In-Reactor Deformation of Solution Annealed
Type 304L Stainless Steel

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By

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IN-REACTOR DEFORMATION OF SOLUTION ANNEALED
TYPE 304L STAINLESS STEEL

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ABSTRACT

Over the past six years at EBR-II, a great deal of information has been obtained on the in-reactor behavior of solution annealed-Type 304L stainless steel. This information consists of the following:

1. Irradiation induced swelling results in the form of immersion density and transmission electron microscopy (TEM) measurements on unstressed material that extend over a temperature range of 395° to 530°C and a neutron fluence range of 1.8×10^{22} to 9.3×10^{22} n/cm² ($E > 0.1$ MeV).
2. Irradiation induced creep results from helium pressurized capsules irradiated at a temperature of 415°C. The hoop stress range covered in the experiment was 0 to 27.3 ksi, and the peak neutron fluence obtained to date is 7.6×10^{22} n/cm² ($E > 0.1$ MeV).
3. Residual stress measurements (slit tube technique) with complementary TEM gradient studies on stressed and unstressed capsules.
4. Comparative swelling studies of stressed cladding material and unstressed capsule material from encapsulated EBR-II driver fuel experiments over wide ranges of temperature and neutron fluences.

The deformation information derived from the four above studies represent an extensive data base from which to obtain an understanding of the in-reactor deformation of austenitic stainless steel. It is the purpose of this paper to review our information on the in-reactor deformation of solution annealed Type 304L stainless steel with particular emphasis on:

1. The stress effect on swelling as evidenced by the lack of either a swelling gradient or residual stress on capsules subjected to significant temperature gradients.
2. The enhanced swelling exhibited by stressed cladding material when exposed to identical neutron fluence and temperature conditions experienced by unstressed capsule tubing.
3. The strong interaction between swelling and creep as observed by the simultaneous increase in creep and swelling rates with neutron fluence accumulation.

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1. Introduction

Stainless steel, when exposed to a fast neutron flux, exhibits a volume increase due to "irradiation induced swelling."¹ If the stainless steel material is subjected to an applied stress while being neutron irradiated, then an "irradiation enhanced creep" behavior is observed in addition to the irradiation induced swelling.² The magnitude of the swelling and creep deformation under fast reactor operating conditions require that both effects be considered in reactor design. To consider the phenomena in design does not require that the phenomena be understood. It is only necessary to carry out enough experiments within an envelope of all projected operating conditions so that the swelling and creep behavior can be empirically described and specific values subsequently interpolated on demand by designers. Unfortunately, we presently do not have a broad enough data base for complete empirical description.

Early experimentation demonstrated that neutron flux, time, and temperature were important parameters for the characterization of swelling.³ In addition to these parameters, applied stress was important for empirical descriptions of creep. Until about three years ago, the goal of in-reactor experiments was to determine the dependencies of

swelling and creep on these parameters. The following behavior was observed at that time. Swelling was dependent on neutron fluence. The flux and time dependencies of swelling did not require separation. As a function of neutron fluence, swelling exhibited initially a low swelling rate that was followed by a higher swelling rate. At constant neutron fluence a maximum swelling rate was exhibited with temperature. Irradiation enhanced creep was linearly dependent on neutron fluence and was thought to be athermal. In addition, creep rates were linearly dependent on applied stress. Creep data from springs and biaxially stressed tubes were compared and the applied stress-strain rate data were successfully correlated by the Soderberg formalism (on the basis of effective stress-strain rates).⁴ Thus, a means existed to treat deformations under complex stress states.

Unfortunately, the experimental data that were used to arrive at the above conclusions lagged in neutron fluence, by an order of magnitude, the goal exposures contemplated for future fast breeder reactors. Therefore, the required interpolation of empirical formulations for swelling and creep was impossible. The erudition of extrapolating current information to high neutron fluences was seriously questioned without answers to the following questions:

- a. Is irradiation induced swelling a function of applied stress?
- b. Are irradiation induced swelling and irradiation enhanced creep interrelated?
- c. Is irradiation enhanced creep athermal?
- d. What are the dependencies of swelling rates and creep rates on the state of stress?

