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IRRADIATION CREEP AND SWELLING OF AISI 316 TO EXPOSURES OF 130 dpa AT 385-400°C

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ABSTRACT

The creep and swelling of AISI 316 stainless steel have been studied at 385 to 400°C in EBR-II to doses of 130 dpa. Most creep capsules were operated at constant stress and temperature but mid-life changes in these variables were also made. This paper concentrates on the behavior of the 20% cold-worked condition but five other conditions were also studied. Swelling at ≤400°C was found to lose the sensitivity to stress exhibited at higher temperatures while the creep rate was found to retain linear dependencies on both stress and swelling rate. The creep coefficients extracted at 400°C agree with those found in other experiments conducted at higher temperatures. In the temperature range of ≤400°C, swelling is in the recombination-dominated regime and the swelling rate falls strongly away from the ~1%/dpa rate observed at higher temperatures. These lower rates of creep and swelling, coupled with the attainment of high damage levels without failure, encourage the use of AISI 316 in the construction of water-cooled fusion first walls operating at temperatures below 400°C.

INTRODUCTION

Type 316 stainless steel is sometimes considered as a candidate structural material for the first wall and other components of proposed fusion devices. While the use of this steel will be limited by its large rates of swelling and creep above ~450°C, the potential exists for its use in devices in which the first wall runs at lower temperatures, particularly for water-cooled devices. Based on available data, the incubation period of swelling is much longer at lower temperatures and creep will also be delayed.[1,2] It is also expected that below some temperature on the order of 400°C, the steady-state swelling rate will fall from the temperature-independent value of ~1%/dpa and eventually vanish as recombination-dominated point defect kinetics comes into play.[3,4] In that event, the design limitations imposed on swelling-related allowable exposure can be relaxed considerably.

The lowest temperature attainable in the U.S. fast reactors employed to test fusion candidate materials is ~370°C. Data on this steel at this temperature do not extend beyond 50 displacements per atom (dpa) and are not being collected at higher fluence levels.[2] Data at 400°C are available to ~70 dpa but are insufficient to determine whether the steady-state swelling rate has begun to decline below the rate of 1%/dpa. The possibility that both creep and steady-state swelling rates are reduced at ~400°C has now been addressed by examining a very comprehensive irradiation creep experiment recently completed in EBR II, in which many creep tubes reached exposures on the order of 130 dpa. The data from these tubes represent the highest exposure level ever reported for an irradiation creep experiment. A previous experiment in this series was conducted at 550°C but was terminated at ~80 dpa.[5,6] The steel employed in both of these experiments was the N-lot heat 87210, previously used as a reference heat in the U.S. breeder reactor program.

Experimental Details

Four cold-work levels (0, 5, 10, 20%) as well as two separate aging conditions were employed. These latter were 20% cold-worked followed by aging at 482°C for 24 hours (Heat Treat C), and Heat Treat C followed by another aging at 704°C for 216 hours (Heat Treat D). This report will concentrate on the 20%

cold-worked condition as the most likely fusion candidate material and will examine the other conditions only to the depth required to determine whether the major conclusions are dependent on the starting condition of the material. The larger body of data on all conditions and test histories will be presented elsewhere.

Hoop stress levels of 0, 206, 276 and 343 MPa (0, 30, 40, 50 ksi) were attained with pressurized helium. Most tubes were irradiated at constant stress and temperature but some were deliberately subjected to abrupt changes in stress level and/or temperature.

The pressurized section of the capsules was 0.98 m in length but the bottom 0.71 m contained a loosely fitting stainless steel rod designed to reduce the pressure pulse that could result from a sudden failure. The outer diameter of the capsule was 0.584 cm with a wall thickness of 0.038 cm. Irradiation was conducted in Row 7 of EBR-II in two thirty-seven pin subassemblies designated X101 and X133. Approximately 5 dpa (±10%) are produced in this reactor for each 1.0×10^{22} n/cm^2 (E>0.1 MeV) depending on the position in reactor. The dpa levels cited for each datum in this paper incorporate the position dependence of this parameter.

To minimize the effect of swelling-induced axial growth on the experiment, only the section at or below the capsule center was used in the analysis. At the end of each irradiation period, a contact profilometer was used to measure the capsule diameter on a spiral trace along the entire length of the capsule. The majority of capsules were measured as many as twenty-two times during the irradiation, averaging between examinations approximately 6 dpa at capsule center. As shown in Figure 1, the temperature over the region of interest rose from 385 to 400°C at capsule center.

When the experiment was terminated, selected capsules were sectioned into 2.5 cm increments and density changes were measured in order to separate the swelling and creep strains. The effects of displacement rate on creep and swelling were determined by comparing the strain at different positions along the capsule.

Results

Figure 2 shows the diameter changes observed in four selected 20% cold-worked capsules at the capsule center position. Each capsule operated at a different level of pressurization and the total center line strain increased with increasing stress. The diameter change ΔD of the unstressed capsule is assumed to be due only to isotropic swelling where $\Delta D/D = \Delta V/3V$, an assumption that has been verified many times previously. The diameter change of pressurized capsules is due to both irradiation creep and swelling, with the latter possibly enhanced by applied stresses. Based on previous studies of this steel, the enhancement of swelling by stress at 400°C is expected to be very small, however.(7,8)

The dependence of swelling on stress can be checked by comparing the density changes of each of these capsules. Figure 3 shows that in the three pressurized capsules, there was no observable effect of stress at any position along the capsule. Whereas the data in Figure 2 were taken all at one position and displacement rate, the data in Figure 3 were derived at different axial locations and incorporate relatively large differences in displacement rate and relatively small differences in temperature. Figure 3 does not contain any density data for the unstressed capsule but does contain the last four measurements of swelling deduced from diameter change at capsule center. These data also confirm the insensitivity of swelling to stress at 400°C. No density data were available for this capsule because the filler rod (which exists at a slightly higher temperature) had swelled into contact with the capsule wall at ~80 dpa, binding with and distorting it. Normally this does not occur at lower fluences or when gas-driven creep is operating on the capsule wall.

The swelling rate $\dot{S}$ implied by the data in Figure 3 is on the order of 0.05 to 0.07%/dpa, much lower than 1%/dpa. This rate is derived over a considerable range of displacement rate, however, and one would expect a dependence on displacement rate whenever a strong dependence on temperature is observed.(9) The effect of the flux and temperature variations on total deformation can be observed in Figure 4. One can deduce from Figure 4 that the swelling rate derived from Figure 3 might be an underestimate. The average stress-free swelling rate under isoflux conditions can be derived from Figure 2 and is indeed somewhat larger at $\dot{S}$ = 0.11%/dpa over the range 70 to 130 dpa.

Figure 5b shows that one cannot place too much confidence in the reproducibility of such estimates under conditions where the swelling rate is changing so strongly. Note that at ~20 dpa, one capsule at 343 MPa (50 ksi) lost its pressure and thereafter swelled stress-free at a relatively constant rate of $\dot{S}$ ≈0.04%/dpa. A similar event occurred at ~60 dpa in a 10% cold-worked capsule initially at 343 MPa and yielded a post-depressurization swelling rate of $\dot{S}$ ≈0.05%/dpa. Another occurred at <6 dpa in one of the aged (Heat Treat D) capsules at 276 MPa and thereafter yielded a remarkably constant swelling rate of $\dot{S}$ ≈0.09%/dpa over the range of 10 to 107 dpa.

Figures 5a and 5b show that the overall strain behavior of nominally identical capsules is quite reproducible. The small differences seen probably reflect minor differences in irradiation conditions at various positions across the subassembly.

One would expect the strain rate to increase if the stress level and/or the temperature were to be increased. Figures 6a and 6b show that this indeed occurs in experiments where deliberate increases were made in these variables. Note in Figure 6b that the combination of higher stress and an increase to 550°C yielded a total deformation rate that approaches the $\Delta\dot{D}$ = 0.33%/dpa limit observed as an upper limit of similar capsules irradiated isothermally at 550°C.[5,6] During isothermal irradiation at 400°C, the total strain rate of 20% cold-worked 316 at 343 MPa (50 ksi) only reached $\Delta\dot{D}$ ≈0.14%/dpa at 125 dpa.

The strain rates of AISI 316 are somewhat sensitive to material condition as well as environmental variables as demonstrated by looking at other conditions in this experiment. In the heat treat D condition the total strain rate $\Delta\dot{D}$ at 400°C reached 0.22%/dpa at 276 MPa (40 ksi), but when the temperature was changed from 400 to 550°C at 32 dpa, the total creep rate of Heat Treat D at 276 MPa immediately went to the 0.33%/dpa limit.

Figure 7 shows the diameter changes of five nominally similar capsules initially irradiated at 550°C. (The experimental details of these irradiations were described in references 5 and 6). At ~30 dpa two of these capsules were subjected to an abrupt decrease in temperature to 400°C. Prior to the changes these capsules were just beginning to exhibit accelerated swelling and creep rates but these quickly subsided from the increasing rates observed in the three capsules maintained at 550°C. The swelling rate of the unstressed capsule was found to be $\dot{S}$ = 0.10%/dpa. This reduction in swelling rate tends to confirm that at 400°C the swelling rate is dominated by the kinetics of point defect recombination.

Discussion

The data presented in this paper show that at 400°C the N-lot heat of AISI 316 stainless steel is right on the steep slope of the recombination-dominated regime of swelling. In this regime, the swelling rate is falling away with decreasing temperature from the 1%/dpa value observed over a large range of temperatures (425 to 725°C).[1-3] One would expect to see in this regime a sensitivity to displacement rate, thermal-mechanical condition and prior irradiation history. All of these sensitivities were indeed observed. If we confine the study to isothermal irradiation of cold-worked steel, the swelling rate has fallen at 400°C to a level on the order of 5 to 10% of the 1%/dpa value. At the lower temperatures expected in a water-cooled fusion first wall, the swelling should be vanishingly small. Since the largest component of the creep rate is thought to be proportional to the swelling rate, creep should also decline in importance.

