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LOW CYCLE FATIGUE ANALYSIS OF STORAGE CANISTERS DUE TO EXPANSION OF CONTENTS

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ABSTRACT

Qualification of storage canisters due to the expansion behavior of plutonium metal during phase transitions requires a combined experimental and analytical modeling effort. Tests were conducted at Los Alamos National Laboratory to define the expansion behavior of plutonium metal during the alpha-beta-gamma phase transitions. Test results showed that the expansion is anisotropic due to the container wall constraint. The plutonium expansion parameters were calculated from test data, and combined with a finite element analysis (FEA) to determine the stress state of the storage canisters. Strain values were computed and compared with the ASME Code secondary and peak stress limits. Since the applied expansion strain exceeds the strain of 10 cycles in the ASME Code design fatigue curve, the ASME Code design fatigue curve was extended to values below 10 cycles.

INTRODUCTION

Plutonium metal has linear thermal expansion coefficients for the thermal ranges of the metal phases, but experiences significant expansion during the phase transformations, as shown in Figure 1[1]. The linear thermal expansion coefficient of α-phase plutonium is about 3.5 times the expansion of stainless steel, and the plutonium expansion during the α-β phase transformation is 3% or about 18 times the expansion of stainless steel from room temperature to the α-β phase transformation temperature of 124°C. Since the plutonium expansion is significant by larger than the stainless steel storage container expansion, the effect of the plutonium expansion on the storage container must be evaluated to assure the integrity of the storage containers.

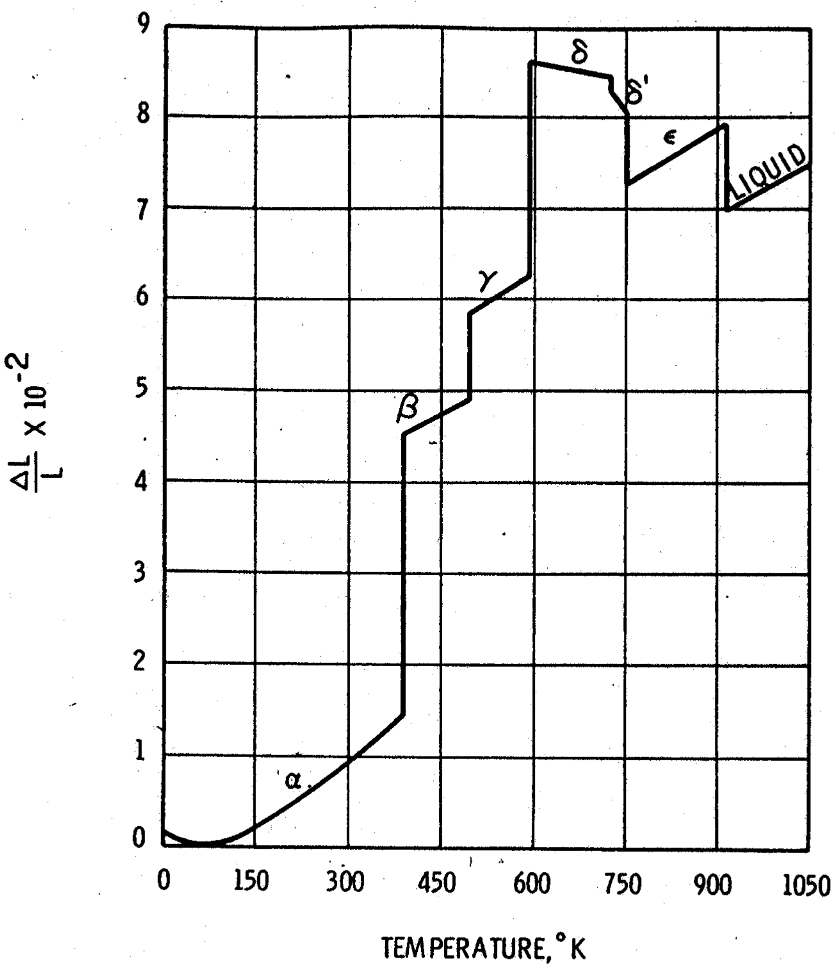


Figure 1 Linear Expansion Behavior of Plutonium

PLUTONIUM EXPANSION TEST CONFIGURATION

Material properties of plutonium are presented in the reference literature [1], [2] for the temperature ranges of the six phases of plutonium metal. The material properties of interest are thermal expansion coefficients, modulus of elasticity, Poisson's ratio, yield stress, and ultimate stress. However, the only information on material properties during the thermal range of a phase transformation is the expansion. Thus, a test was developed with the objective to measure the effective pressure exerted by a plutonium ingot on the test cylinder during the phase transformation.

The basic test components are a cylindrical furnace, a stainless steel test cylinder, and a plutonium ingot. The test configuration is the plutonium ingot inside the stainless steel cylinder with strain gauges and thermocouples attached to the plutonium and test cylinder as shown in Figure 2. The test is conducted with thermal cycles that include heat-up to150°C into the β-phase, hold at 150°C for 30 to 90 minutes, and power-off cool-down to ambient temperature. When the plutonium ingot expands and contacts the test cylinder wall, strain gauge data in the hoop strain direction is produced by the expansion of plutonium. This data is used to calculate the effective pressure exerted by the plutonium ingot during the phase transformation.

