The Use of Aluminum as a Structural Component in a Radioactive Material Package

G. A. Abramczyk
Savannah River National Laboratory
Savannah River Nuclear Solutions
Aiken, South Carolina 29808
(803) 725 2996,
glenn.abramczyk@srnl.doe.gov

B. M. Loftin
Savannah River National Laboratory
Savannah River Nuclear Solutions
Aiken, South Carolina 29808
(803) 725 5319,
bradley.loftin@srnl.doe.gov

C. McKeel
Savannah River National Laboratory
Savannah River Nuclear Solutions
Aiken, South Carolina 29808
(803) 725 2407
charles.mckeel@srs.gov

J. S. Bellamy
Savannah River National Laboratory
Savannah River Nuclear Solutions
Aiken, South Carolina 29808
(803) 725 1083,
steve.bellamy@srnl.doe.gov

ABSTRACT

The metal components of packaging certified for the transportation of DOT Hazard Class 7 – Radioactive Material, that meets the requirements of 10 CFR 71, must be in compliance with NRC Nuclear Regulatory Guide NUREG/CR-3854, *Fabrication Criteria for Shipping Containers*. In the requirements of NUREG/CR-3854, the components of a RAM packaging that are used for shielding or criticality control must be fabricated in accordance with ASME Section III Subsection NG (criticality) or NF (shielding). ASME Code Case N-519 was issued, and subsequently retired, that approved the use of 6061-T6 and 6061-T651 aluminum in the construction of ASME Section III, Division 1, Class 1 welded pressure vessels applications at temperatures up to 300 °F. This paper discusses the need for and justifies the use of aluminum as shielding and criticality control components in applications within Type B radioactive material packages.

Background

Savannah River National Laboratory (SRNL) developed the Model 9977 Radioactive Material (RAM) Packaging for the Department of Energy (DOE) National Nuclear Security Administration (NNSA) as a replacement for the Specification 6M packaging for which the authorization was withdrawn by the U.S. Department of Transportation (DOT) in 2006. The 9977 RAM shipping package Safety Analysis Report for Packaging (SARP) (S-SARP-G-00001, Revision 2) [Ref. 1] was authorized by the DOE Environmental Management (EM) Packaging Certification Program (PCP) Certificate of Compliance (CoC) Revision 0 [Ref. 2] on October 9, 2007 with an expiration date of October 31, 2012, per the requirements of DOE Order 460.1C [Ref. 3]. The SARP and CoC authorized the shipment of a single Content, 100 grams of plutonium and/or uranium "Heat Source" material in two container configurations. The initial SARP established the design of the packaging, its compliance with the requirements of Title 10 of the Code of Federal Regulations (CFR) Part 71 [Ref. 4], its design pressures, temperatures,

shielding and criticality features, its minimum essential operating procedures, its acceptance and maintenance requirements, and its Quality Assurance program. The SARP follows the content and format requirements specified in Regulatory Guide 7.9 [Ref. 5]. The 9977 was authorized with a maximum content weight of 100 pounds and radioactive decay heat rate of 19 watts and has a Containment Vessel maximum design pressure of 800 psi at 300°F.

The utility of the 9977 has been expanded in the years since it was initially certified by the inclusion of additional RAM Contents and packing configurations that support numerous DOE and NNSA sites, programs, and functions. A total of fifteen (15) unique content envelopes, four (4) generic container configurations, and eight (8) specific container configurations (which includes three (3) configurations utilizing Shielded Containers), were authorized. Additional contents and/or configurations were added to the Packaging safety basis through either an Addendum or a Letter Amendment Request, which were reviewed by the DOE Certifying Official and authorized through a new revision of the CoC. Table 1 lists the Contents authorized for shipment in the 9977 and the organizations shipping materials from each envelope. There were a total of seven (7) Addenda and five (5) Letter Amendments issued. The latest authorization for the 9977 is Revision 12 of the CoC. Table 2 is an alignment between the Content additions and the CoCs.

Some of the additional contents and/or configurations use structural components that control the RAM configuration and/or spacing of the contents within the Containment Vessel (CV) to preclude criticality and/or reduce the dose rates on the package exterior to be within the regulatory limits. These criticality and shielding control components are required to be fabricated [Ref. 6] in accordance with American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) permitted material.