It has been proposed that the creep rate $\dot{\varepsilon}$ at any relevant temperature is linearly dependent on stress σ and related to the swelling rate $\dot{S}$ by the following relation.[1,10-12]

$$\frac{\dot{\varepsilon}}{\sigma} = B_0 + D_0 \dot{S}.$$

The creep compliance B_0 has been shown to be approximately equal to 1×10^{-6} MPa^{-1} dpa^{-1} for a wide range of austenitic steels.[11,12] The swelling-enhanced creep coefficient D_0 is likewise thought to be relatively constant at $\sim 10^{-2}$ MPa^{-1} over a wide range of steels and temperatures.

Using the insight gained in this study of stress-independent swelling at 400°C to analyze the data in Figure 2, the values of B_0 and D_0 can be calculated. Note in Figure 8 that the instantaneous creep coefficient ($B_0 + D_0 \dot{S}$) is independent of stress level as predicted and appears to saturate at higher exposures. At zero dpa and therefore zero swelling rate, B_0 is indeed $\sim 1 \times 10^{-6}$ MPa^{-1} dpa^{-1}. Assuming a swelling rate of ~0.04%/dpa and using the 40 ksi curve at 130 dpa, D_0 is calculated to be $\sim 0.6 \times 10^{-2}$ MPa^{-1}. Both estimates of B_0 and D_0 thus appear to be in good agreement with the anticipated values.

The attainment of these results was facilitated by the lack of stress effects on swelling at this temperature. At higher temperatures stress indeed enhances swelling and complicates the analysis somewhat.[6,7] A somewhat surprising recent insight is that the sign of the stress is not important but only its magnitude. Compressive stress states are equally as effective as those of tension in accelerating the onset of swelling.[13,14] In a previous model compressive stresses were assumed to delay the onset of swelling.[6]

It was shown in earlier papers that rate theory considerations alone are insufficient to explain the swelling behavior of AISI 316 and other austenitic stainless steels, particularly in the incubation period of swelling where variables such as stress, gas content, displacement rate and temperature history exert their greatest influence.[1,3,15-17] One must also invoke the time-dependent composition of the alloy matrix as the alloy undergoes a radiation-induced microchemical evolution involving precipitation of elements such as silicon, nickel and phosphorus. These three elements in particular have been shown to have a large effect on void nucleation rates[18-21] and the precipitation sequences are known to be sensitive to irradiation variables such as stress, displacment rate and temperature history.[1,16,17,22]

One would therefore expect to find that the independence of swelling on stress in 20% cold-worked AISI 316 at 400°C would be mirrored in a similar independence of the precipitate evolution and microchemical evolution of the alloy matrix. This supposition is confirmed by the results of an earlier study involving analysis of precipitation in this heat of steel.[22] The experiment was conducted on creep capsules from this same experiment but which were removed at 50 to 70 dpa for destructive examination. Indeed the precipitate evolution of the steel was found to be insensitive to the stress level.

There is an interplay, however, between the effects of the various variables affecting precipitation that precludes confident predictions applicable to all steels and irradiation conditions. Although 20% cold-worked AISI 316 demonstrated an independence of stress at this temperature, a similar study on annealed AISI 304 exhibited stress-affected swelling at core center positions but not at lower displacement rates found toward the bottom of the creep capsule.[23]

Conclusion

In the region around 400°C and below, the neutron-induced swelling rate of AISI 316 declines rapidly from the temperature-independent value of ~1%/dpa observed over a wide range of higher temperatures. The irradiation creep rate decreases correspondingly. While swelling loses its sensitivity to stress in this temperature range, the irradiation creep rate retains its linear dependence on stress and its linear dependence on swelling rate. Creep coefficients derived from higher temperature experiments are found to be applicable at 400°C as well. The cold-worked form of this steel is capable at 400°C of reaching neutron exposures causing damage well in excess of 100 dpa without failure. This capability, coupled with the low rates of swelling and creep, encourage the use of AISI 316 in the construction of water-cooled first walls of fusion devices.

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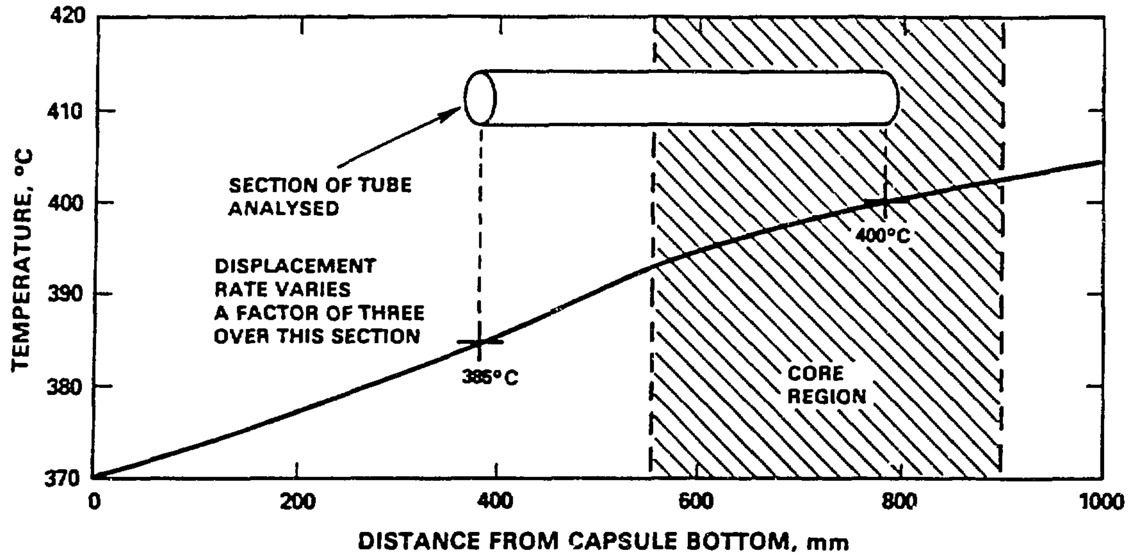

FIGURE 1. Temperature Profile Along Creep Capsule.

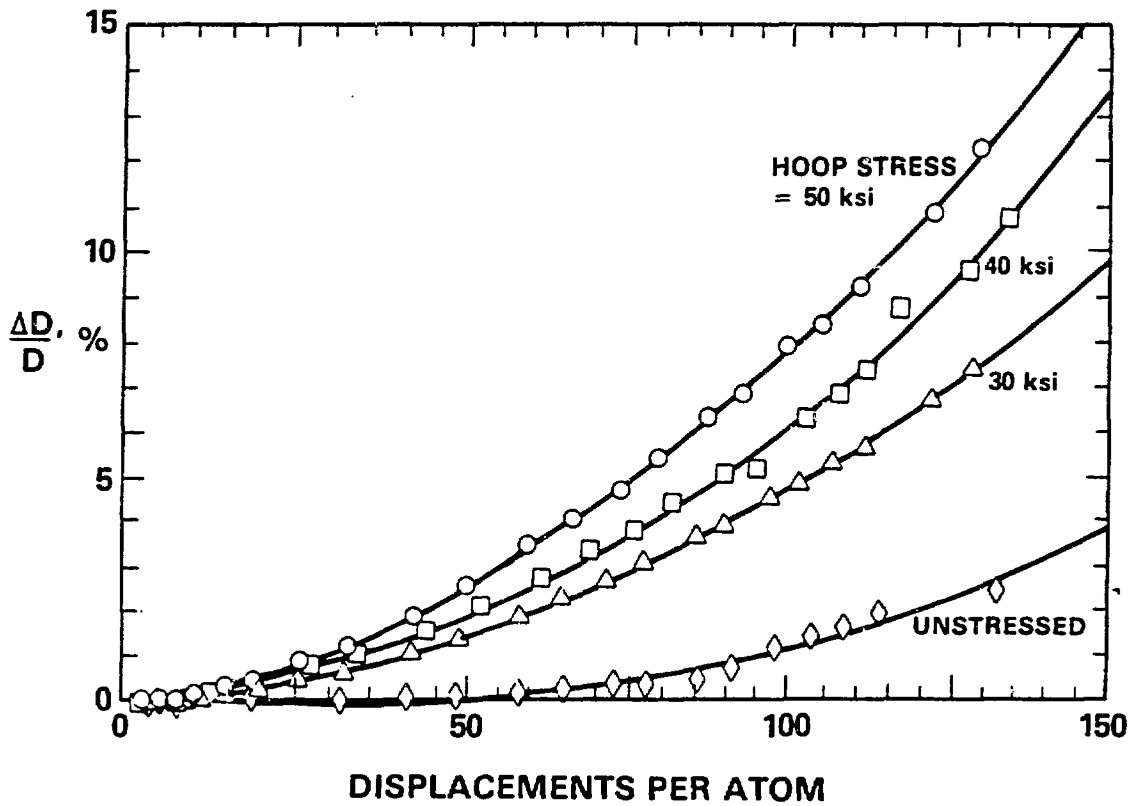

FIGURE 2. Diameter Changes Induced at Capsule Center in Four Selected Creep Capsules Constructed from 20% Cold-Worked AISI 316 Stainless Steel and Irradiated in EBR-II. The hoop stresses ranged from 0 to 343 MPa (0-50 ksi).

