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IRRADIATION TEST
OF
SNAP 8 CANDIDATE SPRING MATERIALS

AEC Research and Development Report

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By

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ABSTRACT

An experiment was conducted to determine the effects of long-term exposure to radiation, high temperature, and vacuum on the performance of two candidate SNAP spring materials. Five René 41 (Ni-Cr-Fe) and five Stauffer 880 (88Ta-12W) springs were tested under constant length conditions at temperatures between 700 and 1300°F. Radiation exposures varied from about 2×10^{17} to 3×10^{19} nvt fast neutrons ($E > 0.1$ Mev) and from about 5×10^9 to 7.5×10^{10} R gamma. Vacuum levels were in the 10^{-4} torr range throughout the approximately 3250-hour experiment.

The irradiated spring data were used to calculate the percentage of energy relaxation and percentage of force relaxation for comparison with nonnuclear test data. It was observed that, in all cases, the percent relaxation of irradiated René 41 springs was less than that of the unirradiated springs. No definite pattern was observable with the Stauffer 880 springs, except that high radiation levels increased the percent relaxation (both force and energy), although the effect was minimal at 1300°F.

It was concluded, based on these tests, that René 41 springs are superior to Stauffer 880 springs at all test temperatures below ~1200°F. Above that temperature, the Stauffer 880 springs may be superior.

I. INTRODUCTION

Testing of springs of various materials for use up to 1200°F at Atomics International prior to mid-1964 indicated that René' 41 (a Ni-Cr-Fe alloy) was a promising high temperature spring material. Unirradiated René' 41 springs showed negligible relaxation at 1000°F in air and even after 10,000 hours at 1100°F in air showed only 25% load relaxation. These results led to an emphasis on testing René' 41 springs.

Irradiation of René' 41 springs had been performed in a previous experiment at 1000°F under nonquantitative conditions. Three René' 41 springs were used to provide pressure contact in "self-weld" (adhesion) tests. Limited analytical tests (change in free length and change in the load versus length characteristics) were performed to determine the effect of radiation on the springs. It was concluded that very little effect was detected and that no serious degradation was observed.

It was apparent that sufficient information was not available on the behavior of René' 41 springs at high temperature in vacuum and under irradiation. Of the undefined variables, radiation was considered to be the most likely to produce serious changes in relaxation behavior.

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II. TEST PARAMETERS

The Battelle Research Reactor (BRR) was chosen for the planned spring irradiation tests. Because the space available in the irradiation capsule was enough for only 10 specimens, statistical sampling was out of the question. It was necessary to weigh the importance of each of the following spring design and use parameters: material, stress level, temperature, radiation dose rates and total irradiation doses, and ambient pressure. These test parameters are discussed in the following sections.

A. MATERIALS

Literature surveys had indicated that refractory metal alloys were the most promising materials for high temperature springs, because they exhibit maximum metallurgical stability under irradiation, and the temperatures of interest in SNAP systems are well below temperatures at which creep was expected to be observable. The potentially strongest alloy which was also suitable for fabrication into a spring configuration was Stauffer 880 (a solid solution alloy of tantalum containing 12.5 wt % tungsten). Stauffer Metals Division, Stauffer Chemical Company, now part of Fansteel Metallurgical Company, provided springs suitable for relaxation tests. During the same period, Rene'41 springs of the same configuration were obtained, and the spring relaxation test fixtures were designed and fabricated.

The two materials were selected for testing because:

- 1) Additional design data was needed for the reference Rene'41 material, and
- 2) A material with a higher temperature capability was needed to meet the problems of higher design operating temperatures.

B. STRESS LEVELS

Review of the data available for direct comparison with irradiation test results revealed that virtually all previous spring relaxation tests had been run at approximately 40,000-psi torsional stress (at temperature) to coincide

with the SNAP 10A ejection spring design. It was also noted that very little difference in relaxation behavior was detected in tests spanning the stress range from 30,000 to 50,000 psi. In order to maintain comparable conditions, variations in stress were arbitrarily eliminated to permit variation in the other parameters considered to be of greater importance. In any SNAP spring designs, the spring torsional stress of 40,000 psi may be readily accommodated since size and configuration are not restricted. Therefore, a fiber stress of 40,000 psi at test temperature was selected for the René' 41 and Stauffer 880 springs to correspond to previous test conditions.

