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LARGE RADIOISOTOPE HEAT SOURCE
CAPSULE PROGRAM
TOPICAL REPORT NO. 10
CREEP OF T-111 RADIOISOTOPE CONTAINMENT
VESSELS UNDER INCREASING PRESSURE

AEC Research and Development Report

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DATE 7/21/70

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Printed in the United States of America
Available from

Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

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By
P. B. FERRY

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CONTRACT: AT(29-2)-2338
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I. INTRODUCTION

The Large Radioisotope Heat Source Capsule is a test vehicle designed to provide the engineering information necessary to design a capsule for alpha emitting radioisotope fuels. The total operating environment for the capsule is to be: launch within one year after manufacture, operation in space vacuum for design life of five years at 2000 °F, reentry into the earth's atmosphere and impact on the ground. The capsule is to contain the fuel and fuel products until recovered.

This mission profile imposes certain failure modes: interdiffusion of various capsule components which could result in loss of function of a component; creep of various components under the pressure of the fuel products to lose function, such as spalling of emittance or compatibility coatings, or even rupture of the major containment members; breach of containment members during impact, resulting in dispersal of the fuel. There are also accident conditions such as exposure of the capsule to high temperature in the event of a launch pad fire or abort.

A capsule design was proposed which would push the limit of state of the art of production processes and materials, in order to evaluate and test their ability to meet the requirements of the mission proposed. The design proposed and adopted for the program is shown in Figure 1. It basically is of tantalum alloy construction. The fuel liner is of all Ta-10W construction. It consists of two tubes held concentrically by fuel retainer rings and capped on both ends with hemispheres. All exterior welds are full penetration, continuous electron beam welds. This seals the 200 watts of fuel and allows for decontamination during manufacture. Welds inside the outer liner are non-continuous to provide paths for the helium gas produced by the fuel to diffuse into the void volume of the capsule. The void volume provides a plenum for the gas to decrease the stress on the strength member. The strength member is of T-111 (Ta, 8W, 2Hf), and consists of a structural shell and hemispherical cap. The structural shell is of completely seamless construction. The strength member is designed to retain the stresses induced by the fuel products and protect the liner during other conditions such as impact and fire. In order to protect the tantalum alloy components during operation in the air, both prior

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Figure 1. Large Radioisotope Heat Source Capsule (LRHSC)

to launch and after reentry, the capsule is canned in a noble metal alloy Pt-10%Rh. To prevent interdiffusion of the oxidation barrier with the structural member, an alumina coating is applied to the structural member. The oxidation clad is coated with iron titanate for maximum emissivity.

Material and process specifications for construction of the test vehicles^{1, 2}, development of fabrication and assembly processes^{3, 4, 5}, and tests of the capsule for high temperature compatibility, impact and fire^{6, 7, 8}, have been reported. A program was designed to develop and test an analytical model for creep of the T-111 pressure vessel under operating conditions. This report discusses that program. It includes procedures and results of that program testing the analytical model of a T-111 pressure vessel under constantly increasing internal pressure. All tests were conducted at the operating temperature of interest (2000 °F), pressurized with helium, and in an external environment of a pressure less than 10^{-8} Torr.

Every effort was made to simulate the environment the capsule would undergo during operation. The environment was designed not to change the alloy content of the material.

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II. ANALYTICAL MODEL

To set up a test program to develop an engineering model for creep of a T-111 pressure vessel under a variable stress, a target model was first proposed. In a constant load, uniaxial program, a single sample can be loaded at a temperature of interest, the strain rate noted, loaded again at higher stress, strain rate noted and so on. From a very few samples the target static independent variable, load, can be selected for a range of strain rates considered adequate to map out and test the creep behavior of a particular material. In a variable, biaxial stress state test the model must also be checked out on a few specimens, but it is a little more complicated than commonly found in the constant load situation. If the strain rates of the specimens are not amenable to engineering treatment, the source of the analytical error must be found, corrected and a new model utilized. This can be quite difficult because of the potential complexity of the model, and the unknown synergistic nature of interacting effects. More will be said on the matter in the operations portion of this report.

Models have been proposed to account for engineering strain in materials with increasing loads^{9,10,11,12}. The basis for the model utilized on this program is Mullendore's. It contains some basic assumptions and additional assumptions were required to develop the test program. The model develops in this manner:

1) The strain of any component under a constantly increasing stress is equal to the integral of all prior instantaneous strains

$$\epsilon = \int_0^{\theta} \epsilon_i d\theta \quad (2)$$

2) Under discrete static load conditions the strain rate is linear and can be described

$$\dot{\epsilon} = \frac{d\epsilon}{d\theta} \quad (3)$$

3) The strain rate is a function of stress, stress state, prior stress, stress rate, prior strain, temperature, prior temperature, and is sensitive to the operating environment;

$$\dot{\epsilon} = f(\sigma_1, \sigma_1^s, \sigma^p, \sigma^o, \epsilon^p, T, T^p, C_{O,H,N,C}) \quad (4)$$

4) Assume further that in test and in actual service that

a) the stress rate is sufficiently low as to be considered zero

$$\dot{\sigma} \rightarrow 0$$

b) the maximum principal stress in the biaxial tests is the only stress producing observable creep

$$\sigma = \sigma_\theta$$

c) prior stresses on the test specimen are sufficiently low as to have no affect on the material

$$\dot{\epsilon} \neq f(\sigma^p)$$

d) that the alloy is stable under prior thermal exposure and test temperature

$$\dot{\epsilon} \neq f(T^p)$$

e) that the alloy is stable in its operating environment

$$\dot{\epsilon} \neq f(C_{O,N,H,C})$$

f) that the strain is sufficiently low as to be considered insignificant

$$\epsilon \rightarrow 0$$

5) If the assumptions of 4) are accepted, then the instantaneous strain rate is a function of the stress and temperature alone.

$$\dot{\epsilon}_i = f(\sigma_i, T_i) \quad (5)$$

6) Inserting this into equation 1, then relates that the strain at any time is equal to the integral of a function of the prior instantaneous conditions of stress and temperature, with the dependent variable being time at each condition.

$$\epsilon = \int_0^\theta f(\sigma_i, T_i) d\theta \quad (6)$$

If the stress vs. strain rate relationship is known for an alloy,

the strain rate induced at each stress can then be determined

If a stress schedule is selected for a test

integration of the instantaneous strain rates results in the strain of the member at any time

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III. TECHNICAL APPROACH

A. INDEPENDENT VARIABLE SELECTION

The test program was designed to develop the stress versus strain rate relationship, and to test the strain rate integration technique. Three further assumptions were required to select the independent variable stress rate, in magnitudes producing measurable strain rates applicable to radioisotope capsule design:

Differentiation of a 1% Larson Miller type parametric correlation of uniaxial constant load data on thin sheet in ultra high vacuum (10^{-9} Torr) adequately describes the stress versus strain rate relationship of that material under test (in this program), and that this would also be directly applicable to biaxially loaded heavy sections in environment with helium on one side and intermediate (10^{-8} to 10^{-9} Torr) vacuum on the other.

The strain in a biaxial creep test shall be that change in diameter of the vessel observed divided by the initial diameter of the vessel prior to pressurizing.

$$\epsilon = \frac{D_i - D_o}{D_o} \quad (7)$$

The only stress causing the strain shall be that stress produced from the thin walled approximation:

$$\sigma_{\theta} = \frac{PD}{2t} \quad (8)$$

The stress versus strain rate relationship for the test program was taken from a Larson Miller type correlation of T-111 uniaxial constant load and hot tensile data, shown in Figure 2¹³. To develop stress rates for the tests, example stress rates were made, strain rate versus time were calculated, and the resulting strain history plotted. An example, developed by Mullendore, of a stress rate selected to produce 1% strain in seven years is shown in Figure 3¹⁴.

Figure 2. Larson Miller Plot of 1% Creep Life Data for T-111 Alloy Annealed 1 Hour at 3000 °F (1649 °C)

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Figure 3. Strain History of Typical Radioisotope Capsule

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Figure 4. Stress Rate Schedule Selection

Note that the strain rates do not become very significant until after five years. The significant strain take place only in the last two years. Utilizing the same techniques for the test program, a similar result is achieved for a test to 1% strain in one year. During the first nine months negligible creep occurs. It is only during the last three months that measurable creep can be observed. From both material and test standpoints, strains below 0.1% are considered negligible.

In order to adequately describe strains below 0.1% the instrumentation must be precise and accurate to 10 microinches. To our knowledge, instrumentation of that precision have not been effectively integrated into high temperature, high vacuum testing. Additional problems occur at that level of precision from vibration, surface finish of the test specimen, alteration of the surface from thermal-vacuum etching, and temperature control and measurement. For example, the surface finish of the part would have to be and stay smoother than 1 microinch average. Even a 1°F uncertainty in temperature exerts a significant influence on the apparent strain. To reiterate, strains at that level are considered insignificant. It does not seem reasonable from a cost and rig utilization standpoint to run all the tests in the mode starting with the pressure at zero. Over 3/4 of the test time is spent without measurable strain.

One way around the problem would be to utilize some of the assumptions made. Those specifically are that there is no effect on the stress versus strain rate relationship by prior strains and stresses. Of course in many cases this is not true; that is when the prior stresses and strains are large. It is quite possibly true when they are very small. If one takes 0.1% strain as being very small and takes the stress at that strain on the stress rate curve beginning at zero as being small then a truncated test procedure can be developed which will have no effect on the relationship to be derived and tested. This type of procedure is shown in Figure 4.

TABLE I

CALCULATED STRESS RATE MODES FOR TEST PROGRAMS

Mode	σ_0 (ksi)	$\frac{d\sigma}{d\theta}$ (psi/hr)	$\theta_{(0.1\%)}^{(hrs)}$	$\theta_{(0.1-1\%)}^{(hrs)}$	ϵ_{Total}
1	17.6	55	58	100	1%
2	12.7	5	480	1000	1%
3	9.1	0.72	2600	6000	1%
4	17.6	0.5	58	100	5%
5	12.7	5	480	2200	Rupt
6	9.1	0.72	2800	6000	5%
7	12.7	5	480	1000	5%
8	0	0.96	0		1%

In the truncated mode a stress rate is selected which will induce a creep rate sufficient to cause the capsule to strain from 0.1 to 1% in 1000 hours. The pressure that would be expected at 0.1%, if the tests were started from zero pressure, is the initial pressure of the test. During the early portion the stress and strain rate is lower than will be experienced during the remainder of the test and its effect should be negligible on any further data analysis. It is an assumption however that should be tested.

The test mode selected for the program is shown in Table 1. It is to include three basic stress rates: to induce strain from 0.1 to 1% in (a) 100, (b) 1000, and (c) 6000 hours. According to calculations, the tests would begin at constant pressure, and achieve 0.1% strain in (a) 58, (b) 480, and (c) 2800 hours respectively. The third or lowest stress rate was designed to have a test duration of one year or 8800 hours. If one replicates the tests, with the exception of not terminating the tests at 1% total strain, but lets the second set continue on to 5% strain then there is overlapping of stress in separate tests. That is in the testing of the intermediate rate test (1000 hours) there are times when the stress is the same as in both the high and low rate tests. In those tests however, both the time, prior strain, prior stress, stress rate and prior stress rate are all different. If it occurs that the strain rate at a particular stress is the same for these tests, the numerous assumptions made to facilitate the test program were valid. If not, then data are available to determine which are affecting variables.