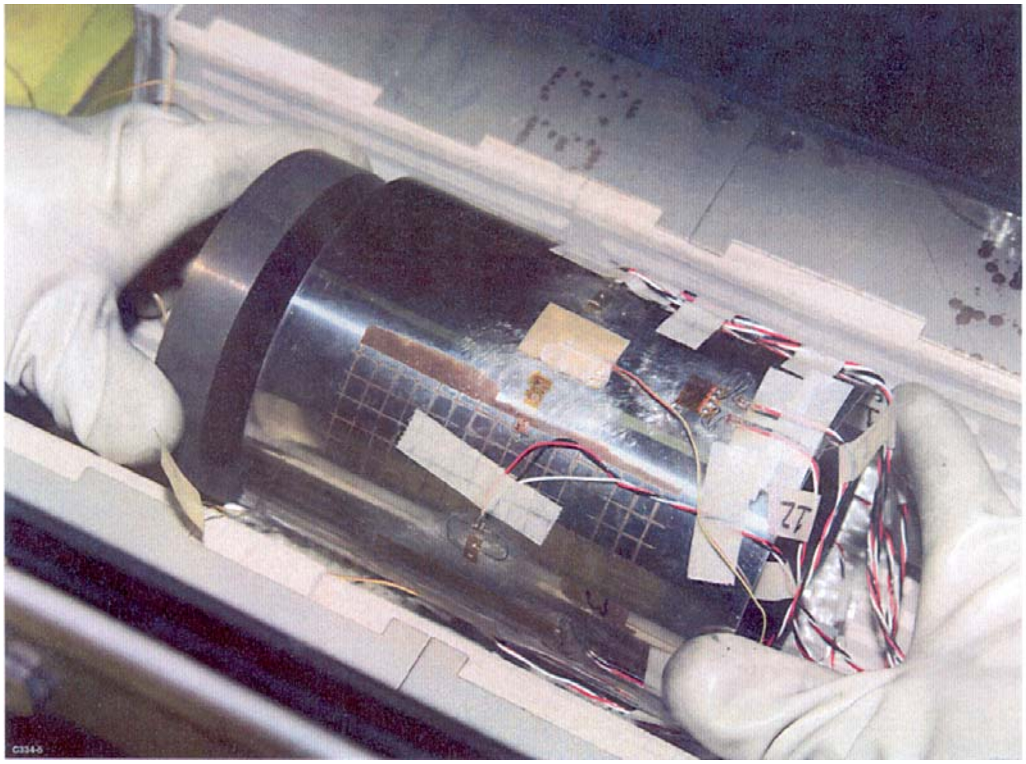


Figure 2 Test Components Plutonium Ingot, Stainless Steel Cylinder, Furnace and Instrumentation

PLUTONIUM EXPANSION TEST RESULTS

The recorded results of the plutonium α-β phase transition expansion test are strain gauge and thermocouple data as a function of time. The hoop tension strain gauges and the thermocouples provide data for calculation of the pressure exerted by the plutonium on the test cylinder during the phase transformation. Thus the test data presented in this section is limited to the hoop tension strain gauges and thermocouples values as a function of time. The test heat-up cycle was repeated six times until there was no increase in strain.

Figures 3 and 4 show the hoop strain in the test cylinder as a function of time and temperature for the first thermal cycle. Figure 5 is the hoop strain data as a function of time for all 6 thermal cycles. The hoop strain in the test cylinder increased during the first four test cycles and decreased during the fifth and sixth cycle. Thus, the test results show that the diameter of the plutonium ingot decreased during the thermal cycles until the contact pressure produced by the plutonium ingot is insignificant.

