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DATA AND ANALYSES FOR INCONEL X750 SPRINGS IRRADIATED IN SURV-1, -3, -4, -5, AND -6

by

L. C. Walters and W. E. Ruther

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DATA AND ANALYSES FOR INCONEL X750 SPRINGS IRRADIATED IN SURV-1, -3, -4, -5, AND -6

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L. C. Walters and W. E. Ruther

EBR-II Project

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ABSTRACT

In 1965, eight surveillance subassemblies were placed in row 12 of EBR-II, where the irradiation temperature would be near the sodium-inlet temperature of 371°C. At the same time, two other surveillance subassemblies were placed in the primary-tank storage basket, which receives minimal neutron exposure but is immersed in primary sodium and experiences a temperature of 371°C. Each subassembly contained 18 preloaded springs made of Inconel X750. Springs from four of the in-core subassemblies and from one subassembly in the storage basket have been evaluated to determine rates of irradiation-enhanced deformation at neutron exposures of up to 4.2 dpa.

The creep coefficient derived from the stress-relaxation measurements on the springs was 1.0×10^{-12} $(\text{Pa}\cdot\text{dpa})^{-1}$ for neutron exposures of 4.2 dpa (3751 days) at an in-reactor temperature of 371°C. The relaxation behavior was adequately described by a creep equation that was linear in neutron fluence and applied stress. Springs encapsulated in helium showed in-reactor relaxation rates identical to those of springs exposed to the flowing primary sodium. The creep coefficient derived from this work in Inconel X750 springs was almost the same as the creep coefficients determined for various austenitic stainless steel alloys.

I. INTRODUCTION

A long-term program is monitoring the irradiation behavior of the materials in service (primarily those in long-term service) in the primary-system sodium and the neutron shield of the EBR-II sodium-cooled fast breeder reactor. In 1965, eight surveillance subassemblies (referred to as SURV subassemblies) were placed in blanket row 12 of EBR-II, where the irradiation temperature would be near the sodium-inlet temperature of 371°C. At the same time, two other surveillance subassemblies were placed in the primary-tank storage basket, which receives minimal neutron exposure but is immersed in the primary sodium and experiences a temperature of 371°C. The two subassemblies in the storage basket allow separation of thermal effects from irradiation-induced effects. All 10 subassemblies contained various types of specimens composed of 15 alloys used in the primary system of EBR-II. In addition, the subassemblies contained neutron-shield graphite canned in Type 304 stainless steel. The results of the routine examination of four row-12 subassemblies and one basket subassembly have been reported in Refs. 1-4.

Each SURV subassembly contained 18 preloaded springs made of Inconel X750, a nickel-base alloy. These springs are used in the EBR-II depleted-uranium blanket elements to secure the stack of uranium slugs in each capsule. The original objective of including the springs in the SURV experiments was to evaluate their performance with respect to their function in the blanket elements. It was recently realized, however, that the information on stress relaxation that can be generated from these springs is important in the design of fast reactors because:

1. Nickel-base alloys will likely be the next generation of structural materials for fast reactors, but very little information exists on in-reactor deformation of these alloys.

2. The springs had up to 3751 days of exposure in liquid sodium and, thus, provide data for some of the longest exposures that have been reached for stressed specimens of any material.

3. The springs were irradiated in a relatively soft spectrum at a low damage rate. Therefore, the information represents a test of existing theories on in-reactor creep at very low dose rates and in low-energy neutron spectra.

4. Duplicate samples were exposed in-reactor both directly to the flowing primary sodium and in capsules filled with a helium atmosphere. Thus, the effect, if any, of the sodium environment on in-reactor deformation can be evaluated.

This report is a complete presentation of the data, analyses, and results gained to date from the Inconel X750 springs in the SURV subassemblies. Sufficient detail is presented so that the report will be valuable in future analyses of the springs still residing in EBR-II.

II. EXPERIMENTAL METHOD

To date, six SURV subassemblies have been removed from the reactor. Table I lists the dates when the subassemblies were removed from the reactor and the number of days that the subassemblies were in-reactor. All the SURV subassemblies were put into the reactor on March 1, 1965.

TABLE I. Summary of SURV Exposures

SURV No.	Date Removed	Days in Reactor
1	12/31/66	671
2[a]	6/28/69	1581
3	2/24/71	2186
4	5/14/73	2995
5	6/9/75	3751
6 (Storage basket)	5/14/73	2995

[a]The springs from the SURV-2 experiment were not measured.

Each SURV subassembly contains 18 preloaded Inconel X750 springs. Three nominal preloads, 10.7, 23.6, and 36.5 N, are used, with six specimens at each. Three specimens at each value of preload are exposed to the reactor sodium in the subassembly, and the other three specimens at each value of preload are encapsulated in helium-filled tubes. For each spring exposed to sodium at a given axial location in the subassembly, a spring encapsulated in helium at the same load is positioned at the same axial location. A typical specimen code number is 3Y19. The first number identifies the nominal preload: 1 means 10.7, 2 means 23.6, and 3 means 36.5 N. The letter Y identifies the specimen as a spring. A single-digit postscript number (1, 2, 3, etc.) means that the specimen was exposed to the sodium coolant, and a two-digit postscript number (17, 18, 19, etc.) means that the specimen was encapsulated in a helium-filled tube. Appendix A gives, for each in-reactor SURV subassembly, the axial height of each spring in a subassembly with respect to the core midplane, the radial location of each spring in the subassembly, and the neutron fluence and dpa as a function of axial position.

One additional set of 18 springs has been stored in air at room temperature as a control set, and this set is remeasured each time a set of springs from a SURV subassembly is removed from the reactor, or basket, and measured.

A commercial vendor fabricated the helical compression springs from 1.19-mm wire of the composition given in Table II. The springs had a free length of 51 mm, an ID of 8.7 mm, an OD of 11.1 mm, and 16 total coils. After fabrication, the springs were heat-treated at 732 ± 14°C for 16 h, and then were air-cooled. They were then compressed and held for 1 h at 425°C. The test specimens were assembled on a 76-mm-long bolt, as shown in Fig. 1, with lengths of sleeves to provide the specimens with the three different nominal preloads.

TABLE II. Chemical Composition (%) of Inconel X750 Springs

Nickel	73.32	Manganese	0.58
Chromium	15.56	Silicon	0.36
Iron	6.42	Cobalt	0.07
Titanium	2.17	Copper	0.05
Niobium	0.87	Carbon	0.03
Aluminum	0.61	Sulfur	0.007

The load on a spring specimen was determined before and after irradiation by use of the apparatus shown in Fig. 2, designed specifically for this task. As shown in Fig. 2, the specimen was inserted into the apparatus with one end held against a force-gauge actuator. The sleeve was gripped by the split-ring clamp, and the two dial gauges were adjusted to zero. The spring was compressed by rotating the screw to advance the sleeve. The force applied to the spring was read directly on the force gauge. The distance the spring was compressed and the distance the force-gauge actuator moved were read on dial gauge A. Since information only on spring deflection with load was required, it was necessary to compensate for movement of the force-gauge actuator. This movement was to be read on dial gauge B. (Dial gauge B was removed from the apparatus for all the in-cell measurements, as it was assumed that the correction required to compensate for movement of the force-gauge actuator was negligible.) The method used for compensation is discussed in Sec. IV dealing with the data and results.

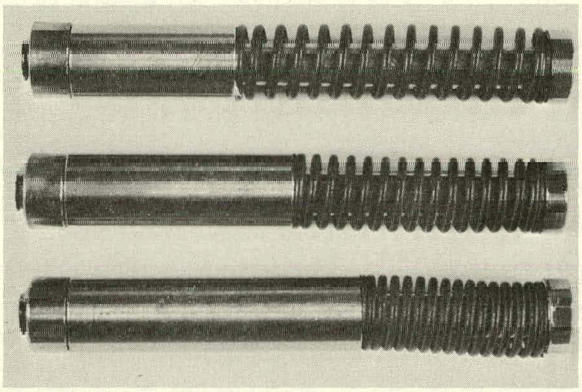


Fig. 1. Photograph of Springs Loaded to Stress Levels of 10.7, 23.6, and 36.5 N with Sleeves 23.0, 31.7, and 40.5 mm Long, Respectively. Specimen length was 76 mm, spring coil diameter was 11.1 mm, and spring-wire diameter was 1.19 mm.