C. TEMPERATURE

Out-of-reactor relaxation tests on René' 41 at AI showed its performance to be satisfactory at 1100°F, but the rapid increase in relaxation at 1100°F, compared to that at 1000°F, indicated that the maximum temperature limit of René' 41 was being approached. It was anticipated that neutron irradiation might induce metallurgical instability in René' 41 and lower the maximum temperature limit. The latest design requirements at the time the test was planned specified springs operating at 1150, 1050, and 950°F. These temperatures were selected as most convenient for generation of design information.

Because the purpose of testing Stauffer 880 was to determine its utility as a spring material for temperatures above those suitable for René' 41 and also for comparison with René' 41, 1150 and 1050°F were selected to provide data directly comparable to René' 41 and 1300°F was selected as the top temperature for the Stauffer 880, based on the limitations of the test fixture.

D. RADIATION DOSE AND DOSE RATE

Analysis indicated that an "intermediate" dose rate of approximately 10^{11} n/cm²/sec (fast neutrons, $E > 0.1$ Mev) most nearly corresponded to the dose rate to be experienced by springs on the reactor. A "high" dose rate of approximately 10^{12} n/cm²/sec would approximate the expected SNAP 8 total dose within a test duration of 2800 hours. A "low" rate of approximately 10^{10} n/cm²/sec was chosen to provide information on the effect of dose rate

on material behavior. These dose rates would provide total doses of approximately 10^{18} , 10^{19} , and 10^{17} nvt (fast neutrons, $E > 0.1$ Mev), respectively, in 2800 hours of testing.

E. AMBIENT PRESSURE (VACUUM)

Jaffee⁽¹⁾ considers that hard space vacuum will be no more deleterious on materials than 10^{-5} torr, because at 10^{-5} torr the Knudsen conditions are approximately attained and the loss of surface material or contaminants becomes only a function of the vapor pressure of the substance which, in turn, is only a function of absolute temperature and not pressure. The irradiation capsule was designed to operate at 10^{-5} torr or lower pressure. The Stauffer 880 springs require an oxygen-free environment at higher temperatures to prevent oxidation.

F. METHODS OF EVALUATION

If a helical spring is compressed by a given amount between parallel plates at elevated temperature, it will be found that the load exerted by the spring will gradually diminish with time. This phenomenon, commonly referred to as stress or load relaxation, is generally determined by experiment. The quantitative evaluation of a material's relaxation behavior is preferably done in one of two ways, namely, by the force (stress) relaxation or by the energy relaxation method, respectively. Figure 1 depicts a force vs deflection diagram of helical and other spring devices known to possess linear characteristics. Selection of the preferred relaxation evaluation procedure depends on the contemplated function of the spring device. For applications, wherein exertion of a predictable force is the primary purpose of a spring, the force relaxation method of analysis is used. Conversely, if storage of a predictable level of energy is the primary requirement of a spring, the energy relaxation method of analysis is more useful.

To preserve flexibility, the results obtained in this series of spring tests was evaluated by both methods. Evaluation of relaxation data for a given set of test conditions requires a knowledge of the parameters F_0 , F_1 , δ_0 , and δ_1 (Figure 1).

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Figure 1. Pre- and Post-Test Performance Characteristics of a Linear Spring

1. Force Relaxation Method

In this method, the relaxation, R_F , is defined as follows:

$$R_F = \frac{F_0 - F_1}{F_0} \times 100 (\%)$$

$$R_F = \% \text{ Relaxation of Force}$$

or equivalently, by letting

$$K_0 = \frac{F_0}{\delta_0} = \text{pre-test spring constant}$$

$$K_1 = \frac{F_1}{\delta_1} = \text{post-test spring constant}$$

then

$$R_F = \frac{K_o \delta_o - K_1 \delta_1}{K_o \delta_o} \times 100 = \left(1 - \frac{K_1 \delta_1}{K_o \delta_o}\right) \times 100 = \left(1 - \frac{F_1}{F_o}\right) \times 100 \quad .$$

2. Energy Relaxation Method

In this method, the relaxation, R_E , is defined as follows:

$$R_E = \left(\frac{E_o - E_1}{E_o}\right) \times 100$$

R_E = % Relaxation of Energy

wherein

$$E_o = \frac{F_o \delta_o}{2}$$

$$E_1 = \frac{F_1 \delta_1}{2}$$

then

$$R_E = \left(\frac{F_o \delta_o - F_1 \delta_1}{F_o \delta_o}\right) \times 100 = \left(1 - \frac{F_1 \delta_1}{F_o \delta_o}\right) \times 100 = \left(1 - \frac{K_o F_1^2}{K_1 F_o^2}\right) \times 100 \quad .$$