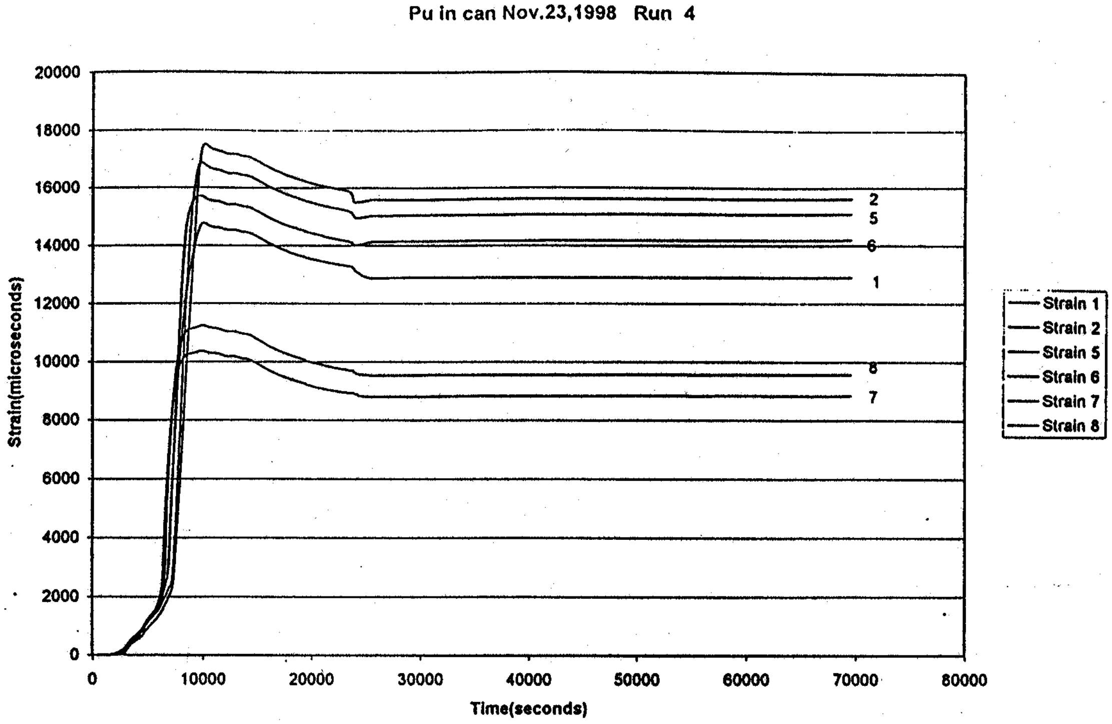


Figure 3 Test Cylinder Hoop Strain vs Time for First Thermal Cycle

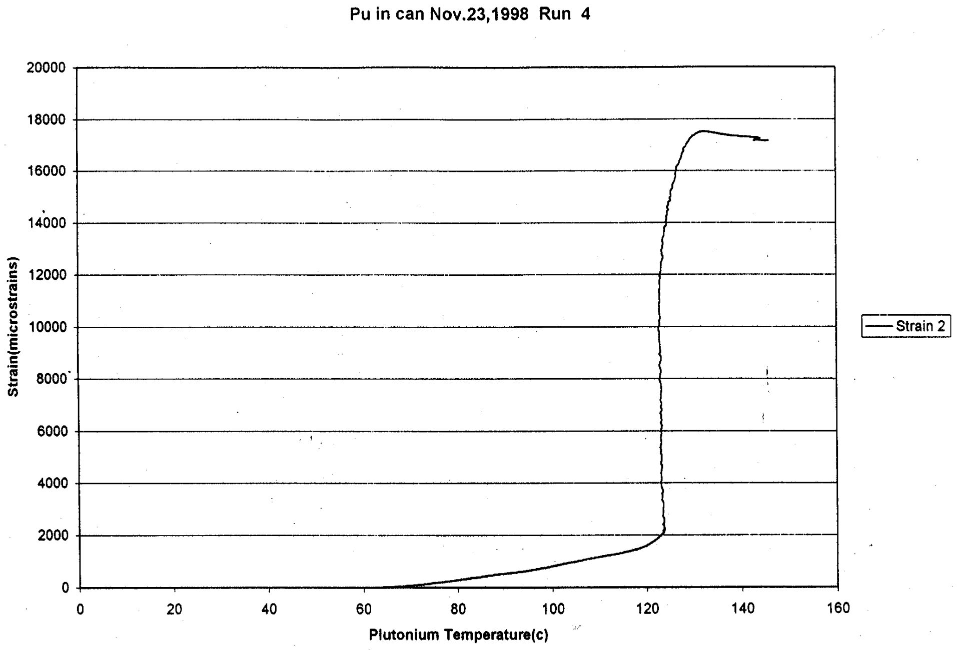


Figure 4 Test Cylinder Max Hoop Strain vs. Temperature for First Thermal Cycle

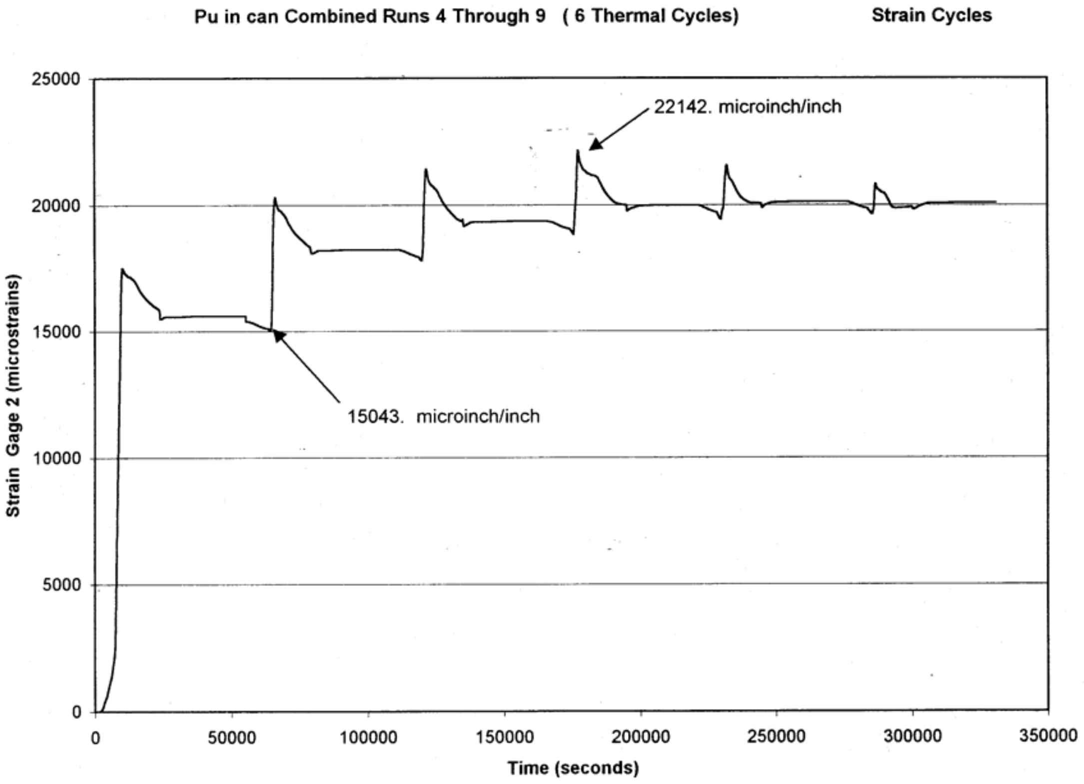


Figure 5 Test Cylinder Hoop Strain vs Time for 6 Thermal Cycles

ANALYSIS OF PLUTONIUM PHASE TRANSITION EXPANSION PRESSURE

The finite element analysis (FEA) was performed on the stainless steel cylinder and plutonium ingot to develop the effective pressure produced on the cylinder wall by the plutonium during the α-β phase transition. An axisymmetric FEA model composed of solid elements for the plutonium, shell elements for the cylinder, and contact surface elements between the cylinder and plutonium, was developed by using the ABAQUS [3] finite element program. The FEA model, shown in Figure 6, has the dimensions of the test cylinder and plutonium ingot.