B. TEST SYSTEM DESIGN

1. Target Performance Requirements

a. Test Environment

Tantalum alloys are subject to contamination at elevated temperatures by active impurities such as carbon, oxygen, nitrogen, hydrogen, hydrocarbons, etc. Additions of these to the alloys change their mechanical properties. The test environment must therefore prevent a reaction of the capsule materials with these impurities.

b. Pressure Attainment and Control

Stresses are to be applied to the test capsule by pressurizing with an inert gas. The control system must be able to apply a constant pressure and variable pressure at rates ranging from 0.1 to 10 psia/hr. The maximum pressure required is 6000 psia, and the actual pressure must be known to 1/4% accurately over the full test range.

The system must operate in either mode over the full pressure test range for the duration of the tests (up to 14,000 hours).

c. Temperature Attainment and Control

The strength of the alloys are temperature dependent; therefore, the test capsule must be isothermal throughout the tests. The allowable temperature tolerance is $\pm 5^{\circ}\text{F}$. The heat source must contain provisions for measuring the capsule diameter at two radial locations. Because the thermocouples are subject to drift during long term operation, provisions must also be made to compensate for this.

d. Strain Measurement

A technique is necessary to measure the diameter of the capsule at the longitudinal midplane, in two radial planes 90° apart. The precision and accuracy must be within 100 micro inches.

2. Test System Design

The test system is divided into four separate but integrated subassemblies. They are the test chamber and vacuum pump, the specimen heater, cathetometer, and pressure control system.

a. Test Chamber

The test chamber is required to contain the capsule and furnace in the 10^{-8} Torr or less pressure range, and to provide the necessary access for measuring the strain of the capsule continually throughout the life of the test.

Three existing chambers, appendage pumped by 1200 l/sec vacuum ion pumps, were selected for modification. These systems were initially designed and built for lower temperature operation and additional cooling coils were required on the walls and upper flanges of the chambers. The cooling tubes were attached to the bell jars by standard staking methods and then thermally bonded with a graphite dispersed cement. At a water flow rate of 4 SCFM the surface of the chamber is maintained below 100°F while the capsule is at 2000°F and 1.5 kw of electrical power is being used.

The overall chamber design is shown in Figure 5. All instrumentation feed throughs are in the upper flange, with the exception of the ion gauge, and sight windows which are on the chamber wall. Initially it was found that the heat radiating from the furnace sight holes overheated the optically flat windows when the capsule was at 2000°F. Stainless steel radiation shields were added to the window ports to eliminate this problem.

Once the design was worked out on these modified systems, two more were designed and constructed specifically for the program. The vacuum pumps for these systems were 400 l/sec. This brought the total number of systems used on the program to five.

Because of the high vacuum desired, all seals were metallic. The joints used were either brazed, welded or metallic gaskets crushed in a set of mating flanges. The feed throughs are shown in Figure 6. The two power feed-throughs are standard high fired ceramic standoffs brazed to a copper conductor, and to the stainless steel flange. The rotational motion feed through uses either eccentric bellows or magnetic coupling to open and close the shutters on both windows simultaneously.

The thermocouple feed through can accommodate four thermocouples. The large (0.040 inch diameter) thermocouples used for high temperature stability, needed to be modified to meet standard feed through design. Portions of the legs of the Pt alloy thermocouples which are not at elevated temperatures

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Figure 5. Overall Biaxial Creep Test Chamber

Figure 6. Upper Support Flange Showing Location of Vacuum Feed Throughs

Figure 7. Design of Rupture Disc Assembly

(less than 1600°F), are reduced in diameter by swaging. After cleaning and annealing, the thermocouple legs are fed through the feed through tubes and brazed at the tube extremity. The wires are electrically insulated from the feed tubes, away from the braze, by fiberglass tubing. This technique eliminated a problem which had occurred during early portions of system shakedown when the feed tube caused a secondary junction which could change the indicated output of the thermocouples at 2000°F by 150°F. This uncompensated drift could be induced by about a 50°F change in the feed through temperature. After the T/C harness is assembled, all thermocouples are calibrated with a copper freezing point standard. The noble metal wires extend to an ice bath which is filled each day, prior to determining the test temperature with a potentiometer. The output of the T/C's is recorded continuously for information only.

The pressure feed tube and the burst diaphragm are brought through a common port with a tee. Neither see the direct radiation from the furnace and both remain at room temperature. The burst diaphragm is a safety feature. It is designed to rupture at 1 atm ΔP inside to outside prior to rupture of the sight windows. The design of the diaphragm is shown in Figure 7. With 1 atm ΔP on the diaphragm from the atmosphere to the chamber the diaphragm is deflected toward the inside of the chamber (normal operation). If the pressure builds up inside the chamber such that there is a 1 atm ΔP from the chamber to the atmosphere, the diaphragm deflects against the knife edges, tears and vents the chamber. The rupture disc assembly is all welded construction. To preclude the possibility of air going back into the system and ruining the specimen and furnace, an expanding chamber capable of containing the total gas supply is attached to the exhaust throat of the rupture assembly. A weather balloon is used for this purpose.

b. Furnace Design and Operation

The furnace and controller are required to maintain the 1-3/4 inch diameter by 8 inch long capsule at 2000 $\pm 5^\circ\text{F}$ for periods up to 15,000 hours. There

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Figure 8. Furnace and Capsule Assembly

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must also be provisions for sighting the edges of the capsule at two diameters in order to observe the strain during operation. Additionally, the furnace design must take into account provisions for the pressure feed tube and thermocouples and a sight port for a black body.

The basic furnace design selected is an alumina insulated, tantalum coil resistance heater, with tantalum radiation shields. The insulators are coated with tungsten to preclude interaction of the tantalum with the alumina. Sight tubes are added for ease of viewing the capsule edges and baffles for diminishing the thermal gradients. The relationship of the capsule to the furnace assembly is shown in Figure 8.

Four 0.005 inch thick, vertical, cylindrical tantalum baffles are positioned between the heater coils and the capsule to smooth out the capsule temperature profile. Without the baffles there was a 150°F radial gradient at 2000°F, caused by the sight holes. The baffles reduce this to less than 3°F. They also provide the means of diminishing the longitudinal thermal gradients. Portions of the baffles are removed above and below the capsule so that the top and bottom regions of the capsule receive the direct radiation of the heater coil. The effect is the same as the use of end guard heaters, compensating for heat loss through the lead tube and the bottom supports. With the baffles running the full length of the furnace the temperatures were: top - 1950°F; middle - 2000°F; and bottom - 1975°F. With the baffles trimmed to proper size (empirically) the longitudinal gradient is less than 5°F. The baffles also provide an excellent means of compensating for the addition of samples for thermal treatment at the same temperature without constructing a new furnace. A stack of coupons can be placed on an insulator pedestal below the capsule. The pedestal receives the direct radiation of the heater which compensates for the heat loss down the pedestal. This is an extension of the same technique used to eliminate the effect of the heat drain from the lead tube at the top of the furnace.

Figure 9. Scalloped Alumina Sight Tubes

Figure 10. Sight Tubes in Contact With Mock Capsule

Thermocouples attached to the specimen are connected to a proportioning controller to provide the temperature regulation. The controller indicates the power requirement to a silicon controlled rectifier. The total variation throughout a capsule during test is less than $\pm 5^{\circ}\text{F}$.

In test, strain measurements are made with a coordinate cathetometer as discussed in the next section. Initially there was a major problem associated with visually locating the edges of the auto illuminated capsule. This difficulty was associated with the inability to discern the small temperature differences between the capsule and the background furnace shields. The furnace was essentially a black body cavity. To alleviate the difficulty, a pair of alumina tubes were scalloped as shown in Figure 9. The scallop radius is about 0.030 inch larger than the capsule radius. Figure 10 shows the sight tubes in contact with a mock capsule. The purpose of the scallops is twofold: position the capsule in two planes and provide visual access, to the capsule at two diameters. The view of the capsule edges in the plane sighting down the tubes was excellent. The overall view in the optically flat window of the two sight tubes and black body is shown in Figure 11. A closeup of the capsule edge in the sight tube is shown in Figure 12. There are two additional sight tubes in the assembly for the obverse plane. The four tubes are shown with the baffle subassembly in Figure 13 and in the total furnace assembly in Figure 14.

c. Strain Measurement

The capsule diameter strain is measured with a single objective coordinate cathetometer. Its precision is 0.00005 inch, in practice less than a decimal point is lost in the optics, and operator. Diameter measurements are made as often as required, more often on the shorter term tests, less on the longer term ones where the creep rate is low. To insure that the cathetometer is in the same location for each measurement, a set of flat washers are bonded to an 1/8 inch thick steel plate. The plate is bolted to the vacuum chamber. The feet of the cathetometer locate on each washer. The bond is more brittle than strong, so that if severely jarred, it becomes unbonded, indicated that it has been moved.

Figure 11. Overall View of Sight Window

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Figure 12. View of Capsule Edge in Sight
Tube at Temperature

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Figure 13. Cylindrical Baffles
and Sight Tubes

Figure 14. Baffles and Sight Tubes
Assembled in Furnace

d. Pressure Attainment and Control

A pressure control system was constructed to complete the test system. The main purpose for the system was to provide automatic pressure rates for the short term tests. It is during these tests that pressure increases should be small so as to approximate a straight line. For the longer term tests where the pressure increases are small (in the order of 1 psi/hour and less) the pressure can be increased at reasonable time periods and the ramp still approximate a straight line. For instance, at 1 psi/hour, a daily increase of 24 psi is very small compared to the actual operating pressure of 3000 to 6000 psi. A significant effort was placed in getting the ramp generator operating reliably without total success. Problems were encountered both during tests and pre-test checkout which indicated that the injection of new pressure at selected time intervals was the reliable method and this was adopted for all tests. The basic system was switched from automatic to manual mode and operated for the remaining tests of the program. The gauge utilized in the system is accurate to $\pm 0.01\%$ FS, and is calibrated as required. Initially it was calibrated each month, until found to be stable over that time period. After then the calibration checks are made each two months, and finally each quarter. Each time the gauge is calibrated, it is isolated and removed from the test system. Following checking, it is reinserted in the system and all piping evacuated prior to resuming pressure increases on the capsule. The capsule is isolated from the system plumbing while this operation is in progress. A recheck of the pressure in the capsule is made after each time the calibration is made.

A common manifold for the four long term test rigs facilitates the use of one pressure control system. Another system is utilized for the short term test rig. The procedure for pressurizing each capsule is straightforward. With all the capsule isolation valves in the operating (closed) position, the manifold is brought to the pressure in the capsule to be checked. The manifold is then sealed. The isolation valve is then opened for the subject capsule and the pressure noted. After noting the pressure to be correct (which it always was

unless of rupture) the pressure in the manifold was then increased to the desired new pressure. The isolation valve was then sealed. The pressure was then checked and increased in the remaining tests one at a time with the same procedure. When a test was terminated, the capsule was removed from the manifold below the isolation valve. When starting up a new test, the capsule was connected to the isolation valve, opened to the manifold, and the whole system evacuated, simultaneously with the test chamber. Following evacuation and bringing the capsule to temperature, the manifold and capsule was repressurized to the required pressure, and the isolation valve closed.

