost all of the potential energy of the package to deformation of the overpack, while the 15° drop angle allows some of the energy to be dissipated in rotational motion. Additionally, since the 27° reduced the wall thickness more than the 15°, it is recommended that the 27° be used for the thermal test in compliance testing.

In conclusion, in performing the compliance tests using a full-scale prototype packagings in the near future, a corner drop orientation with drop angle of 27° is recommended for both the 9 m free drop test and 1 m puncture test to be followed by the thermal test.

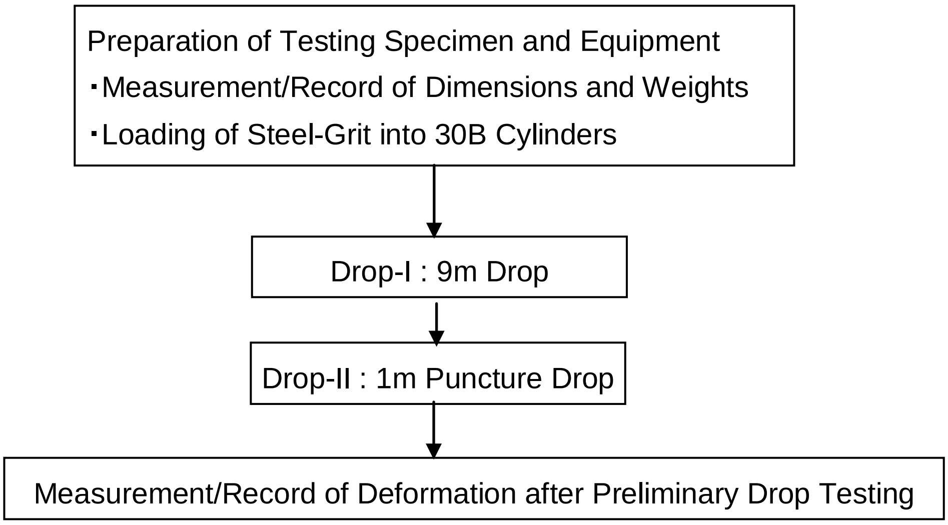


Figure 2.10.2-1 Flow Chart of Preliminary Drop Testing

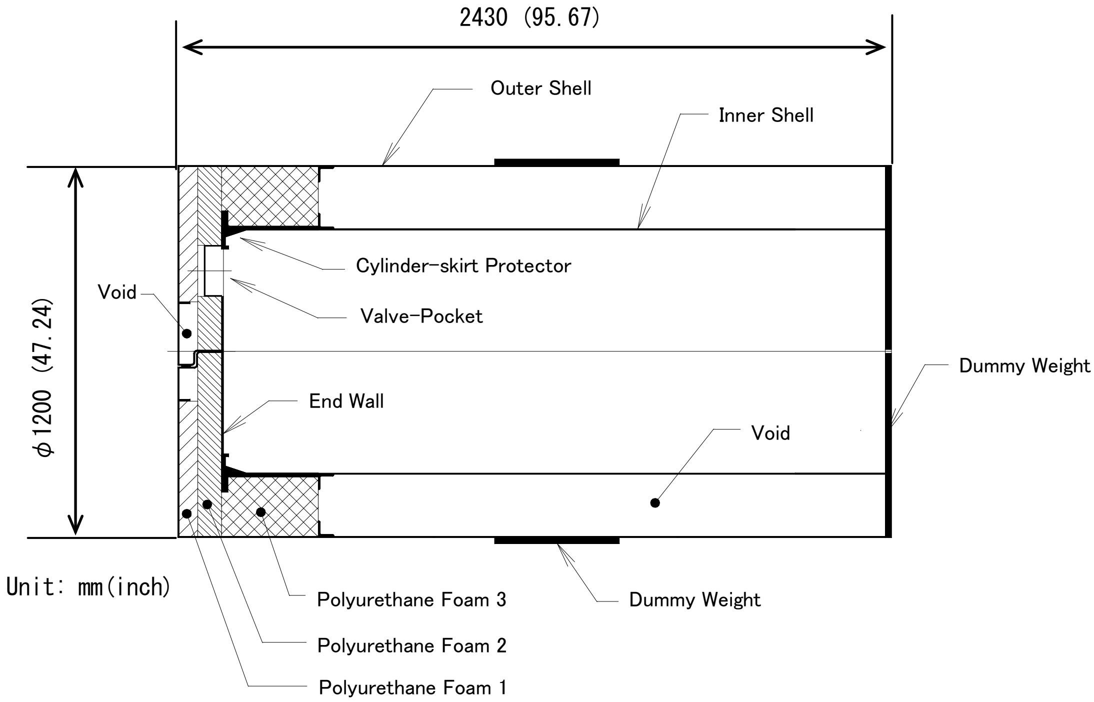
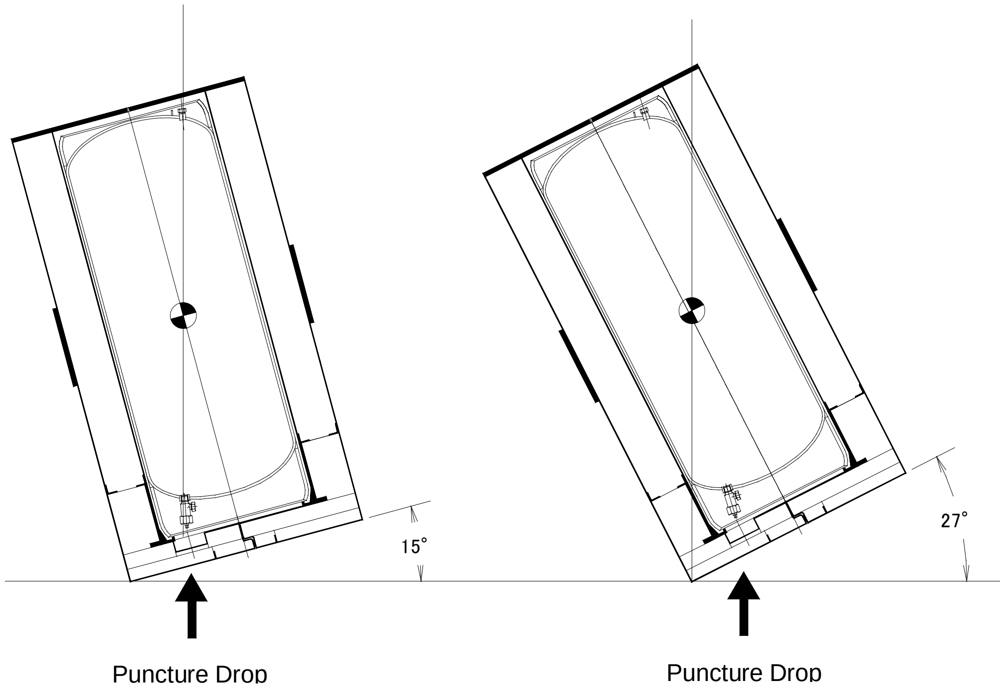


Figure 2.10.2-2 Package for Preliminary Drop Testing

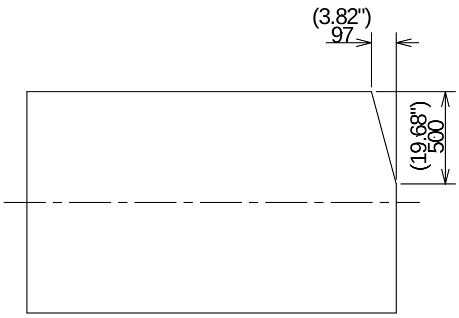
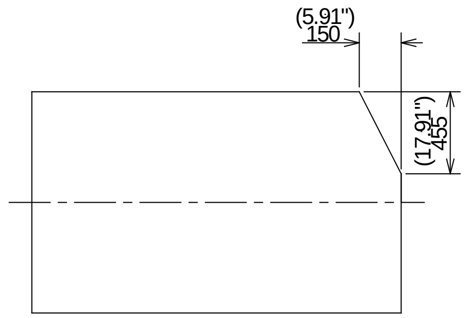
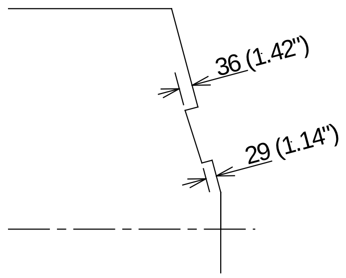
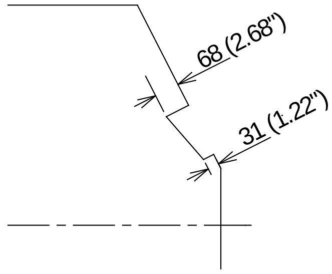


Test-Series No.1 (15°)　　Test-Series No.2 (27°)

Figure 2.10.2-3 Orientation of Package for Drop Tests

Figure 2.10.2-4 Test Series No.1 (15º)

Figure 2.10.2-5 Test Series No.2 (27º)

	Test-Series No.1（15°）	Test-Series No.2（27°）
Drop-I (9m Free Drop)		
Drop-II (1m Puncture Test)		

Unit : mm (inch)

Figure 2.10.2-6 Deformation of Specimens

Appendix 2.10.3

Effect of Fabrication Deviation of Polyurethane Foam

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Effect of Fabrication Deviation of Polyurethane Foam

Fabrication allowances have been specified for the polyurethane foam used as an impact limiter in the MST-30 overpack. As a consequence, the compressive strength of the foam used in the general manufacture MST-30 overpacks may be lower than the compressive strength of the foam used for the prototypes tested. This appendix investigates the effect of fabrication deviations on the compressive strength of the polyurethane foam used and the performance of the overpack with the lower strength foam during NOC and HAC impacts.

1. Allowable Strength Deviations

The compressive stress (strength) of polyurethane foam varies with strain. For the MST-30 prototypes, the total deformation of the overpack for the 9m vertical drop was 15mm on the valve side and 18mm on the plug side (see Appendix 2.10.1) for an initial foam thickness of approximately 100mm. Thus, the macroscopic strain of the polyurethane foam generated by a 9m vertical drop impact is approximately 20%. Therefore, the compressive strength of the polyurethane foam is assumed to be the compressive stress at 20% strain.

The measured strain-stress curves for the polyurethane foams employed for the compliance tests are shown in Figure 2.10.3-1. According to Figure 2.10.3-1, the compressive strength at 20% strain is:

Polyurethane Foam-1 and 3	10.0 N/mm^2	(1,450 psi)
Polyurethane Foam-2	16.7 N/mm^2	(2,420 psi)

As shown Figure 2.10.3-2, the relationship between the compressive strength and the density of the polyurethane foam is nearly linear. Thus, the minimum compressive strength of the foam can be obtained from the lower limit of the polyurethane density by interpolating based on a linear fit.

For the MST-30, the range of foam density is specified as follows:

Polyurethane Foam-1 and 3 :	0.37 ± 0.03 g/cm^3	($21.2 \sim 25.0$ lb/ft^3)
Polyurethane Foam-2 :	0.48 ± 0.03 g/cm^3	($28.1 \sim 31.8$ lb/ft^3)

Therefore, the minimum compressive strength of the foam, from Figure 2.10.3-2 and the linear interpolation is:

Polyurethane Foam-1 and 3	8.1 N/mm^2	(1,170 psi)

Polyurethane Foam-2 14.4 N/mm^2 (2,090 psi)

Thus, the minimum compressive strength of the polyurethane foam-1 and -3 is 19% lower than that employed for prototype package, and the minimum compressive strength of foam-2 is 13% lower than that employed for prototype, as shown in Table 2.10.3-1.

2. Evaluation

The potential energy imparted to a package on impact is consumed by deformation of the overpack. Assuming that the materials are perfectly plastic-rigid, the energy consumed by deformation, E, can be expressed as the product of deformed volume, ΔV, and compressive strength, σ. Therefore, the deformed volume, ΔV, can be expressed as follows:

$$\Delta V = E / \sigma$$

ΔV	Deformed volume
E	Energy consumed by deformation (= Potential Energy)
σ	Compressive strength

Conservatively neglecting the energy consumed by the outer-shell deformation, if the compressive strength is decreased by 19%, the deforming volume, ΔV, is:

$$\Delta V = \frac{E}{(1-0.19)\sigma} = 1.234 \times E / \sigma$$

Therefore, if the polyurethane foam with the minimum strength is used for the overpack, it is expected that the deformation volume will increase approximately 24% above the deformation volume of the test prototype.

Since the maximum deformation of the overpack was produced for the corner drop in the compliance testing, the effect of the decreased polyurethane foam compressive strength is evaluated for this orientation. The deformation of the prototype overpack produced by the corner drop was horseshoe-shaped, as shown in Figure-2.10.3-3. Thus, the deformation model is drawn in a horseshoe shape, as shown in Figure 2.10.3-4. The volume of the horseshoe shape is:

$$V = \frac{h}{3b}\left\{a\left(3r^2 - a^2\right) + 3r^2(b - r)\phi\right\}$$

where, a, b, d, h, r, ϕ are as shown in Figure 2.10.3-4.

Here, a, b and ϕ can be expressed using the radius of the overpack, r; drop angle, θ; and deformed length, d, as follows:

$$a = \sqrt{\overline{BO}^2 - \overline{CO}^2} = \sqrt{r^2 - \left(r - \frac{d}{\sin\theta}\right)^2}$$

$$b = \frac{d}{\sin\phi}$$

$$\phi = \cos^{-1}\left(\frac{\overline{CO}}{r}\right) = \cos^{-1}\frac{r - \frac{d}{\sin\theta}}{r}$$

where, $\overline{BO}, \overline{CO}$ are distance between B and O, and between C and O respectively shown in Figure 2.10.3-4.

Then, deformed volume of overpack at corner drop can be expressed as follows:

$$V = \frac{\tan\theta}{3}\left[\sqrt{r^2 - \left(r - \frac{d}{\sin\theta}\right)^2} \times \left\{2r^2 + \left(r - \frac{d}{\sin\theta}\right)^2\right\} + 3r^2\left(\frac{d}{\sin\theta} - r\right) \times \cos^{-1}\left(\frac{r - \frac{d}{\sin\theta}}{r}\right)\right]$$

where,

r	Radius of Overpack = 600 mm (23.6 in)
θ	Drop Angle for corner drop = 27 degree
d	Deformation of overpack in Length

Using the equation above, the relationship between the deformation and volume are shown in Figure 2.10.3-5.

As shown in Figure 2.10.3-3, the deformation resulting from the corner drop of the prototype package was 112mm. Thus, the deformed volume of prototype package is 8.59 x 10^6 mm^3 according to Figure 2.10.3-5.

As described previously, the deformed volume of an overpack with the minimum strength polyurethane is expected to increase 24%. The deformed volume is therefore:

$$V = 1.24 \text{ x } (8.59 \text{ x } 10^6 \text{ mm}^3) = 1.07 \text{ x } 10^7 \text{ mm}^3 \ (0.378 \text{ ft}^3)$$

For a volume of 1.07 x 10^7 mm^3, the deformed length of the overpack is 123 mm (see Figure 2.10.3-5). Thus, the maximum increase of deformation of the overpack due to the allowable fabrication deviations of the polyurethane foam is expected to be 11mm. As shown in Figure 2.10.3-3, the minimum distance between outer and inner shell at corner drop attitude is 184mm. Thus, the 11mm additional deformation has no significant effect for safety.

3. Conclusion

The additional deformation due to the lower compressive strength of the polyurethane foam does not exceed the minimum foam depth available for a corner impact. An increase of 24% deformed volume has no significant effect on any other drop attitude, since the corner drop presented the worst case. Therefore, the allowable fabrication deviation of the polyurethane foam does not compromise the integrity of the overpack.

Table 2.10.3-1 Compressive Strength (Compressive Stress at 20% Strain)

	Measured Compressive Strength of the Prototype Package	Minimum Compressive Strength of the MST-30 package	Reduction of Compressive Strength
Polyurethane Foam-1 and 3	10.0 N/mm^2 (1,450 psi)	8.1 N/mm^2 (1,170 psi)	19%
Polyurethane Foam-2	16.7 N/mm^2 (2,420 psi)	14.4 N/mm^2 (2,090 psi)	13%

Table 2.10.3-2 Deformation at Corner Drop

	Deformation in Length	Deformation in Volume
Prototype Test Result	112mm (4.41 in)	8.59×10^6 mm^3 (0.303 ft^3)
Minimum Strength	123mm (4.84 in)	(8.59×10^6 mm^3 x 1.24 =) 1.07×10^7 mm^3 (0.378 ft^3)
Difference	11 mm (0.43 in)	2.1×10^6 mm^3 (0.074 ft^3)

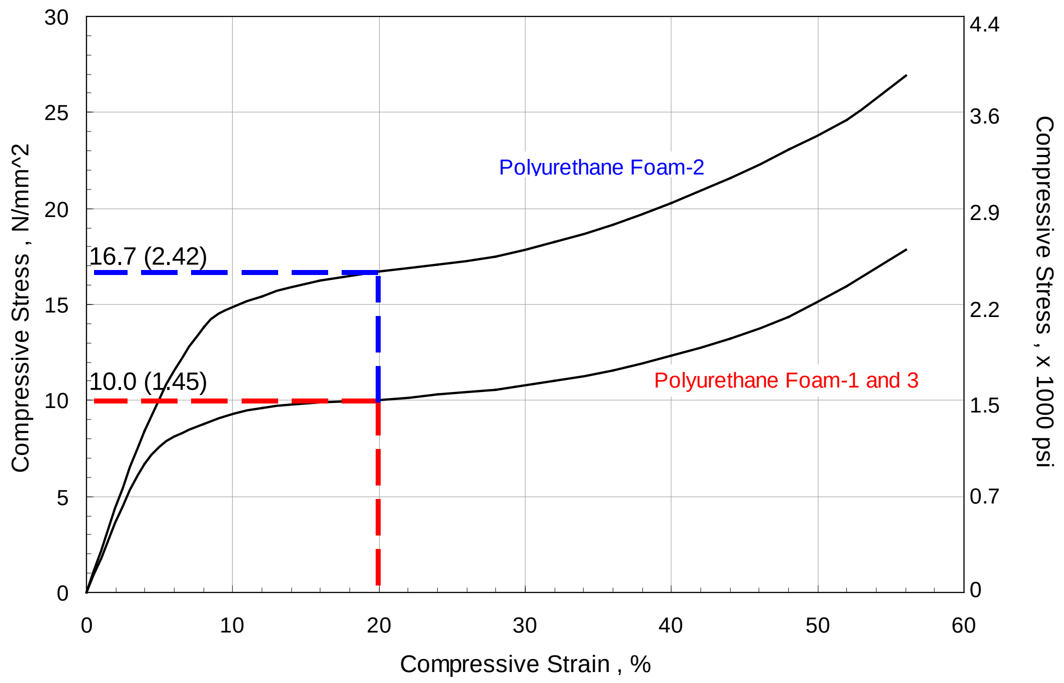

Figure 2.10.3-1 Compressive Strength of Polyurethane Foam used in Prototype Package for Compliance Test

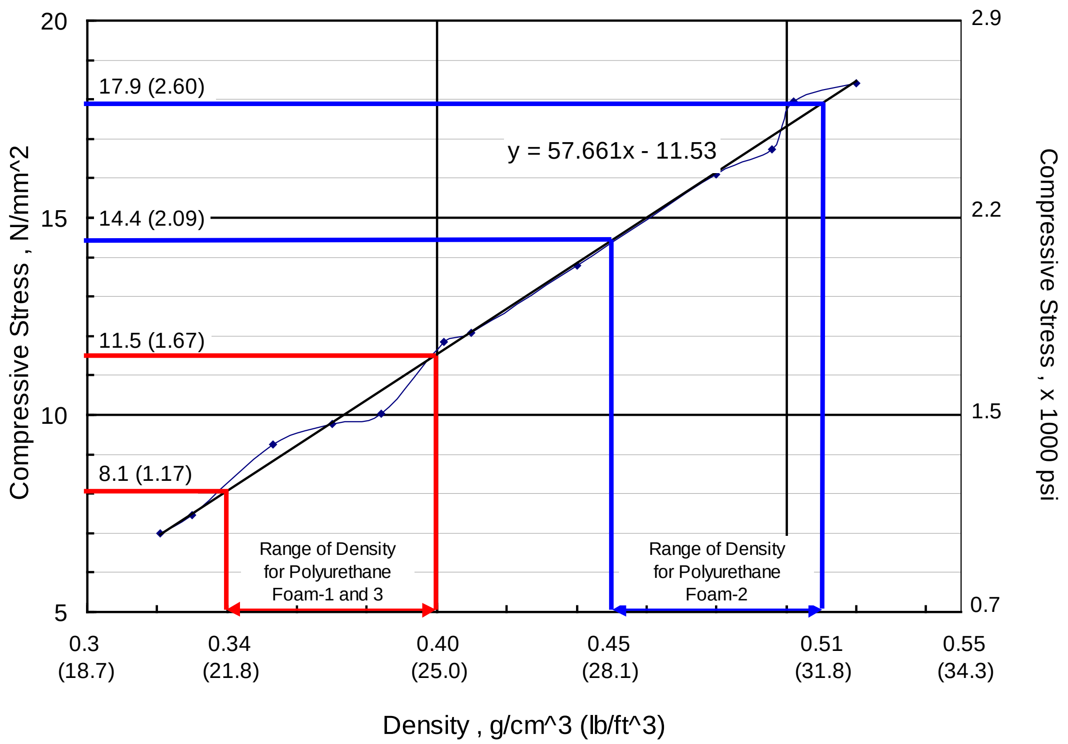

Figure 2.10.3-2 Deviation of Compressive Strength of Polyurethane Foam for MST-30

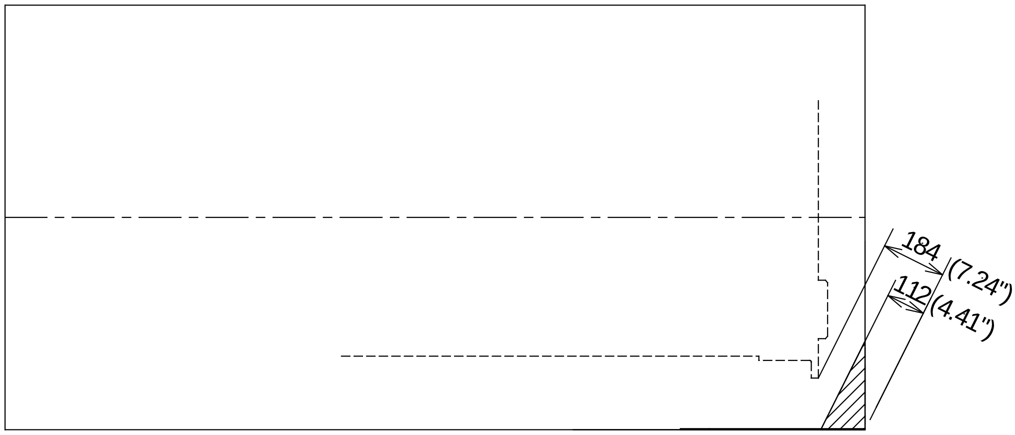

Figure 2.10.3-3 Deformation of Prototype Package after 9m Corner Drop in Compliance Test

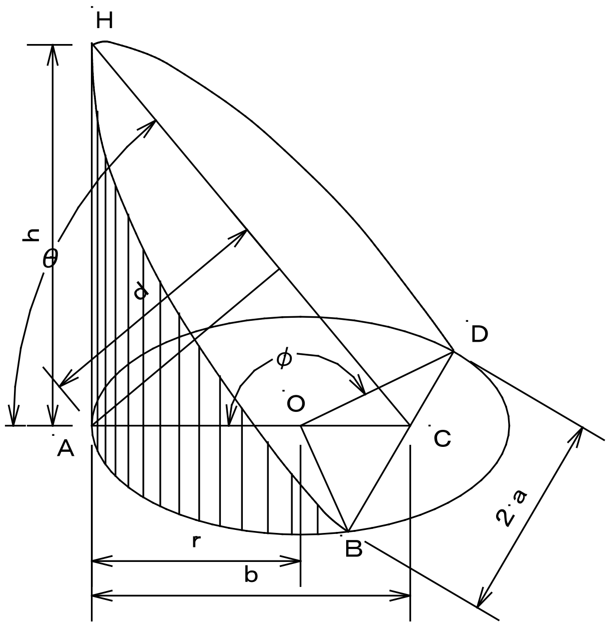

Figure 2.10.3-4 Horse Shoe Model for Deformation of Overpack at Corner Drop

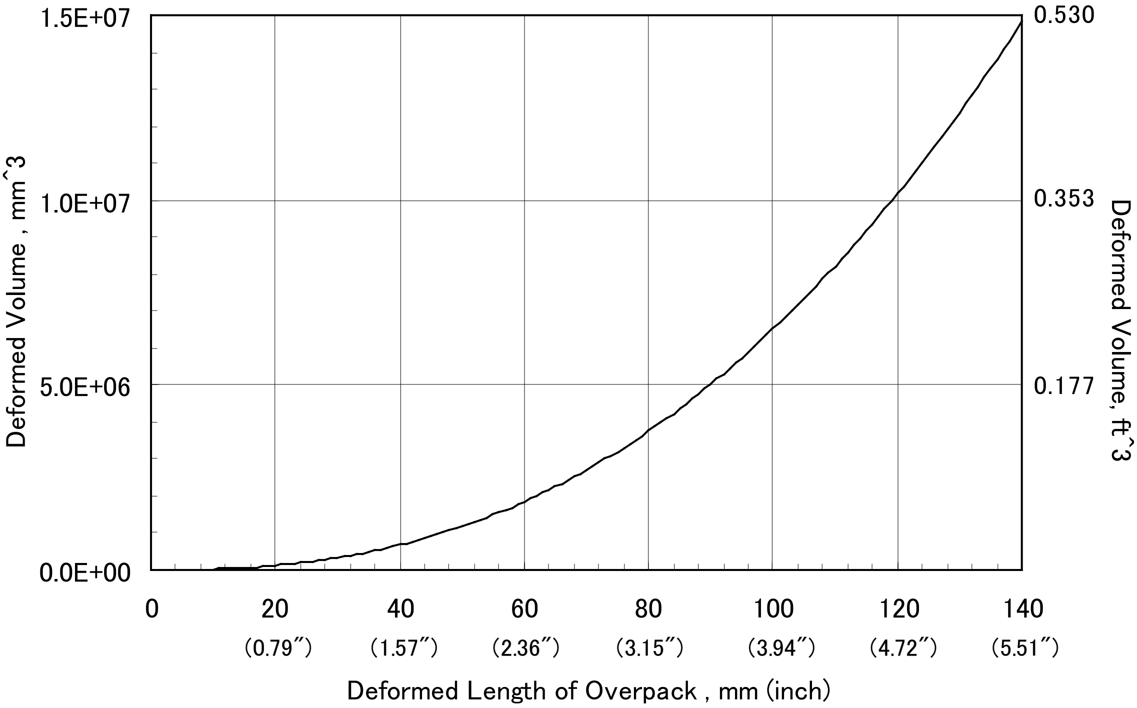

Figure 2.10.3-5 Relation between Deformed Length and Volume

Appendix 2.10.4

Charts for Determining Shell Thickness under External Pressure

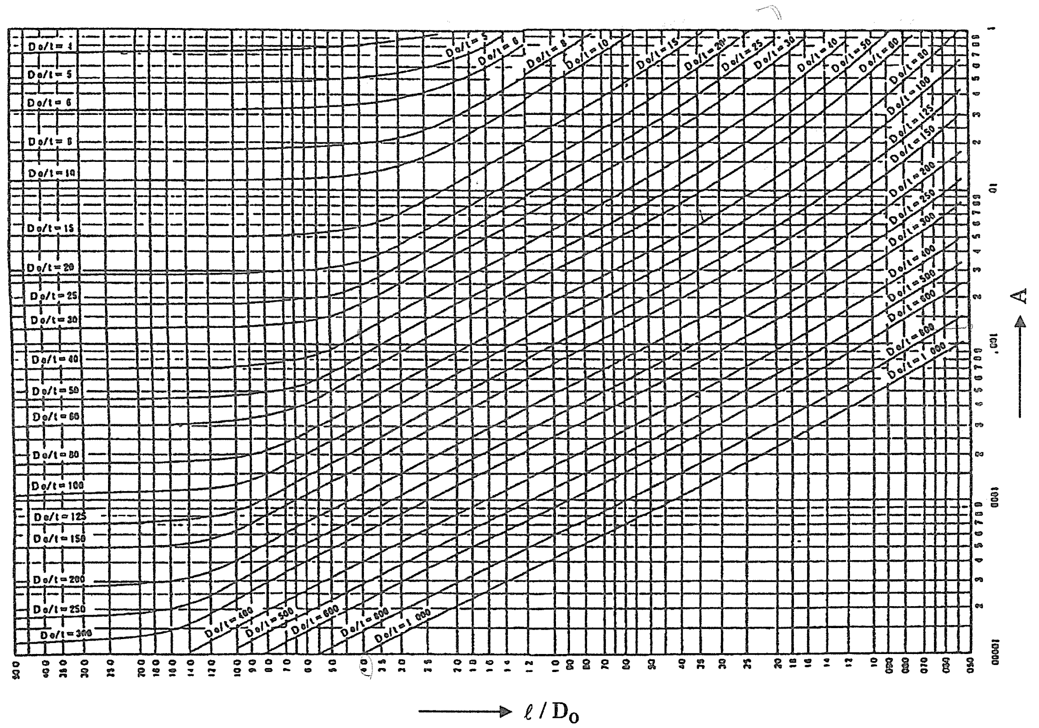

Figure 2.10.4-1 Geometric Chart for Components under External of Compressive Loading

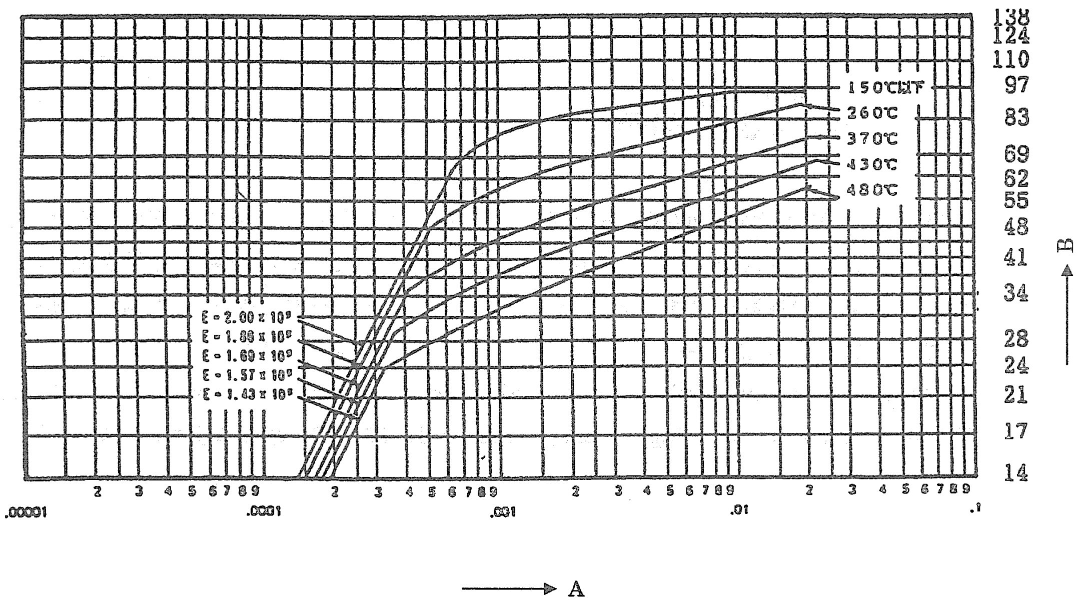

Figure 2.10.4-2 Chart for Determining Thickness of Components under External Pressure When Constructed of Carbon Steel (Specified Minimum Yield Strength165N/mm² (23,900psi) to, but not Including, 210N/mm² (30,500psi))

Appendix 2.10.5

Detailed Description of Helium Leak Tests

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Detailed Description of Helium Leak Tests

1. Purpose

In order to demonstrate the package containment ability under NOC and HAC, the MST-30 prototypes used for the drop and fire tests were leak tested using the helium detection equipment before and after the series of tests. This section describes the procedures, equipment, and calculations used to perform the helium leak tests and evaluate the results.