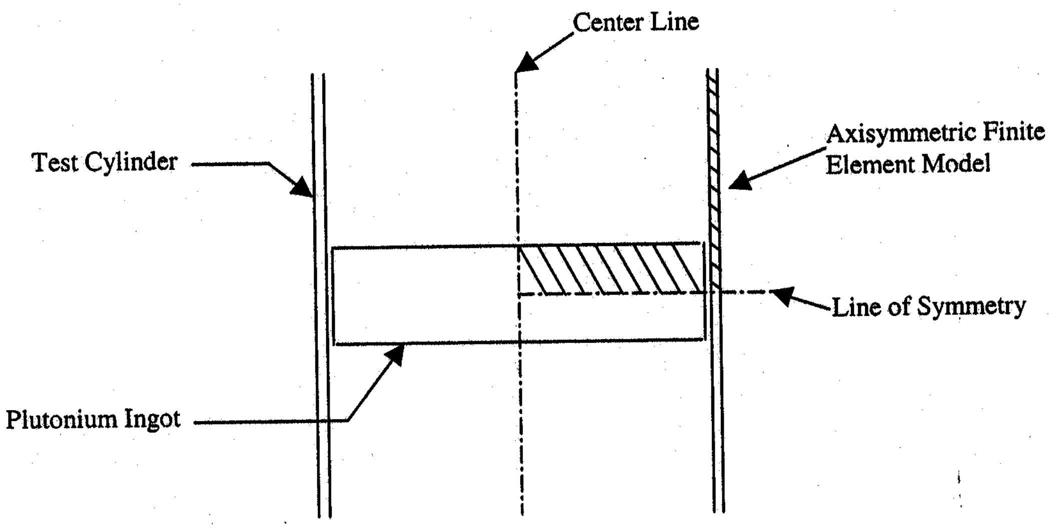


Figure 6 Finite Element Model Lines of Symmetry for Test Configuration

The material properties that are needed as a function of temperature for the test cylinder and plutonium are thermal coefficients of expansion, Poisson's ratio, modulus of elasticity and stress-strain values. The stress-strain values of the test cylinder are from test data of the cylinder material. The thermal expansion coefficients of plutonium include the effect of the phase transition expansion. Since the plutonium stress-strain values during the phase transition are not known, the yield stress value was varied in the FEA until the test cylinder hoop strain values matched the plutonium test data.

The strain results as a function of temperature for six cycles of the plutonium test data are shown in Figure 7, and the strain results as a function of temperature from the FEA results are shown in Figure 8. These two figures show that the FEA results of the hoop strain in the test cylinder match the maximum hoop strain in the plutonium test data when the plutonium material has an apparent yield strength of 2,033 psi during the α-β phase transformation.

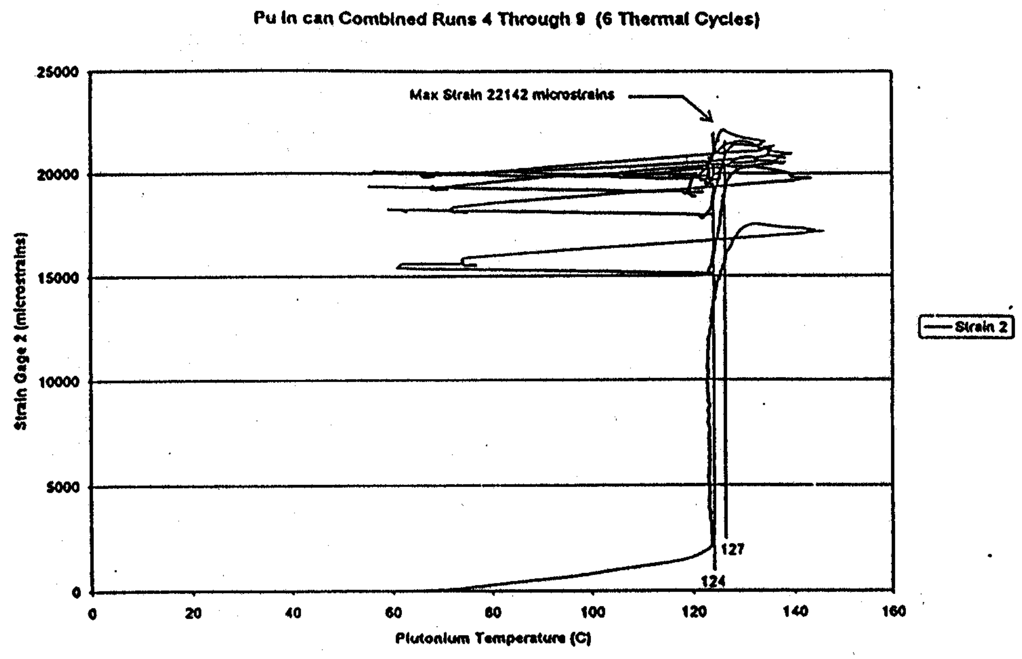


Figure 7 Test Cylinder Strain vs Plutonium Temperature from Test Data of Six Thermal Cycles

