Use of Aluminum as an ASME Code Material for Shielding and Criticality Safety Applications (19-A-1256-PATRAM)

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ABSTRACT
A Type B radioactive material (RAM) packaging consists of structures, systems, and components (SSCs). In demonstrating compliance to the performance requirements of Title 10 of the Code of Federal Regulations (CFR), these SSCs are often credited with specific safety functions. NUREG/CR-3854 defines Component Safety Groups (CSG) for SSC's based on their credited safety function, and specifies criteria for their materials of construction. The criteria are tied to specific sections of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), depending on the CSG. SSCs that perform "Criticality" safety functions must meet Section III, Subsection NG. SSCs that perform "Other Safety" functions are required to meet Section VIII, Division l or Section III, Subsection NF. These “Criticality” and “Other Safety” SSCs are often made of aluminum grades that are not included in the ASME II-D material tables for Class 1 components. The National Nuclear Security Administration (NNSA) Office of Packaging and Transportation (OPT) has developed Interim Guidance 2015-1[]: *Process for Demonstrating Acceptable Structural Performance of Packaging Structures, Systems, and Components (SSCs) that Perform Nuclear Criticality Control or Other Safety Functions Fabricated from Materials Other than those Specified in ASME Boiler and Pressure Vessel Code.* [1] The paper discusses how Interim Guidance 2015-1 was used to demonstrate that aluminum can be used as a material of construction to fabricate SSCs per the applicable ASME BPVC sections.

Introduction

The Model 9977 (9977) is a Type B radioactive material (RAM) Packaging compliant with Title 10 of the Code of Federal Regulations, Part 71 (10CFR71).[2] This Package was first certified for use by the Department of Energy Office of Environmental Management in October 2007. It was subsequently certified by the National Nuclear Security Administration (NNSA) Office of Packaging and Transportation (OPT), beginning in October 2012. The 9977 is currently certified to ship thirteen different contents in various configurations.

Contents at the extremes of the Packaging's limits may have characteristics, such as a high decay-heat rate, a high dose rate, or a significant fissile material content that require additional special purpose components in the Content's loading configuration to supplement the Package in performing its safety functions. A Content with a high decay-heat rate may require a component to increase the heat transfer within the Package and keep the Containment Vessel (CV) within its temperature limits or to preclude local high temperatures within the overpack. Contents with high activities can use spacers or poisons that reduce the radiation source terms outside the CV and/or increase the separation between the sources and the point of compliance. A Content with a fissile material mass exceeding the minimum subcritical mass limits may require configuration control (e.g. separation or content volume morphology) to maintain sub-criticality. The configuration control is established using specifically designed "spacers" made of materials specific to and appropriate for the application. Figure 1 shows the 9977 Package with additional SSCs added (shown in red) that supplement the Package in performing specific safety functions.