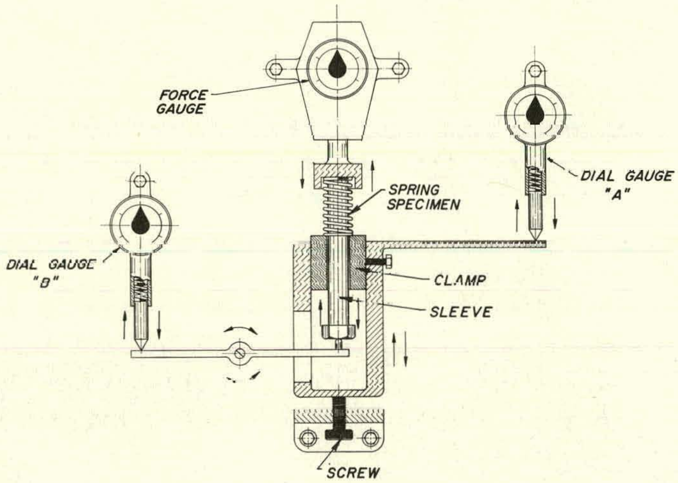
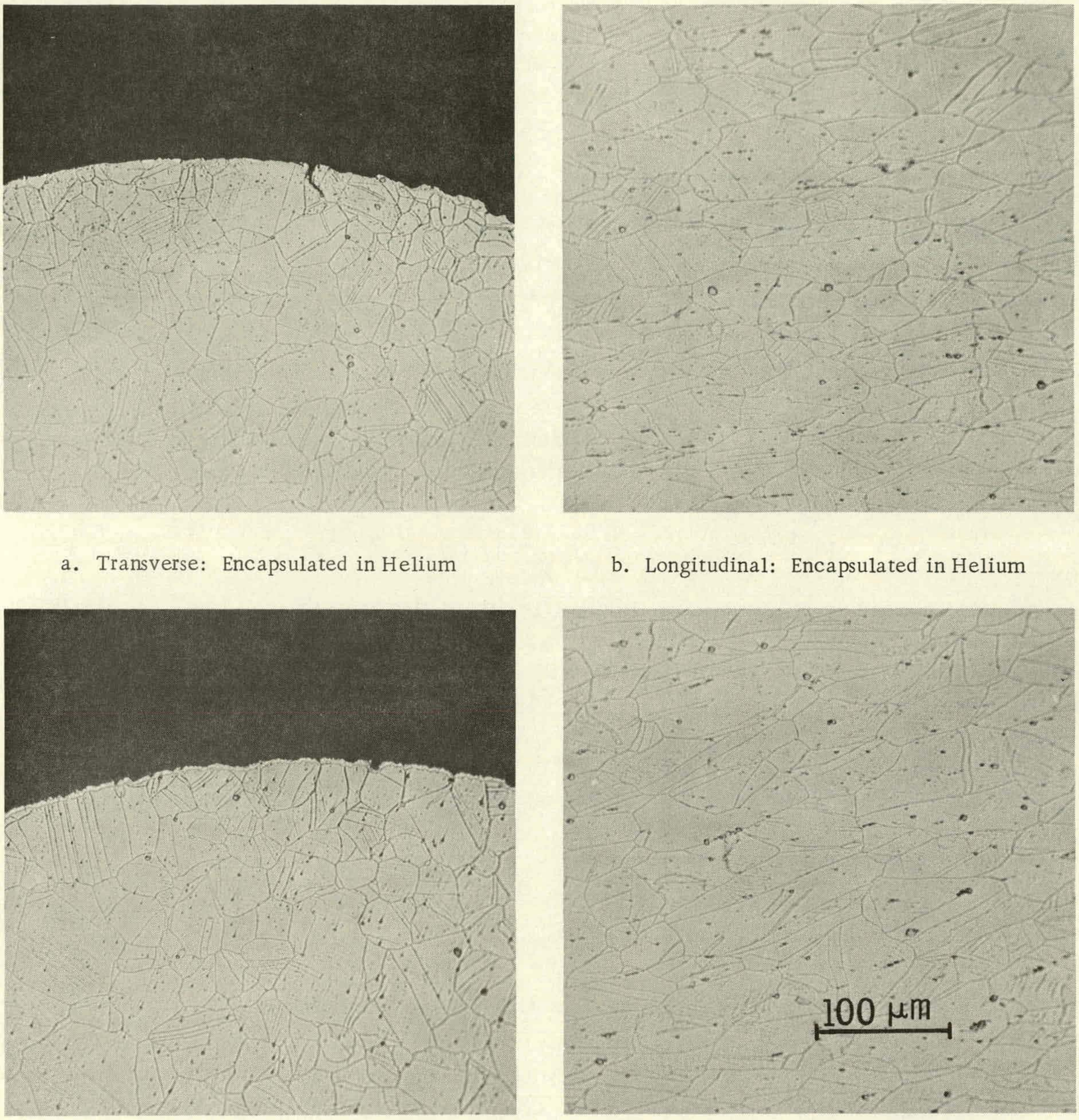


Fig. 2. Drawing of Apparatus for Measuring Spring Deflection with Load

Figure 3 shows photomicrographs from typical samples 3Y7 and 3Y17, which were irradiated in the SURV-5 experiment and received a neutron dose of 3.1 dpa. Both springs experienced high nominal initial stresses (572 MPa maximum shear stress); 3Y7 was exposed to reactor sodium, 3Y17 was encapsulated in helium. Essentially no difference was observed between the microstructures of the springs exposed to sodium and those encapsulated in helium. Both structures exhibited elongated grains (ASTM size 7) in the direction of wire drawing. Because of incomplete washing, a small amount of residual sodium oxide was on the springs exposed to sodium. A few shallow cracks were on the transverse sections of both specimens. These cracks may have existed in the as-fabricated condition. Unfortunately, no unirradiated material was available for metallography and subsequent comparison, except that in the room-temperature-control specimens. It did not appear prudent to sacrifice one of those specimens at this time, since additional SURV subassemblies remain in-reactor and will be examined in future years.



a. Transverse: Encapsulated in Helium

b. Longitudinal: Encapsulated in Helium

c. Transverse: Exposed to Sodium

d. Longitudinal: Exposed to Sodium

Fig. 3. Microstructures of Springs Exposed to Flowing Primary Sodium or Encapsulated in Helium for 3751 days While Receiving Neutron Dose of 3.1 dpa at 371°C. Magnification is same for all four views.

III. METHOD OF ANALYSIS

The method for extracting information on irradiation-induced creep from the load-versus-deflection data obtained from the springs is based upon the following analysis. Let the total shear strain on a spring be represented by the sum of three contributions:

$$\gamma_T = \gamma_e + \gamma_p + \gamma_0, \quad (1)$$

where

γ_T = total shear strain,

γ_e = elastic shear strain,

γ_p = plastic shear strain due to irradiation-induced effects,

and

γ_0 = shear strain that occurs independent of irradiation.

Since the total shear strain in the spring is held constant during the stress-relaxation test in-reactor, the total shear-strain rate is zero. Thus,

$$0 = \dot{\gamma}_e + \dot{\gamma}_p + \dot{\gamma}_0. \quad (2)$$

We will assume in this derivation and demonstrate later in analysis of the data that γ_0, the component of shear strain that is independent of irradiation, comes to a constant value quickly and, thus, is taken to be time-independent. Since $\dot{\gamma}_0$ therefore is zero, it follows that

$$\dot{\gamma}_e = -\dot{\gamma}_p, \quad (3)$$

and from Hook's Law,

$$\dot{\gamma}_e = \frac{\dot{\tau}}{\mu}, \quad (4)$$

where τ is the shear stress and μ is the shear modulus.

At this point, it is necessary to relate the irradiation-induced shear-strain rate, $\dot{\gamma}_p$, to the shear stress. This is accomplished by assuming that the effective strain rate is proportional to the effective stress and neutron flux through the following relationship, which describes data for in-reactor creep:[5]

$$\dot{\bar{\varepsilon}} - B\varphi\bar{\sigma}, \quad (5)$$

where $\dot{\bar{\varepsilon}}$ and $\bar{\sigma}$ are the effective strain rate and stress, respectively, φ is the neutron flux ($E > 0.1$ MeV), and B is the creep coefficient.

The irradiation-induced shear-strain rate and shear stress are related to the effective strain rate and effective stress by the Soderberg Formulation as[6]

$$\frac{\dot{\bar{\epsilon}}}{\bar{\sigma}} = \frac{\dot{\gamma}_p}{3\tau}. \qquad (6)$$

Thus the irradiation-induced shear-strain rate is related to the shear stress as

$$\dot{\gamma}_p = 3B\varphi\tau. \qquad (7)$$

By combining Eqs. 3, 4, and 7, we obtain

$$3B\varphi\tau = \frac{-\dot{\tau}}{\mu}. \qquad (8)$$

Involved in the combination of Eqs. 3, 4, and 7 is the assumption that the instantaneous-plastic-strain rate during a relaxation test is described by Eq. 7, which evolved from observations of in-reactor creep under constant stress. Integration of Eq. 8 gives

$$\tau = \tau_A \exp(-3B\mu\varphi t), \qquad (9)$$

where τ_A is the shear stress on the spring after any immediate relaxation has occurred from time-independent effects. The time-independent relaxation is a result of γ_0, the strain component that is independent of irradiation.

The ratio τ/τ_A is the experimentally determined parameter. When this parameter is plotted as a function of fluence according to the following relation, the slope of the curve is the creep coefficient:

$$\ell n \frac{\tau}{\tau_A} = -3B\mu\varphi t. \qquad (10)$$

It has become more acceptable to determine in-reactor deformation as a function of atomic displacements rather than neutron fluence above a particular energy level. Since we have calculations of both atomic displacement and neutron fluence ($E > 0.1$ MeV) at our disposal, Eq. 10 will be cast in terms of atomic displacements, K, as

$$\ell n \frac{\tau}{\tau_A} = -3B'\mu(K), \qquad (11)$$

where

$$B' = B\frac{\varphi t}{K}. \qquad (12)$$

IV. DATA AND RESULTS

The objective in the reduction of data was to apply Eq. 11 to the observed in-reactor load relaxation of the springs. In addition to the calculation of the creep coefficient, B', the successful application of Eq. 11 to the data would demonstrate that the in-reactor stress relaxation of the springs obeyed the creep relationship of Eq. 5, which predicts a linear dependence of stress-relaxation rate on stress and neutron fluence.

The first step in the reduction of the data was to determine the load on a spring both before and after irradiation. Figure 4 shows the load-versus-deflection (or force-versus-deflection) data obtained from a specimen in the fixture described in Sec. II. The data as shown in Fig. 4 were linear least-squares fit, and both the intercept at zero deflection and the slope of the line were calculated.

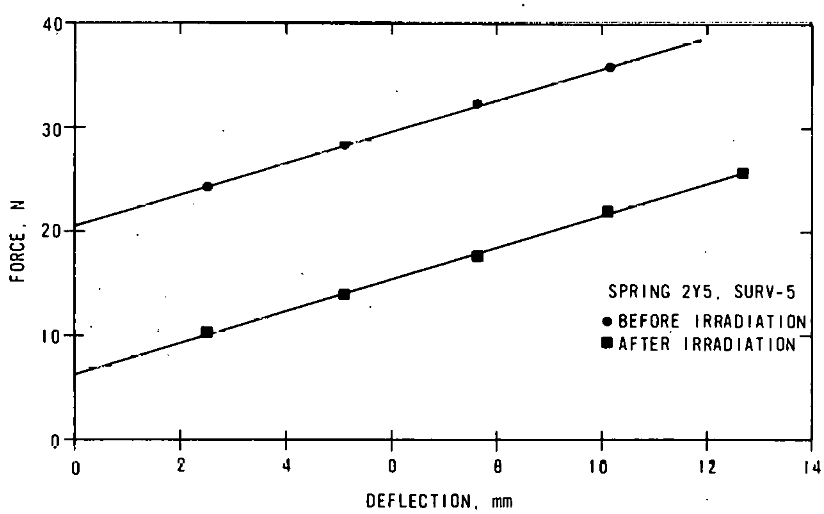


Fig. 4. Typical Force–vs–Deflection Characteristics for a Spring before and after Irradiation. ANL Neg. No. 103–U5983.

If the readings from dial gauge B (see Fig. 2) were properly applied, the intercept at zero deflection would be the actual load on the spring. As stated in Sec. II, dial gauge B was removed from the apparatus for all in-cell measurements, as it was assumed that the correction required to compensate for movement of the force-gauge actuator was negligible. Reexamination of the measurement system showed that the corrections were indeed small, but significant. Thus a description follows on how the loads determined from the intercept at zero deflection were corrected for movement of the force-gauge actuator.