2. Seals Tested

The cylinder valve seals, as well as the valve and plug connection to the cylinder-head were tested.

3. Helium Leak Test Procedure

(1) Prior to the test series, the 30B cylinders were filled with steel grit, evacuated to vacuum, and then filled with helium to a pressure of 2 atm abs.

(2) The cylinder head was tested using a vacuum chamber as illustrated in Figure 1. A schematic of the helium measurement system is shown in Figure 2, and a photograph of the measurement taken during testing is shown Figure 3.

(3) After positioning the vacuum chamber over the cylinder head, the space inside of the chamber was evacuated to approximately 10^{-4} atm abs using the helium leak detector's vacuum pump (ALCATEL ASM-110 TCL) and a supplementary vacuum pump.

(4) After achieving the required vacuum in the vacuum chamber, the valve to the supplementary vacuum pump was closed. The helium detector's pump continued to run, and the amount of helium present in the vacuum stream was measured.

(5) The helium measurement was allowed to stabilize to minimize the effects of out-gassing from the surfaces of the test equipment and to purge any air retained in the helium leak detector. Since normal dry air is approximately 0.0005% helium, residual air causes an erroneous leakage rate measurement. Stabilization of the leakage rate measurement is an indication that these sources of error have been minimized. Once stabilized, the leakage rate was recorded. The helium leakage rate from the detector's standard leak was also noted for each measurement.

4. Conversion of Measured Helium Leakage Rate to Standardized Leakage Rates

(1) Table 2.10.5-1 provides a summary of the helium leak test conditions and the Standard Conditions that were used to calculate the leakage rate for air.

The following equations, taken from ANSI N14.5-1997, were used to convert the measured helium leakage rates to the standardized leakage units:

$Q = LP$ atm·cm^3/s (ANSI N14.5-1997 Equation B.1)

$L_u = (F_c + F_m)(P_u - P_d)(P_a / P_u)$ cm^3/s (ANSI N14.5-1997 Equation B.5)

Where

$F_c = [2.49 \times 10^6 D^4]/(a\mu)$ cm^3/atm·s (ANSI N14.5-1997 Equation B.3)

$F_m = [3.81 \times 10^3 (T/M)^{0.5}]/(aP_a)$ cm^3/atm·s (ANSI N14.5-1997 Equation B.4)

Q	Mass-like leakage rate [atm·cm^3/s]
L	Volumetric leakage rate [cm^3/s]
P	Fluid pressure [atm abs]
L_u	Upstream volumetric leakage rate [cm^3/s]
P_u	Fluid upstream pressure [atm abs]
P_d	Fluid downstream pressure [atm abs]
P_a	Average stream pressure = $1/2(P_u + P_d)$ [atm abs]
D	Leakage hole diameter [cm]
a	Leakage hole length [cm]
μ	Fluid viscosity [cP(centipoise)]
T	Fluid absolute temperature [K]
M	Molecular weight [g/mol]

The product of (B.1) and (B.5) is:.

$$Q = L_u P_u = (F_c + F_m)(P_u - P_d)P_a \quad \text{atm·cm}^3\text{/s} \qquad (*)$$

The above equation was used for the conversion to the standardized leakage rates (std·cc/s). This equation is the same form as equation (B.1) in ISO 12807 1996(E) shown below.

$$Q = 0.0123 \frac{D^4}{\mu \cdot a}(P_u^2 - P_d^2) + 1.204 \frac{D^3}{a}\sqrt{\frac{T}{M}}(P_u - P_d) \quad \text{Pa·m}^3\text{/s}$$

(ISO 12807 Equation B.1)

Table 2.10.5-1 provides the measured test conditions, helium leakage, assumptions, and correlated standard air leakage rate for Cylinder-B. The standard air leakage rate was calculated using the methodology described above. Cylinder-B suffered the most damage during the drop test series, and thus, was selected as the test subject for the fire test sequence. Therefore, Cylinder-B was expected to have the highest post-test leakage rate. This assumption was confirmed during the post-test leakage tests. For more information concerning the drop and fire tests completed, see Section 2.5.1.

5. Test Equipment Sensitivity

The manufacturer of the helium detection equipment specified that the sensitivity of the test equipment is 2 x 10^{-11} atm·cc/sec (He). The magnitude of the leakage rate to be measured was in the range of 10^{-10} - 10^{-7} atm·cc/sec (He) ; therefore, the rated sensitivity is sufficient to provide an accurate measure of the expected leakage.

Table 2.10.5-1 Measured Test Conditions, Leakage Rates, and Standard Condition Correlation

Property	Prior to NOC and HAC test series	After NOC and HAC test series	Equivalent Reference Air
Upstream Pressure, atm	2	2	1.00
Downstream Pressure, atm	0	0	0.01
Temperature, K	295	299	298
Molecular Weight, g/gmol	4	4	29
Viscosity, cP	0.0198	0.0198	0.0185
Assumed hole length, cm	1.27	1.27	1.27
Hole diameter, cm	5.5×10^{-5}	2.2×10^{-4}	
Q Pre-test	1.1×10^{-8} atm·cm^3 /sec		**2.2×10^{-9} std-cc/sec**
Q Post-test		9.7×10^{-7} atm·cm^3 /sec	**2.2×10^{-7} std-cc/sec**

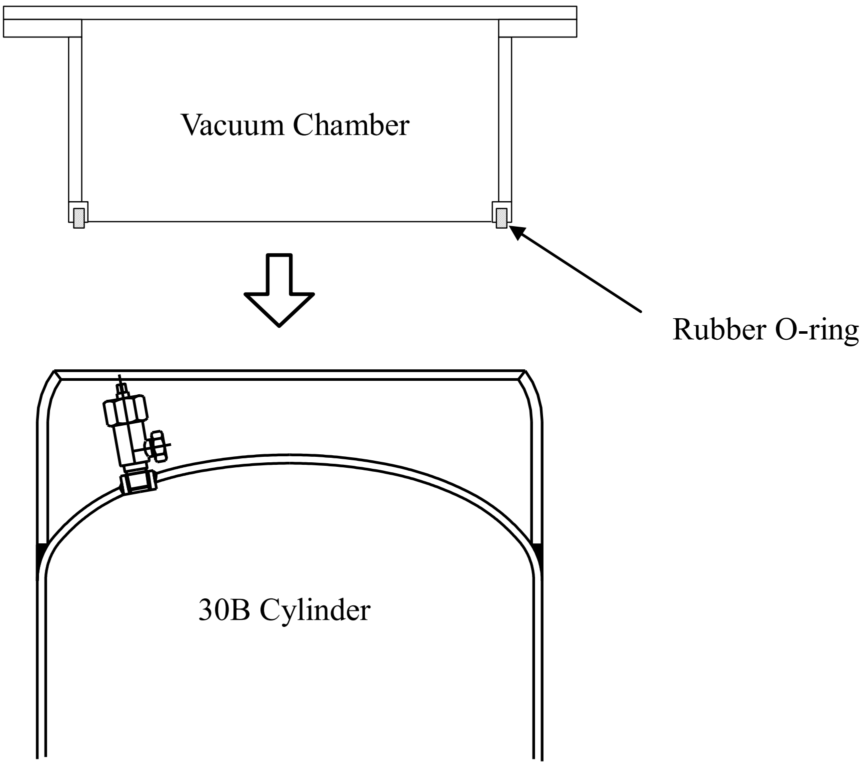

Figure 2.10.5-1 Vacuum Chamber (Cross Sectional View)

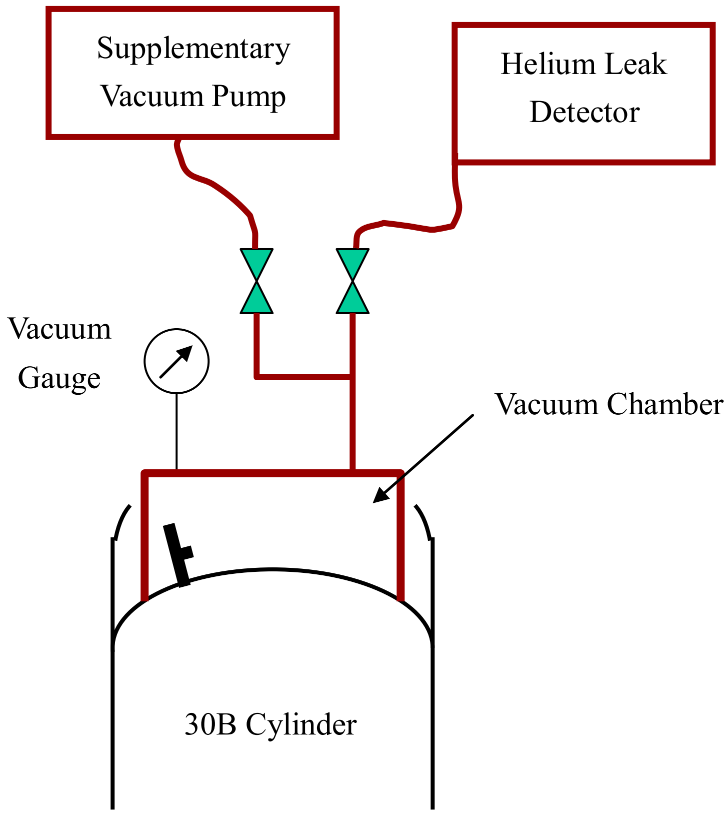

Figure 2.10.5-2 Schematic Configuration of Measurement System

Figure 2.10.5-3 30B Cylinder and Vacuum Chamber during Helium Leakage Measurement

Appendix 2.10.6

Evaluation using LS-DYNA code

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Appendix 2.10.7

Summary of analysis code “LS-DYNA”

Summary of analysis code “LS-DYNA”

A. Summary

The LS-DYNA code is a finite element analysis code by an explicit method. It was commercialized by Livermore Software Technology Corporation established by John O. Hallquist, who was a researcher at the Lawrence Livermore National Laboratory in the U.S.

This code mainly covers collision problems, and is used to analyze linear and nonlinear responses of structures. It can be used for a variety of analyses, including a geometrical nonlinear analysis such as an analysis of a problem with large deformation, contact or buckling, and a material nonlinear analysis such as an analysis of a problem with elasto-plasticity or creep.

In addition, this code has the element library containing many elements for two- and three-dimensional continuous structures, shells, beams, and other structures, and can perform a nonlinear analysis as well as a linear analysis. The element library contains elements for non-compressible materials and for special problems with contact, interface, etc.

Concerning DYNA3D, an analysis code of the LS-DYNA prototype, contact was defined as semi-automatic. In contrast, concerning this LS-DYNA analysis code, a contact algorithm for a single surface has been adopted, which allows for calculation of collision problems of a structure with large deformation and a complex shape. This code can also calculate collision problems at high speed by using reduced integration elements at the same time. Therefore, this is a highly-reliable analysis code which has been supported by many researchers in recent years.

B. Features

The LS-DYNA code is designed to be a very flexible tool which analyzes responses of a structure numerically. Its analysis procedures have been prepared so that the history of problems to be analyzed can be modeled in general to perform linear and nonlinear analyses as freely as possible.

Main features of this analysis code are as follows:

(a) Contact algorithm

With the LS-DYNA code, contact between structures on the surface of continuous structure elements, shell elements and beam elements can be determined automatically without the definition of contact and non-contact surfaces by analysis practitioners. Frictional force due to contact and contact reaction force are added to equivalent nodal force for discretizing external force acting on structures due to contact.

(b) Reduced integration elements

In the finite element analysis, Legendre-Gauss integration is generally used to calculate the rigidity matrix of finite elements at each step. In terms of the reduction of calculation time and the avoidance of shear locking, reduced integration elements to calculate the rigidity matrix using the reduced integration method which has reduced integration points are used.

If reduced integration elements are used, the hourglass mode may arise due to rank deficiencies of the rigidity matrix. In order to resolve this, hourglass control shown below is applied.

(c) Hourglass control

If the reduced integration method previously mentioned in (b) is used, it is known that an hourglass mode, which is a zero-energy mode other than the rigid-body displacement, occurs. In order to prevent such a mode from occurring, hourglass control is applied. For the structural analysis of the package (Mechanical Test, Drop I and Drop II), the method proposed by Flanagan and Belytschko is employed.

The method proposed by Flanagan et al. realizes the numerical stability with minute virtual elastic rigidity that is orthogonal to the rigid body mode defined and added to the normal rigidity matrix.

Appendix 2.10.8

Explanation of derivation methods for material properties used in LS-DYNA

Proprietary Information Withheld Pursuant to 49 CFR 7.14, 49 CFR 105.30, and 10 CFR 2.390

Proprietary Information Withheld Pursuant to 49 CFR 7.14, 49 CFR 105.30, and 10 CFR 2.390

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SECTION 3 THERMAL EVALUATION

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3.0 THERMAL EVALUATION

The MST-30 Protective Shipping Package (MST-30) is a Type A, Fissile UF_6 Package used for the shipment of 30-inch cylinders containing Uranium Hexafluoride (UF_6) enriched up to 5wt% ^{235}U. The MST-30 is designed to conform to the technical and regulatory requirements of a Type A, Fissile UF_6 Package as specified in the Japanese Safe Transport Regulations pursuant to SSR-6. The package is intended to be used for transport from, to, or through foreign countries, including the USA. The MST-30 package is also designed in compliance with the current 10CFR Part 71 and 49CFR Part 173 Subpart I.

3.1 Discussion

The thermal response of the MST-30 has been evaluated through prototype testing and analytical evaluations. The results of the analytical evaluations are presented in Table 3-1. The results of the tests are available in Appendix 2.10.1. The evaluation criteria are provided in Table 3-2.

During all normal and hypothetical accident conditions the package components and contents are maintained below the specified thermal limits. Therefore, the integrity of the 30B cylinder, including its valve, plug and their coupling joints, is maintained throughout normal and hypothetical accident conditions.

3.2 Thermal Properties of Materials

3.2.1 Package Thermal Properties

The MST-30 is provided with insulation to assure that the UF_6 temperature, and thus, the internal pressure of the 30B cylinder, is maintained below the specified design limits. Two types of insulation are used: phenolic foam and polyurethane foam. These insulators have been shown by the manufacturer to perform adequately for the normal condition over extended periods of time, with no shrinkage, settling, or loss of insulative properties. The thermal properties of the MST components used in the thermal evaluation are provided in Table 3-3, and the thermal properties of the UF_6 payload are shown in Table 3-4.

3.2.2 Contents Decay Heat

The worst-case contents of the package consist of unirradiated UF_6 as described in Section 1. The total energy produced by the contents' radiological decay is less than 0.16 W. Therefore, the heat input due to radiological decay is negligible when compared with the insolation and fire heat input.

3.3 Technical Specification of Components

The evaluation criteria for the thermal evaluation are shown in Table 3-2. The 30B cylinders transported in the MST-30 are fabricated in accordance with ANSI N14.1[Reference 3.7.9] or ISO 7195[Reference 3.7.18]. The external and internal design pressure of 30B cylinder are 172kPa (25psig) and 1.38MPa (200psig), respectively. Taking the prevention of hydraulic rapture of 30B cylinder resulting from an expansion of the liquid UF_6 into account, the maximum allowable temperature of the UF_6 contents is 121°C (250°F) when the UF_6 of 2,277kg (5,020lb). This maximum temperature criterion assures that the internal pressure of the 30B cylinder well below the design pressure. The design pressure of the cylinder-valve is 1.38MPa (200 psig).

The maximum service temperature of the Teflon used for the valve gasket is 260°C (500°F) [Reference 3.7.12]. The maximum service temperature (solidus temperature) of the tin-lead solder used as a sealing material at the valve and plug joints to each cylinder-head is 183°C (361°F)[Reference 3.7.10].

3.4 Thermal Evaluation under Normal Conditions of Transport (NOC)

The NOC thermal evaluation is performed analytically using numerical analysis. The temperature distribution of the package was evaluated using a three-dimensional transient thermal analysis code called "ABAQUS" (See Appendix 3.6.1).

3.4.1 Thermal Model

3.4.1.1 Geometric Model

The numerical analysis is performed using the three-dimensional 1/2-symmetric (180°) model shown in Figure 3-1. The package was modeled to the nominal dimensions shown on the drawings provided in Appendix 1.3.2 and 1.3.3.

The ABAQUS model conservatively considers both the NOC and HAC cumulative damage as described in Section 2. All of the deformations caused by the corner, horizontal and vertical drops are taken into account. The combined deformation for the thermal analysis is modeled in such a way that it is much larger than the results of deformation measured by the mechanical testing in Appendix 2.10.1; therefore, the thermal analysis is highly conservative and bounds both the NOC and HAC.

In order to represent the damage accumulated due to NOC and HAC drops, the material properties in the damage zones were adjusted. The dimensions of the package were not reduced. The thermal conductivity value was increased and the heat capacity value was decreased to simulate the required volume reduction. Thus, in the damage zones, the thermal conductivity is fully more (1000W/(m・K)) than the nominal value and the heat capacity is fully less (10^3J/(m^3・K)) than the nominal value of the foam insulation. The valve pocket is also modeled using this method.

3.4.1.2 Finite Element Mesh

Figure 3-2 shows the elements used for ABAQUS input. The colored elements correspond to the damage zones. Boundary conditions at the 0/180 degree boundary are adiabatic.

3.4.1.3 Material Distribution and Properties

The thermal properties of the materials modeled are presented in Table 3-3 for the undamaged zones of the package. The thermal properties in the damage zones were adjusted as described in Section 3.4.1.1.

The thermal conductivity of the phenolic foam is conservatively based on values from literature [Reference 3.7.1], [Reference 3.7.2], [Reference 3.7.8] and values measured by Mitsubishi Materials Corporation. A comparison of these values is shown in Figure 3-3. The thermal conductivity of the polyurethane foam used to the analysis is twice the value specified in the literature [Reference 3.7.3]. As shown in Figure 3-4 [Reference 3.7.1], the thermal conductivity of the polyurethane foam is insensitive to temperature change. Therefore, the thermal conductivity value used bounds any increase over the range of temperatures of interest. The phenolic and polyurethane foam specific heat values are from the literature [Reference 3.7.1], [Reference 3.7.2], [Reference 3.7.3]. The phenolic and polyurethane foam density values are the minimum specified for use in the MST-30.

The thermal properties used for the mild and stainless steel are taken from the JSME Data

Book [Reference 3.7.4].

The UF_6 is modeled as accumulating in the bottom of 30B cylinder as shown in Figure 3-2(2/2), using the heat capacity of the maximum load 2,277kg (5,020lb). The thermal properties used for the UF_6 are taken from literatures [Reference 3.7.6], [Reference 3.7.7] and are listed in Table 3-4.

3.4.1.4 Initial and Boundary Conditions

No significant heat is generated from radioactive decay of the contents during transport; therefore, under the normal condition, the only heat source is that provided by incident solar radiation. The initial conditions and boundary conditions used in the analysis are presented in Table 3-5. The emissivity of the overpack outer surface is conservatively set at 0.1 for the polished stainless steel [Reference 3.7.4]. On the other hand, absorptivity of the overpack outer surface for solar insolation is conservatively set at 0.6. The radiant heat transfer between the overpack inner surface and the cylinder surface is taken into account. The emissivity values of the both surfaces are set at 1.0 so that the temperature rise of the contents is evaluated conservatively.

Cooling of the package is accomplished by natural convection and radiation at the overpack outer surface. The ambient temperature is set at 38°C (100°F) and the heat transfer coefficient is calculated using the following correlation [Reference 3.7.5]:

$$\alpha = Nu \cdot \lambda / l$$

where:

Nu	Nusselt number = $0.13(Pr \cdot Gr)^{1/3}$
Gr	Grashof number = $g\beta(T_w - T_\infty)l^3/\nu^2$
Pr	Prandtl number = ν/κ
λ	Thermal conductivity
g	Acceleration of gravity
β	Thermal expansion coefficient
T_w	Wall temperature
T_∞	Ambient temperature
l	Representative length（a half of circumference length of overpack outer shell）
ν	Kinematic viscosity
κ	Thermal diffusivity

The thermal analysis for NOC is calculated by steady-state analysis applied with a half of solar insolation listed in Table 3-5. The effects in the case that the transient analysis is performed with solar insolation every 12 hours per a day are described in Appendix 3.6.3.

3.4.1.5 Model Run Time

This model is calculated by steady-state analysis.

3.4.2 Maximum Temperatures

Temperature reference points are shown in Figure 3-5 and the analysis results are presented in Table 3-6. The maximum temperature of the contents under NOC is 60°C (140°F). This is well below the allowable temperature limit of 121°C (250°F).

The NOC maximum cylinder temperature of 60°C (140°F) is well below the solidus temperature of solder material for valve and plug, which is 183°C (361°F).

Without insolation and with an ambient temperature of 38°C (100°F), the maximum temperature of the accessible surfaces of the packaging is 38°C (100°F), and the maximum temperature of the contents does not exceed 38°C (100°F).

3.4.3 Minimum Temperatures

Assuming steady state conditions, with no sources of thermal energy present, the minimum temperature reached by the package and contents is -40°C (-40 °F).

3.4.4 Maximum Internal Pressures

The maximum temperature reached by the contents under NOC is clearly much less than the allowable for the contents; therefore, any pressure increase due to vaporization of the contents is well below the internal pressure limit for the package. The maximum pressure attained by the contents under NOC is 123kPa (18psia), which is the UF_6 vapor pressure at 60°C (140°F) [Reference 3.7.11].

Without insolation and with an ambient temperature of 38°C (100°F), the maximum internal pressure is 35kPa (5.1psia). This is well below the atmospheric pressure of 101.3kPa (14.7psia)

3.4.5 Maximum Thermal Stresses

There is no significant thermal stress under NOC conditions.

3.4.6 Evaluation of Package Performance for Normal Conditions of Transport

The package temperatures and the internal pressure under normal conditions of transport are well within the allowable range. The component temperatures and the evaluation criteria are tabulated in Table 3-1 and Table 3-2, respectively.

3.5 Thermal Evaluation under Hypothetical Accident Conditions in Transport (HAC)

Thermal testing of a full-scale prototype was performed and its results are presented in Appendix 2.10.1. The temperatures of critical points in the packaging were monitored throughout the thermal testing.

Because the prototype test was performed in a closed environment, the effects of solar insolation during the pre-fire and cool down periods were not observed. Additionally, the prototype was not maintained in a 38°C (100°F) ambient environment as specified by 10CFR71.73 prior to or during the cool down period of the test. Therefore, the temperature of the package was evaluated analytically using a three-dimensional transient model to assess the impact of the 38°C (100°F) ambient environment and the insolation on the temperature distribution of the package.

3.5.1 Thermal Model

3.5.1.1 Analytical Model and Evaluation

The ABAQUS model described for the normal condition evaluation was used to calculate the package temperature distribution for HAC. In order to calculate the maximum temperature of the package components due to the HAC thermal event, three calculation steps are required:

Step1

Analysis of the initial component temperatures. The temperature of the package is calculated for an ambient temperature of 38°C (100°F) with solar insolation specified in Table 12 in accordance with Para.728 in SSR-6. The results of Step 1 are reported in Section 3.4.2.

Step2

Analysis during the thermal event (800°C (1475°F) for 30 minutes). The temperature of the package components is evaluated for an ambient temperature of 800°C (1475°F) for 30 minutes with solar insolation, on the assumption that the temperature distribution calculated in Step1 is initial condition.

Step3

Analysis during cool-down period following the fire test. The temperature of the package is calculated for an ambient temperature environment of 38°C (100°F) with solar insolation.

The temperature distribution of the package was calculated using the three-dimensional analytical model described in Section 3.4.1.

The verification of appropriateness of thermal evaluation method is shown in Appendix 3.6.2.

3.5.1.1.1 Initial Condition (Step 1)

This evaluation is identical to the NOC evaluation described in Section 3.4. Temperature reference points are shown in Figure 3-5 and the initial condition analysis results are presented in Table 3-6. The maximum cylinder temperature is 60°C (140°F). The maximum contents temperature is 60°C (140°F).

3.5.1.1.2 30-Minute 800°C Thermal Test (Step2)

The heat from the environment of 800°C enters the package through the overpack surface.

During fire event, the pyrolysis gas generated from heated phenolic foam fills the gap between the cylinder and the overpack inner surface, and heats the cylinder surface and the overpack inner surface under the thermal test condition. [Reference 3.7.14] In order to simulate this effect, the heat convection from this generated gas to the cylinder surface and the overpack inner surface is considered. Figure 3-6 shows the space where the generated gas is assumed to exist in the analytical model. The temperature of the generated gas is assumed to be 115°C (239°F) [Reference 3.7.14], at which phenolic foam shows an endothermic peak in DTA (differential thermal analysis) and likely to generate gas. The thermal properties for the generated gas are assumed to be those of air [Reference 3.7.4]. The heat transfer coefficient is assumed to be the value for a developed laminar flow.

The radiant heat transfer is taken into account between the overpack inner surface and the cylinder surface. Emissivity and absorptivity values of the both surfaces are set at 1.0 so that the temperature rise of the content is evaluated conservatively. The initial conditions and boundary conditions used in the analysis are presented in Table 3-7.

3.5.1.1.3 Cooling Period (Step 3)

Since the surface of the overpack outer shell was black with ash after the thermal test, the emissivity value of its surface seems to be almost 1.0. But the emissivity value for the overpack outer shell is set at 0.5 for this cooling period in the analysis.

The generated gas from heated phenolic foam is assumed to continue during the cooling period. In the observation in the compliance test, the smoke continued to be vented from vent holes for about 70 minutes after the thermal test of 800°C for 30minutes. From this observation result, the duration of the generated gas is set for 70 minutes after the thermal test. During this 70 minutes period, the heat transfer coefficient from the generated gas to both the cylinder surface and the overpack inner surface is assumed to decrease linearly to 0.

The calculation is continued until the temperature at each evaluated point reaches the maximum value.

The radiant heat transfer is taken into account between the overpack inner surface and the cylinder surface. Emissivity and absorptivity values of the both surfaces are set at 1.0 so that the temperature rise of the content is evaluated conservatively.

The initial conditions and boundary conditions used in the analysis are presented in Table 3-8.

3.5.1.2 Test Model

Thermal testing under HAC was performed using a full-scale MST-30 prototype. The results of the tests are presented in Appendix 2.10.1. The maximum temperature of the external surface of the specimen reached 841°C (1,546°F). The maximum temperature attained by the 30B cylinder as a result of the fire test was 59.4°C (139°F) at the cylinder skirt, and 51.5°C (125°F) at the cylinder-head in the vicinity of the valve which is the highest value among the containment boundary parts of the cylinder. After the fire test, the package was allowed to cool down in the still air inside of the building. During the cool down period the package remained on the hot truck that had also been heated in the furnace. These conditions provided a highly conservative cooling condition.