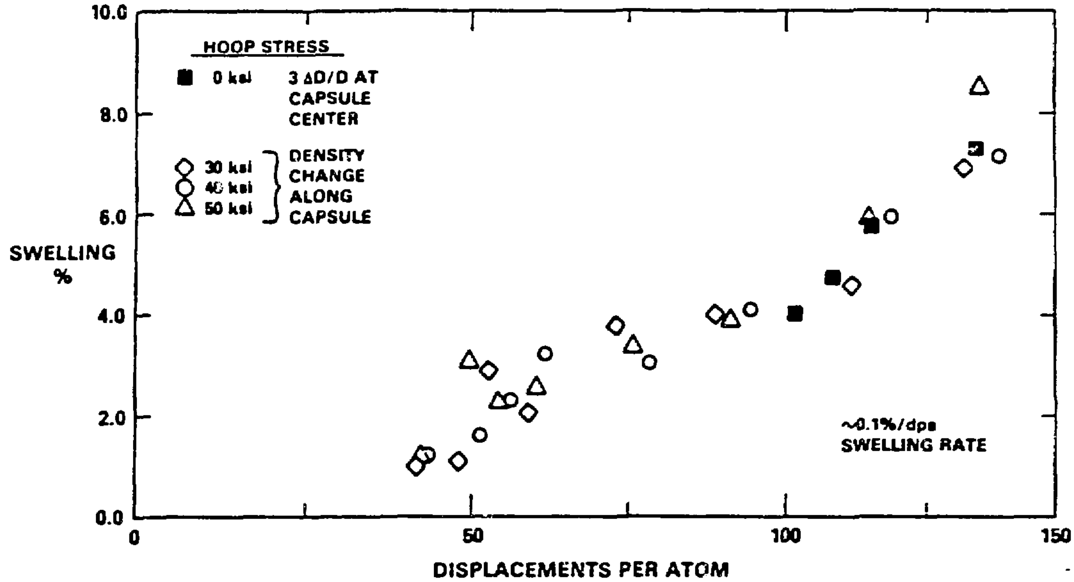

FIGURE 3. Swelling Measured Along the Length of the Three Pressurized Creep Capsules Shown in Figure 2. Also shown are the swelling values inferred from time-dependent diameter change measurements at the center of the unstressed capsule.

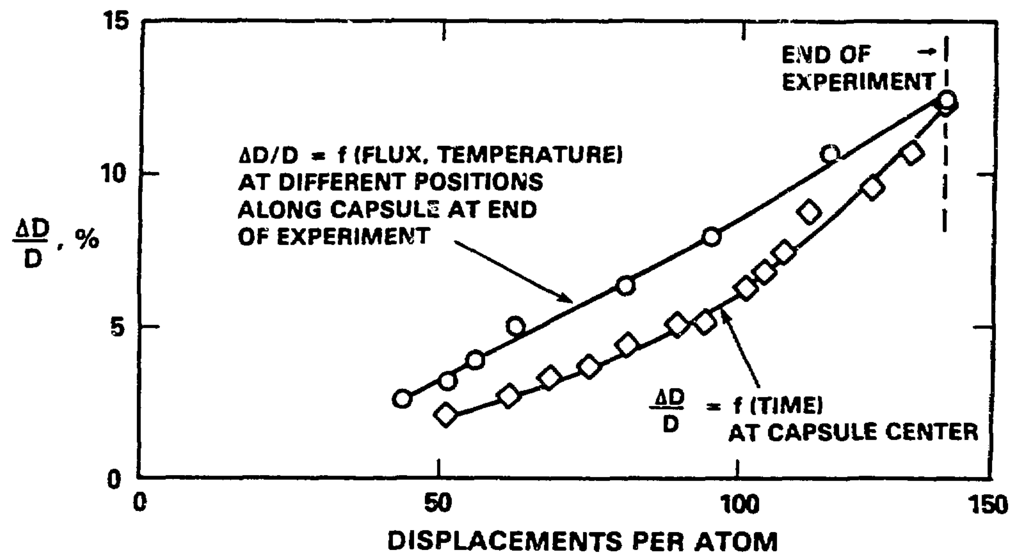

FIGURE 4. Influence of Displacement Rate and Temperature Variations on Total Strain Observed in a 20% Cold-Worked Capsule with a Hoop Stress of 276 MPa (40 ksi).

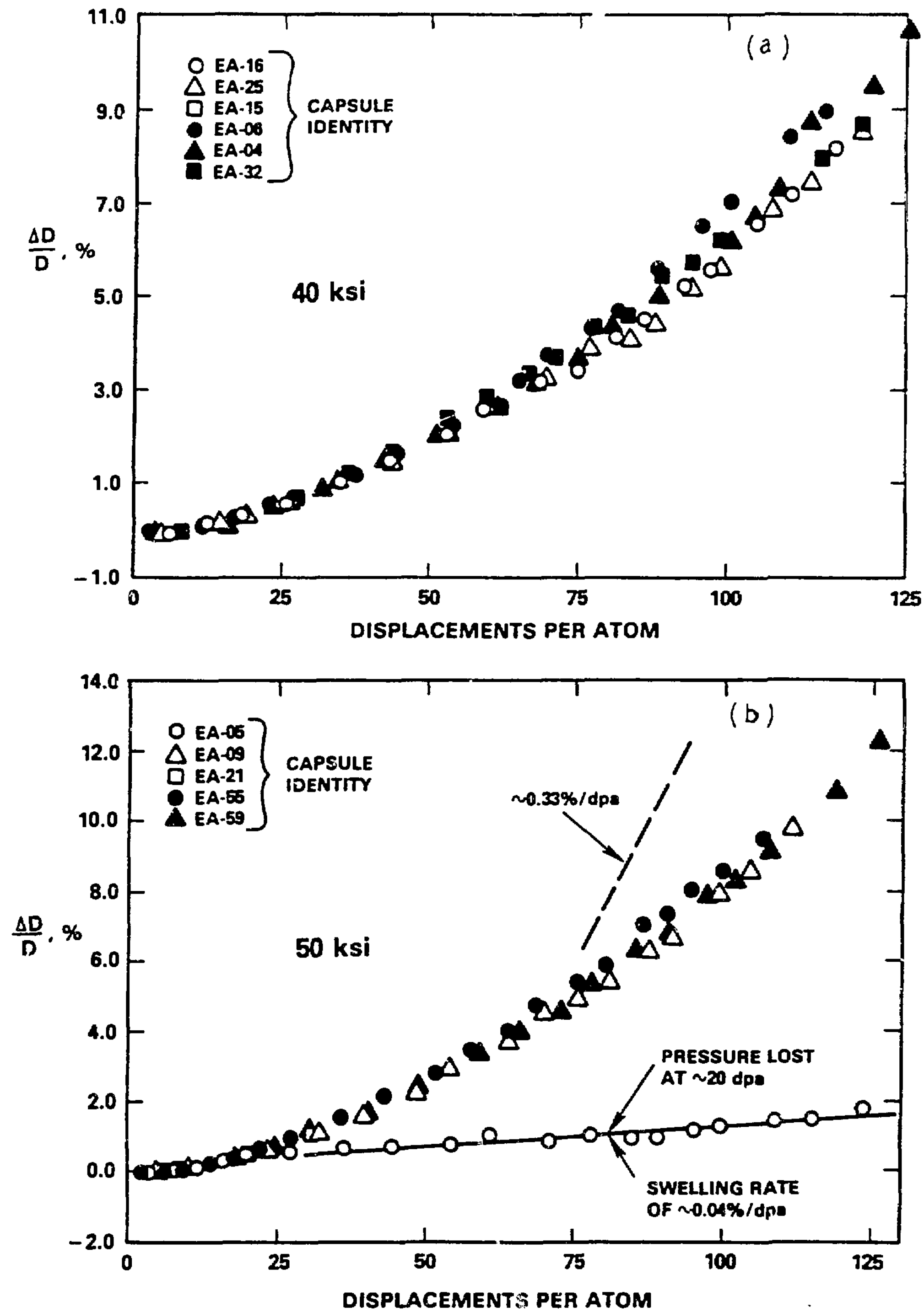

FIGURE 5. Diameter Changes Observed in 20% Cold-Worked Steel for (a) Six Nominally Identical Creep Capsules at 276 MPa (40 ksi) and (b) five Nominally Identical Capsules at 343 MPa (50 ksi). Note that one capsule failed at 20 dpa and swelled without stress thereafter.

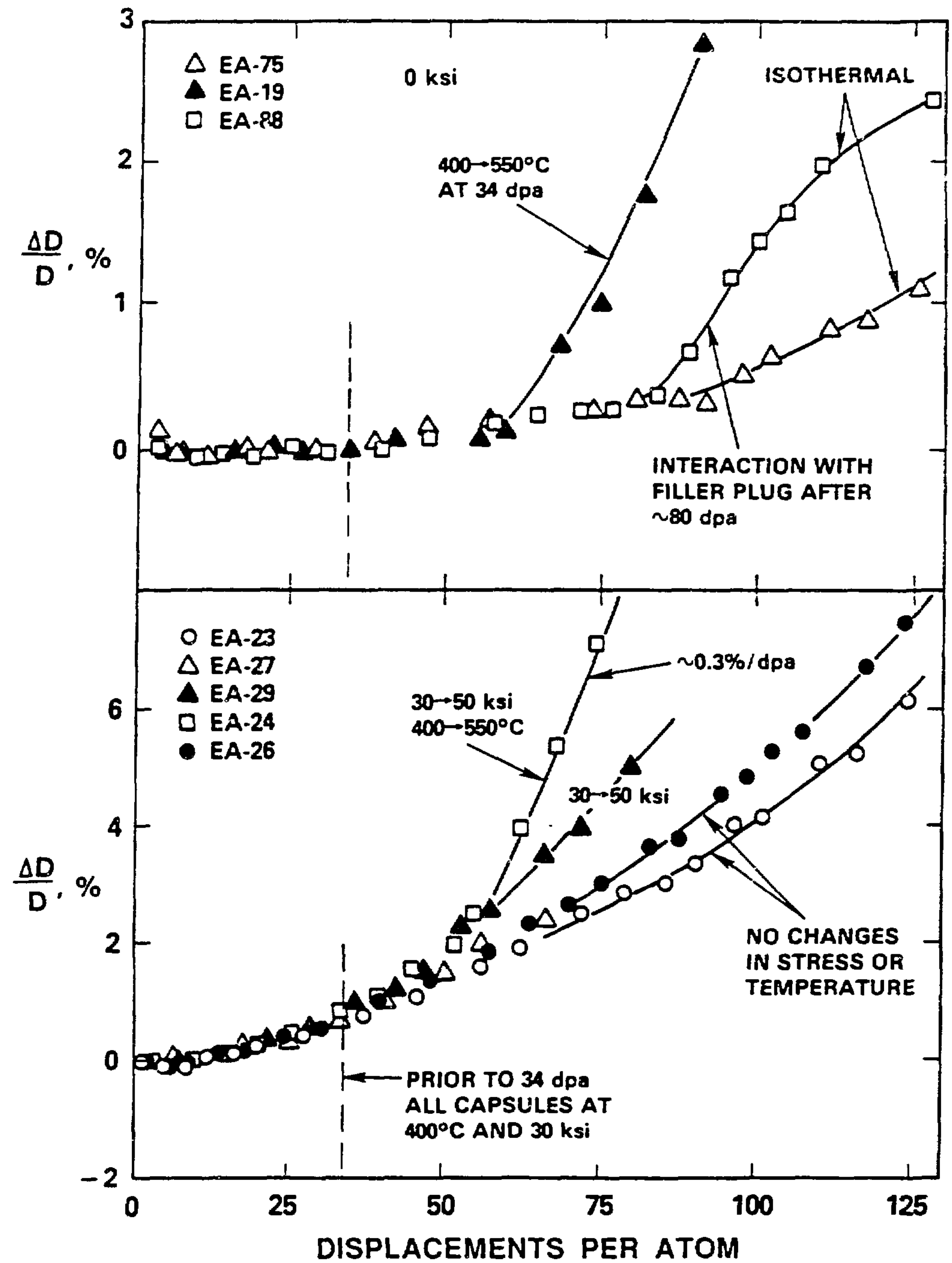

FIGURE 6. Influence of Radiation History on Strain Behavior of 20% Cold-Worked Steel at 400°C. Increasing the stress level accelerates the deformation rate but increasing both the stress and the temperature causes a more pronounced increase in deformation rate.