To determine the load-versus-deflection characteristics of the force-gauge actuator, a solid rod was positioned in the apparatus in place of a spring specimen. The deflection measured on dial gauge A (Fig. 2) with the solid rod would then be the same as the deflection recorded on dial gauge B if dial gauge B were on the apparatus when a spring specimen was placed in it. Figure 5 shows the load-versus-deflection characteristics of the force-gauge actuator.

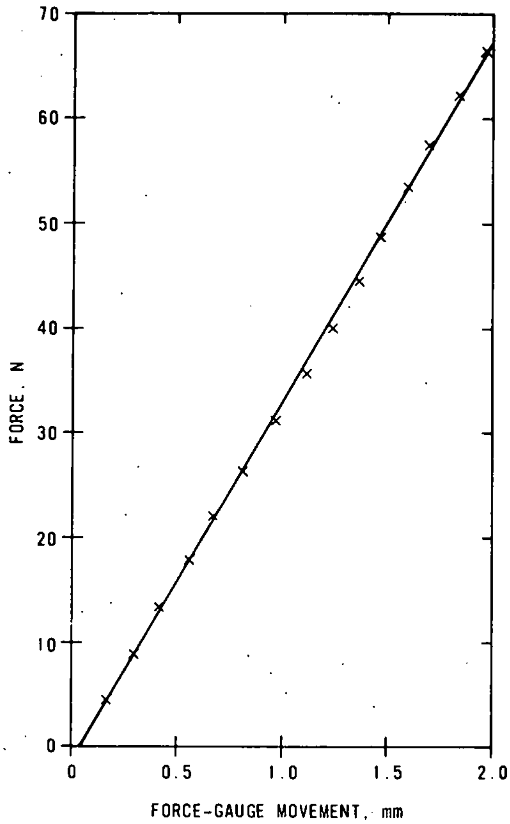


Fig. 5. Movement of Force-gauge Actuator When Force Was Applied by Solid Rod. ANL Neg. No. 103-U5984.

Let the load-versus-deflection characteristics of Fig. 4 (for which dial gauge B was absent) be expressed as

$$L = mX_1 + b \quad \text{and} \quad X_1 = \frac{L - b}{m}, \tag{13}$$

where L is the load, X_1 is the deflection measured on dial gauge A, and m and b are the slope and intercept, respectively.

Let the load-versus-deflection characteristics of Fig. 5 be expressed as

$$L = m_g X_2 + b_g \quad X_2 = \frac{L - b_g}{m_g}, \tag{14}$$

where L is the load, X_2 is the deflection measured on dial gauge B, and m_g and b_g are the slope and intercept, respectively. The actual deflection of the spring, X_3, is

$$X_3 = X_1 - X_2. \tag{15}$$

By substituting Eqs. 13 and 14 into Eq. 15, we have the corrected load-versus-deflection equation for the springs as

$$L = \left[\frac{mm_g}{m_g - m}\right] X_3 + \frac{m_g b - mb_g}{m_g - m}, \tag{16}$$

where the corrected load at zero deflection is the second term on the right side of Eq. 16.

A linear least-squares fit to the data shown in Fig. 5 yielded

$$\left.\begin{aligned} m_g &= 34.3 \text{ N/mm}, \\ &\text{and} \\ b_g &= -1.50 \text{ N}. \end{aligned}\right\} \tag{17}$$

Depending on the stress range, the value for the slope, m, was reasonably constant and was taken as

$$\left.\begin{aligned} m &= 1.5 \text{ N/mm for low-stress range,} \\ m &= 1.6 \text{ N/mm for medium-stress range,} \\ &\text{and} \\ m &= 1.7 \text{ N/mm for high-stress range,} \end{aligned}\right\} \quad (18)$$

where low-stress, medium-stress, and high-stress ranges refer to the springs with initial nominal loads of 10.7, 23.6, and 36.5 N, respectively.

The values taken for the slope m were arithmetic-average values calculated from the data of the room-temperature controls, which were considered to have provided the most reliable set of data. These values for m were compared with the average values determined from the SURV-5 results and agreed within plus or minus one standard deviation.

Thus, to correct a value of b, the intercept at zero deflection, for the movement of the force-gauge actuator, we must substitute the appropriate value of the slope from Eq. 18, the value of the intercept b to be corrected, and the values of m_g and b_g from Eq. 17 into the second term of Eq. 16. Thus, we get

$$b_c = \frac{m_g b - m b_g}{m_g - m}, \quad (19)$$

where b_c is the corrected value of the load at zero deflection.

It was mentioned earlier that all the preirradiation measurements were made with the use of two dial gauges. For completeness, a brief description will be given of the means by which dial gauge B was used in practice to compensate for the movement of the force-gauge actuator. The spring was advanced to a given value of X_1 as read on dial gauge A. The movement of the force-gauge actuator was observed as X_2 on dial gauge B. Thus, the spring was advanced an additional increment, X_2, to compensate for the movement of the actuator, and at the same time the observed load increased. The spring deflection was recorded as the initial X_1 (without the addition of the increment X_2) for the increased load. This is an approximate method of compensation, but it is accurate as long as the movement of the force-gauge actuator is small compared to the spring deflection. That this is true will be demonstrated by the following example calculation.

Take a typical high-stressed spring for which the slope, m, is 1.75 N/mm and the intercept load, b, is 32.5 N. At a deflection, X_1, of 5.1 mm, the load on the spring was 41.4 N. By use of Eq. 14 and with a load of 41.4 N, the movement of the force-gauge actuator, X_2, as measured on dial gauge B is calculated as 1.25 mm. If the spring is advanced an additional increment equal to X_2, then from Eq. 13, the new load is 43.6 N. If the exact relationship, Eq. 16, is used to calculate the load with the actual spring deflection, X_3, taken as 5.1 mm, the load is 43.7 N. The approximate method of compensation for the movement of the force-gauge actuator thus agrees closely with an exact calculation of the effect.

Appendix B shows the results of the linear least-squares fit to the data obtained from the room-temperature-control springs as well as from the springs removed from the SURV-6 subassembly, which had resided in the EBR-II reactor storage basket. Table III is a condensation of the results from measurements of the control springs and the springs from SURV-6. (Recall that each time a set of irradiated SURV springs was measured, the set of room-temperature-control springs was also measured.) Shown in the table are the stress-reduction ratios (R) at the time of measurement. Also shown are the average ratios and the standard deviation for each stress level. The results for both the low-stress room-temperature controls at the time of the SURV-4 measurements and the low-stress SURV-6 springs show significantly

TABLE III. Stress-reduction Ratios (R)[a] for Room-temperature-control Springs Measured at Time of SURV Indicated and for SURV-6 Springs Stored in Reactor Storage Basket at 371°C

Sample Identification	Room-temperature-control Springs				SURV-6 Springs
	SURV-1	SURV-3	SURV-4	SURV-5	
			10.7-N Stress Level		
1Y1	0.94	0.93	0.73	0.95	0.59
1Y2	0.89	0.98	0.76	0.98	0.65
1Y3	0.88	0.89	0.72	0.76	0.66
1Y11	0.97	b	0.79	b	0.64
1Y12	0.96	0.93	0.64	0.86	0.69
1Y13	0.93	0.99	0.81	0.99	0.69
Avg ± one std dev	0.93 ± 0.04	0.94 ± 0.04	0.74 ± 0.06	0.91 ± 0.10	0.66 ± 0.04
			23.6-N Stress Level		
2Y4	0.98	0.94	0.92	0.96	0.84
2Y5	0.97	0.96	0.81	0.97	0.95
2Y6	0.93	0.95	0.92	0.96	0.90
2Y14	0.88	0.94	0.74	0.91	0.81
2Y15	0.89	0.94	0.73	0.90	0.88
2Y16	0.83	0.84	0.74	0.80	0.92
Avg ± one std dev	0.91 ± 0.06	0.93 ± 0.05	0.81 ± 0.09	0.92 ± 0.06	0.88 ± 0.05
			36.5-N Stress Level		
3Y7	0.94	0.81	0.91	0.96	0.78
3Y8	b	0.99	0.95	b	0.82
3Y9	0.94	0.90	0.87	0.94	0.89
3Y17	0.90	0.84	0.82	0.94	0.95
3Y18	0.82	0.81	0.79	0.93	0.89
3Y19	0.93	0.90	0.91	0.95	0.88
Avg ± one std dev	0.91 ± 0.05	0.87 ± 0.07	0.87 ± 0.06	0.94 ± 0.01	0.87 ± 0.06

[a]R is the ratio of the initial load at zero deflection divided into the load at zero deflection (corrected) at the time of the indicated SURV measurements.
[b]R was calculated to be greater than unity.

more stress relaxation than the remainder of the results in Table III. The cause for the behavior was traced to a faulty dial gauge on the force-gauge actuator that did not respond at low loads. The springs were not available for remeasurement at the time of discovery of the problem. The measuring apparatus was restored and recalibrated before the SURV-5 measurements.

From the data shown in Table III, a factor was calculated to account for the stress relaxation that occurred independent of time and irradiation. In the derivation of Eq. 11, the shear stress, τ_A, is the shear stress on the spring after any immediate relaxation has occurred. If all the control values of load-relaxation ratios are averaged (excluding those from SURV-6 and those measured at the time of SURV-4), the average load-relaxation ratio is 0.918, with a standard deviation of 0.056. Thus, all the initial loads for the springs that were irradiated must be reduced by a factor of 0.918 before calculating the shear-stress ratio, τ/τ_A, with Eq. 11.

A second essential observation must be made from the data shown in Table III. The load-relaxation ratio of 0.918 is the load relaxation that occurred quickly at room temperature. Presumably, additional load relaxation that occurs in-reactor is due to irradiation-enhanced deformation. However, the possibility could exist, if not proven otherwise, that additional load relaxation that occurs in-reactor is due only to the in-reactor springs experiencing a higher temperature than the room-temperature controls.