3.5.2 Package Condition and Environment

In the three-dimensional model, the deformation which is larger than that measured as a result of the mechanical testing was applied to the analytical model to represent the worst case condition, as described in Section 3.4.1.1. The deformation modeled for the thermal analysis is much larger than the results due to a regulatory-specified sequence of drops; therefore, the thermal analysis is highly conservative. In this calculation, the mass of UF_6 is assumed to be 2,277kg (5020lb) which is the maximum design contents. A supplementary evaluation for the case that smaller mass of UF_6 is contained is shown in Appendix 3.6.4.

The package subjected to the fire test was subjected to the NOC and HAC mechanical test prior to the fire test as described in Appendix 2.10.1.

3.5.3 Package Temperature

3.5.3.1 Prototype Test Temperatures

The maximum temperature of the external surface of the specimen was 841°C (1,546°F). The maximum temperature attained by the 30B cylinder as a result of the fire test was 59.4°C (139°F) at the cylinder skirt, and 51.5°C (125°F) at the cylinder-head in the vicinity of the valve (the highest value among the containment boundary parts of the cylinder).

3.5.3.2 Analytically Evaluated Temperatures

According to thermal conditions described in Section 3.5.1.1, the calculation for the package under HAC is performed. The results are presented in Figure 3-7. The zoomed up figure of Figure 3-7 is presented in Figure 3-8 .

The temperature history of the content (UF_6) in the vicinity of the cylinder body and the center is presented in Figure 3-9. The maximum temperatures at each point are presented in Table 3-9. The temperature distribution when UF_6 reaches the maximum temperature is presented in Figure 3-10 .

The maximum temperature of UF_6, which is the contents of the package, locally reaches at 117˚C (243°F) (113 + 4˚C), but most of the UF_6 (approximately 96%) except the contact part with cylinder inner surface have been below 64.1˚C (147°F) i.e. the fusion temperature of UF_6 (the triple point of the phases), and remain to be solid as shown in Figure 3-10.

The maximum temperature at the valve and plug coupling part are 105˚C (221°F) (101 + 4˚C) and 103˚C (217°F) (99 + 4˚C) respectively.

3.5.4 Maximum Internal Pressures

The vapor pressure of the contents (UF_6) is 0.64MPa absolute (93psia) (the differential pressure is 0.54MPa (78psig)) at the maximum temperature of 117°C (243°F).

3.5.5 Maximum Thermal stresses

As mentioned in Section 2.7.3, thermal stress by restraint does not occur.

3.5.6 Evaluation of Package Performance for HAC Thermal Conditions

The MST-30 maintained all package components and contents below the maximum allowable temperatures during HAC thermal conditions. Most of the content (UF_6) does not exceed its melting temperature of 64.1°C (147.3°F) i.e. triple point of UF_6 and remains to be solid. The maximum temperature of the content is locally 117°C (243°F) and the maximum internal pressure is 0.64MPa absolute (93 psia) (0.54MPa gauge (79psig) as internal pressure). These results are below the maximum allowable design temperature of 121°C (250°F) and the cylinder design pressure of 1.38MPa gauge (200 psig). The valve and plug joint parts on the cylinder-head are 105°C (221°F) and 103°C (217°F) respectively, which are below the solder solidus temperature 183°C (361°F). Therefore, the integrity of the cylinder is maintained when subjected to the mechanical and thermal testing under HAC for fissile material package.

3.6 Appendices

3.6.1 Summary of analysis code "ABAQUS"

3.6.2 Verification of appropriateness of thermal evaluation method by comparison between analytical results and test results

3.6.3 Effects of non steady solar insolation every 12 hours per a day

3.6.4 Analysis for the case that smaller mass of UF_6 is contained

3.7 Reference

3.7.1 K/GT-301 CONF-890631-39 "Thermal Properties Evaluation of Insulation in Overpack Containers for UF_6 Transport" J. L. Frazier.

3.7.2 PATRAM'86, Davos, 1987, vol. 2, p.275-p.282, W. A. Pryor, J. L. Frazier.

3.7.3 General Plastics Catalog "GENERAL PLASTICS LAST-A-FOAM®FR-3700 for CRASH & FIRE PROTECTION of NUCLEAR MATERIAL SHIPPING CONTAINERS."

3.7.4 JSME Data Book：Heat Transfer 4th edition, 1986, The Japan society of Mechanical Engineers (written in Japanese).

3.7.5 Safety series No.37, IAEA Safety Guides, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (1985 Edition), IAEA, Vienna, 1990.

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3.7.8 K/PS-1128 "Thermal Properties Evaluation of UF_6 Cylinder Overpack Insulation", J. L. Frazier, 1985.

3.7.9 ANSI N14.1 American National Standard for Nuclear Materials; Uranium Hexafluoride Packaging for Transport; 30B Cylinder.

3.7.10 ASTM B32 American Society for Testing and Materials; Standard Specification for Solder Material.

3.7.11 The Chemistry of Uranium and Its Binary and Related Compounds, Katz, J. J., and Rabinowitch. E, Dover Publications, New York, 1961.

3.7.12 Chemistry Cyclopedia (Popular Edition), Morikita Shuppan Inc., 1981 (written in Japanese).

3.7.13 "ABAQUS THEORY MANUAL", Hibbitt, karlsson & Sorensen, Inc

3.7.14 CRIEPI[*1] "Study for Behavior of UF_6 Package in Fire Event", 'Technical Study for Nuclear Energy Peaceful Use' entrusted by the JPN Competent Authority, i.e. STA, 1983.
(*1) CRIEPI: An abbreviation of Central Research Institute of Electric Industry

3.7.15 GAT-280,“Uranium Hexafluoride: A Survey of the physic-chemical Properties”, Goodyear Atomic Corporation Portsmouth Ohio, R.DeWitt, 1960”.

3.7.16 Iron & Steel Handbook, Volume No.4 “Cast Iron, Forged Iron and Powder Metallurgy”

3.7.17 Orr. C., “Particulate Technology” 1966, p.238.

3.7.18 ISO 7195 International Organization for Standardization ; Nuclear Energy - Packaging of Uranium Hexafluoride (UF_6) for Transport.

3.7.19 “Introduction to Heat Transfer”, Rev.28, Yoshirou Koutou, published by Youkendou Bookseller, 1989.

Table 3-1 Thermal Analysis Results

Condition	Peak Contents Temperature		Peak Exterior Package Temperature		Peak Cylinder Internal Pressure		Peak Valve Solder Temperature	
	°C	°F	°C	°F	kPa	psia	°C	°F
Normal Hot Transport	60	140	60	140	123	18	60	140
Normal Cold Transport	-40	-40	-40	-40	0	0	-40	-40
Fire Event	117	243	794	1461	640	93	105	221

Table 3-2 Evaluation Criteria for Thermal Evaluation

Object for Evaluation	Material	Evaluation Criterion	Remarks
Contents Maximum Temperature	UF_6	Not more than 121°C (NOTE) (250°F)	The criterion to prevent from hydraulic rupture resulting from expansion of the liquid UF_6 when the UF_6 of 2,277 kg is contained.
Solder for Valve/Plug Maximum Temperature	ASTM B32 Sn50 or Equivalent	Not more than 183°C (361°F)	To be evaluated by cylinder temperature
Cylinder Internal Pressure	Mild Steel ASTM A516	Not more than 1.38 MPa (200psig)	To be evaluated by the vapor pressure of UF_6

(NOTE)When the maximum temperature of UF_6 partly exceed 121˚C, the criterion is that the volume of the UF_6 shall not exceed 0.699 m^3 (95% of the minimum volume of 30B cylinder i.e. 0.736m^3 (26ft^3)).

Table 3-3 Thermal Properties of Materials of Components used in Thermal Evaluation

Component	Material	Density (kg/m³)	Specific Heat (J/kg·K)		Thermal Conductivity (W/m·K)		Remarks
Outer Shell And Inner Shell	Stainless Steel Plates	7640	499	27°C	16.0	27°C	Reference 3.7.4
			511	127°C	16.5	127°C	
			556	327°C	19.0	327°C	
			620	527° C	22.5	527° C	
			644	727° C	25.7	727° C	
Cylinder	Mild Steel	7710	473	27°C	51.6	27°C	Reference 3.7.4
			529	227°C	47.8	227°C	
			690	527°C	38.2	527°C	
Shock Absorber and Thermal Insulator for Overpack	Polyurethane Foam-1 & Polyurethane Foam-3	340	1350	Overall temperature range	0.122	Overall temperature range	See Section 3.4.1.3
	Polyurethane Foam-2	450	1350	Overall temperature range	0.136	Overall temperature range	
	Phenolic Foam	100	1047	60°C	0.09	20°C	
			1130	100°C	0.18	550°C	
			1256	150°C			
			1298	200°C	0.35	>600°C	
			702	802°C			

Table 3-4 Thermal Properties of Contents (UF_6) [Reference 3.7.6], [Reference 3.7.7]

Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)	Triple Point (°C)	Latent Heat (J/kg)
477(Solid) 544(Liquid)	0.0473(Solid) 0.16(liquid)	64.1 (147.3°F)	54661

Table 3 -5 Initial Conditions and Boundary Conditions for Calculation of the Package for Normal Conditions of Transport

Initial Condition	Boundary Condition	
	Overpack Outer Surface	**Cylinder Surface and Overpack Inner Surface**
38°C (100°F) All parts	・Thermal Radiation to Environment of 38°C ・Heat transfer by natural convection to Environment $Nu=0.13\cdot(Pr\cdot Gr)^{1/3}$ [Reference 3.7.5] ・Thermal Radiation Emissivity Overpack Outer Surface : 0.1 Environment : 1.0 Absorptivity Overpack Outer Surface : 1.0 Environment : 1.0 ・Solar Insolation Absorptivity : 0.6 Overpack Outer Shell : 400 W/m^{2} (*1) Overpack Outer Plates :200 W/m^{2} (*1) (*1) A steady-state analysis applying a half of above solar insolation.	・Heat Conduction across Air Gap ・Thermal Radiation Emissivity/Absorptivity Overpack Inner Surface : 1.0 Cylinder Surface : 1.0

Table 3 -6 Maximum Temperature at Each Point of Package for Normal Conditions of Transport

Points	Maximum Temperature (°C)
Overpack Outer Surface	59.96
Overpack Inner shell	60.03
Overpack Inner plate (Valve side)	59.95
Cylinder body	60.03
Cylinder-head (Valve coupling part)	60.01
Cylinder-head (Plug coupling part)	60.01
Content (At center)	60.03

Table 3 -7 Initial Conditions and Boundary Conditions for Calculation of the Package during Thermal Test

<table>
<tr><th rowspan="2">Initial Condition</th><th colspan="2">Boundary Condition</th></tr>
<tr><th>Overpack Outer Surface</th><th>Cylinder Surface and
Overpack Inner Surface</th></tr>
<tr><td>Temperature
Distribution
Calculated
in Step 1</td><td>・At 800°C Environment

・Convection
Heat Transfer
Coefficient:10W/(m^2·K)

・Thermal Radiation
Emissivity/Absorptivity
Frame : 0.9
Overpack Outer Surface : 0.8

・Solar Insolation
Absorptivity : 1.0
Overpack Outer Shell : 400W/m^2
Overpack Outer Plates : 200W/m^2</td><td>・Heat Transfer form Gas
Generated from Phenolic Foam

・Thermal Radiation
Emissivity/Absorptivity
Overpack Inner Surface : 1.0
Cylinder Surface : 1.0</td></tr>
</table>

Table 3 -8 Initial Conditions and Boundary Conditions for Calculation of the Package after Thermal Test (Cooling Period)

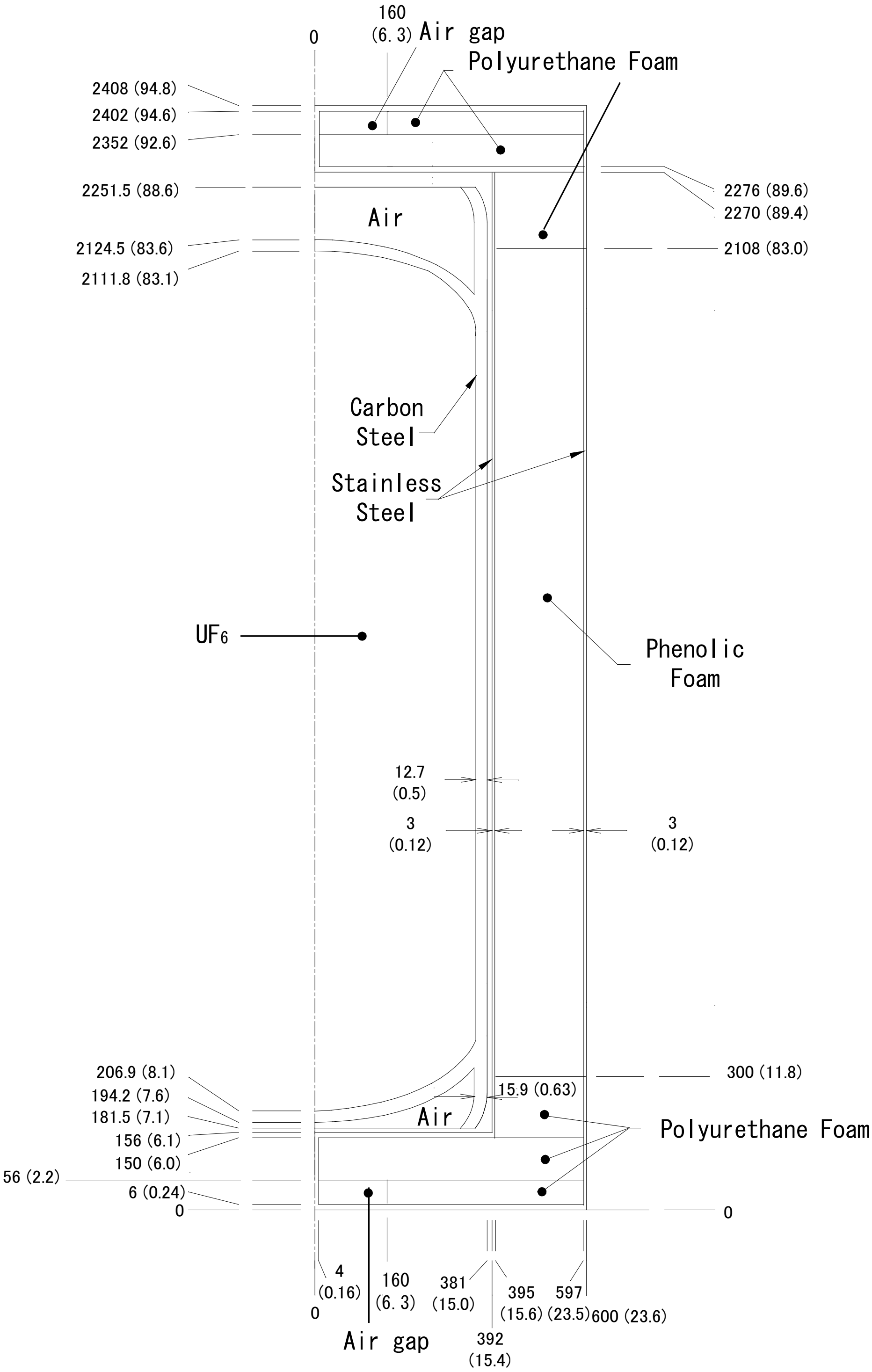
Initial Condition	Boundary Condition	
	Overpack Outer Surface	**Cylinder Surface and Overpack Inner Surface**
Temperature Distribution Calculated in Step 2	・Thermal Radiation to environment of 38˚C ・Heat transfer by natural convection to Environment $Nu=0.13\cdot(Pr\cdot Gr)^{1/3}$ ・Thermal Radiation Emissivity/Absorptivity Overpack Outer Surface : 0.5 Environment : 1.0 ・Solar Insolation Absorptivity : 1.0 Overpack Outer Shell : 400 W/m^2 Overpack Outer Plates :200 W/m^2	< Until 70 Minutes after Thermal Test of 800°C – 30minutes > ・Heat Transfer form Gas Generated from Phenolic Foam ・Heat Conduction across Air Gap ・Thermal Radiation Emissivity/Absorptivity Overpack Inner Surface : 1.0 Cylinder Surface : 1.0 < After 70 Minutes Period above > ・Heat Conduction across Air Gap ・Thermal Radiation (Emissivity/Absorptivity values are the same as above)

Table 3-9 Analysis Results : Maximum Temperature under HAC

Temperature Reference Points	Maximum Temperature ˚C	Time Elapsed after Start of Thermal Test of 800˚C for 30min. (minutes)
Overpack Outer Surface	794	30
Overpack inner Shell	210 (+9, -13)*1	31
Overpack Inner Plate (Valve Side)	326 (+9, -13)*1	33
Cylinder Body	115 (+4, -7)*1	66
Cylinder-head (Valve coupling part)	101 (+4, -7)*1	133
Cylinder-head (Plug coupling part)	99 (+4, -7)*1	144
Content (Maximum temperature)	113˚C (+4, -7)*1	58
Content (At center)	60˚C (+0.1, -0.1)*2	720

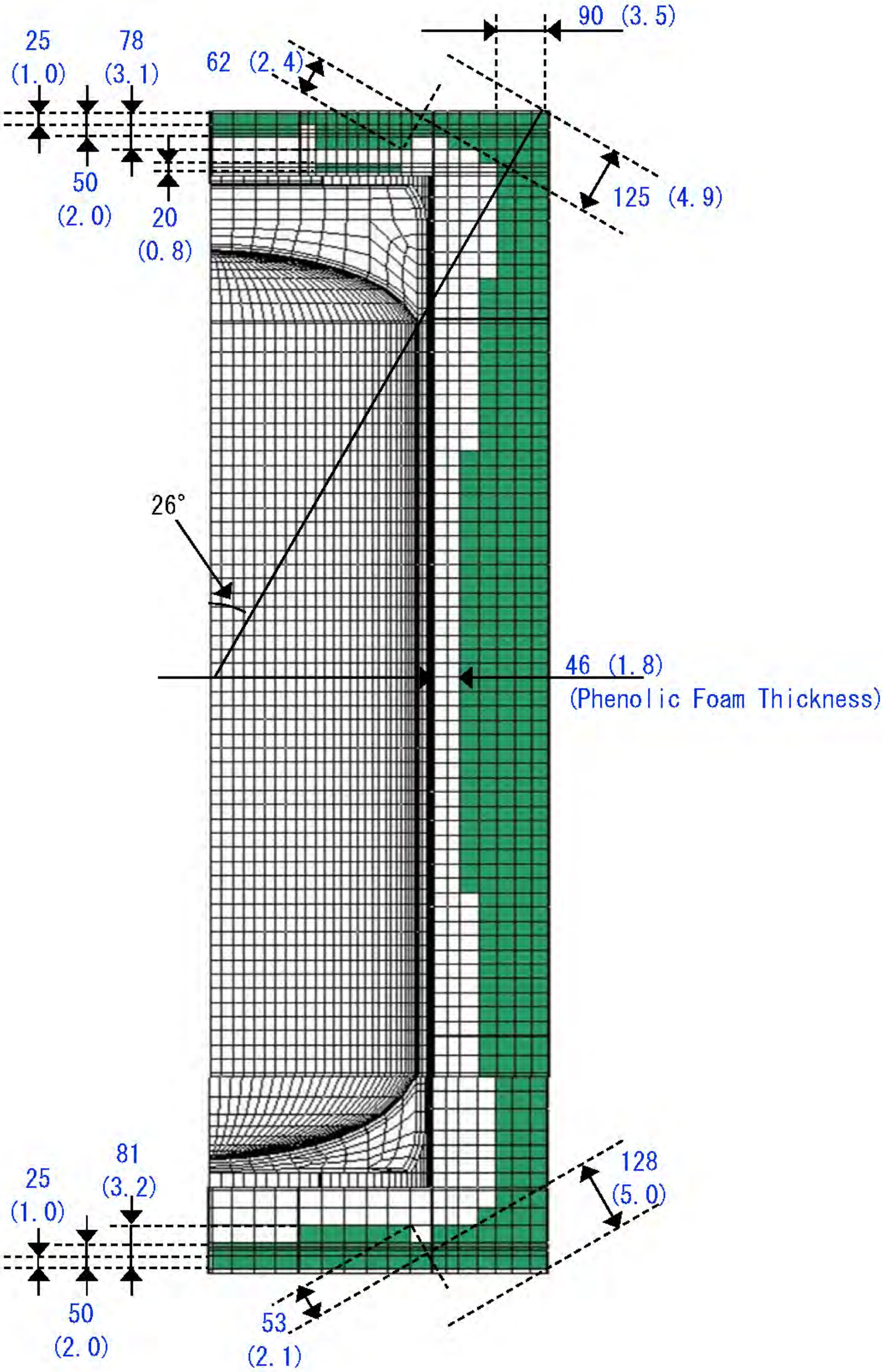
＊1 Parenthetical values indicate the temperature amplitude due to applied with solar radiation under initial thermal conditions. (See Appendix 3.6.3)

＊2 As shown in Appendix 3.6.3 and in Figure 3-10 , most of the content (UF_6) except the contact part with the cylinder inner surface are not affected by the temperature amplitude due to solar insolation every 12 hour.



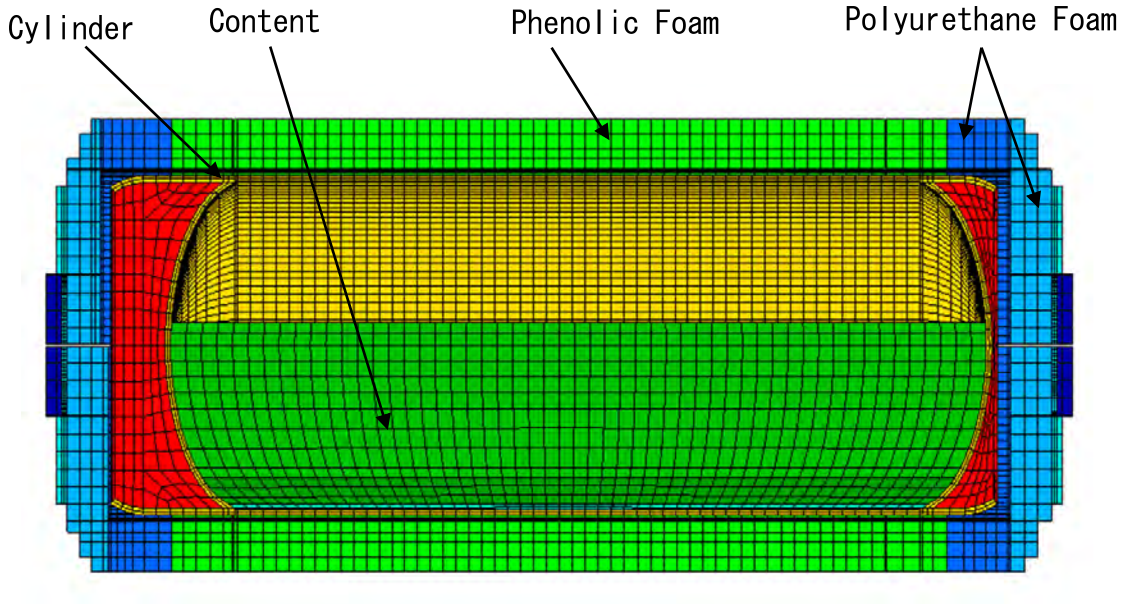
Unit: mm (inch)

Figure 3-1 Geometric Model

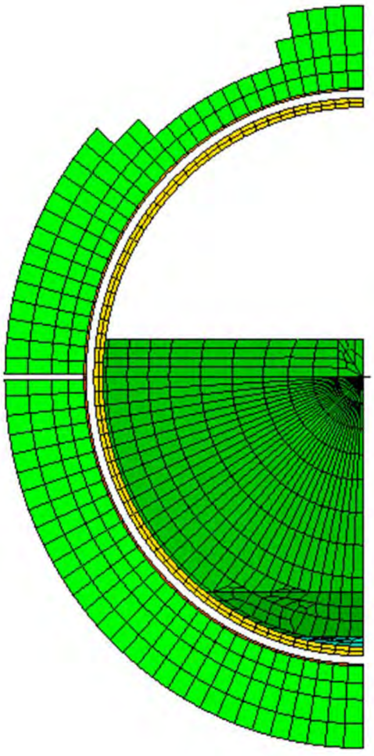


Unit: mm (inch)

Figure 3-2 Analytical Model Node Division (1/2)



Axial Section



(NOTE)
The deformed area which is colored in previous page is removed in this figure.

Radial Section

Figure 3-2 Analytical Model Node Division (2/2)

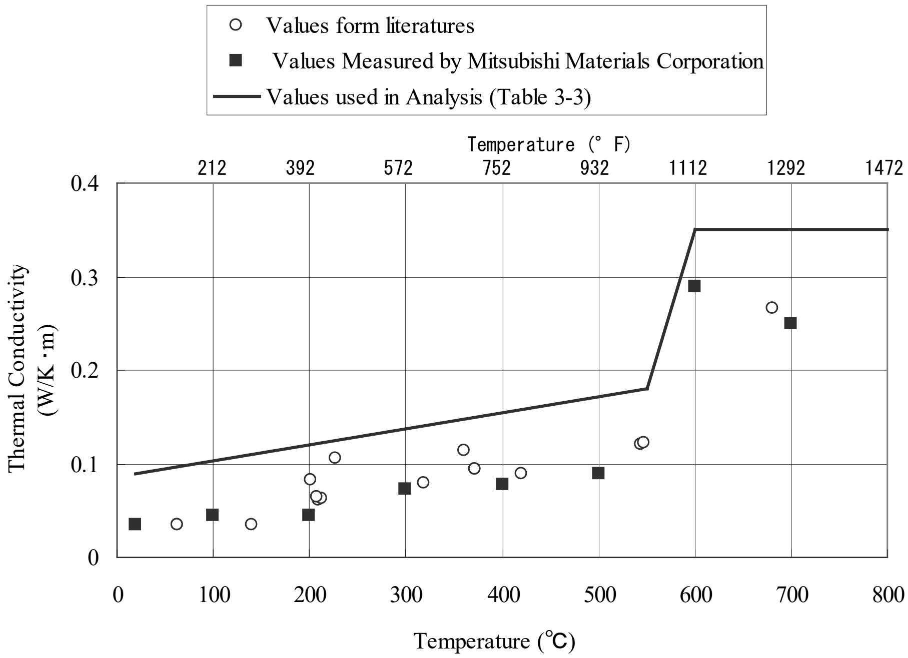


Figure 3-3 Phenolic Foam Thermal Conductivity Values Used in Analysis

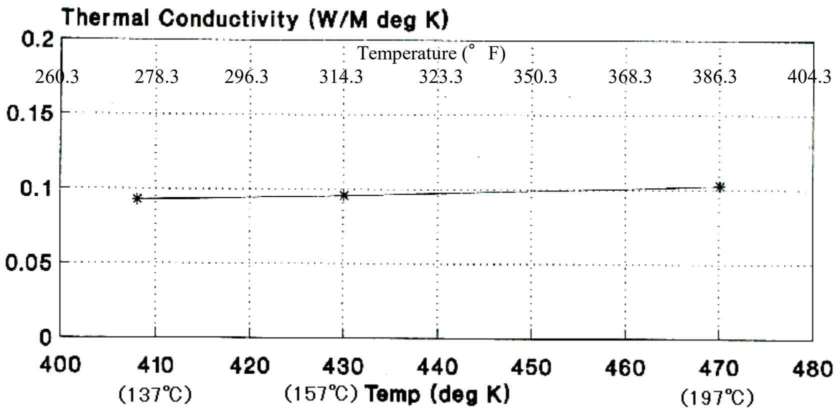


Figure 3-4 Polyurethane Foam Thermal Conductivity

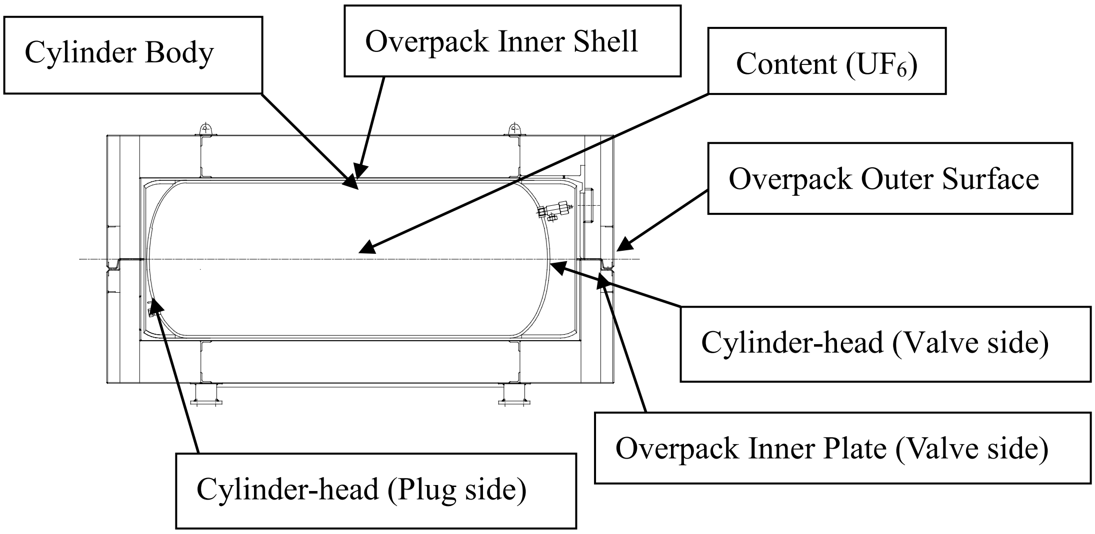


Figure 3-5 Temperature Reference Points

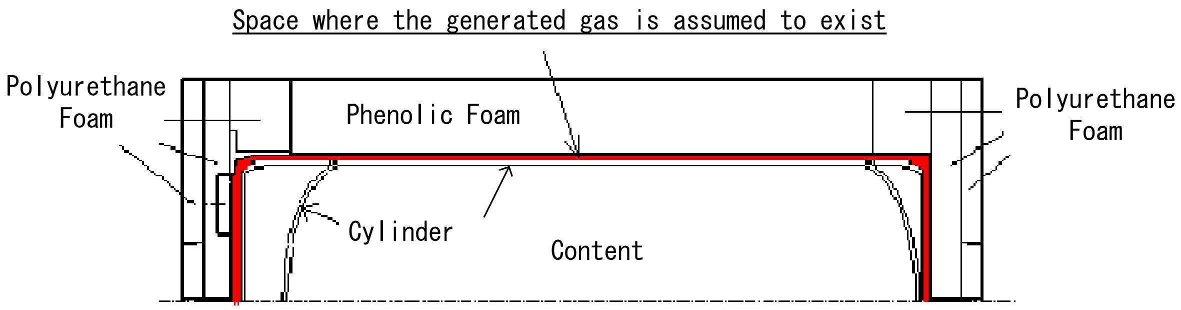


Figure 3-6 Space where pyrolysis gas generated from heated phenolic foam is assumed to exist

