PNL-SA--19951

DE93 004406

THE INFLUENCE OF SPECIMEN SIZE ON
MEASUREMENT OF THERMAL OR IRRADIATION
CREEP IN PRESSURIZED TUBES

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

F. A. Garner
M. L. Hamilton
R. J. Puigh
A. S. Kumar

C. R. Eiholzer
D. R. Duncan
M. B. Toloczko

August 1992

Received OSTI

DEC 14 1992

Presented at the
16th ASTM Symposium on Effects
of Radiation on Materials
June 22-24, 1992
Denver, Colorado

Prepared for
U.S. Nuclear Regulatory Commission
under Contract DE-AC06-76RLO 1830
NRC FIN B2911

Pacific Northwest Laboratory
Richland, Washington 99352

MASTER

Frank A. Garner¹, Margaret L. Hamilton¹, Raymond J. Puigh², Cheryl R. Eiholzer², Darrel R. Duncan², Mychailo B. Toloczko³, and Arvind S. Kumar⁴

THE INFLUENCE OF SPECIMEN SIZE ON MEASUREMENT OF THERMAL OR IRRADIATION CREEP IN PRESSURIZED TUBES

REFERENCE: Garner, F. A.; Hamilton, M. L.; Puigh, R. J.; Eiholzer, C. R.; Duncan, D. R.; Toloczko, M. B.; and Kumar, A. S., "The Influence of Specimen Size on Measurement of Thermal or Irradiation Creep in Pressurized Tubes", Effects of Radiation on Materials: 16th International Symposium, ASTM STP 1175, A. S. Kumar, D. S. Gelles and R. K. Nanstad, Eds., American Society for Testing and Materials, Philadelphia, 1993.

ABSTRACT: Thin-walled pressurized tubes have been developed for measurement of thermal creep and irradiation creep. Miniaturization of these tubes allows more tests to be conducted in the limited reactor space available and decreases the impact of displacement rate gradients and temperature gradients. Studies conducted on a variety of tube sizes show that, when specimen fabrication history and irradiation conditions are properly accounted for, miniaturization can be successfully achieved without producing invalid data.

KEY WORDS: thermal creep, irradiation creep, void swelling, size effects, austenitic stainless steel, pressurized tubes.

There is a very limited amount of fission reactor test space available at high neutron fluxes in which to conduct irradiation experiments with well-defined temperatures and well-characterized neutron flux/spectra. The various advanced neutron source concepts currently being proposed

---

¹Pacific Northwest Laboratory, Richland, WA is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

²Westinghouse Hanford Company, Richland, WA

³University of California, Santa Barbara, CA

⁴University of Missouri, Rolla, MO

for fusion-relevant irradiations will involve even smaller test volumes with larger gradients in displacement rate and possibly temperature. These considerations provide an incentive to miniaturize irradiation test specimens in order to maximize the amount of data obtained and to avoid gradients in both neutron exposure and temperature across a specimen. This in turn requires that detailed studies be conducted to determine the effect of size reduction on the validity of the measurements obtained.

Although a significant amount of progress has been made for tensile and fracture properties (see refs 1-4 for examples), no studies have been published on the miniaturization of the thin-walled pressurized tubes used to study irradiation creep. This paper outlines the results of a number of size effects studies on both thermal and irradiation creep that were conducted under the sponsorship of the U.S. Liquid Metal Reactor (LMR) and fusion reactor programs.

As shown in figure 1, the LMR program eventually centered its research on two standard "NCD" sizes⁵ (5.84 mm and 4.57 mm OD) which are shown compared with the more conventional uniaxial creep specimens that are very difficult to test in reactor. Also shown in figure 1 is a smaller (2.54 mm OD) pressurized tube that was previously under development for the Fusion Materials Irradiation Test (FMIT) facility[5]. When the FMIT project was discontinued, the development effort on this tube was also stopped. This effort may be resurrected if a fusion-relevant neutron source is eventually built. Table 1 compares the dimensions of these three pressurized tubes. Figure 2 shows details of tube construction.

Whatever size is employed, pressurized tubes have inherent advantages for irradiation creep studies. Not only are they relatively small in mass and volume, but the stress is maintained without attachments within the reactor or its externals. Additionally, the nearly biaxial stress state is almost an exact simulation of the stress state found in the fuel cladding used in the LMR program and the resultant strains are easily applied to other stress states[6]. Lastly, the stress is maintained at a nearly constant value even for relatively large creep-induced strains ($\leq 20\%$). This is due to the fact that the drop in gas pressure with creep strain is almost exactly offset by the thinning of the tube wall. It should be noted that swelling-induced dimensional changes lead to a drop in gas pressure that is not compensated by wall thinning. Changes in stress, however, are negligibly small for swelling levels less than 10%.