Discussion

The 9977 uses aluminum components within the 9977 package that are credited (implicitly or explicitly) with criticality control, are used to provide distance for shielding, and are used to increase heat transfer from the contents. The aluminum components are the Heat Dissipation Sleeve (HDS), the Food-Pack Can Assembly (FPCA), the 3013 Spacer (Spacer), and the Sleeve and Plug (S&P) assembly.

NUREG/CR-3854 provides fabrication criteria for the metal components of shipping containers used for transporting radioactive materials. The criteria are divided into three categories that are associated with the levels of safety for the types and quantities of radioactive materials being transported. For each category, the fabrication criteria are subdivided into three component safety groups that are formed according to their safety function. The three packaging safety functions specified are; “Containment”, “Criticality”, and “Other Safety” (in the case of the 9977 this function being “Shielding”). The NUREG criteria are based on the ASME BPVC Code and are summarized in its Table 1.1, ***Summary of fabrication criteria based on the ASME code***, for each of the categories and component safety groups. NUREG/CR-3854 Section 4.0 gives

detailed fabrication criteria, including permitted exceptions or modifications. NUREG Table 1.1 requires criticality control devices to be fabricated per ASME Section III, Division 1, Subsection NG and other safety (shielding) devices to be fabricated per ASME either Section VIII, Division 1, or Section III, Subsection NF. Table 1 above lists the Content Envelopes analyzed for shipment within the Model 9977 Package and the configuration component, if any, which performs a NUREG/CR-3854 safety function.

Table 1 – Summary of 9977 Content Configurations

Content	Descriptor	Shielding		Subcriticality		Thermal
		NCT	HAC	NCT	HAC	
77C.1	Heat Source	-	-	-	-	-
77C.2	Np Pieces	-	-	-	-	-
77C.3	Np Sphere	S&P	-	-	-	-
77C.4	BeRP Ball	-	-	-	-	-
77C.5	Pu/U	S&P	-	S&P	S&P (1)	-
77C.6	Pu/U Metal in S&P	-	-	S&P	S&P (1)	-
77C.7	Pu/U Metal in 6CV	-	-	-	-	-
77C.8	U Metal	-	-	S&P	S&P (1)	-
77C.9	U Metal	-	-	S&P	S&P (1)	-
77C.10	SGQ - Special Actinides	-	-	-	-	-
77C.11	SGQ - Fissile Nuclides	-	-	-	-	-
77C.12	SGQ - Metal	-	-	-	-	-
77C.13	LANL - OSRP	-	-	-	-	-
77C.14	INL AGR-1 Fuel	-	-	-	-	-
77C.15	Training Sources	-	-	-	-	-
77C.16	Pu/U Metal Gram Based	-	-	S&P	S&P (1)	-
77C.17	Pu/U Oxide Gram Based	-	-	S&P	S&P (1)	-
77C.18	ARIES Pu/U Oxide	-	-	Spacer	-	HDS
77C.19	ARIES Pu/U Metal	FPCA	-	FPCA	FPCA	HDS
77C.20	U-Al Alloy	-	-	-	-	-
77C.21	Pu Metal	Spacer	-	Spacer	-	-
77C.22	Pu Metal	Spacer	-	Spacer	-	-
77C.23	Pu Metal	Spacer	-	Spacer	-	-
77C.24	Pu Oxide	-	-	-	-	-
77C.25	Pu Oxide	-	-	-	-	-

Note 1: The Sleeve and Plug may not be needed for sub-criticality but was included in the analyzed configuration.

