EGG-M-91097
Conf-910602--50

INTRODUCTION OF A NEW STRUCTURAL MATERIAL FOR SPENT NUCLEAR FUEL TRANSPORTATION CASKS

EGG-M--91097

DE91 018754

W. J. Severson, R. M. Mello and A. P. Ciez

Westinghouse Electric Corporation
Scientific Ecology Group, Inc.
Pittsburgh, Pennsylvania

ABSTRACT

The From-Reactor Transportation Cask Initiative of the DOE Office of Civilian Radioactive Waste Management (OCRWM) has, since 1988, supported the development of cask systems for the shipment of spent nuclear fuel by both legal weight truck (LWT) and rail or barge. The design basis fuel to be transported would be 10 years out-of-reactor with maximum burnups of 35 and 30 GWD/MTU for PWR and BWR assemblies, respectively. Westinghouse's work on the program led to the development of a common use LWT cask design capable of transporting either three PWR or seven BWR assemblies. This payload in a common use cask is achieved by the use of depleted uranium for the gamma shielding material and Grade 9 titanium as the principal structural material. The use of Grade 9 titanium for cask structures has no certification precedent. This paper describes the work performed to characterize the material and the status of steps taken to gain its acceptance by the NRC, which includes ASME approval of its use in the construction of Section III Class 1 components.

INTRODUCTION

The Department of Energy (DOE), through its Office of Civilian Radioactive Waste Management (OCRWM), is developing spent fuel transportation casks with the objective of having a licensed, tested, and proven operational cask fleet by the time that the Monitored Retrievable Storage (MRS) facility opens which has been identified as being in 1998. Cask systems for all modes of transportation (truck, rail and barge) are being developed. When the cask development program began, innovation was encouraged by the DOE with the aim of developing safe, reliable, and economical spent fuel transportation cask systems within the framework of existing regulations. Obviously, higher payloads than those offered by the current fleet of casks were desired.

The TITAN LWT cask, being developed by Westinghouse, is one of three LWT casks in the OCRWM transportation cask program. The TITAN cask is a common use cask which accommodates both PWR as well as the longer BWR fuel assemblies. The other two casks are single use casks (for either BWR or PWR fuel). The gross weight limit for a LWT is 80,000 pounds. Westinghouse believes that 54,000 pounds is a reasonable upper limit on the allocation of weight to the loaded cask including its impact limiters.

The challenge is to maximize the payload of the cask within this weight limit. The new fleet of casks will be transporting older (in terms of

years out-of-reactor) fuel than that for which the current casks were designed, and this is of benefit both in terms of shielding and heat rejection. This change in the design requirements would permit an increase in payload from a single PWR assembly (current common use LWT capability) to a cask capable of transporting two PWR assemblies even if conventional materials of construction were used. The challenge was to increase the payload from two PWR assemblies to three.

Cask weight for a given cask cavity diameter can be minimized if the gamma shielding is placed as close to the cask cavity as possible. This is why all-steel casks were replaced with designs using lead gamma shields. The weight of the cask is reduced still further if the lead is replaced by depleted uranium. The structural material for the cask is normally stainless steel. If a stainless steel/depleted uranium design were used, the payload objectives for the common use cask could not be met and still meet the structural and shielding requirements. So lighter structural materials were considered which would permit a transfer of some of the shielding normally provided by the stainless steel to the depleted uranium which is both closer to the cask cavity and a more effective shielding material. Titanium was selected as the structural material for the TITAN cask.

CASK DESIGN DESCRIPTION

The TITAN LWT cask is a Type B package as defined in 10 CFR Part 71 (Reference 1). Figure 1 identifies the design details and features of the cask assembly. The principal structural components of the cask body and closure lid are fabricated from Grade 9 titanium alloy. Depleted uranium (alloyed with 0.2 percent molybdenum) is used as the primary gamma shield material. A solid fire resistant neutron shielding material with a high hydrogen content is installed outside the main structural boundary of the cask. This material is protected from the elements and radioactive contamination by a relatively thin covering of Grade 2 titanium. The lid attachment and seals are of conventional design.

The cask configuration shown includes aluminum honeycomb impact limiters. The honeycomb material is encased in a stainless steel sheathing to provide protection against the elements.

Interchangeable baskets permit the transport of either PWR or BWR spent fuel assemblies. The baskets employ a conventional design and are fabricated from Type 316 stainless steel with borated aluminum neutron poison plates. Subcriticality for all conditions, including postulated hypothetical accident conditions, is assured without taking credit for fuel burnup.

LICENSING CONSIDERATIONS

Based on interactions with the Transportation Branch of the NRC, the principal certification issue with the TITAN cask is the choice of material for the structural components. There have been no applications for a Certificate of Compliance for a cask employing titanium as the structural material. This lack of precedent for the cask's structural material has focused the NRC's concerns on the titanium.

The NRC prefers to have applicants use material property values in their Safety Analysis Reports for Packaging that are taken from the ASME B&PV Code. NRC Regulatory Guide 7.6 (Reference 2), for example, specifies structural design limits that are comparable to the requirements for an ASME B&PV Code, Section III, Class 1 nuclear component (Reference 3). This Regulatory Guide also requires that material properties and design stress limits be taken from the ASME Code. When Westinghouse first began a dialog with the NRC on the TITAN cask, Grade 9 properties were absent from Section III of the Code and its Appendices.