Figure 6 plots, as a function of the initial nominal loads, the load-relaxation ratios from the room-temperature controls at the time of SURV-4 and from the SURV-6 springs that were kept in the reactor storage basket at 371°C. Also shown on each datum point is an error bar representing plus

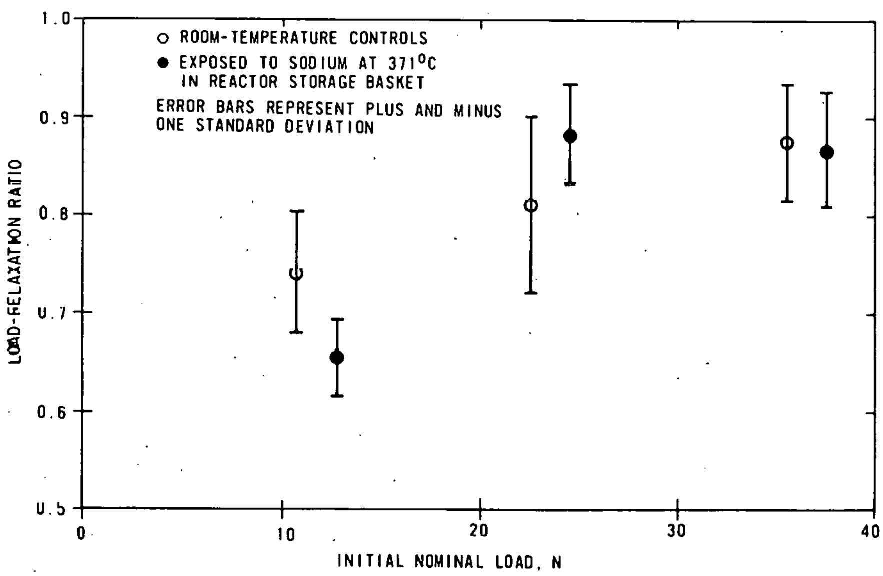


Fig. 6. Load Relaxation for Room-temperature-control Springs at Time of SURV-4, Compared to That for SURV-6 Springs That Resided in Reactor Storage Basket at 371°C. ANL Neg. No. 103-U5985.

and minus one standard deviation. Although the results are subject to some question because of the malfunctioning force actuator, we can still conclude from the results shown in Fig. 6 that no significant temperature effect exists for the load relaxation observed in the controls. Therefore, any in-reactor load relaxation significantly less than the calculated ratio of 0.918 must be attributed to irradiation-enhanced effects.

Before describing the results obtained from the irradiated springs, we reemphasize, for the sake of clarity, the adjustments made in making the calculations:

1. Every in-cell determination of the load on a spring at zero deflection was adjusted by Eq. 19 to account for the movement of the force-gauge actuator.

2. The initial loads for the irradiated springs do not require the above adjustment, since a compensating dial gauge was used for determination of these loads. However, the initial loads on the irradiated springs were reduced by a factor of 0.918 to account for the time- and irradiation-independent load relaxation.

Appendix C shows the results of the analyses of the information obtained from the springs that were irradiated. In Eq. 11, the stress-reduction ratio, τ/τ_A, is the ratio of the load after irradiation at zero deflection (corrected for the movement of the force-gauge actuator) divided by the initial load at zero deflection (corrected for the relaxation of the unirradiated control). Equation 11 predicts that a semilogarithmic plot of τ/τ_A versus the accumulated neutron-irradiation exposure in displacements per atom should be a straight line from which the creep coefficients B or B' are directly calculable. Table IV shows the stress-reduction ratio as well as the corresponding neutron exposure in displacements per atom for each spring. From the results shown in the table, we see that no significant difference exists between the stress-reduction ratios of the springs exposed to reactor sodium and those encapsulated in a helium atmosphere. Thus, no distinction will be made in subsequent analyses.

The neutron exposures shown in Table IV are based upon only the axial position of the springs. However, if we examine the data in the table closely, we note that a pattern which repeats itself from one SURV experiment to the next indicates that the stress-reduction ratio is sensitive to location within the subassembly. For example, springs 3Y8 and 3Y18 always exhibit stress-reduction ratios that are somewhat lower than a nominal value for each SURV experiment. This pattern could not be explained by variations in radial positions within the core. Thus, it is probably due to variations in shielding within the subassembly, as some of the tubes contained tantalum and other effective neutron-absorbing materials. The inability to quantitatively account for the effect does not appreciably alter the results or conclusions drawn from the data.

TABLE IV. Stress-reduction Ratio (τ/τ_A) and Accumulated Neutron Exposure in Displacements per Atom (dpa) for Inconel X750 Springs Irradiated in Row 12 of EBR-II

Sample Identification[a]	SURV-1		SURV-3		SURV-4		SURV-5	
	τ/τ_A	dpa	τ/τ_A	dpa	τ/τ_A	dpa	τ/τ_A	dpa
1Y1	0.77	0.16	0.87	0.68	0.90	1.26	0.35	2.00
1Y2	0.91	0.27	0.80	1.24	0.76	2.29	0.28	3.55
1Y3	0.91	0.32	0.79	1.48	0.69	2.75	0.30	4.20
1Y11-He	0.96	0.16	0.78	0.68	0.79	1.26	0.41	2.00
1Y12-He	0.80	0.27	0.82	1.24	0.71	2.29	0.33	3.55
1Y13-He	0.91	0.32	0.87	1.48	0.84	2.75	0.35	4.20
2Y4	1.00	0.19	0.73	0.83	0.63	1.53	0.43	2.40
2Y5	0.92	0.31	0.73	1.42	0.48	2.65	0.38	4.05
2Y6	0.92	0.25	0.78	1.11	0.71	2.05	0.53	3.15
2Y14-He	0.91	0.19	0.71	0.83	0.67	1.53	0.50	2.40
2Y15-He	0.95	0.31	0.71	1.42	0.47	2.65	0.38	4.05
2Y16-He	0.90	0.25	0.73	1.11	0.68	2.05	0.51	3.15
3Y7	0.83	0.24	0.66	1.10	0.61	2.02	0.47	3.10
3Y8	0.80	0.23	0.58	1.01	0.55	1.88	0.37	2.85
3Y9	0.91	0.19	0.66	0.84	0.63	1.57	0.59	2.45
3Y17-He	0.92	0.24	0.68	1.10	0.60	2.02	0.44	3.10
3Y18-He	0.75	0.23	0.65	1.01	0.53	1.88	0.40	2.85
3Y19-He	0.90	0.19	0.79	0.84	0.64	1.57	0.59	2.45

[a]He signifies that the specimen was encapsulated in a helium atmosphere. The other samples were exposed directly to the flowing primary sodium.

Figure 7 shows the stress ratios from Table IV as a function of neutron dose for the medium- and high-stressed springs. Data from the low-stressed springs were not included in Fig. 7 or in further analyses to determine creep coefficient B', because these data were considered unreliable. As mentioned previously, the results for the low-stressed springs from SURV-4 were questionable because of the use of a faulty gauge. Furthermore, during measurement of the SURV-5 springs, it was observed that the measurements on low-stress springs could show large variations due to a small misalignment of the springs or frictional effects if the spring interfered with the collar of the force-gauge actuator.

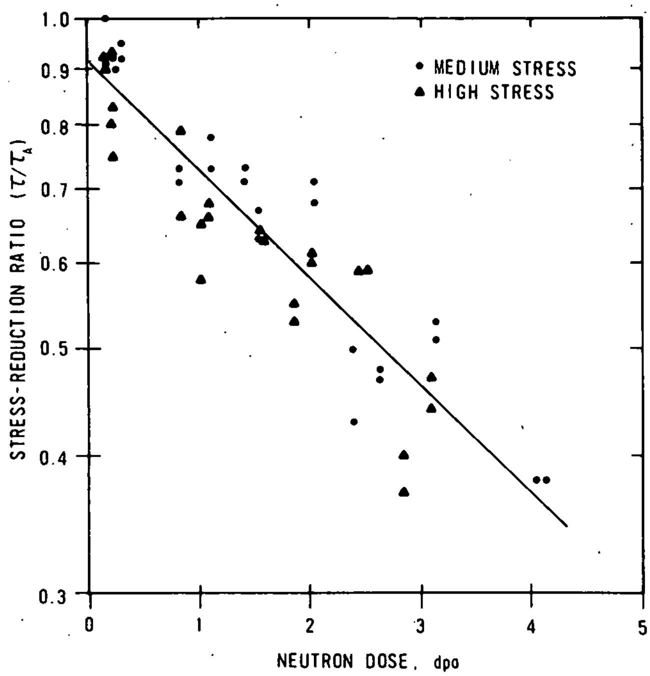


Fig. 7

Stress–reduction Ratio as a Function of Neutron Dose for Medium– and High–stressed Inconel X750 Springs Irradiated in SURV–1, –3, –4, and –5. ANL Neg. No. 103–U5986.

A least-squares line was fit to the data shown on Fig. 7. The slope of the line was -0.23 dpa^{-1}, with a standard deviation of 0.014 dpa^{-1} for the slope. From Eq. 11, the slope of the line is related to the creep coefficient by

$$B' = \frac{\text{slope}}{3\mu},$$

where $\mu = 7.58 \times 10^{10}$ Pa.[7] Thus, $B' = 1.0 \times 10^{-12}\ (\text{Pa}\cdot\text{dpa})^{-1}$.

V. DISCUSSION

The results on the springs from the SURV subassemblies were consistent when it is appreciated that the original intent of the experiment was not to generate precise information on stress relaxation. We have clearly shown that the values for stress relaxation presented in Table IV and Fig. 7 are a result of an irradiation-enhanced effect, since the contribution to stress reduction from irradiation-independent effects was removed by use of the information generated from the SURV-6 (storage-basket subassembly) and the room-temperature-control springs.

We have also pointed out that, for exposure times of up to 3751 days at 371°C, no difference existed between the results for springs exposed to reactor sodium and those encapsulated in helium. It is satisfying to know that the presence of sodium does not affect the results for Inconel X750. This observation indicates that, at this temperature, the short-time in-reactor mechanical properties of this alloy can be extrapolated without regard to possible compositional or structural changes.

Early in the derivation of Eq. 11, the springs were assumed to relax according to an empirical creep relationship that predicts a linear dependence of the strain rate on stress and neutron dose. A more basic assumption was involved then: that a creep relationship could even be used to predict deformation when the stress was continuously changing. That this assumption and the linear dependence of stress on neutron dose are true is verified by the linear dependence of stress-reduction ratio on dose, as exhibited in Fig. 7, and the fact that the data from the two different stress ranges are indistinguishable.