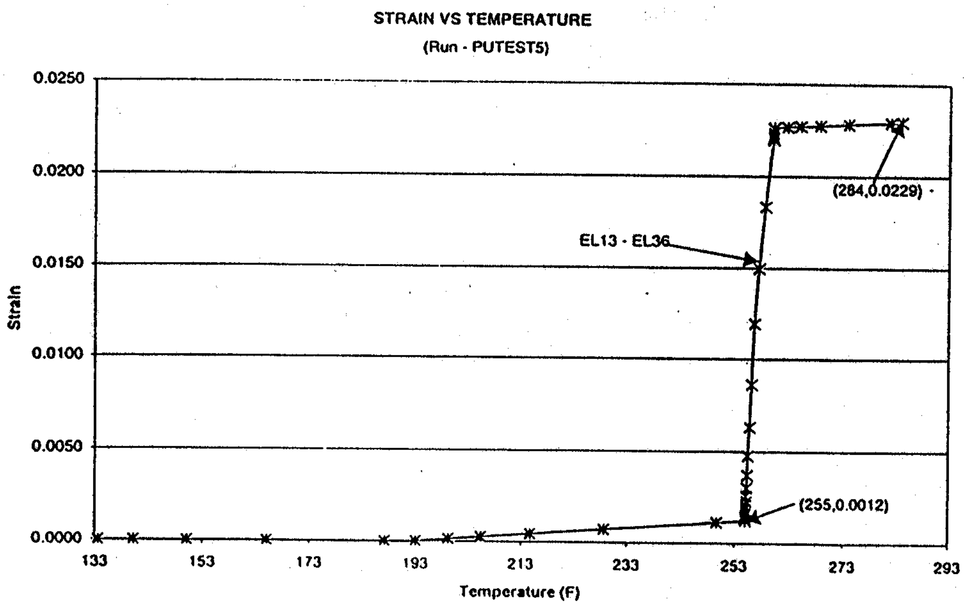


Figure 8 Test Cylinder Strain vs Plutonium Temperature from FEA Results

Review of yield strengths in Figure 9 at the end of the α-phase and at the beginning of the β-phase shows that the 2033 psi apparent yield strength of plutonium during the α-β phase transformation is a significant reduction in strength. The test cylinder imposes a radial pressure on the plutonium ingot, but the top and bottom surfaces are free. Thus the plutonium ingot experiences non-uniform loading during the expansion. Dilatometry data taken during the plutonium test[4] show that the plutonium ingot thickness increased 5.8% during the heating cycles. Since this is twice the expected linear expansion of 3% for the α-β phase transformation, anisotropic expansion of the plutonium ingot was observed.

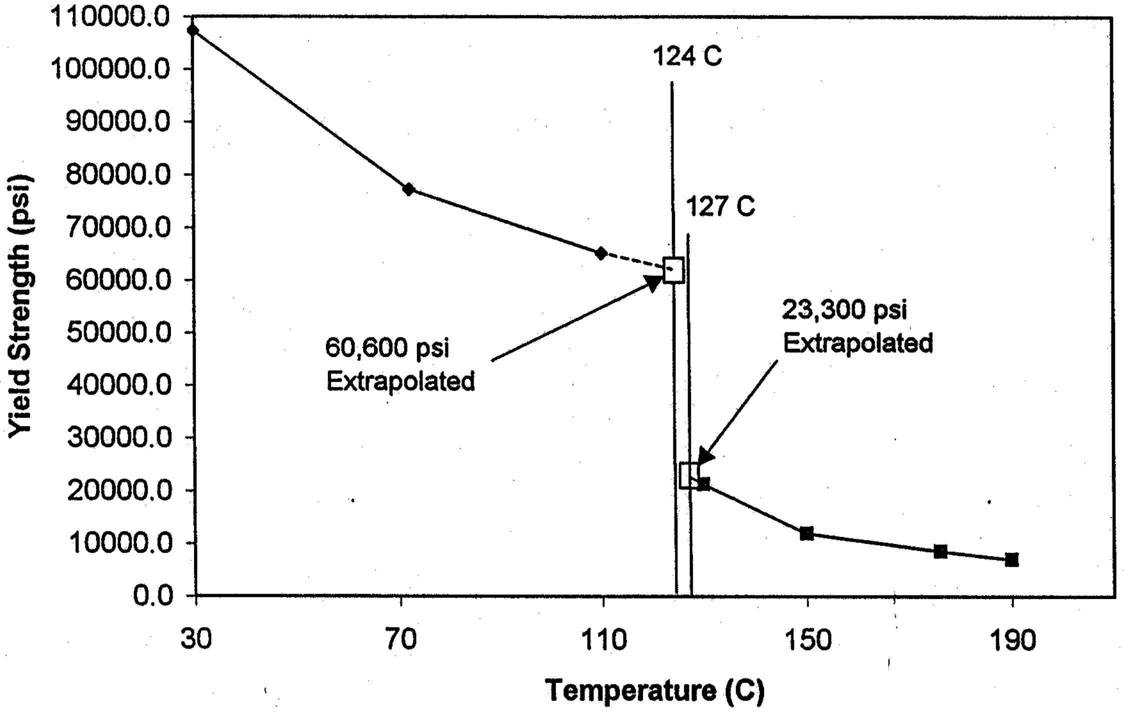


Figure 9 Plutonium Compressive Yield Strength vs Temperature for α&β Phases

ANALYSIS OF PLUTONIUM STORAGE CONTAINER

The inner plutonium storage container is a cylinder with a formed bottom and a welded plug head as shown in Figure 10. The cylinder wall thickness, plutonium ingot thickness and initial radial gap between the plutonium and cylinder wall are the same for the test cylinder and storage container. The major differences between the two are the storage container has a top, a bottom, and lower material strength properties. The material strength properties are the ASME Boiler & Pressure Vessel Code[6] minimum properties.

