N73-26672

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Experimental Evaluation of Thermal Ratcheting Behavior in UO_2 Fuel Elements

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PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

CONTENTS

ABSTRACT

The effects of thermal cycling of UO_2 at high temperatures has been experimentally evaluated to determine the rates of distortion of UO_2/clad fuel elements. Two capsules were tested in the 1500°C range, one with a 50°C thermal cycle, the other with a 100°C thermal cycle. It was observed that eight hours at the lower cycle temperature produced sufficient UO_2 redistribution to cause clad distortion. The amount of distortion produced by the 100°C cycle was less than double that produced by the 50°C, indicating smaller thermal cycles would result in clad distortion. An incubation period was observed to occur before the onset of distortion with cycling similar to fuel swelling observed in-pile at these temperatures.

I. INTRODUCTION

The swelling of uranium dioxide fuel elements in pile at high temperatures can be produced, not only by fission product generation, but also by thermal ratcheting. The thermal ratcheting deformation mechanism consists of small temperature gradient thermal cycles. Fuel redeposition occurs at the lower temperature, followed by a small temperature increase. Stress and accompanying deformation are the result of thermal expansion coefficient mismatches. An understanding of stress and deformation behavior of the fuel emitter composite is necessary at temperatures of about one-half the melting point of the materials since at these temperatures rapid relaxation of thermal stresses and significant creep rates occur, even for stress levels at the 100-N/cm^2 range. Because of the relatively high temperatures involved, the most significant mode of deformation is creep.

Thermal and stress analyses have been performed to evaluate time-dependent stress and deformation behavior (Ref. 1). Radial, axial, azimuthal, and principal stress distributions were computed, along with deformations. The method used was an adaptation of a finite element, viscoelastic method, applying numerical techniques for computer solution. Thermal analysis was performed with the aid of the computer program TACTIC (Ref. 2), which is a general-purpose, two-dimensional heat transfer program. An accompanying elastic stress analysis was done with the program called HULA (Ref. 3), which computed thermal and mechanical stresses for axisymmetric thin shells of various configurations. The effects of fission product swelling were also calculated by assuming a linear swelling behavior of 0.15 $\Delta V/V$ per 10^{20} F/cm^3, which was independent of temperature. Power density was assumed to be 70 W/cm^3.

The results of these high-temperature thermal cycling analyses and fuel swelling analyses indicated that the clad provided almost no restraint in the temperature cycle case, whereas in the fuel swelling case, fuel was forced to deform to accommodate large fuel volume changes. This was explained by the difference in stress levels (caused by the difference in deformation rate), and the different creep behavior of the UO_2 and tungsten. In the thermal cycle problem, the temperature increase was assumed to be imposed rapidly and the stress levels were initially quite high — 10,000 N/cm^2 (15,000 psi) in the tungsten, +2000 to -5000 N/cm^2 (+3000 to -7500 psi) in the fuel. In the fuel swelling, the rate of strain in the fuel was very low, and with stress relaxation taking place, the stress levels remained low. Levels were typically about 70 N/cm^2 (100 psi) in the tungsten, and an average of about -35 N/cm^2 (-50 psi) in the fuel.

The experimental evaluation of the fuel behavior under thermal ratcheting conditions was undertaken, not only to evaluate the accuracy of the calculated thermal ratcheting behavior, but also to evaluate the redistribution time for uranium dioxide needed to produce thermal ratcheting, and to obtain indications of the effects of changes in thermal cycle temperatures on behavior.

II. TEST METHODS

A schematic of the test capsule is shown in Fig. 1. The outer test capsule used in the experiment was 3.18-cm (1-1/4-in.) diameter, 0.10-cm (0.040-in.) wall × 6.35-cm (2-1/2-in.) length of tungsten vapor-deposited by the fluoride process. The inner capsule for electron bombardment surface was also vapor-deposited tungsten 0.95-cm (3/8-in.) diameter × 5.72-cm (2-1/4-in.) length. The UO_2 was cold-pressed without a binder and vacuum-sintered at 1800°C for eight hours. The disks of UO_2 were approximately 0.48 cm (3/16 in.) thick, after sintering. The capsule was sealed by electron beam welding at approximately 1×10^{-5} torr (approximately 10^{-3} N/m^2).

Test capsule temperature and thermal gradient were controlled by a combination of electron bombardment power at the centerline of the test capsule, and external buffer heater power. The electron bombardment heater, insulator, heater support, and test capsule are shown in Fig. 2.

Calculation of temperatures using the HEATING II computer program indicated maximum centerline tungsten crucible temperatures to be approximately 2000°C, with surface temperatures of 1600°C.

III. TEST RESULTS

Two capsules were cycled: one with 100°C ΔT; the other with a 50°C ΔT. Results of diametral measurements, after intervals of five cycles with varying times, are shown in Tables 1 through 4.

Capsule 1 was cycled through a 100°C ΔT. The initial data taken on this capsule is shown in Table 1. This initial data, taken using a cycle of 12 hours hot/60 hours cold, indicated a slight increase in the rate of diametral growth with cycling, suggesting an incubation period for redistribution of the UO_2.