Experiments are in progress in the United States as well as other countries that will eventually answer these questions.

The purpose of this paper is to present the information obtained to date from experiments performed on solution annealed 304L stainless steel. This information provides insight into the four questions listed above. Experimental details and complete presentations of the data obtained from the various experiments will be presented in future publications.

2. Experimental

The swelling and creep results to be presented and discussed later in this paper originate from following three areas of experimental investigation: creep, capsule-clad swelling, and swelling gradients. A brief description of each area follows:

Creep

The creep experiment on solution annealed 304L stainless steel consists of irradiating helium pressurized capsules in row 7 of EBR-II.^{5,6} The capsules are 152.4 cm in length with an outer diameter of 0.737 cm, a 0.051 cm wall, and a nominal grain size of ASTM 6. The irradiation temperature of 415°C has been measured by thermal expansion difference monitors. The applied hoop stress on the capsules ranges from 0 to 27.3 ksi. Diameter measurements are made along the entire length of each capsule after each irradiation period. Thus, total hoop strain as a function of neutron fluence is determined by cycling the capsules into and out of the reactor. The hoop strain from the unstressed capsules is subtracted from the total hoop strain of the stressed capsules to yield the contribution to the total strain from irradiation enhanced creep with the following reservation. If

irradiation induced swelling is a function of applied stress, then the hoop strain values remaining for the stressed capsules after the hoop strain from the unstressed capsules has been subtracted contains a strain contribution due to the effect of stress on irradiation induced swelling. The only direct method of determining the existence of a stress effect on swelling is to subject a stressed capsule to destructive examination and obtain immersion density measurements. These immersion density measurements have been obtained on sections from stressed capsules at neutron fluences of 1.4×10^{22} and 5.1×10^{22} n/cm² (E > 0.1 MeV). To date, the capsules from this creep experiment have attained neutron fluences of 7.6×10^{22} n/cm² (E > 0.1 MeV).

Capsule-Clad Swelling

The capsule-clad swelling work involves an investigation that has been ongoing at EBR-II for the past five years. This swelling investigation was a consequence of a program to develop the Mark-II driver fuel element for the EBR-II fast breeder reactor. Mark-II driver fuel elements, clad with solution annealed 304L stainless steel,* (outer diameter 0.442 cm) were encapsulated in solution annealed 304L stainless steel capsules from the same tubing lot as used in the creep experiments. The driver fuel elements were sodium bonded in the capsules. The purpose of the program was to run the elements to failure such that the burnup limit on Mark-II driver fuel elements could be determined.⁷ Failed driver fuel elements as well as driver fuel elements removed from the experiment prior to failure were subjected to destructive examination.

* Mark-II driver fuel currently used in the EBR-II reactor is clad with seamless-solution annealed-316 stainless steel.

Swelling measurements of the cladding were one of a series of observations required to evaluate the performance of the driver fuel element. During the course of the cladding evaluations, swelling measurements were obtained on sections from the capsule material used to encapsulate the driver fuel elements. These measurements were made on the capsules because it was an ideal source of material from which to gain swelling data that could subsequently be formulated into empirical relationships. The capsule material is well characterized in terms of the in-reactor temperature and accumulated neutron exposure since the detailed neutronics and thermal calculations carried out for the driver fuel elements apply equally well to the capsule material. In addition, the capsule material was not subjected to an applied stress. Swelling data in the form of immersion density measurements and transmission electron microscopy analyses have been obtained on the capsule material over a temperature range of 395°C to 530°C and a neutron fluence range of 1.8×10^{22} to 9.3×10^{22} n/cm² ($E > 0.1$ MeV). Thus, the unstressed swelling behavior of solution annealed 304L stainless steel has been well characterized from information gained on the capsule material over wide ranges of temperature and fluence.