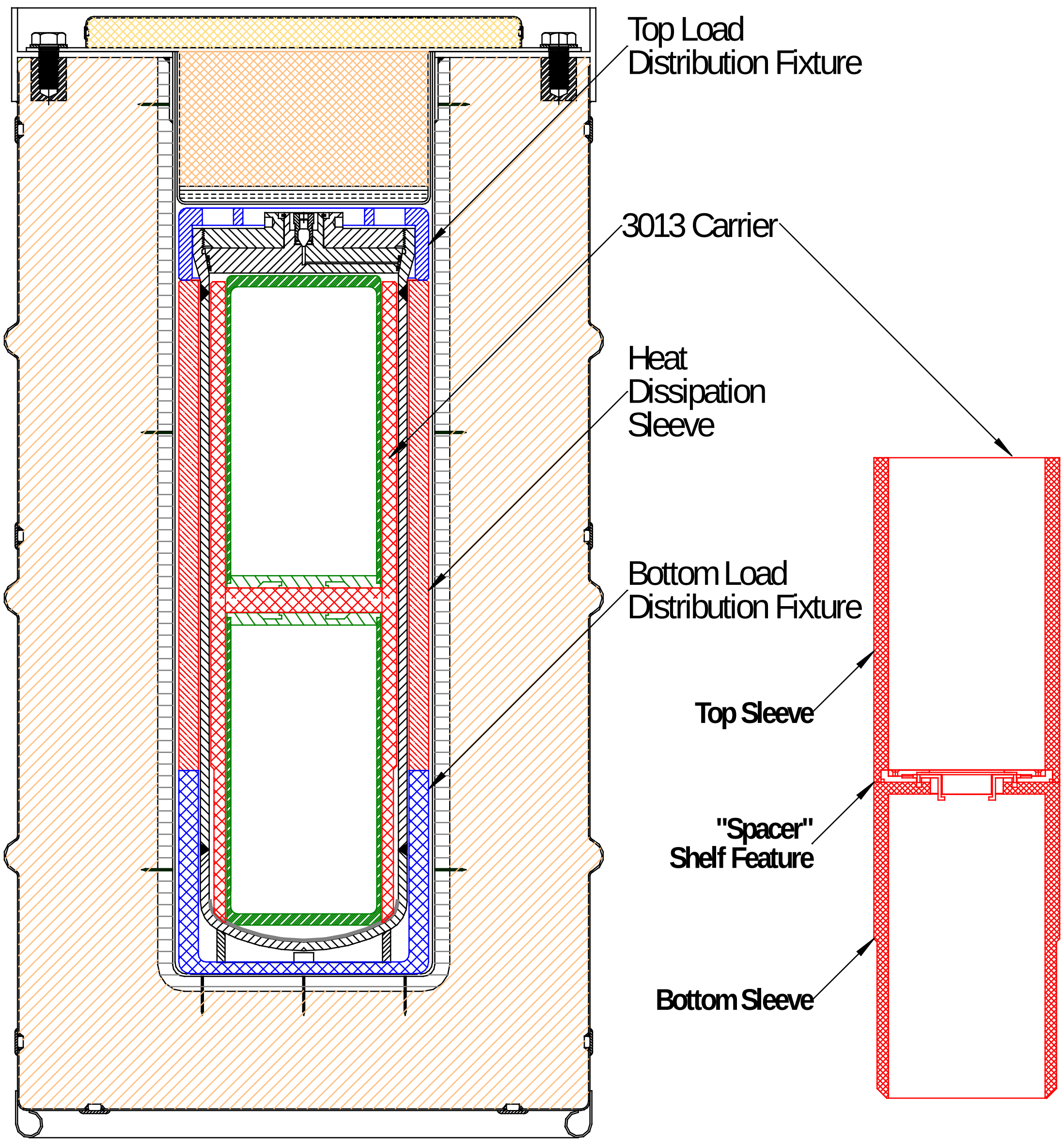


Figure 1 – The Model 9977 Packaging showing the Containment Vessel located with the Heat Dissipation Sleeve and the Load Distribution Fixtures containing the 3013 Carrier

Discussion

One Content in the 9977 pushes two of the three content limits; decay-heat rate and RAM mass. The Content produces up to 38 watts of decay-heat and permits a maximum of 7.9 kg of fissile material loaded and distributed within two DOE-STD-3013 storage containers (3013s). The thermal and criticality analyses of the 9977 with this Content placed directly into the CV (i.e. without special configuration controls) determined the potential for localized overheating of the drum overpack insulating foam and a k_{eff} greater than k_{safe} for both the 10CFR71 Section 55 (10CFR71.55) Single Package and Array Conditions. This Content requires a loading configuration which incorporates:

- a feature to maximize the conductance of heat out of the package (called a "Heat Dissipation Sleeve" (HDS))
- a "spacer" component to establish a minimum separation of the RAM in the two 3013 Containers as it behaves as two essentially equal and separate masses to maintain sub-criticality for the Single Package cases (10CFR71.55(b)), and
- a "sleeve" component that limits the Content volume to a critically safe configuration of a maximum 5-inch outside diameter tube, to maintain sub-criticality for the Package Array cases (10CFR71.59).

Heat Dissipation Sleeve

The Content configuration uses the HDS, an ASME SB-221 6061-T6 aluminum tube that fills the void space between the 6CV and the drum liner. See Figure 1. The outer diameter of the HDS is sized to be close fit within the drum liner and its inner diameter to contain the 6CV. The sleeve length of 15.7 inches fills the gap between the Top and Bottom Load Distribution Fixtures. The HDS acts to evenly distribute the content heat output in the CV over its length and eliminates "hot spots" in the CV, the drum liner, and the foam insulation. The HDS, with its increased thermal conductivity, was included in the thermal analysis of the 9977 with this Content.