Grade 9 titanium (Ti-3Al-2.5V) was selected because it has higher strength than the unalloyed (or "commercially pure") grades but more ductility and fracture toughness than Grade 5 (Ti-6Al-4V), the most common grade of the titanium alloys. However, while some materials property data were available from industry sources (References 4, 5, 6 and 7) as well as from some Naval programs, the kinds of data required to characterize the material to the extent required by the ASME Code either were not known or not available.

It became obvious that if the NRC were to accept the material, two actions were required. The alloy had to be tested to obtain the information to fully characterize the material, and steps needed to be taken to gain ASME approval of the use of the material for Class 1 components under the rules of Section III of the Code. Such approval would establish a consensus on the materials property values.

Therefore, an engineering test program was initiated to obtain both thermophysical and mechanical property data for the alloy; and approval of a Code Case was sought which would permit the use of Grade 9 titanium for the construction of Section III, Division 1, Class 1, 2 and 3 components. The materials testing program was completed and the Code Case (Case N-492), allowing the use of Grade 9 titanium, has been approved.

TESTING PROGRAM AND RESULTS

The tests given in the matrix shown in Table 1 were planned and conducted. The material for the tests were from three mill annealed billets (two round billets weighing 323 pounds each and one rectangular billet weighing 760 pounds) from three different heats of Grade 9 titanium per ASTM B348-83, "Standard Specification for Titanium and Titanium Alloy Bars and Billets." The rectangular billet or slab was rolled to a 1.5 inch thick plate which was then annealed at 1450 F for two hours, air cooled and conditioned.

Nearly all the mechanical testing was performed by an independent testing laboratory; weldments from the three heats of material were provided by an outside organization experienced in the fabrication titanium components; and the thermophysical data were obtained by a university laboratory.

The tests which provided information and data for the Code Case are discussed below.

Thermophysical Properties

1. Specific Heat: Tests on four specimens were conducted over a

temperature range of -40 F to 300 F. per ASTM E968-83. The two specimens that bounded the data were then tested from 300 F to 600 F. The curve which best fits the data is described by the following equation:

$$cp = 0.121 + 7,169 \text{ E-06 } T - 5.451 \text{ E-08 } T^2 \qquad (1)$$

where cp = specific heat, Btu/lb-F
T = Temperature, F

The specific heat for Grade 9 titanium is about 10 percent higher than Type 304 stainless steel as shown in Figure 2.

2. Thermal Conductivity: Tests were performed using the "Modified Kohlrausch Method for Determining Thermal Conductivity" on four specimens over a temperature range of -137 F to 300 F and then on two specimens from 120 F to 1159 F. The best fit curve is described by the equation

$$k = 7.1577 \exp[(T-851.78)^2 / -1,824,400] \qquad (2)$$

where k = conductivity, Btu/hr-ft-F
T = Temperature, F

The thermal conductivity of Grade 9 titanium is about 65 percent of that of Type 304 stainless steel as shown in Figure 3.

3. Thermal Diffusivity: In spite of the differences in the thermal conductivities between the titanium alloy and stainless steel, the thermal diffusivities of the two materials are nearly equal because the ratio of the densities is nearly the same as the ratio of the conductivities. A comparison of Grade 9 titanium and 304 stainless steel thermal diffusivity is shown in Figure 4.

4. Thermal Expansion: Tests were performed on four specimens over a range of -40 to 300 F. Then the two specimens which bounded the upper and lower values were tested from 100 F to 600 F. The equation best fitting the data is:

$$L/L = -3.316 \text{ E-04 } + 4.646 \text{ E-06}T + 7.962 \text{ E-10 } T^2 \qquad (3)$$

where L/L = expansion, inches/inch
T = Temperature, F

The coefficients for mean, instantaneous, and linear thermal expansion given in Table 2 were computed from equation 3 according to the definitions given in ASTM E228-85.

Base Material Mechanical Properties

5. Modulus of Elasticity: 135 data points from measurements made over a temperature range of -40 F to 800 F were used to define the temperature dependence of the modulus of elasticity. The equation which best fits the data is:

$$E = 1 \text{ E-06}/[3.53 \text{ E-08 } (T + 137.59)^2 + 0.062] \qquad (4)$$

where E = modulus of elasticity, psi
T = temperature, F

The modulus of elasticity for Grade 9 is 15.9 million psi at room temperature (compared to 15.5 million psi for unalloyed titanium) but reduces to 12.4 million psi at 600 F as shown in Table 3. These values are about half of those for austenitic steels (28.3 million psi at room temperature and 25.3 million psi at 600 F).

6. Strengths: Tensile tests were performed per ASTM E8-87a and E21-79 at -40 F, room temperature, 150 F, 300 F and 600 F. on both transverse and longitudinal specimens taken from all three heats.

The equations which best fit the data for the yield and ultimate strengths are:

$$Sy = 1000/[6.4 \text{ E-}12(T + 1012.96)^2 + 0.870] \quad (5)$$

$$Su = 1000/[-3.0 \text{ E-}13(T - 20374.2)^2 + 0.000134] \quad (6)$$

where Sy = yield strength, psi
Su = ultimate strength, psi
T = temperature, F

Yield and tensile strengths using these equations are given in Table 4 for temperatures ranging from 70 to 600 F.

