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COMPRESSION SPRINGS FOR LONG TIME OPERATION IN VACUUM AT 1000° F

Prepared by
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Cincinnati, Ohio 45215
for Lewis Research Center

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16. Abstract

Electrical switchgear for large space power systems operating in a temperature environment of 1000° F require various springs that must operate reliably for long periods. Suitable materials are quite limited, and designs must be conservative to obtain low relaxation. An extensive investigation of possible materials and design parameters led to the selection of Inconel 718 with triple heat treatment for opening and contact wipe springs. Tests over a 2000 hour period at 1000° F showed low relaxation and good performance.

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FOREWORD

The investigation described in this report was conducted by the General Electric Company under NASA contract NAS 3-9421. Mr. Ernest A. Koutnik, of the Space Power Systems Division, NASA Lewis Research Center, was the Project Manager. The report was originally issued as General Electric report GESP-345.

TABLE OF CONTENTS

I. SUMMARY

This report describes the investigation, design and test of two different compression springs that were developed for use in a 1000°F vacuum environment and a minimum life of 10,000 hours. The springs were for use in the Breaker and Contactor being developed under Contract NAS3-9421, for use in Space Nuclear Electrical Systems.

The environment temperature limited the materials which were available as candidates for the compression springs. A suitable candidate material must have low relaxation over a long time at the operating temperature of 1000°F, yet must be workable so the desired design characteristics can be obtained within the available space.

Characteristics of many possible materials were reviewed in detail, but Inconel 718, with a suitable initial temper to permit cold forming, followed by a triple heat treatment, was the preferred material.

Samples of the springs to be used in the Switchgear units were built, carefully checked for load-deflection characteristics, and then endurance tested under normal full load,and at solid height,at 1050°F and 1150°F. Lengths of the springs at "no load", checked before the test series, and again after various periods of heat soaking at test temperature, were used to determine the relaxation. Final load-deflection data is compared with the original spring conditions, to indicate suitability of the Inconel 718 for long time operation in a 1000°F environment.

II. INTRODUCTION

Switchgear units (AC Breaker and DC Contactor) under development for use in a space nuclear electrical system , required compression springs which would provide long life while in a 1000°F ambient temperature. Furthermore, various restrictions on spring dimensions, based on available space and motion of the switchgear units, required new design approaches and development of spring characteristics which were not available in published literature or the files of spring manufacturers.

Materials available for high temperature use are quite limited. Possible candidates include Inconel 718 and X750, Rene'41, A286 Stainless Steel, Cobalt base L608 and S816, Haynes 25, and Udimet 700. Data from wire manufacturers for the size of springs involved in applications such as the switchgear units is too limited to provide more than general guidance in the high temperature design area.

A summary of data obtained on high temperature spring material from suppliers and spring manufacturers, is presented in this report. Spring design calculations with several material parameters are used to provide the best compression springs with maximum force in a limited space. The selected material and design was used to build samples of two sizes of springs as shown in Figure 1.

Tests of the samples determined creep performance data over a 2000 hour period at temperatures of 1050°F and 1150°F. The resulting data provides definite new guidelines for selecting material and designing long life springs for a 1000°F environment.

III. SELECTION AND PREPARATION OF CANDIDATE MATERIALS

The high temperature springs are intended for use at 1000°F to 1050°F, in vacuum, for periods of time in the order of 10,000 hours. This required that the springs retain their load carrying capacity under these time-temperature conditions with minimum loss due to stress relaxation. A service temperature of 1000°F for high performance springs required to operate at or below a recommended nominal of 40,000 psi stress, with less than a 10% load relaxation in thousands of hours, is a most severe requirement demanding the use of a material with excellent stress relaxation characteristics.

The high temperature strength properties of metals are measured in terms of their elastic and plastic characteristics. Short time tensile tests indicate the recoverable elastic strain (and stress) which the material will support; the proportional limit indicates the elastic recoverable stress and various levels of the material at minor levels of permanent deformation. In the temperature range from about 900 to 1300°F many of the high temperature superalloys make a transition from elastic limiting properties to plastic, or creep, limiting properties. This transition temperature is defined as the equi-cohesive temperature; below this temperature the short time yield strengths are the limiting material property; above this temperature long time creep processes prevail in defining strength characteristics. Longer periods of test time tend to lower this transition temperature.

Creep characteristics are reported as the stress required to produce a total plastic strain of a given percentage under a steady load at a designated temperature and test (time) duration. Plastic strain under load can also be considered as the internal strain which occurs in a metal after it is initially strained elastically and held in that position at elevated temperature for a period of time; creep occurs within the specimen, elastic strain is converted to plastic strain, and the stress in the metal member decreases. This stress relaxation phenomenon occurs in bolts and springs which are initially installed under relatively high elastic stress at elevated temperature but which slowly lose their stress carrying capability through the internal creep process.

While the tensile and steady load creep characteristics are generally well established for most of the current high strength superalloys, stress relaxation data required for the design of high temperature springs and bolts is not as well documented; frequently this data must be developed at the specific design conditions. Nevertheless, a knowledge of the elastic (yield strength) and plastic (rupture strength) properties of alloys in the intended temperature range is a useful starting point in the selection of spring materials. These properties are indicated in Figures 2 and 3 for the following alloys which have been considered for the two springs that are described in this report.