The test cycle times were changed after a total of 15 thermal cycles to 8 hours hot/16 hours cold. An additional 15 cycles at these conditions produced a relatively constant rate of diametral growth (Table 2), which was only slightly less than the average rate produced by the initial slower cycling rate.

After a total of 30 cycles, the cycle times were again reduced to allow only 8 hours at the lower temperature for UO_2 redistribution. These results (Table 3) indicate that the rate of diametral growth is unchanged. The ΔT remained at 100°C for all of these tests; however, the absolute temperatures decreased 50°C for the last series of thermal cycles.

Testing was discontinued at this point, since the capsule had distorted sufficiently to make diametral measurements inaccurate. The final profile of the capsule, with deformation exaggerated by a factor of 10, after a total of 40 cycles is shown in Fig. 3. A radiograph of the capsule after test is shown in Fig. 4. Redistribution of the UO_2 is not complete since portions of the UO_2 disks remain, particularly in the cooler top half of the capsule.

Capsule 2 was tested using a 50°C ΔT with the 8-hour hot/16-hour cold test cycle. These results (Table 4) show more clearly the incubation period needed to produce capsule distortion. The rate of distortion of this capsule was somewhat less than the first capsule with the 100°C ΔT, but not half as much.

IV. DISCUSSION

A computational evaluation of thermal ratcheting of the UO_2/tungsten capsule was based on creep rates of UO_2 and tungsten, shown in Fig. 5. The capsule was assumed to be 2.79-cm (1.1-in.) diameter, with a 0.10-cm (0.040-in.) wall. The UO_2 was assumed to be fully redistributed against the tungsten at an average capsule temperature of 1650°C. A 50° temperature rise was calculated to produce a maximum radial deformation of 0.0076 mm (0.0003 in.). At 1700°C, the stresses produced will rapidly relax. Approximately one-half hour was calculated necessary to allow stresses at the center of the capsule to decrease to negligible levels, while stresses at lower temperature areas and end cap areas decreased to negligible levels in less than four hours.

The test capsule operated with a 50°C ΔT cycle, but at slightly lower temperatures than assumed in the above calculation, produced a 0.0076-mm (0.0003-in.) radial deformation (0.015 mm (0.0006 in.) diametral) per cycle, after an incubation period. This deformation occurred near the center of the capsule, away from the end caps which restrained the diametral deformation. The high-temperature time was eight hours, which appeared sufficient to allow essentially full stress relaxation, even with the lower temperatures used in the experiment.

Comparison of the 50°C ΔT cycle data in Table 4 with the 100°C ΔT cycle data in Table 1 would suggest that the incubation period (period for sufficient UO_2 redistribution to occur to produce deformation) is test time-dependent rather than cycle-dependent. This is based on the reduced incubation period in the 100°C cycle test, where an initial test cycle of 12 hours hot/60 hours cold (total test time of 360 hours for 5 cycles) was used as compared to the 50°C cycle tests where the initial cycle was 8 hours hot/16 hours cold (total test time of 120 hours for 5 cycles). The data from the 100°C cycle tests indicate the incubation period to be less than 360 hours, when the first measurement was taken, which indicated deformation while the 50°C cycle test results indicate an incubation period of 240 hours (10 cycles) before significant deformation occurred. In terms of reactor fuel element lifetimes, these incubation periods are negligible.

Similar incubation periods are present in UO_2-fueled in-pile thermionic converter tests run at Gulf General Atomic. The swelling of the emitter clad as measured by neutron radiography is plotted in Fig. 5. The incubation period varies from negligible to approximately 4000 hours. The variation occurred in two emitters in the same 2-cell device (2E2), which were supposedly identical in construction, symetrically placed within the reactor core, and underwent the same thermal cycles.

A more significant result of these tests is the effect of ΔT on deformation. The 50°C ΔT cycle produced a 0.015-mm (0.0006-in.) diametral deformation per cycle, as compared to approximately 0.020 mm (0.0008 in.)/cycle for the 100°C ΔT cycle. This nonlinear behavior suggests that small temperature fluctuations, less than 50°C, could result in significant deformation of the fuel elements.

In addition to the total ΔT, rate of change of temperature will play a significant role in deformation. The test cycle used in these tests, i.e., the step change, is the most detrimental. A rapid temperature change results in high stress levels. As can be seen from Fig. 6, creep rates for UO_2 fuel and tungsten clad at high stress levels become similar, while at low stress levels, produced by slow temperature changes, the creep rate of the UO_2 fuel is much more rapid than that for tungsten, allowing stress relaxation via fuel deformation, rather than clad deformation which results in external, dimensional changes.

V. CONCLUSIONS

The postulated thermal ratcheting mechanism in UO_2 under thermal gradient conditions has been experimentally verified. The magnitude of the deformation is generally in agreement with calculated deformations based on viscoelastic behavior of tungsten and UO_2.