7. Allowable stresses: A set of allowable stresses for Grade 9 titanium from room temperature to 600 F were developed in accordance with ASME Code criteria. These stresses include the minimum yield strength, minimum ultimate strength, the design stress intensity, Sm, for Class 1 components and the allowable stress, S, for Class 2 and 3 components. Approval of these values came first through approval of Case 2081 (Reference 8), a Section VIII Code Case for the use of Grade 9 under the rules of Section VIII, and then through approval of Case N-492 which permits the use of Grade 9 titanium in the construction of Class 1, 2 and 3 components under the rules of Section III, Division 1 of the ASME B&PV Code.

The data base supporting the Case 2081 inquiry was more extensive in the sense that strength data were obtained at 100 F intervals and at 700 F, 100 F beyond the values established for the Code Case. Thus the trend curves developed for Case 2081 were used to establish the design allowables for the Section III Code Case. However, a comparison of the data obtained for the Section VIII Code Case with the data obtained from the Westinghouse materials property testing program showed excellent agreement.

The allowable stresses are given in Table 5. Comparisons of Grade 9 titanium and Type 304 stainless steel minimum tensile strengths, minimum yield strengths and design stress intensities are given in Figures 5, 6 and 7.

8. Fatigue strength: Base material low cycle strain fatigue tests were conducted on 108 specimens (36 from each heat) per ASTM-E606-80 at three different temperatures: 70 F, 300 F and 600 F. The strain ranges were

0.006, 0.008, 0.010, 0.012, 0.014 and 0.017 inches/inch. The specimens were cycled using uniaxial tension/compression with zero mean stress to 100,000 cycles or to failure, which ever came first. The values for Sa given in Table 5 were computed using Code rules for generating the Design Fatigue Curve for zero mean stress, and the modified Goodman diagram as a basis for establishing mean stress effects on the fatigue strength.

9. Fracture toughness: Because this material is a non-ferrous material, fracture toughness is not of concern to the Code. However, this property is of particular importance for a cask structural material and is one of the expressed concerns of the NRC. In order to characterize the fracture toughness of the titanium alloy, 24 conventional Charpy V-notch tests were performed per ASTM E23-86, 18 J-integral tests were performed per ASTM E813-87, and to estimate the K -Id values, 30 instrumented (pre-cracked) Charpy tests were performed per ASTM E2401-81-1 (draft). The results are provided in Tables 6, 7, and 8.

All these tests bear out that the material is reasonably tough and in the temperature range of -40 F to 300 F exhibits only a mild toughness transition behavior. Stable behavior is noted in all the load-displacement traces obtained in J-Ic testing and in all the load-time traces of the pre-cracked Charpy tests. The plate material exhibits higher toughness than the billets. The material is fairly isotropic. It is apparent that for rolled plate (with assumed cross rolling) one should expect a Charpy energy of around 50 ft-lbs or greater between -40 F and 300 F. A J-Ic of around 500 in-lb/in^2 or greater is also to be expected. In addition, the toughness is not decreased by testing dynamically. Grade 9 titanium has been shown to exhibit reasonable structural and crack tolerance properties and its use as the structural material for a cask should be acceptable.

10. Creep: Creep data clearly indicate that the tensile properties govern the establishment of the allowable stresses rather than creep considerations for the temperatures under consideration.

<u>Weld Material Mechanical Properties</u>

11. Tensile tests: Tensile tests were performed on weldments made from the plate material. Data from these 10 tests showed good agreement with the results for the base material. The yield strengths are within 10% of the average yield strength for base metal at all temperatures. The tensile strengths are within 5 %. The reduction-in-area data for welded specimens fell within the range of data for the base metal. The elongation values at -40 F and 70 F were somewhat lower than the values from base metal testing.

12. Fracture toughness: Instrumented, pre-cracked Charpy tests on four specimens yielded estimates of K-Id values at room temperature that were higher than those for the base material at the same temperature.

13. Fatigue: Seventeen fatigue tests of specimens from both billet and plate weldments were conducted at room temperature to compare the behavior of these specimens with those of the base material. The results were within the data ranges obtained for the room temperature base material fatigue tests with the exception of two points at the 0.012 inches/inch

strain range.

14. Creep: Four longitudinal specimens and four transverse specimens were creep tested at room temperature and 600 F. The results indicated that the weld material has less resistance to creep than the base material but the creep rates are not high and would not constrain a cask design because the cask does not experience the combination of stress level, temperature and time that could potentially result in significant creep related distortions.

CONCLUSIONS

ASME Approval

As mentioned earlier, the NRC prefers to have outside approval of the properties of materials used in the construction of transportation casks. In the case of structural materials, ASME B&PV Code approval is preferred.

At the time Westinghouse proposed the use of the alloy, Grade 9 was not included in all of the ASTM standard specifications for titanium and titanium alloys for the product forms of interest. This issue has been resolved. Grade 9 is now included in the applicable ASTM specifications and has been approved for inclusion in the companion specifications given in Section II of the B&PV Code.

The use of Grade 9 titanium is now permitted for construction of components under the rules of Section VIII, Division 1 (Case 2081) as well as under the rules for Class 1, 2 and 3 components given in Section III, Division 1 of the B&PV Code. Case 2081 was approved in early 1990. The Board of Nuclear Codes and Standards approved the Section III Code Case, Case N-482, in December, 1990. Now a request has been made to include the material in Case N-482 in the Code itself.

NRC Approval

A topical report (Reference 9) on Grade 9 titanium has been prepared and transmitted to the NRC which details the tests discussed above and provides other information on weldability, corrosion resistance and radiation resistance as these aspects relate to spent fuel shipping casks. It is our belief that the information in the topical report together with the actions that have been taken by the various B&PV Code bodies will form a basis for the NRC to accept the use of the material in the construction of a cask for the transport of spent nuclear fuel.