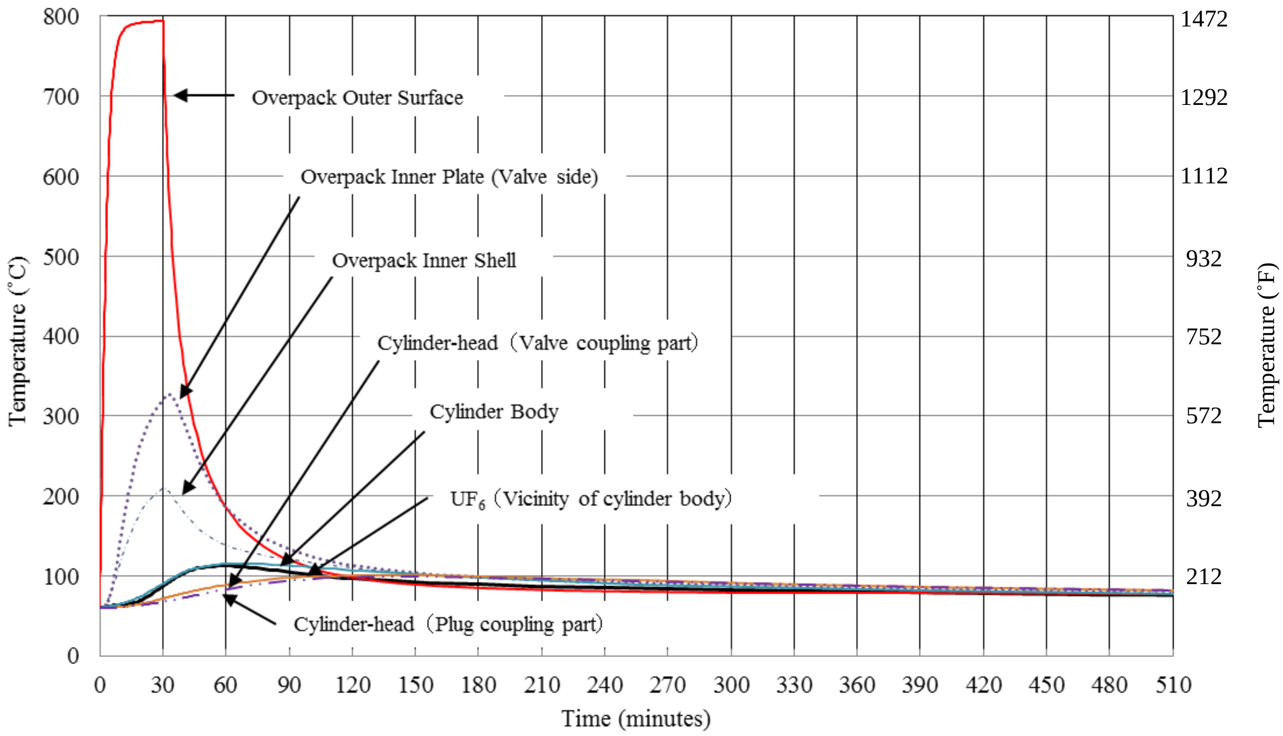


Figure 3-7 Analysis Results for HAC

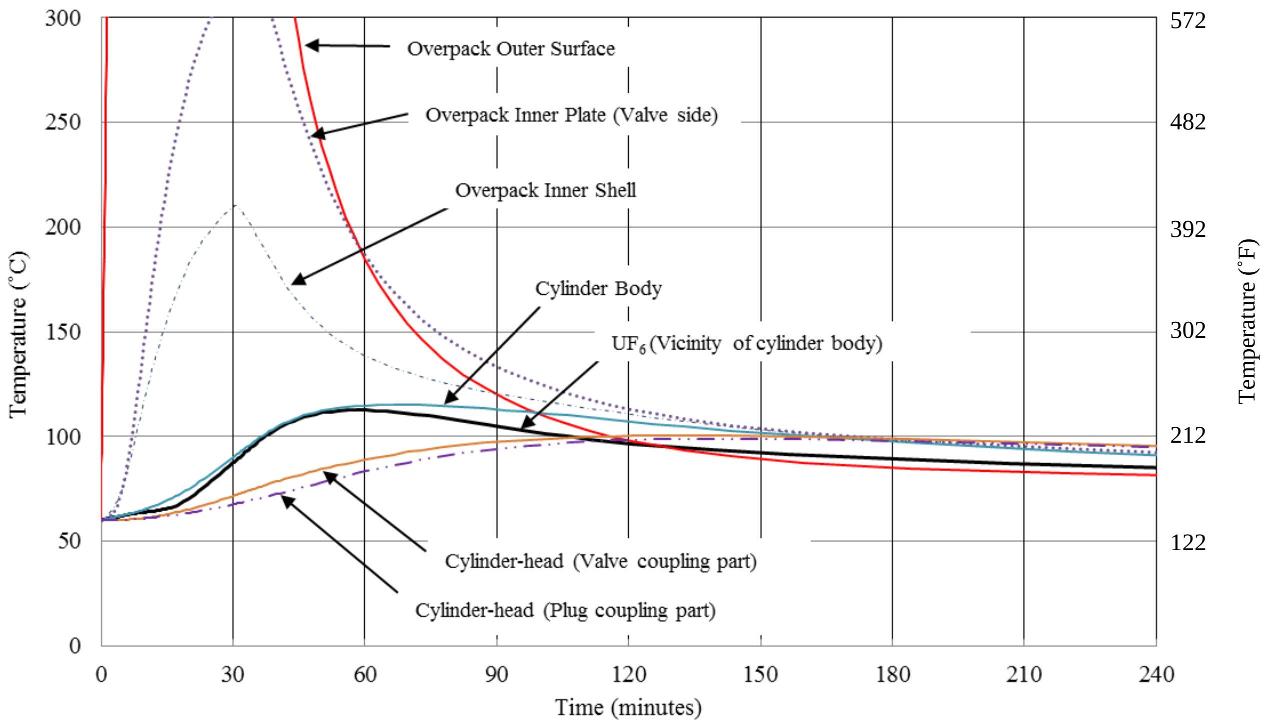


Figure 3-8 Analysis Results for HAC (Zoomed Up Figure)

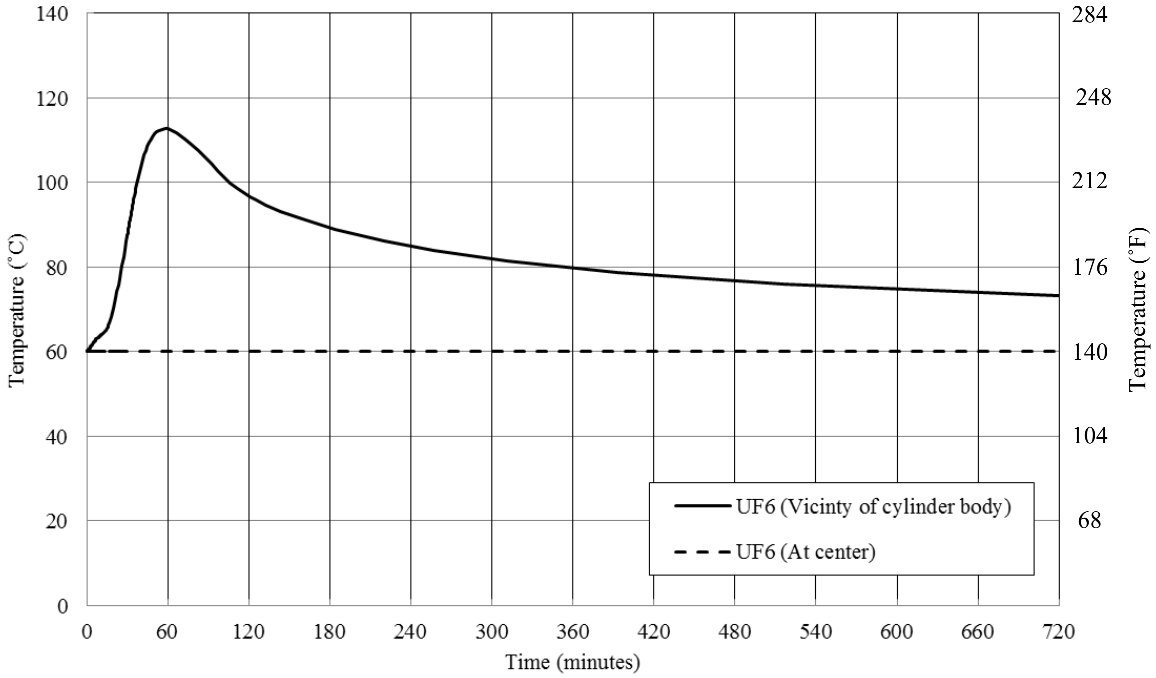


Figure 3-9 Analysis Results of UF_6 for HAC

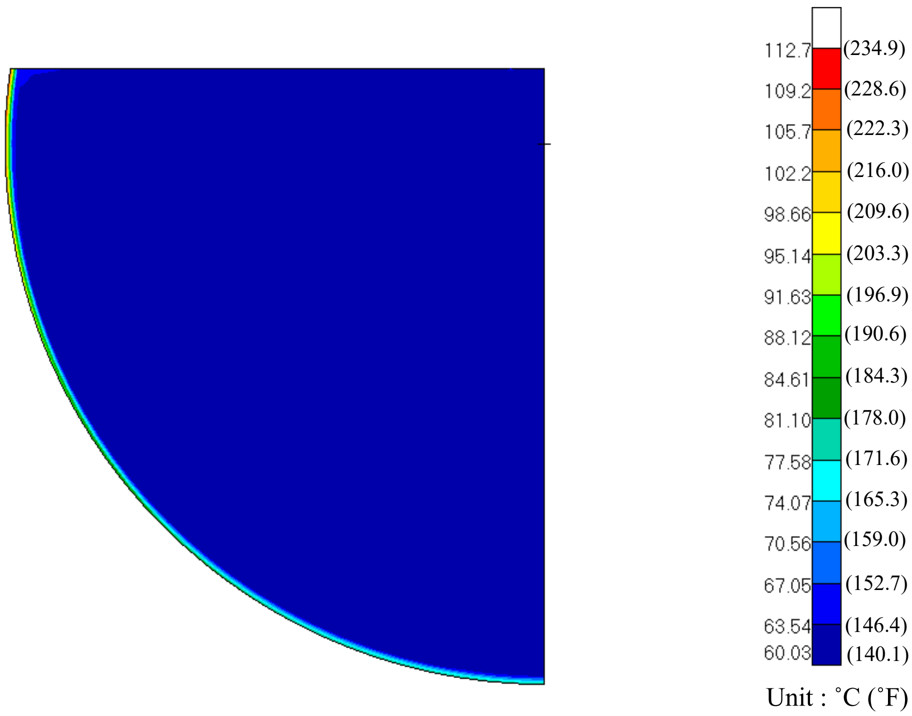


Figure 3-10 The Temperature Distribution at the Maximum Temperature of UF_6

Appendix 3.6.1

Summary of analysis code “ABAQUS”

Summary of analysis code "ABAQUS"

1. Summary

The ABAQUS code is a general-purpose program system for finite element analysis developed and improved by Hibbitt, Karlsson & Sorensen, Inc. (HKS).

This code was developed for analysis of linear and nonlinear problems in the area of structural analysis. The code is used for a variety of analysis, including geometric nonlinear analysis such as analysis of large deformation, contact and buckling problems, nonlinear material analysis such as analysis of elasto-plastic and creep problems, dynamic analysis, and heat conduction analysis for thermal stress problems.

It has a library of a large number of elements for two- and three-dimensional continuous structures, shells, beams, and other structures so that it can be applied to various shapes. It can perform both linear and nonlinear analysis. The element library contains elements for non-compressible materials and those for special problems such as contact and interface problems.

Program components of the ABAQUS system

The system consists of the following programs:

- Pre-program
- Main program

The pre-program is a preprocessor for the main program. It checks input data, plots a model and creates a database for analysis. The main program is the main component of the system and capable of elastic, elasto-plastic, creep, large deformation, buckling, and dynamic analysis. In addition, as post-processing, it prints out analysis results, generates a result file and generates a restart file for restart analysis.

2. Heat conduction analysis

ABAQUS has the capability to analyze a heat conduction (diffusion) problem and can perform steady-state and non-steady-state analysis for linear and nonlinear problems.

The solution for a steady-state problem can be directly obtained without time integration. Time integration by the backward difference method (modified Crank-Nicholson method) is performed for a non-steady-state problem. This integration method is unconditionally stable for linear problems.

Heat conduction analysis is often performed to obtain a temperature field used for thermal stress analysis. ABAQUS provides an easy-to-use interface to allow the result file output from a heat conduction analysis to be used as input data for a stress analysis.

ABAQUS uses iteration for a nonlinear heat conduction problem. It basically uses Newton's method as iteration, which was modified to ensure stability in the presence of highly nonlinear latent heat.

An element library for heat conduction analysis is provided to allow modeling of most problems. Shell heat conduction elements are provided for an analysis of a shell structure.

Boundary conditions in heat conduction analysis include heat flux (distribution or concentration), temperature specification, heat transfer, and radiation. All of these can be given as a function of time.

ABAQUS has a capability of analysis for fully coupled heat conduction-stress problem.

Appendix 3.6.2

Verification of appropriateness of thermal evaluation method by comparison between analytical results and test results

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Verification of appropriateness of thermal evaluation method by comparison between analytical results and test results

1 Purpose

The simulation analysis is performed with the thermal conditions of the compliance test in order to verify the appropriateness of the analytical model described in Section 3.5.1.

2 Calculation Condition

2.1 Difference from Section 3.5.1

The following thermal conditions of the compliance test are different from the conditions used in the analysis described in Section 3.5.1.

(1) Thermal properties of thermal insulators

The values of thermal properties used in the simulation analysis are determined from literatures [Reference 3.7.1], [Reference 3.7.2], [Reference 3.7.3]. Table 3.6.2-1 shows thermal properties used in the simulation analysis.

(2) Geometry model

The geometry model for the simulation analysis is made based on the dimension of the prototype package used in the compliance test. The deformed dimensions of the package are also based on the drop test results of the compliance test.

(3) Initial thermal condition

The initial temperature of the package is set at 28°C, which is the measured value on the compliance test.

(4) Emissivity values of the cylinder surface and the overpack inner surface

The emissivity value of the overpack inner shell is 0.11 [Reference 3.7.4] and that of the cylinder surface is 0.69 [Reference 3.7.19], which is the value of aluminum paint on the cylinder surface.

(5) Content

The simulant for the content is “steel grit” whose bulk density is 3300kg/m^3, specific heat is 502J/(kg·K), and thermal conductivity is 0.2W/(m·K), which is modeled in the simulation analysis.

(6) Temperature of the overpack outer shell

The measured temperature history of the overpack outer surface in the thermal (furnace) test is input to the all outer surface of the package as a boundary condition.

(7) Cooling period

(a) Environment temperature

The environment temperature is set at 28°C, which is the measured value in the compliance test.

(b) Solar insolation

Because the thermal test of the compliance test was performed in the building, solar insolation is not taken into account.

(c) Emissivity value of the overpack outer surface during the cooling period

Because the overpack outer surface was covered with black ash, emissivity value for the overpack outer surface is set at 1.0 during the cooling period.

2.2 Steel grit

Physical properties of the steel grits were calculated in the following manner. The steel grits used for the thermal testing to simulate UF_6 were the Article No. GH-4 made by Shintou Blader Co., Ltd.Compositions of the steel grits are mainly Iron (Fe), and include approximately 1% of Carbon (C), Silicon (Si), Manganese (Mn) and approximately 0.02% of Sulfur (S).

(1) Density:

The density in the product specification is 3300 kg/m^3. On the other hand, the true density (theoretical density) in the metal ingot is 7600 kg/m^3. The average grain size is approximately 0.5 mm.

(2) Specific Heat:

0.12 cal/g·°C (The specific heat of modular cast iron [Reference 3.7.16], of which chemical composition is equivalent to that of the steel grits, was used as a specific heat for the steel grit)

(3) Thermal Conductivity:

Thermal conductivity like that of steel grit should usually be calculated on the basis of thermal conductivity in the state of metal ingot. However, because it was not easy to find the thermal conductivity in the state of metal ingot for steel grit directly, thermal conductivity (Kp) in the state of metal ingot for modular cast iron [Reference 3.7.16], of which chemical composition is nearly equivalent to that of steel grit, was used as a thermal conductivity in the state of metal ingot for steel grit.

The thermal conductivity of steel grit (Kb) was determined using the graphs shown on Figure 3.6.2-7 [Reference 3.7.17] in such a manner as follows:

Thermal Conductivity in the state of metal ingot (Kp) : 46.0 W/m·K

Thermal Conductivity of Air (Kg) : 0.026 W/m·K (27°C)

The ratio of Kp to Kg is : Kp/Kg = 1.77×10^3

ε (Spacing Percentage) = (7600 – 3300)/7600 ≒ 0.57

When plotting Kb/Kb from Figure 3.6.2-7 [Reference 3.7.17] using these values, it is approx. 7.5.
Therefore,

Kb (thermal conductivity of steel grit) = 7.5 x 0.026 ≒ <u>0.20 W/m·K</u>

2.3 Summary of Calculation Condition

The initial conditions and boundary conditions for the simulation analysis are presented in Table 3.6.2-2.

3. Calculation Result

The comparison of maximum temperature values between the analysis results and test results is presented in Table 3.6.2-3 and the temperature reference points are shown in Figure 3.6.2-1. The histories of the temperature at the reference points are shown in from Figure 3.6.2-2 to Figure 3.6.2-6.

4. Conclusion

The simulation analysis results agree well with the test results. The simulation analysis results of the cylinder temperature to be important for the evaluation are always greater than test results. Therefore, the analytical model described in Section 3.5.1 is appropriate.

Table 3.6.2-1 Thermal Properties of Thermal insulators used in Simulation Analysis

	Phenolic Foam		Polyurethane Foam
Thermal Conductivity (W/(m·K))	0.035	(63˚C)	0.0611 (Foam-1&3)
	0.061	(210˚C)	0.0682 (Foam-2)
	0.093	(372˚C)	
	0.121	(543˚C)	
Specific Heat (J/(kg·K))	1047	(60˚C)	1350
	1130	(100˚C)	
	1256	(150˚C)	
	1298	(200˚C)	
	702	(802˚C)	

Table 3.6.2-2 Initial Conditions and Boundary Conditions for Simulation Analysis

	Initial Condition	Boundary Condition	
		Overpack Outer Surface	Cylinder Surface and Overpack Inner Surface
Thermal Test (Furnace Test)	28° (82.4°F) at All Parts (Measured Value)	・ Measured Temperature History	・Heat Transfer form Gas Generated from Phenolic Foam ・ Thermal Radiation Emissivity/Absorptivity Overpack Inner Surface : 0.11 Cylinder Surface : 0.69
Cooling Period (after Furnace Test)	Temperature Distribution Calculated above	・ Thermal Radiation to environment of 28°C ・ Thermal Radiation Emissivity/Absorptivity Overpack Outer Surface :1.0 Environment :1.0 ・ Heat transfer by natural convection to Environment $Nu=0.13\cdot(Pr\cdot Gr)^{1/3}$ [Reference 3.7.5]	< 70 Minutes after Furnace Test > (after the package was withdrawn from the furnace): ・Heat Transfer form Gas Generated from Phenolic Foam ・Heat Conduction across Air Gap ・Thermal Radiation (Emissivity/Absorptivity values are the same as above) < After 70 Minutes Period above > ・Heat Conduction across Air Gap ・Thermal Radiation (Emissivity/Absorptivity values are the same as above)

Table 3.6.2-3 Comparison of Maximum Temperature
between Analysis Results and Test Results

	Temperature Reference Point	Test Result ˚C (˚F)	Analysis Result ˚C (˚F)
1	Overpack Inner Shell (Center)	87.3* (189.1)	85 (185)
2	Overpack Inner Plate (Valve Side)	150-160 (302-320)	245 (473)
3	Overpack Inner Plate (Plug Side)	130-140 (266-284)	212 (413.6)
4	Cylinder Surface (Center)	50.7* (123.3)	58 (136.4)
5	Cylinder Surface (Valve Side)	<50 (122)	58 (136.4)
6	Cylinder Surface (Plug Side)	<50 (122)	56 (132.8)
7	Cylinder Skirt Inner Surface (Valve Side)	59.4* (138.9)	60 (140)
8	Cylinder Skirt Inner Surface (Plug Side)	55-60 (131-140)	56 (132.8)
9	Cylinder-head Surface (Valve Side)	51.5* (124.7)	57 (134.6)
10	Cylinder-head Surface (Plug Side)	<50 (122)	55 (131)

(Notice) Values with *is the maximum temperature measured with thermocouples, other data are measured values with thermo-labels.

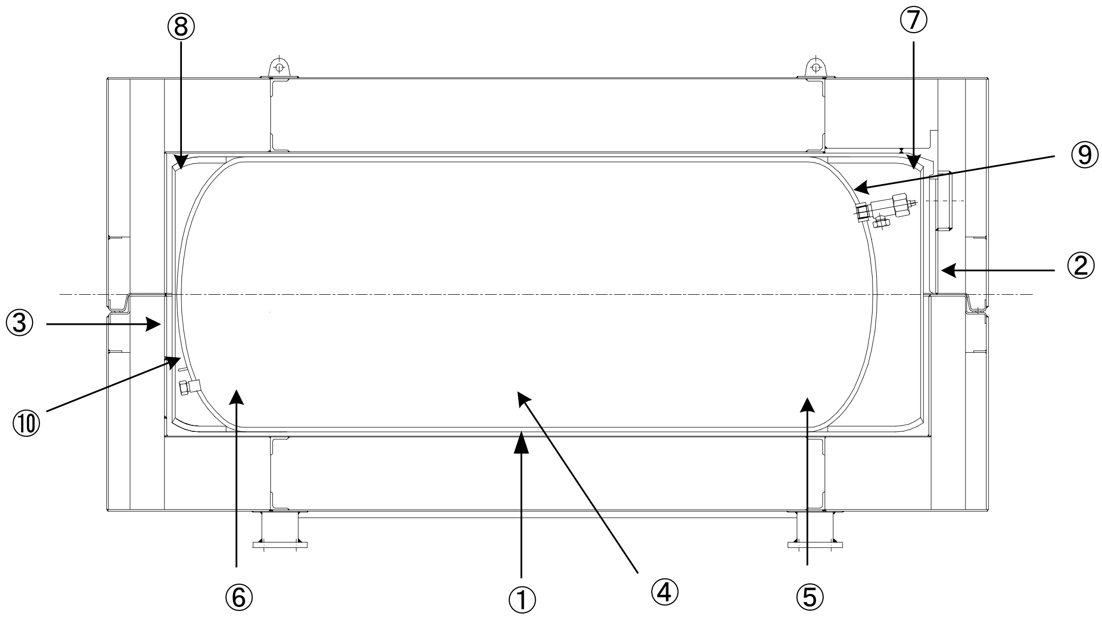


Figure 3.6.2-1 Temperature Reference Points

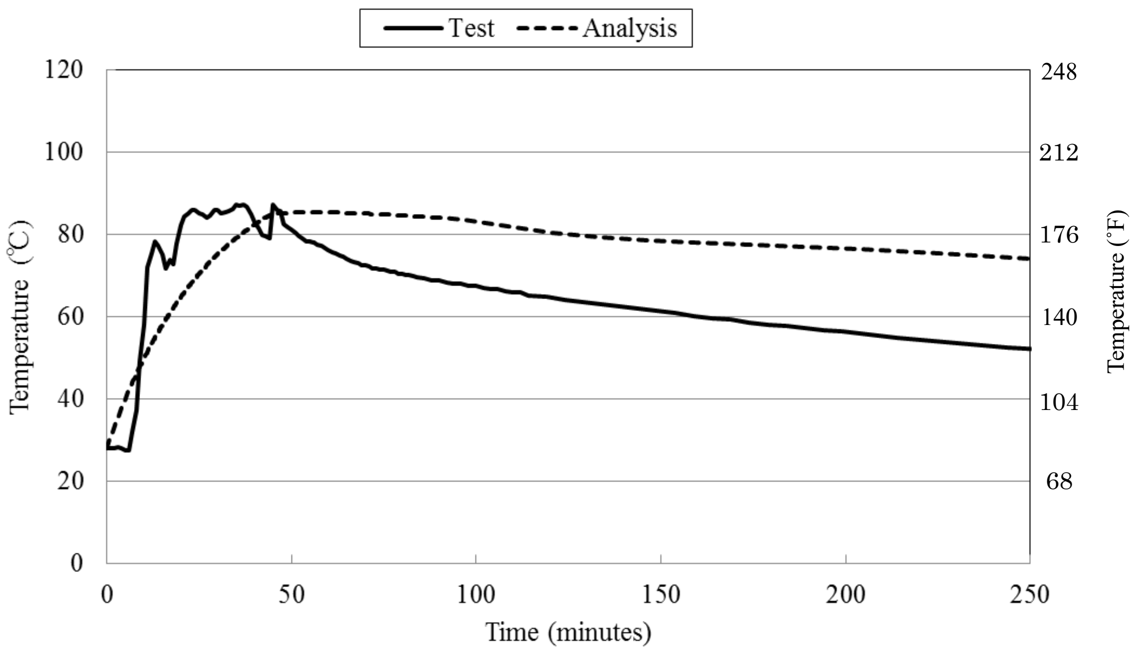


Figure 3.6.2-2 Comparison between the Analysis Results and the Testing Results of Temperatures at the Center of the Overpack Inner Shell

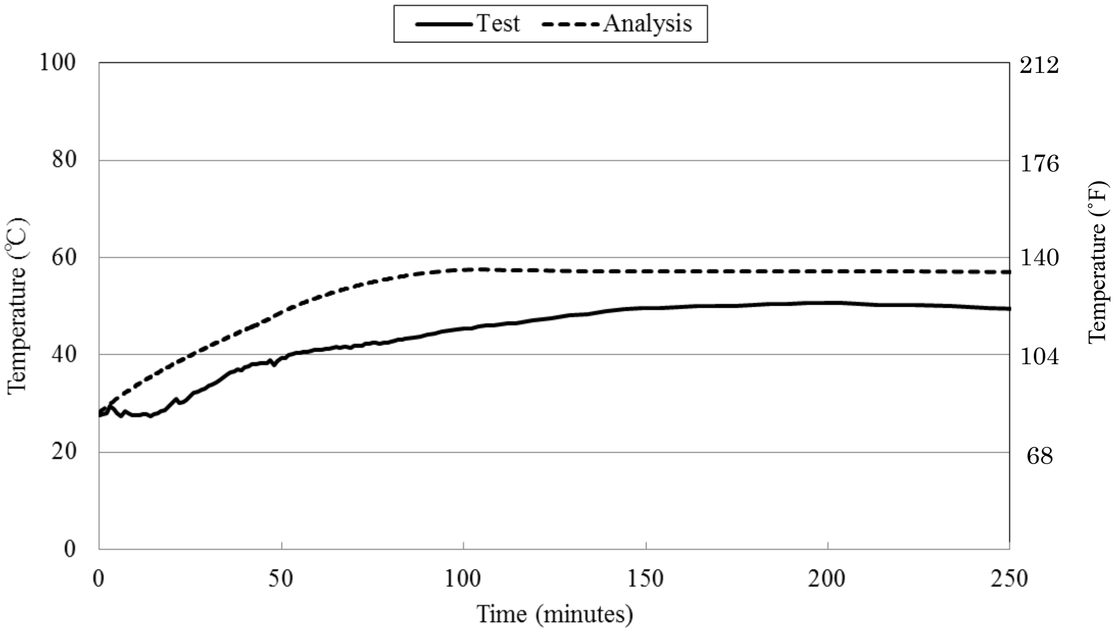


Figure 3.6.2-3 Comparison between the Analysis Results and the Testing Results of Temperatures at the Center on the Surface of Cylinder-body