Criticality Control Components

The 3013 Carrier assembly is used with the Content and is credited with criticality control. For Single Package flooded scenario of 10CFR71.55(b), the criticality control function is performed by volume control provided by the Top and Bottom Sleeves of the Carrier Assembly, and the separation spacing provided by the Shelf Section of the Bottom Sleeve and Shelf Plate. For Normal Conditions of Transport (NCT) and post Hypothetical Accident Conditions (HAC) damage (the array configurations), the credited criticality control is provided by the additional spacing (wall thickness and content separation) provided by the Carrier Sleeve and Shelf.

The 3013 Carrier Assembly is credited with criticality control. Credited functions are:

Shelf Thickness: Minimum 0.75 inch separation.

Sleeve Sections: Consume volume within the 6CV.

As in prior criticality control feature designs used in the 9977, the Carrier would need to be fabricated mostly from aluminum. For criticality evaluations, aluminum is essentially transparent to neutrons. While steel would structurally perform equal or better than aluminum through the NCT and the HAC transportation scenarios, steel is a neutron reflector and increases the system reactivity. Therefore, the criticality analysis establishes an upper limit for the amount of steel used in the final design.

Methods

Per NUREG/CR-3854, design criteria for the SSCs are in accordance with ASME BPVC Section III, Division 1, Subsection NG (ASME III-NG). The credited sections of the Carrier Assembly are fabricated from ASME SB-221 6061-T6 aluminum. The aluminum is not included in the list of ASME materials permitted for use as Class 1 components. However, NUREG/CR-3854 (Table 4.1, note 2) and Regulatory Guide (RG) 7.6 Part C item 1, allow the use of additional materials, provided justification is made. The justification process for the aluminum material will be per the specific steps delineated in the NNSA Interim Guidance 2015-1.[4] These steps address the materials, design, fabrication, and examination of the component.

Material Properties and Specifications

The aluminum used for the LDFs, the HDS and for the 3013 Carrier Assembly is in accordance with ASME SB-221 6061-T6. The material properties for the LDFs and HDS are from the 2004 edition of ASME II-D and are listed in Table 2. The material properties for the 3013 Carrier Aluminum components are from the 2017 edition of ASME II-D and are also listed in Table 2.

Design

Per the 2015-1 guidance, the acceptable performance of the SSC must be demonstrated by analytical and test methods used in standard engineering practice. For the 3013 Carrier Assembly and the HDS, structural demands were determined using ABAQUS/Explicit to conduct analytical simulations of worst case NCT and HAC loadings. As per Regulatory Guide 7.6, Part C, Item 1, the resulting stresses are compared to allowable stresses developed based on ASME BPVC, Section II, Part D, Mandatory Appendix 2, Table 2-100(a). ASME III-NG Level A Service Limits are used for NCT and Level D Service Limits are used for HAC (Figure 2). The criticality control components are used as spacers and are primarily loaded in compression. Bearing stresses are evaluated per ASME BPVC Section III, Division 1, Subsection NG-3227.1.

The performance of the 6061-T6 aluminum at reduced and elevated temperatures is assessed based on design criteria per ORNL/TM-99-208[2] and MIL-HDBK-5J.[7] Fracture toughness is assessed though the Aluminum Design Manual (ADM-2010 [5]) and Oak Ridge National Lab Documents. Per ADM-2010, aluminum 6061-T6 is notch insensitive. Per ORNL/TM-99-208, fracture toughness, yield, and ultimate properties all increase with decreasing temperature. Therefore, fracture and cold temperature performance for temperatures encountered during transportation is demonstrated by compliance with the stress criteria of ASME III-NG.[3] For performance at elevated temperature, the aluminum material is evaluated based on stress criteria from ASME II-D and additional data from MIL-HDBK-5J and ORNL/TM-99-208 to accurately assess creditable high temperature strength levels.