ACKNOWLEDGMENT

The work reported in this paper was performed under Contract DE-AC07-88ID12699 with the U. S. Department of Energy, Idaho Operations. Mr. B. R. Nair was the Lead Technical Manager on the TITAN cask when the decision to use Grade 9 titanium was made and was largely responsible for its selection. RMI Company was responsible for the procurement of the titanium billets (from Teledyne Wah Chang Albany) and for contracting the mechanical testing work at the Westmoreland Mechanical Testing and Research, Inc. and the thermophysical testing at the Thermophysical Properties Research Laboratory, Purdue University.

TABLE 1
Grade 9 Titanium Material Property Tests

Test	Specification
Base Material	
Mechanical Properties	
Tensile properties	ASTM E8-87a,
Yield strength	& ASTM E21-79
Tensile strength	
Elongation	
Reduction in Area	
Modulus of Elast.	
True Stress-True Strain	
Poisson's Ratio	ASTM E132-86
Charpy V-notch	ASTM E23-86
J-Ic	ASTM E813-87
K-Id	ASTM E2401 -81-1 (Draft)
Fatigue	ASTM E606-80
Creep	ASTM E139-83
Thermophysical Properties	
Specific Heat	ASTM E968-83
Thermal Conductivity	Mod. Kohl-rausch Method
Thermal Expansion	ASTM E228-85
Emmisivity	ASTM E408-71
Weld Material	
Mechanical Properties	
Tensile properties	ASTM E8-87a ASTM E21-79
Creep	ASTM E139-83
K-Id	ASTM E2401
Fatigue	ASTM E606-80

TABLE 2
Nominal Coefficients of Thermal Expansion for Grade 9 Titanium

TEMPERATURE (°F)	INSTANTANEOUS COEFFICIENT OF THERMAL EXPANSION (IN/IN*F)	MEAN COEFFICIENT OF THERMAL EXPANSION (IN/IN*F)	COEFFICIENT OF LINEAR THERMAL EXPANSION (IN/FT)
70	4.76E-06	N/A	0.0
100	4.81E-06	4.70E-06	0.0017
150	4.88E-06	4.79E-06	0.0046
200	4.96E-06	4.84E-06	0.0076
250	5.04E-06	4.89E-06	0.0106
300	5.12E-06	4.93E-06	0.0136
350	5.20E-06	4.97E-06	0.0167
400	5.28E-06	5.01E-06	0.0199
450	5.36E-06	5.05E-06	0.0230
500	5.44E-06	5.09E-06	0.0263
550	5.52E-06	5.13E-06	0.0296
600	5.60E-06	5.17E-06	0.0329

TABLE 3
Moduli of Elasticity for Grade 9 Titanium

Temperature deg. C	(deg F)	Modulus of Elast. GPa	(psi E6)
21	70	110	15.9
38	100	108	15.7
66	150	107	15.5
93	200	105	15.3
121	250	103	15.0
149	300	101	14.6
177	350	98.5	14.3
204	400	95.8	13.9
232	450	93.7	13.6
260	500	90.9	13.2
288	550	88.2	12.8
316	600	85.4	12.4

TABLE 4
Tensile Test Results: Average Sy and Su

Temperature C	(F)	Yield Strength MPa	(ksi)	Ultimate Strength MPa	(ksi)
21	(70)	583	(84.6)	634	(92.0)
38	(100)	562	(81.6)	613	(89.0)
66	(150)	531	(77.1)	582	(84.4)
93	(200)	502	(72.8)	553	(80.3)
121	(250)	474	(68.8)	528	(76.6)
149	(300)	449	(65.1)	505	(73.3)
177	(350)	425	(61.7)	484	(70.2)
204	(400)	403	(58.5)	464	(67.4)
232	(450)	382	(55.5)	446	(64.8)
260	(500)	363	(52.7)	430	(62.4)
288	(550)	345	(50.1)	414	(60.1)
316	(600)	329	(47.7)	400	(58.1)

TABLE 5
Sm, S, and Minimum Sy and Su for Grade 9 Titanium

For Metal Temperature Not Exceeding °F	Design Stress Intensity S_m, ksi (Class 1 Const.)	Allowable Stress S, ksi (Class 2/3 Const.)	Minimum Yield Strength S_y, ksi	Minimum Ultimate Strength S_u, ksi
70	30.0	22.5	70.0	90.0
100	30.0	22.5	67.9	87.3
150	30.0	22.5	65.1	83.7
200	29.0	21.8	61.6	79.2
250	27.7	20.8	58.1	75.6
300	26.4	19.8	55.3	72.0
350	24.8	18.6	52.5	67.5
400	23.4	17.6	49.7	63.9
450	22.4	16.8	46.9	61.2
500	21.1	15.8	44.8	57.6
550	20.5	15.3	43.4	55.8
600	20.1	15.1	41.3	54.9

TABLE 6
Values of Alternating Stress, Sa, for Grade 9 Titanium

Number of Cycles	Zero Mean Stress MPa	Zero Mean Stress (ksi)	Max. Mean Stress MPa	Max. Mean Stress (ksi)
10	1044	151.6	1044	151.6
20	912	132.4	912	132.4
50	763	110.8	763	110.8
100	667	96.8	667	96.8
200	583	84.6	583	84.6
500	488	70.8	468	67.9
1000	426	61.9	391	56.7
2000	373	54.2	326	47.3
5000	311	45.2	258	37.4
10000	271	39.4	216	31.4
20000	237	34.4	183	26.6
50000	199	28.9	150	21.8
100000	178	25.8	132	19.1
200000	169	24.6	127	18.5
500000	161	23.4	123	17.9
1000000	156	22.6	120	17.4