3. Correlation Between Methods

Solving both of the above final equations for R_F and R_E respectively for F_1/F_o yields

$$\frac{F_1}{F_o} = 1 - \frac{R_F}{100} = \frac{\delta_o}{\delta_1} \left(1 - \frac{R_E}{100}\right)$$

wherefrom

$$R_F = \left[100 - (100 - R_E) \frac{\delta_o}{\delta_1} \right] (\%)$$

or equivalently,

$$R_E = \left[100 - (100 - R_F) \frac{\delta_1}{\delta_o} \right] (\%) .$$

By inspection it can be seen that $R_E > R_F$ since $\delta_o > \delta_1$.

III. IRRADIATION TESTS

A. FABRICATION HISTORY

Fifty-one Stauffer 880 springs and fifty René 41 springs were fabricated to the same dimensional requirements as follows:

O. D.	-	0.932 ± 0.015
Wire Size	-	0.125 ± 0.010
Free Length	-	2.090 ± 0.030
Number of Active Coils	-	9
Number of Inactive Coils	-	7
Close Ends, Grind Square	-	Within 1°

The René 41 springs were age-hardened at 1400°F for 16 hours in hydrogen for optimum creep resistance prior to use in relaxation tests. Table 1 lists the chemical compositions of the spring materials.

B. PRE-IRRADIATION PERFORMANCE DATA

The exact dimensional data for both the Stauffer 880 and René 41 springs were measured and recorded.

The load-spring length characteristics (spring rate) were measured and recorded (see Figure 5, Section IV) for post-test comparison. Three Stauffer 880 and two René 41 springs were selected at random, sectioned, and the microstructures were examined and photographed (see Figures 6 and 8 in Section IV).

C. FIXTURE CALIBRATION CALCULATIONS

The determination of room temperature set length and set load to provide 40,000-psi maximum torsional stress at temperature is not a simple matter. Thermal expansion of the test fixtures and springs and the change in spring elastic shear modulus with temperature must be accounted for to assure reasonable accuracy for the test.

TABLE 1
CHEMICAL COMPOSITIONS OF RENE' 41
AND STAUFFER 880 SPRINGS

Element	Composition (wt %)	
	René' 41	Stauffer 880
Carbon	0.08	0.0024
Manganese	0.10	NA
Aluminum	1.50	NA
Sulfur	0.006	NA
Silicon	0.20	NA
Chromium	19.06	NA
Nickel	Bal	NA
Cobalt	10.85	NA
Molybdenum	9.91	NA
Titanium	3.12	NA
Boron	0.0045	NA
Tantalum	NA	Bal
Tungsten	NA	12.16
Oxygen	NA	0.0024
Nitrogen	NA	0.0023
Iron	0.59	NA

NA = Not Applicable

The calculations were further complicated by lack of data on Stauffer 880. None of the necessary physical or mechanical properties were available for the high temperature range. The available information⁽²⁾ on the room temperature tensile elastic modulus (28 to 30×10^6 psi) and thermal expansion pertained to 90Ta-10W alloy. Stauffer 880 contains 12.5% tungsten. The Metals Handbook⁽³⁾ lists the Poisson's ratio of pure tantalum to be 0.35 and presents graphs showing a linear decrease in tensile elastic modulus between room temperature and 1400°F. Using the expression from theory of elasticity for the relation between

shear and tensile elastic moduli for isotropic elastic media, the elastic shear moduli for the selected temperatures were calculated.

$$G = \frac{E}{2(1 + \nu)} \quad (1)$$

where

G = shear modulus,

E = tensile modulus, and

ν = Poisson's ratio.

The calculation was based on Poisson's ratio for pure tantalum with no change with temperature, and on the tensile modulus for 90Ta-10W alloy. It was also assumed that the change of tensile modulus with temperature is the same as that quoted for tantalum. Tungsten has a higher tensile modulus with linear change up through 1400°F than tantalum. Thus, the calculated shear modulus may be slightly lower than the actual shear modulus. The calculated stress for a given deflection may also be slightly lower than the actual stress.