---

⁵NCD = National Cladding and Duct

FIG. 1--Comparison of various tensile specimens and creep tubes used to study thermal or irradiation creep in the LMR and fusion reactor materials programs.

Table 1--Dimension of Small Tubes Employed in Current Studies

	Outer Diameter	Length	Wall Thickness
LMR "NCD" Tubes	5.84 mm (0.230 in)	2.82 cm	0.38 mm
	4.57 mm (0.180 in)	2.24 cm	0.20 mm
"FMIT" Tube	2.54 mm (0.100 in)	1.44 cm	0.25 mm

When considering the use of pressurized tubes to study creep, other factors become important and can impinge on the validity of using these miniature specimens. Whereas solid tensile specimens must meet certain minimum dimensional tolerances, thin-walled pressurized tubes require even more

USE OF FILM HOLES FOR PRESSURIZATION

When analyzing the performance of miniature tubes, there are two types of size effects to be considered: direct and indirect. Direct size effects concern the influence of end effects and diameter-to-thickness ratios. Both of these influence the degree of triaxiality of the stress state. Indirect size effects arise from the trade-offs sometimes made in constructing smaller tubes. For instance, heating effects associated with the welding of end-caps to the tube may change the microstructure of a significant portion of the length of relatively small tubes. Second, a reduction of the tube diameter from one size to another may require some changes in processing history and these effects are not always negligible. Finally, irradiation creep is strongly dependent on the void swelling rate[7-10], and void swelling is often strongly dependent on processing variables[11-13].

The majority of the studies reported here were conducted as thermal creep tests or stress rupture tests in order to define optimum size ranges. A wider variety of sizes was employed in the early LMR studies, and although these appear in various figures in this paper they were not listed in Table 1 since they were discontinued early in the program. The most pertinent studies will be reported last and concern the in-reactor creep behavior of the two NCD tube sizes.

EXPERIMENTAL DETAILS

The construction of the pressurized tubes has been described elsewhere[14] and is shown schematically in figure 2. In the earliest of the studies described in this paper, the diameter of the tubes were measured at five equidistant locations using differential LVDT probes[15]. The center three measurements were used to assure the absence of end effects, and the average of the three measurements is shown in various figures to follow. In the more recent studies these measurements were made using a non-contacting laser system[16]. Stress-rupture tests were conducted at constant internal pressure in a furnace under argon cover gas. Irradiations were conducted under sodium in the Fast Flux Test Facility (FFTF) and were maintained at $\pm 5^\circ\text{C}$ of their target temperature in the Materials Open Test Assembly (MOTA)[14].

RESULTS: OUT-OF-REACTOR TESTS

Figure 3 presents results of a comparison of thermal creep response for three different stress states in the regime of nonlinear response to stress. Note that two of these stress states involve the use of tubes and the other is a rod specimen. In spite of the different stress states and specimen geometries, relatively good reproducibility between identical specimens and relatively good agreement

FIG. 3--Effect of geometry and stress state on thermal creep at 650°C of 20% cold-worked 316 stainless steel after 100 hours[15].

between differing stress states was obtained when compared on the basis of effective stress/effective strain.

In the current studies, the effect of tube length was investigated. Figure 4 shows a comparison of superimposed strain data for nominally identical tubes varying only in their length. It was determined that lengths in excess of 1" (2.54 cm) were unnecessary. It was also determined that the influence of end effects in these tubes was easily avoided by the diameter measurement technique described earlier.

A variety of thermal creep and stress rupture tests have been conducted out of reactor to determine the influence of both tube diameter and length. Figures 5 and 6 show the results of both types of tests conducted on the FFTF first core heats of 20% cold-worked 316 stainless steel, demonstrating no effects of either variable. As shown in figure 7, an even wider range of tube diameters were tested in a study on the LMR improved D9-type steel based on titanium-modified 316 stainless steel. Note that many of the different tube diameters were produced with varying levels of cold-work. While the D9 heat used to produce the data in figure 7 does not appear to respond strongly to size and cold-work differences, another group of silicon and molybdenum modified D9 heats appears to show a pronounced effect of tube size (figure 8). This effect appears to be relatively insensitive to variations in Si and Mo content. As shown in figure 9, the differences in rupture behavior were mirrored in the hardness measurements performed on the two sizes of specimen after thermal aging.