The stress analysis of the inner storage container was conducted to show that the container meets the stress requirements of the ASME Boiler & Pressure Vessel Code[6] Section VIII, Division 2. The analysis was performed using the finite element method with the ABAQUS[3] finite element code. An axisymmetric FEA model composed of solid elements for the plutonium, shell elements for the storage container and contact surface elements between the plutonium and cylinder wall was developed as shown in Figure 11. The material properties of the plutonium are the properties developed for plutonium in the test cylinder model.

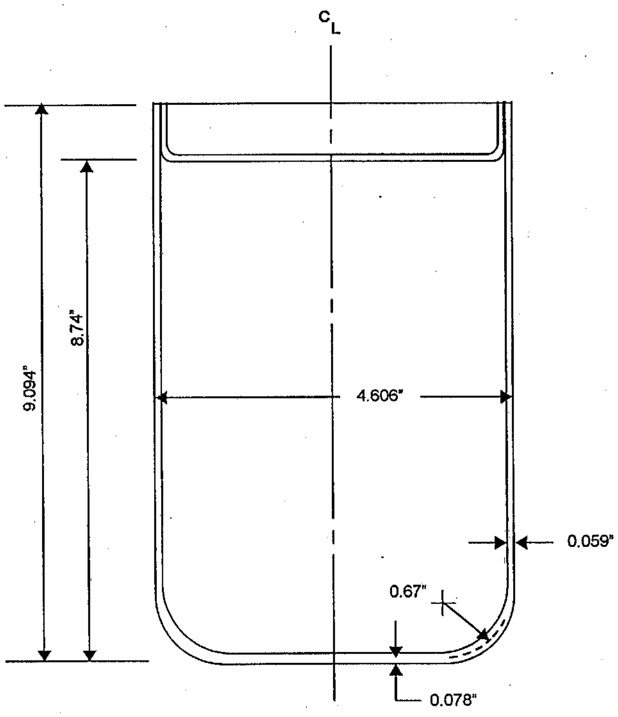


Figure 10 Plutonium Storage Canister

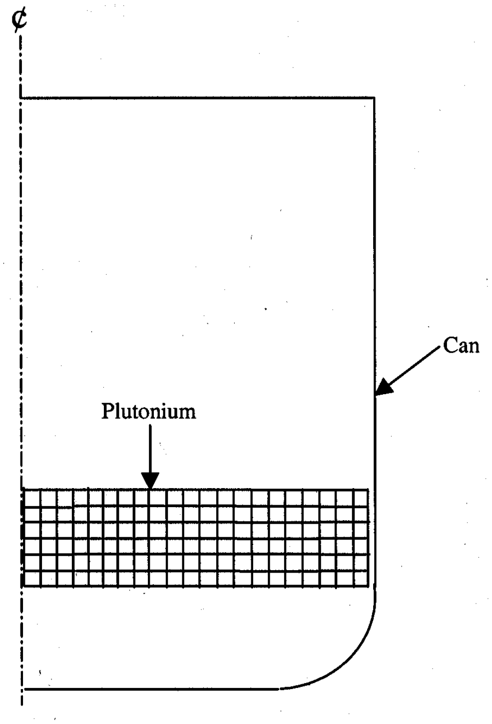


Figure 11 Plutonium and Storage Canister Finite Element Model

The governing loading condition on the storage container is the deformation produced by expansion of the plutonium ingot. Since these stresses are produced by thermal expansion of the plutonium, they are displacement controlled stresses and classified by the ASME Code as secondary stresses. Secondary stresses are allowed to exceed the yield strength and produce plastic strains. The failure mechanism produced by secondary stresses is excessive distortion or progressive distortion produced by cycles of secondary stress. In addition, fatigue failure must be addressed because there are stress cycles. These two failure modes are addressed in this section.

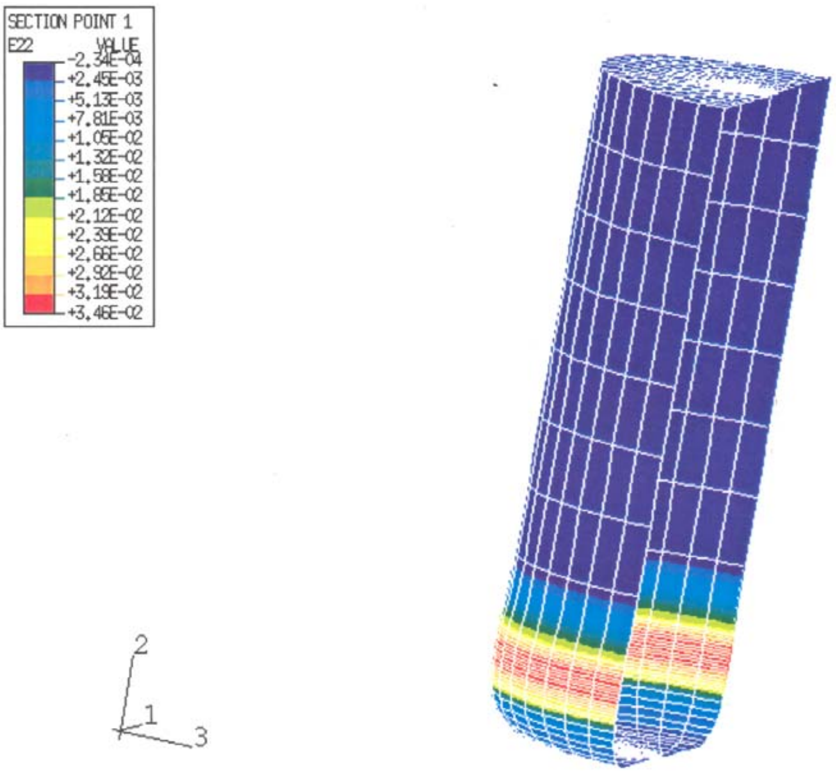
The local distortion produced by the secondary stress does not violate the storage function of the container, and the test data in Figure 5 shows that progressive distortion stopped after four thermal cycles. Thus the secondary stresses produced by plutonium expansion meet the ASME Code secondary stress limits.