SSC's Performing Other Safety

Per NUREG/CR-3854, criteria for the items performing "other safety" functions are in accordance with ASME BPVC Section III, Subsection NF or ASME BPVC, Section VIII, Division 1. Both of these Code Subsections permit the use of materials identified for Class 1, Class 2 and Class 3 components in the ASME BPVC Section II, Part D. The aluminum is included in that list. The NCT and HAC criteria are similar to that used for the Containment and Criticality, shown in Figure 2. Allowable stresses are developed based on ASME BPVC, Section II, Part D, Mandatory Appendix 1, Table 1-100 and Appendix 2, Table 2-100(a), as appropriate.

Per Appendix A of ASME B&PV Section II-Part D, 2004 Edition, 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."

Fabrication

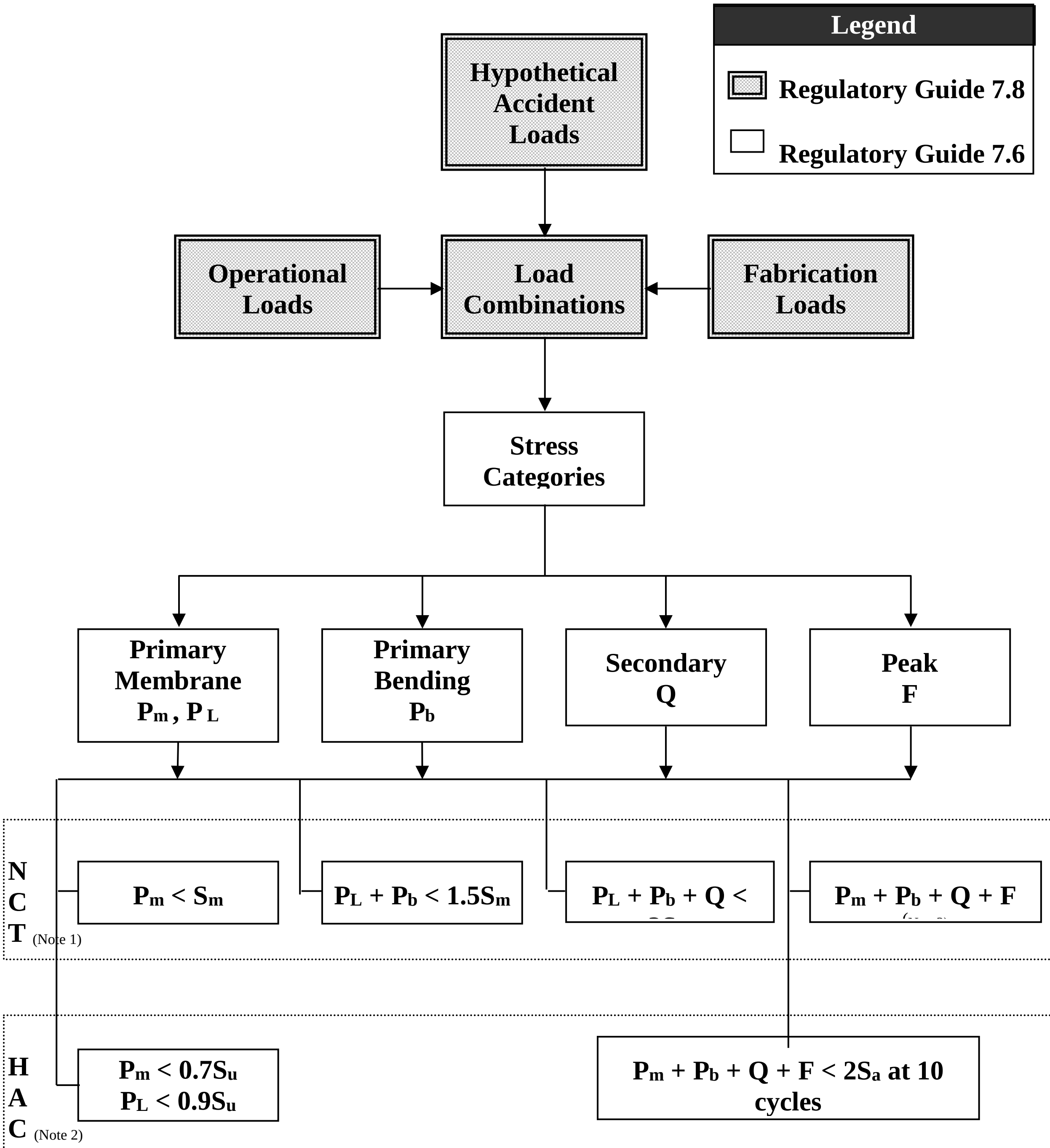
The HDS and 3013 Carrier Assembly are machined from ASME SB-221 6061-T6 aluminum rod, bar, or tube. Justification of the fabrication as equivalent to ASME III-NG was based on the following. The aluminum material meets the NG-2300 non-ferrous exemption, such that NG-4213 is not applicable. There is no welding associated with the construction of the 3013 Carrier Assembly. Therefore, the requirements of NG-4230, NG-4240 and NG-4600 are not applicable.