Deformation does not appear to be a linear function of the magnitude of the thermal cycle, since a 100°C ΔT cycle produced only slightly more deformation than a 50°C ΔT cycle. While this nonlinear behavior may be due to heating rate effects, its major significance lies in the possibility that repeated temperature changes of less than 50°C can produce significant fuel element distortion.

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Table 1. Dimensional changes produced by 12 h--1625°C/60 h--1525°C UO_2/tungsten thermal cycles

Location	Starting diameter, cm (in.)	5 Cycles		10 Cycles		15 Cycles	
		Diameter, cm (in.)	ΔD, cm (in.)	Diameter, cm (in.)	ΔD, cm (in.)	Diameter, cm (in.)	ΔD, cm (in.)
0° Top	3.1808 (1.2523)	3.1775 (1.2510)	-0.0033 (-0.0013)	3.1791 (1.2516)	+0.0015 (+0.0006)	3.1811 (1.2524)	+0.0020 (+0.0008)
2.54 cm (1 in.)	3.1819 (1.2527)	3.1834 (1.2533)	+0.0015 (+0.0006)	3.1897 (1.2558)	+0.0064 (+0.0025)	3.2047 (1.2617)	+0.0150 (+0.0059)
5.08 cm (2 in.)	3.1849 (1.2539)	3.1943 (1.2576)	+0.0094 (+0.0037)	3.2060 (1.2622)	+0.0117 (+0.0046)	3.2296 (1.2715)	+0.0236 (+0.0093)
Bottom	3.1824 (1.2529)	3.1841 (1.2536)	+0.0018 (+0.0007)	3.1951 (1.2579)	+0.0109 (+0.0043)	3.2167 (1.2664)	+0.0216 (+0.0085)
90° Top	3.1814 (1.2525)	3.1750 (1.2500)	-0.0064 (-0.0025)	3.1750 (1.2500)	0	3.1808 (1.2523)	+0.0058 (+0.0023)
2.54 cm (1 in.)	3.1768 (1.2507)	3.1732 (1.2493)	-0.0036 (-0.0014)	3.1788 (1.2515)	+0.0056 (+0.0022)	3.1981 (1.2591)	+0.0193 (+0.0076)
5.08 cm (2 in.)	3.1857 (1.2542)	3.1872 (1.2548)	+0.0015 (+0.0006)	3.2083 (1.2631)	+0.0211 (+0.0083)	3.2385 (1.2750)	+0.0302 (+0.0119)
Bottom	3.1806 (1.2522)	3.1821 (1.2528)	+0.0015 (+0.0006)	3.1966 (1.2585)	+0.0145 (+0.0057)	3.1976 (1.2589)	+0.0010 (+0.0004)
Maximum total ΔD		+0.0094 (+0.0037)		+0.0226 (+0.0089)		+0.0528 (+0.0208)	
Maximum ΔD/cycle		+0.0018 (+0.0007)		+0.0023 (+0.0009)		+0.0036 (+0.0014)	

Capsule size 3.18-cm (1 1/4-in.) OD × 6.35-cm (2 1/2-in.) length × 0.10-cm (0.040-in.) wall

Table 2. Dimensional changes produced by 8 h--1625°C/16 h--1525°C UO_2/tungsten thermal cycles

Location	Starting diameter, cm (in.)	5 Cycles		10 Cycles		15 Cycles	
		Diameter, cm (in.)	ΔD, cm (in.)	Diameter, cm (in.)	ΔD, cm (in.)	Diameter, cm (in.)	ΔD, cm (in.)
0° Top	3.1811 (1.2524)	3.1874 (1.2549)	+0.0064 (+0.0025)	3.1925 (1.2569)	+0.0051 (+0.0020)	3.1968 (1.2586)	+0.0043 (+0.0017)
2.54 cm (1 in.)	3.1793 (1.2517)	3.2149 (1.2657)	+0.0102 (+0.0040)	3.2202 (1.2678)	+0.0053 (+0.0021)	3.2339 (1.2732)	+0.0137 (+0.0054)
5.08 cm (2 in.)	3.2296 (1.2715)	3.2365 (1.2742)	+0.0069 (+0.0027)	3.2413 (1.2761)	+0.0048 (+0.0019)	3.2461 (1.2780)	+0.0048 (+0.0019)
Bottom	3.2167 (1.2664)	3.2273 (1.2706)	+0.0107 (+0.0042)	3.2314 (1.2722)	+0.0041 (+0.0016)	3.2377 (1.2747)	+0.0064 (+0.0025)
90° Top	3.1808 (1.2523)	3.1852 (1.2540)	+0.0043 (+0.0017)	3.1880 (1.2551)	+0.0079 (+0.0031)	3.1928 (1.2570)	+0.0048 (+0.0019)
2.54 cm (1 in.)	3.1981 (1.2591)	3.2052 (1.2619)	+0.0071 (+0.0028)	3.2075 (1.2628)	+0.0023 (+0.0009)	3.2268 (1.2704)	+0.0193 (+0.0076)
5.08 cm (2 in.)	3.2385 (1.2750)	3.2504 (1.2797)	+0.0119 (+0.0047)	3.2540 (1.2811)	+0.0036 (+0.0014)	3.2568 (1.2822)	+0.0028 (+0.0011)
Bottom	3.1976 (1.2589)	3.2283 (1.2710)	+0.0053 (+0.0021)	3.2332 (1.2729)	+0.0048 (+0.0019)	3.2403 (1.2757)	+0.0071 (+0.0028)
Maximum total ΔD		+0.0107 (+0.0042)		+0.0155 (+0.0061)		+0.0287 (+0.0113)	
Maximum ΔD/cycle		+0.0020 (+0.0008)		+0.0015 (+0.0006)		+0.0018 (+0.0007)	