After a series of capsules was pressurized, it was necessary to decrease the pressure in the manifold to repeat the operation. The helium in the line was released into a pressure chamber to assure that the whole system was a closed cycle and prevent diffusion of air into the manifold during venting.

The short term tests were isolated to one system because of the high ramp rates required. This precluded the need for pressurizing and depressurizing of the long term, low ramp manifold. Operation of this system was the same only this manifold had only one test to maintain.

3. Test System Operation

The test is assembled to the upper support plate or flange of the test chamber, checked out, and then inserted in and mated to the test chamber. This procedure has a number of advantages over a design which assembles the test in or on the test stand chamber and then covers it with a chamber or jar. In the preassembly technique the time the chamber is vented to air is minimal. When a test is concluded, it is pulled out and a preassembled one inserted. The venting time then is only the bolting and unbolting time. This decreases the pump down bakeout cycle time. Secondly, the laboratory personnel can be better utilized. While tests are operating, the next test assembly is built up, evening out the manpower requirements for the laboratory. Thirdly, the assembly is performed in one place. All necessary tools such as

Figure 15. Creep Capsule Mounted
to Support Plate

Figure 16. Creep Capsule with Lead Tube

welders, bending tools, and shears are centrally located in the assembly area. Once the test is assembled it is then rolled to the test chamber rather than having to move the assembly equipment.

The following is a typical assembly sequence. The upper support flange is bolted to a cantilevered support fixture, as shown in Figure 15. During assembly this fixture is bolted to the assembly table. This suspends the plate about six feet from the floor, a convenient working height. After the support plate is mounted, the vacuum feed throughs are mounted and tested for function. The furnace support rods are then screwed into the flange. A keyway is provided in the threaded male section to provide a vent path for the trapped gases in the threads. The thermocouples to be used inside the furnace are then led through the upper furnace shields. The upper shields are brought into place and held during primary assembly by a temporary support wire secured from slipping by grooves in the support rods. The capsule and lead tube is shown in Figure 16. The pressure tube is field brazed to the feed through. Because the braze is required to operate at only 1 atm ΔP , it is not a critical process and stringent inspection is not required. The thermocouples are attached to the test piece by thin foil bands which have been prewelded and contain a small cup for the thermocouple junction. The bands are slipped up the capsule to the desired location and the thermocouple inserted. The band material is of the same base metal as the exterior of the test piece to prevent a change in properties by interdiffusion. The cups also provide metal protection of the thermocouple and the test piece from each other. The cup provides a cavity to protect the thermocouple from the direct radiation of the furnace. For a system with little heat flow the indicated temperature of the thermocouples attached by this method is the same as those peened into the test piece.

The furnace is brought up around the capsule, bolted to the support rods, and power leads hooked up. The total assembly is unbolted from the assembly table, and secured to the tines of a laboratory hydraulic lift. The assembly and a portable table are shown in Figure 17. The assembly is rolled to and

Figure 17. Furnace and Assembly Fixture

Figure 18. Mating of Test to Chamber

lowered into the test chamber. The assembly, half into the chamber, is shown in Figure 18. The flange is sealed. The system is then evacuated as shown in Figure 19 and baked out at 600°F. The ion pumps are then started and the chamber pressure reduced to below 10^{-6} Torr range.

The capsule is brought to the test temperature and allowed to stabilize for about a day. After stabilizing the test chamber pressure is nominally in the mid 10^{-8} Torr range. The capsule is then pressurized.

During this period the capsule diameter is measured to obtain the initial diameter D_0 , and the relationship between the indicated temperature of the black body and the thermocouples is established.

Figure 19. Roughing of Chamber

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IV. MATERIALS

The test vessels for the program were fabricated from one heat of material by a single reproducible process and with the exception of one capsule, B5. Details of the fabrication and assembly sequences are contained in two other reports from the program^{3, 5}. The semi-stock was procured from the Metals Division of Norton Company in the form of 0.170 inch thick plate. The pressure vessels were then deep drawn in eight stages to the finished configuration. In the case of the short term, high stress rate tests, an additional ironing stage was utilized in order to reduce the wall thickness to a nominal 0.090 inch thick. This was required in order to achieve the required stresses with the 5000 psia limit required as a safety feature of the pressure control system. The single stage coined end caps were electron beam welded to the body to complete the vessel. A Ta-10W pressure feed tube was welded to a boss on the cap to facilitate pressurization. Once out of the heat zone of the furnace, a high strength steel tube was brazed to the tantalum alloy pressure feed tube. The Ta-10W components for the "A" capsules were also procured from Norton. The liners were procured as tubing, the mating caps and rings were bought as sheet and coined into the required configuration. These components were also electron beam welded.

All components were heat treated after forming, and prior to welding and service. With the exception of capsule B5, all pressure vessel bodies and caps were heat treated at 3000°F for one hour. The components for B5 were welded and tested in the "as-formed" condition. All of the Ta-10W components were heated for one hour at 2600°F.

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V. RESULTS

The detailed results of all tests are contained in Appendix 1.

A. ADJUSTMENT OF STRESS SCHEDULE

Figures 20a and 20b indicate a problem which occurred and indicates the reason for reduction of the wall thickness on subsequent high stress rate tests. The stress-strain rate relationship utilized to set up the program predicted strain rates approximately one order of magnitude lower for an equivalent stress than experienced on this program. In order to produce strain rates of interest to the program, the stress and stress rates had to be increased by almost 50%. The uniaxial, constant load data produced in ultra high vacuum indicated that the material was much weaker than observed in this test, and in tests of the remainder of the program. Calculation methods and criteria for applying uniaxial data to biaxial conditions were thoroughly examined to determine if this could be at the source of the difference, with no avail. The results reported here will utilize the thin wall right circular cylinder stress model and apparent strain. There is sufficient detail in the appendix so that the reader can make an independent analysis utilizing his own models.

The problem posed by this gross difference was then, what stress-strain rate relationship should be utilized for the program? This was found experimentally by increasing the stress and stress rate on each subsequent test until the target strain rate schedules were achieved. A number of tests were run on this first capsule to determine if the observed low strain rate was a test induced variable, such as contamination of the material from the test environment. Pretest and post-test interstitial analysis of the specimen in Table III indicated no such change, and if anything, a slight decrease in some of the interstitial strengtheners. Evaluation of the overall chemical composition of the material also indicated that this heat was not high in any strategic strengtheners. Table II shows that the heat was a nominal heat of T-111 and if

8-J6-099-49
Figure 20-a. Tangential Stress - Capsule B-1a

8-J6-099-50
Figure 20-b. Mid-Point Diametral Strain -
Capsule B-1a

TABLE II
CERTIFIED CHEMICAL COMPOSITION
T-111 PLATE - HEAT #8048

	<u>ppm</u>
O	29-38
H	2.2, 0.98
N	22 25
C	31 44
Co	25 25
Cr	<1 <1
Fe	10 15
Mo	15 20
Nb	200 200
Ni	<1 <1
V	<1 <1
Zr	400 450
W	7.53 7.64*
Hf	1.88 1.91*

* Wt %

TABLE III
INTERSTITIAL ANALYSIS OF TEST B 1-a

	As Received T-111 (ppm)	After Test (ppm)
Carbon	38	40
Nitrogen	25	30
Hydrogen	5	10
Oxygen	65	45

Conclusion: Increased creep strength not due to interstitial contamination

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PRE-TEST

POST-TEST
(600 HOURS)

POST TEST WITH 2700°F
FOR 1 HOUR ANNEAL

- CLEAN STRUCTURE
- UNIFORM GRAIN SIZE
- COMPLETE RECRYSTALLIZATION

- EXTENSIVE PRECIPITATES
- GRAINS UNCHANGED

- 90% REDUCTION IN PRECIPITATES
- GRAINS UNCHANGED

8-J6-099-45

Figure 21. Aging of T-111 Structure (B-1a)

anything, could be considered "clean" of strengtheners. The microstructure of the materials shown in Figure 21 indicated that there had been a significant change from the solution annealed condition of the pretest capsule. There were a number of precipitates in the matrix leading to a strong belief that the high strength could well have come from contamination in the test environment. Strengthening of these class of alloys is common by interstitial additions. The logical development of this was the NASA sponsored alloy development program whose direction was to strengthen the alloy by instertial additions.

The result of this evaluation concluded that the apparent strength increase was real (that is, not an uncontrolled test induced variable) and the test program continued. After a few tests, the stress schedules selected approximated the strain schedules selected though with a slightly low strain rate bias, i. e., the tests took a little longer to conclude than initially planned. The exceptions to this were tests B3 and B6 which achieved their target 1% strain exactly as scheduled, one year. Figure 22 shows the engineering (independent) stress schedules as recorded in the data books for the tests. It can be seen from this plot that the tests fell into three categories of stress rates, and there are steps in the independent variable. Figure 23 shows the resulting instantaneous stress schedules which take into account the variation in specimen configuration during test. It was assumed that the material was of constant volume and therefore any strain resulted in a direct increase in diameter and decrease in wall thickness. The exact pressures and diameters are included in the appendix to facilitate independent analysis of the technique. This program assumed that neither of the analyses were valid over the whole range tested but that the engineering stress was sufficient to calculate pressure schedules during testing (as is done in a constant load test) and the instantaneous apparent strain was more valid for calculating stress schedules in the analysis. The consideration was that the instantaneous stress was probably valid for strains up to at least 1% might not be valid for strains as high as 5%, and was not valid for strains higher than 5%.

ALL TESTS

13/0526A

Figure 22. Summary of Engineering Hoop Stress Schedules

B. RUPTURE

This was test B5a. The results of this test are shown in Figure 24. It can be seen that there was significant ductility in the material after thousands of hours under creep to experience a very ductile failure. It is noted, however, that prior to rupture, the capsule was creeping at a very rapid rate of a percent each day. It is common under constant stress of pressure vessels that rupture in creep occurs in a very low energy mode such as an intergranular fracture growth. Again referring to Figure 24, it can be seen that there was a lot of energy required for the fracture propagation, and that there was at least a 50% reduction in wall thickness during the rupture. While this can pose a serious problem in one phase of a system analyses, it is quite evident that there is a very ductile material after significant creep such that survival of high strain rate deformations such as impact is highly probable. The problem posed is evident in Figure 25. These are photos showing the damage to the furnace during the rupture event. While the damage that would occur to a real radio-isotope heat source capsule would not be nearly as significant as is shown because in that case there is a volume of gas to contain, not a pressure. In other words, after straining 15%, the capsule can now contain a significantly larger volume of gas than if it were assumed that the capsule retained launch dimensions.