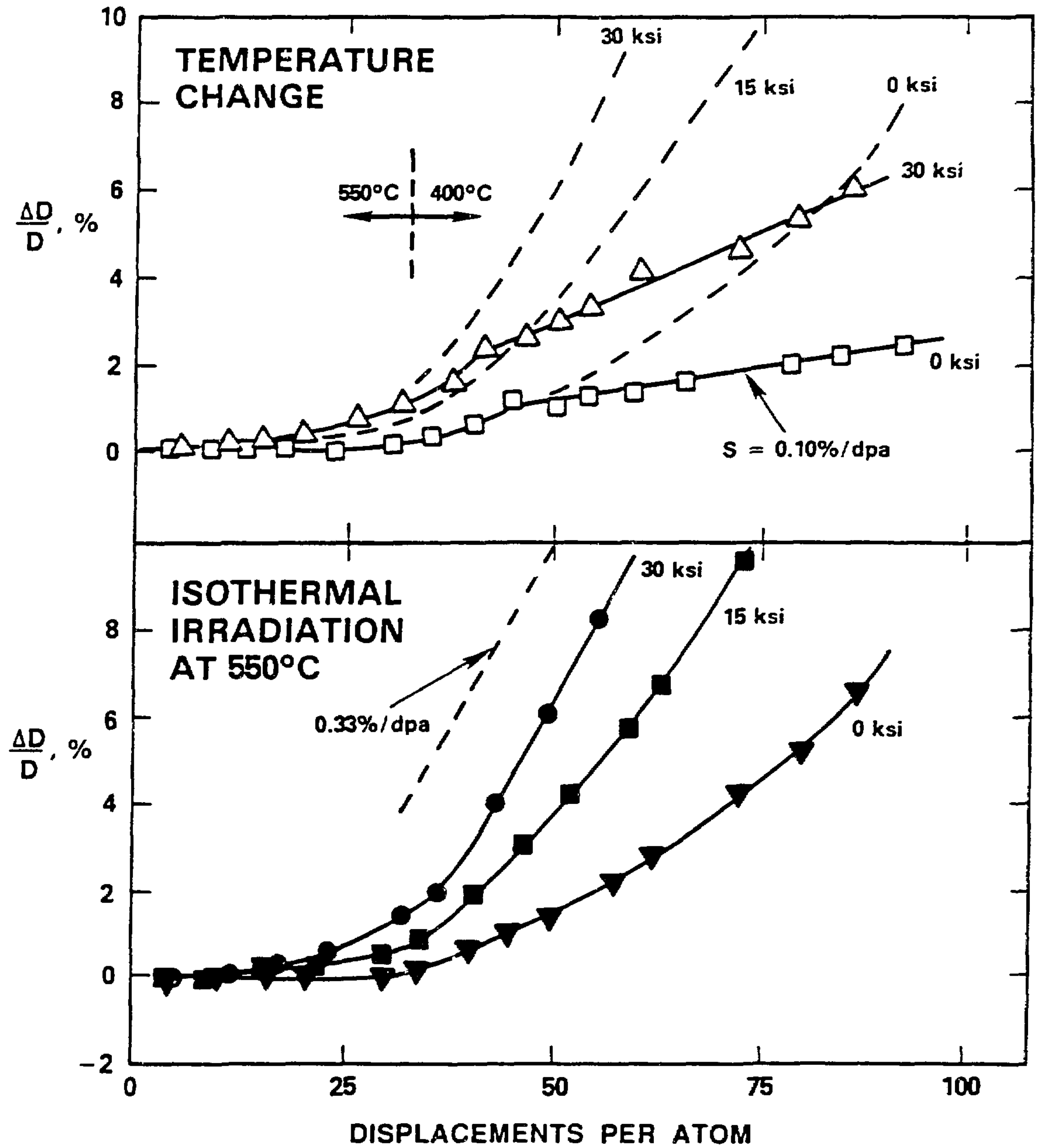

FIGURE 7. Diameter Changes of (a) Two 20% Cold-Worked Capsules at 0 and 206 MPa (30 ksi), Subjected to an Abrupt Decrease in Temperature and (b) Three Others Irradiated Only at 550°C at 0, 103 and 206 MPa (0, 15, 30 ksi).

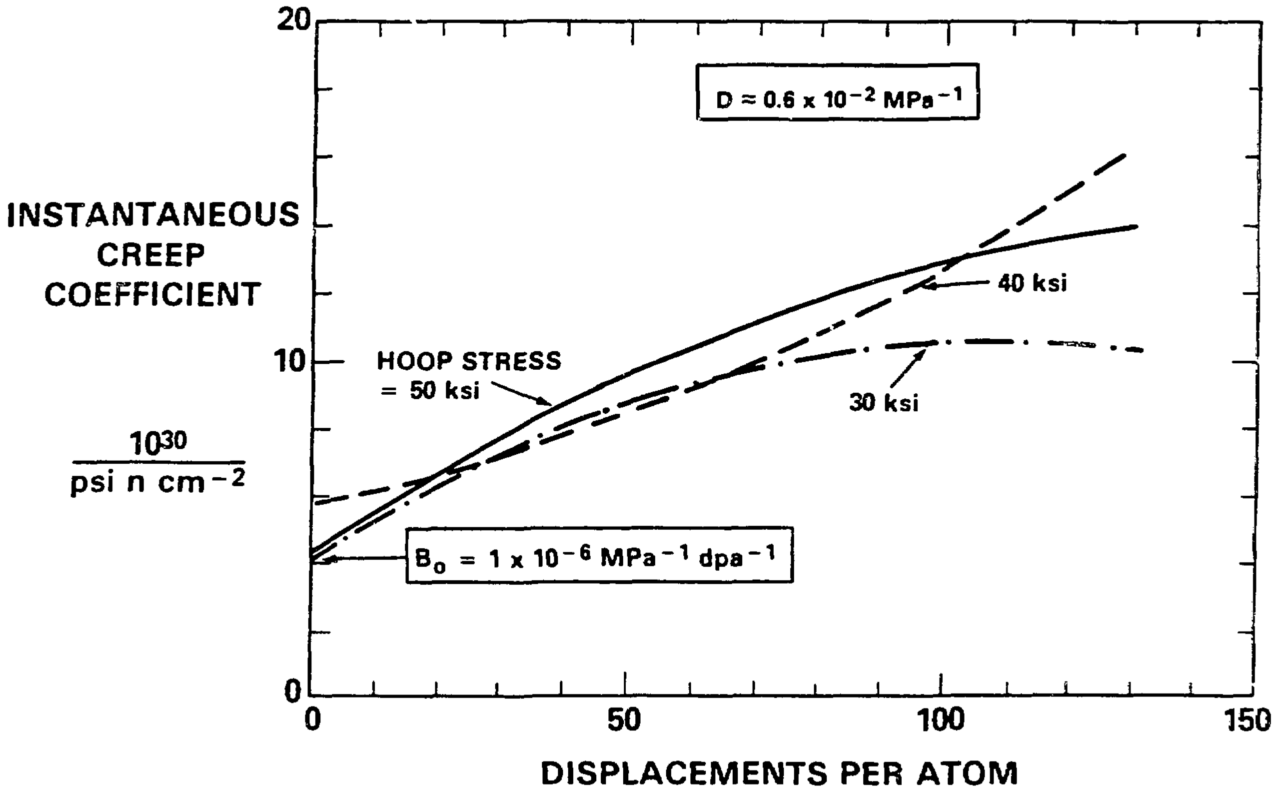

FIGURE 8. Determination of Instantaneous Creep Coefficients from the Data Shown in Figure 2. The creep rate is linear with stress and increases as the swelling rate increases.