A fatigue analysis is performed with the results from the FEA. The maximum hoop strain of 3.46% is produced in the container wall region adjacent to the plutonium ingot, as show in Figure 12.

the maximum longitudinal strain of -3.09% is produced by bending in the cylinder wall regions adjacent to the top and bottom edges of the plutonium ingot as shown in Figure 13. The (Tresca) maximum shear stress failure theory, used by the ASME Code, produces the maximum effective stress for a biaxial stress state with the combination of positive hoop and negative longitudinal principal stress components. Since the maximum negative longitudinal stress is on the inside surface near the edges of the plutonium ingot, the point of maximum Tresca stress is on the cylinder wall inside surface near the edges of the plutonium ingot. The point of maximum effective stress was obtained from the FEA listing of hoop and longitudinal strain components. The maximum effective Tresca strain (0.0638 in/in) is produced by hoop strain of 0.0335 in/in and longitudinal strain of -0.0303 in/in.

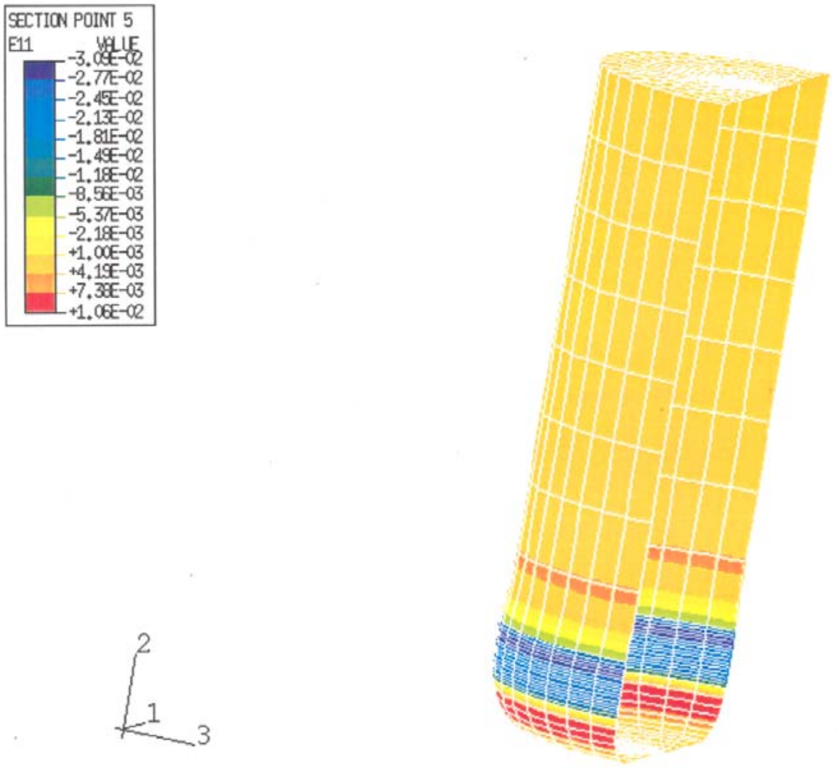
There is a local undercut region on the container wall produced by the laser process which applied the barcode. This discontinuity produces a strain intensification factor of 1.06. Thus the peak or maximum fatigue strain produced in the cylinder wall is 0.0677 in/in.

The strain gauge test data for six thermal cycles is used to construct the strain cycle diagram as shown in Figure 14. Examination of the strain loading from the plutonium test data in the figure shows that the plastic strain increased to a maximum value and has 4 ½ cycles of small alternating strain.



RUN – BNFL6C, STEP=6, TEMP. = 370^0 F, PRESS. = 100 psi

Figure 12 Hoop Strain in Container Wall at the End of the Heat-Up Cycle



RUN – BNFL6C, STEP=6, TEMP. = 370^0 F, PRESS. = 100 psi

Figure 13 Longitudinal Strain on Container Inside Wall at the End of the Heat-Up Cycle