C. ANALYSIS

Figures in the Appendix show the stress, strain, and time relationships graphically for each test. The strain-time relationship at each measuring plane under a stress rate was determined for each test utilizing a stepwise regression analysis. For this first analysis only the portion of the relationship after the test reached 0.2% strain was utilized. The form of equations utilized were:

$$\epsilon = e \left[A_1 + A_2 T + A_3 e^{A_4 T} \right]$$

ALL TESTS

730506
052670 ODA

Figure 23. Summary of Instantaneous Hoop Stress Schedule

RESULTS

- TEST TIME—3500 HOURS AT 2000°F
- STRAIN PRIOR TO FAILURE—15%
- DUCTILE FAILURE
- INCIPIENT FAILURE POINTS FOUND ELSEWHERE IN CAPSULE

CONCLUSIONS

- STRAIN PRIOR TO FAILURE OVER DOUBLE EXPECTED VALUE
- DUCTILITY REMAINED HIGH AFTER 3500 HOURS

9-F13-022-1

Figure 24. Creep Rupture Test Results

a. After Rupture of B5a

b. Upper Shield

Figure 25. Test Furnace

The fit for these equations were statistically significant. Once the strain-time relationships were determined, the equations were differentiated and a strain-time relationship was calculated. Comparison of the common dependent variable, time, in the stress-time, and strain rate-time relationships facilitated development of a relationship between stress and strain rate.

1. High Stress Rate Tests

Figure 26a and 26b displays that relationship for the high rate test B4. It can be seen from a comparison of the two curves that the engineering stress (assuming constant dimensions throughout the test) poses a positively increasing slope as the strain gets large, and the instantaneous stress (assuming wall thinning and diameter increase through the test) poses a positively decreasing slope as strain occurs. At small strains, i. e., below 2% strain, the relationship is almost equivalent. It is at the large strains where each approximation deviates. This becomes very significant at strains as high as 5%.

2. Intermediate Stress Rate Tests

Figure 27a and 27b show the same relationship for the intermediate stress rate tests: B2a, B5a, B7 and A2a. The digits in the plot relate to the test number, i. e., 2:B2a and A2a, 7:B7, and 5:B5a. It can be seen that these data fall within a relatively narrow scatter band over the stress range observed. Comparison of Figures 27a and 27b indicate that the very same bias of engineering and instantaneous stress occurs as in B4, as the strain exceeds a few percent. Extrapolation of the relationships beyond 30 to 35ksi should not assume either to be correct but some intermediate relationship. It is noted here that this stress range includes the 0.2% offset strength of the material. One would not anticipate operation of a capsule at so high a stress. One can note that in the case of B5a which was taken to rupture, that at 10% strain, the stress calculations differed by 20%. The difference in strain rates would be expected to be in the range of a few orders of magnitude at this high a stress. It is reiterated that the stress-strain rate relationship appears to be very good over the strain range where stress calculations remain valid.

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(a)

(b)

Figure 26. Stress-Strain Rate Relationship for High Stress Rate Test

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(a)

(b)

Figure 27. Stress-Strain Rate Relationship for Intermediate Stress Rate Test

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3. Low Stress Rate Tests

Figures 28a and 28b show the relationship for the long term tests B3 and B6. As in the previous case, the digits in the plot designate each test. Note in the case of these tests that the scatter band is extremely low. It is difficult to differentiate between the two on the plots. At this time, the tests have both achieved only 1% total strain, therefore, the difference between the two stress assumptions is almost nil.

4. Strain Rate of Cold Worked T-111

Figures 29a and 29b show the relationship for a fourth class of test - a capsule that was not solution annealed prior to testing. This was not an effort to study the effect of heat treatment on the stress-strain rate relationship, but merely to provide preliminary data on a potential problem area, an inadvertent inclusion of a non-heat treated capsule in a system. For this test, B5, the strain rate for an equivalent stress to the remaining tests was higher by more than an order of magnitude at intermediate stresses, but approached that of the other tests as the stress approached the 0.2% offset of the material.

5. Comparison of All Tests

Figures 30a and 30b summarize the tests in single figures. A number of things are evident from this summary. The very high and intermediate stress rate tests represent a single family of curves with very little scatter. The test without the pretest heat treatment, B5, was significantly weaker than the body of the tests until very high stresses were achieved. The long term tests B3 and B6 represent a body of conditions which are not a part of the other tests. There is a statistically significant difference between these long term tests and the remaining body. The progress of the long term tests to date strongly indicate that they represent a condition which is slightly weaker than that indicated by either of the other two groups.

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(a)

(b) Figure 28. Stress-Strain Rate Relationship for Low Stress Rate Tests

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(a)

(b)

Figure 29. Stress-Strain Rate Relationship for Cold Worked Pressure Vessel

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(a)

(b) Figure 30. Stress-Strain Rate Relationship for all Tests

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D. DISCUSSION

Figure 31 shows the comparison of the body of the stress-strain rate relationship from this program with that of the uniaxial constant load tests by Sheffler and Steigerwald¹³. The line was derived from the relationship

$$\dot{\epsilon} = 1.65 \times 10^9 \left[\text{Sinh} (6.6 \times 10^{-5} \sigma) \right]^{3.17} e^{-90,000/RT}$$

which was reported to be valid for tests from 1600 to 2400°F, and strain rate in the range of 10^0 to 10^{-4} %/hour. The curve represents the relationship expected at 2000°F, the test temperature of this program. All of the specimens in the NASA sponsored, Sheffler program, were a nominal 0.030-inch thick sheet and were given a pretest heat treatment of one hour at 3000°F, which was the same as for this program. The operating environment of the uniaxial program was ultra high vacuum, in the range of 10^{-9} to 10^{-11} Torr. The operating environment for the biaxial program was 10^{-8} to 10^{-9} on one side of the nominal 0.125-inch thick vessel, and high purity helium (less than 2 ppm active impurities) on the other. By some models the inert gas could be considered to represent the same number of impurity atoms as in a vacuum of 10^{-3} Torr. While this is not the place to discuss the equivalence, sticking probabilities, and solid state chemistry of the vacuum versus inert gas environments, some general observations can be made.

Inouye¹⁵ has shown that at temperatures where diffusion can occur that a refractory metal will seek some equilibrium with the environment. In very high vacuums the strategic strengthening interstitial elements can be removed from the material; in intermediate vacuums the equilibrium will be no net change; in low vacuums there will be an addition of interstitials. The definition of low, intermediate and high will depend upon the specific alloy and temperature. At high temperatures (in excess of 1600°F) the diffusion rate is high and the reactions are more rapid. There is also some equilibrium condition for a refractory metal in an inert gas. That is to say, if an inert gas were sealed within a refractory metal vessel and taken to temperature, in time there will be

Figure 31. Comparison of Stress-Strain Rate Relationship
Between Uniaxial and Biaxial Test Programs

a net change in the interstitial content (H, O, N, C) of the metal, and the impurity content of the gas (H_2O , CO, CH_4 , etc.). The balance will depend strongly upon the temperature of the environment.

Evidence of this can be made by a direct comparison of the change in interstitial content of the test specimens between the two programs. Analyses of the intermediate and high stress rate tests by the biaxial program indicated that there appeared to be little if any change in strategic interstitials of the test vessels. Analyses of the uniaxial program specimens by Sheffler indicated that there was a significant loss in strategic interstitials during testing at high temperatures¹³. One can calculate that equilibrium could be reached in the thin sheet of the uniaxial tests within a matter of hours at 2000°F. This equilibrium would be in the range of less than 10 or 20 ppm of the strategic interstitials. This did not occur even after many hundreds of hours in the environment of this test program. The chemistry of the test specimen remained "as fabricated" and "specified" for at least a few thousand hours.

A major difference between the two programs was a significant environmental difference. The quantitative contribution to strength by these strategic interstitials is difficult to assess, but it is well known that the T-111 class of alloys is strengthened by precipitates¹⁶. Evaluation of test data by Sheffler at temperatures lower than 2000°F, where the diffusion was low enough to be observed, indicates that the strain rate could increase for a given stress by as much as one order of magnitude and possibly two or three. The difference of one order of magnitude in strain rate between the two test programs would then not be unexpected from this one factor alone.

There is no evidence in the constant load and increasing load tests of the NASA program that there is a significant stress rate effect on the stress-strain rate relationship. There too, does not appear to be an effect in this program either, save for the two long term tests B3a and B6. While there does not appear to be a large difference between these two tests and the other tests, it can be

observed statistically. It is postulated that these two tests are beginning to lose the strategic interstitials after the very long term exposure to the vacuum and inert gas environment. This could well account for the very slight loss of creep strength observed.

The postulation appears to be reasonable, and there need be only a limited post test examination of the specimens to confirm or disprove the theory.

The data from the two test programs was also compared utilizing compensating models for uniaxial and biaxial stress states and effective strains. There were a number of forms utilized but most were derivatives of the Von Mises criteria. In all cases the compensation decreased the differences between the two bodies of data but not much more than 30%. This was considered insignificant compared to the apparent differences. It was considered inappropriate at this time to try to independently force the two bodies of data together utilizing compensatory models which may or may not be applicable to the conditions of the two test programs. Other areas such as a quantitative relationship of strain ageing of T-111, described by Sheffler, must first be developed prior to application of compensating models to prevent confounding the real behavior of the material. The author cautions independent analysts to consider this also.

E. SUMMARY AND RECOMMENDATIONS

Over the stress and stress rate ranges noted the analytical model utilized to develop the test program is valid. The only apparent error was in the application of a stress-strain rate relationship developed under ultra high vacuum conditions. Under this test program the environment appeared to be inert and the results will reflect the strength of commercial T-111 with nominal interstitial content of 50 ppm oxygen, 50 ppm carbon and 50 ppm nitrogen. As represented by the difference between the results of tests operated in ultra high vacuum and this test program, care should be taken in application of these data to a structure operating in an environment where the T-111 could lose interstitials. T-111 remains very ductile in rupture at 2000 F. Compensatory

stress and strain models alone do not adequately relate the tests of this program and uniaxial tests of T-111 in the literature. None of the stress models examined appear to be valid within themselves at strains exceeding more than 4%. The stress rate test technique appears to be a valuable approach to analysis of the behavior of members under variable stress conditions.

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APPENDIX

TEST DATA

AI-AEC-12943

BEST FIT EQUATIONS CHOSEN FOR STRAIN vs TIME

Test	t _o (hr)	EQUATION (t', hr) where (t' = t - t _o) (ε, %)	99.0% Constant Confidence Interval†		Multiple Correlation Coefficient	Number of Observations
			t _{+0.99}	t _{-0.99}		
A2A	1128	$\epsilon = 4.106 \times 10^{-2} \exp[1.120 \exp(0.001t')]^*$	1.157	0.8642	0.9891	14
B2A	1698	$\epsilon = 5.559 \times 10^{-2} \exp[1.431 \exp(0.001t')]^*$	1.068	0.9361	0.9988	21
B3A	3616	$\epsilon = 0.1936 \exp(3.466 \times 10^{-4} t')$	1.064	0.9399	0.9988	40
B4	88	$\epsilon = 6.373 \times 10^{-12} \exp[2.962 \times 10^{-9} t'^4 + 24.19 \exp(0.001t')]^*$	1.119	0.8932	0.9998	8
B5	321	$\epsilon = 1.043 \times 10^{-2} \exp[2.524 \times 10^{-6} t'^2 + 4.077 \exp(0.001t')]^*$	1.066	0.9380	0.9997	11
B5A	1410	$\epsilon = 0.1098 \exp[-6.239 \times 10^{-11} t'^3 + 0.6617 \exp(0.001t')]^*$	1.140	0.8772	0.9993	55
B6	3388	$\epsilon = 0.1646 \exp[3.427 \times 10^{-4} t' + 1.202 \times 10^{-3} \exp(0.001t')]^*$	1.070	0.9343	0.9989	47
B7	1679	$\epsilon = 0.2326 \exp(8.429 \times 10^{-7} t'^2 + 3.344 \times 10^{-11} t'^3)$	1.063	0.9408	0.9995	68

*The double exponent is intentional – the justification is strictly empirical.