IRRADIATION CREEP AND SWELLING OF AISI 316 TO EXPOSURES OF 130 dpa AT 385-400°C

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OBJECTIVES

- DETERMINE CREEP AND SWELLING RESPONSE OF 20% COLD-WORKED AISI 316 AT LOWEST ATTAINABLE TEMPERATURE AND VERY HIGH DISPLACEMENT LEVELS

- ASSESS POTENTIAL FOR THIS STEEL TO BE USED IN CONSTRUCTION OF A WATER-COOLED FIRST WALL

WHCM 8709-131.1

BACKGROUND

- USE OF LONG CREEP CAPSULES ALLOWS STUDY OF INFLUENCE OF DISPLACEMENT RATE AS WELL AS STRESS AND TEMPERATURE

- A PREVIOUS EXPERIMENT AT ~550°C SHOWED THAT CREEP ACCELERATED WITH THE ONSET OF SWELLING BUT DECLINED THEREAFTER WHEN SWELLING REACHED STEADY-STATE RATE OF ~1%/dpa

- THE CURRENT EXPERIMENT AT ~400°C IS DESIGNED TO STUDY SWELLING-CREEP INTERACTIONS IN VICINITY OF RECOMBINATION-DOMINATED REGIME

WHCM 8709-131.4

LONG CREEP CAPSULES AT ~400°C

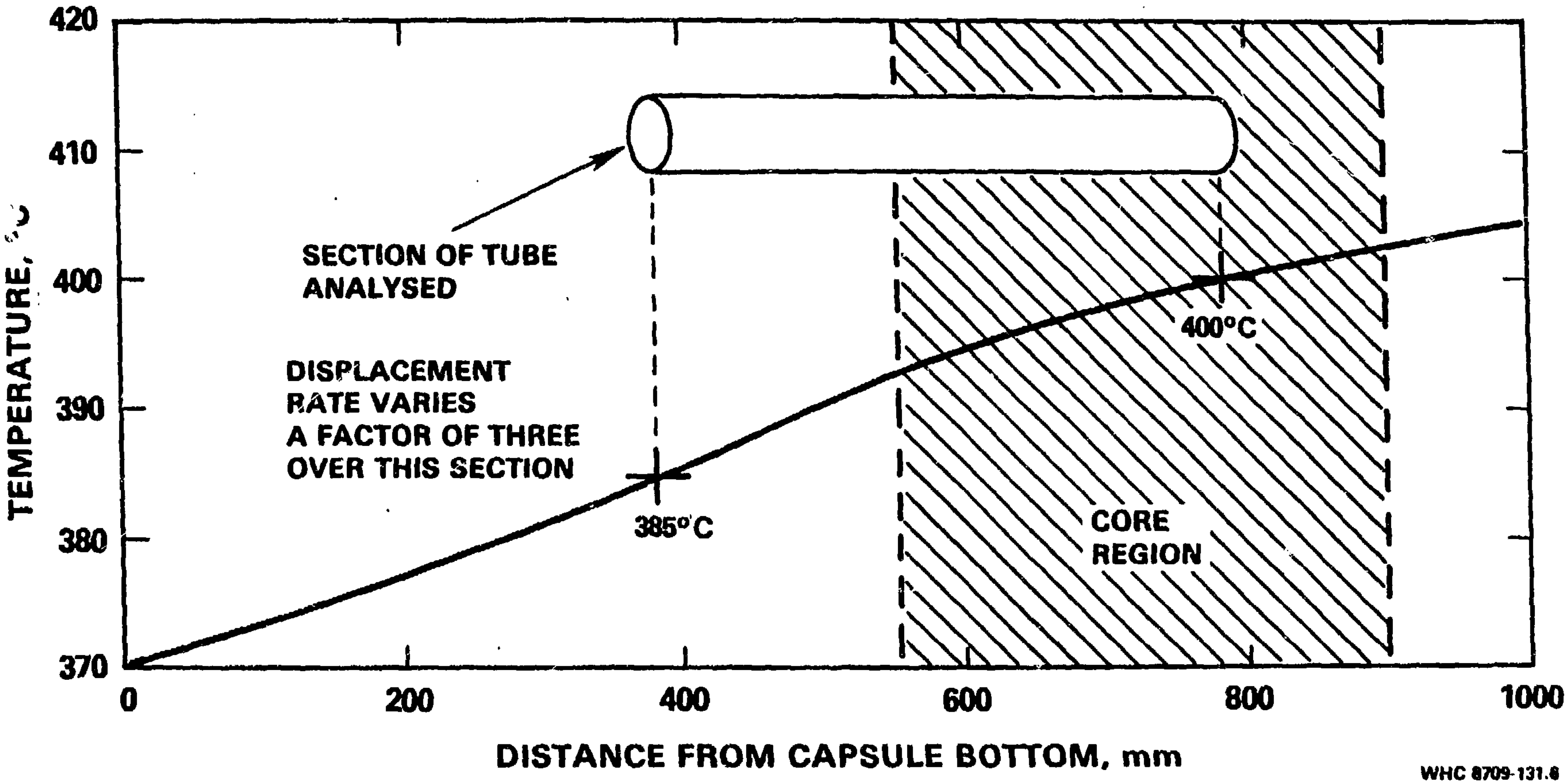
- AISI 316 (N-LOT) BREEDER REFERENCE HEAT
- ROW 7 IN EBR-II
- HELIUM PRESSURIZED
- 0.96 m LENGTH
- 0.584 cm OUTER DIAMETER
- 0.038 cm WALL THICKNESS

(LENGTH, OUTER DIAMETER, WALL THICKNESS: PRESSURIZED SECTION)