When the differences in data between the various heats in figure 8 and 9 are examined in detail, it becomes obvious that some chemical variations are more sensitive to processing history than are others. It appears, however,

Fig. 4--Effect of tube length on thermal creep of 20% cold-worked 316 stainless steel at 650°C.

FIG. 5--Effect of tube diameter on thermal creep at 575°C of 20% cold-worked 316 stainless steel after 3,000 hours. (NCD tubes described in table 1.)

that the differences in rupture behavior for the 5.84 and 4.57 mm diameter tubes are illusory and reflect only slight differences in processing history as shown in Table 2.

The only in-reactor tests on size effects were conducted on D9 heat 83508 and are described in the next section. As shown in figures 10 and 11, the effect of specimen size, if any, on the thermal creep of these tubes is relatively small at 550 and 750°C. The apparent differences at 575 and 605°C for some pressures are thought to reflect undetected loss of tube pressure prior to the start of the final segment of the aging and measurement sequence.

Table 2--Processing History of Pressurized Tubes Constructed From the Chemical Variable Heats of D9

<u>Tube O.D.</u>	<u>Homogenization Temperature</u>	<u>Interpass Anneal Temperature</u>
0.230 in (5.84 mm)	1175°C (5 hrs)	~1070°C
0.180 in (4.57 mm)	1175°C (5 hrs)	~1070°C
	1200°C (24 hrs)*	one intermediate solution treatment at 1175°C

*hot rolled at 1175°C and annealed (1025°C/1hr/WQ) between homogenization treatments.

FIG. 6--Influence of tube size on stress rupture behavior of 20% cold-worked 316 FFTF first core stainless steel at 650°C.

RESULTS: IN-REACTOR TESTS

Figures 12 and 13 present the irradiation creep and void swelling strains. The differences in deformation behavior for the two tube sizes are relatively small. Upon closer comparison it is obvious that the largest of these relatively small differences occur when the two sizes of specimens were irradiated at significantly different positions in core, as evidenced by measurable differences in their dpa levels. Thus, even these relatively small differences probably arise from the flux and temperature sensitivity of void swelling and its very large impact on irradiation creep.

DISCUSSION

The experimental results presented in this paper clearly indicate that, within the range of sizes explored in these studies, there are no significant effects of specimen size on thermal creep or irradiation creep. It is possible, however, to produce the appearance of a size effect if some other variable is inadvertently introduced into the comparison. Relatively small changes in heat treatment and radiation environment, for example, have been shown to produce such a result.

FIG. 7--Influence of tube diameter and cold-work level on the stress-rupture behavior of titanium-modified alloy D9-C1.

FIG. 8--Stress rupture behavior of chemical variations (Si and Mo) of 20% cold-worked D9 alloy. The apparent size effect is an artifact of differences in production history. LMP is the Larson-Miller parameter.

FIG. 9--Hardness of the chemical variable heats of D9 following aging at 650, 704 and 760°C, showing different behavior at two tube sizes. The range of hardness response reflects the individual sensitivity of each variant to processing and aging history.

FIG. 10--Effect of specimen size on thermal creep of D9 alloy (heat 83508) at 550, 575 and 605°C.

FIG. 11--Effect of specimen size on thermal creep of D9 alloy (heat 83508) at 670 and 750°C.

The role of heat treatment is known to be particularly strong. In a recent study[17] it was shown that small differences in radiation variables could produce significant differences in swelling behavior, but even larger changes could be induced by variables that are normally thought unnecessary to control. The interpass annealing or "temper" annealing temperature between successive cold-work reductions exerts a particularly large effect on void swelling, primarily by affecting the duration of the transient regime of swelling[13]. The influence of the temper annealing temperature on recrystallization has also been found to be unexpectedly strong, overshadowing the influence of minor variations in alloy composition[18]. The processes involved in recovery and recrystallization are also involved in determining the high temperature behavior of thermal and irradiation creep.

The strong interaction between the cold-work level and the recovery processes involved in creep and swelling have also been demonstrated recently to depend on the stress level and temperature in a complex non-monotonic manner[19,20]. Thus variations in cold-work level that accompany the production of different size tubes may also exert influence on the creep behavior. The sensitivity to

FIG. 12--Influence of specimen size on irradiation creep in FFTF/MOTA of D9 alloy (heat 83508) at 400 to 495°C.