Capsule size 3.18-cm (1 1/4-in.) OD × 6.35-cm (2 1/2-in.) length × 0.10-cm (0.040-in.) wall

Table 3. Dimensional changes produced by 8 h--1475°C/16 h--1575° UO_2 thermal cycles

Location	Starting diameter, cm (in.)	5 Cycles Diameter, cm (in.)	5 Cycles ΔD, cm (in.)	10 Cycles Diameter, cm (in.)	10 Cycles ΔD, cm (in.)
0° Top	3.1968 (1.2586)	3.1994 (1.2596)	+0.0025 (+0.0010)	3.2004 (1.2600)	+0.0010 (+0.0004)
2.54 cm (1 in.)	3.2339 (1.2732)	3.2355 (1.2738)	+0.0015 (+0.0006)	3.2497 (1.2794)	+0.0142 (+0.0056)
5.08 cm (2 in.)	3.2461 (1.2780)	3.2537 (1.2810)	+0.0076 (+0.0030)	3.2568 (1.2822)	+0.0030 (+0.0012)
Bottom	3.2377 (1.2747)	3.2456 (1.2778)	+0.0079 (+0.0031)	3.2492 (1.2792)	+0.0036 (+0.0014)
90° Top	3.1928 (1.2570)	3.1976 (1.2589)	+0.0028 (+0.0011)	3.1938 (1.2574)	-0.0038 (-0.0015)
2.54 cm (1 in.)	3.2268 (1.2704)	3.2311 (1.2721)	+0.0043 (+0.0017)	3.2405 (1.2758)	+0.0094 (+0.0037)
5.08 cm (2 in.)	3.2568 (1.2822)	3.2667 (1.2861)	+0.0099 (+0.0039)	3.2715 (1.2880)	+0.0048 (+0.0019)
Bottom	3.2403 (1.2757)	3.2464 (1.2781)	+0.0061 (+0.0024)	3.2598 (1.2834)	+0.0135 (+0.0053)
Maximum total ΔD		+0.0099 (+0.0039)		+0.0196 (+0.0077)	
Maximum ΔD/cycle		+0.0020 (+0.0008)		+0.0020 (+0.0008)	

Capsule size 3.18-cm (1 1/4-in.) OD × 6.35-cm (2 1/2-in.) length × (0.040-in.) wall

Table 4. Dimensional changes produced by 8 h--1525°C/16 h--1475°C UO_2/tungsten thermal cycles

Location	Starting diameter, cm (in.)	5 Cycles		10 Cycles		15 Cycles		20 Cycles	
		Diameter, cm (in.)	ΔD, cm (in.)	Diameter, cm (in.)	ΔD, cm (in.)	Diameter, cm (in.)	ΔD, cm (in.)	Diameter, cm (in.)	ΔD, cm (in.)
0° Top	3.1803 (1.2521)	3.1798 (1.2519)	-0.0005 (-0.0002)	3.1836 (1.2534)	+0.0038 (+0.0015)	3.1831 (1.2532)	-0.0005 (-0.0002)	3.1918 (1.2566)	+0.0086 (+0.0034)
2.54 cm (1 in.)	3.1811 (1.2524)	3.1854 (1.2541)	+0.0043 (+0.0017)	3.1862 (1.2544)	+0.0008 (+0.0003)	3.1999 (1.2598)	+0.0137 (+0.0054)	3.2073 (1.2627)	+0.0074 (+0.0029)
5.08 cm (2 in.)	3.1808 (1.2523)	3.1773 (1.2509)	-0.0036 (-0.0014)	3.1796 (1.2518)	+0.0023 (+0.0009)	3.1928 (1.2570)	+0.0132 (+0.0052)	3.2022 (1.2607)	+0.0094 (+0.0037)
Bottom	3.1791 (1.2516)	3.1783 (1.2513)	-0.0008 (-0.0003)	3.1786 (1.2514)	+0.0003 (+0.0001)	3.1826 (1.2530)	+0.0041 (+0.0016)	3.1836 (1.2534)	+0.0010 (+0.0004)
90° Top	3.1796 (1.2518)	3.1763 (1.2505)	-0.0033 (-0.0013)	3.1803 (1.2521)	+0.0041 (+0.0016)	3.1816 (1.2526)	+0.0015 (+0.0006)	3.1913 (1.2564)	+0.0097 (+0.0038)
2.54 cm (1 in.)	3.1768 (1.2507)	3.1791 (1.2516)	+0.0023 (+0.0009)	3.1826 (1.2530)	+0.0036 (+0.0014)	3.1941 (1.2575)	+0.0114 (+0.0045)	3.2055 (1.2620)	+0.0114 (+0.0045)
5.08 cm (2 in.)	3.1765 (1.2506)	3.1750 (1.2500)	-0.0015 (-0.0006)	3.1763 (1.2505)	+0.0013 (+0.0005)	3.1847 (1.2538)	+0.0084 (+0.0033)	3.1935 (1.2573)	+0.0089 (+0.0035)
Bottom	3.1783 (1.2513)	3.1783 (1.2513)	0	3.1770 (1.2508)	-0.0013 (-0.0005)	3.1811 (1.2524)	+0.0041 (+0.0016)	3.1852 (1.2540)	+0.0041 (+0.0016)
Maximum total ΔD		+0.0043 (+0.0017)		+0.0058 (+0.0023)		+0.0188 (+0.0074)		+0.0287 (+0.0113)	
Maximum ΔD/cycle		+0.0008 (+0.0003)		+0.0005 (+0.0002)		+0.0015 (+0.0006)		+0.0015 (+0.0006)	