The interest in the present paper lies not in the unstressed swelling behavior of stainless steel, but rather on the effects of stress on irradiation induced swelling. However, the unstressed swelling behavior must be at least empirically described before departures from unstressed swelling behavior can be shown to exist. By comparing swelling measurements from cladding material to swelling measurements from the unstressed capsule material, it was observed that at identical temperature and identical neutron exposures the cladding swelled

more than the capsule material. The departure in swelling behavior between clad and capsule material increased with neutron fluence and also temperature. It is, of course, tempting to attribute this departure to the effect of stress on swelling because the cladding material experiences an applied stress due to the combined effect of the fission gas pressure and the U - 5wt% Fs* fuel pin expanding outward against the cladding. These results are discussed in detail in a later section.

Swelling Gradients

The third area of study involves the investigation of swelling gradients and the residual stresses that could originate from swelling gradients. In a typical fast breeder reactor, EBR-II being no exception, significant neutron flux and thermal gradients exist. Since irradiation induced swelling is a function of neutron fluence and temperature, it follows that swelling gradients should exist in stainless steel components subjected to neutron flux and thermal gradients. These swelling gradients should lead to residual stresses. In fact, if no competing mechanism existed (irradiation enhanced creep or an effect of stress on swelling) the residual stresses could build up with exposure to a level where a component could yield or fracture.

The solution annealed 304L stainless steel capsules, discussed previously, again become a good source to investigate swelling gradient phenomena. A significant temperature gradient exists across the wall of the capsules with the inner surface (that nearest the fuel element) always being at the higher temperature. Using an electrical discharge

* Fissium is an equilibrium concentration of fission-product elements left by the pyrometallurgical reprocessing cycle designed for EBR-II and consists of 2.4 wt% molybdenum, 1.9 wt% ruthenium, 0.3 wt% rhodium, 0.2 wt% palladium, 0.1 wt% zirconium, and 0.01 wt% niobium.

cutting system, specimens of 2.54 cm in length were cut from the capsules and axial slits were made in these specimens. The slitting technique and related measurements are illustrated in fig. 1. The amount the slit opens or closes represents the magnitude of residual hoop stress present in the tube. This opening or closing can be determined by measuring the slit width or diameter change.

To complement the residual stress measurements, void gradient examinations were carried out by transmission electron microscopy (TEM) on some of the same specimens that were used for the residual stress measurements. The TEM samples used for these void studies were obtained from a series of rings (four per ring) near the axial center of each 2.54 cm-long specimen. At least one sample per ring was thinned at each of the I.D., midwall and O.D. locations. Five to eight electron micrograph stereopairs were obtained for each location. From the electron micrographs, the size, number density and volume change of the voids were determined.

3. Results

This section states the results obtained from the three areas of experimental investigation (i.e., creep, capsule-clad swelling, and swelling gradients). A detailed presentation of the complete spectrum of results from each area of experimental investigation is reserved for future publications.

Creep

Fig. 2 shows typical diameter change measurements for unstressed capsules and capsules stressed to a hoop stress of 27.3 ksi. The capsule diameters were determined from profilometer traces. The capsule diameters were continuously measured over their entire length. The diameter change data shown on fig. 2 were determined at the peak diameter locations from

the profilometer traces. These peak diameter locations do correspond to the core midplane locations. The creep curve was obtained by subtracting the swelling component (zero stressed tube data) from the total strain curve. A composite of all the total diameter change data from the creep experiment on solution annealed 304L stainless steel is shown on fig. 3.

A notable feature of the data shown on figs. 2 and 3 is that a change in slope of the creep curve occurs at approximately the same fluence that the swelling rate increases. The creep strain dependence on fluence can be taken as linear by the construction of two straight lines through the low fluence and high fluence portion of each creep curve. However, a curve can be fitted through the data at each stress level. In addition, the creep rates (slope of each straight line portion) exhibits a linear dependence on hoop stress.