1. Inconel X750
2. Inconel 718
3. Rene'41
4. Udimet 500
5. Udimet 700 (Astrolloy)
6. Stellite L605
7. A286 Stainless

The chemical compositions of these alloys are shown in Table I, while mechanical properties are shown in Table II.

All the alloys have appreciable high temperature yield strengths, and all the age hardened alloys offer reasonable thermal stability in this 1000-1200°F range so are therefore worthy of consideration. Inconel X750 in the cold worked and aged condition has yield strengths appreciably higher than that indicated in Figure 2, and as spring temper wire (65% cold worked and heat treated) it develops a 0.2% yield strength at room temperature of over 200,000 psi. L605 alloy wire, cold drawn to 20-25% reduction in area, will also develop strengths nearly equivalent to the very high strength age hardenable superalloys. The high strength cold worked spring alloys such as Inconel X offer relatively more stable spring properties at reasonable working stress levels below 1000°F. However, near or above that temperature, thermal instabilities in microstructure and in creep-relaxation processes severely limits their usefulness as deterioration in spring performance occurs with increasing temperature, time, and stress. Figure 3 relates a parameter (temperature and time combined) to stress, and shows how the stress rupture properties decrease with increase of the parameter.

An extensive amount of information on the subject of Inconel and Inconel X springs, with design guidelines, processing, and heat treatment considerations, stress relaxation data and recommended stress levels is contained in an available technical bulletin (Reference 1). A review of various available materials for springs to be used at temperatures above 400°F is given in a recent technical article (Reference 2).

Besemer and Stanton (Reference 3) have summarized the stress relaxation characteristics of several high temperature spring alloys at temperatures up to 1400°F. Some of the data is included in Table III. Note that the relaxation of the springs is indicated by percentage of loss in load after compression to various stress values. The percent load loss is relatively high for the L-605 and Inconel X-750. The text indicates that even at relatively high stress levels, for a 600°F test a 3-5% loss in load after 140 hours is typical, and the superiority of Inconel X750 at this temperature is indicated by its load loss of 1% or less. But at 1000°F, as shown in Table III, the percentage load loss for Inconel X750 increases significantly and A-286, Rene' 41, and L605 are equivalent or superior. Above 1000°F, the percentage load relaxation increases rapidly even for short test periods and relatively low spring stresses.

The need for helical spring materials having better stress relaxation characteristics than Inconel X750 for jet engines prompted a comparative study recently by the Aircraft Gas Engine Division of General Electric, of Inconel X750, Inconel 718, Rene' 41, U500, U700 and L605 for small helical springs. Some of the data which has been made available shows that in 100 hour load relaxation tests at 1000°F the most relaxation resistant alloys were Inconel 718, Rene' 41, and U500. All the alloys had grain size in the ASTM 3-4 or 3-5 range and were optimally processes. The wires were made from vacuum consumable electrode remelted or double vacuum melted material; wire drawing induced 50-60% initial cold work in Inconel X750 and Inconel 718, 25% cold work in Rene' 41, U500, U700.

The springs made from these alloys were subsequently heat treated through recrystallization/solution treatment and aging. The L605 alloy was prepared in spring form with 25% cold work followed by a stress relief heat treatment. The springs had a wire diameter of 0.080 inches, an OD of 3/4 inch, and a free length of slightly over one inch; and a load of about 13 pounds in the test condition. A summary of the relaxation testing results for these springs is listed in Table IV. A more complete list of the Inconel 718 relaxation data from the information that was made available, for springs at 1000°F, 1100°F, and 1200°F, are shown in Table V.

Other studies that have been made of the long-time stability of Inconel 718 at temperatures from 1000 to 1300°F while under stress have also been reviewed. Evaluation included optical and electronic microscopy, X-ray diffraction, and X-ray fluorescence methods of phase analysis before and after exposure. Except for the expected over aging at 1300°F, there were no detrimental instabilities observed. The exceptional stability of this alloy in the temperature range under consideration offers substantial reasons for its excellent performance, and is a major reason for considering Inconel 718 to be superior to the other alloys for the Switchgear spring applications.

IV. SPRING DESIGN

The original springs made of Inconel X-750 were found to have relaxed excessively after 1000 hours in vacuum and at a temperature of 1000 to 1050°F. Maximum stress on these springs was about 30,000 psi.

Therefore in designing the springs using the preferred Inconel 718, every effort was made to reduce the normal room temperature stress to less than 25,000 psi, with a maximum of 30,000 psi when fully compressed. At this low stress level it was felt that the relaxation of Inconel 718 should be minimal and acceptable over a long period of time.

Furthermore, the new springs were designed to have the same configuration, i.e., round wire compression springs, and as near to the same size as possible, so they could be immediately applied to the switchgear program.

The basic formulas for round-wire compression springs are as follows:

$$S = \frac{8PD}{\pi d^3} Kw; \text{ and } P = \frac{fGd^4}{8D^3N}$$

The symbols used in these formulas, and the spring calculations, are shown below.