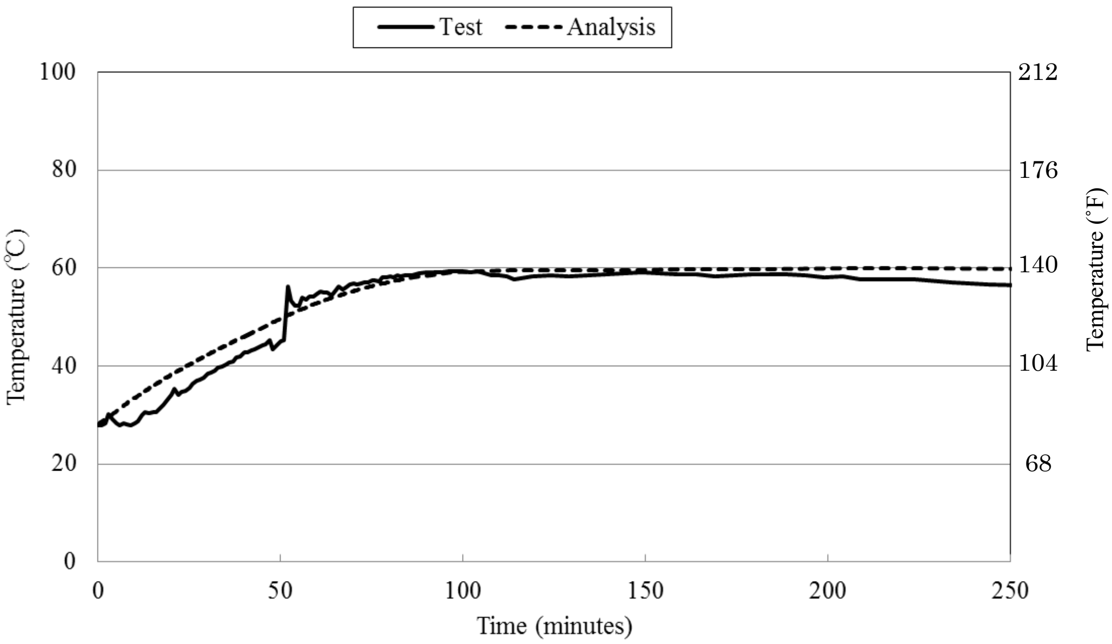


Figure 3.6.2-4 Comparison between the Analysis Results and the Testing Results of Temperatures on the Cylinder-skirt (Valve side)

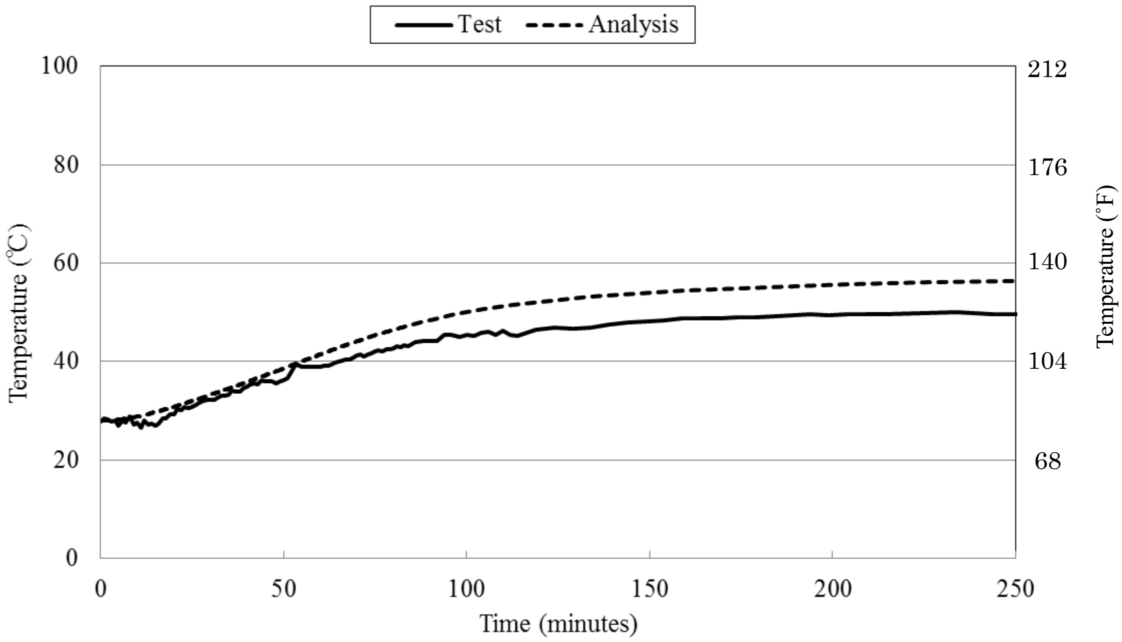


Figure 3.6.2-5 Comparison between the Analysis Results and the Testing Results of Temperatures on the Cylinder-head (Valve side)

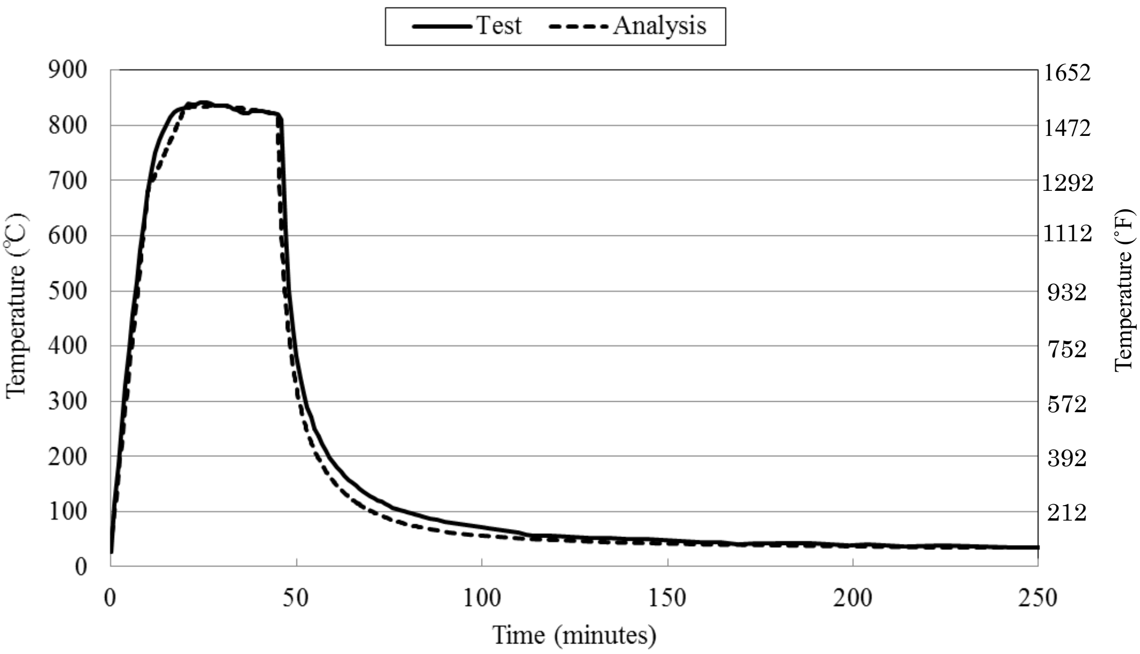
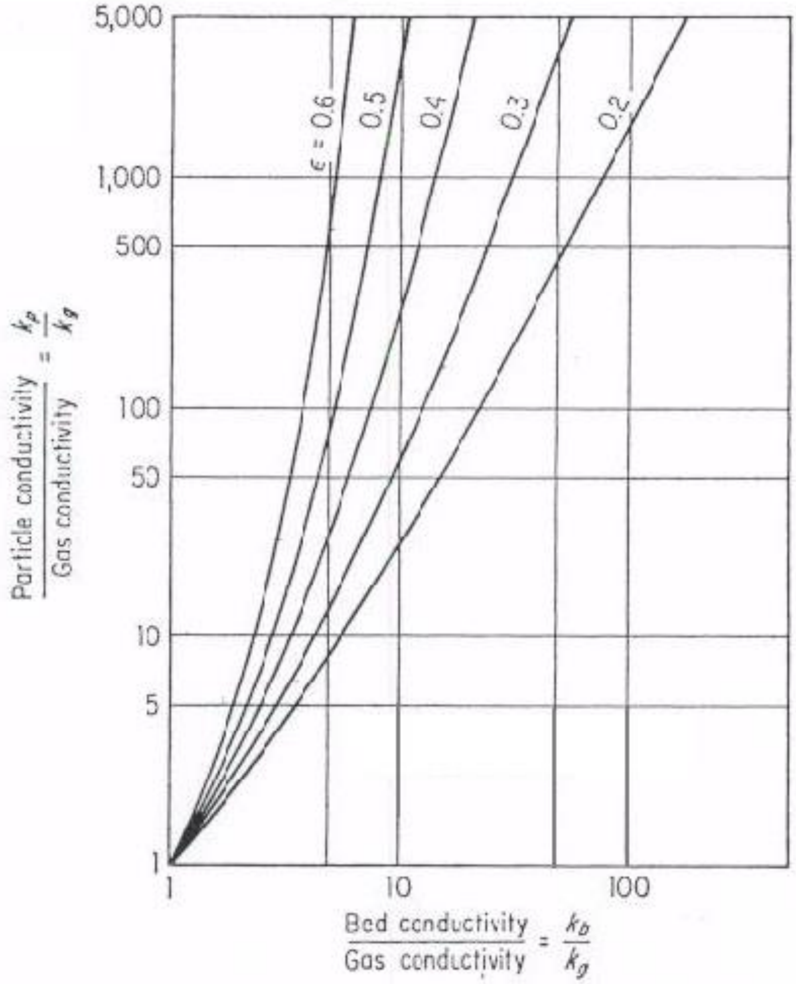


Figure 3.6.2-6 Comparison between the Analysis Results and the Testing Results of Temperatures on the Surface of Overpack Outer Shell



Correlation for the thermal conductivity of packed beds with gas filling the interstices. [After R. G. Deissler and C. S. Eian, *Investigation of Effective Thermal Conductivities of Powders* (Washington, D.C.: National Advisory Committee for Aeronautics, RM E52C05, 1952).]

Figure 3.6.2-7 Measure for Determing Thermal Conductivity for Steel Powder

Appendix 3.6.3

Effects of non steady solar insolation every 12 hours per a day

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Effects of non steady solar insolation every 12 hours per a day

1 Purpose

The initial condition of thermal test (solar insolation under NOC in Section 3.4) is calculated by means of steady-state analysis. In this calculation, solar insolation is applied as a half of 400W/m^2 at outer shell and 200W/m^2 taking existence or non-existence of solar insolation in a day and night (12 hours per day) into account. In this appendix, the transient analysis is performed to confirm the effects for the case that solar insolation every 12 hours per a day is applied.

2 Calculation Condition

The initial temperatures are cited from the result in Section 3.4 (Section 3.5.1.1.1) and the period of analysis is 7 days (168 hours). The other conditions are the same as these of steady-state analysis before thermal test.

3 Calculation Result and Conclusion

The temperature histories at the points of the package are shown in Figure 3.6.3-1. The temperature at the each point of the package converges as time passes and these points reach at approximately steady state on the seventh day.

The temperature amplitudes at the points of the package on the seventh day are shown in the Table 3.6.3-1. In this table, the temperature amplitude of the cylinder-head conservatively applies to that of the content (UF_6). Taking these temperature amplitudes into account, the thermal analysis after thermal test is evaluated in Table 3-9.

Table 3.6.3-1 Temperature amplitude at each point of the package

Temperature Reference Points	Temperature amplitude (˚C)
Overpack Outer Surface	+14, -18
Overpack Inner Shell	+6, -8
Overpack Inner plate (Valve side)	+9, -13
Cylinder body	+4, -7
Cylinder-head (Valve coupling part)	+4, -7
Cylinder-head (Plug coupling part)	+4, -7
Content (Maximum temperature)	+4, -7
Content (At center)	+0.1, -0.1

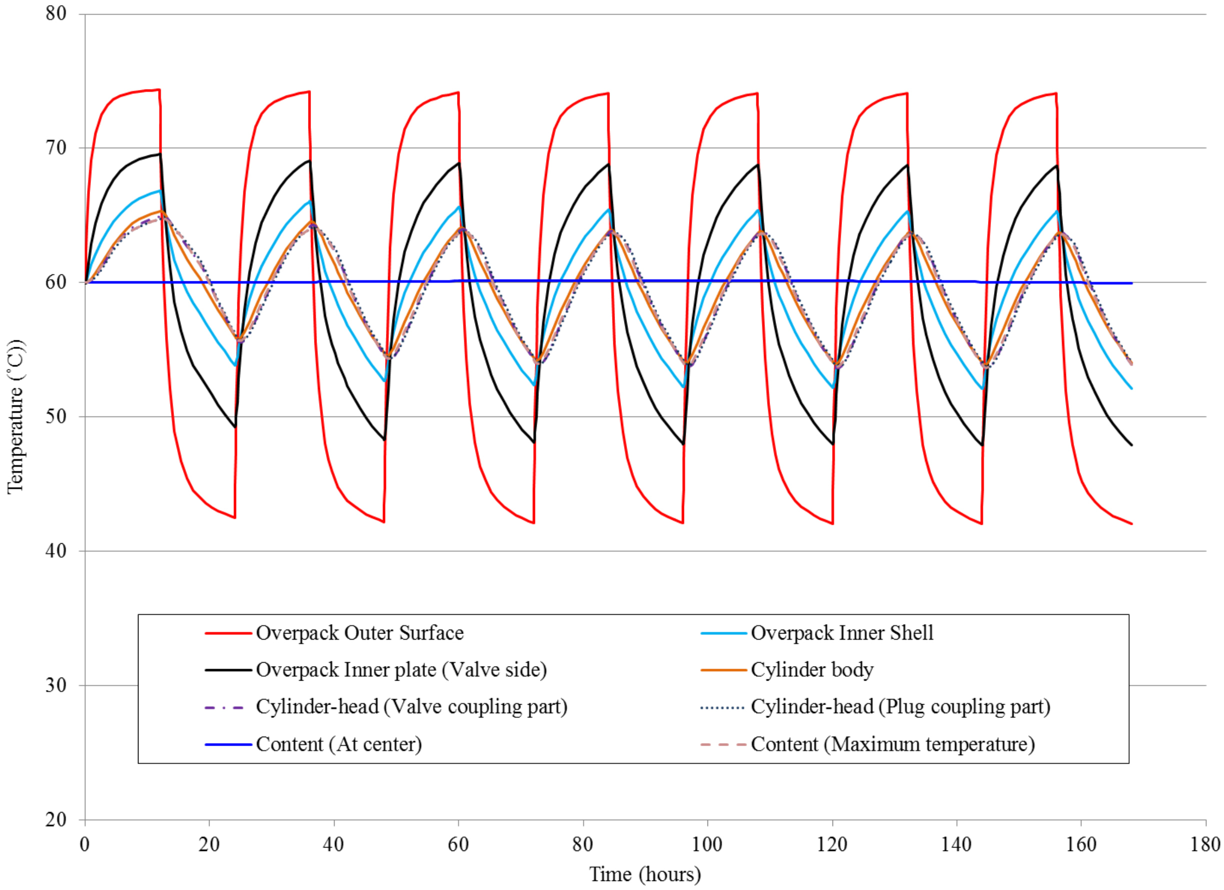

Figure 3.6.3-1 Temperature histories at each point of the package

Appendix 3.6.4

Analysis for the case that smaller mass of UF_6 is contained

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Analysis for the case that smaller mass of UF_6 is contained

1 Purpose

In this appendix, supplemental evaluation is performed for the case that UF_6 mass contained in a cylinder is smaller than the design maximum of 2,277kg (5,020lb).

2 Calculation Condition

The analyses are carried out for the case that the mass of the content is 11.34kg (25lb) and 200kg (441lb). 11.34kg (25lb) is the value of the maximum heel (the value of the maximum residue after removing UF_6 from the cylinder) specified in ANSI N14.1 and ISO 7195 which are the standards for the cylinder. The conditions other than the mass of content are the same as those in Section 3.5.

3 Calculation Results and Evaluation

3.1 Temperature of Package

The result of the maximum temperature at each point of the package is shown in Table 3.6.4-1. The temperature histories of UF_6 and cylinder-head at valve and plug coupling part are shown in Figure 3.6.4-1, Figure 3.6.4-2 and Figure 3.6.4-3. Furthermore, the temperature distributions when UF_6 reaches the maximum temperature are shown in Figure 3.6.4-4 and Figure 3.6.4-5.

The maximum temperature at the coupling of the valve and plug of the cylinder-head is 126˚C (259°F) when the mass of content is 11.34kg (25lb). This is well below the solidus temperature of tin-lead solder of 183 ˚C (361°F).

The maximum temperature of UF_6 as the content is 126˚C (259°F) when the mass of UF_6 is 11.34kg (25lb). It exceeds 121˚C (250°F) which is the temperature criterion for the cylinder containing 2,277kg (5,020lb) of UF_6 (criterion to prevent from hydraulic rupture resulting from expansion of the liquid UF_6 at the maximum content).

Hereafter, the volume of UF_6 is conservatively evaluated for the case that whole UF_6 of 200kg (441lb) is homogeneously 126˚C (259°F) which is the maximum temperature when the mass of UF_6 is 11.34kg (25lb).

$$V = \frac{m}{\rho} = \frac{2\times10^5}{3.21} = 6.3\times10^4 \text{cm}^3 = 0.063\text{m}^3$$

$$\rho = 3.630 - 5.805\times10^{-3}\times(t - t_f) - 1.36\times10^{-5}(t - t_f)^2$$
$$= 3.21 \text{g/cm}^3$$

Where,

V : Volume of UF_6 [m^3]

m : Mass of UF_6 = 200kg= 2×10^5g

ρ : Density of UF_6 (Liquid) [g/cm^3] [Reference 3.7.15]

t : Temperature of UF_6 = 126˚C

t_f = 64.052˚C [Reference 3.7.15]

As shown above, the volume of UF_6 is $0.063m^3$. It does not exceed $0.699m^3$ which is 95% of the minimum volume of 30B cylinder i.e. $0.736m^3$ ($26ft^3$). Therefore, hydraulic rupture of 30B cylinder does not occur due to expansion of the liquid UF_6.

3.2 Maximum Pressure

As a result in the previous section, the maximum temperature of the content is 126˚C (259°F) when the mass of content is 11.34kg (25lb). The vapor pressure of UF_6 at this temperature is 0.77MPa absolute (112psia) (0.67MPa gauge (97psig) as internal pressure) [Reference 3.7.15].

4 Conclusion

Supplemental evaluation is carried out for the case that the mass of UF_6 as the content is 11.34kg (25lb) and 200kg (441lb).

As the result, the maximum temperature of cylinder-head at the coupling of valve and plug is 126˚C (259°F) when the mass of the content is 11.34kg (25lb). It does not exceed the solder’s solidus temperature of 183˚C (361°F).

The maximum temperature of UF_6 is 126˚C (259°F) when it’s mass is 11.34kg (25lb), which exceeds the temperature criterion of 121˚C (250°F) for the cylinder containing 2,277kg (5,020lb) of UF_6. (the criterion for the prevention of hydraulic rupture due to expansion of liquid UF_6). However, even if whole 200kg of UF_6 is conservatively assumed to be 126˚C (259°F), the volume of UF_6 is $0.063m^3$. It does not exceed $0.699m^3$ (95% of the minimum volume of 30B cylinder i.e. $0.736m^3$ ($26ft^3$). Consequently, hydraulic rupture of the cylinder does not occur due to expansion of liquid UF_6.

The vapor pressure of UF_6 is 0.77MPa absolute (112psia) (0.67MPa gauge (97psig) as internal pressure) when its mass is 11.34kg and is below 1.38MPa gauge (200psig) which is the design pressure of 30B cylinder.

Therefore, the integrity of the cylinder is maintained even if the mass of UF_6 as content is reduced.

Table 3.6.4-1 Maximum temperature

Points	Maximum Temperature (°C)			Evaluation Criterion
	UF_6 : 11.34kg	UF_6 : 200kg	UF_6 : 2,277kg (Reference)	
Overpack Outer Surface	794	794	794	—
Overpack Inner Shell	210 (+9, -13)	210 (+9, -13)	210 (+9, -13)	—
Overpack Inner Plate (Valve side)	327 (+9, -13)	327 (+9, -13)	326 (+9, -13)	—
Cylinder body	125 (+4, -7)	121 (+4, -7)	115 (+4, -7)	—
Cylinder-head (Valve coupling part)	122 (+4, -7)	117 (+4, -7)	101 (+4, -7)	Not to exceed the solder's solidus temperature of 183°C
Cylinder-head (Plug coupling part)	122 (+4, -7)	117 (+4, -7)	99 (+4, -7)	Not to exceed the solder's solidus temperature of 183°C
Content (Maximum Temperature)	122 (+4, -7)	109 (+4, -7)	113 (+4, -7)	Volume of UF_6 as contents shall not exceed 0.699m^3 at the evaluated temperature
Maximum internal pressure in the cylinder (MPa)	0.77	0.58	0.64	Not to exceed the cylinder design pressure of 1.38MPa

＊ Parenthetical values indicate temperature amplitude due to applied with solar insolation every 12 hours.

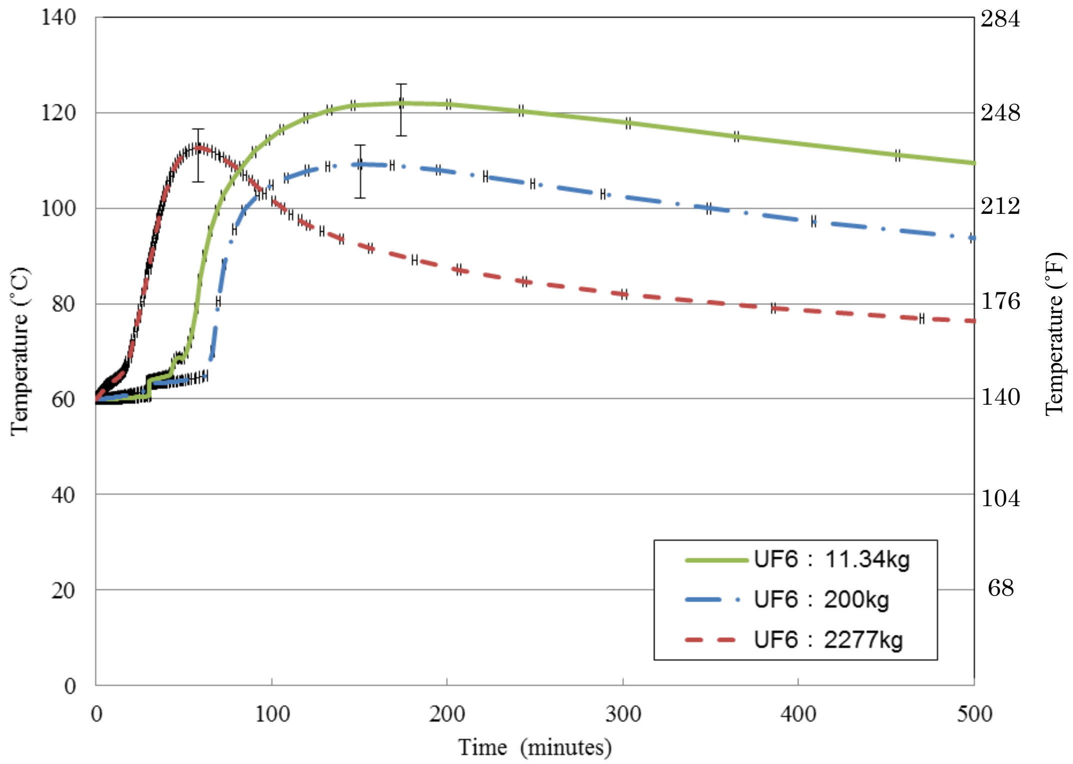

Figure 3.6.4-1 Temperature histories on the point where UF_6 shows the maximum temperature

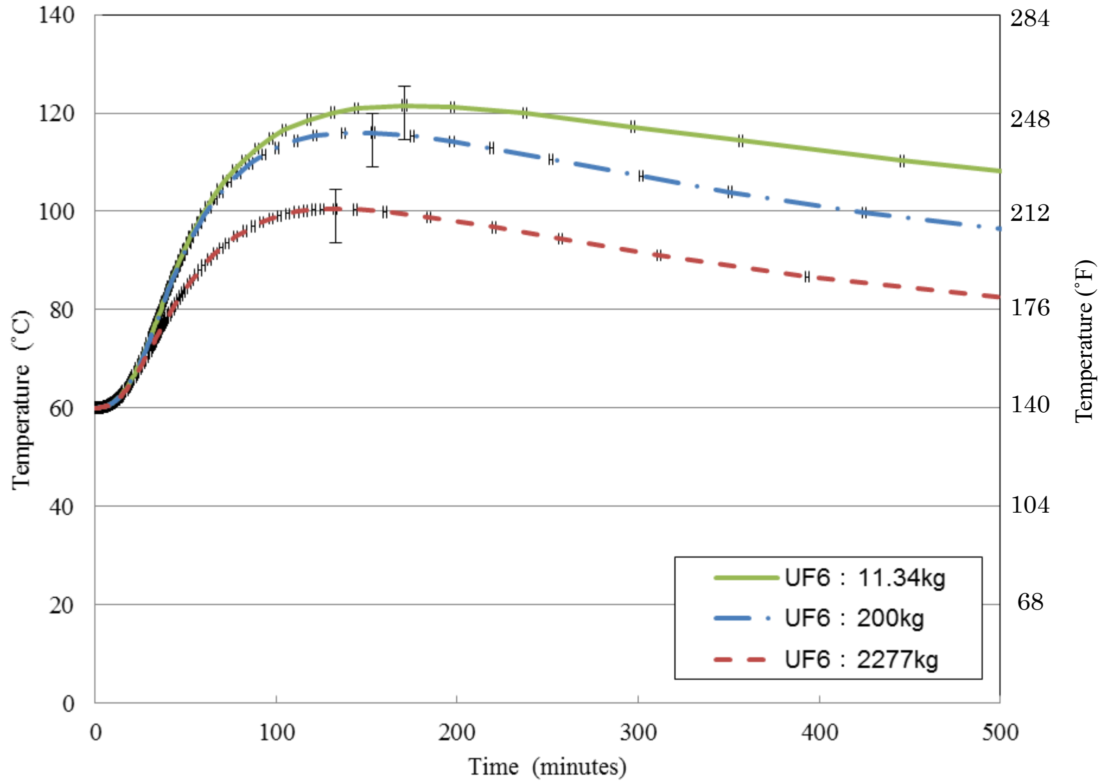

Figure 3.6.4-2 Temperature histories on the cylinder-head (Valve side)

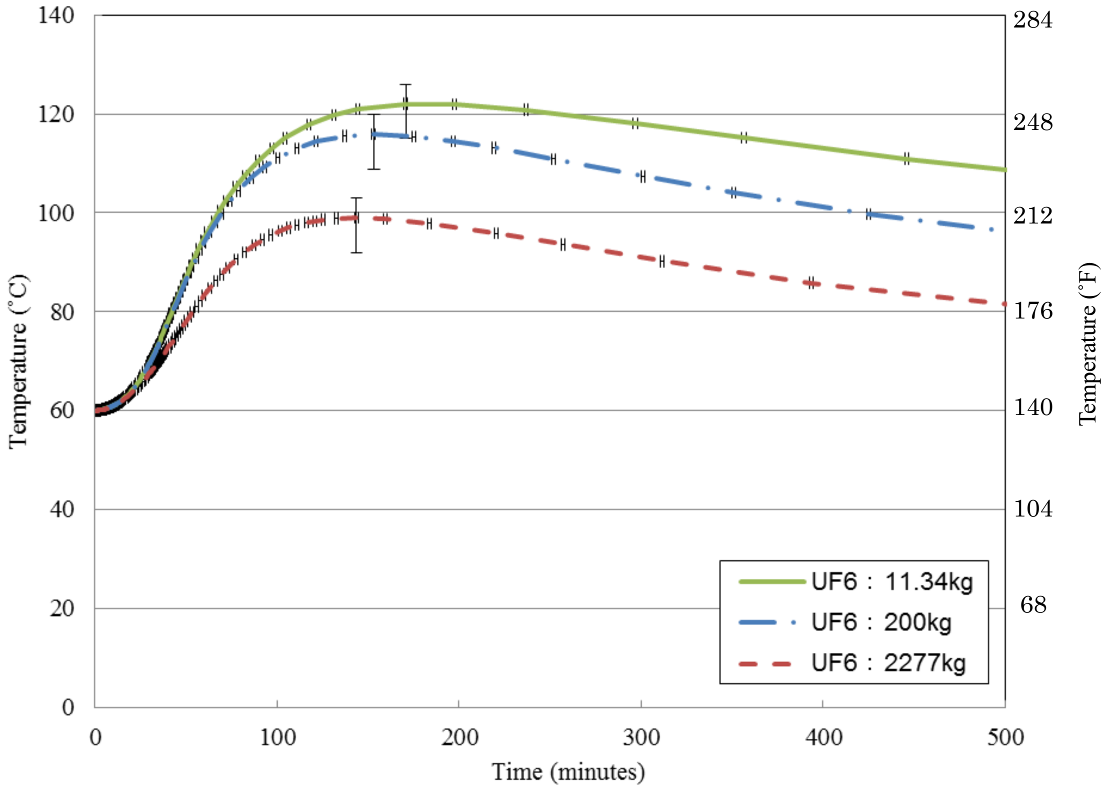

Figure 3.6.4-3 Temperature histories on the cylinder-head (Plug side)