It could be argued that the increase in the slope of the creep curve is not due to creep (deviatoric strain) but rather due to the effect of stress on swelling. At a neutron fluence of $1.4 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) a stressed capsule, with an in-reactor hoop stress of 27.3 ksi, and an unstressed capsule were subjected to destructive examination. Immersion density and transmission electron microscopy (TEM) results showed that there was no effect of applied stress on swelling.⁶ However from figs. 2 and 3 it is observed that the fluence of $1.4 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) is below the fluence where the creep and swelling rates increase. At the fluence of $5.1 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$) another stressed capsule, with an in-reactor hoop stress of 22.8 ksi, was subjected to destructive examination. Fig. 4 shows the results of immersion density measurements made on 2.54 cm sections that were removed at

intervals along the creep capsule. The data points shown on fig. 4 are one third the fractional volume change, where the fractional volume change was calculated as

$$\frac{\Delta V}{V_0} = \frac{\rho_0 - \rho_f}{\rho_f} \quad (1)$$

where ρ_0 and V_0 are the initial density and volume, respectively, and ρ_f is the postirradiated immersion density value. The initial density, ρ_0 , was taken to be 7.898 gm/cm^3 as determined from unirradiated archive material. The curve shown on fig. 4 is the fractional diameter change profile for a neighboring unstressed capsule. (An unstressed capsule was not sacrificed at this point for destructive examination because only two unstressed capsules remain in the experiment.) It is readily observed that one third the fractional volume change obtained from the stressed capsule agrees with the fractional diameter change data of the unstressed capsule. Therefore, at a neutron fluence of $5.1 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$), an in-reactor temperature of 415°C , and an applied hoop stress of 22.8 ksi, no effect of applied stress on swelling was observed. It should be emphasized that the apparent absence of a stress effect on swelling relates to a specific set of operating conditions, namely low temperature, because later in this paper evidence is presented that suggests an effect of stress on swelling exists at higher inreactor operating temperatures. It should also be noted that prior to sectioning the creep capsules (for both examination at 1.4×10^{22} and $5.1 \times 10^{22} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$), the capsules were punctured under vacuum with a laser to determine the gas pressure and volume. The pressures determined were in excellent agreement with expected pressures, thus providing proof that the stressed capsules had retained the helium during irradiation.

Capsule-Clad Swelling

The next set of results deals with the comparison of capsule swelling to cladding swelling. Fig. 5 illustrates in a very graphic manner the magnitude of the enhanced swelling behavior. Shown on fig. 5 are the diameter traces obtained from a profilometer for the capsule and the cladding. The cladding diameter trace is the upper curve on fig. 5. Also shown on fig. 5, as the middle profile, is the contribution to the cladding diameter change from irradiation induced swelling. The irradiation induced swelling contribution was determined by removing the fuel from 2.54 cm sections of cladding and then obtaining immersion density measurements using the same method employed for the creep capsules. The capsule/cladding combination shown on fig. 5 attained a peak neutron fluence of $7.2 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ Mev}$) with a peak operating temperature of 570°C . Since both cladding and capsule material were solution annealed 304L stainless steel and since both cladding and capsule material experienced the same axial neutron flux profile, the diameter profile from the capsule ought to agree with one third the swelling profile from the cladding material. It should be noted that at equivalent axial locations the cladding operates at a somewhat higher temperature. However, even with consideration of the temperature differences (e.g. approximately 50°C) between capsule and cladding material, the cladding swelling far exceeds the capsule swelling.

The differences between capsule and cladding swelling is perhaps more quantitatively presented on figs. 6 and 7. On figs. 6 and 7, the swelling of the cladding material is compared to the capsule swelling as a function of neutron fluence at the irradiation temperatures of 465°C and 530°C , respectively. The observation of importance is that

at the lower temperature the departure in behavior between the capsule and cladding material occurs at a much higher fluence. At higher temperatures (e.g. fig. 7) the swelling divergence with increasing neutron fluence is quite marked. The conclusion could be drawn that a continually increasing stress due to the fission gas pressure and fuel expanding against the cladding caused the enhanced cladding swelling. However, it is well to consider the possibility that chemical compositional changes in the cladding could produce the same result.⁸ For example, it is known that carbon is a swelling inhibitor in stainless steel and if the cladding experiences a preferential carbon loss, the swelling could be enhanced. At this point in time, we do not have experimental proof that a carbon loss has taken place in the cladding as our electron microprobe capability does not provide sufficient sensitivity to carbon. However, at the clad-fuel interface, a significant nickel depletion does occur, with the nickel diffusing into the fuel. A ferritic layer is formed on the inner surface of the cladding due to the nickel depletion with the maximum observed thickness of the ferritic layer being about .05 mm of the .30 mm thick cladding. Nickel depletion beyond this ferritic layer, toward the outer cladding surface, does not exist.