Capsule size 3.18-cm (1 1/4-in.) OD × 6.35-cm (2 1/2-in.) length × 0.10-cm (0.045-in.) wall

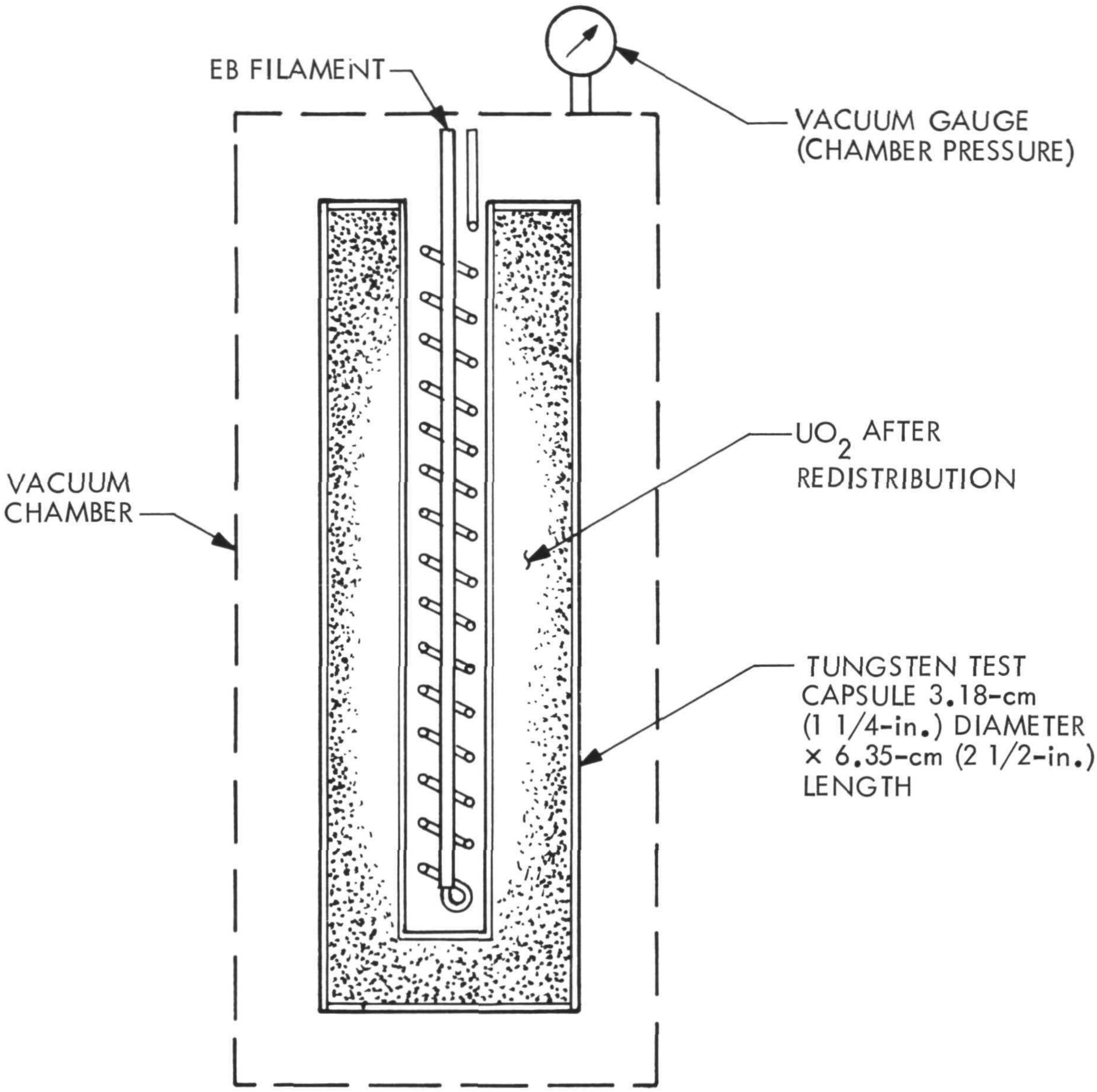

Fig. 1. UO_2 thermal cycling test setup