SYMBOLS

G	Shear Modulus, 10^6 psi
O.D.	Outside Diameter, in.
I.D.	Inside Diameter, in.
d.	Wire Diameter, in.
D.	Mean Diameter (O.D.-d), in.
N	Number of active coils
P	Load, lb.
f	Deflection, in.
L	Length, in.
S	Stress, 10^3 psi
T	Temperature, °F
kW	Wahl Correction Factor

SUBSCRIPTS:

1 Indicates initial load condition
2 Indicates maximum working condition
3 Indicates solid height

The Wahl correction factor corrects the computed stress for curvature of the wire and shear load. This formula was published in "Mechanical Engineering" by Dr. A. M. Wahl. The correction factor is a function of the spring index D/d, and is defined as follows:

$$Kw = \frac{4\ D/d - 1}{4\ D/d - 4} + \frac{.615}{D/d}$$

These formulas were used to calculate the forces and stresses in designing the springs. Initial calculations were based on a room temperature modulus, and the final designs were checked for maximum stress at 1200°F.

Three springs were designed, and two were tested. This information will cover the two that were tested, and will be designated as Design A and Design B. They are shown in Figure 1.

Some of the iterations in the design of A are shown in Table VI. The first cut was made using the dimensions of the previously tested Inconel X750 springs but with the new (Inconel 718) material (refer to column 1). Force levels were low, so free length was increased (column 2), then wire diameter was increased (column 3). Stresses were low (23,000 psi when solid) so spring rate (P/f - load/deflection) was increased to 10.6, leading to the final design (column 4). This design was then recalculated to check stress at 1200°F (column 5) which was above the design temperature but would thus provide additional operating margin. Final design (column 4) yielded a spring with a nominal (working) force of 7.9 pounds (P_2) and a stress of 19,000 psi at room temperature.

The design work on spring design B is summarized in Table VII, which shows some of the iterations investigated. The first cut again was the change in material only (column 1). Force level was so high that the decision was made to use two different springs in place of a single one, with the two springs mounted concentrically. Thus, the second design iteration (column 2) shown has the I.D. opened up to clear the original diameter spring. These values had to be adjusted slightly (column 3) to agree with inner spring on operating length and solid height, and provided a maximum operating stress of 25,000 psi. After this adjustment, spring characteristics were checked at 1200°F, and as noted (column 4) operating stress was 20,000 psi at working height and the high temperature.

Based on all available data, these springs (designs A and B) were conservatively designed and should provide the desired forces over a long period of time at 1000°F. Samples were therefore obtained for test purposes.

V. TEST SAMPLES, APPARATUS, AND PROCEDURES

A. Test Samples

Test plans called for endurance testing a total of 16 springs, 8 each of Design A and B, built in accordance with the parameters described in Section IV. The springs were ordered from the Wallace Barnes Division of the Associated Spring Corporation, in Bristol, Connecticut.

The springs were specified to be made of Inconel 718, spring temper, with a 25 to 35% reduction to obtain the spring characteristics. After forming the springs (and before final grinding of the ends) the springs were to be "triple" heated as follows (in an unstressed condition).

1 - 1750°F for 1 hour and cool to room temperature.

2 - 1325°F for 8 hours and furnace cool at 100°F/hour to

3 - 1150°F then hold for 8 hours and furnace cool to room temperature.

Note: The heat treatment was done in vacuum at the General Electric Material Development Laboratory Operation in Evendale.

Mechanical specifications for the springs are listed below:

	(G.E. Dwg. #165A5300)	(G.E. Dwg. #165A5297)
Maximum Outside Diameter	1.075"	2.40"
Minimum Inside Diameter	.85"	2.00"
Free Length	3.250" (Ref.)	1.77" (Ref.)
Maximum Solid Height	2.205"	1.05"
Diameter of Wire	0.105 ± .001"	0.192 ± .001"
Active turns	19	3.6
Gradient	10.6 lb/in. (Room Temp)	48 lb/in. (Room Temp.)
Operating Condition	(Room Temperature)	(Room Temperature)
Initial Length	2.875" (3.7 to 4.0 lb.)	1.312" (21 to 24 lb.)
Final Length	2.500" (7.5 to 8.0 lb.)	1.188" (27 to 30 lb.)
Minimum Operations (no set)	500	500

A total of 16 Design A and 12 Design B were obtained from the spring manufacturer, out of a total of 24 Design A and 18 Design B springs which had been wound and heat treated. Final selection of those that best met mechanical specifications provided the total for this test program, while the balance were used for other test activity.

Material for the springs was obtained from Techalloy Co. A certified material analysis provided the following characteristics of the wire used to make the springs.

	Design A	Design B	Typical Composition
Wire Diameter	0.105"	0.192"	
Tensile Strength	187,500 psi	147,000 psi	
Chemical Analysis	(Heat #7120 EV)	(Heat #7118 EV)	
Carbon	0.05	0.05	NIL
Chromium	18.74	18.75	18.4
Iron	18.91	18.77	19.2
Titanium	0.84	0.87	0.9
Columbium	5.15	5.10	5.3
Aluminum	0.30	0.30	0.5
Molybdenum	3.05	3.09	3.1
Manganese	0.21	0.21	0.2
Nickel	52.29	52.37	52.0
Copper	0.04	0.04	0.1
Silicon	0.33	0.33	0.3
Sulphur	0.007	0.007	NIL

Data from the analyses of the materials used may be compared with the expected typical values shown in Table I, and reproduced in the third column above. The results were within acceptable limits.