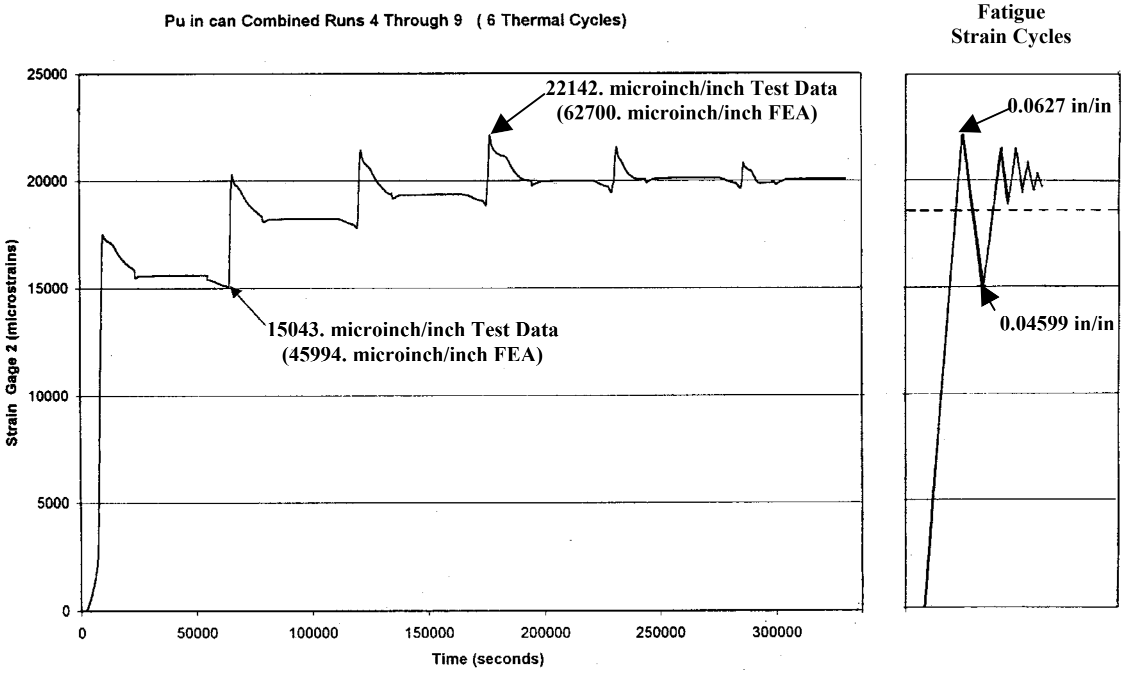


Figure 14 Hoop Strain in Test Cylinder for 6 Thermal Cycles and Fatigue Strain Cycles

The FEA showed that the maximum strain is produced by the combination of hoop and longitudinal strains on the inside surface of the canister. Since the test strain data did not include the longitudinal strain on the inside surface, the test data of the strain cycles was increased by the ratio of Max FEA Strain over the maximum test strain, as shown in Figure 14. The FEA fatigue cycles are divided into two groups, a ½ cycle with the maximum strain range of 0.0677 in/in and 4 ½ cycles with the largest strain range of the group (0.0677-0.04599) 0.0217 in/in. The ½ cycle strain exceeds the strain range for 10 cycles of the ASME Code design fatigue curve. Since the ASME fatigue curve was developed from displacement controlled test data and the plastic strain in the canister is displacement controlled, it is reasonable to use strain levels for cycles below the 10 cycles of the fatigue curve.

ASME Code fatigue data will be extroplated by using the data presented in the ASME Code Criteria documents, References [7 and 8]. The "Best Fit" equation of the fatigue data for austenitic stainless steel from Equation (1) of Reference [7] is;

$$S_{alt} = \frac{E}{4\sqrt{N}} \ell n\left[\frac{100}{100-RA}\right] + S_e \qquad (1)$$

Where S_{alt}=Alternating Stress (psi)
N = Fatigue Cycles (Cyc)
RA = Reduction of Area in Tensile Specimen (72.6%)
S_e= Endurance Limit (43,500 psi)
E = Modulus of Elasticity (26E6 psi, Ref. [8] Eqn. 8)

Substituting the above values, changing Modulus of Elasticity to 28.3E6 psi, and applying factors of 2 on stress and 20 on cycles to the "Best Fit" equation produces the ASME Code "Design" fatigue equation;

$$S_{alt} = \text{Lesser of} \left\{ \begin{array}{c} \frac{28.3E6}{4\sqrt{20N}} \ell n \frac{100}{100-72.6} + 47,400 \\ \text{and} \\ \frac{1}{2}\left(\frac{28.3E6}{4\sqrt{N}} \ell n \frac{100}{100-72.6} + 47,400 \right) \end{array} \right\} \qquad (2)$$

It is noted that the equation with 20 on cycles is the governing equation for low cycle fatigue, and the equation with 2 on stress is the governing equation for high cycle fatigue. Applying equation (2) to the two groups of cycles produces the allowable fatigue cycles, as shown in Table 1. Combining the fatigue usage ratios of the two groups produces a total fatigue usage of 0.173.

Table 1 Fatigue Analysis Results

Group	**Number of Cycles n(cyc)**	**Strain Range ε_r(in/in)**	**Alternating Stress*** $S_{ALT}= \frac{1}{2} E\varepsilon_r$ **(psi)**	**Allowable Cycles N (cyc)**	**Applied to Allowable Cycles Ratio** $R = \frac{n}{N}$
1	0.5	0.0677	976,000	5	0.10
2	4.5	0.0217	307,100	62	0.073

*Modulus of Elasticity of E= 28.3E6 psi

REFERENCES

[1] Wick, O.J., “Plutonium Handbook A Guide to the Technology”, The American Nuclear Society, LaGrange Park, Illinois, 1980.

[2] Grison, E., Lord, W.B.H., and Fowler, R.D., “Plutonium 1960", Cleaver-Hume Press Ltd., April 1960.

[3] Hibbit, Karlsson & Sorensen, “ABAQUS User’s Manual”, HKS, Inc. Pawtucket, Rhode Island, Version 5.8, 1998.

[4] Spearing, D.R., Veirs, D.K., and Prenger, F.C., “Effects of the Plutonium α-β Phase Transition Expansion on Storage Can Integrity”, Los Alamos National Laboratory Report Number LA-UR-99-147, January 14, 1999.

[5] Flanders, H.E. and Krishnan, R.P, “Plutonium Alpha-Beta Expansion & BNFL (3013) Inner and Outer Storage Cans Evaluation (U)”, Westinghouse Savannah River Co. Report T-CLC-G-00113.

[6] American Society of Mechanical Engineers, “ASME Boiler and Pressure Vessel Code”, Section VIII, Division 2, 1995 Edition.

[7] American Society of Mechanical Engineers, “Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis in Sections III and VIII, Division 2", The ASME, New York, 1969.

[8] Langer, B.F., “Design of Pressure Vessels for Low-Cycle Fatigue”, Transactions of the ASME, Journal of Basic Engineering, 1961.