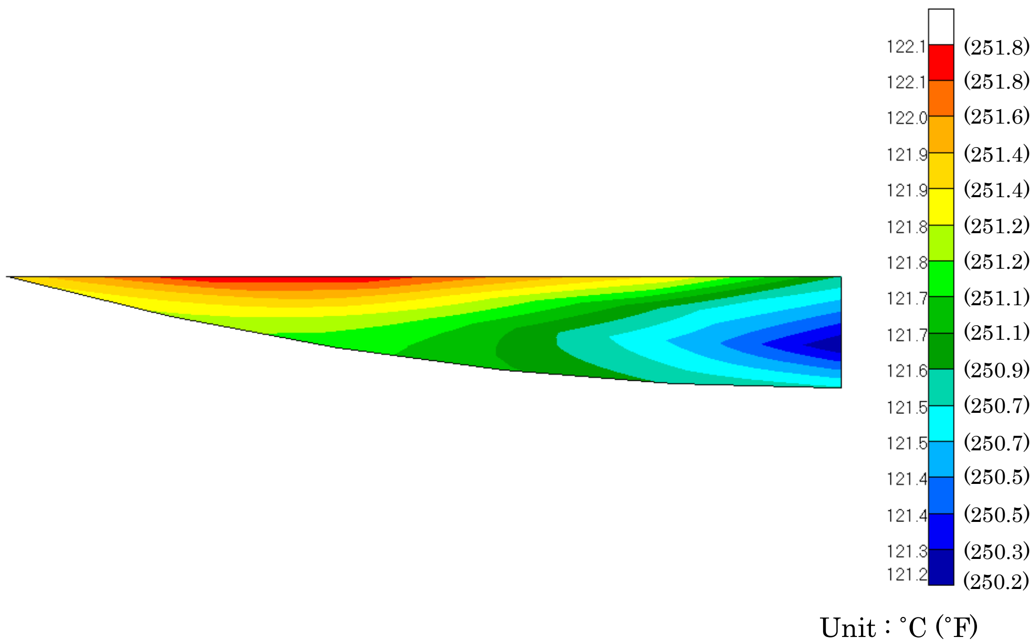

Figure 3.6.4-4 Temperature distribution when the mass of UF_6 is 11.34kg (25lb)
(At the maximum temperature of UF_6)

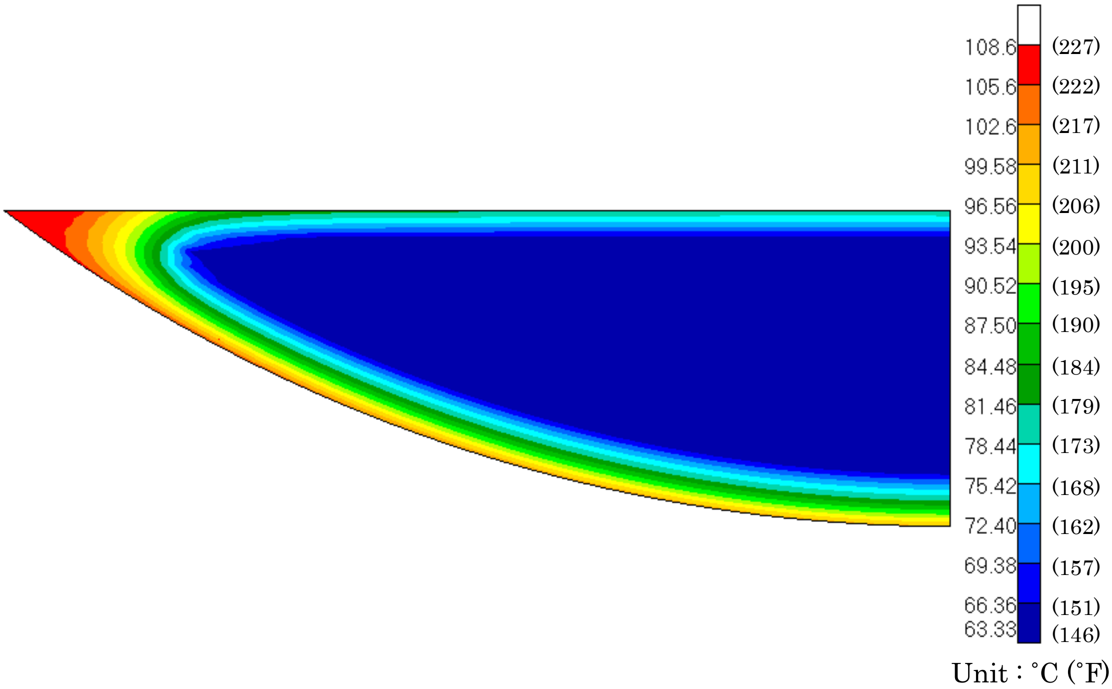

Figure 3.6.4-5 Temperature distribution when the mass of UF_6 is 200kg (441lb)
(At the maximum temperature of UF_6)

SECTION 4 CONTAINMENT

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4.0 CONTAINMENT

4.1 Containment Boundary

The containment system of this package is composed of the 30B cylinder-body, the valve and the plug. The design and specifications of the containment system are specified by ANSI N14.1 or ISO 7195. In the case of the MST-30 package, the type of plug allowed is a socket head plug only. A hex head plug is not available. A cylinder which does not have any plug and plug-coupling may be used.

4.1.1 Containment Vessel

4.1.1.1 Design Pressure of Cylinder-Body, Valve and Plug

The design differential pressure of the cylinder-body, valve and plug is 172 kPa (25 psig) for external loads and 1.38MPa (200 psig) for internal loads for the design temperature range of –29°C (-20°F) to 121°C (250°F). Minimum transport temperature is -40°C (-40°F).

4.1.1.2 Specifications for Hydrostatic Pressure Test of Cylinder-Body and Plug

At the time of manufacture and every five years thereafter, the cylinder is hydrostatically tested. The initial hydrostatic test pressure is 2.76MPa (400psig). The pressure is then lowered to 2.07MPa (300psig) while the cylinder is inspected for leaks. No leaks are permitted.

4.1.1.3 Specifications for Air Leak-Tightness of the Valve

At the time of manufacture and valve installation (after cleaning the cylinder), the valve seat and stem, cap and packing nut are tested for seat leakage at 2.76MPa (400psig) by bubble bottle, by striking a soap bubble across the face of the valve outlet, or by immersing the valve in water. No leakage is permitted.

4.1.1.4 Specifications for Air Leak-Tightness of the Cylinder installed with Valve and Plug

At the time of manufacture and every five years thereafter, and valve installation (after cleaning the cylinder) an air test at 690kPa (100psig) is carried out. All connections and fittings (including the valve seat and packing) are leak tested using Carbona soapless lather or an approved equivalent. No leakage is permitted.

4.1.2 Containment Penetrations

There are no penetrations into the containment boundary.

4.1.3 Seals and Welds

The cylinder valve is sealed using Teflon packing (5 required) attached to the valve-stem and a Teflon gasket attached to the valve cap as shown in Figure 4-2. The service-temperature of Teflon is within the range between -100°C and 260°C (-148°F and 500°F).

The cylinder valve is tinned with the specified lead-tin solder material having a solidus temperature of 183 °C (361°F), effectively sealing the valve/coupling threads on the cylinder-head. Further, ANSI N14.1 and ISO 7195 requires that 7-12 threads be engaged on the valve, using 271-542 N·m (200-400 ft.-lbf) of torque. The lead-tin solder is also used to tin the threads of the plug/coupling on the other head of the cylinder. The socket head plug shall be installed with a maximum of three threads (6.63 mm (0.261 in.)) above flush with the outer face of the cylinder coupling to a maximum of two threads (4.42 mm (0.174 in.)) beyond flush with the outer face of the cylinder coupling, using between 203-881 N·m (150-650 ft.-lbf) of torque for 1 in. plug and between 271-1803 N·m (200-1330 ft.-lbf) of torque for 1-1/2 in. plug.

As illustrated in Figure 4-1, the cylinder joints consist of a full-penetration longitudinal weld on the cylinder-shell, circumferential welds between the shell and the heads, and the welds between the couplings and the cylinder-heads.

A minimum of one spot X-ray examination for each cylinder is required to inspect the cylinder welds in accordance with Section UW-52 of ANSI/ASME Code. Unless otherwise directed by ASME Code inspector, locations of the spot shall be at the juncture of the longitudinal seam and the circumferential head weld, alternating ends for successive cylinders. Weld imperfections indicated by radiographs shall not exceed the defects permitted by Section UW-52 of ANSI/ASME Code, except for rounded indications, which shall be required to meet Section UW-51 of the ANSI/ASME Code.

Each cylinder is hydrostatically tested at 2.76 MPa (400 psig) in accordance with the ANSI N14.1 or ISO 7195 to assure a leak-free containment boundary.

4.1.4 Closure

The 30B cylinder has a single operational closure: a special 1" gas valve at the upper head. The valve is fabricated, inspected, tested, and maintained in accordance with USEC-651 and ANSI N14.1 or ISO 7195.

4.2 Requirements for Normal Conditions of Transport

4.2.1 Containment of Radioactive Material

The Japanese Safe Transport Regulations pursuant to SSR-6 require that any package containing 0.1 kg or more of Uranium Hexafluoride (UF_6) be designed such that there is no loss or dispersal of radioactive material and no damage of its containment system, including the valve, under Normal Conditions of Transport (NOC) as specified in Para. 632(b) of SSR-6. Additionally, Para. 648(a) states that a Type A package must be designed such that there is no loss or dispersal of radioactive material under normal conditions of transport. Sections 2 and 3 demonstrate that the integrity of the containment system is maintained under both normal and hypothetical accident conditions of transport.

4.2.2 Pressurization of Containment Vessel

The results of the thermal evaluations reported in Section 3 show that the pressure of the cylinder never exceeds the design pressure under both Normal and Hypothetical Accident conditions. The maximum internal pressure under NOC thermal condition is 123kPa absolute (18 psia). Even under HAC, the maximum internal pressure is 0.64MPa absolute (93psia). Both maximum pressures are well below the cylinder design pressure 1.38MPa gauge (200psig).

4.2.3 Containment Criterion

The 30B cylinder transported in the MST-30 overpack is manufactured and maintained per the requirements of ANSI N14.1 or ISO 7195.

4.3 Containment Requirements for Hypothetical Accident Conditions

4.3.1 Fission Gas Products

There are no fission gas products contained within the MST-30 package.

4.3.2 Containment of Radioactive Materials

The Japanese Safe Transport Regulations pursuant to SSR-6 require that any package containing 0.1 kg or more of UF_6 shall be designed to withstand the thermal test without rupture of the containment system as specified in Para.632(c) of SSR-6. The current Japanese Regulations also require that any packaging containing Fissile Uranium Hexafluoride (UF_6) enriched up to 5wt% ^{235}U shall be designed such that there is no physical contact between the cylinder valve and any other component of the packaging after the mechanical tests and, in

addition, the valve remain leak-tight after the thermal test and water immersion test, as specified in Para.680 (b) (i) of SSR-6.

Sections 2 and 3 demonstrate that the integrity of the containment system is maintained throughout and following the mechanical and thermal tests specified by regulation for Normal and Hypothetical Accident conditions.

4.3.3 Containment Criterion

The 30B cylinder transported in the MST-30 overpack is manufactured and maintained per the requirements of ANSI N14.1 or ISO 7195.

4.4 Appendix

4.4.1 Effect of Moist Air Ingress

4.5 References

4.5.1 Science Annual Handbook 1999 (written in Japanese)

4.5.2 ORNL/TM-11947 “Criticality Safety Review of 2 1/2-, 10-, and 14 –Ton UF6 Cylinders” B.L. Broadhead, Martin Marietta Energy Systems, Oak Ridge National Laboratory, 1991

4.5.3 “A Nuclear criticality Safety Assessment of the Loss of Moderation Control in 2-1/2 and 10-ton Cylinders Containing Enriched UF6” by Richard L. Newvahner (Portsmouth Gaseous Diffusion Plant) and William A. Pryor (PAI Corporation), 2nd International Conference of “Uranium Hexafluoride Handling” in 1991, CONF-110117

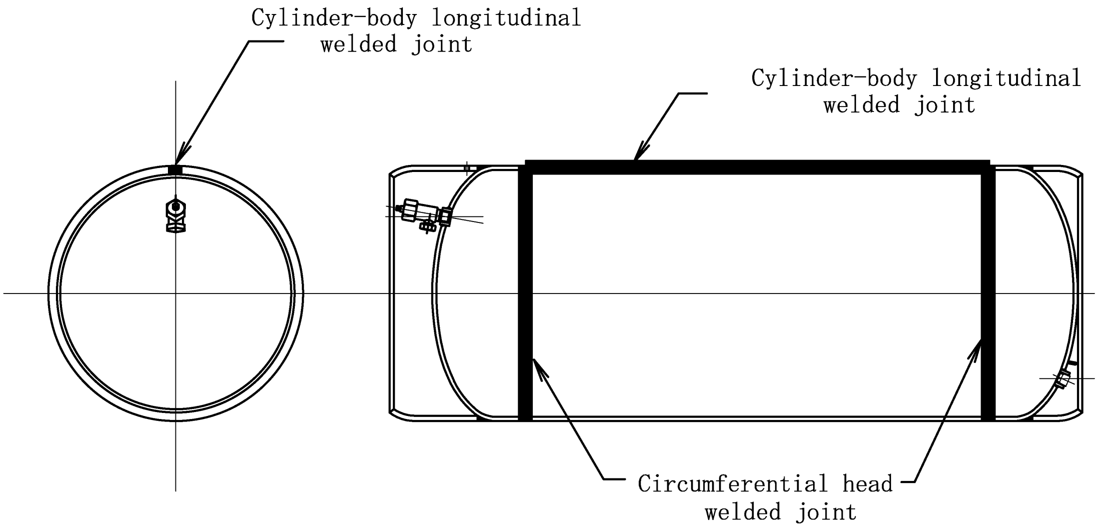
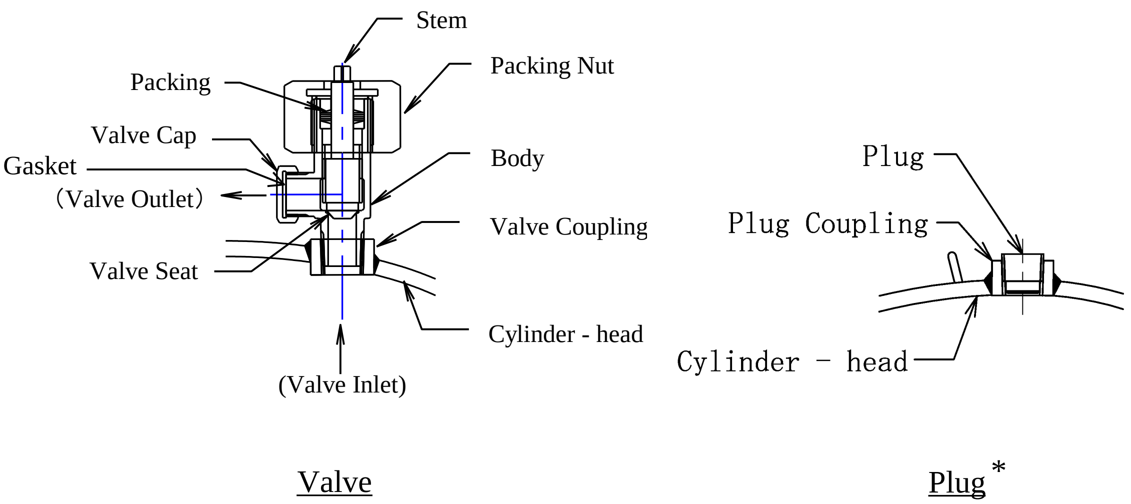


Figure 4- 1 Welded Portions of Cylinder-Body



* In some cases, a cylinder without plug and plug-coupling may be used.

Figure 4- 2 Installation of Valve and Plug into Cylinder-head

Appendix 4.4.1

Effect of Moist Air Ingress

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Effect of Moist Air Ingress

1 Introduction

As shown in Section 2, the integrity of the containment system is maintained throughout and following the mechanical and thermal tests specified by regulation for Normal and Hypothetical Accident conditions. The maximum leak rate measured following the compliance test was 2.2 x 10^{-7} std•cc/s (see in Appendix 2.10.1).

Even though the post-test measured leak rate is very small, it is not zero. Liquid water can not leak into the cylinder through this fine leak. However, a gaseous material such as air or vapor water may leak into the cylinder. Therefore, this appendix considers water vapor leakage into the cylinder and the number of water molecules that may accumulate, assuming the leak rate measured following the compliance test.

2 Calculation

Conditions assumed:

Leak rate of 2.2 x 10^{-7} std•cc/s
External pressure: 1 atm (Atmospheric pressure)
Internal pressure of cylinder: 0 atm (Vacuum)
Ambient temperature: 40°C (104°F)

The density of saturated water vapor at 40°C (104°F) is 0.0512 x 10^{-3} g/cc [Reference 4.5.1].

Using the maximum leak rate measured following the NOC and HAC performance tests (2.2 x 10^{-7} std•cc/s), the cumulative amount of vapor water that may enter the cylinder in one year is:

$$2.2 \times 10^{-7} \text{ (cc/s air)} \times 0.0512 \times 10^{-3} \text{ (g/cc)} \times 3600\text{(sec)} \times 24\text{(hrs)} \times 365 \text{ (days)}$$
$$= 3.6 \times 10^{-4} \text{ g/yr water (0.36mg/yr).}$$

This weight of water molecules corresponds to 2.4 x 10^{19} atoms of hydrogen.

3 Discussion

The criticality analysis in Reference 4.5.2 includes

$$7.6800 \times 10^{-4} \text{ (atms/barn•cm)} \times 10^{24} \text{ (barn/cm}^2\text{)} \times 736000 \text{ (minimum cylinder volume, cc)}$$
$$= 5.6525 \times 10^{26} \text{ atoms of hydrogen in the 30B cylinder,}$$

modeled as impurities (HF).

Thus, the additional hydrogen added to the cylinder due to the post-test leakage rate is very small in comparison to the HF hydrogen. The ratio is $2.4 \times 10^{19} / 5.6525 \times 10^{26} = 1 / 2.3552 \times 10^{7}$ … about 1 / 24million. Therefore, even if the water vapor is taken into account, the results of the criticality evaluation do not change.

Additionally, the amount of water required to increase the criticality multiplication factor to 0.95 and 1.00 is 4.7 gallons (17,791 cc) is 6.0 gallons (22,713 cc), respectively, for a 30B cylinder that contains 5%-enriched Uranium with the maximum allowable impurities [Reference 4.5.3]. Thus, less than a mg order of water is completely negligible to the conditions concerning criticality.

4 Conclusion

Thus, the measured leak rate 2.2×10^{-7} std•cc/s is low enough to maintain subcriticality and meets requirements for a Type A fissile material package.

SECTION 5 SHIELDING EVALUATION

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5.0 SHIELDING EVALUATION

The MST-30 Protective Shipping Package (MST-30) is a Type A, Fissile Material and Uranium Hexafluoride(UF_6) Package used for the shipment of 30-inch cylinders containing Uranium Hexafluoride (UF_6) enriched up to 5 wt% ^{235}U. The package is designed to conform to the technical and regulatory requirements as specified in the Japanese Safe Transport Regulations pursuant to SSR-6. The package is intended to be used for transport from, to, or through foreign countries, including the USA. The MST-30 package is also designed in compliance with the current 10CFR Part 71 and 49CFR Part 173 Subpart I.

The MST-30 package was approved by the Japanese Authority and certified as a Type A Fissile UF_6 Package. A copy of the NRA Certificate in English is provided in Appendix 1.3.1. Drawings of the package are available in Appendix 1.3.2 and 1.3.3.

5.1 Discussion and Results

The MST-30 is designed to transport uranium hexafluoride (UF_6) with a maximum enrichment of 5 wt% ^{235}U and a maximum quantity of 2,277 kg (5,020lb)UF_6. The shielding evaluation source term is conservatively based on ASTM specification C-996 (2010, Enriched Commercial Grade) for the maximum quantity of UF_6 to be transported, with daughter nuclides calculated for a ten-year storage time using ORIGEN-2.2. The results of shielding evaluation are shown in Table 5-1. For the highly conservative worst-case condition evaluated, all dose rates during routine transport and under normal conditions of transport are well within the limits specified by current USNRC, USDOT, IAEA and JPN regulations.

5.2 Source Specification

The shielding evaluation source term is conservatively based on ASTM specification C-996 (2010) for the maximum quantity of UF_6 to be transported, with daughter nuclides calculated using ORIGEN-2.2 [1]. The radiation dose rates on the external surface of the overpack and at 1 m(40in) were calculated using the point kernel code QAD-CGGP2R [2]. The references of the code are described in Section 5.5.

[1] ORIGEN-2.2 is a computer code system for calculating the buildup, decay, and processing of radioactive materials and was released in 2002. It is available from Radiation Shielding Information Center, Oak Ridge National Laboratory as CCC-371.

[2] QAD-CGGP2R is a point-kernel code for calculating the gamma-ray penetration through various shield configurations defined by combinatorial geometry specifications. The code evaluates the effective dose using the conversion coefficients in ICRP Pub 74. The code is a revised version of QAD-CGGP code which is available from Radiation Shielding Information Center, Oak Ridge National Laboratory as CCC-493.

5.2.1 Gamma-ray Source

The source term used to evaluate the MST-30 is provided in Table 5-2. The percentage of the uranium isotopes and ^{99}Tc are specified by ASTM C-996 for the UF_6 to be transported. In addition, the dose contribution by the daughter nuclides is calculated and evaluated.

The ORIGEN-2.2 code is used to calculate the production rate of the daughter nuclides. For conservatism, it is assumed that the UF_6 has been stored for ten (10) years prior to the shipment to allow an accumulation of the ^{232}U daughters. Since the quantity of the daughter gamma-rays produced increases with the percentage of ^{235}U contained in the UF_6, the source term is based on the maximum enrichment of 5 wt% ^{235}U. The gamma-ray spectrum (18 energy group structure) calculated by ORIGEN-2.2 code is shown in Table 5-3.

5.2.2 Neutron Source

Neutrons are produced by UF_6 contained in the package due to spontaneous fission reaction of the uranium isotopes. Additional neutrons are generated by the reaction of α-rays with light elements (mainly ^{19}F). However, the dose contribution of the neutrons produced is negligible in comparison with the gamma-rays contribution. Therefore, the contribution of the neutrons to the radiation dose rate is neglected.

5.3 Model Specification

5.3.1 Routine Transport

The radiation source is assumed to be a right circular cylinder having the internal dimensions of the 30B cylinder (74.5 cm (29.33 in) ID x 191.9 cm (75.55 in) long) : the diameter is to be the value subtracting the thickness of the cylinder wall (1.2 cm (4.47 in)) from the allowable maximum diameter of the cylinder (76.9 cm (30.25 in)) and the length is to be subtracting the thickness of both cylinder-heads from the allowable maximum length of the cylinder-

body (194.3 cm (76.5 in)). The source is assumed to be distributed homogeneously throughout the volume, with a density of 2.72 g/cm^3 (169.8 lb.ft^3). The shielding effectiveness of the overpack and a ring plate is conservatively neglected. The spaces from the external surface of the cylinder to the external surface of outer shell of the overpack are 16.8 cm (6.61 in) on the end wall side and 20.8cm (8.19 in) on the cylindrical side. So, the spaces of the model are assumed to be 16 cm (6.3 in) and 20 cm (7.9 in), respectively. A schematic of the model is shown in Figure 5-1.

5.3.2 Normal Conditions of transport (NOC)

For the NOC model, the maximum deformation of the overpack due to testing (see Section 2) is applied. The maximum deformation is due to 1.2m free drop with slanting drop attitude. The dimensions of the overpack are conservatively reduced in length and diameter by 6 cm from that for the routine conditions of transport. The shielding effectiveness of the overpack is conservatively neglected. The radiation source is the same as that during the routine conditions of transport. The schematic of the NOC model is shown in Figure 5-2.

5.3.3 Dose Points

Because the package is axis-symmetric and the overpack wall is conservatively neglected, only a few points must be evaluated to obtain the worst-case dose rates. For the routine conditions of transport, four dose points are evaluated:

- the external surface of the package at the center of one end,
- the external surface of the package at the axial midpoint at the parting plane,
- a point 1 meter(40in) from the package surface at the center of one end, and
- a point 1 meter(40in) from the surface of the package at the axial midpoint at the parting plane.

For the NOC, two dose points are evaluated:

- the external surface of the package at the center of one end, and
- the external surface of the package at the axial midpoint at the parting plane.

The model neglects any shielding provided by the overpack walls; however, the dose points are located relative to external surface of outer shell of the overpack. Figures 5-1 and 5-2 provide a schematic of the dose points evaluated.

5.3.4 Shielding Regional Densities

The density of UF_6 is assumed to be 2.72 g/cm^3(169.8lb.ft^3). The density of the steel cylinder is assumed to be 7.6 g/cm^3(475.7lb.ft^3). The atomic number densities in each region of analysis model used for the evaluation is shown in Table 5-4.

5.4 Shielding Evaluation

5.4.1 Routine Transport

The maximum dose rates of the package during routine conditions of transport are calculated by the QAD-CGGP2R code with the radiation source specified in Section 5.2. The build-up factor for iron (Fe) is used.

The gamma fluxes are converted to dose rates with the photon conversion factors calculated using the tables in ICRP Pub.74. The dose rates calculated during routine conditions of transport are provided in Table 5-1.

5.4.2 Normal Conditions of transport (NOC)

The dose rates under NOC were calculated in the same manner described for routine conditions of transport. The dose rates calculated are provided in Table 5-1.

5.5 References

5.5.1 Y.Harima et al., "Validity of the Geometric-Progression Formula in Approximating Gamma-Ray Buildup Factors,"Nucl.Sci.Eng.94, 24-35(1986).

5.5.2 Y.Sakamoto and S.Tanaka, "QAD-CGGP2 and G33-GP2: Revised versions of QAD-CGGP and G33-GP Codes with Conversion Factors from Exposure to Ambient and Maximum Dose Equivalents," JAERI-M 90-110,Japan Atomic Energy Research Institute (1990).

5.5.3 Y.Sakamoto et al., "Shielding Calculation Constants for use in effective dose evaluation of photons, neutrons and bremsstrahlung from beta-ray, "JAERI-Date/Code 2000-044,Japan Atomic Energy Research Institute (2000).