Examination

The aluminum components in the 9977 include the LDFs, the HDS, and the 3013 Carrier Assembly. As no welding is associated with the construction, and these components are not pressure retaining, examinations include verification of material properties per ASME SB-221 6061-T6, and verification of credited dimensions. The 3013 Carrier Assembly is a criticality control device and is examined per applicable requirements of ASME III, Subsection NG. The credited features are the Shelf thickness and the inner diameter and outer diameter of the Sleeves, which are examined during fabrication per Quality Assurance verification of “Q Item” dimensions listed on the Carrier Assembly drawings. The drawing and ASME SB-221 satisfy the applicable general NG-5100 requirements. Since no welding is involved, and the material is aluminum, the requirements of NG-5200, NG-5300, and NG-5500 are not relevant. Ultrasonic testing (per ASTM B594) is not performed for this component, as the purpose of the ASTM B595 testing is to identify internal discontinuities parallel to the surface of the product, and the package aluminum components are loaded in compression only stress conditions.

Conclusion

Using the guidance in NUREG/CR-3854 and the NNSA Interim Guidance 2015-1, the use of aluminum material for the fabrication of SSC that perform "Criticality" and "Other Safety" safety functions was justified. The process includes demonstrating that a package SSC material of construction is manufactured to a recognized national standard, and then designed, fabricated and examined in a manner equivalent to the ASME BPVC section specified by NUREG/CR-3854 for the specific safety function of the SSC. The aluminum SSCs in the 9977 Packaging were specifically evaluated and justified.



Notes – 1) Level A Service Limits for Stress.
2) Level D Service Limits for Stress, the BPVC, Section III, Appendix F, Article F-1341.2.
3) The allowable stress intensity for the full range of fluctuations is 2 S_a per Figure NB-3222-1.

Figure 2 - Load Combinations and Stress Intensity Limits from Regulatory Guides 7.6 and 7.8

Table 1 - Summary Criteria for a Category I Radioactive Material Packaging - 9977

Acceptance	**Component Safety**								
	Containment [Note 4]		**Criticality** [Note 1]	**Other Safety Features**					
				Overpack [Note 3]		Impact limiters		Tie-down	Lifting
	6CV Body	Seals		Drum	Bolted closure	Load Distribution Fixtures [Note 5]	Insulation		
Design	ASME NB-3000	NB-3000	ASME III-1 NG-3000	UN 1A2	ASME VIII, Div 1 and ASME NF-3000	Per Design	Commercial [Note 2]	10 CFR 71.45(b)	ANSI N14.6
Materials	NB-2000	AMS-R-83485	ASME III-1 NG-2000	NF-2000	ASME SA-193, 194 & 320	Section VIII, Div 1	Commercial	NF-2000	NF-2000
Forming, Fitting and Aligning	NB-4200	Commercial	Commercial	UN 1A2	NF-4200	Per Design	Commercial	Per Design	Per Design
Fabrication and Examinations	NB-5000	Commercial	ASME III-1 NG-5000	UN 1A2	NF-4000 NF-5000	Per Design	Commercial	Per Design	Per Design
Acceptance Testing	NB-6000	ANSI-N14.5	Commercial	UN 1A2	NF-2581.2	Per Design	Commercial	Per Design	Per Design

Note

1. The 9977 Package Overpack does not incorporate materials or other design features acting as criticality control. For certain contents, such as 3013 Containers, the 6CV is fitted with an aluminum 3013 Carrier which is credited with a criticality control function. NNSA Interim Guidance Document is used to apply ASME III-1 NG methods.
2. The use of the term "Commercial" implies that specific vendor data was used to evaluate the material for use in the 9977 package.
3. The overpack consists of the drum (drum flange weldment and lid construction) and its bolted closure, drawings R-R2-G-00017 and R-R2-G-00018.
4. Containment Vessel body and O-ring seals are shown on Drawing R-R2-G-00042.
5. Load Distribution Fixture Details fabrication details, including those for the HDS, are shown in Drawing R-R4-G-00032. For payloads requiring the use of the HDS, the HDS is credited with temperature control. NNSA Interim Guidance Document is used to apply ASME VIII-1 methods.