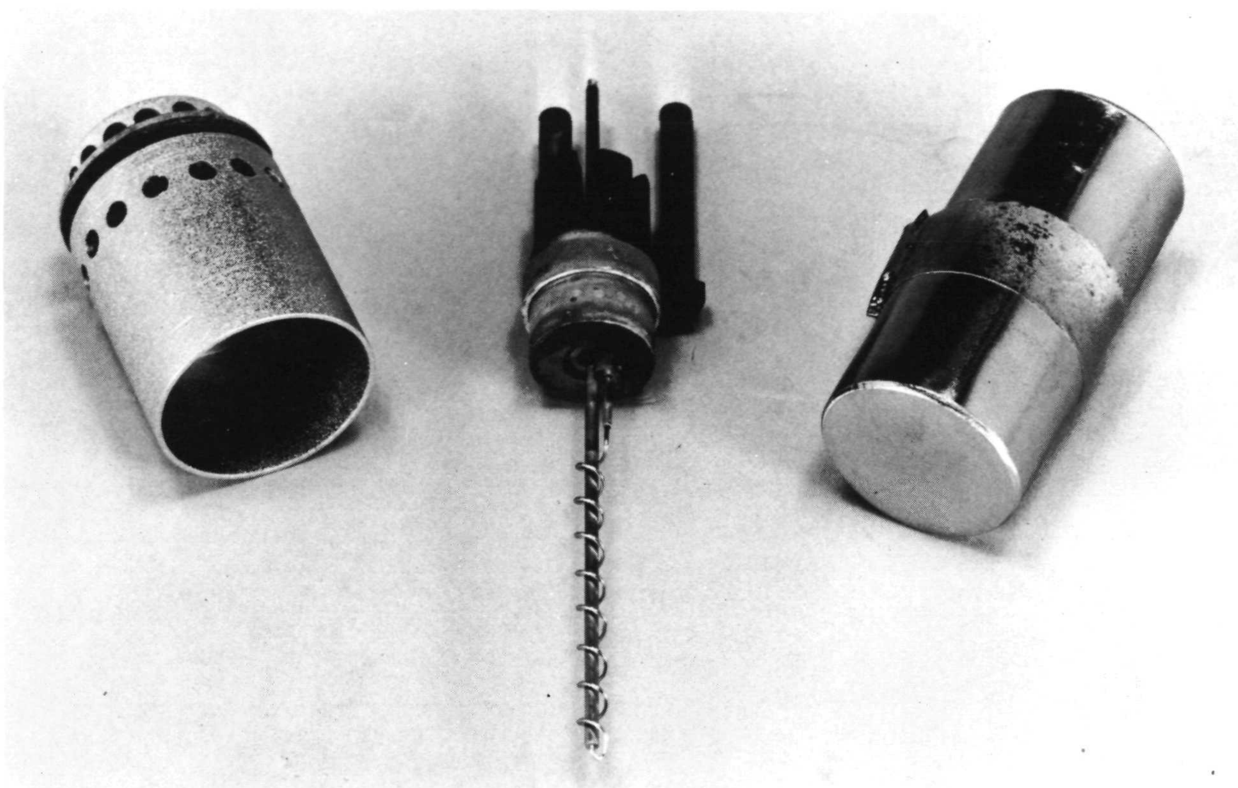

Fig. 2. Test capsule 1 after test

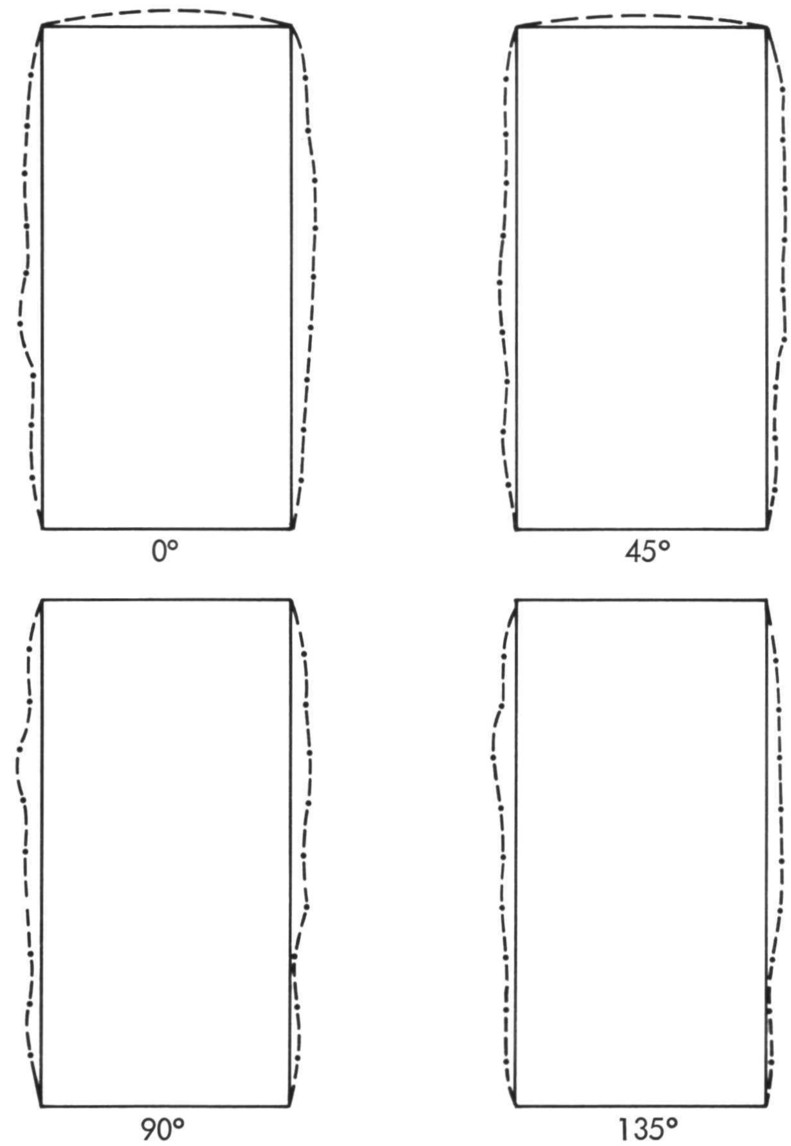