To provide additional insight into the question of whether the enhanced swelling observed on the cladding is due to a stress effect or chemical composition change, an experiment is being performed in EBR-II. The experiment consists of reirradiating sections of cladding material, with the fuel removed, and capsule material, as controls, to determine if the enhanced swelling rates observed in the cladding persists after the sources of stress (fuel and fission gas pressure) have

been eliminated. If the cladding swelling rate decreases to that of the capsule material, the conclusion may be reached that swelling is a function of applied stress. If the cladding swelling rate continues to be high, the conclusion is not as simple. Results from this experiment will be forthcoming in approximately one year.

Swelling Gradients

The last set of results to be presented originates from the study to determine the magnitude of residual stresses brought about by swelling gradients. Table I shows the unexpected results that were obtained from the solution annealed-304L stainless steel capsule specimens. Capsules 1 and 2 are archive capsules and as such, the slit width openings shown represent residual stresses which remain from the tube forming operations even though the tubes are solution annealed. To put perspective on the slit width measurements, a slit width change of 2.54×10^{-3} cm is equivalent to a peak residual hoop stress of 5 ksi. The specimens from capsules 264, 263, and 267 (the six specimens that follow those from capsules 1 and 2 in Table I) received the appreciable neutron fluence shown in the Table and were subjected to a rather large temperature gradient across the wall as indicated in Table I. Shown on the Table are the predicted slit width changes that should have occurred due to the expected swelling gradient which would arise from the temperature gradient. Also given on the Table are the predicted slit width changes that would occur from the relaxation of the stresses caused by the thermal expansion variation across the tube wall. The measured slit width change should be the algebraic sum of the slit width change due to swelling and relaxation of the thermal stresses if there are no contributions from irradiation enhanced stress relaxation or stress

affected swelling. As is observed on the last column of Table I, the measured slit width changes are well below those predicted by the sum of the two components, but are in agreement with the slit width change predicted by only relaxation of the thermal stresses. The measurements on the last two specimens provide additional information for interpretation of the residual stress results. These two specimens were located an appreciable distance from the core midplane and experienced no temperature gradient and a small, but significant neutron fluence. Therefore, there was no temperature gradient to produce swelling variations or thermal stresses across the capsule wall, and yet there probably existed sufficient time at elevated temperature with a small neutron flux to relax the residual stresses due to the tube forming operations. Thus the measured result was a negligible slit width change.

Without a doubt, a very effective mechanism was available to relieve the residual stresses that would originate from the swelling gradients. If irradiation enhanced stress relaxation (plastic flow) were solely responsible for relief of the residual stresses, then a swelling gradient should exist across the capsule wall after irradiation. On the other hand, the absence of a residual stress could be evidence that a swelling gradient does not exist. Further, if a swelling gradient does not exist, even though the temperature gradient dictates the presence of a swelling gradient, then it must be concluded that swelling does depend on stress.

Experiments were conducted to determine by transmission electron microscopy (TEM) analysis whether a swelling gradient exists across the capsule walls. Figs. 8 and 9 show representative TEM photographs

of the voids from foils extracted from locations near the inner surface, midwall, and outer surface of the same specimens that were used for the residual stress measurements. Prior to the extraction of the foils, immersion density measurements were made on the specimens to determine the bulk volume change due to irradiation induced swelling. The assumption is usually made that the volume occupied by the voids is identical to the volume change determined from immersion density measurements. Thus, by determination of the void diameter and number density, a local measurement was obtained of the void volume change due to irradiation induced swelling. A large number of voids, approximately 4000, were counted and measured at each location to achieve a representative sample. It is quite obvious from examination of the photographs shown on figs. 8 and 9 that the void size and number density do vary across the capsule wall.