We have recognized for some time, as has Harries[8] recently in a review article, that irrespective of the particular austenitic stainless steel, the creep coefficient, B, is reasonably constant in the absence of appreciable irradiation-induced swelling. A recent theory predicts that perhaps the irradiation-creep behavior is not sensitive to the many material variables and irradiation parameters before the onset of significant irradiation-induced swelling.[9] At the low neutron fluences experienced by the Inconel X750 springs, the irradiation-induced swelling is expected to be negligible.[10]

Table V compares the irradiation-induced-creep coefficients from various investigations on austenitic stainless steels with the creep coefficient derived from the present work on a nickel-base alloy (Inconel X750). The creep coefficients listed by Harries were converted to an effective stress-strain basis by use of Eq. 6, which requires that the creep coefficient derived from the spring tests be divided by a factor of three.

The data for the stainless steels shown in Table V were obtained under an extremely wide range of experimental conditions. For example, the deformation information was generated with either pressurized tubes or springs, some of the material was cold-worked, and the irradiations took place in different reactors at different temperatures. Nevertheless, the creep coefficient is reasonably constant. The present work represents an extreme variation in that the creep coefficient was generated from stress-relaxation information on a nickel-base alloy that was irradiated at a very low dose rate for a long duration.

TABLE V. Creep Coefficients for Several Austenitic Stainless Steels, Compared with That for Nickel-base Alloy Inconel X750

Material	Creep Coefficient, 10^{-12} (Pa·dpa)$^{-1}$	Reference
Solution-treated Type 304L	0.8	Flinn, McVay, and Walters[11]
Solution-treated Type M316	0.93-1.3[a]	Harries
20%-cold-worked Type M316	0.73-1.5[a]	Harries
Solution-treated FV 548	1.5[a]	Harries
20%-cold-worked FV 548	1.4[a]	Harries
Solution-treated En 58B	1.5[a]	Harries
20%-cold-worked En 58B	1.4[a]	Harries
Inconel X750	1.0	Present paper

[a]These creep coefficients originated from the work of D. Mosedale and G. W. Lewthwaite and appeared in the review paper by Harries.[8]

The simplified creep relationship derived from the SIPA (stress-induced preferred absorption mechanism) theory by Bullough and Hayns[9] shows that the in-reactor creep coefficient is inversely proportional to the bulk shear modulus through the relationship

$$\epsilon = 0.47 \frac{\sigma}{\mu e} K, \tag{21}$$

where

ϵ = creep strain,

σ = applied stress,

e = relaxation volume strain associated with an isolated interstitial,

K = neutron dose in displacements per atom,

and

μ = bulk shear modulus.

If the relaxation volume strain, e, is assumed to be near unity, then the creep coefficient in Eq. 21 is $0.47/\mu$, which is equal to about 6×10^{-12} (Pa·dpa)$^{-1}$ for the alloys listed in Table V. Even though this creep coefficient is somewhat higher than the experimental values listed in Table V, Eq. 21 does predict a reasonably constant creep coefficient, since the bulk shear moduli do not vary appreciably for the alloys in the table.

VI. CONCLUSIONS

1. The creep coefficient derived from the stress-relaxation measurements on Inconel X750 springs was 1.0×10^{-12} $(\text{Pa}\cdot\text{dpa})^{-1}$ for springs irradiated up to 4.2 dpa (3751 days) at an in-reactor temperature of 371°C.

2. The relaxation behavior was adequately described by a creep equation in which creep varies linearly with neutron fluence and applied stress.

3. At the same stress level and axial position in the reactor, relaxation rates were identical for springs exposed to flowing primary sodium and springs encapsulated in helium. This observation shows that exposure to liquid sodium at 371°C for times up to 3751 days caused no structural or compositional changes in the springs that affected the in-reactor deformation rates.

4. The creep coefficients for both the nickel-base alloy Inconel X750 and several austenitic stainless steels were relatively constant. This was observed for both the cold-worked and solution-annealed conditions for the stainless steels as well as for both springs and pressurized tubes irradiated in different fast reactors.

5. The information obtained on the Inconel X750 springs represents long irradiation times at a low neutron dose rate and in a relatively low-energy neutron spectral region of EBR-II [2.7×10^{21} n/cm^2 ($E > 0.1$ MeV)/dpa]. Therefore, these data represent a test of current theories at low dose rates and low-energy neutron spectra.

APPENDIX A

Axial Location, Radial Location, and Neutron Exposure for Springs from SURV Subassemblies 1, 3, 4, and 5

Table VI shows the axial location of the Inconel X750 springs, which is common to all SURV subassemblies. Table VII shows the neutron exposure of the center tube of the SURV subassemblies as a function of axial location. The neutron dose in dpa (displacements per atom) shown in Table IV and Fig. 7 in the text of this report was determined from the data shown in these two tables. No allowance was made for differences in radial location within each SURV subassembly.

TABLE VI. Axial Position of Inconel X750 Springs in SURV Subassemblies

Sample Identification	Distance from Core Midplane,[a] m	Sample Identification	Distance from Core Midplane,[a] m
1Y1	-0.315	2Y14	-0.271
1Y2	-0.150	2Y15	-0.073
1Y3	-0.026	2Y16	0.190
1Y11	-0.315	3Y7	-0.194
1Y12	-0.150	3Y8	0.222
1Y13	-0.026	3Y9	0.266
2Y4	-0.271	3Y17	-0.194
2Y5	-0.073	3Y18	0.222
2Y6	0.190	3Y19	0.266

[a]A negative sign before a number means that the spring is below midplane.

TABLE VII. Neutron Exposure as a Function of Axial Distance from Core Midplane for SURV Subassemblies 1, 3, 4, and 5

Distance above Core Midplane, m	SURV-1		SURV-3		SURV-4		SURV-5	
	dpa	$10^{24}\varphi t$,[a] n/m^2	dpa	$10^{25}\varphi t$, n/m^2	dpa	$10^{25}\varphi t$, n/m^2	dpa	$10^{26}\varphi t$, n/m^2
0	0.321	8.64	1.49	4.05	2.76	7.51	4.25	1.15
0.05	0.314	8.50	1.46	3.96	2.70	7.34	4.15	1.12
0.10	0.295	8.00	1.36	3.71	2.52	6.86	3.88	1.05
0.15	0.271	7.31	1.23	3.33	2.27	6.16	3.51	0.949
0.20	0.236	6.37	1.06	2.87	1.96	5.31	3.05	0.823
0.25	0.200	5.36	0.887	2.39	1.64	4.40	2.57	0.689
0.30	0.165	4.36	0.717	1.92	1.32	3.54	2.07	0.554
0.36	0.129	3.41	0.560	1.49	1.03	2.75	1.65	0.440
0.41	0.098	2.58	0.426	1.13	0.785	2.09	1.28	0.338
0.46	0.072	1.87	0.313	0.82	0.580	1.53	0.957	0.252
0.51	0.051	1.32	0.222	0.58	0.415	1.09	0.699	0.183
0.56	0.035	0.91	0.152	0.39	0.284	0.74	0.494	0.129
0.61	0.022	0.57	0.092	0.24	0.172	0.45	0.322	0.085

[a]Neutron fluence (E > 0.1 MeV).

Figure 8 shows the radial location of the springs in SURV subassemblies 1, 3, 4, and 5 with respect to the center of the reactor core. This information was not used in determining the neutron exposures shown on Table IV and Fig. 7 in the text, because no consistent dependence of relaxation rates on radial location was observed.

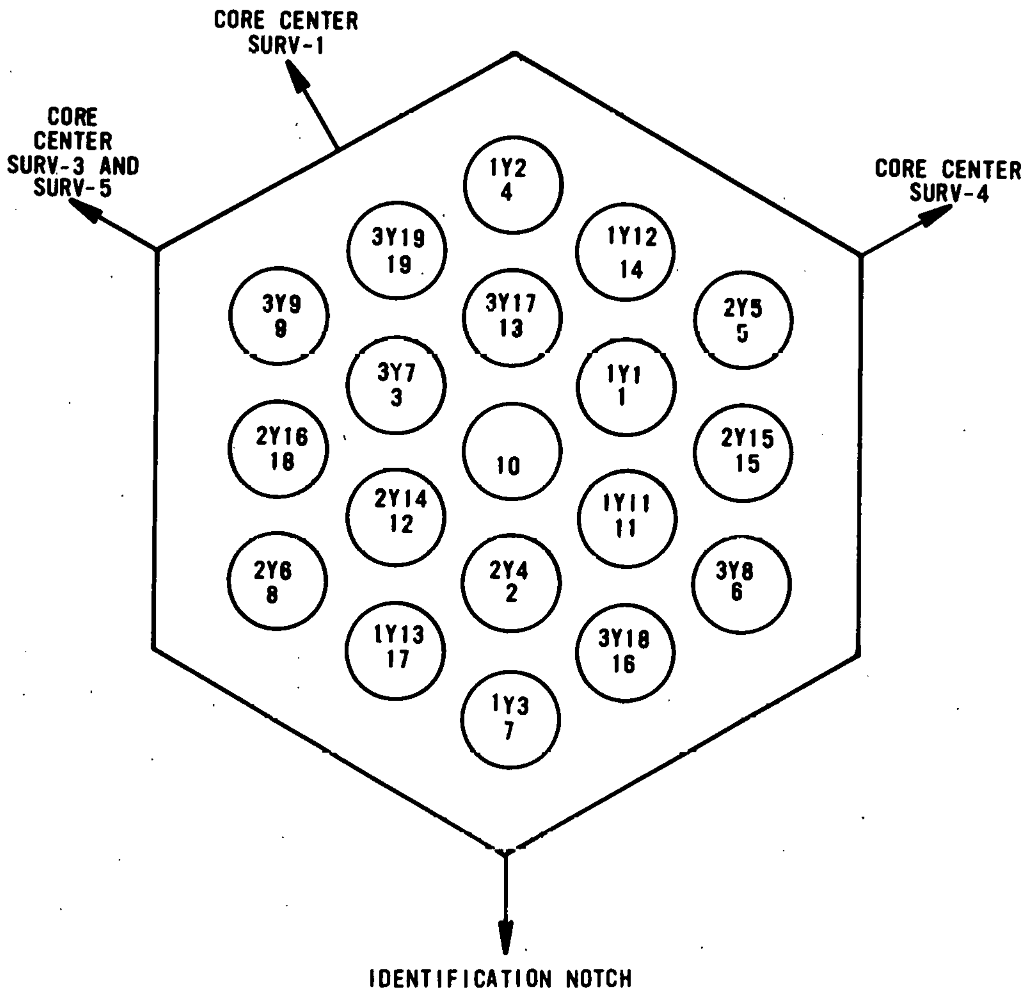


Fig. 8. Radial Location of Inconel X750 Springs in SURV Subassemblies 1, 3, 4, and 5 with Respect to Center of Reactor Core. Numbers without the letter Y are capsule numbers. ANL Neg. No. 100-U6982.