- 0, 5, 10, 20% COLD-WORKED, HEAT TREAT C, HEAT TREAT D
- HOOP STRESSES 0, 200, 233, 267 MPa
  0, 30, 40, 50 ksi

WHCM 8709-131.5

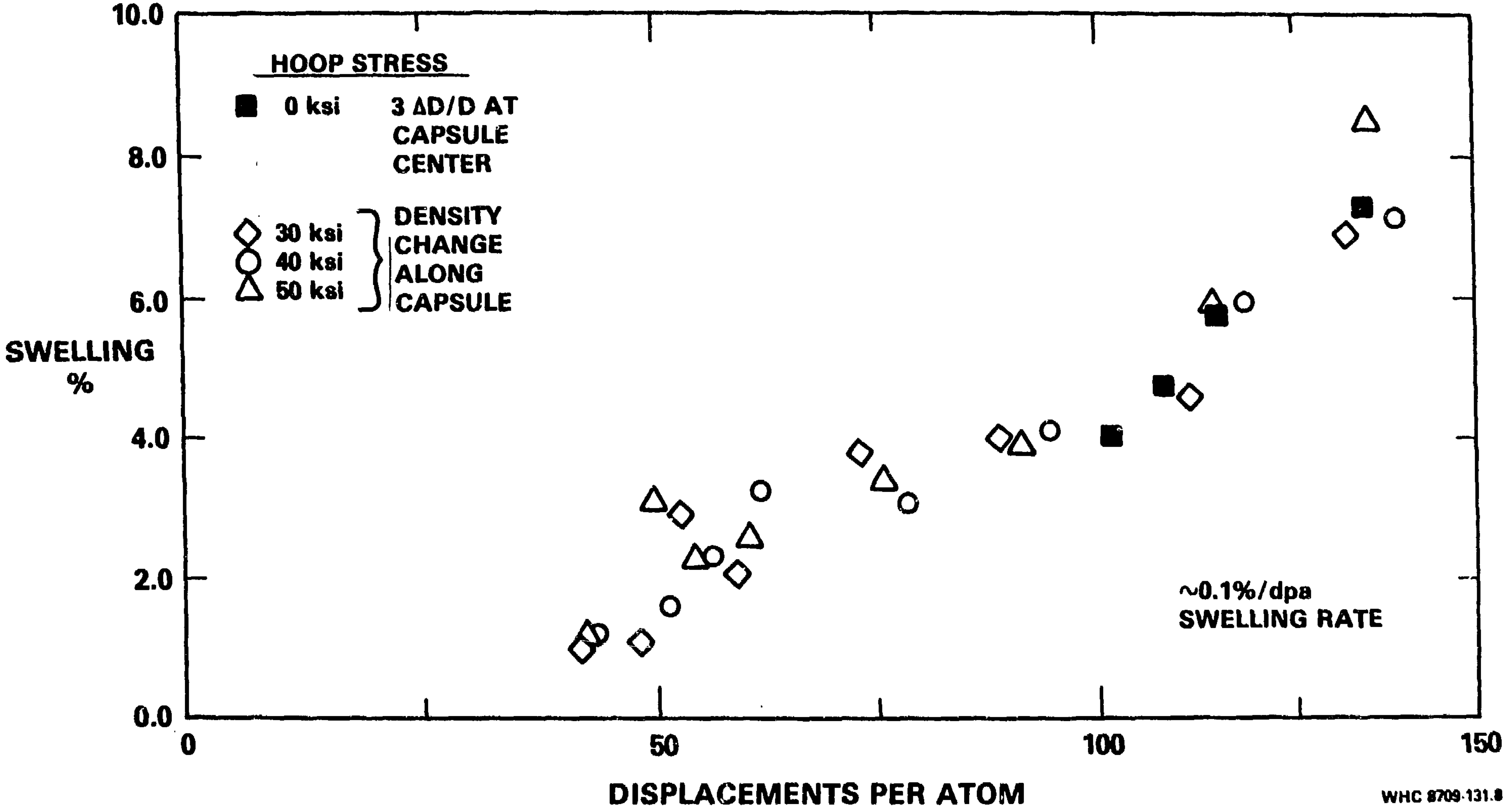
TEMPERATURE PROFILE ALONG CREEP CAPSULE



WHC 8709-131.6

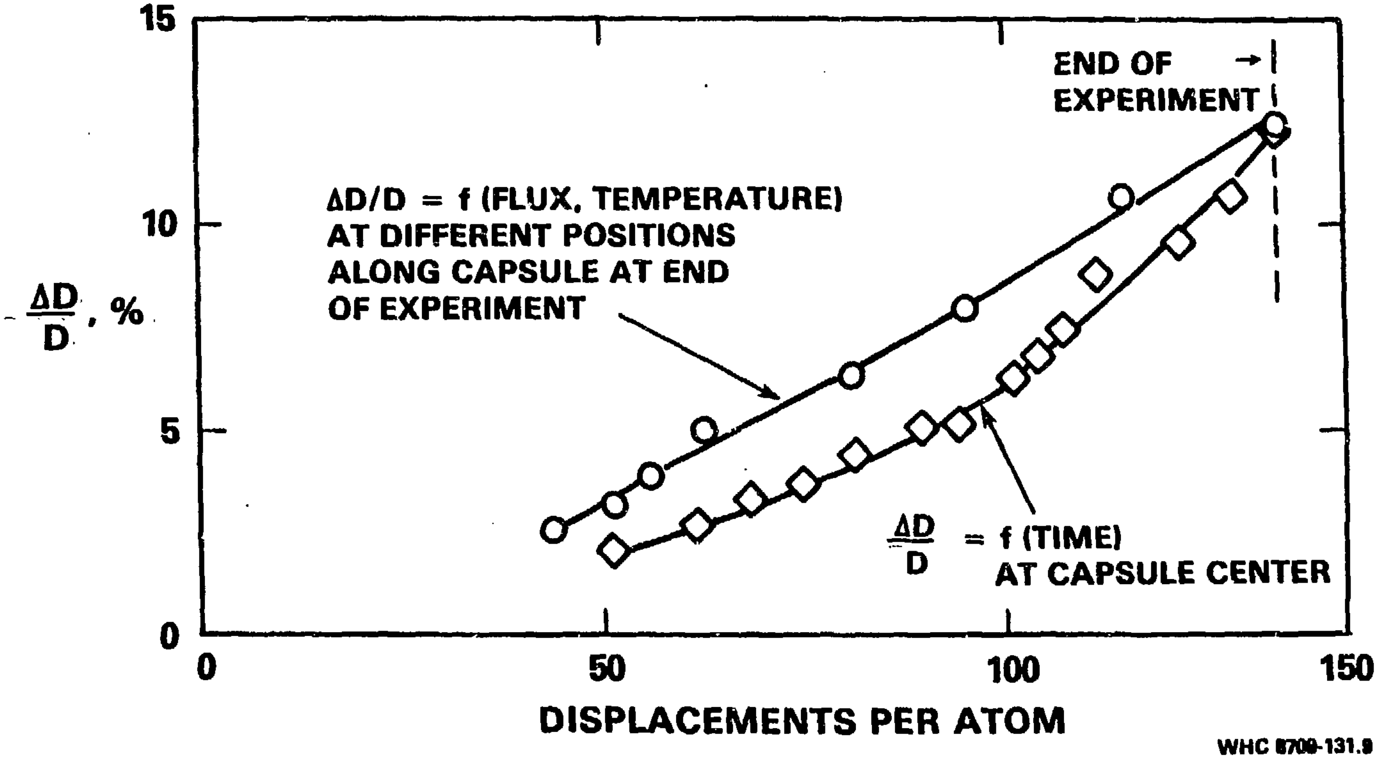
STRESS-INDEPENDENT SWELLING AT 400°C

20% COLD-WORKED AISI 316
EBR-II, ROW 7



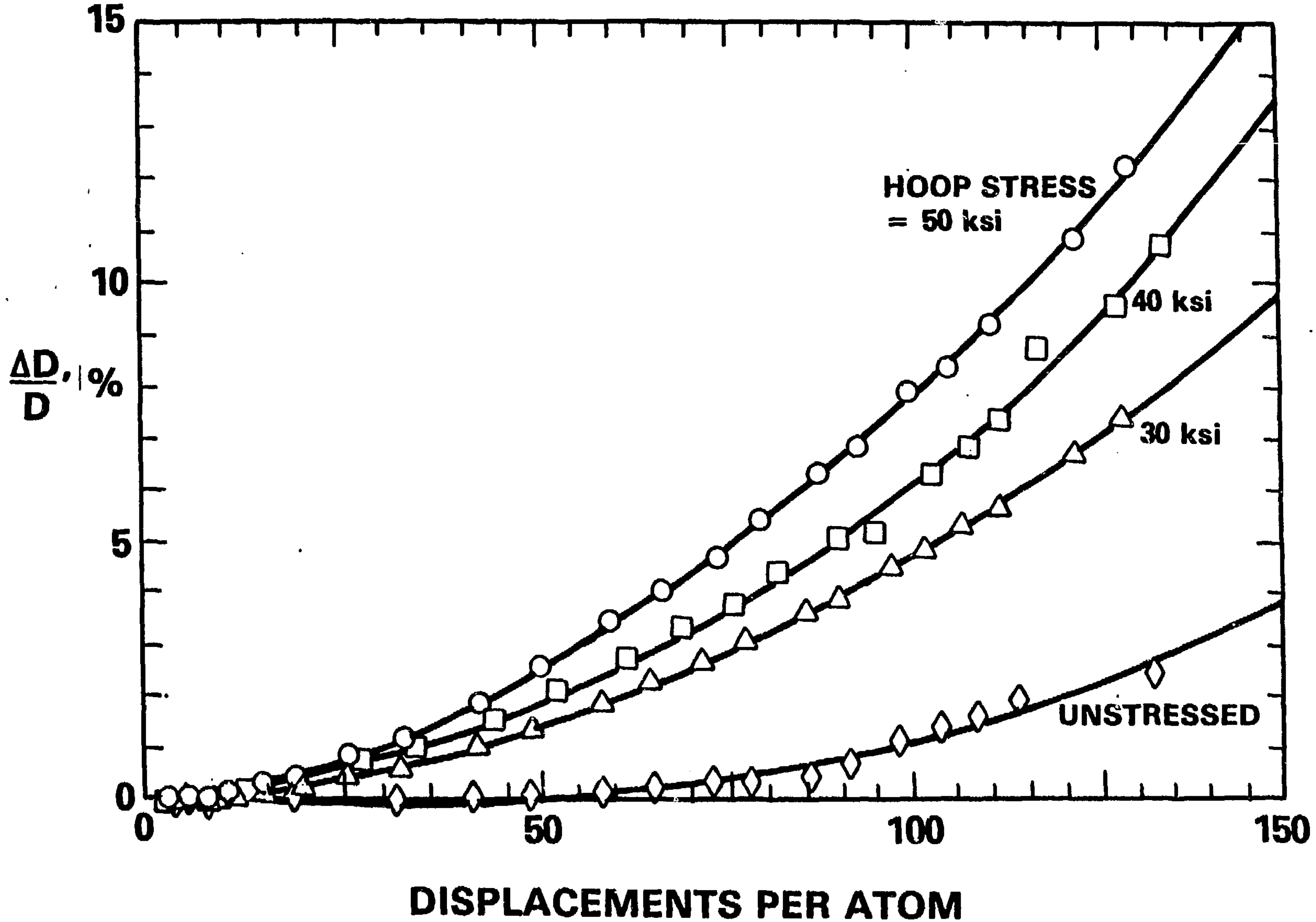
EFFECT OF FLUX AND TEMPERATURE ON STRAIN RATE