The sequence followed in the calculation of set length and set load at room temperature to produce the desired conditions at temperature was as follows:

a) Calculate change in fixture length due to temperature change assuming values in Table 2 and spring set length $\approx$ 1.75 in.

b) Calculate change in spring length and force height due to temperature change using values in Table 3 and measured spring dimensions.

c) Calculate load to produce 40,000 psi at temperature using measured spring dimensions.

d) Calculate deflection at temperature produced by the above calculated load using Table 3 and measured spring dimensions.

e) Calculate set length at temperature using (b) and (d).

f) Calculate room-temperature set length using (a) and (e).

g) Determine room-temperature set load using (f) and spring calibration measurements.

Figure 2. Spring Test Module

TABLE 2
MEAN COEFFICIENT OF THERMAL EXPANSION
FOR INCONEL X-750⁽⁵⁾

Temperature (° F)	Mean Coefficient in./in./° F x 10 ⁻⁶
950	8.0
1050	8.2
1150	8.3
1300	8.6

TABLE 3
PHYSICAL AND MECHANICAL PROPERTIES OF RENE' 41
AND STAUFFER 880 SPRING MATERIALS

Temperature (° F)	Shear Elastic Modulus (10 ⁶ psi)		Thermal Expansion* in./in./° F x 10 ⁶	
	René' 41 ⁽⁴⁾	Stauffer 880	René' 41 ⁽⁴⁾	Stauffer 880
Room	12.1	10.20	-	-
950	10.25	-	7.38	-
1050	10.10	9.83	7.53	3.5
1150	9.80	9.31	7.75	4.0
1300	-	9.76	-	-
1350	-	-	-	4.5

*From room temperature to the indicated temperature.

D. FIXTURES AND ASSEMBLY

The spring test fixture, shown in Figure 2, consists of an Inconel tube, spring pedestals, a bellows assembly upon which is attached the magnetic probe for position sensing, a position transducer, a heater, Chromel-Alumel thermocouples, and the locking or positioning accessories needed for assembly. The stainless-steel-sheathed heater, not shown in Figure 2, is inside of the

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Figure 3. Vacuum Irradiation Facility at Front Core Face of the Battelle Research Reactor

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Inconel tube with leads emerging from the middle of the tube. The outer surface of each tube was flame-sprayed with chrome oxide to increase the emissivity.

Each module was assembled so that when the bellows was not pressurized, the test spring was maintained at the pre-set length. This was accomplished by first positioning the bellows assembly in the fixture and locking it in place. Next, the spring was positioned on the guide at the base of the bellows assembly and the pedestal put in place. The spring was then loaded by tightening the inner locking ring at the base of the pedestal. The outer ring was tightened to lock the assembly and tack-welded in place to ensure that the spring length would not change during the test. The position transducer was then placed in position. The test modules were mounted on a stainless-steel support structure designed to fit into the vacuum capsule at the Battelle Research Reactor (BRR). The test assembly was designed to provide the irradiation dose and test temperature for test samples as shown on Table 4.

The in-pile operation of the test modules consisted of periodically pressurizing the bellows slowly with helium until the output of the position transducer indicated a slight change from the null position. The pressure required to produce position transducer movement can be readily converted to force remaining in the test spring. Thus, the relaxation of spring force can be determined in-pile.

E. TEST OPERATION

The test was run in the vacuum irradiation facility at the BRR facility. The BRR is a 2-Mw pool-type research reactor which normally operates on a 12-day irradiation cycle at full power followed by a 2-day reactor shutdown between cycles. The fuel elements were rearranged to form a pocket in the front face of the core to accommodate the capsule and associated shielding. Figure 3 shows a schematic drawing of the BRR vacuum irradiation facility. Table 5 shows a summary of reactor operations and total time at operating temperature and vacuum levels.

TABLE 4
SPRING MATERIALS AND TEST CONDITIONS*

Material	Test Temperature (°F)	Fast Neutron Dose Rate	Set Length at Room Temperature (in.)	Set Load at Room Temperature (lb)
Rene' 41				
No. 1	950	High	1.745	34.2
No. 2	1050	High	1.753	34.0
No. 3	1150	High	1.716	35.4
No. 4	1150	Intermediate	1.740	35.9
No. 5	1150	Low	1.741	35.0
Stauffer 880				
No. 1	1050	High	1.754	32.6
No. 2	1300	High	1.736	32.4
No. 3	1150	High	1.725	31.0
No. 4	1150	Intermediate	1.732	32.9
No. 5	1150	Low	1.715	32.6

*Stress at test temperature for all samples was 40,000 psi.