Table 2 – References and Information for Table 1

Acronym	Name	Drawing	Sub-Component	Material
HDS	Heat Dissipation Sleeve	R-R4-G-00032	-	6061-T6
S&P	Sleeve and Plug	R-R4-G-00053	-	6061-T6
Spacer	3013 Spacer	R-R4-G-00081	-	6061-T6
FPCA	Food-Pack Can Assembly	R-R2-G-00091	"Spool"	6061-T6

Criticality - NUREG/CR-3854 only states that for criticality control features "fabrication", not "materials", should be per Section III, Subsection NG. The SRNL basis for using aluminum is the guidance provided by SG-100 [Ref. 7], which states that aluminum components should be fabricated per ASME Section III, Subsection NG to comply with the NUREG. SG-100 Table 2-6, which reproduces the information contained in NUREG/CR-3854, is reproduced below. The 9977 Package aluminum criticality component fabrication methods, as specified on the component fabrication drawings, comply with NG-4000 (Fabrication). NG-4000 includes a statement that the materials must comply with NG-2000; which could be interpreted as excluding aluminum as it is not included in the listed "non-ferrous materials". However, NG-2000 specifically refers to reactor core support structures. To address this short-coming, SRNL relies on SG-100. SG-100 addresses this apparent conflict by specifically including aluminum in its list of typical metals for criticality control devices and provides stress performance targets. SG-100 states (*Criticality Control*, Page 2-67): "In the design of internal structures to maintain relative position of the fissile material and neutron absorbers, the structures are normally fabricated from metal (e.g., stainless steel, **aluminum**, steel)." SG-100 goes on to require that, "The material should be able to sustain the loads from the regulatory performance tests without loss of structural integrity and/or loss of relative position. As an aid to the structural design engineer, the term 'loss of structural integrity' is normally defined as yielding." The structural analysis for the 9977 Package uses criteria consistent with the SG-100 (e.g. deformation control). However, not all aluminum components were addressed in a single section of the SARP. The SARP is currently being revised to correct this, as indicated in the flow chart below.

SG-100 Table 2-6. Summary of NRC-Recommended Package Construction Criteria for Metal Components Based on ASME BPVC

Component safety group	**Container contents**		
	Category I	**Category II**	**Category III**
Containment	Section III, Division I, Subsection NB	Section III, Division I, Subsection ND	Section VIII, Division 1
Criticality	Section III, Subsection NG		
Other safety	Section VIII, Division 1 or Section III, Subsection NF		

Source: NUREG/CR-3854.

Per Appendix A of ASME B&PV Section II-Part D [24], aluminum 6061-T6 "does not experience a transition range at low temperature. The static tensile strength increases as the temperature decreases, and the ductility as measured by percent elongation is not adversely affected to any significant degree. For these reasons low temperature impact tests of nonferrous materials are not required."