The completed sample springs were checked to determine load deflection characteristics in the "as received" condition and before starting the test program. The curves in Figures 4 and 5 indicate the load-length (mechanical) characteristics of the springs (Design A and B) before starting the endurance tests. Data supporting the curves is given in Tables VIII and IX.

After the heat treat cycle, a sample was cut from the end of a Design A and a Design B spring for sectioning and photomicrographs. The surfaces of the sections (at 100X and 1000X) of the Design A sample are shown in Figure 6. Sections (at 100X and 1000X) of the Design B sample are shown in Figure 7.

Photomicrographs of sections from both Designs of springs after the 1000 hour test are included in Section VII of this report to provide for a direct comparison with the material condition before testing started.

B. Test Apparatus and Set-Up

The endurance test was planned so as to obtain data at two temperatures, 1050°F and 1150°F with springs at both the maximum working height and at solid height. It was also planned to obtain part of the data after a series of short periods of testing, and the balance after a relatively long period without interruption.

To accomplish the goals, four fixtures were built, each holding four sample springs (2 of Design A and 2 of Design B). They were made of stainless steel, as were the washers and bolts used to compress the springs. Details of a fixture and the springs in their test condition, are shown in Figure 8. Figure 9 shows a test fixture with 4 sample springs on the fixture, ready for placement in an oven for endurance testing.

All the springs were marked on the flat (ground surfaces - each end) with an identifying number using a vibrating stylus. The springs were then carefully checked to determine their free length using a comparator for the Design A springs, and a vernier caliper for the larger diameter Design B springs. The springs were also checked to determine the force in pounds when compressed to the maximum working height and the solid height. Data for the springs prior at start of the tests, is given in Tables VIII and IX.

The basic spring data, along with a designation of the fixture to which each spring was assigned, the test loads, and the test temperature, is summarized in Table X. The footnotes indicate in detail the temperature applied to each fixture (and related springs) as well as which ones were tested for long or short periods between the measurements to check changes in the spring lengths.

Two small furnaces, heated by electrical resistance wire elements, were used. Each furnace held two fixtures with a small clearance top and sides during the endurance tests. The controls were capable of holding the test sample area to the desired temperature (1050°F or 1150°F) within a range of ± 10°F. A thermostat in the oven was used for the power control, and the furnace temperature capability was checked with a calibrating thermocouple mounted on a metal plate in the oven, prior to start of the test.

Each spring was set up for test by adjusting the holding bolt until the springs were compressed to the desired length, as measured by a calibrated vernier caliper. After each test period the free length of the springs was measured in the same way as for the initial free length (with a comparator gage for Design A and vernier caliper for Design B).

Also, prior to starting the first test, each spring was checked to determine its load-deflection characteristics. The information is shown by the curves in Figures 4 and 5. Similar data was obtained at the close of the tests, as will be described in Section VI of this report.

VI. TEST RESULTS AND DISCUSSION

A. Test Program

A schedule was established to provide a variety of test conditions for the sample springs. Half of the samples of each design were tested at 1050°F and half at 1150°F; half of each temperature group was held at the "working" load length and the others at full solid compressed height. Some were checked intermittently (interrupted after approximately 100, 200, 400, 600, 800 and 1000 hours of test) while others were checked only after 1000 and 2000 hours of testing.

The basic information on the spring test arrangement is given in Table X. It indicates sample reference number, lengths, test fixture used for each sample, and test load. The test schedule was established so the "interrupted" readings (fixtures II and IV) could be made during normal working hours, after approximately the test periods desired. At each time of measurement the springs were carefully checked for overall length and then returned to the proper location and test condition on the fixtures.

B. Test Results and Discussion

Results from the "interrupted" endurance tests are summarized in tables XI and XII. Table XI shows the data obtained on 2 samples each of Designs A and B, at 1050°F and two load conditions, after short intervals of test time. Table XII shows data on 2 samples of Designs A and B but at 1150°F after short time intervals. Relaxation (%) as related to test time is plotted to provide the curves shown in Figures 10 and 11. The single circles and squares show the data for the "interrupted" tests.

The data in Tables XI and XII shows that the relaxation obtained in the first 100 hours of testing at 1050°F was more than half of the total relaxation that was measured over the 2000 hour period. Furthermore, after about 400 hours, there was little additional relaxation for springs tested at 1050°F. Refer, for example, to sample #2 with 3.9% relaxation after 101 hours, but only 6.6% after 2000 hours in a temperature of 1050°F.

On the other hand, tests in the 1150°F environment showed that relaxation continued at a rapid rate, and after 2000 hours the total was nearly 2-1/2 times the amount obtained in the first 1000 hours. The initial rate of relaxation was also much higher on the springs in the 1150°F temperature than was the rate on the 1050°F springs.

Results from the long time test periods (1000 hours each) are summarized in Tables XIII and XIV. This data shows the change in length and relaxation (%) for 4 samples each of Design A and B, at 1050°F (Table XIII) and 1150°F (Table XIV), and two load conditions, after 1000 and 2000 hours of testing. The information is plotted with the other data (curves) in Figures 10 and 11 to provide an easy comparison of the various results. The uninterrupted data is indicated by double circles and squares.