Two fixture heaters failed during the course of the experiment. Stauffer 880 Spring No. 3 heater failed after 4.5 hours of reactor operation and temperatures thereafter were between 980 and 1020°F when the reactor was in operation and between 680 and 690°F during periods when the reactor was not at power. The heater in Rene' 41 Spring No. 1 fixture failed after the first reactor cycle and operated at 675 to 725°F during reactor operating periods thereafter. Both thermocouples on Stauffer 880 Spring No. 5 failed during the first reactor cycle. The heater and the thermocouple attached to the position transducer on the test fixture were still operable. The heater was controlled by using the transducer thermocouple and the ΔT from an adjacent test fixture as a guide. As the temperature was increased, one of the "failed" thermocouples began functioning. Operating temperature was achieved after ~690 hours had elapsed. After 1150 hours of the experiment had elapsed, the thermocouple

TABLE 5
SUMMARY OF REACTOR OPERATIONS

	Accumulated Time In-Pile at 2 Mw (hr)	Total Time at Temperature and Vacuum (hr)
Start Cycle 1	0	27
End Cycle 1	281.97	309
Start Cycle 2	281.97	452
End Cycle 2	445.44	618
Start Cycle 3	445.44	642
End Cycle 3	757.69	956
Start Cycle 4	757.69	980
End Cycle 4	989.34	1269
Start Cycle 5	989.34	1344
End Cycle 5	1248.53	1606
Start Cycle 6	1248.53	1654
End Cycle 6	1531.93	1940
Start Cycle 7	1531.93	1993
End Cycle 7	1838.21	2244
Start Cycle 8	1838.21	2320
End Cycle 8	2078.24	2556
Start Cycle 9	2078.24	2605
End Cycle 9	2326.16	2840
Start Cycle 10	2326.16	2924
End of Irradiation	2597.5	3228

failed once again. During the remainder of the test, the power setting on the heater control was maintained at the same level and the transducer thermocouple monitored. It was estimated that the desired temperature was maintained within $\pm 25^{\circ}\text{F}$. Temperature control problems were also experienced with Rene'41 Spring No. 4 during the last two reactor cycles. The temperature averaged 50 to 100°F too high for the remainder of the test. The operating temperatures are summarized in Table 6.

TABLE 6
SUMMARY OF MECHANICAL PERFORMANCE OF IRRADIATED SPRINGS

Spring		Test Conditions*		Characteristic Relaxation Parameters at Room Temperature										
Material	Serial Number	Average [†] Test Temperature (°F)	Relative [§] Radiation Exposure	Free Length		Spring Constant			Set Load**			Strain Energy		
				Pre-Test (in.)	Post-Test (in.)	Pre-Test (lb/in.)	Post-Test (lb/in.)	Change (%)	Pre-Test (lb)	Post-Test (lb)	Change (%)	Pre-Test (in. -lb)	Post-Test (in. -lb)	Change (%)
Rene' 41	1	675 to 725 (340)	High	2.088	2.033	101.4	106.9	+5.4	34.2	31.9	-6.7	5.73	4.72	-17.6
Rene' 41	2	1050	High	2.103	2.066	101.4	103.8	+2.4	34.0	32.6	-4.1	5.70	5.15	-9.6
Rene' 41	3	1150	High	2.080	1.985	101.4	102.0	+0.6	35.4	27.9	-21.2	6.18	3.81	-38.3
Rene' 41	4	1150	Intermediate	2.105	2.022	100.8	102.0	+1.2	35.9	29.3	-18.4	6.37	4.22	-33.8
Rene' 41	5	1150	Low	2.100	2.063	100.3	103.2	+2.9	35.0	32.6	-6.9	6.04	5.15	-14.7
Stauffer 880	1	1050	High	2.115	1.886	88.3	90.2	+2.1	32.6	12.3	-62.3	5.92	0.84	-85.8
Stauffer 880	2	1300	High	2.105	1.822	85.9	91.6	+6.6	32.4	8.7	-73.2	6.09	0.41	-93.3
Stauffer 880	3	975 to 1025 (680)	High	2.091	2.036	83.7	84.9	+1.4	31.0	26.5	-14.5	5.73	4.13	-27.9
Stauffer 880	4	1140	Intermediate	2.100	2.061	89.1	89.9	+0.9	32.9	30.4	-7.6	6.05	5.15	-14.9
Stauffer 880	5	1150	Low	2.084	2.011	88.5	89.1	+0.7	32.6	27.3	-16.3	5.98	4.19	-29.9

*The pressure was less than 2×10^{-4} torr and duration was 3200 hr for all specimens.