Fig. 3. Test capsule distortion after 40 cycles (exaggerated scale)

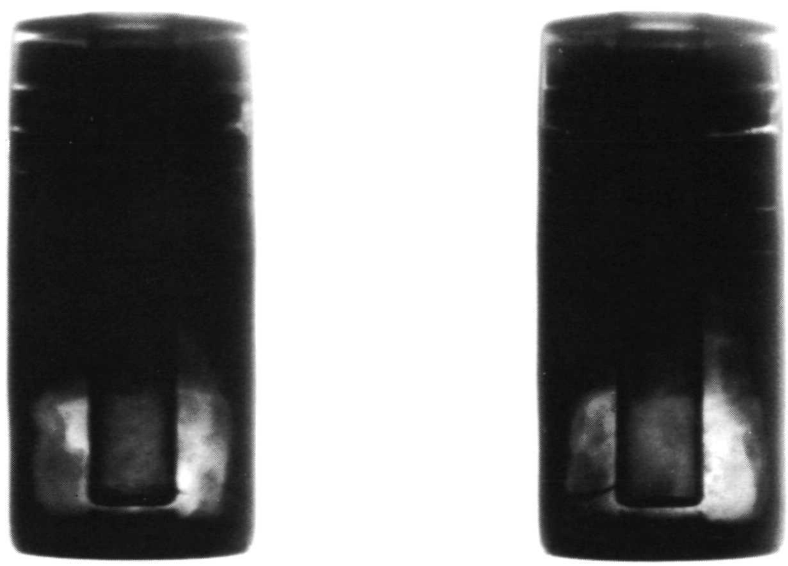

Fig. 4. Radiograph of test capsule after 40 cycles (0° and 90° views)