APPENDIX B

Data and Analysis for Room-temperature-control Springs and SURV-6 Springs

Tables VIII-XII list the measurements of load and deflection for the room-temperature-control set of springs. The measurements were obtained on the apparatus shown in Fig. 2. For the initial measurements (Table VIII), the apparatus had the dial gauge B (Fig. 2); thus, the measurements include the movement of the force-gauge actuator. For the data shown on Tables IX-XII, however, dial gauge B was absent from the apparatus. Each time an irradiated set of springs was measured, the control set was measured.

Tables XIII and XIV, respectively, give the original load and deflection measurements for the springs from the SURV-6 subassembly before exposure in the reactor storage basket to the sodium coolant at 371°C and after exposure in the basket. The initial measurements (Table XIII) were taken with the use of dial gauge B; the measurements shown on Table XIV, after exposure in the basket, were obtained without the use of dial gauge B.

Table XV shows the results of linear-least-squares analysis of the data for the room-temperature-control set from Tables VIII-XII. The intercept at zero deflection is b; the slope of the line is m. The intercept from the initial measurements required no correction, as the movement of the force-gauge actuator was taken into account by the use of dial gauge B. Intercept b for all other measurements was corrected to b_c by the use of Eq. 19 in Sec. IV of this report.

TABLE VIII. Load (lb_f) vs Deflection for Room-temperature-control Set of Springs: Initial Measurements Taken June 22, 1965[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		3.45		4.35	5.10	6.10	6.95
1Y2		3.30		4.15	5.05	5.90	6.75
1Y3		3.40		4.35	5.10	6.00	6.85
1Y11		3.20		4.10	4.95	5.80	6.65
1Y12		3.35		4.25	5.10	6.10	6.90
1Y13		3.30		4.15	5.00	5.85	6.70
2Y4		5.40		6.25	7.10	7.95	
2Y5		5.50		6.40	7.25	8.10	
2Y6		5.50		6.35	7.20	8.10	
2Y14		6.35		7.25	8.05	8.95	
2Y15		6.30		7.20	8.00	8.75	
2Y16		6.35		7.20	8.05	8.80	
3Y7	8.10	8.60	9.00				
3Y8	7.80	8.20	8.80				
3Y9	8.75	9.15	9.50				
3Y17	8.65	9.05	9.40				
3Y18	8.80	9.20	9.60				
3Y19	8.90	9.20	9.60				

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE IX. Load (lb_f) vs Deflection for Room-temperature-control Set of Springs: Measured at Time of SURV-1 Measurements, July 27, 1967[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		3.00		3.90	4.75	5.65	6.45
1Y2		2.85		3.55	4.55	5.30	6.25
1Y3		2.90		3.75	4.60	5.50	6.35
1Y11		2.90		3.75	4.65	5.45	6.30
1Y12		3.05		3.95	4.80	5.70	6.75
1Y13		2.90		3.70	4.60	5.45	6.25
2Y4		4.95		5.85	6.65	7.50	8.35
2Y5		5.00		5.95	6.70	7.60	8.45
2Y6		4.80		5.70	6.55	7.55	8.25
2Y14		5.25		6.20	7.10	7.95	8.70
2Y15		5.40		6.20	7.00	7.95	8.70
2Y16		5.10		5.95	6.70	7.65	8.40
3Y7	7.15	7.50	8.00	8.40			
3Y8	7.30	7.65	8.20	8.60			
3Y9	7.85	8.35	8.95	9.50			
3Y17	7.35	7.75	8.35	8.60			
3Y18	6.85	7.25	7.70	8.20			
3Y19	7.85	8.30	8.80	9.25			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE X. Load (lb_f) vs Deflection for Room-temperature-control Set of Springs: Measured at Time of SURV-3 Measurements, May 5, 1971[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		3.00		3.80	4.60	5.60	6.30
1Y2		3.00		3.79	4.25	5.30	6.20
1Y3		2.85		3.65	4.50	5.25	6.10
1Y11		3.00		3.79	4.60	5.40	6.25
1Y12		2.85		3.80	4.60	5.45	6.25
1Y13		3.00		3.80	4.60	5.40	6.25
2Y4		4.95		5.60	6.60	7.60	8.45
2Y5		4.90		5.80	6.59	7.30	8.20
2Y6		4.95		5.80	6.60	7.70	8.40
2Y14		5.65		6.50	7.35	8.15	9.15
2Y15		5.70		6.40	7.20	7.95	9.00
2Y16		5.15		5.85	6.55	7.45	8.30
3Y7	6.10	8.00	8.25	8.70			
3Y8	7.10	7.90	8.20	8.80			
3Y9	7.45	8.20	9.00	9.10			
3Y17	7.85	8.55	9.25	11.35			
3Y18	7.20	8.00	8.80	9.90			
3Y19	8.00	8.20	8.70	10.00			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XI. Load (lb_f) vs Deflection for Room-temperature-control Set of Springs: Measured at Time of SURV-4 and -6 Measurements, February 7, 1974[a]

Sample Identification	Deflection, in. 0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		2.45		3.30	4.15	5.00	5.75
1Y2		2.40		3.30	4.20	4.95	5.70
1Y3		2.45		3.30	4.15	4.95	5.80
1Y11		2.45		3.28	4.23	5.00	5.75
1Y12		2.23		3.20	4.05	4.87	5.88
1Y13		2.55		3.50	4.35	5.20	5.95
2Y4		4.73		5.50	6.43	7.20	8.15
2Y5		4.28		5.20	6.05	6.95	7.75
2Y6		4.72		5.60	6.30	7.10	8.00
2Y14		4.68		5.43	6.28	7.00	8.20
2Y15		4.62		5.50	6.43	7.38	8.24
2Y16		4.67		5.57	6.43	7.32	8.20
3Y7	7.15	7.70	8.70	9.15			
3Y8	6.75	7.28	7.60	8.07			
3Y9	7.43	7.85	8.62	9.20			
3Y17	6.70	7.15	7.50	7.98			
3Y18	6.60	7.00	7.50	7.90			
3Y19	7.62	8.17	8.62	9.06			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XII. Load (lb_f) vs Deflection for Room-temperature-control Set of Springs: Measured October 22, 1976, near Time of SURV-5 Measurements (January 10, 1977)[a]

Sample Identification	Deflection, in. 0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		3.05		3.85	4.75	5.55	6.40
1Y2		3.00		3.80	4.65	5.45	6.35
1Y3		2.60		3.45	4.25	5.15	6.00
1Y11		3.00		3.80	4.60	5.40	6.30
1Y12		2.75		3.55	4.40	5.25	6.10
1Y13		3.05		3.85	4.75	5.55	6.40
2Y4		4.95		5.80	6.60	7.60	8.45
2Y5		5.05		5.90	6.80	7.60	8.60
2Y6		5.00		5.85	6.70	7.60	8.50
2Y14		5.55		6.40	7.25	8.20	9.15
2Y15		5.50		6.40	7.30	8.20	9.05
2Y16		5.00		5.90	6.80	7.75	8.60
3Y7	7.40	7.85	8.35	8.95			
3Y8	7.45	7.90	8.35	8.90			
3Y9	7.80	8.30	8.80	9.30			
3Y17	7.70	8.10	8.55	9.05			
3Y18	7.75	8.15	8.60	9.20			
3Y19	8.00	8.40	8.90	9.40			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XIII. Load (lb_f) vs Deflection for Unexposed SURV-6 (Storage-basket-control) Springs: Measurements Taken June 22, 1965[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		3.40		4.20	5.10	5.90	6.70
1Y2		3.30		4.25	5.05	5.90	6.75
1Y3		3.30		4.10	5.05	5.90	6.75
1Y11		3.25		4.10	5.00	5.80	6.65
1Y12		3.30		4.18	5.00	5.85	6.70
1Y13		3.35		4.25	5.10	6.00	6.85
2Y4		5.55		6.45	7.30	8.15	
2Y5		5.65		6.50	7.45	8.30	
2Y6		5.45		6.30	7.10	8.00	
2Y14		6.30		7.15	8.00	8.75	
2Y15		6.35		7.05	8.05	8.85	
2Y16		6.20		7.10	7.95	8.70	
3Y7	8.10	8.50	9.00				
3Y8	8.70	9.10	9.40				
3Y9	8.70	9.10	9.45				
3Y17	8.50	9.15	9.50				
3Y18	8.65	9.05	9.40				
3Y19	8.70	9.05	9.40				

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XIV. Load (lb_f) vs Deflection for Exposed SURV-6 (Storage-basket-control) Springs: Measurements Taken March 6, 1975[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		2.30		3.40	4.20	5.10	6.40
1Y2		2.30		3.30	4.10	5.00	6.00
1Y3		2.20		3.00	4.20	4.80	5.60
1Y11		2.20		3.00	3.95	4.65	5.60
1Y12		2.45		3.20	4.10	4.95	6.00
1Y13		2.40		3.20	4.00	4.90	5.80
2Y4		5.00		6.20	6.90	7.80	10.20
2Y5		5.60		6.40	7.20	8.00	10.40
2Y6		5.00		6.20	7.00	8.00	9.80
2Y14		4.95		5.90	6.70	7.60	8.45
2Y15		5.30		6.10	6.90	7.90	8.60
2Y16		5.40		6.25	7.00	7.95	8.70
3Y7	7.20	8.00	9.20	11.40			
3Y8	7.60	8.10	8.40	10.60			
3Y9	7.40	8.50	8.80	9.60			
3Y17	7.60	8.00	8.40	9.00			
3Y18	7.40	7.80	8.30	9.00			
3Y19	7.20	7.55	8.00	8.35			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XV. Results from Linear-least-squares Analysis of Data Shown in Tables VIII-XII for Room-temperature-control Springs[a]