TABLE 7
Charpy V-notch Results for Grade 9 Titanium

rientation[a]	Test Temp. (°F)	Energy (ft-lbs)	Mils Lateral Expansion	Percent Shear Fracture
	Heat 8768940 (Plate)			
L-T	-40	48	42	50
L-T	Room	74	50	60
L-T	150	65	58	50
L-T	300	111	50	70
T-L	-40	68	46	60
T-L	Room	66	60	60
T-L	150	102	56	60
T-L	300	109	52	70
	Heat 8768060 (Billet)			
C-R	-40	48	32	40
C-R	Room	48	44	50
C-R	150	68	46	50
C-R	300	83	46	50
L-R	-40	40	30	40
L-R	Room	53	50	50
L-R	150	62	52	50
L-R	300	82	54	50
	Heat 8768280 (Billet)			
C-R	-40	43	30	40
C-R	Room	56	50	50
C-R	150	64	42	50
C-R	300	74	50	50
L-R	-40	38	30	40
L-R	Room	52	48	50
L-R	150	48	44	50
L-R	300	68	54	50

TABLE 8
J-Ic Values for Grade 9 Titanium

Orientation[a]	Test Temp. (°F)	J_{Ic} (in-lbs/in^2)
	Heat 8768940 (Plate)	
L-T	-40	457
L-T	Room	531
L-T	300	960
T-L	-40	541
T-L	Room	462
T-L	300	963
	Heat 8768060 (Plate)	
C-R	-40	300
C-R	Room	272
C-R	300	375
L-R	-40	482
L-R	Room	356
L-R	300	676
	Heat 8768280 (Plate)	
C-R	-40	215
C-R	Room	216
C-R	300	552
L-R	-40	409
L-R	Room	311
L-R	300	564

TABLE 9
Estimates of K-Id from Pre-cracked Charpy Tests of Grade 9 Titanium

Orientation[a]	Test Temp. (°F)	K_{Id} Estimate (ksi $\sqrt{\text{inches}}$)
	Heat 8768940 (Plate)	
L-T	-40	106
L-T	Room	75
L-T	150	79
L-T	300	72
L-T	600	71
T-L	-40	89
T-L	Room	83
T-L	150	77
T-L	300	77
T-L	600	65
	Heat 8768280 (Billet)	
C-R	-40	85
C-R	Room	74
C-R	150	84
C-R	300	72
C-R	600	58
L-R	-40	82
L-R	Room	80
L-R	150	70
L-R	300	68
L-R	600	62
	Heat 8768060 (Billet)	
C-R	-40	75
C-R	Room	74
C-R	150	77
C-R	300	67
C-R	600	63
L-R	-40	93
L-R	Room	75
L-R	150	83
L-R	300	69
L-R	600	62