FIG. 13--Influence of specimen size on irradiation creep in FFTF/MOTA of D9 alloy (heat 83508) at 550 to 665°C.

cold-work level varies strongly from steel to steel, however.

CONCLUSIONS

It appears that thin-walled pressurized tubes can be reduced in size without introducing any problems in data generation or creep analysis. Care must be taken, however, to avoid the inadvertent introduction of other uncontrolled variations in tube manufacture or irradiation environment.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contracts DE-AC06-76RLO 1830 and DE-AC06-76FF02170. The participation of M. B. Toloczko and A. S. Kumar was supported by the Northwest College and University Association for Science (Washington State University) under Grant DE-FG06-89ER-75522 with the U.S. Department of Energy.

REFERENCES

- [1] Kumar, A. S., Garner, F. A., Hamilton, M. L. and Loudon, B. S., "Recent Improvements in Size Effects Correlations for DBTT and Upper Shelf Energy of Ferritic Steels", ASTM International Symposium on Small Specimen Test Technology and Their Application to Nuclear Reactor Pressure Vessel Annealing and Plant Life Extension, New Orleans LA, January 29-30, 1992 (in press).
- [2] Garner, F. A., Hamilton M. L., Heinisch H. L., and Kumar, A. S., "Application of Miniature Tensile Specimens to Studies of Radiation Damage in Metals", *ibid.*
- [3] Lucas, G. E., Metallurgical Transactions 21A(1990)1105.
- [4] "The Use of Small-Scale Specimens for Testing Irradiated Material," ASTM STP 888, W. R. Corwin and G. E. Lucas, Eds., American Society for Testing and Materials, Philadelphia, 1983.
- [5] Hagan, J. W., Opperman, E. K. and Trego, A. L., Journal of Nuclear Materials 122 & 123 (1984) 958.
- [6] Malvern, L. E., "Introduction to the Mechanics of a Continuous Medium", Prentice-Hall, Inc., 1969, pg. 364-366.

- [7] Garner, F. A. and Gelles, D. S., Journal of Nuclear Materials 159 (1988) 286.
- [8] Garner, F. A. and Porter, D. L., Journal of Nuclear Materials 155-157 (1988) 1006.
- [9] Toloczko, M. B., Garner, F. A. and Eiholzer, C. R., Journal of Nuclear Materials 191-194 (1992) in press.
- [10] Woo, C. H., Garner, F. A. and Holt, R. A., these proceedings.
- [11] Brager, H. R., and Garner, F. A., "Dependence of Void Formation on Phase Stability in Neutron-Irradiated Type 316 Stainless," Effects of Radiation on Structural Materials, ASTM STP 683, J. A. Sprague and D. Kramer, Eds., American Society for Testing and Materials, 1979, pp. 207-232.
- [12] Garner, F. A., Journal of Nuclear Materials 122 & 123 (1984) 459.
- [13] Garner, F. A., Bates, J. F., and Mitchell, M. A., Journal of Nuclear Materials, 189(1992)201.
- [14] Puigh, R. J. and Schenter, R. E., "In-Reactor Stress Rupture Experiment in the Materials Open Test Assembly (MOTA)", Effects of Radiation on Materials: Twelfth International Symposium, ASTM STP 870, F. A. Garner and J. S. Perrin, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 795-802.
- [15] Gilbert, E. R. and Blackburn, L. D., Transaction of the ASME (1977) 168.
- [16] Gilbert, E. R. and Chin, B. A. "Irradiated Materials Measurement Technology", Effects of Radiation on Materials: Tenth conference, ASTM STP 725, D. Kramer, H. R. Brager and J. S. Perrin, Eds., American Society for Testing and Materials, 1981, pp. 665-679.
- [17] Garner, F. A., Heinisch, H. L., Simons, R. L. and Mann, F. M., Radiation Effects and Defects in Solids, 113 (1990) 229.
- [18] Paxton, M. M., Knecht, R. L., and Holmes, J. J., IERSM Semiannual Progress Report, HEDL TME 74-51, Hanford Engineering Development Laboratory (1974) pp. HEDL:58-61.
- [19] Garner, F. A., Hamilton, M. L., Eiholzer, C. R., Toloczko, M. B., and Kumar, A. S., Journal of Nuclear Materials 191-194 (1992) in press.

[20] Garner, F. A., Hamilton, M. L., Eiholzer, C. R.,
Toloczko, M. B., and Kumar, A. S., these proceedings.

END

DATE
FILMED

3 / 24 / 93