†The first value or range of values is the temperature during reactor operation, the second value corresponds to the reactor-off condition as heaters failed early in the test.

§For exact radiation exposures, consult Table 7.

**The room temperature set load is such that the torsional stress at test temperature is 40,000 psi.

Radiation doses to the test springs are listed in Table 7. Neutron doses were determined from wire dosimeters (iron and cobalt) attached to the test specimens during irradiation and from mockup dosimetry measurements made prior to the actual test. Gamma exposures were calculated from the total irradiation time and gamma dose rates measured in the mockup capsule.

The pressure levels in the test section ranged from 1×10^{-4} to 2×10^{-4} torr throughout the experiment. The higher than design pressure of the test capsule was attributed to one or both of two sources, either a small untraceable leak or continued outgassing of the glass fiber insulation used on the instrumentation leads. The exact effect of the higher pressure on the performance of the springs is not known.

TABLE 7
RADIATION EXPOSURES

Spring Number		Neutron Exposures (n/cm^2)			Gamma Dose R
		Thermal	Resonance	Fast	
Rene' 41	1	8.16×10^{18}	1.15×10^{19}	1.31×10^{19}	5.04×10^{10}
	2	5.35×10^{18}	1.26×10^{19}	1.98×10^{19}	4.78×10^{10}
	3	3.73×10^{18}	0.71×10^{19}	1.01×10^{19}	4.57×10^{10}
	4	1.47×10^{18}	4.03×10^{18}	3.11×10^{18}	1.77×10^{10}
	5	3.07×10^{17}	2.79×10^{17}	2.36×10^{17}	6.49×10^9
Stauffer 880	1	6.65×10^{18}	1.45×10^{19}	1.90×10^{19}	5.97×10^{10}
	2	9.27×10^{18}	1.77×10^{19}	2.94×10^{19}	7.50×10^{10}
	3	3.35×10^{18}	0.80×10^{19}	0.98×10^{19}	4.98×10^{10}
	4	1.64×10^{18}	3.76×10^{18}	3.37×10^{18}	1.71×10^{10}
	5	2.78×10^{17}	2.74×10^{17}	1.97×10^{17}	5.19×10^9

*Neutron energy intervals: thermal $E < 0.4$ ev; Resonance, 0.4 ev $< E < 0.1$ mev; Fast, $E > 0.1$ Mev.

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Figure 4. René 41 and Stauffer 880 Spring Force

IV. IRRADIATION TEST RESULTS

The spring force vs test time data from five springs are presented as Figure 4. Mechanical binding which affected in-pile measurements on two of the test fixtures and the failure of three position transducers reduced the number of available in-pile test data.

At the conclusion of the irradiation, the test assembly was transported to the Battelle Hot-Cell Facility for disassembly and examination. The dosimeter wires were removed from the test fixtures for radioanalysis.

After the test springs had been removed from the test fixtures, their free lengths were measured and length vs load characteristics were determined. Spring length measurements were taken at 5-lb intervals as load was increased and again as load was decreased. Care was taken during these measurements not to load the springs to greater than 50 lb or to compress the springs to below 1.500 in. The typical results of these tests are shown in Figure 5 along with pre-test data for each test spring taken at decreasing loads.

A summary of the mechanical performance of the test springs was shown in Table 6. Post-test room temperature load values in the table are the load at the pre-test set length as illustrated in Figure 5. Strain energy calculations were also done at the pre-test set length using equations in Sect. II-F.

The test results on René 41 Springs 3, 4, and 5 at 1150°F indicate definite effects from the different radiation doses. The greater relaxation of Spring No. 1 over that of Spring No. 2 is probably due to the repeated temperature cycling on Spring No. 1 because of early heater failure.

No definite trends are obvious in the results of the Stauffer 880 springs although the high radiation dose appears to have produced significantly more relaxation. The reason for the widely differing amount of relaxation exhibited by these springs is not known.

The force vs time curves for René 41 (Figure 4) show a smaller relaxation of force at 1050°F and below, than at 1150°F. The Stauffer 880 springs show less force relaxation at approximately 1000°F than the 1150°F samples.