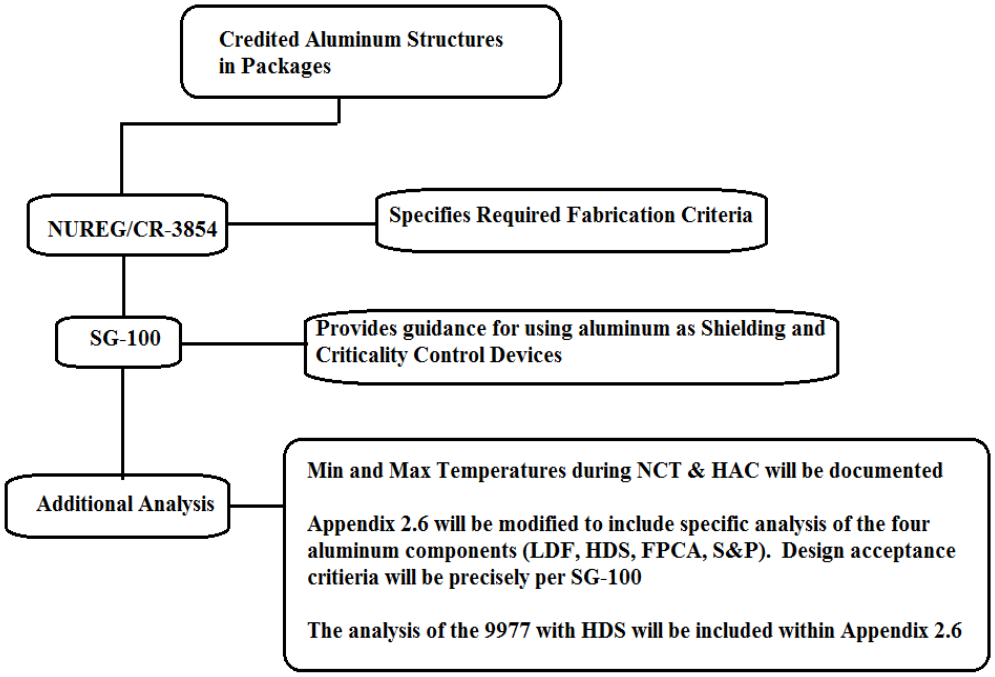


Figure 1 – 9977 Criticality/Shielding Component Requirements and Analyses

Other Safety (i.e. Shielding) - NUREG/CR-3854 again states that for shielding features "fabrication" should be per Section VIII, Division 1 or Section III, Subsection NF. The SRNL use of aluminum follows SG-100, which states that aluminum components should be fabricated per ASME Section III, Subsection NF to comply with the NUREG. The aluminum shielding component fabrication methods, as specified on the component drawings, comply with NG-4000 (Fabrication). NG-4000 includes a statement that the materials must comply with NG-2000, which could be interpreted as excluding aluminum. However, NG-2000 specifically refers to reactor core support structures. To address this short-coming, SRNL relies on SG-100. SG-100 discusses the use of a variety of materials for shielding devices and provides performance targets. SG-100 states (Section *2.6.3 Structural Features in Design and Selection, Shielding*, Page 2-66): "In the majority of NNSA packages, structural parts of the containment vessel are sufficient to provide shielding of short-range radiation such as alpha and beta, and usually are sufficient to reduce gamma and neutron radiation to acceptable levels. In cases where this is not true, shielding against gamma radiation can be achieved by using relatively dense materials such as lead, steel, or depleted uranium. At times, materials such as polyethylene or boron carbide are added to provide neutron shielding." SG-100 requires that, "In all cases, the design should

assure that the mechanical configuration of any shielding materials is maintained." The SRNL structural analysis for the 9977 Package uses criteria consistent with the SG-100 (e.g. deformation control).

Aluminum Properties – All aluminum components used in the 9977 as criticality or shielding control features are fabricated from ASME Specification SB-221 6061-T6. Material property data are taken from the ASME BPVC Section II Part D [Ref. 8] for Young's Modulus, Yield Stress, Tensile Stress, and the Expansion Coefficient. The ASME Code data is supplemented with more extensive time-temperature data from Military Handbook MIL-HDBK-5H [Ref. 9]. The Military Handbook data is shown graphically in Figure 2 below with an ASME data overlaid to demonstrate consistency. The Elongation data was taken from ASTM Specification B221-12 [Ref. 10].

ASME SB-221 6061-T6 is an ASME VIII-1 and VIII-2, and an ASME B31.3 approved material, and is used extensively in aerospace industry and by Department of Defense. Temperature dependent material properties are obtained from ASME B&PVC, Section II-D and from Military Specification MIL-HDBK-5D. The ASME Code presents data from room temperature up to 400 °F with the basis for this data to address 100,000 hours of sustained use (See ASME II-D appendices). The MIL-spec presents data from -400 °F to 800 °F with time-dependence explicitly shown. Figure 2 compares the ASME yield data to the MIL-Spec data. The comparison shows the ASME data aligns with the long-term duration conditions from the MIL-Spec.