Sample Identification	Initial b, lb_f	SURV-1			SURV-3			SURV-4 and -6			SURV-5		
		m, lb_f/in.	b, lb_f	b_c, lb_f	m, lb_f/in.	b, lb_f	b_c, lb_f	m, lb_f/in.	b, lb_f	b_c, lb_f	m, lb_f/in.	b, lb_f	b_c, lb_f
1Y1	2.57	8.65	2.16	2.40	8.40	2.14	2.38	8.30	1.64	1.86	8.40	2.20	2.45
1Y2	2.44	8.55	1.94	2.17	7.91	2.14	2.38	8.25	1.64	1.86	8.35	2.15	2.39
1Y3	2.58	8.65	2.03	2.26	8.10	2.04	2.28	8.35	1.63	1.84	8.50	1.74	1.96
1Y11	2.36	8.50	2.06	2.30	8.11	2.18	2.42	8.32	1.65	1.87	8.20	2.16	2.40
1Y12	2.46	9.15	2.11	2.35	8.45	2.06	2.29	8.91	1.36	1.57	8.40	1.89	2.12
1Y13	2.45	8.45	2.05	2.28	8.10	2.18	2.42	8.50	1.76	1.99	8.40	2.20	2.45
2Y4	4.55	8.45	4.13	4.48	9.00	3.94	4.28	8.54	3.84	4.18	8.80	4.04	4.39
2Y5	4.65	8.55	4.18	4.53	8.10	4.13	4.48	8.69	3.44	3.76	8.80	4.15	4.50
2Y6	4.63	8.75	3.95	4.29	8.80	4.05	4.40	8.06	3.93	4.27	8.75	4.11	4.46
2Y14	5.50	8.65	4.45	4.81	8.65	4.77	5.15	8.61	3.74	4.07	9.00	4.61	4.98
2Y15	5.53	8.35	4.55	4.92	8.15	4.81	5.19	9.12	3.70	4.03	8.90	4.62	5.00
2Y16	5.55	8.30	4.27	4.63	7.90	4.29	4.65	8.81	3.80	4.13	9.05	4.10	4.45
3Y7	7.67	8.50	6.70	7.23	16.10	5.75	6.23	14.00	6.43	6.94	10.30	6.85	7.39
3Y8	7.27	8.90	6.83	7.36	10.80	6.65	7.18	8.56	6.36	6.87	9.60	6.95	7.50
3Y9	8.38	11.10	7.28	7.84	11.50	7.00	7.55	12.20	6.76	7.29	10.00	7.30	7.86
3Y17	8.28	8.70	6.93	7.47	22.40	6.45	6.97	8.38	6.29	6.80	9.00	7.23	7.78
3Y18	8.40	9.00	6.38	6.89	17.80	6.25	6.76	8.80	6.15	6.65	9.60	7.23	7.78
3Y19	8.53	9.40	7.38	7.94	13.00	7.10	7.65	9.54	7.18	7.73	9.40	7.50	8.07

[a]Conversion factors: 1 lb_f = 4.448 N; 1 lb_f/in. = 175.1 N/m.

Table XVI shows the results of linear-least-squares analysis of the data from the SURV-6 subassembly in Tables XIII and XIV. The intercept at zero deflection is b. The intercept from the initial measurements required no correction, but the other intercepts were corrected to b_c by the use of Eq. 19 in Sec. IV of this report.

TABLE XVI. Results from Linear-least-squares Analysis of Data Shown in Tables XIII and XIV for SURV-6 (Storage-basket-control) Springs[a]

Sample Identification	Initial b, lb_f	After Exposure b, lb_f	After Exposure b_c, lb_f
1Y1	2.57	1.31	1.52
1Y2	2.49	1.41	1.62
1Y3	2.41	1.38	1.59
1Y11	2.41	1.35	1.55
1Y12	2.47	1.49	1.70
1Y13	2.49	1.51	1.72
2Y4	4.70	3.62	3.95
2Y5	4.75	4.16	4.51
2Y6	4.60	3.78	4.12
2Y14	5.50	4.11	4.46
2Y15	5.45	4.44	4.81
2Y16	5.40	4.57	4.94
3Y7	7.63	5.50	5.97
3Y8	8.37	6.35	6.86
3Y9	8.33	6.85	7.39
3Y17	8.05	7.10	7.65
3Y18	8.28	6.80	7.34
3Y19	8.35	6.80	7.34

[a]Conversion factor: 1 lb_f = 4.448 N.

The units used in Appendix B are not SI units (although conversion factors are footnoted). "Hard" conversion to only SI units was not done, because the data and results given here are intended to be used as a convenient reference when subsequent SURV experiments are removed from the reactor and measured.

APPENDIX C

Data and Analysis for Springs from SURV Subassemblies 1, 3, 4, and 5

Tables XVII-XXIV list the measurements of load and deflection for the springs from SURV-1, -3, -4, and -5 before and after irradiation. The measurements were obtained on the apparatus shown in Fig. 2. For all the initial measurements taken before irradiation, the apparatus had dial gauge B (Fig. 2); thus, the measurements include the movement of the force-gauge actuator. For all the postirradiation measurements, dial gauge B was absent from the apparatus.

TABLE XVII. Load (lb_f) vs Deflection for SURV-1 Springs: Initial Measurements Taken June 1965[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		3.35		4.30	5.15	6.00	6.85
1Y2		3.45		4.35	5.20	6.05	6.90
1Y3		3.45		4.35	5.15	6.05	6.95
1Y11		3.35		4.30	5.10	6.00	6.85
1Y12		3.35		4.30	5.10	6.00	6.80
1Y13		3.35		4.30	5.10	6.00	6.85
2Y4		5.85		6.75	7.60	8.45	
2Y5		5.85		6.75	7.65	8.45	
2Y6		5.70		6.55	7.45	8.25	
2Y14		5.50		6.40	7.35	8.10	
2Y15		5.40		6.30	7.15	8.00	
2Y16		5.40		6.30	7.20	8.05	
3Y7	8.70	9.10	9.70				
3Y8	8.75	9.15	9.60				
3Y9	8.45	8.90	9.35				
3Y17	8.60	9.05	9.35				
3Y18	8.65	9.05	9.40				
3Y19	8.65	9.10					

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XVIII. Load (lb_f) vs Deflection for SURV-1 Springs: Postirradiation Measurements Taken July 1967[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		2.60		3.70	4.40	5.60	6.70
1Y2		2.80		3.70	4.65	5.45	6.35
1Y3		2.85		3.70	4.70	5.55	6.50
1Y11		2.90		3.65	4.75	5.55	6.40
1Y12		2.50		3.45	4.40	5.40	6.05
1Y13		2.75		3.60	4.60	5.40	6.30
2Y4		5.00		6.15	7.00	7.65	
2Y5		4.95		5.50	6.70	7.45	8.60
2Y6		4.70		5.45	6.35	7.35	
2Y14		4.35		5.20	6.15	7.00	7.65
2Y15		4.55		5.35	6.30	7.10	8.10
2Y16		4.25		5.15	6.00	6.80	7.70
3Y7	6.90	7.45	8.45	9.75			
3Y8	6.15	6.65	7.05	7.75			
3Y9	6.50	7.10	7.35	7.80			
3Y17	6.95	7.25	7.75	8.25			
3Y18	5.75	6.35	6.90	7.30			
3Y19	6.70	7.40	8.00	8.30			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XIX. Load (lb_f) vs Deflection for SURV-3 Springs: Initial Measurements Taken June 1965[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		2.60		3.50	4.40	5.25	6.10
1Y2		2.70		3.60	4.50	5.35	6.20
1Y3		2.95		3.80	4.70	5.55	6.40
1Y11		2.65		3.55	4.40	5.25	6.10
1Y12		2.75		3.65	4.55	5.40	6.25
1Y13		2.65		3.55	4.45	5.30	6.10
2Y4		5.45		6.35	7.20	8.10	
2Y5		5.45		6.30	7.15	8.00	
2Y6		5.45		6.30	7.15	8.00	
2Y14		6.30		7.10	7.90	8.70	
2Y15		6.30		7.20	8.05	8.80	
2Y16		6.35		7.20	8.05	8.85	
3Y7	8.00	8.50	9.00				
3Y8	8.70	9.15	9.50				
3Y9	8.65	9.00	9.35				
3Y17	8.65	9.10	9.45				
3Y18	8.70	9.10	9.45				
3Y19	8.70	9.15	9.50				

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XX. Load (lb_f) vs Deflection for SURV-3 Springs: Postirradiation Measurements Taken May 7, 1971[a]

Sample Identification	Deflection, in. 0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		2.00		3.00	3.80	4.60	5.50
1Y2		2.10		2.80	3.80	4.40	5.60
1Y3		2.10		3.00	3.80	4.40	5.50
1Y11		2.00		2.80	3.70	4.40	5.50
1Y12		2.10		2.80	4.00	4.50	5.50
1Y13		2.10		2.90	3.80	4.50	5.50
2Y4		3.80		4.70	5.80	6.60	7.80
2Y5		3.90		4.50	5.40	6.30	7.60
2Y6		4.10		4.60	5.50	6.30	7.60
2Y14		4.20		5.20	5.70	7.10	7.80
2Y15		4.00		4.60	5.40		
2Y16		4.50		5.30	6.50	7.50	8.50
3Y7	5.00	5.30	5.90	7.00			
3Y8	4.70	5.30	5.80	6.70			
3Y9	6.20	6.60	8.10	9.80			
3Y17	5.50	6.30	7.00	7.80			
3Y18	5.00	6.40	7.00	7.30			
3Y19	6.10	6.70	7.10	7.80			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XXI. Load (lb_f) vs Deflection for SURV-4 Springs: Initial Measurements Taken June 1965[a]

Sample Identification	Deflection, in. 0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		2.50		3.35	4.20	5.10	5.95
1Y2		2.70		3.60	4.45	5.30	6.10
1Y3		2.65		3.60	4.45	5.35	6.20
1Y11		2.65		3.50	4.40	5.25	6.10
1Y12		2.65		3.50	4.45	5.30	6.15
1Y13		2.60		3.50	4.35	5.20	6.05
2Y4		5.50		6.45	7.30	8.10	
2Y5		5.60		6.50	7.30	8.15	
2Y6		5.50		6.35	7.25	8.10	
2Y14		6.25		7.15	7.90	8.80	
2Y15		6.30		7.25	8.05	8.70	
2Y16		6.30		7.10	8.00	8.80	
3Y7	8.20	8.70	9.10				
3Y8	8.80	9.25	9.60				
3Y9	8.70	9.15	9.45				
3Y17	8.60	9.05	9.45				
3Y18	8.80	9.20	9.55				
3Y19	8.70	9.10	9.45				