†e.g., $\epsilon_{+0.99} = \epsilon_{\text{PRED}} \times t_{+0.99}$

$\epsilon_{-0.99} = \epsilon_{\text{PRED}} \times t_{-0.99}$

TABLE A-1

TEST B4

730511
060170 00

Figure A-1. Test B4, Stress and Strain vs. Time

Figure A-2. Test A2A, Stress and Strain vs. Time

TEST B2A

73051
650170 α

Figure A-3. Test B2A, Stress and Strain vs. Time

TEST B5A

Figure A-4. Test B5A, Stress and Strain vs. Time

TEST B7

7307
0601

Figure A-5. Test B7, Stress and Strain vs. Time

Figure A-6. Test B3A, Stress and Strain vs. Time

TEST B6

73
06

Figure A-7. Test B6, Stress and Strain vs. Time

Figure A-8. Test B5, Stress and Strain vs. Time

TABLE A-2
Biaxial Creep Test Bla
(Sheet 1 of 2)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.68360	1.67781	-	-
0	2250	1.68380	1.67820	0.012	0.023
0	2850	1.68393	1.67833	0.020	0.031
2.0	2840	1.68414	1.67867	0.032	0.051
8.0	2840	1.68377	1.67870	0.010	0.053
24.0	2840	1.68393	1.67861	0.020	0.048
30.1	2840	1.68337	1.67782	-	-
94.4	2810	1.68387	1.67889	0.016	0.064
97.6	3230	1.68390	1.67817	0.018	0.021
99.2	3230	1.68344	1.67748	-	-
101.9	3230	1.68319	1.67766	-	-
118.4	3230	1.68372	1.67750	0.007	-
124.9	3230	1.68439	1.67803	0.047	0.013
126.1	3230	1.68366	1.67833	0.004	0.031
142.4	3225	1.68436	1.67810	0.045	0.017
145.2	3230	1.68432	1.67817	0.043	0.021
147.8	3230	1.68446	1.67834	0.051	0.031
150.3	3400	1.68449	1.67838	0.053	0.034
167.9	3400	1.68455	1.67928	0.056	0.088
167.9	3400	1.68451	1.67952	0.056	0.102
192.9	3400	1.68469	1.67959	0.065	0.106
198.2	3400	1.68484	1.67985	0.074	0.122
262.3	3400	1.68488	1.67990	0.076	0.125
290.0	3400	1.68513	1.68026	0.091	0.146
294.4	3400	1.68530	1.68033	0.1010	0.150
311.0	3400	1.68549	1.68073	0.1122	0.175
317.5	3400	1.68599	1.68096	0.1420	0.188
336.5	3550	1.68648	1.68129	0.1711	0.207

TABLE A-2 (Cont'd)
Biaxial Creep Test Bla
(Sheet 2 of 2)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
342.5	3550	1.68664	1.68159	0.1806	0.225
359.5	3550	1.68706	1.68194	0.2055	0.246
366.2	3695	1.68717	1.68208	0.2120	0.254
430.0	3930	1.68794	1.68289	0.2578	0.303
437.7	4485	1.68889	1.68328	0.3142	0.326
453.5	4665	1.68993	1.68398	0.3760	0.368
461.1	4800	1.69073	1.68481	0.4235	0.417
479.0	5000	1.69111	1.68554	0.4461	0.461
502.0	5000	1.69235	1.68709	0.5197	0.553
509.5	5000	1.69258	1.68725	0.5334	0.563
526.0	5000	1.69357	1.68822	0.5922	0.620
533.5	5000	1.69398	1.68864	0.6165	0.645
574.0	5000	1.69447	1.68925	0.6456	0.682
577.0	600	1.69155	1.68641	0.472	0.513
578.5	600	1.69184	-	0.489	-
580.0	-	1.69190	1.68668	0.493	0.529

TABLE A-3
Biaxial Creep Test Ala
(Sheet 1 of 1)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.67757	1.68725	-	-
0	2800	-	-	-	-
1.0	2800	1.67997	1.68983	0.143	0.153
19.0	2800	1.68152	1.69140	0.235	0.246
22.0	2800	1.68183	1.69138	0.253	0.245
25.0	2550	-	-	-	-
41.0	2550	1.68287	1.69308	0.316	0.346
65.0	2550	1.68342	1.69397	0.349	0.398
89.0	1500	-	-	-	-
89.5	2700	-	-	-	-
95.0	2700	1.68445	1.69498	0.410	0.458
99.0	2200	-	-	-	-
115.0	2000	-	-	-	-
115.5	2850	-	-	-	-
120.0	2850	1.68578	1.69579	0.489	0.506
120.5	2850	1.68590	1.69646	0.496	0.545
126.0	2850	1.68717	1.69817	0.572	0.647
143.0	2960	1.69017	1.70093	0.751	0.811
151.5	3010	1.69143	1.70278	0.826	0.920
167.0	3100	1.69625	1.70708	1.114	1.175
170.5	3115	1.69735	1.70807	1.179	1.234
173.5	3150	1.69947	1.70975	1.305	1.334
175.0	3160	1.70000	1.71035	1.337	1.376
175.5	700	1.69870	1.70853	1.260	1.261
191.0	-	-	-	-	-

TABLE A-4
Biaxial Creep Test B4
(Sheet 1 of 1)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.60989	1.61518	-	-
1.5	3345	1.61105	1.61648	0.072	0.080
19.0	3345	1.61162	1.61687	0.1075	0.1046
41.0	3345	1.61232	1.61725	0.1509	0.1282
47.8	3345	1.61240	1.61735	0.1559	0.1344
66.0	3475	1.61245	1.61750	0.1590	0.1436
73.0	3520	1.61247	1.61750	0.1603	0.1436
88.0	3630	1.61322	1.61815	0.2068	0.1839
97.0	3740	1.61407	1.61883	0.2596	0.2260
113.0	3830	1.61592	1.62045	0.3746	0.3263
121.0	3960	1.61707	1.62097	0.4460	0.3585
161.0	4175	1.63303	1.63603	1.437	1.291
169.0	4250	1.63792	1.64040	1.741	1.561
185.0	4430	1.66092	1.66300	3.170	2.961
193.5	4500	1.67978	1.68160	4.341	4.112
195.0	4510	1.68370	1.68470	4.585	4.316
212.0	750	1.68252	1.68368	4.511	4.241

TABLE A-5
Biaxial Creep Test A2a
(Sheet 1 of 3)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.68789	1.68763	-	-
0	0	1.68803	1.68781	-	-
0	1000	1.68804	1.68790	-	-
0	2000	1.68850	1.68971	-	-
0	2000	1.68836	1.68875	-	-
0	3040	-	-	-	-
19.2	3040	1.68890	1.68888	0.010	0.074
43.4	3040	1.68843	1.68849	0.032	0.051
67.2	3040	1.68885	1.68818	0.057	0.032
91.7	3040	1.68870	1.68908	0.047	0.086
163.2	3040	1.68872	1.68928	0.049	0.098
187.2	3040	1.68912	1.68900	0.073	0.081
214.2	3040	1.68905	1.68948	0.068	0.110
220.9*	0	-	-	-	-
242.3	3040	1.68948	1.68840	0.041	0.061
266.3	3040	1.68931	1.68821	0.031	0.048
289.3	3040	1.68960	1.68858	0.048	0.071
312.3	3040	1.68963	1.68795	0.050	0.034
384.8	3040	1.68978	1.68837	0.059	0.059
408.2	3040	1.68943	1.68827	0.038	0.053
432.2	3040	1.68975	1.68850	0.057	0.067
456.2	3040	1.68955	1.68818	0.046	0.048
481.2	3040	1.68955	1.68877	0.046	0.083
552.4	3040	1.69007	1.68872	0.076	0.080
575.9	3040	1.68960	1.68900	0.046	0.097
600.3	3040	1.68967	1.68870	0.053	0.079
648.3	3040	1.68953	1.68873	0.044	0.081
720.1	3040	1.68955	1.68880	0.046	0.085

TABLE A-5 (Cont'd.)
 Biaxial Creep Test A2a
 (Sheet 2 of 3)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
767.9	3040	1.68987	1.68897	0.058	0.095
792.8	3040	1.69010	1.68902	0.078	0.098
816.2	3040	1.69007	1.68913	0.076	0.104
881.1	3040	1.68973	1.68908	0.056	0.101
892.6	3071	-	-	-	-
911.9	3071	1.68965	1.68912	0.052	0.104
913.1	3102	-	-	-	-
936.5	3102	1.69002	1.68905	0.073	0.100
937.7	3133	-	-	-	-
960.0	3133	1.69007	1.68938	0.076	0.119
961.1	3165	-	-	-	-
984.5	3165	1.69023	1.68933	0.086	0.116
985.6	3228	-	-	-	-
1057.8	3228	1.69042	1.68947	0.097	0.124
1058.9	3290	-	-	-	-
1081.2	3290	1.69040	1.68948	0.096	0.125
1082.3	3320	-	-	-	-
1109.0	3320	1.69052	1.68953	0.103	0.128
1110.1	3350	-	-	-	-
1127.9	3350	1.69048	1.68977	0.101	0.142
1129.0	3380	-	-	-	-
1153.1	3380	1.69047	1.68967	0.100	0.136
1154.2	3445	-	-	-	-
1415.7	3445	1.69090	1.69018	0.126	0.167
1417.7	3540	-	-	-	-
1440.2	3540	1.69117	1.69033	0.142	0.175
1441.2	3665	-	-	-	-

TABLE A-5 (Cont'd.)
 Biaxial Creep Test A2a
 (Sheet 3 of 3)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
1464.5	3665	1.69137	1.69087	0.153	0.207
1465.6	3790	-	-	-	-
1488.3	3790	1.69165	1.69095	0.170	0.212
1490.3	3855	-	-	-	-
1560.3	3855	1.69193	1.69115	0.187	0.224
1563.7	3915	-	-	-	-
1584.0	3915	1.69215	1.69137	0.200	0.237
1585.0	3945	-	-	-	-
1608.3	3945	1.69240	1.69182	0.214	0.264
1610.3	3975	-	-	-	-
1632.2	3975	1.69281	1.69198	0.239	0.273
1633.2	4005	-	-	-	-
1656.3	4005	1.69295	1.69208	0.247	0.281
1657.3	4065	-	-	-	-
1753.2	4065	1.69377	1.69283	0.295	0.324
1755.2	4125	-	-	-	-
1776.2	4125	1.69417	1.69318	0.319	0.344
1778.2	4195	-	-	-	-
1800.7	4195	1.69438	1.69363	0.332	0.371
1802.7	4225	-	-	-	-
1824.0	4225	1.69475	1.69398	0.354	0.392
1825.1	4285	-	-	-	-