20% COLD-WORKED AISI 316
385-400°C, 40 ksi HOOP STRESS



IRRADIATION CREEP IN AISI 316 AT 400°C

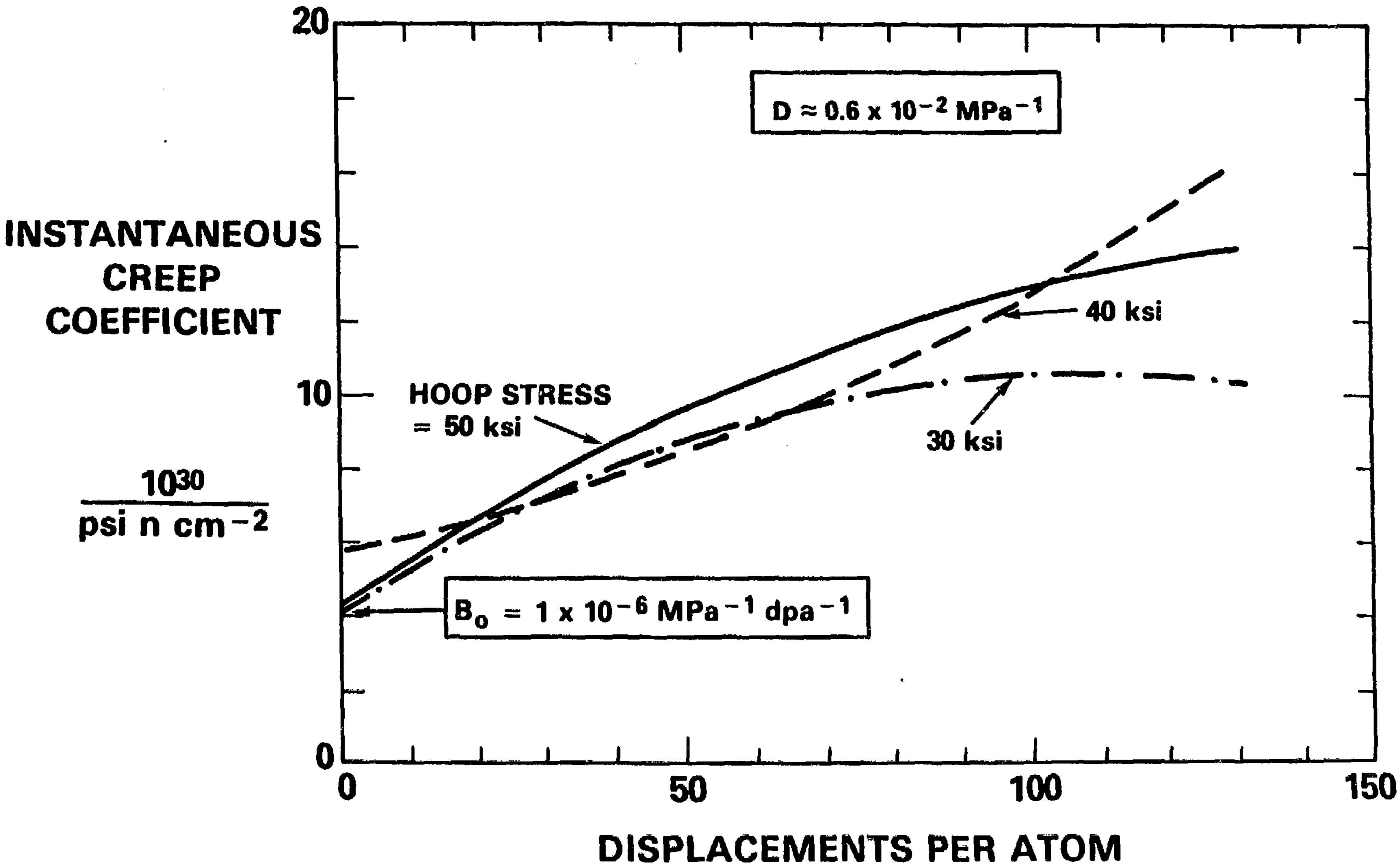
PORTER AND GARNER
EBR-II, PRESSURIZED TUBES
20% COLD-WORKED



HEDL 8706-065.8

IRRADIATION CREEP IN AISI 316 AT 400°C

PORTER AND GARNER
EBR-II, PRESSURIZED TUBES
20% COLD-WORKED



CREEP-SWELLING RELATIONSHIP

$$\frac{\dot{\varepsilon}}{\sigma} = B_o + D\dot{S}$$

CREEP RATE	CREEP COMPLIANCE	"SWELLING-ENHANCED" CREEP RATE

$B_o \approx 1 \times 10^{-6}\ MPa^{-1}\ dpa^{-1}$

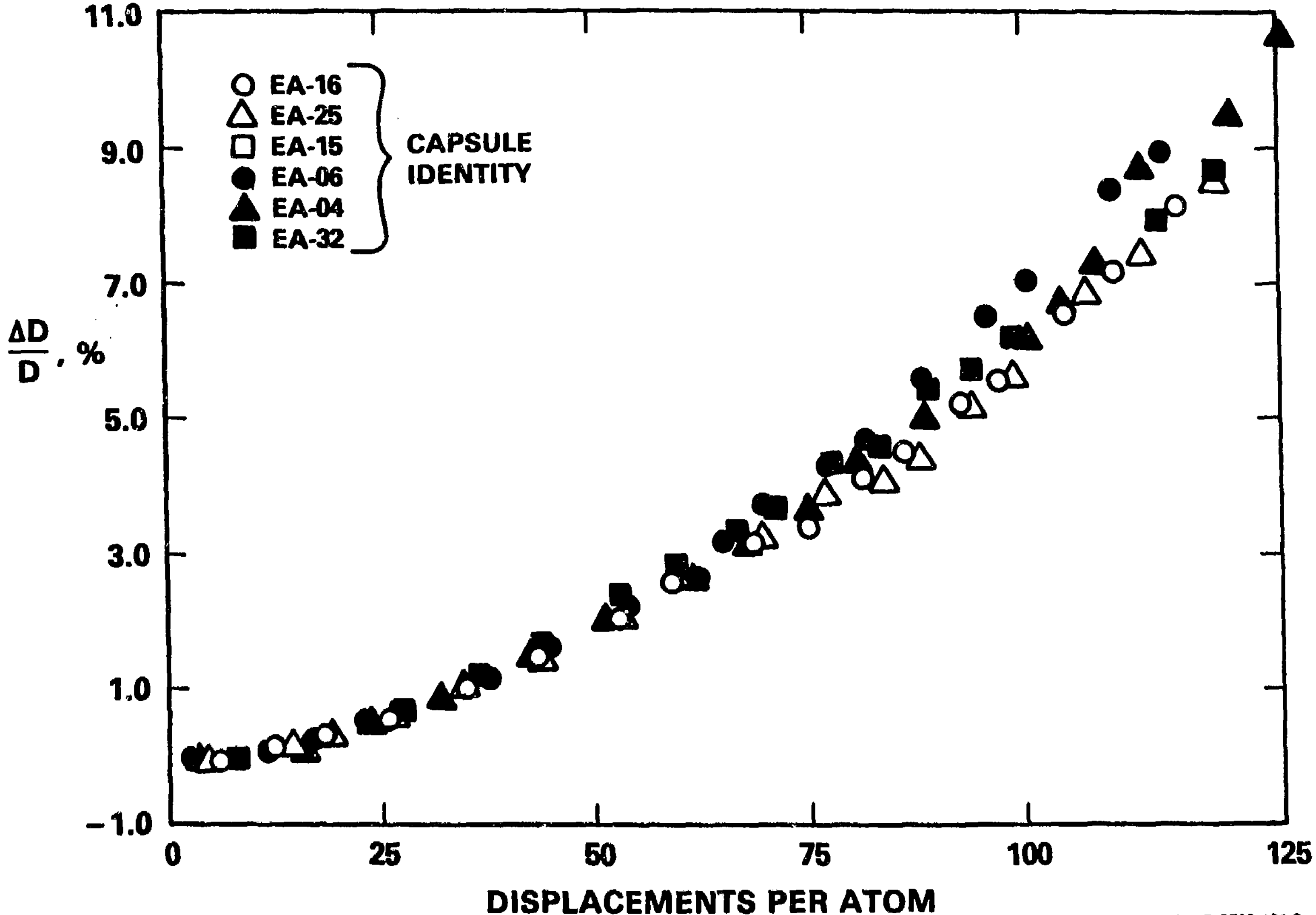
$D \approx 1 \times 10^{-2}\ MPa^{-1}$

} RELATIVELY INSENSITIVE TO COMPOSITION AND TEMPERATURE

HEDL 8309-064.8

BEHAVIOR OF NOMINALLY IDENTICAL CAPSULES

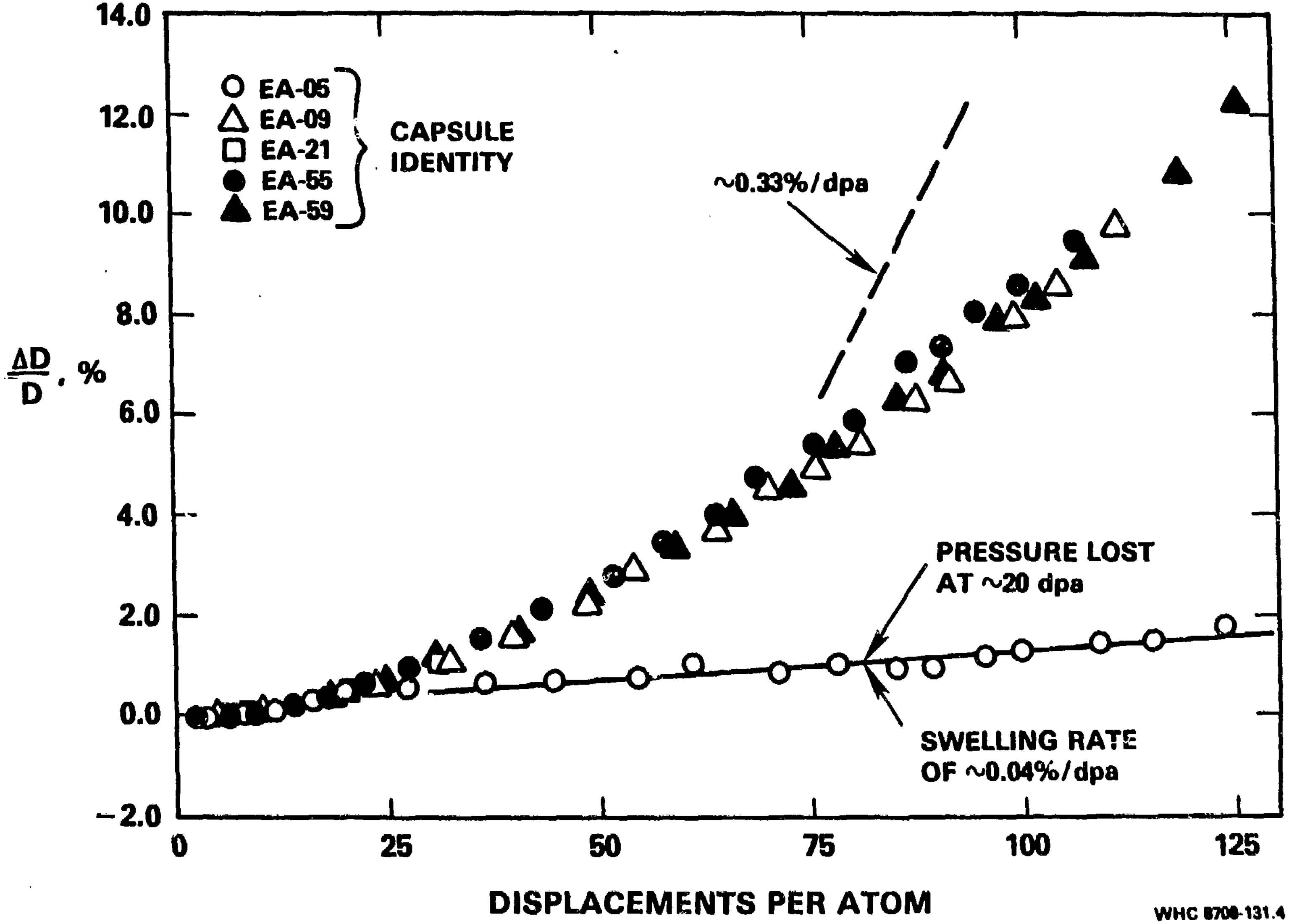
20% COLD-WORKED AISI 316
400°C, 40 ksi HOOP STRESS