The data shown in Tables XIII and XIV with springs which were cooled to room temperature for measurements only once during the 2000 hours tended to confirm the results from the test series which involved frequent cooling to room temperature for measurements. However, for the 1150°F condition (Table XIV) the relaxation was lower for the springs having only one interruption from temperature as compared with those having the frequent interruption (Table XII).

Load-deflection data was also obtained on two each of spring samples of Designs A and B after the 1000 hour endurance test at 1050°F. Data is shown in Table XV. Load-length characteristics of these four springs are shown by the curves in Figures 12 and 13, indicating the initial (before test) condition and the characteristics after the 1000 hours at temperature. Lengths are calculated from the free length values (before and after the tests).

Curves showing relaxation (%) for the test periods are included as Figures 10 and 11 for spring designs A and B, respectively. A few discontinuities will be noted from the plotted data, principally in connection with the 1150°F tests. However, the trends are generally consistent and provide enough basic guidance to determine that operation at 1050°F is satisfactory, but probably not at 1150°F, for any long time application due to excessive relaxation.

It is apparent from a comparison of the curves in Figure 12 and 13 that there is very little difference in the change of load-length relationship between springs that were tested at the "working" length and at "solid" height. Furthermore, the spring properties have not been affected as indicated by the fact that the load-deflection curves "before" and "after" relaxation testing are essentially parallel.

The endurance test results (Tables XI to XIV), plotted to provide the curves of Figure 10 and 11, indicate that Inconel 718 will provide springs with relatively low relaxation when operated in a temperature of 1050°F. However, the springs tested in temperature of 1150°F had high relaxation, indicating this material should be used with much caution at or above this high temperature.

Sections of small pieces cut from spring samples #4 (Design A) and #14 (Design B) after 1000 hours at 1050°F were polished, etched and recorded at 100X and 500X magnification. The results are shown in Figures 14 and 15, and indicate that essentially no change has taken place in the basic properties of the material, while under the stress and temperature conditions of this test.

The results shown by Tables XI, XII, XIII, and XIV, when compared with limited published data on relaxation, indicates a somewhat higher value was obtained than should be expected for the relatively low stresses in these springs. Reference to the design data in Tables VI and VII show that maximum (solid height) shear stress (at 1200°F) was calculated as 22,000 and 25,000 psi (Design A and B) which is well below the values of at least 40,000 psi that both wire manufacturers and other investigations suggest as maximum. However, long time relaxation data (beyond a few hundred hours) is not available from any other sources so the information provided in this spring investigation will serve to supplement the existing data for long time space applications.

It is apparent from the data that if a spring application requires a minimum of relaxation and load change over a period of time, the designer could use a "heat set" procedure to eliminate the initial change length in characteristics. In this procedure the spring design would involve the setting of a free length greater than desired by 7 or 8% and then "aging" the spring in the maximum "working" position and temperature for up to 400 hours (200 hours minimum). The data (curves) in Figures 10 and 11 indicate this procedure would obtain the major relaxation change and provide a spring that under the same temperature condition would show very little additional change in length and load.

VII. CONCLUSIONS

A review of available high temperature spring material characteristics led to the selection of Inconel 718 as the preferred material for long time operation in a 1000°F environment. Two springs were designed using Inconel 718 and working length shear stress values of 25,000 psi. Samples were obtained and long time tests conducted.

The final results indicated that with a maximum operating temperature of 1050°F, most (at least 80%) of the relaxation takes place in the first 600 hours in the environment. A limited amount of additional relaxation was noted from 600 hours up to the 2000 hour test limit. The relaxation, or change in length (and therefore load for the specified operating length), averaged only 6%.

Springs tested in a 1150°F temperature continued to relax even up to 2000 hours. For example, after 600 hours the change was 12 to 18 percent (as compared with 6 percent for springs in the 1050°F temperature). However, after 2000 hours at temperature, some of the samples had relaxed (free length had reduced) as much as 20%, so the load carrying ability was appreciably reduced.

It is concluded that suitable springs can be built of Inconel 718 for long time operation in a 1000°F environment. However, even short time operation at 1100 to 1150°F could cause appreciable relaxation and reduce the load-length characteristics of the Inconel 718 springs. This investigation, therefore, leads to these conclusions:

1. Springs for long time operation in a 1000°F environment should be designed of Inconel 718 and proportioned to have relatively low shear stresses (25,000 to 30,000 psi).

2. To obtain stability of the load length characteristics of Inconel 718 springs, the major relaxation could be eliminated by recognizing the change which will take place by increasing the original length (design) dimensions and then "aging" the springs at a temperature slightly (50°) above the operating temperature for up to 400 hours, prior to installation for the long time application.