TABLE A-6
Biaxial Creep Test B2a
(Sheet 1 of 2)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.67550	1.67700	0	0
1338	3120	1.67551	1.67592	0.0060	-
1362	3120	1.67591	1.67722	0.0245	0.0131
1386	3120	1.67600	1.67762	0.0298	0.0370
1411	3120	1.67536	1.67732	-	0.0191
1483	3120	1.67686	1.68004	0.0812	0.1813
1506	3330	1.67672	1.67996	0.0728	0.1765
1530	3330	1.67678	1.68004	0.0764	0.1813
1554	3330	1.67679	1.68000	0.0770	0.1789
1578	3390	1.67700	1.68045	0.0895	0.2057
1650	3503	1.67724	1.68097	0.1038	0.2260
1674	3503	1.67734	1.68091	0.1098	0.2332
1698	3535	1.67744	1.68101	0.1158	0.2391
1722	3535	1.67782	1.68129	0.1385	0.2558
1842	3590	1.67812	1.68171	0.1564	0.2808
1866	3760	1.67851	1.68187	0.1796	0.2904
1890	3760	1.67871	1.68216	0.1916	0.3077
1914	3760	1.67869	1.68242	0.1904	0.3232
1986	3906	1.67973	1.68338	0.2525	0.380
2011	3906	1.67983	1.68361	0.2584	0.394
2058	3906	1.68050	1.68410	0.2984	0.423
2082	3993	1.68108	1.68464	0.3330	0.456
2105	4108	1.68144	1.68521	0.3545	0.490
2154	4108	1.68267	1.68609	0.4279	0.542
2178	4108	1.68323	1.68652	0.4614	0.568
2202	4108	1.68385	1.68719	0.4984	0.608
2226	4166	1.68426	1.68754	0.5228	0.628
2250	4166	1.68471	1.68808	0.5497	0.661

TABLE A-6 (Cont'd.)
 Biaxial Creep Test B2a
 (Sheet 2 of 2)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
2322	4310	1.68717	1.69053	0.6965	0.807
2346	4310	1.68793	1.69125	0.7418	0.850
2370	4367	1.68906	1.69235	0.8093	0.915
2394	4367	1.69005	1.69328	0.8684	0.971
2418	4400	1.69135	1.69462	0.9460	1.051
2444	4511	1.69306	1.69604	1.0480	1.135
2450	0	1.69133	1.69410	0.9448	1.020
2490	0	1.69102	1.69407	0.9263	1.018

TABLE A-7
Biaxial Creep Test B5a
(Sheet 1 of 3)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.67739	1.67672	-	-
16.0	2405	1.67853	1.67806	0.068	0.079
23.0	2405	1.67843	1.67800	0.062	0.076
40.0	2405	1.67842	1.67810	0.061	0.082
64.0	2405	1.67827	1.67793	0.052	0.070
136.0	2405	1.67833	1.67795	0.056	0.073
184.0	2405	1.67835	1.67722	0.057	0.030
208.0	2405	1.67833	1.67775	0.056	0.061
241.5	2405	1.67842	-	0.061	-
255.0	2405	1.67845	1.67765	0.063	0.055
328.5	2405	1.67825	1.67772	0.051	0.060
376.0	2405	1.67835	1.67740	0.057	0.041
400.0	2405	1.67853	1.67750	0.068	0.047
473.0	2405	1.67872	1.67790	0.079	0.070
496.0	2405	1.67857	1.67748	0.070	0.045
520.0	2405	1.67902	1.67808	0.097	0.081
544.0	2405	1.67887	1.67778	0.088	0.063
568.0	2405	1.67875	1.67775	0.081	0.061
640.0	2405	1.67882	1.67767	0.085	0.057
664.0	2405	1.67890	1.67792	0.090	0.072
688.0	2405	1.67902	1.67750	0.097	0.047
712.0	2405	1.67902	1.67780	0.097	0.064
737.0	2405	1.67887	1.67770	0.088	0.058
808.0	2405	1.67920	1.67790	0.108	0.070
832.0	2452	1.67922	1.67788	0.109	0.069
856.0	2490	1.67933	1.67798	0.116	0.075
880.0	2515	1.67937	1.67800	0.118	0.076
904.0	2540	1.67942	1.67795	0.121	0.073
977.0	2560	1.67943	1.67805	0.122	0.079

TABLE A-7 (Cont'd.)
 Biaxial Creep Test B5a
 (Sheet 2 of 3)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
1001.0	2630	1.67948	1.67798	0.125	0.075
1025.0	2650	1.67953	1.67800	0.128	0.076
1049.0	2675	1.67965	1.67817	0.135	0.086
1073.0	2700	1.67990	1.67808	0.150	0.081
1145.0	2720	1.68007	1.67805	0.160	0.079
1169.0	2790	1.68017	1.67810	0.166	0.082
1193.0	2810	1.68028	1.67815	0.172	0.085
1218.0	2835	1.68050	1.67840	0.185	0.100
1242.0	2860	1.68040	1.67808	0.179	0.081
1313.0	2880	1.68053	1.67800	0.186	0.076
1338.0	2950	1.68018	1.67797	0.166	0.075
1361.0	2970	1.68032	1.67812	0.175	0.083
1385.0	2995	1.68045	1.67807	0.182	0.080
1410.0	3015	1.68042	1.67815	0.180	0.085
1482.0	3040	1.68080	1.67852	0.203	0.107
1506.0	3110	1.68103	1.67843	0.217	0.102
1530.0	3130	1.68107	1.67852	0.219	0.107
1554.0	3155	1.68113	1.67852	0.223	0.107
1578.0	3180	1.68113	1.67855	0.223	0.109
1650.0	3200	1.68138	1.67857	0.238	0.110
1672.0	3270	1.68182	1.67898	0.264	0.135
1696.0	3290	1.68200	1.67940	0.275	0.160
1816.0	3310	1.68268	1.67967	0.315	0.176
1840.0	3425	1.68272	1.67943	0.318	0.162
1864.0	3450	1.68300	1.67973	0.334	0.180
1894.0	3470	1.68307	1.67947	0.338	0.164
1912.0	3500	1.68310	1.67992	0.340	0.191
1985.0	3520	1.68433	1.67962	0.360	0.173
2008.0	3580	1.68347	1.67347	0.362	0.178

TABLE A-7 (Cont'd.)
Biaxial Creep Test B5a
(Sheet 3 of 3)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
2034.0	3600	1.68355	1.67968	0.367	0.176
2056.5	3630	1.68398	1.68018	0.393	0.206
0	3650	-	-	-	-
2086.0	3700	-	-	-	-
2152.0	3700	1.68468	1.67968	0.435	0.176
2176.0	3740	1.68495	1.68018	0.451	0.206
2200.0	3760	1.68545	1.68035	0.480	0.216
2224.5	3790	1.68567	1.68057	0.494	0.230
2392.0	3900	1.68770	1.68213	0.615	0.323
2418.0	3970	1.68808	1.68273	0.637	0.358
2489.0	4000	1.68953	1.68358	0.724	0.409
2560.0	4060	1.69057	1.68450	0.736	0.464
2584.0	4130	1.69162	1.68540	0.848	0.518
2706.0	4150	1.69497	1.68835	1.048	0.694
2730.0	4270	1.69650	1.68920	1.139	0.744
2753.0	4290	1.69742	1.69008	1.194	0.796
2824.0	4310	1.70043	1.69268	1.374	0.952
2850.0	4380	1.70183	1.69385	1.457	1.022
2874.0	4380	1.70327	1.69543	1.543	1.116
2898.0	4380	1.70482	1.69648	1.635	1.178
2926.0	4450	1.70700	1.69835	1.765	1.290

TABLE A-8
Biaxial Creep Test B7
(Sheet 1 of 6)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.67580	1.67620	-	-
0	2450	-	-	-	-
16.5	2450	1.67700	1.67693	0.072	0.044
40.5	-	1.67672	1.67705	0.055	0.051
112.8	-	1.67670	1.67720	0.054	0.060
136.3	-	1.67670	1.67713	0.054	0.055
160.5	-	1.67682	1.67730	0.061	0.066
184.4	-	1.67682	1.67732	0.061	0.067
208.4	-	1.67670	1.67722	0.054	0.061
280.5	-	1.67675	1.67720	0.057	0.060
304.1	-	1.67670	1.67715	0.054	0.057
328.3	-	1.67683	1.67715	0.061	0.057
352.2	-	1.67670	1.67715	0.054	0.057
376.3	-	1.67687	1.67715	0.064	0.057
448.5	-	1.67685	1.67715	0.063	0.057
472.5	-	1.67683	1.67720	0.061	0.060
496.7	-	1.67675	1.67705	0.057	0.051
520.5	-	1.67707	1.67730	0.076	0.066
544.4	-	1.67682	1.67720	0.061	0.060
617.7	-	1.67698	1.67724	0.070	0.062
641.3	-	1.67698	1.67710	0.070	0.054
666.5	-	1.67682	1.67725	0.061	0.063
690.2	-	1.67707	1.67715	0.076	0.057
714.2	-	1.67710	1.67712	0.078	0.055
785.6	2450	1.67747	1.67698	0.100	0.047
786.3	2493	-	-	-	-
809.2	2493	1.67698	1.67705	0.070	0.051
809.8	2517	-	-	-	-

TABLE A-8 (Cont'd.)
Biaxial Creep Test B7
(Sheet 2 of 6)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
833.9	2517	1.67718	1.67705	0.082	0.051
836.2	2540	-	-	-	-
857.8	2540	1.67723	1.67722	0.085	0.061
858.3	2563	-	-	-	-
881.4	2563	1.67723	1.67712	0.085	0.055
882.2	2632	-	-	-	-
953.4	2632	1.67740	1.67692	0.095	0.043
953.9	2656	-	-	-	-
977.3	2656	1.67738	1.67712	0.094	0.055
977.8	2679	-	-	-	-
1001.5	2679	1.67763	1.67728	0.109	0.064
1001.8	2702	-	-	-	-
1026.0	2702	1.67762	1.67728	0.109	0.060
1026.4	2725	-	-	-	-
1050.2	2725	1.67765	1.67743	0.110	0.073
1050.5	2795	-	-	-	-
1121.7	2795	1.67808	1.67622*	0.136	.1*
1122.1	2818	-	-	-	-
1145.7	2818	1.67802	1.67722	0.132	0.061
1146.7	2841	-	-	-	-
1169.5	2841	1.67798	1.67748	0.130	0.076
1170.0	2864	-	-	-	-
1193.7	2864	1.67808	1.67722	0.136	0.061
1194.1	2887	-	-	-	-
1217.4	2887	1.67793	1.67725	0.127	0.063
1218.1	2957	-	-	-	-
1294.1	2957	1.67800	1.67728	0.131	0.064
1294.5	2980	-	-	-	-