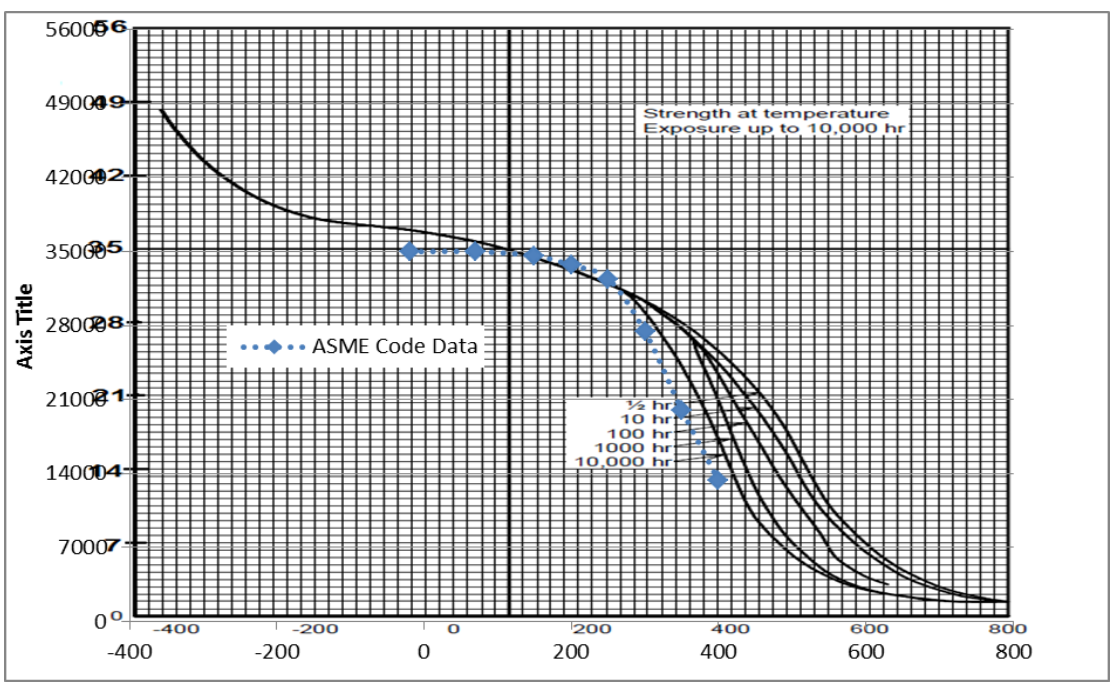


Figure 2 – Comparison of ASME Yield Data and MIL-HDBK-5D for Aluminum 6061-T6.
(Note: The ASME Code Data is for exposure up to 100,000 hr)

T6-Temper - The material properties used are specific to the T6 temper. Per ORNL/TM-99-208 [Ref. 11], the T6 strength levels can be maintained provided the service temperature does not exceed 320 °F for a prolonged period. ORNL/TM-99-208 also states that even transients above 200 °C (393 °F) will reduce its strength and a single excursion to 425 °C (797 °F) will totally erase the T6 temper and reduce its strength by 55%, down to the strength of annealed 6061. MIL-HDBK-5D presents a more quantified, more technically robust assessment of aluminum at high temperature. This reference shows critical exposure conditions of (1/2 hour @ 380 °F, 100 hours @ 350 °F, 1000 hours at 300 °F, or 10,000 hours at 260 °F) to initiate the loss of the T6 temper. Loss of temper strength reduction is accounted for in any aluminum component

with temperatures exceeding the above conditions. The credited strength of the aluminum is based on the assumption of long-term exposure to the stress-temperature condition. This approach is conservative for the NCT and HAC impacts, where only the elevated temperature is long-term, and the stress condition from drops is of very short durations.

Strain-Rate Effects and Creep - The aluminum components are only used for positioning. During normal conditions, the stress levels are due only to weights distributed over large contact areas, resulting in stresses sufficiently low to preclude creep effects. During NCT and HAC impacts, the short time durations (~0.001 sec, SARP Appendix 2.6) will also preclude creep. The allowable stress levels listed in ASME B&PV Section II-D are based on 100,000 hours of sustained stress at each given temperature, already accounting for creep effects when applicable.

Based on the short time durations of the impacts, any deformations of aluminum would engage high strain rate response effects. The response of aluminum 6061-T6 are elevated temperatures and at various strain rates has been established [Ref. 12]. Stress-strain responses are presented at 212 °F, 393 °F, and 662 °F. There is a significant strength gain under dynamic conditions, on the order of 2 times at strain rates of 1000 s-1. Aluminum components are evaluated [SARP Appendix 2.6, Attachment E] based on G-values and time durations determined from the FEA analysis. Strain-rate strength enhancements are conservatively not credited.