VIII. REFERENCES

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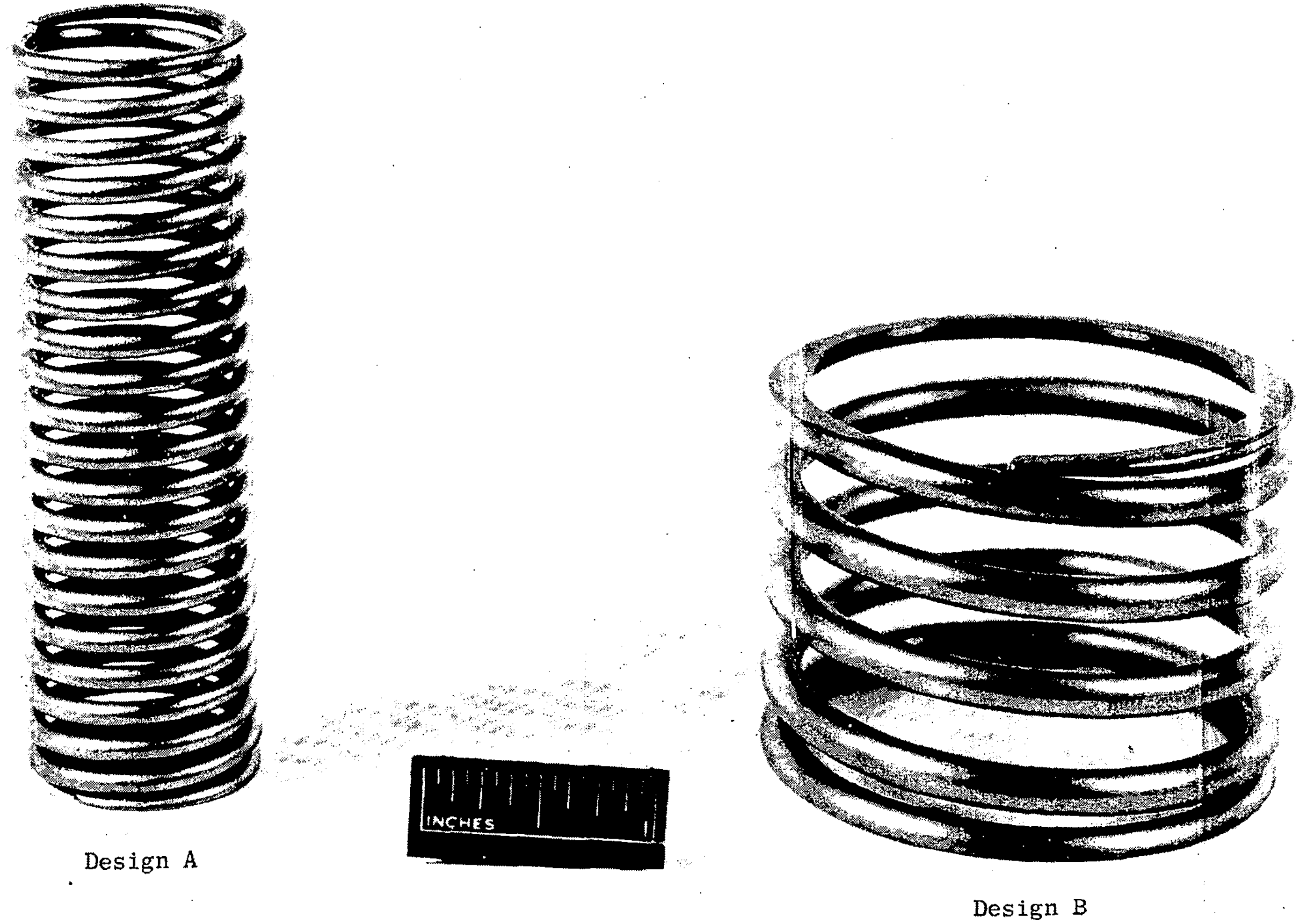


Figure 1. Sample Springs Made of Inconel 718 for Endurance Test at 1050°F and 1105°F, Designated Design A and Design B.