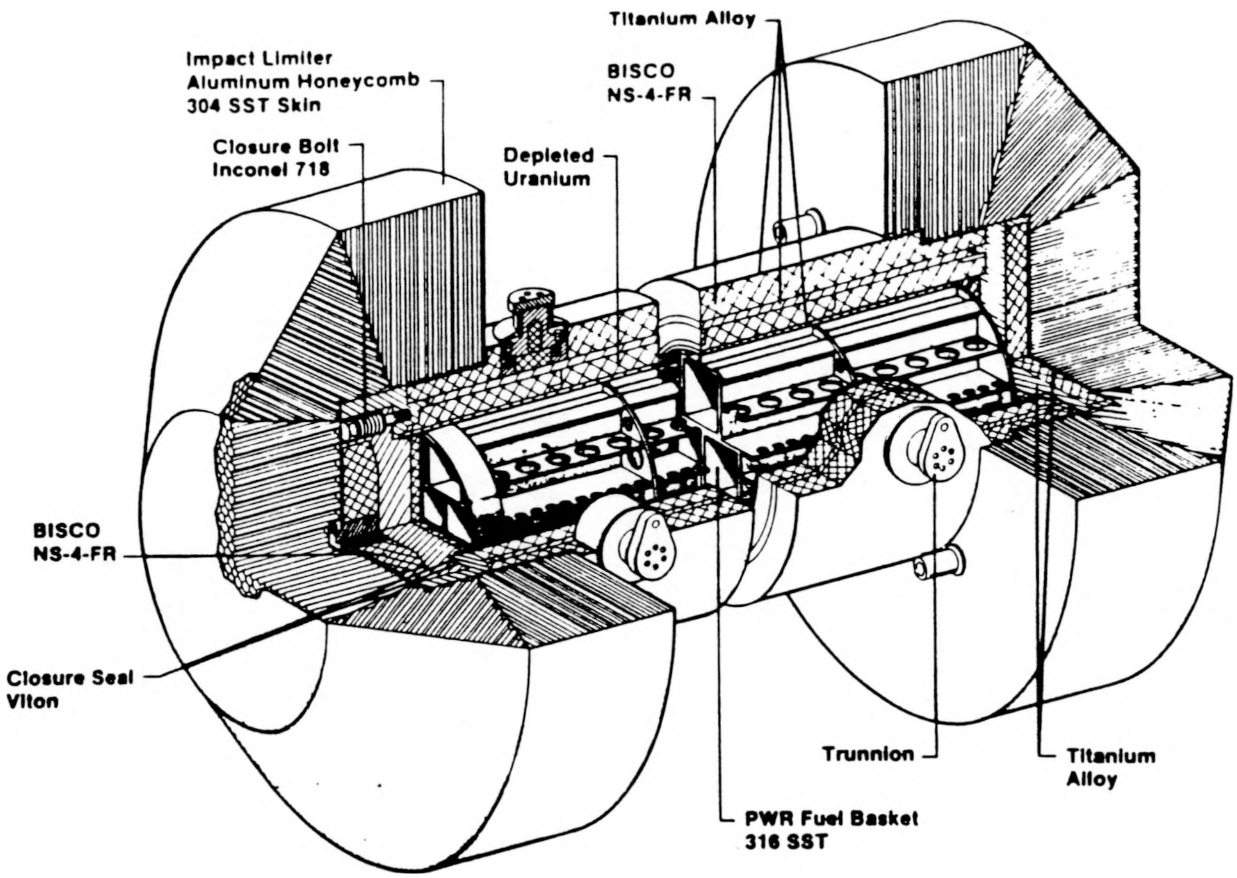

Fig. 1 TITAN Legal Weight Truck Cask

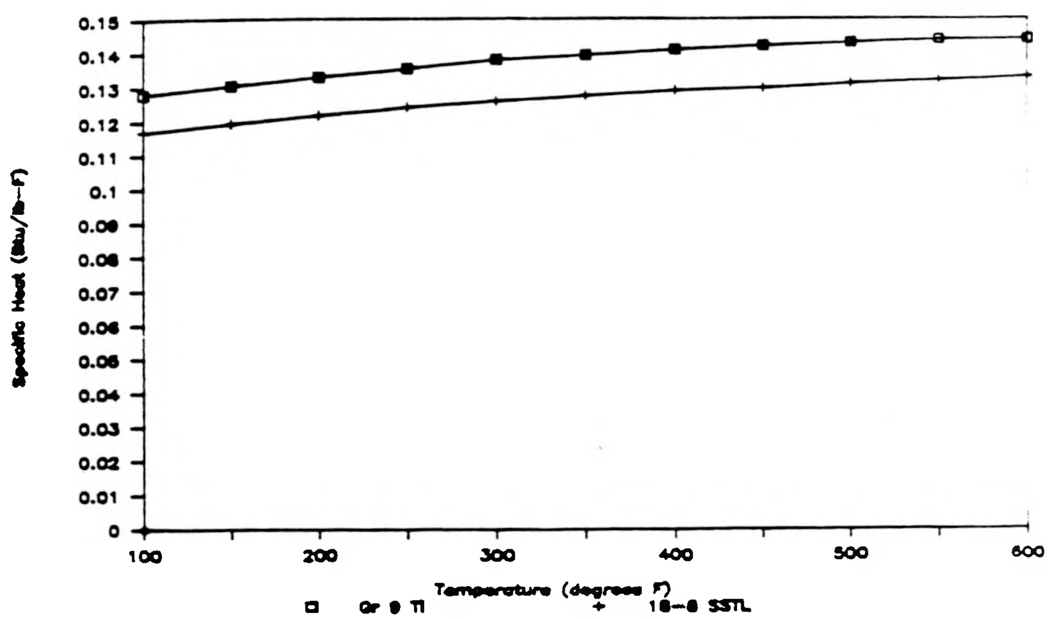

Fig. 2 Comparison of Specific Heats
for Grade 9 Titanium and Type 304 SStl

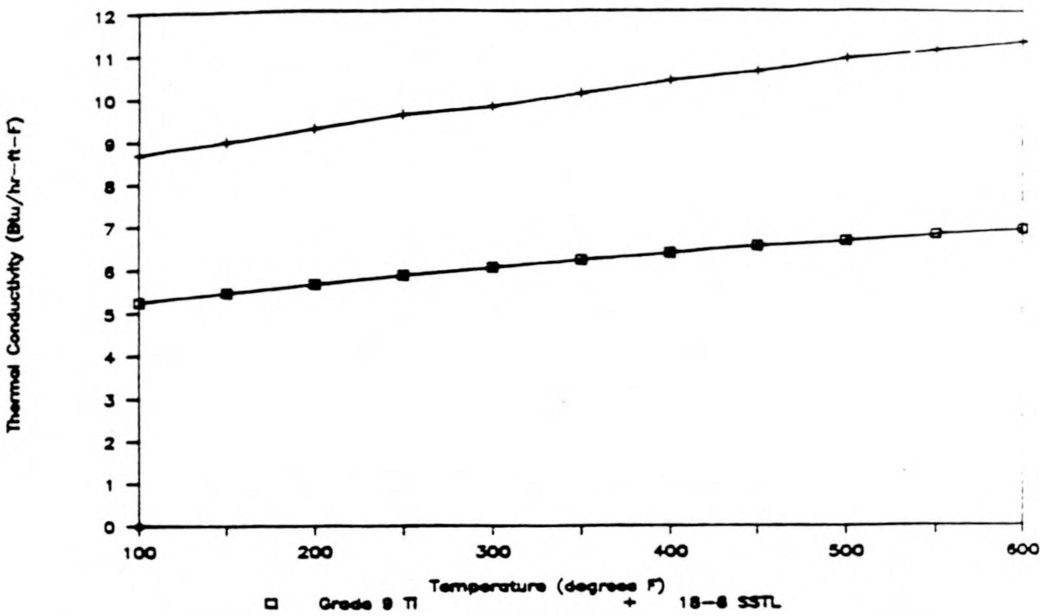

Fig. 3 Comparison of Thermal Conductivity