Figs. 10 and 11 describe the variation in the void diameter and number density and also show the volume change calculated from the void diameter and number density. The outstanding feature of the data is that the variation in the void number density is compensated by the variation in void diameter in such a manner that the volume change calculated from the void number density and void diameter remains constant. Furthermore, the volume change calculated from the void characteristics agrees closely with the volume change determined from the bulk immersion density measurements. The conclusion that must be reached, provided it is accepted that the void diameter and number density are good indicators of a swelling gradient, is that a swelling gradient does not exist.

4. Discussion

Prior to an attempt at interrelating the various observations and measurements on solution annealed-304L stainless steel, it is appropriate to summarize each significant result and at the same time provide an assessment of the alternate explanations for the result.

- a. Swelling and creep are coupled in that the creep rate increases at the same fluence that the increase in swelling rate is observed. The obvious reason for the increase in the creep rate (due to a stress assisted swelling component) is discounted in the next item (item b. below). No credible alternate explanation is available other than creep and swelling are related.
- b. For the in-reactor conditions of the creep experiment, no effect of applied stress on irradiation induced swelling existed. It must be remembered that this is a relatively low temperature experiment (415°C).
- c. From the study of the capsule-cladding swelling behavior, an enhanced swelling was observed on the cladding with the differences between clad and capsule behavior diminishing at low temperature and neutron fluence. The possibility was mentioned that the enhancement could be a result of the clad composition changing with time. An experiment is in progress to investigate this possibility. The enhanced swelling observed from the cladding material could not be correlated with applied stress because the magnitude of the applied stress as well as the stress state on the cladding is unknown. A reasonable description of the plenum pressure

above the fuel as a function of exposure is available. However, the applied stress on the cladding is a combination of that from the plenum pressure and the force exerted by the fuel swelling out against the cladding. Thus, it is impossible to quantitatively express the enhanced swelling observations on the cladding as a function of applied stress.

- d. The swelling gradient investigation on the capsule material without a doubt demonstrates the absence of large residual stresses when a significant temperature gradient is known to exist across the capsule wall. Furthermore, a swelling gradient was not discovered by TEM analysis of the void characteristics as a function of distance across the capsule wall. There appear to be two alternate explanations for the lack of a residual stress component due to a swelling gradient. The first alternative is that swelling is a function of applied stress such that a swelling gradient never exists. This alternative appears to be supported by the TEM analysis across the capsule wall that shows, on the basis of void diameter and number density, that no swelling gradient exists. The second alternative is that the residual stresses are relaxed by an enhanced relaxation (plastic flow) mechanism. This explanation would imply that a swelling gradient exists, which is apparently in contradiction with the TEM observations of the voids. However, this explanation only contradicts the assumption that the void diameter and number density are good measures of the existence of a swelling gradient. Voids do not cause swelling but rather the interstitials that have not

recombined with vacancies produce the swelling. Thus, the existence or nonexistence of an interstitial gradient marks the real measure of a swelling gradient. We do not have experimental information on the interstitial gradients from TEM analysis.

To quantitatively relate the various observations from the above discussion, certain assumptions must be made since alternate explanations are available for some of the observations. The first assumption is that the creep rate and swelling rate are interrelated. This relationship between the two phenomena will be described by the coefficient, D . The second assumption is that swelling is a function of the hydrostatic component of the applied stress through the coefficient, P . A third assumption requires that the P coefficient be at least a function of temperature and possibly of neutron fluence to account for the absence of an effect of stress on swelling at low temperatures (creep experiments) and a large effect of stress on swelling at high temperatures (capsule-clad comparison and the residual stress measurements on the capsule specimens). Beginning with the following two equations, an empirical expression will be derived and fit to the data of the creep experiment:

$$\frac{\dot{\epsilon}}{\epsilon} = (B\phi + D \dot{\Sigma}_0) \bar{\sigma} \quad (2)$$

$$\dot{\Sigma} = \dot{\Sigma}_0 (1 + P\sigma_H) \quad (3)$$

where:

$\frac{\dot{\epsilon}}{\epsilon}$ = effective strain rate, hr^{-1}

ϕ = neutron flux ($E > 0.1 \text{ MeV}$)

$\dot{S}_0$ = swelling rate with no applied stress, hr^{-1}

$\bar{\sigma}$ = effective stress, psi

σ = hoop stress, psi

$\dot{S}$ = swelling rate, including stress effect, hr^{-1}

σ_H = hydrostatic stress, psi

P = coefficient for effect of stress on swelling, psi^{-1}

D = coefficient for effect of swelling on creep, psi^{-1}

B = coefficient to describe creep in the absence of swelling, $(\text{n/cm}^2 \text{ sec})^{-1}$

The following two equations, (4) and (5) relating effective stress and strain to the principal stresses and strains and a third expression (6) relating the hydrostatic stress to the principal stresses are combined with equations (2) and (3) to yield an empirical expression for the total hoop strain rate, $\dot{\epsilon}_{\text{total}}$.

$$\bar{\sigma} = \frac{\sqrt{2}}{2} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{1/2} \quad (4)$$

$$\bar{\epsilon} = \frac{\sqrt{2}}{3} \left[(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2 \right]^{1/2} \quad (5)$$

$$\sigma_H = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad (6)$$

$$\dot{\epsilon}_{\text{total}} = 3/4 B \phi \sigma + \dot{S}_0/3 + (D + 2/9 P) 3/4 \dot{S}_0 \sigma \quad (7)$$

The total hoop strain rate is comprised of contributions from both swelling and creep. It was experimentally determined that at the temperature and neutron fluence attained by the creep experiment there was no effect of stress on swelling and, thus, $P = 0$. Since each of the strain-fluence curves, shown on fig. 3, exhibits two linear portions, one equation

exists for each strain rate and the two equations can be solved for B and D at each stress level. The coefficients B and D were calculated to be $B = (2.8 \pm 4.3) \times 10^{-30} \text{ cm}^2/\text{n} \cdot \text{psi}$ and $D = (2.26 \pm 0.9) \times 10^{-5} \text{ psi}^{-1}$. The measure of error shown represents one standard deviation as calculated on the basis of six determinations of B and D at each of the six stress levels.

Unfortunately, nothing quantitative can be said about the coefficient P from the results presented in this paper. The enhanced swelling measurements gained from the cladding as well as the absence of a large residual stress from the capsule specimens appear to point toward a significant effect of applied stress on swelling. If this is true, then the coefficient P must increase from a negligible value at the temperature of the creep experiments (415°C) to values comparable to those of the D coefficient for temperatures in the range of 500°C.

5. Summary

It is appropriate to readdress the four questions raised early in this paper and determine the extent to which we have answered these questions from our work on solution annealed-304L stainless steel.

- a. Is irradiation induced swelling a function of applied stress?

At a temperature of 415°C, a neutron fluence of $5.1 \times 10^{22} \text{ n/cm}^2$ ($E > 0.1 \text{ MeV}$), and a peak hoop stress of 22.8 ksi irradiation induced swelling is not a function of applied stress. However, the enhanced swelling observed in cladding as well as the lack of a residual stress in the capsule material suggests an effect of stress on swelling, at least, at higher temperatures. It is realized that an alternate explanation exists for the behavior noted in the capsule-clad data sets.

- b. Are irradiation induced swelling and irradiation enhanced creep interrelated? The data generated from the creep experiments leave little doubt that creep and swelling are interrelated. Alternate explanations do not exist for the observed increase in creep rate of the stressed capsules concurrent with the increase in swelling rate of the unstressed capsules.
- c. Is irradiation enhanced creep athermal? If it is accepted that creep and swelling are interrelated, then irradiation enhanced creep is necessarily a function of temperature because swelling is known to be a strong function of temperature.
- d. What are the dependencies of swelling rates and creep rates on the state of stress? The information presented in this paper provides no additional insight into this important question. The importance of an answer to this question lies in the need of the LMFBR designer who must constantly predict deformation of components under complex stress states where the basis of his predictions rests with information generated from simple stress states. In-reactor experiments are in progress to determine the effect of stress state on irradiation induced swelling and irradiation enhanced creep.