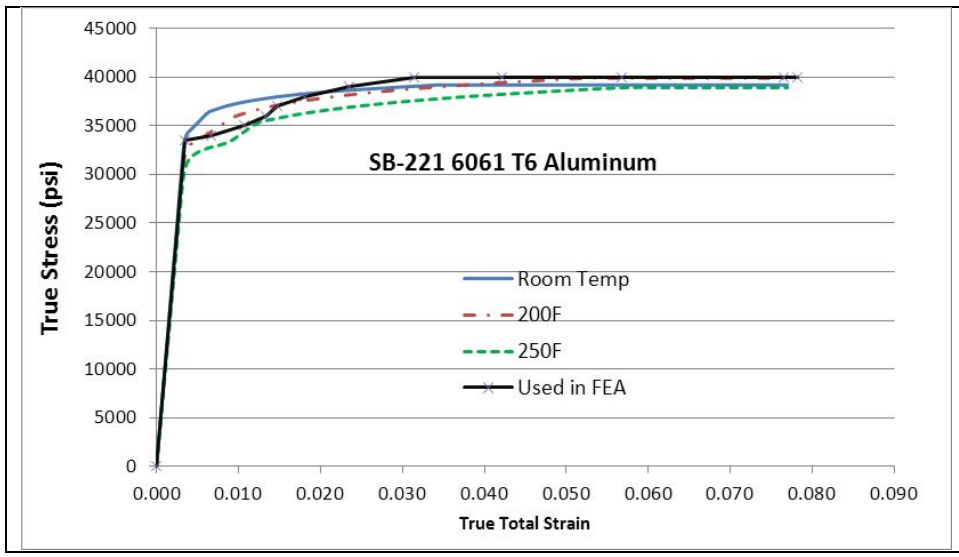
Aluminum Fracture Resistance - Per ADM-2010 [Ref. 13], aluminum has a notch-yield ratio greater than 1, corresponding to high toughness and resistance to fracture. Per ORNL/TM-99-208, the ductility and fracture toughness of 6061-T6 improves with reduced temperatures, down to near absolute zero. Per ASME B31.3, the minimum allowed service temperature for ASME SB-221 6061-T6 is -452 °F. The aluminum fixtures (loaded principally in compression) are not subject to fracture for the temperatures encountered during transportation.

Stress-Strain - The stress-strain curve used to describe the 6061-T6 material is per ASME VIII-2, Annex 3.D. The curve is keyed to the ASME Code specification required strength parameters (yield, ultimate, elongation, modulus) using the Code equations. Aluminum specific curve fitting parameters are shown below. The Code equation is used to establish stress-strain curves at room temp, 200 °F, and 250 °F. The values are shown in Figure 3, along with the stress-strain curves used in the analysis.

$$\varepsilon_t = \frac{\sigma_t}{E_y} + \gamma_1 + \gamma_2$$

m2 = 0.52(0.98-R) εp = 5e-6

Some aluminum components will experience temperatures above the 250 °F condition modeled. The difference in aluminum stiffness and stress response at higher temperatures is addressed within the aluminum component analysis section of SARP Appendix 2.6. The analysis shows that the aluminum remains essentially elastic. The change in elastic modulus over the aluminum temperature range is only +/- 10% and even this change does not have a significant effect on package performance. The conservative modeling approach would be to model the aluminum as stiff as reasonably expected. In the case of the 9977, none of the ASME SB-221 6061-T6 aluminum components are plastically dissipating any impact energy of significance.



True Stress	True Pl Strain
33500,	0.000
34000,	0.003065
35000,	0.006987
36000,	0.009636
37000,	0.010883
38000,	0.014094
39000,	0.019507
40000,	0.02730
40000,	0.03805
40000,	0.05266
40000,	0.0723
40000,	0.074