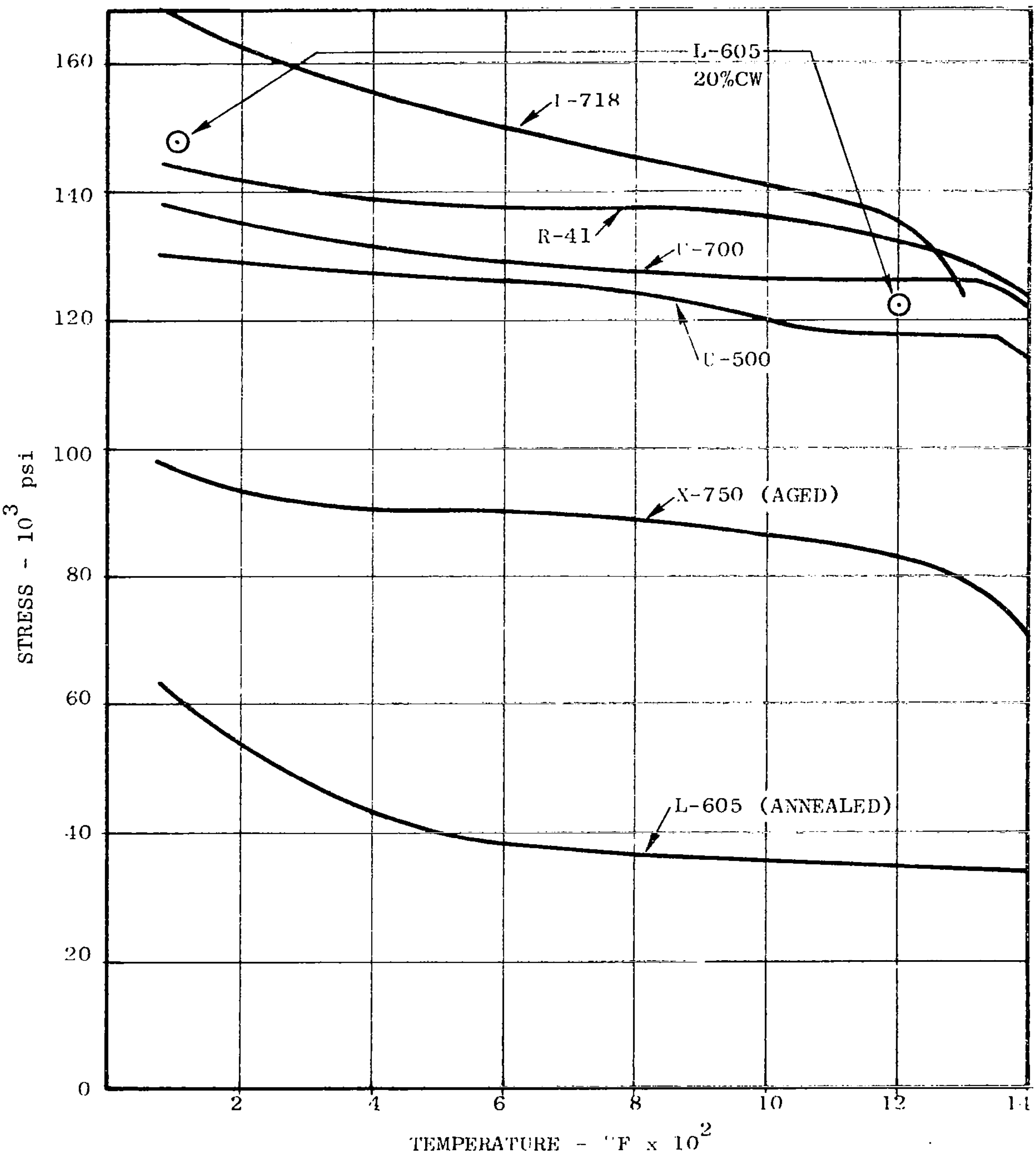


Figure 2. Curves Showing the 0.2% Yield Strength of Potential High Temperature Spring Materials, Based on Data in the General Electric Materials Handbook.