TABLE A-8 (Cont'd.)
 Biaxial Creep Test B7
 (Sheet 3 of 6)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
1313.3	2980	1.67783	1.67735	0.121	0.069
1313.6	3003	-	-	-	-
1558.3	3003	1.67890	1.67802	0.185	0.109
1559.0	3235	-	-	-	-
1630.5	3235	1.67895	1.67852	0.188	0.138
1631.0	3304	-	-	-	-
1655.0	3304	1.67898	1.67808	0.190	0.112
1655.5	3327	-	-	-	-
1678.8	3327	1.67893	1.67803	0.187	0.109
1679.3	3350	-	-	-	-
1721.4	3350	1.67945	1.67810	0.218	0.113
1722.3	3443	-	-	-	-
2033.7	3443	1.67990	1.67867	0.245	0.147
2034.3	3573	-	-	-	-
2130.4	3573	1.68005	1.67872	0.254	0.150
2130.9	3790	-	-	-	-
2226.7	3790	1.68047	1.67893	0.279	0.163
2227.2	3929	-	-	-	-
2345.5	3929	1.68138	1.67963	0.333	0.205
2346.2	4000	-	-	-	-
2370.2	4000	1.68183	1.67983	0.360	0.217
2370.6	4013	-	-	-	-
2394.3	4013	1.68212	1.68000	0.377	0.227
2394.7	4091	-	-	-	-
2465.5	4091	1.68225	1.68047	0.385	0.255
2466.0	4115	-	-	-	-
2489.5	4115	1.68285	1.68055	0.421	0.260
2513.5	4115	1.68262	1.68037	0.407	0.249

TABLE A-8 (Cont'd.)
Biaxial Creep Test B7
(Sheet 4 of 6)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
2537.5	4115	1.68298	1.68063	0.428	0.246
2545.2	4186	-	-	-	-
2563.7	4186	1.68377	1.68088	0.476	0.279
2564.3	4254	-	-	-	-
2634.0	4254	1.68477	1.68202	0.535	0.347
2634.4	4277	-	-	-	-
2657.3	4277	1.68498	1.68228	0.548	0.363
2657.8	4300	-	-	-	-
2681.8	4300	1.68522	1.68255	0.562	0.379
2682.3	4323	-	-	-	-
2705.7	4323	1.68587	1.68287	0.601	0.398
2706.3	4346	-	-	-	-
2729.5	4346	1.68588	1.68340	0.602	0.430
2802.0	4346	1.68738	1.68438	0.691	0.488
2802.5	4439	-	-	-	-
2827.5	4439	1.68787	1.68497	0.720	0.523
2827.5	4472	-	-	-	-
2856.5	4472	1.68890	1.68573	0.782	0.569
2856.9	4485	-	-	-	-
2873.3	4485	1.68958	1.68632	0.822	0.604
2873.7	4508	-	-	-	-
2897.4	4508	1.68990	1.68695	0.841	0.641
2897.7	4578	-	-	-	-
2969.5	4578	1.69302	1.68948	1.028	0.792
2969.9	4601	-	-	-	-
2993.7	4601	1.69400	1.69062	1.086	0.860
2994.0	4624	-	-	-	-
3017.7	4624	1.69493	1.69168	1.142	0.924

TABLE A-8 (Cont'd.)
 Biaxial Creep Test B7
 (Sheet 5 of 6)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
3018.0	4647	-	-	-	-
3041.5	4647	1.69602	1.69277	1.207	0.989
3042.2	4670	-	-	-	-
3065.3	4670	1.69728	1.69403	1.282	1.064
3065.7	4740	-	-	-	-
3137.5	4740	1.70213	1.69867	1.571	1.341
3138.0	4763	-	-	-	-
3161.2	4763	1.70382	1.70027	1.672	1.436
3209.5	4763	1.70718	1.70370	1.873	1.641
3210.0	4833	-	-	-	-
3234.2	4833	1.70948	1.70608	2.010	1.783
3234.5	4902	-	-	-	-
3305.9	4902	1.71812	1.71467	2.525	2.295
3306.3	4926	-	-	-	-
3329.4	4926	1.72103	1.71777	2.699	2.480
3329.9	4948	-	-	-	-
3353.3	4948	1.72460	1.72138	2.912	2.695
3353.8	4974	-	-	-	-
3378.0	4974	1.72905	1.72555	3.178	2.944
3378.4	4995	-	-	-	-
3402.0	4995	1.73298	1.72973	3.412	3.198
3402.5	5067	-	-	-	-
3473.6	5067	1.75030	1.74727	4.446	4.240
3474.0	5090	-	-	-	-
3502.2	5113	1.75195	1.74930	4.544	4.361
3521.2	5113	1.75798	1.75543	4.904	4.727
3521.8	5136	-	-	-	-
3523.3	5136	1.75915	1.75640	4.949	4.810

TABLE A-8 (Cont'd.)
 Biaxial Creep Test B7
 (Sheet 6 of 6)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A"	Apparent Diametral Strain "B"
3528.0	5136	1.76000	1.75732	5.024	4.840
3545.0	5136	1.76620	1.76365	5.394	5.217
3545.7	200	-	-	-	-
3548.3	200	1.76403	1.76180	5.265	5.107

TABLE A-9
Biaxial Creep Test B3a
(Sheet 1 of 4)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "A" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.68879	1.68678	-	-
0	2660	-	-	-	-
23.8	2660	1.68938	1.68702	0.035	0.014
95.4	2660	1.68945	1.68702	0.035	0.014
142.7	2660	1.68968	1.68715	0.053	0.022
192.5	2660	1.68973	1.68725	0.056	0.028
265.6	2660	1.68967	1.68712	0.052	0.020
312.3	2660	1.68943	1.68715	0.038	0.022
431.2	2660	1.68962	1.68703	0.049	0.015
527.5	2660	1.68973	1.68723	0.056	0.027
646.7	2660	1.69020	1.68788	0.083	0.065
695.4	2660	1.69005	1.68785	0.075	0.063
937.7	2660	1.69027	1.68773	0.088	0.056
985.2	0	-	-	-	-
1104.3	2660	1.69038	1.68768	0.094	0.053
1151.9	2660	1.69045	1.68796	0.098	0.070
1200.4	2660	1.69042	1.68792	0.097	0.068
1271.8	2660	1.69017	1.68793	0.082	0.068
1319.7	2660	1.69062	1.68795	0.101	0.069
1440.7	2660	1.69063	1.68793	0.109	0.068
1776.4	2660	1.69082	1.68827	0.120	0.088
2208.0	2660	1.69090	1.68865	0.125	0.110
2280.0	2660	1.69053	1.68860	0.103	0.108
2376.7	2660	1.69020	1.68858	0.084	0.107
2447.3	2660	1.69027	1.68888	0.088	0.125
2495.2	2660	1.69047	1.68867	-	-
2544.5	2660	1.69065	1.68873	0.110	0.104
2615.9	2660	1.69068	1.68882	0.112	0.121

TABLE A-9 (Cont'd.)
 Biaxial Creep Test B3a
 (Sheet 2 of 4)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
2663.5	2660	1.69107	1.68897	0.135	0.130
2783.8	2660	1.69110	1.68912	0.137	0.139
2831.8	2660	1.69107	1.68913	0.135	0.139
2880.0	2660	1.69108	1.68918	0.136	0.142
2951.6	2660	1.69150	1.68945	0.160	0.158
3004.3	2660	1.69112	1.68938	0.138	0.154
3048.6	2660	1.69115	1.68938	0.140	0.154
3312.6	2660	1.69140	1.68961	0.155	0.168
3360.2	2660	1.69155	1.68975	0.163	0.176
3455.6	2660	1.69163	1.68980	0.168	0.179
3456.9	2720	-	-	-	-
3504.8	2720	1.69175	1.69002	0.175	0.192
3551.6	2720	1.69180	1.69008	0.178	0.196
3648.1	2720	1.69197	1.69017	0.188	0.201
3649.8	2745	-	-	-	-
3695.9	2745	1.69201	1.69020	0.191	0.202
3815.6	2745	1.69220	1.69038	0.202	0.213
3815.9	2765	-	-	-	-
3887.1	2765	1.69232	1.69055	0.209	0.224
3959.0	2765	1.69233	1.69060	0.211	0.226
3960.5	2785	-	-	-	-
4031.6	2785	1.69245	1.69073	0.217	0.234
4125.0	2810	-	-	-	-
4200.8	2810	1.69250	1.69077	0.220	0.237
4392.3	2810	1.69255	1.69078	0.223	0.237
4465.0	2810	1.69282	1.69102	0.239	0.251
4467.5	2850	-	-	-	-
4516.9	2850	1.69295	1.69110	0.246	0.256

TABLE A-9 (Cont'd.)
 Biaxial Creep Test B3a
 (Sheet 3 of 4)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
4560.6	2850	1.69317	1.69125	0.259	0.265
4561.8	2870	-	-	-	-
4584.6	2870	1.69320	1.69133	0.261	0.270
4800.1	2870	1.69333	1.69162	0.269	0.287
4996.6	2870	1.69368	1.69203	0.290	0.311
4998.5	2890	-	-	-	-
5041.4	2890	1.69380	1.69225	0.297	0.324
5304.1	2890	1.69430	1.69275	0.326	0.354
5305.1	2910	-	-	-	-
5473.1	2910	1.69453	1.69300	0.340	0.369
5473.7	2935	-	-	-	-
5549.4	2935	1.69460	1.69313	0.344	0.376
5645.7	2935	1.69500	1.69340	0.368	0.392
5646.0	2960	-	-	-	-
5690.2	2960	1.69522	1.69365	0.381	0.407
5737.5	2960	1.69533	1.69372	0.387	0.411
5833.8	2960	1.69548	1.69377	0.396	0.414
5834.7	3000	-	-	-	-
5976.2	3000	1.69570	1.69415	0.409	0.437
5977.0	3045	-	-	-	-
6145.1	3045	1.69623	1.69460	0.441	0.464
6145.9	3065	-	-	-	-
6159.0	0	-	-	-	-
6230.1	3065	1.69643	1.69478	0.452	0.474
6231.2	3085	-	-	-	-
6277.6	3085	1.69685	1.69495	0.477	0.484
6397.3	3085	1.69705	1.69512	0.489	0.494
6398.5	3110	-	-	-	-

TABLE A-9 (Cont'd.)
 Biaxial Creep Test B3a
 (Sheet 4 of 4)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
6499.1	3110	1.69748	1.69553	0.515	0.518
6566.1	3110	1.69767	1.69578	0.526	0.534
6567.2	3135	-	-	-	-
6663.1	3135	1.69810	1.69623	0.551	0.560
6732.8	3135	1.69844	1.69650	0.571	0.576
6733.5	3155	-	-	-	-
6805.5	3155	1.69865	1.69668	-	-
6900.9	3155	1.69895	1.69703	0.602	0.608
6902.1	3175	-	-	-	-
6973.6	3175	1.69908	1.69715	0.609	0.615
7068.9	3175	1.69927	1.69738	0.621	0.628
7069.3	3200	-	-	-	-
7306.1	3200	1.70085	1.69881	0.714	0.713
7307.0	3245	-	-	-	-
7575.5	3245	1.70150	1.69950	0.753	0.754
7576.0	3265	-	-	-	-
7837.5	3265	1.70295	1.70050	0.838	0.813
7838.2	3285	-	-	-	-
7908.7	3285	1.70345	1.70113	0.868	0.851
7909.0	3305	-	-	-	-
7959.0	3305	1.70373	1.70150	0.885	0.872
8007.4	3305	1.70403	1.70185	0.902	0.893
8077.3	3305	1.70460	1.70220	0.936	0.915
8078.0	3325	-	-	-	-
8126.0	3325	1.70472	1.70258	0.943	0.937
8244.1	3325	1.70585	1.70370	1.010	1.003