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TABLE 1. RESIDUAL STRESS INDICATIONS FROM SLIT WIDTH CHANGES

Capsule	Temperature (°C)		ϕt (10^{22} n/cm ²) (E>0.1 MeV)	Measured	Swelling $\Delta V/V_0$ (%)				Slit width Change (10^{-3} in.)		
	Midwall	ΔT			Calculated				Swelling Gradient	Relaxation of Thermal Stresses	Measured
					O.D.	Midwall	I.D.	δ			
1	---	0	----	0	----	----	----	----	---	---	+5.3
2	---	0	----	0	----	----	----	----	---	---	+5.7
264	443	36	4.70	2.87	2.26	2.87	3.38	+1.12	+29	-4.1	-4.0
264	499	32	3.89	1.97	2.08	1.97	1.71	-0.37	-9.8	-3.7	-4.5
263*	434	36	6.40	4.96	3.67	4.96	6.01	+2.34	+64	-4.1	-4.0
263*	508	34	5.40	5.08	5.64	5.08	4.13	-1.51	-46	-3.9	-5.0
267	444	36	7.50	7.08	5.55	7.08	8.27	+2.72	+71	-4.1	-5.0
267*	501	34	6.22	6.70	7.19	6.70	6.09	-1.10	-41	-3.9	-5.0
267	474	0	----	0.11	----	----	----	----	0	0	0
200	468	0	----	0.15	----	----	----	----	0	0	0

*Samples for TEM Gradient Studies

FIGURE CAPTION LIST

- Fig. 1 Tube Slitting Procedure for Hoop-Type Residual Stress Measurements
- Fig. 2 Peak Diameter Change As a Function of Neutron Fluence for Type 304L Stainless Steel Capsules
- Fig. 3 Composite of All Diameter Changes vs Fluence Data from the Type 304L Stainless Steel Creep Experiment
- Fig. 4 Comparison of Swelling for an Unstressed Capsule, P-19, (Profilometer Traces) and Immersion Density Measurements on Sections of a Stressed (~ 8 ksi Hoop Stress) Companion Capsule, P-57
- Fig. 5 Diametral Changes for Type 304L Stainless Steel Capsule/Element 265
- Fig. 6 Type 304L Stainless Steel Capsule/Cladding Swelling at $T = 465^{\circ}\text{C}$
- Fig. 7 Type 304L Stainless Steel Capsule/Cladding Swelling at 530°C
- Fig. 8 Void Gradients Across the Wall of Capsule 263 (Fluence = $6.4 \times 10^{22} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$)
- Fig. 9 Void Gradients Across the Wall of Capsule 263 (Fluence = $5.4 \times 10^{22} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$)
- Fig. 10 Void Associated Measurements at Various Radial Positions Across the Tube Wall for Capsule 263 (Fluence = $6.4 \times 10^{22} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$)
- Fig. 11 Void Associated Measurements at Various Radial Positions Across the Tube Wall for Capsule 263 (Fluence = $5.4 \times 10^{22} \text{ n/cm}^2$, $E > 0.1 \text{ MeV}$).

①

**DIAMETER
MEASUREMENTS**

②

**INITIAL SLIT
WIDTH MEASUREMENTS**

③

**FINAL DIAMETER
AND SLIT WIDTH
MEASUREMENTS**

Fig. 1

Fig. 2

Fig. 3 $\phi t (E > 0.1 \text{ MeV}) \times 10^{-22} \text{ n/cm}^2$

Fig. 4

DISTANCE FROM BOTTOM, in.

Fig. 5

Fig. 6

Fig. 7

a) O.D. Location, $T=416^{\circ}\text{C}$

b) Midwall Location, $T=434^{\circ}\text{C}$

c) I.D. Location, $T=452^{\circ}\text{C}$

a) O.D. Location, $T=491^{\circ}\text{C}$

b) Midwall Location, $T=508^{\circ}\text{C}$

c) I.D. Location, $T=525^{\circ}\text{C}$

Fig. 10

Fig. 11