Figure 5. Typical Curve of Spring Force vs Length

Five of the test springs were sectioned and photomicrographs taken. The five springs examined included René 41 Springs 2 thru 5 and Stauffer 880 Spring 2. Typical microstructures are shown in Figures 6, 7, 8, and 9. No appreciable metallurgical changes occurred in either the René 41 or the Stauffer 880 due to the in-pile test conditions.

a. 100X: Active coil

HC-18222

b. 100X: Center of active coil

HC-18223

6-14-67 UNC

7695-55355

Figure 6. Typical Pre-Test Microstructures of
René 41 Springs

a. 100X: Active coil

HC-18242

b. 100X: Center of active coil

HC-18243

6-14-67 UNC

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Figure 7. Typical Post-Test Microstructures of
René 41 Springs

a. 40X: Active Coil

5568-(8-A)-2

b. 250X: Center of Active Coil
6-14-67 UNC

5568-(31-A)-4
7695-55357

Figure 8. Typical Pre-Test Microstructures
of Stauffer 880 Springs

a. 100X: Active coil

HC-18255

b. 100X: Center of active coil

HC-18256

6-14-67 UNC

7695-55358

Figure 9. Typical Post-Test Microstructures of
Stauffer 880 Springs

V. OUT-OF-REACTOR TESTS

Representative springs selected from the same two groups of springs from which the irradiated springs had been taken were tested in a nonnuclear environment under essentially the same time-temperature-stress conditions in an effort to separate the effects of radiation. Table 8 summarizes the test conditions.

The test assemblies used for the nonnuclear test included provisions for measuring the relaxation during the test. Power shutdowns and equipment failures during the test resulted in temperature cycling of the springs. The inconsistencies of force relaxation vs time data are attributed to their inadvertent thermal cycles. The pre-post-test evaluation method was used to interpret the effects.

A. MECHANICAL PERFORMANCE DATA

The mechanical performance characteristics for each spring were measured prior to and after completing the test cycle. The pre- and post-test spring force vs deflection data for a typical spring are shown on Figure 10. The indicated nonlinearity of the curve at low force near free length is due to the difficulty of measuring low forces accurately. A summary of the data from the test is shown in Table 9.

B. METALLOGRAPHIC EXAMINATION

Photomicrographs were taken of sections of two René 41 and Stauffer 880 springs selected at random from the same batch as the test springs. No significant differences were noted between these photomicrographs and those made from the post out-of-reactor test springs.

C. CONCLUSIONS

An evaluation of the nonnuclear test results suggests that in the environment of an operating temperature of 1150°F over long periods of time, the ultimate capabilities of René 41 as a spring material may be approached. This

TABLE 8
NONNUCLEAR SPRING TEST CONDITIONS

	Test Specimen					
	René 41			Stauffer 880		
Nominal Test Temperature (°F)	1050	1150	1150	1050	1150	1035
Actual Mean Test Temperature (°F)	1051	1154	1149	1070	1160	975
Serial Number	26	29	27	26	28	27
Wire Diameter (in.)	0.125	0.125	0.125	0.125	0.125	0.125
Mean Coil Diameter (in.)	0.803	0.807	0.800	0.818	0.808	0.815
Wahl Factor	1.234	1.233	1.235	1.228	1.233	1.226
* Net Test Load, 70°F (lb)	35.0	34.6	34.8	33.1	32.0	32.6
* Set Length, 70°F (in.)	1.735	1.743	1.733	1.692	1.709	1.678

*Calculations are based on 40,000-psi-corrected fiber stresses at test temperature.

Figure 10. Typical Curve of Spring
Force vs Length, Out-of-Pile
Correlation Test

TABLE 9
SUMMARY OF MECHANICAL PERFORMANCE OF NONIRRADIATED TEST SPRINGS

Spring		Test Condition*		Effective Free Length		Characteristic Relaxation Parameters at Room Temperature								
Material	Serial Number	Mean Temperature (°F)	Duration (hr)	Pre-Test (in.)	Post-Test (in.)	Spring Constant			Set Load†			Strain Energy		
						Pre-Test (lb/in.)	Post-Test (lb/in.)	Change (%)	Pre-Test (lb)	Post-Test (lb)	Change (%)	Pre-Test (in./lb)	Post-Test (in./lb)	Change (%)
Rene' 41	26	1051	3800	2.075	2.040	102.5	105.7	+2.0	35.0	32.3	-7.8	6.03	4.92	-17.5
Rene' 41	27	1149	3800	2.072	1.980	102.0	104.5	+2.5	34.8	26.1	-25.0	6.04	3.23	-46.5
Rene' 41	29	1154	3800	2.085	2.015	101.5	103.1	+1.6	34.6	28.3	-18.2	5.92	3.83	-42.2
Stauffer 880	26	1070	2920	2.060	2.010	88.0	88.9	+1.02	33.1	28.2	-14.8	6.07	4.47	-28.1
Stauffer 880	27	975	2920	2.065	2.035	84.2	85.1	+1.07	32.6	30.3	-7.0	6.31	5.41	-14.6
Stauffer 880	28	1160	2920	2.067	1.956	88.9	90.7	+0.90	32.0	22.5	-29.7	5.83	2.78	-51.4