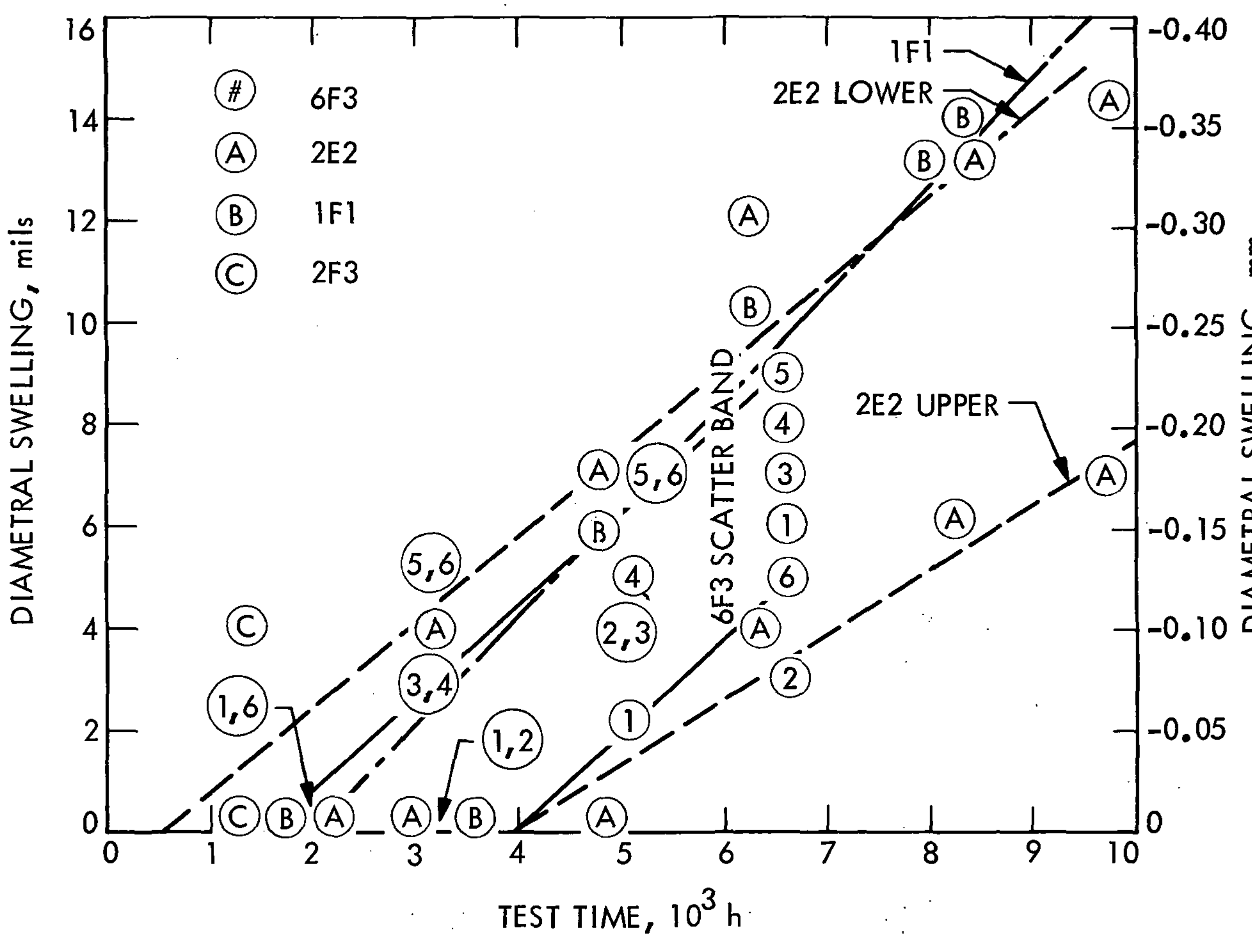

Fig. 5. Swelling of UO_2-fueled thermionic converters during in-pile tests

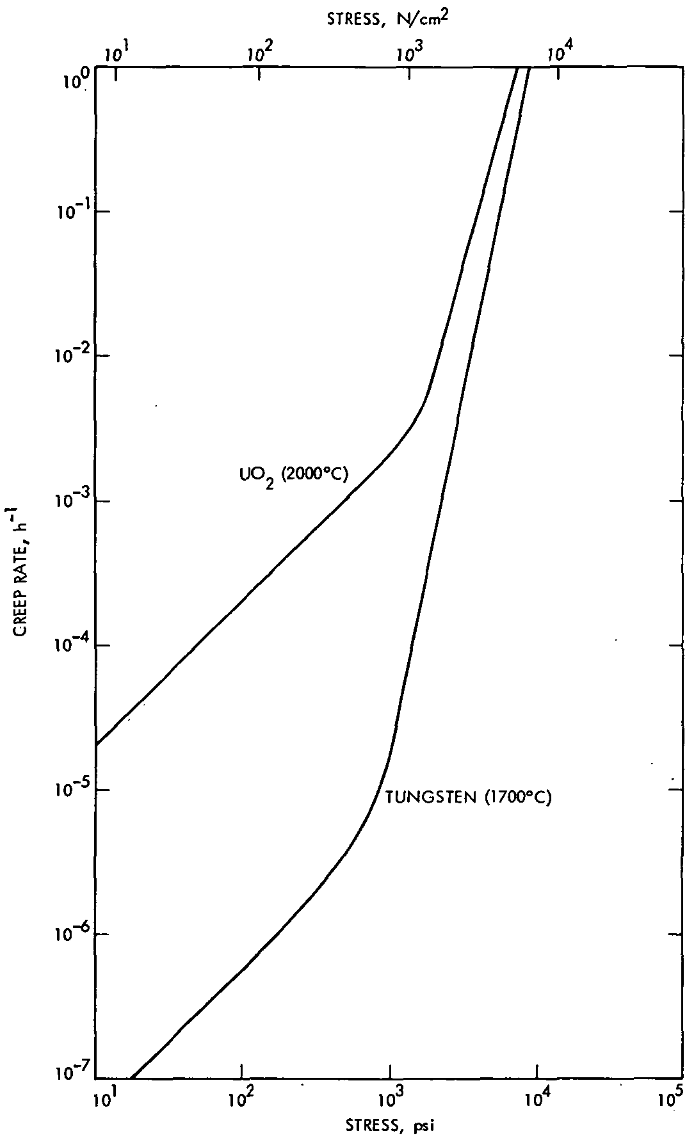

Fig. 6. UO_2 and tungsten creep rates used in calculations

NASA — JPL — Coml., L.A., Calif.