for Grade 9 Titanium and Type 304 SStl

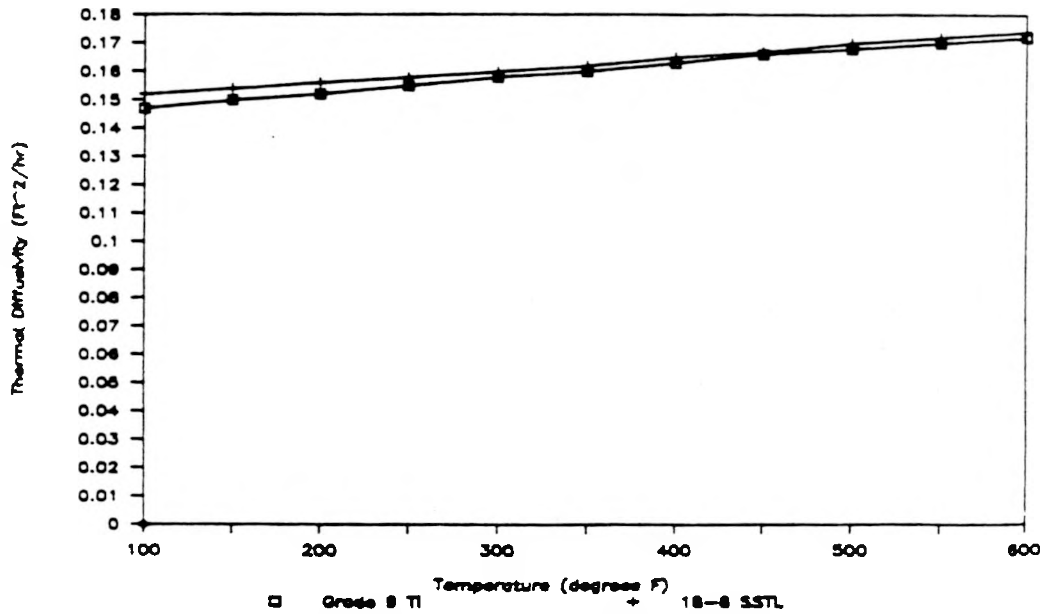

Fig. 4 Comparison of Thermal Diffusivity
for Grade 9 Titanium and Type 304 SStl

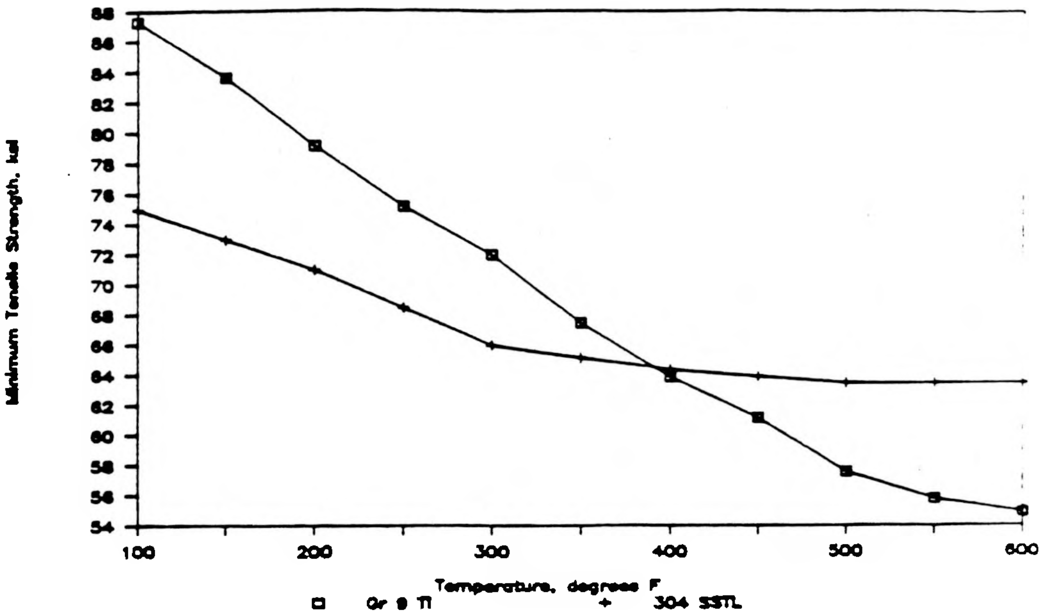

Fig. 5 Comparison of Min. Tensile Strength
for Grade 9 Titanium and Type 304 SStl