*The pressure was less than 2×10^{-5} torr during the test.

†The room temperature set load is such that the torsional stress at test temperature is 40,000 psi.

Figure 11. Comparison of Nonirradiated Spring Materials

conclusion is based on the observation that the relaxation at 1150°F is about 2-1/2 times higher than that observed at a temperature only 100°F lower. The relaxation ranging from about 8% at 1050°F to 25% at 1150°F for force relaxation and correspondingly 18% to 45% for energy relaxation may be expected.

An appraisal of the Stauffer 880 spring specimens shows a similar magnitude of relaxation; i. e. , 15% at 1070°F to 30% at 1160°F for force relaxation and correspondingly, 28% to 51% for energy relaxation. Stauffer 880, like Rene'41, appears to be approaching its ultimate capability as a spring material at 1200°F operating temperature.

The nonnuclear test data presented graphically, in Figure 11, show that the Rene'41 spring exhibits a lower percent relaxation than does the Stauffer 880 spring at all temperatures tested, although the relaxation slope for Rene'41 is larger than that for Stauffer 880. It should be noted that the result is a cross-over point where both materials should exhibit equal performance. Beyond this point (~1200°F) the Stauffer 880 should show less relaxation than Rene'41.

Figure 12. Comparison of Irradiated to Nonirradiated Spring Force Relaxation

VI. COMPARISON OF IRRADIATED AND NON-IRRADIATED SPRING TEST RESULTS

The 3300-hour irradiation test points were plotted similarly to the nonirradiated test points in an attempt to show a relaxation vs temperature relationship and the points were coded as to radiation level (Figures 12 and 13). It was not possible to draw a smooth curve through the data points. The curves from Figure 11 are superimposed on the appropriate figure to assist in a comparison of the data. Some interesting observations are possible:

- 1) All values of energy relaxation (R_E) and force relaxation (R_F) for irradiated Rene' 41 lie below the corresponding unirradiated spring relaxation values. This implies that radiation decreases the percent relaxation (both force and energy) in Rene' 41. This was also indicated on an earlier irradiation test of Rene' 41 at 1000°F.

- 2) The data indicate that the total relaxation in a given time for irradiated Rene' 41 may be increased with temperature, and at 1150 to 1200°F, the percent relaxation for the unirradiated and the irradiated are about equal.

- 3) If the effect of radiation at a constant temperature (R-3, R-4, and R-5) is considered, it appears that the percent relaxation is a function of the dosage. An obvious conclusion, although a dangerous one to make with the limited amount of data available, would be that a small amount of radiation may be beneficial. It is conceivable that a low fast neutron dosage "hardens" the precipitation-hardened alloy slightly, but continued fast neutron irradiation acts to "over-age" the alloy, increasing the relaxation.

- 4) The effects of radiation on the solid-solution, Stauffer 880 alloy show no apparent pattern, except that a high fast neutron dosage appears to increase the percent relaxation at the lower temperatures.

- 5) The one data point (S-2) at 1300°F and approximately 10^{19} n/cm² is significant, if true, in that the percent relaxation for the irradiated Stauffer 880 spring agrees very well with the extrapolated nonnuclear data. The significance of the information is that at elevated temperatures the

Figure 13. Comparison of Irradiated to Nonirradiated Spring Energy Relaxation

effects of radiation on the solid-solution alloy may be minimal, and that the relaxation is essentially temperature and time induced.

The conclusions to be drawn from the evaluation of the unirradiated and irradiated spring test data are that the René 41 springs appear to be superior in both cases to the Stauffer 880 springs at all test temperatures up to approximately 1150°F based on percent energy relaxation and percent force relaxation. At 1200°F and above, the Stauffer 880 springs may be superior, although both springs exhibit high percentage relaxations.

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