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XXII. Load (lb_f) vs Deflection for SURV-4 Springs: Postirradiation Measurements Taken March 6, 1975[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		2.00		2.80	3.80	4.60	5.40
1Y2		2.00		2.60	3.40	4.20	5.10
1Y3		1.90		2.50	3.40	4.20	5.20
1Y11		2.00		2.65	3.55	4.30	5.25
1Y12		1.80		2.60	3.40	4.20	5.10
1Y13		2.00		2.70	3.50	4.35	5.15
2Y4		3.60		4.60	5.60	6.60	8.00
2Y5		3.20		4.20	5.00	5.90	8.00
2Y6		3.70		4.60	6.00	7.00	7.60
2Y14		4.00		4.80	6.00	6.75	7.70
2Y15		3.10		4.00	4.90	5.80	6.80
2Y16		4.00		4.70	5.60	6.65	7.30
3Y7	4.20	5.50	5.80	6.00			
3Y8	4.80	5.20	5.90	7.00			
3Y9	5.20	6.20	7.50	7.70			
3Y17	4.65	4.80	5.40	5.90			
3Y18	4.20	4.70	5.10	5.60			
3Y19	4.90	5.40	5.90	6.20			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XXIII. Load (lb_f) vs Deflection for SURV-5 Springs: Initial Measurements Taken June 1965[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		3.30		4.10	5.00	5.85	6.65
1Y2		3.30		4.15	5.05	5.85	6.70
1Y3		3.40		4.25	5.10	5.95	6.85
1Y11		3.25		4.15	5.00	5.85	6.70
1Y12		3.30		4.25	5.10	5.95	6.80
1Y13		3.35		4.25	5.10	5.95	6.80
2Y4		5.55		6.45	7.30	8.10	
2Y5		5.50		6.40	7.25	8.10	
2Y6		5.50		6.45	7.30	8.10	
2Y14		6.40		7.20	8.00	8.80	
2Y15		6.35		7.20	8.00	8.75	
2Y16		6.30		7.10	7.95	8.70	
3Y7	8.10	8.50	9.00				
3Y8	8.65	9.10	9.45				
3Y9	8.75	9.20	9.55				
3Y17	8.55	8.90	9.30				
3Y18	8.70	9.20	9.55				
3Y19	8.70	9.10	9.40				

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

TABLE XXIV. Load (lbf) vs Deflection for SURV-5 Springs: Postirradiation Measurements Taken January 10, 1977[a]

Sample Identification	Deflection, in.						
	0.05	0.10	0.15	0.20	0.30	0.40	0.50
1Y1		1.45		2.30	3.10	3.95	4.80
1Y2		1.35		2.10	3.00	3.80	4.70
1Y3		1.35		2.20	2.95	3.80	4.65
1Y11		1.60		2.30	3.10	3.95	4.80
1Y12		1.50		2.40	3.10	3.95	4.80
1Y13		1.60		2.25	3.00	3.85	4.75
2Y4		2.50		3.35	4.20	5.05	6.00
2Y5		2.30		3.15	4.00	4.95	5.80
2Y6		2.95		3.75	4.60	5.55	6.40
2Y14		3.20		4.15	5.00	5.90	6.80
2Y15		2.60		3.55	4.40	5.30	6.20
2Y16		3.20		4.10	5.00	5.85	6.85
3Y7	3.45	3.90	4.40	4.85			
3Y8	3.00	3.40	3.85	4.40			
3Y9	4.60	5.00	5.50	6.00			
3Y17	3.45	3.85	4.35	4.80			
3Y18	3.20	3.60	4.15	4.60			
3Y19	4.60	5.00	5.45	5.95			

[a]Conversion factors: 1 lb_f = 4.448 N; 1 in. = 25.4 mm.

Tables XXV-XXVIII show the results of linear-least-squares analyses of the data given in Tables XVII-XXIV. The intercept of the least-squares fit to the preirradiation data is b_i. This value for the intercept requires no correction for movement of the force-gauge actuator, because dial gauge B was used to compensate for the movement. The value b_A is the intercept b_i reduced by a factor of 0.918 to account for irradiation-independent relaxation. This correction was discussed in Sec. IV of this report. The intercept of the least-squares fit to the postirradiation data is b. The intercept b was corrected to b_c by the use of Eq. 19 in Sec. IV of this report. This correction was necessary to account for movement of the force-gauge actuator, since dial gauge B was removed from the measuring apparatus for the postirradiation measurements. The ratio b_c/b_A is the ratio of the shear stresses recorded in Table IV and plotted in Fig. 7 of the text.

The units used in Appendix C are not SI units (although conversion factors are footnoted). "Hard" conversion to only SI units was not done, because the data and results given here are intended to be used as a convenient reference when subsequent SURV experiments are removed from the reactor and measured.

TABLE XXV. Results from Linear-least-squares Analysis of Data Shown in Tables XVII and XVIII for SURV-1 Springs[a]

Sample Identification	Preirradiation		Postirradiation		
	b_i, lb_f	b_A, lb_f	b, lb_f	b_c, lb_f	b_c/b_A
1Y1	2.52	2.31	1.57	1.79	0.77
1Y2	2.61	2.40	1.94	2.17	0.91
1Y3	2.58	2.37	1.92	2.15	0.91
1Y11	2.51	2.30	1.98	2.22	0.96
1Y12	2.53	2.32	1.65	1.87	0.80
1Y13	2.51	2.30	1.86	2.09	0.91
2Y4	5.00	4.59	4.25	4.61	1.00
2Y5	5.00	4.59	3.87	4.20	0.92
2Y6	4.85	4.45	3.75	4.08	0.92
2Y14	4.65	4.27	3.55	3.87	0.91
2Y15	4.55	4.18	3.63	3.95	0.95
2Y16	4.53	4.15	3.42	3.73	0.90
3Y7	8.17	7.50	5.75	6.23	0.83
3Y8	8.32	7.64	5.60	6.07	0.80
3Y9	8.00	7.34	6.15	6.65	0.91
3Y17	8.25	7.57	6.45	6.97	0.92
3Y18	8.28	7.60	5.28	5.73	0.75
3Y19	8.20	7.53	6.25	6.76	0.90

[a]Conversion factor: 1 lb_f = 4.448 N.

TABLE XXVI. Results from Linear-least-squares Analysis of Data Shown in Tables XIX and XX for SURV-3 Springs[a]

Sample Identification	Preirradiation		Postirradiation		
	b_i, lb_f	b_A, lb_f	b, lb_f	b_c, lb_f	b_c/b_A
1Y1	1.75	1.60	1.20	1.40	0.87
1Y2	1.85	1.69	1.16	1.36	0.80
1Y3	2.09	1.91	1.30	1.51	0.79
1Y11	1.81	1.66	1.10	1.30	0.78
1Y12	1.90	1.74	1.23	1.43	0.82
1Y13	1.82	1.67	1.24	1.44	0.87
2Y4	4.58	4.20	2.77	3.06	0.73
2Y5	4.60	4.22	2.78	3.07	0.73
2Y6	4.60	4.22	3.01	3.31	0.78
2Y14	5.50	5.05	3.27	3.58	0.71
2Y15	5.50	5.05	3.27	3.58	0.71
2Y16	5.53	5.07	3.40	3.72	0.73
3Y7	7.50	6.89	4.15	4.54	0.66
3Y8	8.32	7.64	4.00	4.39	0.58
3Y9	8.30	7.62	4.60	5.02	0.66
3Y17	8.27	7.59	4.75	5.18	0.68
3Y18	8.33	7.65	4.55	4.97	0.65
3Y19	8.32	7.64	5.55	6.02	0.79

[a]Conversion factor: 1 lb_f = 4.448 N.

TABLE XXVII. Results from Linear-least-squares Analysis of Data Shown in Tables XXI and XXII for SURV-4 Springs[a]

Sample Identification	Preirradiation		Postirradiation		
	b_i, lb_f	b_A, lb_f	b, lb_f	b_c, lb_f	b_c/b_A
1Y1	1.63	1.49	1.14	1.34	0.90
1Y2	1.88	1.73	1.12	1.32	0.76
1Y3	1.80	1.65	0.95	1.14	0.69
1Y11	1.79	1.64	1.11	1.30	0.79
1Y12	1.77	1.63	0.96	1.15	0.71
1Y13	1.76	1.62	1.16	1.35	0.84
2Y4	4.68	4.29	2.44	2.71	0.63
2Y5	4.78	4.38	1.87	2.12	0.48
2Y6	4.63	4.25	2.72	3.01	0.71
2Y14	5.43	4.98	3.05	3.35	0.67
2Y15	5.58	5.12	2.16	2.42	0.47
2Y16	5.45	5.00	3.09	3.39	0.68
3Y7	7.77	7.13	3.95	4.34	0.61
3Y8	8.42	7.73	3.90	4.28	0.55
3Y9	8.35	7.67	4.45	4.86	0.63
3Y17	8.18	7.51	4.10	4.50	0.60
3Y18	8.43	7.74	3.75	4.13	0.53
3Y19	8.33	7.65	4.50	4.92	0.64

[a]Conversion factor: 1 lb_f = 4.448 N.

TABLE XXVIII. Results from Linear-least-squares Analysis of Data Shown in Tables XXIII and XXIV for SURV-5 Springs[a]

Sample Identification	Preirradiation		Postirradiation		
	b_i, lb_f	b_A, lb_f	b, lb_f	b_c, lb_f	b_c/b_A
1Y1	2.45	2.25	0.62	0.79	0.35
1Y2	2.46	2.26	0.47	0.64	0.28
1Y3	2.53	2.32	0.53	0.70	0.30
1Y11	2.41	2.21	0.74	0.91	0.41
1Y12	2.47	2.27	0.71	0.75	0.33
1Y13	2.51	2.30	0.72	0.82	0.35
2Y4	4.73	4.34	1.61	1.84	0.43
2Y5	4.65	4.27	1.40	1.62	0.38
2Y6	4.68	4.30	2.04	2.29	0.53
2Y14	5.60	5.14	2.33	2.59	0.50
2Y15	5.58	5.12	1.73	1.96	0.38
2Y16	5.50	5.05	2.29	2.55	0.51
3Y7	7.63	7.00	2.98	3.31	0.47
3Y8	8.27	7.59	2.50	2.81	0.37
3Y9	8.37	7.68	4.10	4.49	0.59
3Y17	8.17	7.50	2.98	3.31	0.44
3Y18	8.30	7.62	2.70	3.02	0.40
3Y19	8.37	7.68	4.13	4.52	0.59

[a]Conversion factor: 1 lb_f = 4.448 N.

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