TABLE A-10
Biaxial Creep Test B6
(Sheet 1 of 5)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
0	0	1.68561	1.68964	-	-
0	2686	-	-	-	-
65.7	2686	1.68624	1.68996	0.037	0.019
89.8	2686	1.68631	1.68992	0.042	0.017
96.1	-	-	-	-	-
0	0	1.68597	1.69068	-	-
148.0	2686	1.68695	1.68155	0.058	0.051
171.1	2686	1.68655	1.69073	0.034	0.003
195.3	2686	1.68675	1.69068	0.046	0.000
291.1	2686	1.68650	1.69067	0.031	0.000
363.5	2686	1.68648	1.69092	0.030	0.014
434.2	2686	1.68673	1.69058	0.045	0.000
482.5	2686	1.68680	1.69062	0.049	0.000
530.6	2686	1.68678	1.69070	0.048	0.001
602.7	2686	1.68710	1.69102	0.067	0.020
650.2	2686	1.68680	1.69055	0.049	0.000
698.3	2686	1.68687	1.69098	0.053	0.018
771.7	2686	1.68698	1.69108	0.060	0.024
866.0	2686	1.68722	1.69100	0.074	0.019
1034.2	2686	1.68705	1.69115	0.064	0.028
1131.4	2686	1.68713	1.69120	0.069	0.031
1276.2	2686	1.68713	1.69147	0.069	0.047
1442.7	2686	1.68747	1.69167	0.089	0.059
1490.6	2686	1.68720	1.69152	0.073	0.050
1538.4	2686	1.68737	1.69140	0.083	0.043
1610.4	2686	1.68755	1.69152	0.094	0.050
1658.1	2686	1.68765	1.69155	0.100	0.051
1707.0	2686	1.68757	1.69148	0.095	0.047

TABLE A-10 (Cont'd.)
 Biaxial Creep Test B6
 (Sheet 2 of 5)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
1779.1	2686	1.68758	1.69170	0.095	0.060
1874.7	2686	1.68772	1.69177	0.104	0.064
2114.6	2686	1.68802	1.69205	0.122	0.081
2548.5	2686	1.68888	1.69295	0.173	0.134
2620.9	2686	1.68865	1.69253	0.159	0.109
2668.4	2686	1.68830	1.69250	0.138	0.108
2717.1	2686	1.68868	1.69258	0.161	0.112
2885.0	2686	1.68887	1.69310	0.172	0.143
2955.9	2686	1.68918	1.69297	0.190	0.135
3004.2	2686	1.68955	1.69300	0.212	0.137
3026.2	2686	1.68940	1.69297	0.203	0.135
3051.7	2686	1.68925	1.69295	0.195	0.134
3123.8	2686	1.68968	1.69315	0.220	0.146
3128.8	2710	-	-	-	-
3171.1	2710	1.68945	1.69320	0.206	0.149
3219.8	2710	1.68927	1.69305	0.196	0.140
3290.2	2710	1.68977	1.69333	0.225	0.157
3292.2	2736	-	-	-	-
3344.3	2736	1.68955	1.69328	0.212	0.154
3388.5	2736	1.68972	1.69335	0.222	0.158
3652.4	2736	1.68998	1.69350	0.238	0.167
3653.5	2786	-	-	-	-
3723.2	2786	1.69013	1.69380	0.247	0.185
3795.8	2786	1.69035	1.69397	0.260	0.195
3796.3	2810	-	-	-	-
3844.6	2810	1.69043	1.69398	0.265	0.195
3891.4	2810	1.69062	1.69412	0.276	0.203
3988.1	2810	1.69068	1.69413	0.279	0.204
3989.1	2835	-	-	-	-

TABLE A-10 (Cont'd.)
 Biaxial Creep Test B6
 (Sheet 3 of 5)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
4058.5	2835	1.69080	1.69422	0.286	0.209
4154.5	2835	1.69090	1.69432	0.292	0.215
4155.5	2860	-	-	-	-
4226.3	2860	1.69105	1.69440	0.301	0.220
4299.0	2860	1.69115	1.69448	0.307	0.225
4300.0	2885	-	-	-	-
4371.2	2885	1.69128	1.69462	0.315	0.233
4540.7	2885	1.69137	1.69472	0.320	0.239
-	2910	-	-	-	-
4731.0	2910	1.69150	1.69482	0.322	0.245
4795.5	0	-	-	-	-
4819.5	2910	1.69245	1.69527	0.384	0.272
4958.0	2910	1.69273	1.69545	0.410	0.282
4959.0	2935	-	-	-	-
5112.9	2935	1.69282	1.69550	0.406	0.285
5113.9	2960	-	-	-	-
5156.2	2960	1.69300	1.69600	0.417	0.315
5205.0	2960	1.69320	1.69614	0.429	0.323
5299.8	2960	1.69325	1.69632	0.432	0.334
5300.0	2985	-	-	-	-
5443.8	2985	1.69337	1.69647	0.439	0.342
5444.8	3010	-	-	-	-
5611.0	3010	1.69383	1.69683	0.466	0.364
5612.0	3035	-	-	-	-
5659.6	3035	1.69400	1.69698	0.475	0.373
5780.9	3035	1.69402	1.69702	0.476	0.374
5781.9	3060	-	-	-	-
5931.9	3060	1.69403	1.69727	0.476	0.390
5932.9	3085	-	-	-	-

TABLE A-10 (Cont'd.)
Biaxial Creep Test B6
(Sheet 4 of 5)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
6020.4	3085	1.69468	1.69778	0.517	0.420
6115.4	3085	1.69498	1.69783	0.534	0.423
6116.7	3115	-	-	-	-
6211.6	3115	1.69533	1.69808	0.555	0.438
6282.6	3115	1.69538	1.69815	0.558	0.442
6283.7	3140	-	-	-	-
6331.6	3140	1.69603	1.69863	0.600	0.470
6450.6	3140	1.69638	1.69902	0.617	0.493
6451.7	3165	-	-	-	-
6552.1	3165	1.69650	1.69908	0.625	0.497
6620.3	3165	1.69660	1.69928	0.630	0.509
6621.3	3190	-	-	-	-
6716.2	3190	1.69700	1.69962	0.654	0.529
6787.2	3190	1.69747	1.69998	0.682	0.550
6788.4	3230	-	-	-	-
6858.4	3230	1.69767	1.70008	0.694	0.556
6955.6	3230	1.69795	1.70043	0.710	0.577
6956.6	3245	-	-	-	-
7026.7	3245	1.69822	1.70093	0.727	0.606
7123.1	3245	1.69830	1.70100	0.731	0.610
7124.0	3275	-	-	-	-
7459.8	3275	1.69997	1.70260	0.830	0.705
7460.5	3325	-	-	-	-
7631.8	3325	1.70087	1.70340	0.884	0.752
7633.0	3350	-	-	-	-
7890.9	3350	1.70238	1.70553	0.973	0.878
7891.8	3375	-	-	-	-
7963.2	3375	1.70285	1.70575	1.001	0.891
7964.2	3400	-	-	-	-

TABLE A-10 (Cont'd.)
 Biaxial Creep Test B6
 (Sheet 5 of 5)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
8012.6	3400	1.70298	1.70600	1.008	0.906
8061.2	3400	1.70348	1.70647	1.038	0.940
8131.4	3400	1.70426	1.70663	1.085	0.945
8132.5	3425	-	-	-	-
8180.7	3425	1.70502	1.70735	1.130	0.990
8226.1	3425	1.70530	1.70760	1.147	1.007

TABLE A-11
Biaxial Creep Test B5
(Sheet 1 of 2)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
50.0	2600	1.68251	1.67871	0.105	0.072
117.5	2600	1.68418	1.68076	0.204	0.194
141.0	2600	1.68513	1.68232	0.261	0.287
165.0	2600	1.68589	1.68290	0.306	0.322
196.0	2600	1.68639	1.68394	0.336	0.334
213.0	2600	1.68731	1.68418	0.390	0.398
225.0	0	-	-	-	-
248.4	2600	1.68799	1.68553	0.431	0.479
273.5	2600	1.68911	1.68624	0.497	0.521
297.5	2600	1.69030	1.68715	0.568	0.575
298.5	2660	-	-	-	-
302.5	2660	1.69041	1.68727	0.575	0.582
308.2	2770	-	-	-	-
320.5	2770	1.69114	1.68837	0.618	0.648
321.5	2850	-	-	-	-
328.0	2850	1.69131	1.68846	0.628	0.653
328.2	2910	-	-	-	-
346.2	3040	-	-	-	-
367.7	3100	-	-	-	-
370.2	3240	-	-	-	-
382.2	3340	-	-	-	-
392.2	3340	1.69519	1.69256	0.859	0.898
393.5	3440	-	-	-	-
400.0	3440	1.69529	1.69284	0.865	0.914
400.5	3500	-	-	-	-
416.5	3500	1.69702	1.69445	0.968	1.010
418.0	3640	-	-	-	-

TABLE A-11 (Cont'd.)
 Biaxial Creep Test B5
 (Sheet 2 of 2)

Time (hr)	Pressure (psia)	Apparent Diameter "A" (in.)	Apparent Diameter "B" (in.)	Apparent Diametral Strain "A" (%)	Apparent Diametral Strain "B" (%)
424.5	3700	-	-	-	-
440.5	3700	1.69880	1.69601	1.074	1.103
441.0	3820	-	-	-	-
448.0	3890	-	-	-	-
464.5	3890	1.70130	1.69847	1.223	1.250
466.0	4020	-	-	-	-
472.5	4080	-	-	-	-
488.5	4080	1.70451	1.70166	1.33	1.34
489.5	4210	-	-	-	-
496.0	4280	-	-	-	-
516.0	4440	-	-	-	-
537.5	4440	1.71225	1.70948	1.874	1.906
538.0	4640	-	-	-	-
564.0	4840	-	-	-	-
585.0	4840	1.72365	1.72083	2.55	2.58
585.5	4900	-	-	-	-
609.0	4900	1.73069	1.72767	2.97	2.99
616.0	5260	-	-	-	-
635.0	5260	1.74053	1.73746	3.557	3.574
635.5	5370	-	-	-	-
640.0	5450	-	-	-	-
657.0	5450	1.75013	1.74562	4.128	4.061
657.5	5560	-	-	-	-
663.5	5560	1.75396	1.75000	4.356	4.322
664.5	5660	-	-	-	-
686.5	5660	1.76860	1.76426	5.227	5.172
688.5	0	1.76663	1.76098	5.110	4.976

TABLE A-12
TEST CAPSULE DIMENSIONS

Test	Mean Diameter (in.)	Minimum Wall Thickness (in.)
A2A	1.546	0.1272
B2A	1.6440	0.1170
B3A	1.5480	0.1247
B4	1.5063	0.0853
B5	1.5433	0.1223
B5A	1.5491	0.1127
B6	1.5480	0.1260
B7	1.5465	0.1148