WHC 8709-131.2

BEHAVIOR OF NOMINALLY INDENTICAL CAPSULES

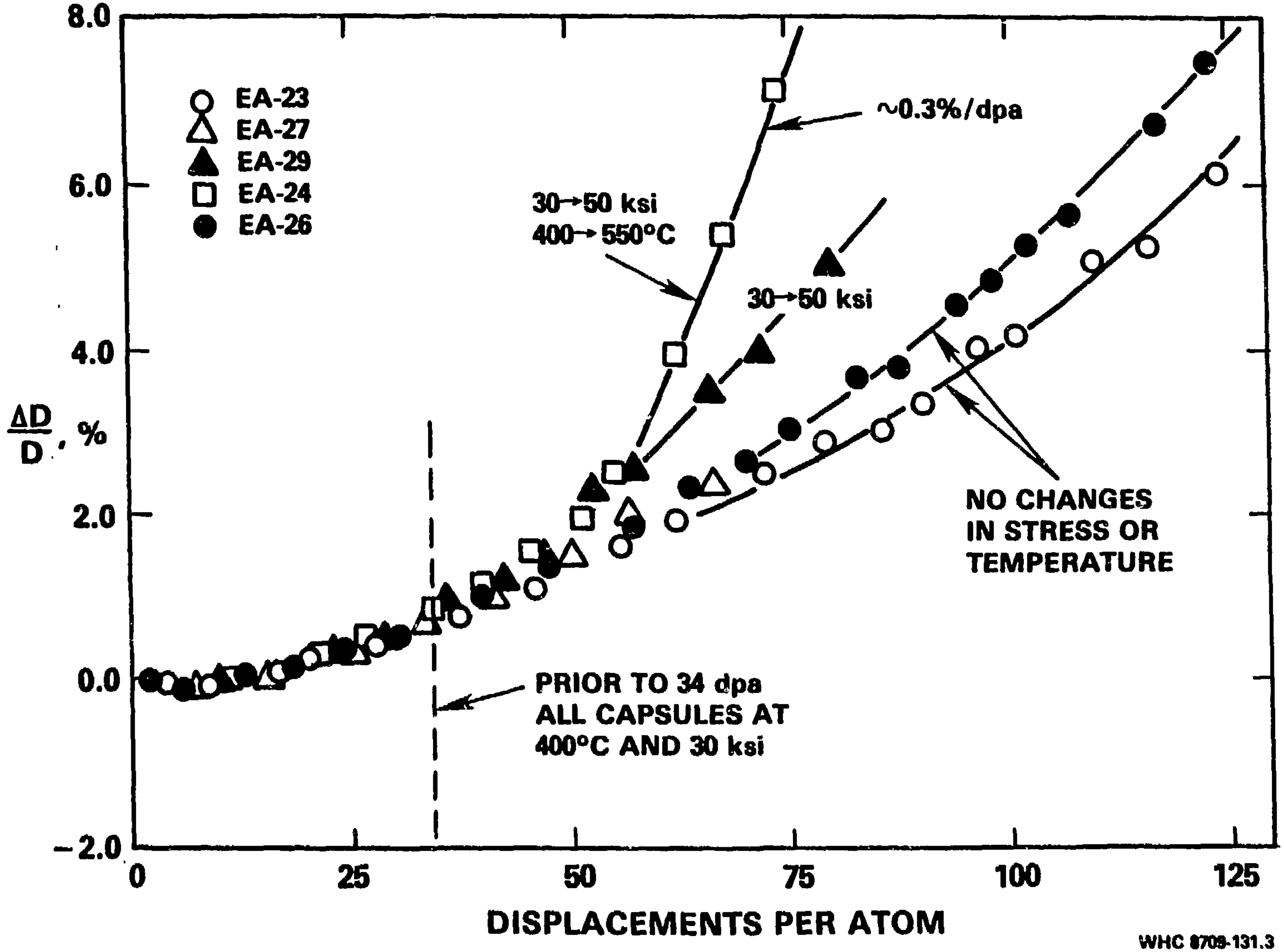
20% COLD-WORKED AISI 316
400°C, 50 ksi HOOP STRESS



WHC 8708-131.4

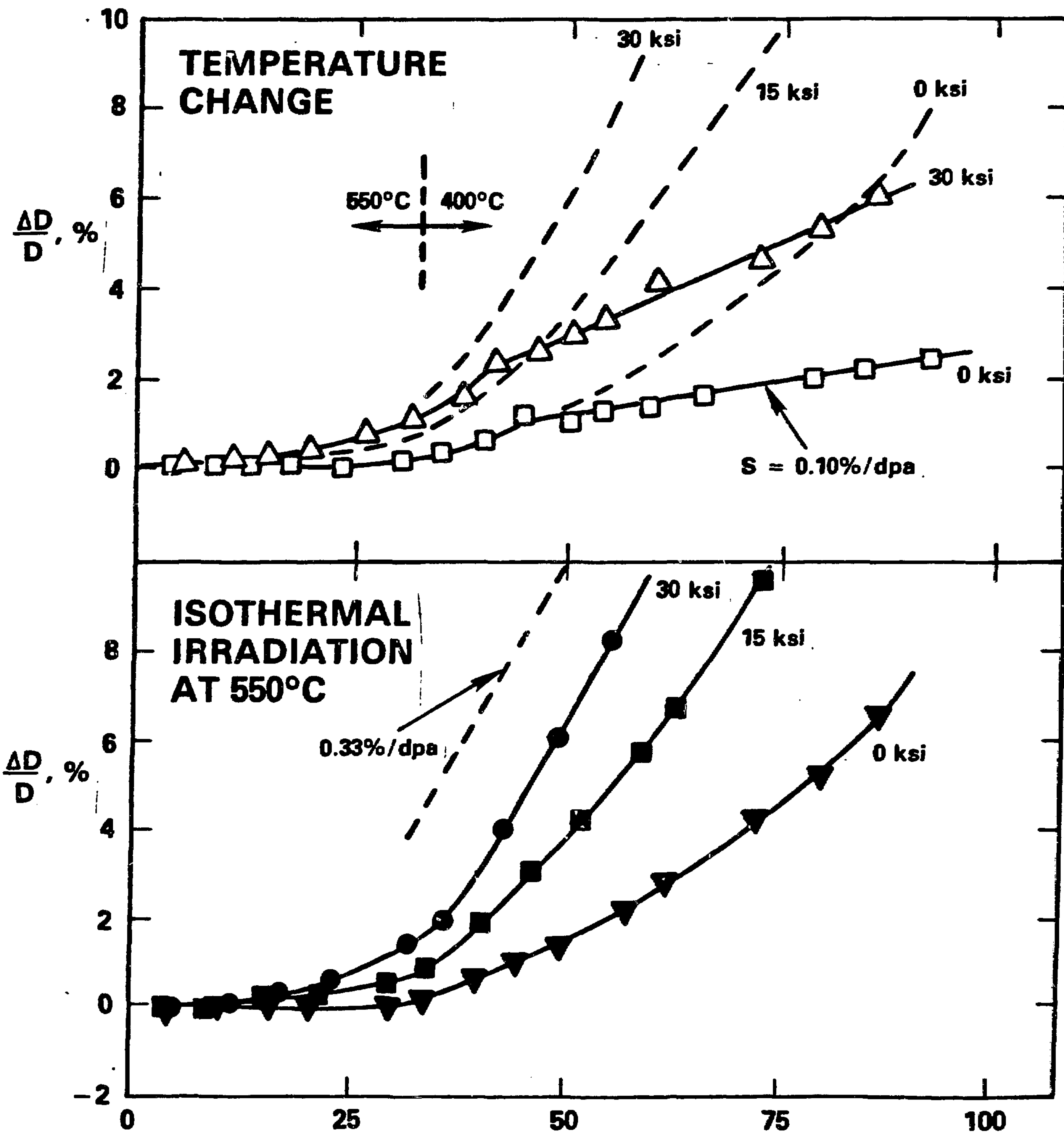
RESPONSE TO CHANGES IN ENVIRONMENT

20% COLD-WORKED AISI 316



RESPONSE TO CHANGES IN ENVIRONMEN

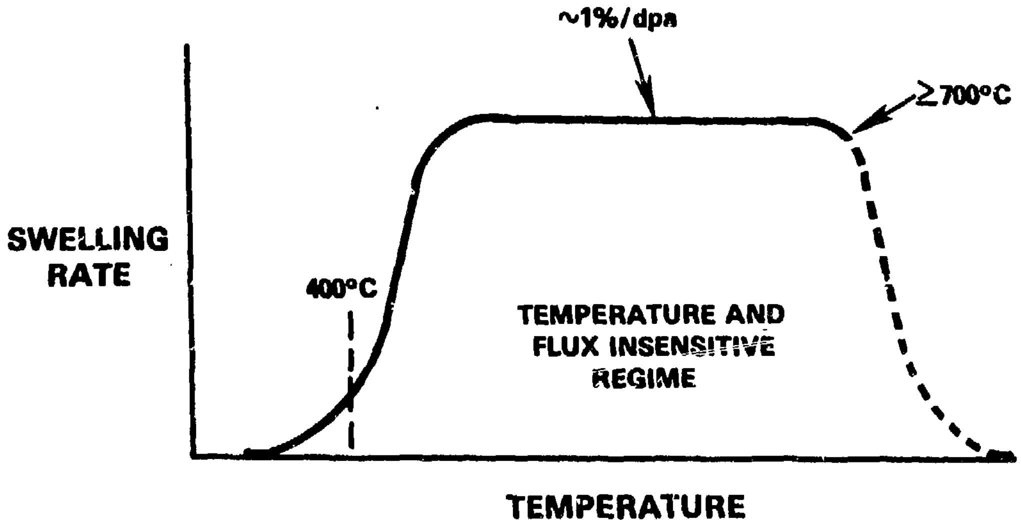
20% COLD-WORKED AISI 316



WHC 8709-131.7

RESULTS

COMPARISON OF THESE RESULTS AND THOSE OF OTHER COLD-WORK LEVELS AND AGING CONDITIONS LEADS TO THE CONCLUSION THAT AT 400°C SWELLING IS IN THE RECOMBINATION-DOMINATED REGIME



- SENSITIVITY TO DISPLACEMENT RATE AND ENVIRONMENTAL HISTORY
- MUCH LOWER SWELLING RATES
- COMPARABLE DECREASE IN CREEP RATES

WHC 8709-131.1

CONCLUSIONS: 20% CW AISI 316

- AT TEMPERATURES BELOW 400°C BOTH NEUTRON INDUCED CREEP AND SWELLING AT VERY LARGE EXPOSURES WILL BE QUITE LOW

- LARGE EXPOSURES CAN BE REACHED WITHOUT SIGNIFICIANT LEVELS OF FAILURE

- AISI 316 WOULD BE A GOOD CANDIDATE FOR CONSTRUCTION OF WATER-COOLED FUSION FIRST WALLS

WHCM 8709-131.3

RESULTS

- SWELLING IS STRESS-INSENSITIVE AT 400°C
- CREEP RATE IS LINEARLY PROPORTIONAL TO BOTH STRESS LEVEL AND SWELLING RATE
- $B_0 + D_0\dot{S}$ CREEP MODEL CONFIRMED
- CREEP COEFFICIENTS B_0 AND D_0 APPEAR TO BE RELATIVELY INDEPENDENT OF TEMPERATURE

WHCM 8709-131.2