Table 5-1 Shielding Analysis Results and Acceptance Criteria

Condition	Dose Point	Calculated Dose Rates (mSv /hr)	Acceptance Criteria (mSv /hr)
During Routine Transport	External surface of the package at the axial midpoint at the parting plane	0.017	< 2.0
	External surface of the package at the center of the end plate	**0.024**	**< 2.0**
	One meter (1m) from the external surface of the package at the axial midpoint at the parting plane	**0.0041**	**< 0.1**
	One meter (1m) from the external surface of the package at the center of the end plate	0.0024	< 0.1
Under NOC	External surface of the package at the axial midpoint at the parting plane	0.020	< 2.0
	External surface of the package at the center of the end plate	**0.028**	**< 2.0**

Table 5-2 Shielding Source Term

Radio-nuclides	Source based on ASTM C-996, wt%	Total Maximum Source (Bq)
^{232}U	1.00×10^{-8}	1.11×10^{8}
^{234}U	5.50×10^{-2}	1.96×10^{11}
^{235}U	5.00×10^{0}	6.16×10^{9}
^{236}U	2.50×10^{-2}	9.22×10^{8}
^{238}U	94.92×10^{0}	1.82×10^{10}
^{99}Tc	1.00×10^{-6}	9.66×10^{6}
^{231}Th	---	6.16×10^{9}
^{234}Th	---	1.82×10^{10}
^{234m}Pa	---	1.82×10^{10}
Total	100.00	**2.65×10^{11}**

Table 5-3 Energy Spectrum of Gamma-ray

Gamma-ray Energy (MeV)	Photons (photons/sec/gU)
0.010	2.90×10^{4}
0.025	1.91×10^{3}
0.0375	8.59×10^{2}
0.0575	1.91×10^{3}
0.085	2.23×10^{3}
0.125	1.22×10^{3}
0.225	2.92×10^{3}
0.375	3.09×10^{2}
0.575	1.91×10^{2}
0.850	1.19×10^{2}
1.25	7.55×10^{1}
1.75	1.40×10^{1}
2.25	5.50×10^{-3}
2.75	2.46×10^{1}
3.50	1.73×10^{-3}
5.00	7.39×10^{-4}
7.00	8.48×10^{-5}
9.50	9.73×10^{-6}

Table 5-4 Composition and Atomic Number Densities

Region	Actual Composition	Modeled Material Density, g/cm^3	Modeled Composition	Atomic Number Density, atoms/barn-cm	Remarks
Radiation Source	UF_6	2.72	Uranium Fluoride	4.66×10^{-3} 2.79×10^{-2}	Distributed homogeneously in the cylinder
Cylinder wall	Steel	7.6	Iron	8.23×10^{-2}	N/A
Overpack wall	Steel/foam	N/A	Void	N/A	Conservatively neglected

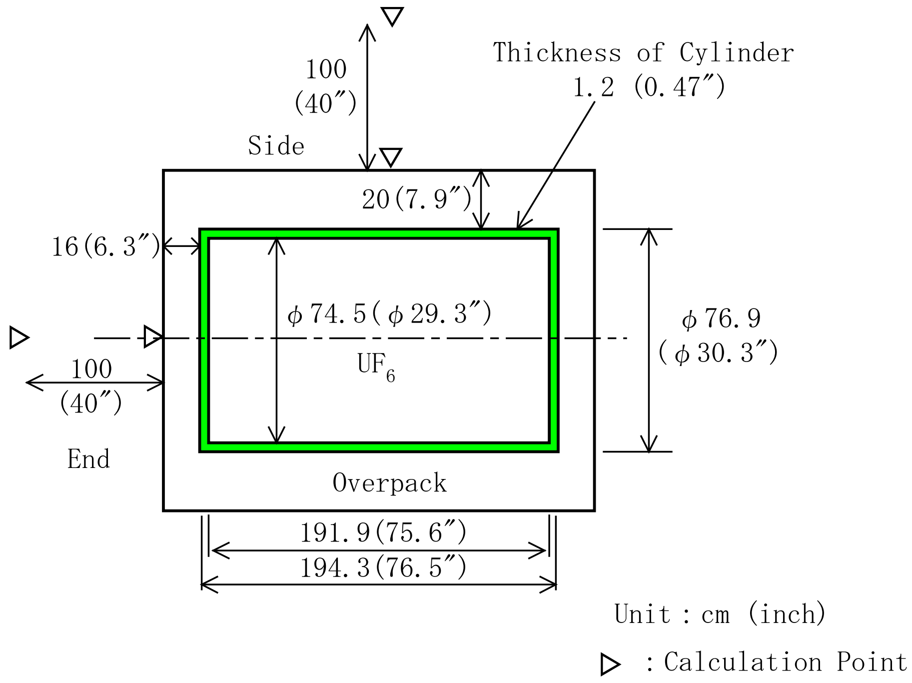

Figure 5- 1 Schematic of Shielding Model during Routine Transport

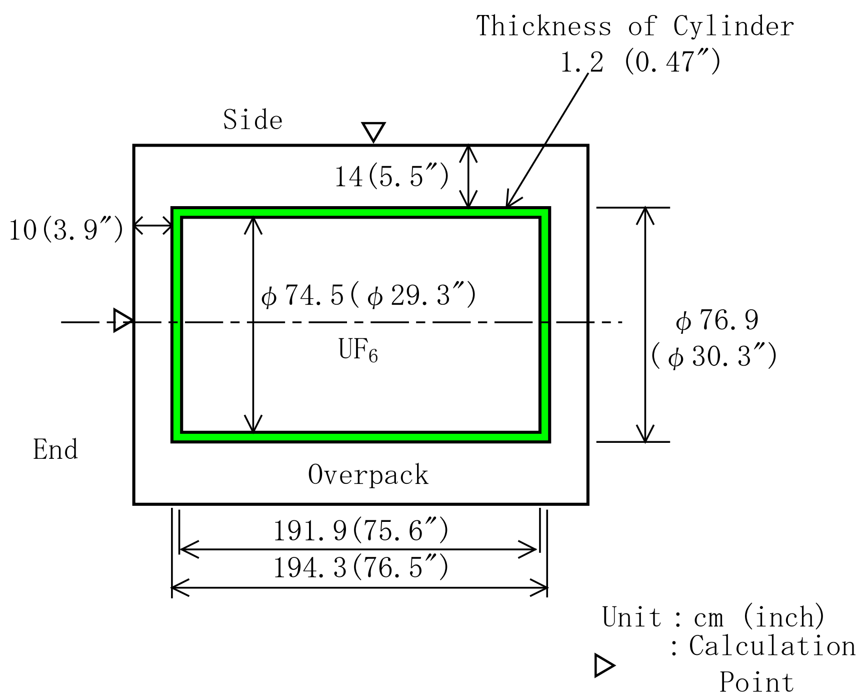

Figure 5- 2 Schematic of Shielding Model under NOC

SECTION 6 CRITICALITY EVALUATION

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6.0 CRITICALITY EVALUATION

The MST-30 Protective Shipping Package (MST-30) is a Type A, Fissile Material and Uranium Hexafluoride (UF_6) Package used for the shipment of 30-inch cylinders containing Uranium Hexafluoride (UF_6) enriched up to 5 wt% ^{235}U. The package is designed to conform to the technical and regulatory requirements as specified in the Japanese Safe Transport Regulations pursuant to the SSR-6. The package is intended to be used for transport from, to, or through foreign countries, including the USA. The MST-30 package is also designed in compliance with the current 10CFR Part 71 and 49CFR Part 173 Subpart I.

The MST-30 package was approved by the Japanese Authority and certified as a Type A Fissile UF_6 Package. A copy of the NRA Certificate in English is provided in Appendix 1.3.1. Drawings of the package are available in Appendix 1.3.2 and 1.3.3.

The MST-30 has been rigorously tested according to the regulatory requirements to assure water leak-tightness of the UF_6 cylinder. UF_6 is not only a radioactive material but also a toxic and corrosive material, classified into Class 6 / Division 6.1 and Class 8 of the United Nations (UN) Recommendations on the Transport of Dangerous Goods (Para. 110 of SSR-6). UF_6 rapidly reacts in the presence of water, even the low percentage of water vapor present in the air. When exposed to moisture, UF_6 generates hydrogen fluoride (HF), which has the potential to cause serious damage to people and vegetation (Para. 507 of SSR-6). Additionally, inleakage of water may compromise criticality control. Therefore, the primary goal for the design of the MST-30 was to assure water leak-tightness of package under the severest of conditions. The exacting and comprehensive test program completely confirms that the design of the MST-30 maintains water leak-tightness of the cylinder under all regulatory conditions.

6.1 Discussion and Result

In evaluating the nuclear safety (criticality safety) of a Fissile Material Package, the following six (6) cases shall be evaluated in accordance with the Japanese ("JPN" for short) relevant regulations pursuant to SSR-6:

Namely,
- (A) Packages in routine conditions of transport;
- (B) Individual package in isolation;
- (C) Individual package under NOC in isolation;
- (D) Individual package under HAC in isolation;
- (E) Package arrays under NOC;
- (F) Package arrays under HAC.

As previously described in the structural, thermal and containment evaluations, the overpack was deformed and damaged under both NOC and HAC, but the 30B cylinder kept its integrity (i.e., containment-ability and geometry). Therefore, it came to the conclusion that there would be no possibility of water leakage into the cylinder at all.

Accordingly, in this evaluation, it was assumed that water did not leak into the cylinder, and the damaged overpack and ring plate outside the cylinder was replaced with a water layer in the analysis model. On this assumption, a thickness of water layer was determined so as to increase the effective neutron multiplication factor of the package to the maximum. Based on such a condition that neutrons were closely reflected at the external boundary of water layer around any circular cylinders, it was assumed in the evaluation that any number of packages was arranged in an arbitrary configuration. In conducting the criticality evaluation of this package, the effective neutron multiplication factors were calculated using the SCALE Code System developed by Oak Ridge National Laboratory (ORNL).

As a result of the evaluation, it was confirmed that the criticality safety (sub-criticality) of this package remains sufficient under any conditions of transport including both NOC and HAC.

6.2 Object for Analysis

6.2.1 Contents of Package

Since the content contained in this packaging is unirradiated uranium hexafluoride (UF_6), burn-up and fission products are not taken into consideration. In addition, the contents do not contain any burnable poison. The authorized maximum loading quantity of UF_6 to be contained in the package is 2,277 kg. The UF_6 purity is more than 99.5 % and the maximum enrichment of the UF_6 is 5.0 wt.% ^{235}U. Since the structural, thermal and containment evaluations concluded that the containment-ability of 30B cylinder was maintained, no change of the contents was taken into consideration.

6.2.2 Packaging

This packaging is composed of an overpack, a 30B cylinder and a ring plate. The overpack is a horizontal right cylindrical container which is separated into top (upper) and bottom (lower) halves, and comprises a space for loading the cylinder horizontally. The annulus between the outer and inner stainless steel shells is filled with a shock-absorbent material and a thermal insulator. As a result of the structural and thermal evaluation, the overpack experienced a little deformation and damage cumulatively under both NOC and HAC.

30B cylinder is a right cylindrical container made of carbon steel. As a result of the structural evaluation, it was shown that, except for the horizontal puncture drop, there was no notable deformation on the cylinder and the cylinder maintained its integrity. In the horizontal puncture drop, the deformation of the overpack reached the cylinder, but the cylinder’s deformation was small and limited to the impacted area of the cylindrical part. Even so, the containment-ability of the cylinder was maintained. As a result of the thermal analysis, even if the cylinder filled with the contents (UF_6) experienced a thermal effect, the containment-ability was maintained.

6.2.3 Neutron Absorber

This packaging does not use any neutron absorber.

6.3 Model Specification

6.3.1 Analysis Model

As previously described in 6.1, there are six (6) cases of criticality analysis models to be evaluated in accordance with the JPN relevant regulations pursuant to SSR-6. Namely,

- Case (A) : Packages in routine conditions of transport;
- Case (B) : Individual package in isolation;
- Case (C) : Individual package under NOC in isolation;
- Case (D) : Individual package under HAC in isolation;
- Case (E) : Package arrays under NOC;
- Case (F) : Package arrays under HAC.

Sub-criticality of Case (F) was evaluated as a representative case that may result in the severest condition in the criticality analyses. The bases for selecting Case (F) are described below.

- It is assumed that water leaks into the damaged overpack of the package under HAC. Accordingly, water leakage into the overpack is assumed to occur, both for package in isolation and packages in array. Under this condition, packages in array are severer than package in isolation due to a mutual interference effect of neutrons between the neighboring packages.

- Regardless of isolation or array configuration, under HAC it is considered that water leaks into the overpack and forms a water layer closest to the fuel region of the package. Therefore, due to the moderation effect of the water layer, the criticality evaluation of the packages is severer under HAC than in routine conditions of transport.

The model used in the criticality analysis is constructed based on the following thoughts:

This fissile material package is composed of the 30B cylinder containing low-enriched UF_6, the overpack to package the cylinder, and the ring plate. As stated in the structural, thermal and containment evaluations, the cylinder almost does not deform and maintains its containment-ability after subjected to NOC and HAC. Accordingly, it was assumed in this evaluation that water did not leak into the cylinder. The configuration of the cylinder for the analysis model is assumed to be a right cylinder enveloping the fuel region. The outside diameter and length of the right cylinder were determined to be 76.9 cm and 194.3 cm respectively as a maximum dimension, taking the manufacturing tolerance into consideration. As shown in Section 6.7.1.1, the effective neutron multiplication factor tends to increase as the wall thickness of the cylinder decreases. Therefore, the wall thickness of the cylinder was

determined to be 1.1 cm at all the part thereof, which is the lower control limit described in Section 8. No overpack and no ring plate were assumed to exist around the cylinder, as previously described. A water layer was assumed to exist around the cylinder and the thickness of this water layer was determined so as to increase the effective neutron multiplication factor to the maximum. Considering that neutrons are completely reflected at the external boundary of water layer around any circular cylinders, the model assumes a configuration of an infinite number of packages.

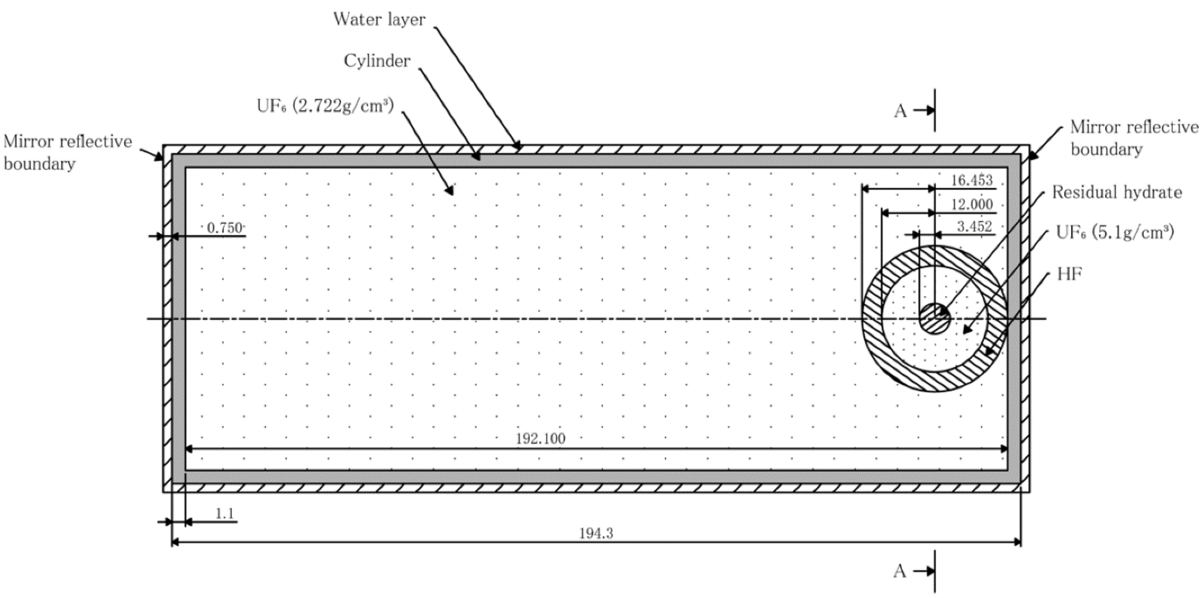
It was assumed that the purity of UF_6 to be filled in the cylinder was 99.5%. In addition, all the impurities contained in the UF_6 (equivalent to 0.5% of the content weight in maximum) are modeled as hydrogen fluoride (hereafter HF) so as to evaluate hydrogen (H) concentration conservatively. As shown in Section 6.7.1.4, the effective neutron multiplication factor of the package may become larger when considering an uneven distribution of impurities, therefore uneven distribution of HF was considered in the analysis.

As shown in Section 7, the cylinder is repeatedly used after withdrawal of UF_6, once the interior of the cylinder has been cleaned and dried. Although the interior of the cylinder is fully cleaned, a small amount of UO_2F_2 hydrates generated by hydrolysis of UF_6 may remain and could be considered as additional moderators. Therefore, the effect of the UO_2F_2 hydrate remaining in the cylinder (hereafter residual hydrate) was also taken into account in this evaluation.

In the criticality analysis model, severer conditions were assumed by considering uneven distribution of the impurities contained in UF_6 and the residual hydrate at the same time.

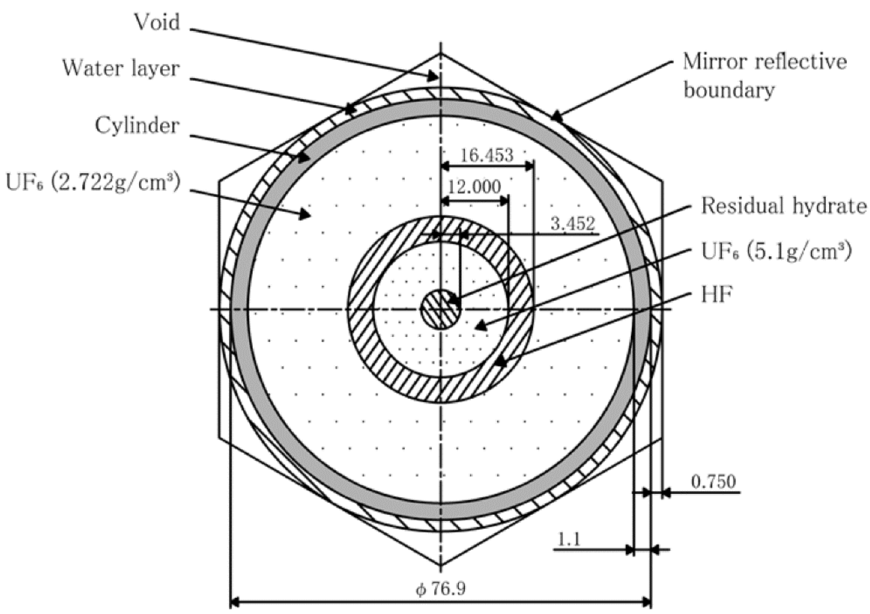
Based on the above descriptions, the criticality analysis model is shown in Figure 6-1. The model assumes the presence of unevenly distributed impurities and residual hydrate in the UF_6 filling the cylinder. These unevenly distributed elements are modelled as three spherical layers, which are as follows: residual hydrate (UO_2F_2-5.5H_2O) of 300 gU in the center, unevenly distributed UF_6 with a density of 5.1 g/cm^3 around the residual hydrate, and unevenly distributed impurities (HF) around the UF_6. The total mass of UF_6 in the cylinder was assumed as the authorized maximum loading quantity, i.e. 2,277 kg. The severest conditions were selected based on sensitivity analyses for the following parameters: the dimensions of UF_6 and HF which are unevenly distributed around the residual hydrate, the density of UF_6 filled in the interior of the cylinder, and the thickness of water layer around the cylinder. The details considered in determining the analysis model are described in Section 6.7.1.1 to 6.7.1.6.

In this analysis, the existence of the overpack and the ring plate is ignored, however the evaluation in consideration of the existence of the overpack is described in Section 6.7.1.7.



(Unit: cm)

Figure 6-1(a) Criticality Analysis Model (axial direction)



(Unit: cm)

Figure 6-1(b) Criticality Analysis Model (A-A cross section in radial direction)

6.3.2 Atomic Number Density of Each Region for Analysis Model

This analysis model consists of UF_6, unevenly distributed materials, the cylinder and water. Unevenly distributed materials consist of three (3) regions, which are the residual hydrates in the center, surrounded by the unevenly distributed UF_6 which is itself surrounded by the impurities contained in UF_6 (i.e., HF). The atomic number densities of each region used for the evaluation are shown in Table 6-1. Since the cylinder is made of carbon steel, the content of the carbon(C), which has a moderation effect, was assumed to be 0.3% in maximum. All the impurities except the carbon(C) were conservatively assumed to be iron (Fe).

Table 6-1 Atomic Number Densities of Each Region

Region		Element or Radio-nuclide	Atomic Number Densities (atoms/barn・cm)	Remarks
UF_6		^{235}U ^{238}U F	2.36×10^{-4} 4.42×10^{-3} 2.80×10^{-2}	Density: 2.722 g/cm^3 Enrichment: 5.0 wt.%
Unevenly distributed materials	Residual hydrate	^{235}U ^{238}U O H F	2.23×10^{-4} 4.19×10^{-3} 3.34×10^{-2} 4.91×10^{-2} 8.82×10^{-3}	UO_2F_2-5.5H_2O, 300 gU was assumed to remain
	UF_6	^{235}U ^{238}U F	4.42×10^{-4} 8.29×10^{-3} 5.24×10^{-2}	Density: 5.1 g/cm^3 Enrichment: 5.0 wt.%
	HF	H F	3.02×10^{-2} 3.02×10^{-2}	All the impurities contained in UF_6 were assumed as HF
Cylinder		C Fe	1.06×10^{-3} 8.39×10^{-2}	Density: 7.8 g/cm^3
Water		H O	6.69×10^{-2} 3.34×10^{-2}	Density: 1.0 g/cm^3

6.4 Criticality Calculation

6.4.1 Calculation Conditions

(1) Contents (UF_6):

- The enrichment of uranium (U) was assumed to be 5 wt.% ^{235}U at a maximum. The existence of uranium isotopes other than ^{238}U, which has the effect of neutron absorption, was neglected.
- The mass of UF_6 was assumed to be the authorized maximum loading quantity, i.e. 2,277 kg.
- All the impurities contained in UF_6 were assumed to be HF in order that the concentration of hydrogen (H) in the cylinder could be estimated as high as possible, and uneven distribution inside the cylinder were also taken into account.
- The existence of residual hydrates in the cylinder was taken into account.

(2) Packaging:

It was assumed that no overpack and no ring plate existed around the cylinder, and that a water layer existed around the cylinder in place of the overpack. The thickness of water layer was determined in order to increase the effective neutron multiplication factor to maximum. Thus, the criticality evaluation of this package was conducted conservatively.

6.4.2 Water Leakage into Packages

(1) Water leakage into or out of packages:

As for water leaking into the packages, taking into account the overpack being damaged and immersed by water, the existence of the overpack and the ring plate was ignored and replaced with a water layer in the analysis model. In addition, the structural and thermal evaluations showed that the containment-ability of 30B cylinder was maintained. Thus, water leaking into the cylinder was not taken into account in the analysis. In order to conservatively estimate the concentration of hydrogen in the cylinder, all the impurities contained in UF_6 were assumed as HF, and the existence of residual hydrates in the cylinder was taken into account in the evaluation. The evaluation for water leaking out of the packages was not applicable to this analysis.

(2) Reduction of spaces between the packages due to changes in the arrangement of packages:

As mentioned in (1) above, in the analysis, the existence of the overpack and the ring plate was ignored and replaced by a water layer. In addition, neutrons were assumed to be closely and completely reflected at the external boundary of the water layer around any circular cylinder. Since this assumption means that any number of packages (infinite number of packages) are arranged closest to one another, the effective neutron multiplication factor does not increase due to reduction of spaces between the packages or the radioactive contents (UF_6).

(3) Possible rearrangement of the radioactive contents:

This analysis was conducted on such an assumption that the shape, the arrangement of UF_6, the impurities contained in UF_6, and the residual hydrates in the cylinder were properly taken into account so that the effective neutron multiplication factor of the package would increase to maximum (See Section 6.7.1.2, 4, 5 and 6).

(4) Packages becoming immersed in water or buried in snow:

Since it was assumed in the analysis that the overpack and the ring plate were replaced by an arbitrary thickness of water layer and that the water thickness is optimized to maximize the effective neutron multiplication factor, the effective neutron multiplication factor would not increase due to immersion of the packages in water or snow.

(5) Possible effects of temperature changes:

Since in the analysis model the overpack and the ring plate were replaced by an arbitrary thickness of water layer and the water thickness is optimized to maximize the effective neutron multiplication factor, the changes of water density due to temperature changes do not need to be considered.

6.4.3 Calculation Procedures

The sub-criticality calculation of this package was conducted using the SCALE Code System developed by Oak Ridge National Laboratory (ORNL) (See: Appendix 6.7.2 "Summary of analysis code "SCALE"" attached hereto). The SCALE code system consists of the Resonance Calculation Code BONAMI, CENTRM, PMC, and Criticality Analysis Code KENO-VI, etc. The reliability and validity of the SCALE Code system used in this evaluation was verified by benchmark calculations employing a large amount of criticality experimental data.

The flow of the criticality calculation is shown in Figure 6-2. The macroscopic-cross sections for nuclear reaction (238 energy groups) were produced by BONAMI, CENTRM, and PMC

codes using ENDF/B-VII library based on the atomic number densities for UF_6, cylinder and water. The effective neutron multiplication factor of the packages was calculated by the KENO-VI code using the macroscopic-cross sections.

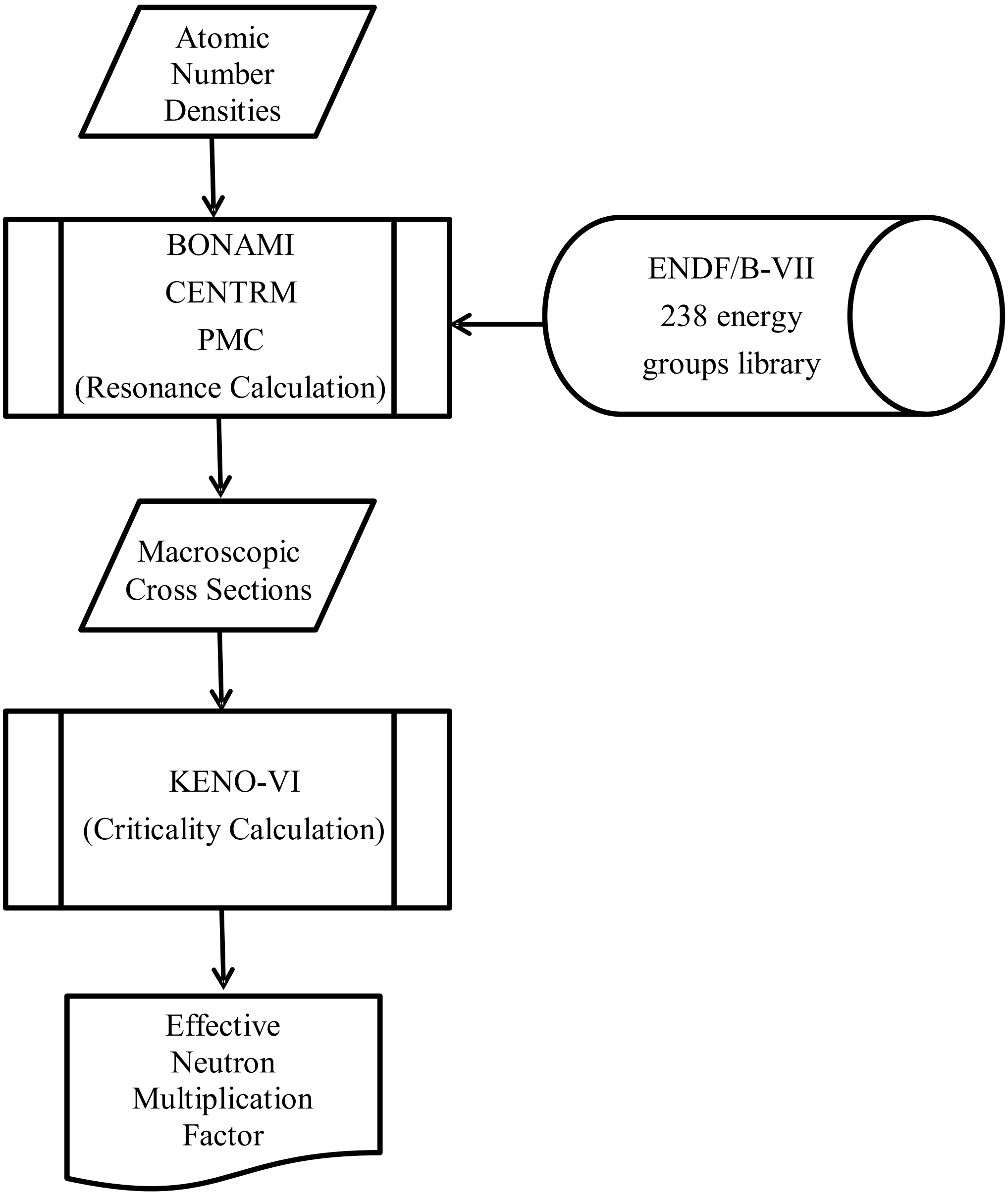


Figure 6-2 Flow of Criticality Calculation for the Packages

6.4.4 Results of Criticality Calculation

As shown in Figure 6-1, by taking into account the uneven distribution of impurities contained in UF_6 and residual hydrates, the effective neutron multiplication factors for the severest conditions in criticality analysis were calculated by replacing the overpack and the ring plate outside the cylinder with a water layer.

The result of the effective neutron multiplication factor is shown in Table 6-2. The effective neutron multiplication factor becomes maximum under the condition shown in Figure 6-1. The effective neutron multiplication factor to which three (3) times the standard deviation was added (i.e. $K_{eff} + 3\sigma$) was 0.949.

Table 6-2 Calculation Results of Effective Neutron Multiplication Factor

	$K_{eff} + 3\sigma$	σ
Effective Neutron Multiplication Factor	0.949	< 0.001

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Proprietary Information Withheld Pursuant to 49 CFR 7.14, 49 CFR 105.30, and 10 CFR 2.390

6.6 Summary of Analysis Results and the Evaluation

In this criticality evaluation, the sub-criticality was evaluated for package arrays under HAC, which would be the severest condition in nuclear safety (criticality safety). The analysis model is based on the results of the structural evaluation, thermal evaluation and containment evaluation under both NOC and HAC. As a result of the evaluation, even if three (3) times the standard deviation (3σ) is added, the effective neutron multiplication factor (keff+3σ) is 0.949.

Therefore, it comes to the conclusion that this package is fully sub-critical in any transport conditions including both NOC and HAC.

In this analysis, the overpack and the ring plate were ignored, and the cylinders were set adjacent to each other. As shown in Section 6.7.1.7, the maximum effective multiplication factor (keff+3σ) was 0.934 when the cylinders were set adjacent to each other taking the presence of the overpack into account but ignoring the presence of the overpack materials, and was 0.857 when the stainless steel plate in the outer and inner shells of the overpack was taken into account. According to the Section 6.7.1.7, the analysis result for this package shown above (keff+3σ = 0.949) was based on safety assumptions and the package had sufficient safety margin for subcriticality maintenance.

6.7 Appendices

6.7.1 Sensitivity analysis on the modeling conditions of criticality evaluation

6.7.1.1 Parametric evaluation of the wall thickness of the cylinder
6.7.1.2 Parametric evaluation of UF_6 configuration and mass
6.7.1.3 Parametric evaluation of air moisture inleakage into the cylinder
6.7.1.4 Parametric evaluation of the uneven distribution of impurities contained in UF_6
6.7.1.5 Parametric evaluation of the hydrate remaining in the cylinder
6.7.1.6 Combined effect of the uneven distribution of residual hydrates and impurities contained in UF_6
6.7.1.7 Evaluation taking into account the presence of the overpack

6.7.2 Summary of analysis code "SCALE"

6.8 References

6.8.1 PATRAM 2016 Paper No.2029, "Hydration of uranium residues contained in enriched UF_6 cylinders", Mathieu Milin, et. al.