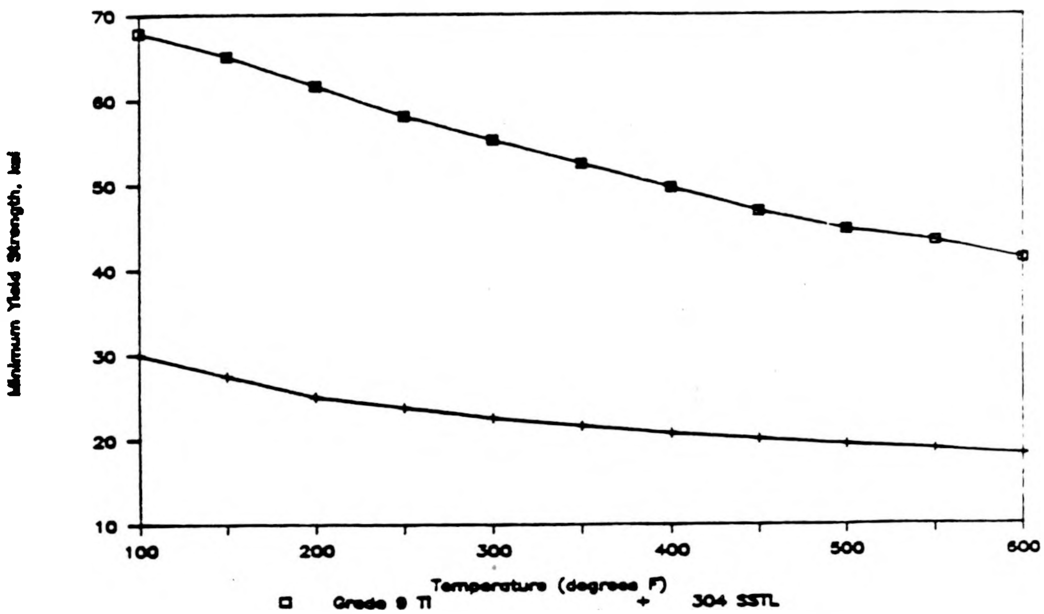

Fig. 6 Comparison of Min Yield Strength
for Grade 9 Titanium and Type 304 SStl

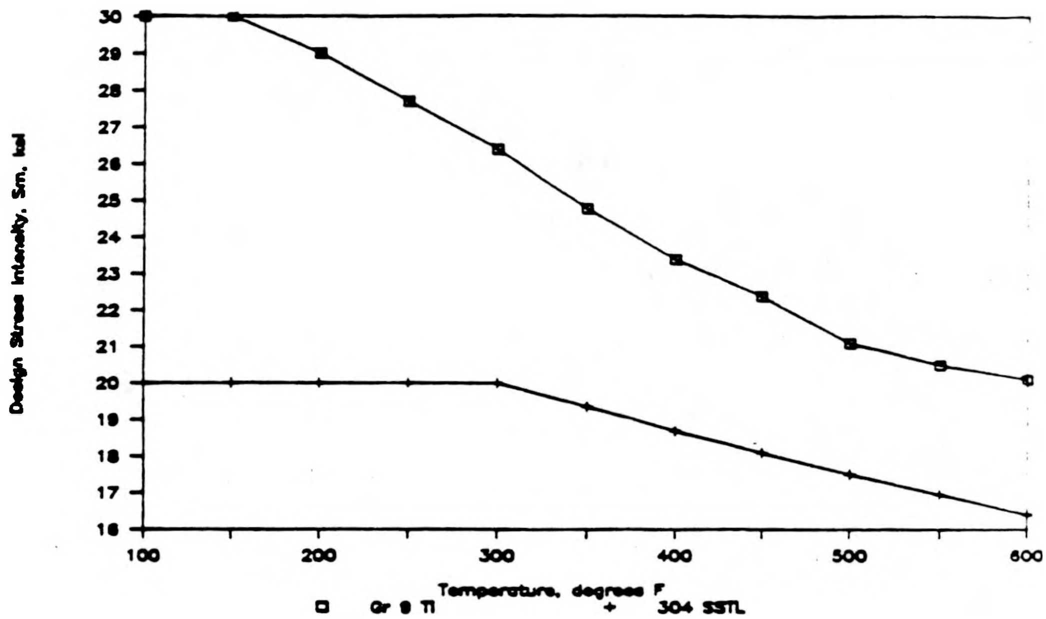

Fig. 7 Comparison of Sm for Grade 9 Ti
and Type 304 Stainless Steel

REFERENCES

1. Code of Federal Regulations, Title 10, Chapter 1, Part 71, "Packaging and Transportation of Radioactive Material," May 31, 1988

2. Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels," U.S. Nuclear Regulatory Commission, March 1978

3. ASME Boiler and Pressure Vessel Code, "Section III Rules for Construction of Nuclear Power Plant Components, Division 1-Subsection NB," American Society of Mechanical Engineers, New York, NY 1989

4. Russo, P. A. and Seagle, S. R., "Properties of Titanium for Industrial Applications with Emphasis on Ti-3Al-2.5V," Industrial Applications of Titanium and Zirconium: Third Conference, ASTM STP 830, R. T. Webster and C. S. Young. Eds., American Society for Testing and Materials, 1984, pp. 99-112.

5. Forney, Clyde E. Jr. and Schemel, John H., "Ti 3Al 2.5V Seamless Tubing Engineering Guide," Second Edition, Sandvik Special Metals Corp, May 1987

6. Metals Handbook, Ninth Edition, American Society for Metals, Metals Park OH, 1987

7. Aerospace Structural Materials Handbook, March 1980, Code 3725

8. Case 2081, "Use of Titanium Grade 9, Section VIII, Division 1," announced in "Mechanical Engineering," April 1990

9. "Suitability of Grade 9 Titanium for the Structural Material for Spent Fuel Shipping Casks," NWT-TR-038, Westinghouse Electric Corporation, Nuclear Waste Technology, Pittsburgh, PA, January 1991