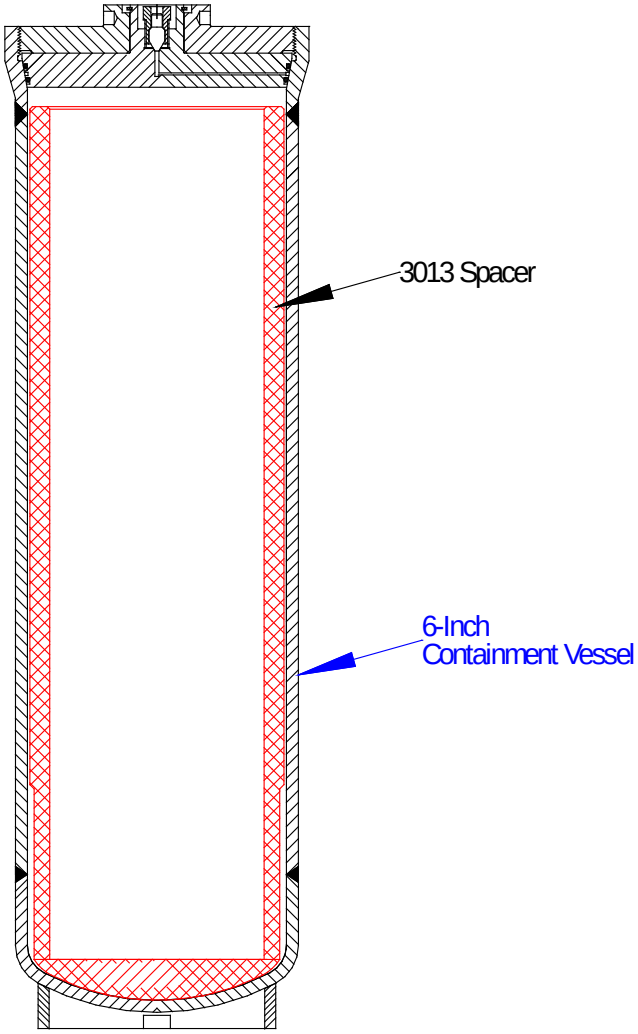
Figure 3 - ASME Code Stress-Strain Curves for SB-221 6061-T6 (&-T651, -T6511)

<u>Example – The 3013 Spacer</u>

The 3013 spacer, Figure 4, functions to provide a 5 inch (nominal) diameter configuration to keep 3013 vessels in position and within criticality requirements. Details of the spacer are obtained from drawing R-R4-G-00081. The following analysis is summarized from the 9977 SARP Appendix 2.6.

The Bending Response Frequency, Dynamic Load Factor, and material strength for NCT and HAC impacts for 3013 Spacer were determined. From this data a stress and deformation evaluation was performed for the Package side drop orientation, which bounds the Package end (top and bottom) and Center-of-Gravity-over-Corner drops. The maximum stress is 17,315 psi verses the aluminum's 23,700 psi yield. The maximum ovalization (deformation) is 0.021 inches and elastic and recoverable. Therefore, the spacer will maintain its credited configuration during Side drops, and will not impose additional loads onto the 6CV wall that aren't already reflected in the analytical simulations or physical drops tests. The spacer is also shown to be geometrically stable (no buckling, either as a beam or a shell).

Figure 4 – The "3013 Spacer" Configuration Component in the 9977 6CV



Purpose	Provides configuration (diameter) control (maintains a critically safe configuration) and positional control (distance to dose rate point of compliance).	
Drawing	R-R4-G-00081	
Materials / Function	Aluminum	- maintains a critically safe content shape (i.e. a 5-inch diameter cylinder) - maintains content distance from the package side wall for dose rate
Maximum Temperature	324 °F for NCT and HAC impacts, 406 °F for HAC Fire	
Discussion	The "critically safe" configuration is required for the NCT special case of the Single Package Flooded condition. Under all other NCT and HAC the 6CV is leaktight and a flooded configuration is not possible. The NCT and HAC loads on the spacer do not cause deformation, therefore, no loss of volume or positional control.	

References

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3 DOE O 460.1C, *Packaging and Transportation Safety*, U.S. Department Of Energy Office of Environmental Management, (May 2010)
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5 Regulatory Guide 7.9, Standard Format and Content of Part 71 Applications for Approval Of Packages For Radioactive Material, Revision 2 (March 2005)
6 NUREG/CR-3854, *Fabrication Criteria for Shipping Containers*, U.S. Nuclear Regulatory Commission (March 1985)
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12 Relationship Between Mechanical Properties and Microstructural Response of 6061-T6 aluminum alloy Impacted at Elevated Temperatures, Materials and Design 58 (2014), Pages 116-124, Elsevier
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