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Sensitivity analysis on the modeling conditions of criticality evaluation

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Appendix 6.7.2

Summary of analysis code "SCALE"

Summary of analysis code "SCALE"

1. Outline of SCALE

SCALE is a calculation code system developed by Oak Ridge National Laboratory (ORNL) for assessment by U.S. Nuclear Regulatory Commission (NRC). It includes the evaluation code for criticality and shielding analysis.

SCALE code system is currently under modification. In this criticality safety evaluation, SCALE 6.0 code system with CSAS6 module is used.

1.1 BONAMI

BONAMI code is used for the generation of cross section data in the fast neutron energy region which includes unresolved resonance range. The cross section data is used for the calculation of multi-group neutron energy spectra in CENTRM code.

1.2 CENTRM

CENTRM code is developed for the purpose of accuracy enhancement of resonance calculation in the resolved resonance energy range. It evaluates continuous energy neutron spectra by solving Boltzmann transport equation using pointwise cross section data.

1.3 PMC

PMC generates cross section set used in the calculation by KENO-VI, which is collapsed to energy group structure of multi-group cross section libraries by utilizing continuous energy neutron spectra including resolved resonance range produced by CENTRM.

1.4 KENO-VI

KENO-VI is a three-dimensional multi-group Monte Carlo criticality calculation code developed by Oak Ridge National Laboratory. It can evaluate the effective multiplication factor under complex geometric system.

This code evaluates the history of neutron range using the decrease in probabilistic weight of a neutron which depends on the absorption rate. The extinction of neutron is determined by

Russian roulette when the weight of a neutron becomes less than the certain value. The effective multiplication factor is calculated from the following equation.

$$\frac{\sum_{j=1}^{NPB} \sum_{i=1}^{NCOLL} WTij \frac{\nu \Sigma f}{\Sigma t}}{\sum_{j=1}^{NPB} WToj}$$

where,

NPB : number of neutrons produced per batch

NCOLL : number of neutron collisions

WTij : neutron weight at the time of fission

WToj : initial weight of a neutron

ν : number of neutrons produced per fission

Σf : macroscopic fission cross section

Σt : macroscopic total cross section

SECTION 7 OPERATING PROCEDURES

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LIST OF FIGURE

7.0 OPERATING PROCEDURES

The MST-30 overpack is loaded and unloaded and the 30B UF_6 cylinder is filled, tested, and handled in accordance with standard, in-plant operating procedures at various enrichment plants and at various nuclear fuel facilities. The basic procedural requirements are described in USEC-651 and ANSI Standard N14.1. As a minimum, the specific procedures include steps described in the subsequent sections.

7.1 Procedures for Loading the Package

7.1.1 Receipt and Filling of 30B Cylinder

Receipt and filling of the 30B cylinder shall be performed in accordance with in-plant operating procedures at the facility and ANSI N14.1.

7.1.2 Cylinder Inspection

Complete an inspection of the 30B cylinder per USEC-651 or equivalent in-plant procedures and ANSI N14.1 prior to insertion into the MST-30 overpack. Any defective conditions must be corrected and the cylinder must be re-certified prior to use.

7.1.3 Overpack Inspection

The user shall establish and implement written procedures to inspect the MST-30 overpack and the ring plate prior to each use to assure the following (See: Figure 7-1 and Figure 7-2):

(a) The overpack legs and supports are sound with no broken welds or components.

(b) The overpack inner and outer shells are intact with no broken welds and no holes, tears, or excessive abrasions.

(c) The inner liner is free of debris and standing water.

(d) The inner liner is intact and is not in a deteriorated or damaged condition.

(e) The gaskets and cylinder support pads are in place and intact and are not in a deteriorated or damaged condition.

(f) The gasket surfaces are free from nicks and deep scratches.

(g) The inner and outer shell plates (cover plates) and welds are sound and undamaged.

(h) The overpack halves fit together properly with no gaps.

(i) The fastening devices are undamaged.

(j) All vent ports are sound and undamaged.

(k) The tie-down and lifting supports are in place and are not in a deteriorated or damaged condition.

(l) The shackles are in place and are not in a deteriorated or damaged condition.

(m) The tamper proof feature (security seal apparatus) is undamaged.

(n) The ring plate is intact with no crack and no excessive deformation.

Following the inspection, an inspection report shall be completed verifying that the overpack is free from damage and is in working order. Any defective condition must be corrected and the overpack must be re-certified prior to use.

7.1.4 Procedure for Loading the 30B Cylinder

The MST-30 overpack is loaded and unloaded and the 30B cylinder is filled, tested, and handled in accordance with standard, in-plant operating procedural requirements at the facility and ANSI Standard N14.1. The type of plug allowed for the 30B cylinder loaded in the MST-30 overpack is a socket head plug only. The use of a hex head plug is not allowed in the case of MST-30.

The cylinder into which UF_6 is loaded shall be a clean and washed out cylinder. Loading of UF_6 into an uncleaned cylinder after withdrawal of UF_6 shall not be conducted.

Leak-tightness of the UF_6 filled cylinder shall have been previously verified using a test having a sensitivity of at least 1×10^{-3} ref-cc/sec.

Prior to loading of UF_6 filled cylinder into the MST-30 Overpack, the cylinder contents shall be verified to be solidified. Since the internal pressure of the cylinder depends on the vapor pressure of UF_6, the internal pressure of cylinder is inevitably below the atmospheric pressure during transport.

Prior to loading into the MST-30 Overpack, the valve port and valve boss/coupling shall be inspected for solid deposits. Solid deposits around the valve port or valve boss/coupling indicate a leak condition, and the cylinder shall not be loaded into the overpack. Corrective measure shall be taken to remedy the leak as prescribed by the facility's operating procedures. If the valve port and valve boss/coupling are free of solid deposits, the cylinder may be loaded into the MST-30 Overpack.

7.1.5 Procedure for Loading the MST-30 Overpack

(a) The inspection required by Section 7.1.2 shall be performed and documented prior to loading a 30B cylinder into the overpack.

(b) Carefully lift the 30B cylinder horizontally, directing the cylinder-valve toward the inner shell of the wall end of the bottom half on which step-joint the cylinder positioning device is installed. Then, carefully load the cylinder into the bottom half with the cylinder-valve positioned up at one (1) o'clock position. Then, securely insert the pin of cylinder positioning device into the hole of cylinder-skirt; otherwise the top half (lid) is prevented from proper seating and closure due to contact with the pin of positioning device located on the bottom half.

(c) Insert a ring plate into the gap on the plug side between the overpack and the 30B cylinder.

(d) Carefully place the top half on the bottom half of overpack.

(e) Tighten all fastening devices alternating first corner-to-corner (4 devices) followed by side-to-side (6 devices).

(f) Install tamper-proof seals and record their numbers.

(g) Complete radiation survey and assign Transport Index as per applicable regulations.

(h) Remove old labels and re-label following the applicable regulations.

7.2 Procedures for Unloading the Package

7.2.1 Procedure for Unloading the MST-30 Overpack (See: Figure 7-1)

(a) Visually inspect the exterior of overpack as possible for damage using the steps provided in Section 7.1.3 (a), (b), (g), (h), (i), (j), (k), (l) and (m). Document any damage observed. Complete receiving report as required by the facility's operating procedures.

(b) Remove and record the overpack tamper-proof seals.

(c) Loosen all fastening devices.

(d) Remove the upper half of overpack. Then, remove the cylinder positioning device from the hole of cylinder-skirt.

(e) Remove the ring plate from the overpack.

(f) Remove the cylinder from the overpack.

(g) Clean any loose debris from the interior of overpack.

(h) Close the overpack prior to storage.

7.2.2 Procedure for Unloading the 30B Cylinder

(a) Prior to unloading the cylinder, the cylinder shall be visually inspected and weighed in accordance with requirements at the facility. At the MNF facility, weighing shall be conducted in the presence of authorized inspector of the Japan Maritime Inspection Institute as a witness as required by the facility's operating procedures (prepared by MNF based on USEC-651).

(b) The 30B UF_6 cylinder is emptied and handled in accordance with the standard and in plant operating procedures at the facility.

7.3 Shipment of Empty Packages

In principle, all empty cylinders to be shipped from the MNF facility must be loaded into the overpack so as to protect the cylinder, valve and skirt from damage and/or deformation during transport.

7.3.1 Preparation of an Empty Cylinder for Shipment

(a) Prior to the shipment of each empty cylinder, the interior of the empty cylinder shall be completely washed out.

(b) Load the cylinder into the MST-30 using the procedure provided in Section 7.1.5.

(c) Insert the ring plate into the overpack using the procedure provided in Section 7.1.5.

(d) Survey radiation level on the external surface of the overpack. The radiation level on any external surface of the overpack may not exceed 5 μSv/hr. If the radiation level exceeds 5μSv/hr, then the empty cylinder once loaded into the overpack shall be unloaded therefrom and may not be used for shipment until the radiation level of the cylinder is reduced sufficiently.

(e) Remove old labels and re-label as per applicable regulations. Washed empty cylinders may be shipped as a Type L Package, which is a package category specified in JPN transport regulations and corresponds to Excepted Package specified in SSR-6, in Japan. In other countries including USA, it may be shipped as an Excepted Package or other package type which is complied with regulations in each country.

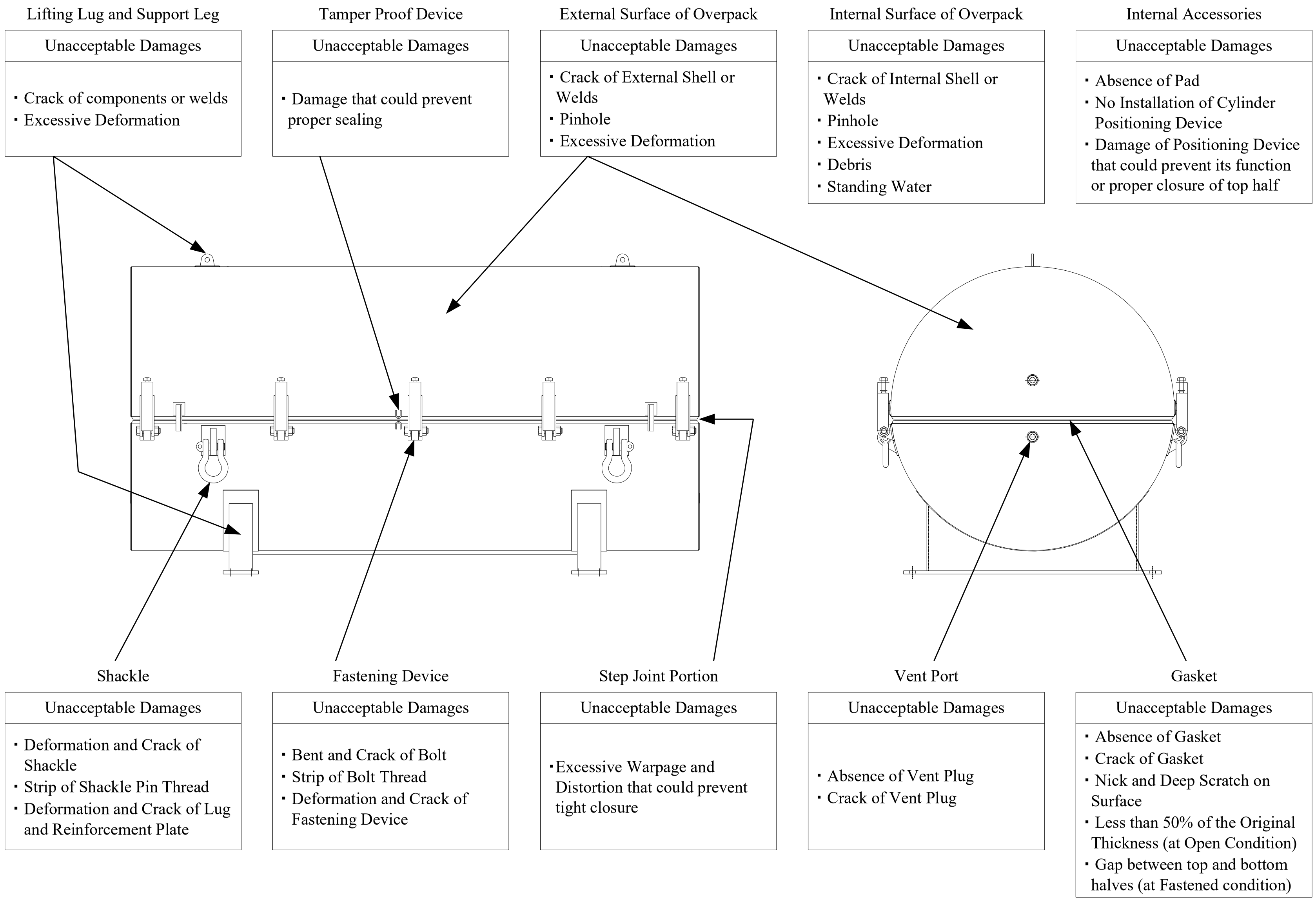

Figure 7-1 Visual Inspection Criteria of MST-30 Overpack

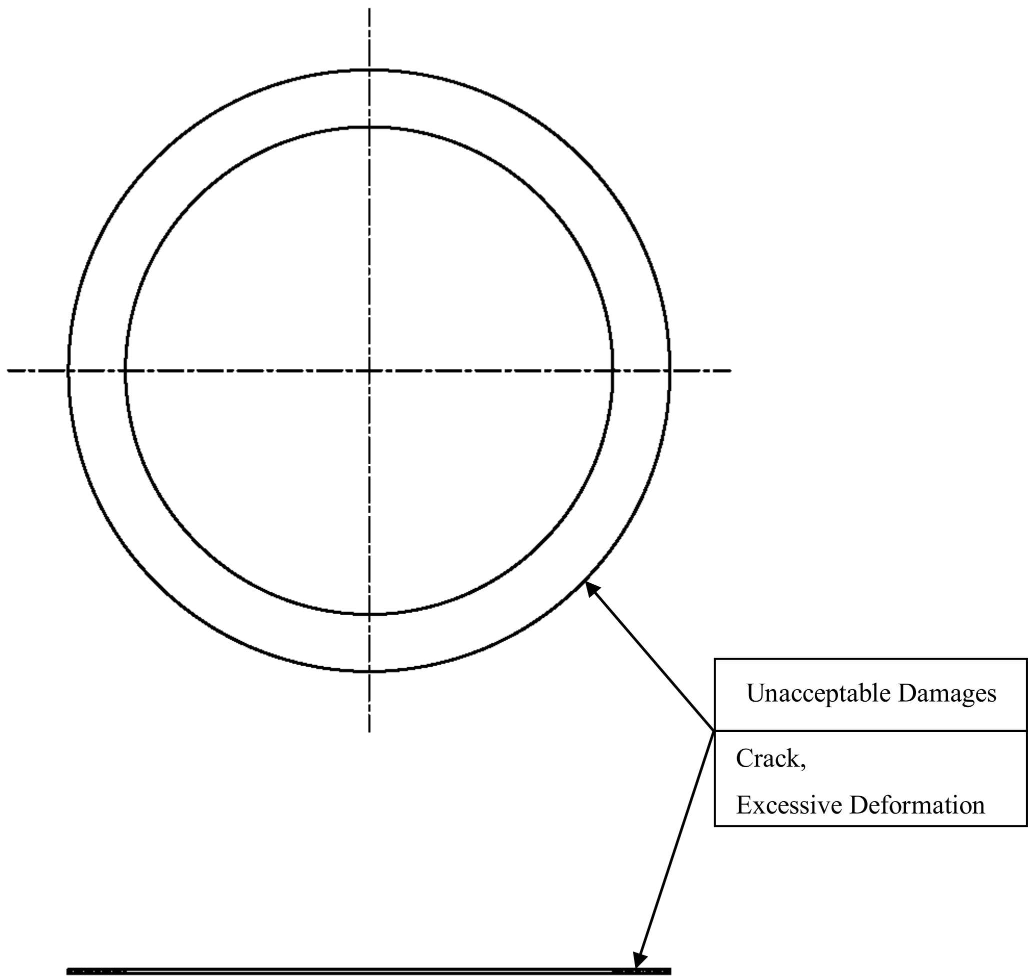

Figure 7-2 Visual Inspection Criteria of Ring Plate

SECTION 8 ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

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8.0 ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

This section describes the activities to be performed in compliance with the provisions for both Application Arrangement of Packaging Approval and Package Inspection prior to Each Shipment specified in the JPN transport regulations to assure that the MST-30 package conforms to the requirements of this Safety Analysis Report.

8.1 Acceptance Tests

8.1.1 Acceptance Tests for the MST-30 Overpack

Each overpack shall be inspected at the time of fabrication to document compliance with the following drawing requirements:

(a) Installation of gaskets and cylinder support pads.

(b) Lid (Top Half of the Overpack) to cylinder-body fit.

(c) Fastening device fit-up and operability.

(d) Installation of lifting shackles and tamper-proof seal lugs.

(e) Actual weights of the top and bottom half.

(f) Visual inspection of all welds.

(g) Visual verification of no cracks or defects on the packaging that could reduce its effectiveness.

(h) Proper permanent marking and nameplates per 10 CFR §71.85 (c), 49 CFR Part 172 as well as the relative provisions of the JPN transport regulations and ANSI N14.1 or ISO 7195 (latest revision).

8.1.2 Acceptance Tests for the Cylinder

Acceptance tests for the 30B cylinder at the time of fabrication shall be performed in accordance with the latest version of ANSI N14.1 or ISO 7195 at the time. As a minimum the following tests shall be completed:

(a) Hydrostatic Pressure Test of Cylinder-Body and Plug

The initial hydrostatic test pressure of each cylinder installed with plug is 2.76MPa (400psig). The pressure is then lowered to 2.07MPa(300psig) while the cylinder is inspected for leaks. No leaks are permitted.

(b) Air Leak-Tightness Test of Cylinder-Valve

The seat and stem, cap and packing nut of each cylinder-valve are bench-tested for seat leakage at 2.76MPa (400psig) using bubble bottle, by striking bubble across the face of the valve outlet, or immersing the valve in water. No leaks are permitted

(c) Air Leak-Tightness Test of Cylinder installed with Valve and Plug

Each cylinder installed with the valve and plug is air-tested at 690kPa(100psig). All connections and fittings (including the valve seat and packing) are leak-tested using Carbona soapless lather or an approved equivalent. No leaks are permitted.

(d) X-ray Examination for Cylinder

A minimum of one spot X-ray examination for each cylinder shall be required in accordance with Section UW-52 of the ANSI/ASME Code using a fine-grain X-ray film (Kodak Type AA, or a purchaser-approved equivalent). Unless otherwise directed by the ASME Code inspector, the locations of the spot shall be at the juncture of the longitudinal seam and the circumferential head weld, alternating ends for successive cylinders. The weld imperfection indicated by the radiographs shall not exceed the defects permitted by Section UW-52 of the ANSI/ASME Code, except for rounded indications, which shall be required to meet Section UW-51 of the ANSI/ASME Code.

8.1.3 Package Inspection Prior to Each Shipment

Prior to each shipment of package(s) containing the specified UF_6, each package shall be inspected and tested in accordance with USEC-651 or equivalent in-plant procedures at the facility and US DOT Regulations 49CFR §173.420, and also using the procedures provided in Appendix 8.3.1 in accordance with the JPN transport regulations.

The UF_6 in the 30B cylinder must be in solid form prior to shipment, and the internal pressure the cylinder must be less than atmospheric pressure when offered for shipment, as stated in USEC-651 and 49CFR § 173.420. These conditions shall be verified by the shipper, prior to loading the cylinder into the MST-30.

8.2 Maintenance Program

8.2.1 Maintenance Program for the MST-30 Overpack

The user shall establish and implement written procedures for the periodic maintenance and inspection of each MST-30 overpack. The following steps shall be used as a minimum in accordance with the provisions of the JPN transport regulations.

8.2.1.1 Annual Inspection

Once a year, the overpacks and the ring plates shall be inspected visually to ensure that they are not damaged and are adequate for their use. Furthermore, when the packagings are used for transport more than 10 times per year, this annual inspection shall be conducted every 10 times use in accordance with JPN transport regulations.

As a minimum, the following point shall be checked:

(a) Visually inspect the lifting shackles, fastening devices with bolts, and tie-down supports (legs) for unacceptable discontinuities, damage and deterioration. Repair as necessary to the original drawings and specifications.

(b) Visually inspect the vent ports and verify that the plastic caps are in place. Replace the plastic cap as necessary with new one.

(c) Visually inspect the inner and outer shells for corrosion, pitting and unacceptable discontinuities. Repair as necessary to the original drawings and specifications.

(d) Visually inspect the step-joint portions for damage or discontinuities and repair as necessary to the original drawings and specifications.

(e) Visually inspect all welds for the presence of discontinuities. Any questionable welds shall be subject to further examination to assure that unacceptable discontinuities are not present. Weld defects shall be repaired.

(f) Visually inspect the top and bottom halves for warpage and distortion that prevent tight closure. Repair as necessary to the original drawings and specifications.

(g) Visually inspect the gasket for damage and deterioration including nicks or deep scratches on the sealing surface that may prevent proper sealing. Replace the gasket as necessary with new one.

(h) Assure that the tamper-proof devices are functional and capable of maintaining their integrity when the devices are used. Repair as necessary to the original drawings and specifications.

(i) Check that the outer and inner surfaces of overpack are free from debris or standing water. Remove as necessary any debris or standing water.

(j) Visually inspect the ring plate for damage and deterioration. Repair as necessary according to the original drawings and specifications.

8.2.1.2 Weight Inspection

Whenever the overpack is shipped from owner's facility (i.e. MNF (Mitsubishi Nuclear Fuel Co., LTD)) for use, the weight of each half (top and bottom) of overpack shall be inspected. Even if an overpack in service is not used for 5 years, this weight inspection shall be conducted once per five years at least.

This inspection shall be performed as follows:

(a) Individually weigh each half (top and bottom) of each overpack to verify that neither half has gained by water more than 25 pounds (approx. 11.3 kg). If the reason of weight gain is not clear, the weight gain shall be assumed to be water. If either half exhibits a weight gain by water of more than 25 lb (11.3 kg), the overpack must be removed from service.

(b) Top and bottom half weights are permanently marked on the name plate once every five (5) years (at intervals not more than 5 years) as a representative weight.

8.2.1.3 Re-certification of Overpack

Whenever an application for renewal of Packaging Approval in JPN, which is a registration of individual packagings to JPN competent authority required by the JPN transport regulations, is made (every 5 years in normal case), annual inspection reports described in 8.2.1.1 shall be submitted to JPN competent authority and reviewed by the authority.

The overpack owner is responsible for certifying the MST-30 overpack to be maintained its condition properly and meet original design specifications in accordance with the provisions specified in the JPN transport regulations. Therefore, the five-year recertification requirement defined by USEC-651 is satisfied with the renewal process of the Packaging Approval in JPN.

8.2.2 Maintenance Program for the 30B Cylinder

The user shall establish and implement written procedures for the periodic maintenance and inspections of each 30B cylinder being requiring the following as a minimum, based on ANSI N14.1 or ISO 7195 in accordance with the JPN transport regulations.

8.2.2.1 Annual Inspection

Once a year, 30B cylinder shall be inspected visually to ensure that it is not damaged and it is adequate for its use. Furthermore, in case the packaging is used for transport more than 10 times per year, this annual inspection shall be conducted every 10 times use in accordance with JPN transport regulations.

As a minimum, the following point shall be checked:

(a) Visually inspect all components of 30B cylinder (e.g., cylinder-body(shell), heads, skirts, couplings for valve and plug and their welds) for unacceptable deformations, cracks, damage and deterioration. Repair as necessary to the original drawings and specifications.

(b) Visually inspect the valve and plug for unacceptable deformation, cracks, damage and deterioration.

8.2.2.2 Every Five (5) Year Inspection

Every five year inspection of each 30B cylinder in service shall be performed in the presence of a qualified inspector in accordance with ANSI N14.1 or ISO 7195. A cylinder which is filled with UF_6 at the time of expiry of the five year period need not be emptied for this test, but shall not be transported until 5 year periodic inspection is conducted after being emptied.

The following inspections shall be performed:

(a) Hydrostatic Pressure Test of the Cylinder-Body at 400 psig (2.76 MPa G);

The acceptance criteria are such that:

(1) No abnormal deformation is found on the cylinder-body.
(2) No water leaks from the cylinder body and valve and plug couplings for valve and plug.

(b) Air Leak Tightness Test of 30B Cylinder with the Valve and Plug at 100 psig (690kPa G) using soapy water (soapless lather);

The acceptance criterion is such that:
No soap bubbling visible at the engaged portions of the valve and/or plug into the couplings.

(c) Cylinder Shell Thickness Inspection Using Ultrasonic Thickness Gage;

The acceptance criterion is such that:
The thickness of cylinder-shell is to be maintained more than 11.3 mm (approx. 0.445 inch).

(note)
The criterion of 11.3 mm for the cylinder shell thickness is decided by adding a corrosion margin for 5 years to 11 mm to ensure that the thickness is not less than 11 mm. The corrosion margin is assumed to be 0.254 mm (0.0508 mm/year [Reference 8.4.1] × 5 years).

8.2.2.3 Valve Inspection

In addition to the valve inspection at the time of its manufacture, each valve is inspected at the time of installation in each cylinder after the cleaning operation of the cylinder.

8.2.2.4 Re-certification of 30B Cylinder

Whenever an application for renewal of Packaging Approval in JPN is made (every 5 years in normal case), annual inspection reports described in 8.2.2.1 and five year inspection reports described in 8.2.2.2 shall be submitted to the JPN competent authority and reviewed by the authority.

8.3 Appendix

8.3.1 Procedures for Package Inspection Prior to Each Shipment

8.4 Reference

8.4.1 POEF-TS-02, "Review of Corrosion in 10- and 14-Ton Mild Steel Depleted UF_6 Storage Cylinders", Michael L. Lykins, August 1995

Appendix 8.3.1

Procedures for Package Inspection Prior to Each Shipment

Procedures for Package Inspection Prior to Each Shipment (1/2)

Inspection Item	How to inspect	Acceptance Criteria
Visual Inspection	Visually inspect the outside of MST-30 overpack, ring plate and 30B cylinder.	· No unacceptable discontinuities, cracks, damage or deterioration shall be detected. Both halves of overpack shall be tightly fastened with fastening devices. · The type of the plug installed on the cylinder shall be the socket head plug. (*1) · The ring plate shall be inserted on the plug side. (*1)
	Visually inspect portions around the fittings of 30B cylinder, such as, valve, plug, their couplings, etc.	· No solid deposits around the fittings shall be detected.
Lifting Inspection	Visually inspect whether the lifting shackles, pins & their supports have any damage or anomaly when the package is lifted up by a crane.	· No damage or anomaly shall be detected on the shackles, pins and/or supports.
Weight Inspection	Weigh the cylinder containing UF_6 and check the contents (UF_6) weight. Check the package weight (calculated by adding the cylinder gross weight to the maximum design weight of the overpack and the ring plate).	· The contents (UF_6) weight shall not exceed 2,277 kg (approx.5,020 lbs) · The gross weight of the package shall not exceed 4,170 kg (approx. 9,193 lbs).
External Surface Contamination Survey	Survey the contamination level per unit area at any external surface of the overpack by smear method.	· Surface contamination level shall not exceed 0.4 Bq / cm^2 for alpha emitters and 4Bq/cm^2 for non alpha emitters.
Survey of Radiation Dose Rate	Survey γ-ray radiation level of the package in which the specified UF_6 is contained by survey meter.	· Not more than 2mSv/hr at any external surface of the overpack. · Not more than 0.1mSv/ hr at any point of 1 m from any external surface of the overpack.
Sub-criticality Inspection	Visually inspect the cylinder for defects, damage, and/or deterioration of the valve, plug or couplings through which water-ingress may occur	· No unacceptable defect, damage and deterioration shall be detected on the valve, plug or couplings. · No significant deformation of the cylinder shall be detected.

(*1) In the case of 30B cylinders with no plug, inspection for plugs and ring plates are not required, and use of ring plates is optional.

Procedures for Package Inspection Prior to Each Shipment (2/2)

Inspection Item	How to inspect	Acceptance Criteria
Verification of Data for Contents (the UF_6 contained in the package)	Check the data for specifications of the UF_6 contained, such as, enrichment, each loading quantity of UF_6, U content & ^{235}U content and other nuclides contents (^{232}U, ^{234}U, ^{236}U & ^{99}Tc)	Conformity of the data received with the required specifications shall be verified. · The enrichment of the contents shall not exceed 5 wt.% ^{235}U · The contents of ^{232}U, ^{234}U, ^{236}U and ^{99}Tc shall satisfy the following value, respectively.(*2) $^{232}U \leq 0.0001$ μg/gU $^{234}U \leq 11.0\times10^{3}$ μg/g^{235}U $^{236}U \leq 5000$ μg/g^{235}U $^{99}Tc \leq 0.01$ μg/gU · The purity of UF_6 shall be more than 99.5%. · The contents weight shall not exceed 2,277kg.

(*2) When the ^{236}U measurement result is less than 125μg/gU, confirmation of ^{232}U and ^{99}Tc can be omitted in accordance with ASTM C996.