Table 2 - Mechanical and Physical Properties of the Overpack Containment Vessel Spacers

Packaging Component	Materials of Construction[a]	Property[b] (units)	Value	Temperature (°F)
Upper and Lower Load Distribution Fixtures Heat Dissipation Sleeve (HDS) 3013 Carrier Assembly	ASME SB-221, Grade 6061-T6, Aluminum 2004 Edition for LDF and HDS, 2017 Edition for 3013 Carrier Assembly Aluminum Components. ASME Code Section II,Part-D, 2004 Edition Properties are listed. 2017 Edition values are shown in parenthesis when differing from 2004 Edition.	Minimum Yield Strength (psi)	35,000	-20 to100
			34,600 (34,400)	150
			33,700 (34,200)	200
			32,400 (32,500)	250
			27,400 (27,200)	300
			20,000 (19,900)	350
			13,300	400
		Minimum Tensile Strength (psi)	38,000	--
		Elongation (%)	8 - 10	--
		Poisson's Ration	0.33	--
		Density (lb/in^3)	0.098	--
		Average Thermal Expansion from 70°F Coefficient B (in./in./°F)	--	-100
			12.1×10^{-6}	70
			12.4×10^{-6}	100
			13.0×10^{-6}	200
			13.3×10^{-6}	300
			13.6×10^{-6}	400
			13.9×10^{-6}	500
		Modulus of Elasticity, E (psi)	10.5×10^{6}	-100
			10.0×10^{6}	70
			--	100
			9.6×10^{6}	200
			9.2×10^{6}	300
			8.7×10^{6}	400
			8.1×10^{6}	500

a) ASME Code, Section II, Part B, Subsection ASME SB-221, [36] - Elongation, Table 2

b) ASME Code, Section II, Part D, 2004 edition [24] and 2017 Edition.[72]
- Yield Strength, Table Y-1, Page 602, Line 8, (Page 735, Line 25 for ASME II-D 2017 Ed)
- Tensile Strength, Table 2B, Page 358, Line 9, Poisson's Ratio, Table NF-1, pg. 702,
- Density, Table NF-2, Page 703,
- Thermal Expansion, Table TE-2, Page 672, and
- Modulus of Elasticity, Table TM-2, Page 698.

References

1. *Process for Demonstrating Acceptable Structural Performance of Packaging Structures, Systems, and Components (SSCs) that Perform Nuclear Criticality Control or Other Safety Functions Fabricated from Materials Other than those Specified in ASME Boiler and Pressure Vessel Code*, NNSA Office of Packaging and Transportation Interim Guidance 2015-1
2. *Packaging and Transportation of Radioactive Material.* Code of Federal Regulations, Title 10, Part 71, Washington, DC (January 2019).
3. ORNL/TM-99-208, Materials Selection for the HFIR Cold Neutron Source, Oak Ridge National Laboratory, K. Farrell, Published August 2001.
4. ASME Boiler and Pressure Vessel Code Section III, "Rules for Construction of Nuclear Facility Components," Division 1, Subsection NG, American Society of Mechanical Engineers, New York, NY (2004)
5. NNSA Office of Packaging and Transportation Interim Guidance 2015-1, Process for Demonstrating Acceptable Structural Performance of Packaging Structures, Systems, and Components (SCCs) [sic] that Perform Nuclear Criticality Control or Other Safety Functions Fabricated from Materials Other than those Specified in ASME Boiler and Pressure Vessel Code, April 2015.
6. AA ADM-2010, Aluminum Design Manual, 2010 Edition, The Aluminum Association.
7. MIL-HDBK-5J, METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES, Department of Defense, 2003 (Also titled as MMPDS-01).