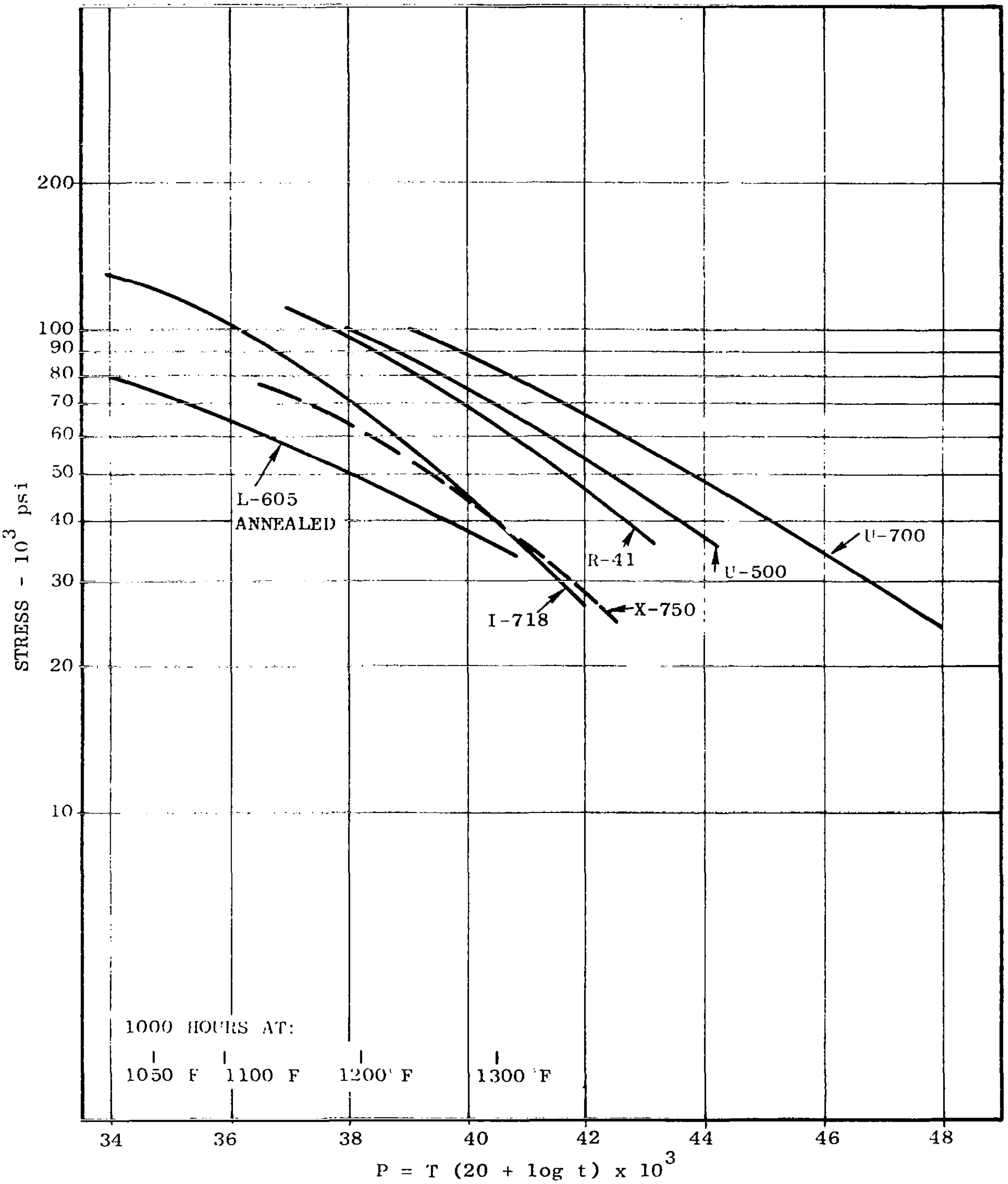


Figure 3. Rupture Properties of Potential High Temperature Spring Materials, Showing a Parameter (P) Involving Temperature and Time at which Rupture Occurs at Various Stresses.

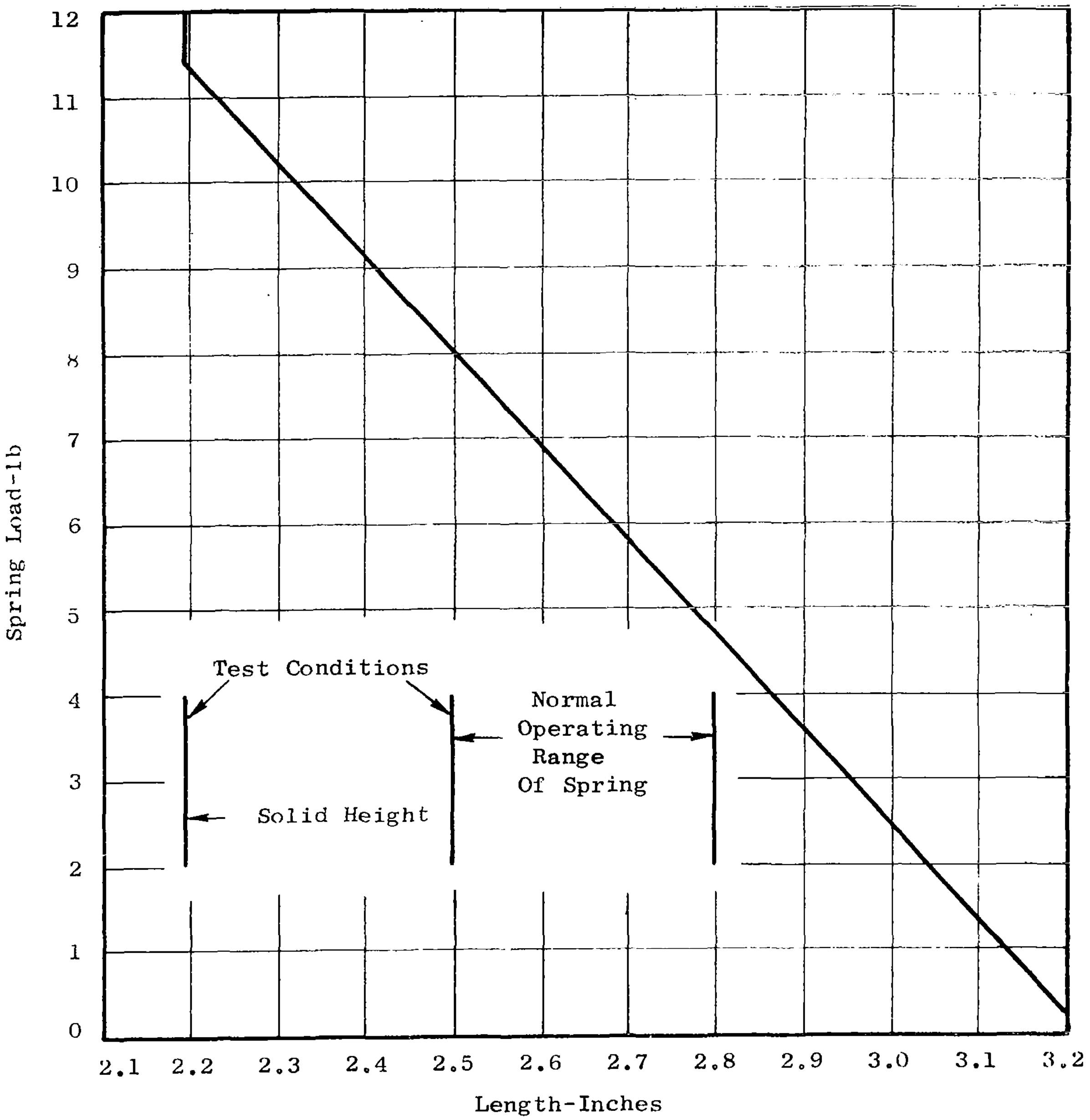


Figure 4. Load-Length Characteristics of Sample Spring Design A Prior to Start of Endurance Tests.

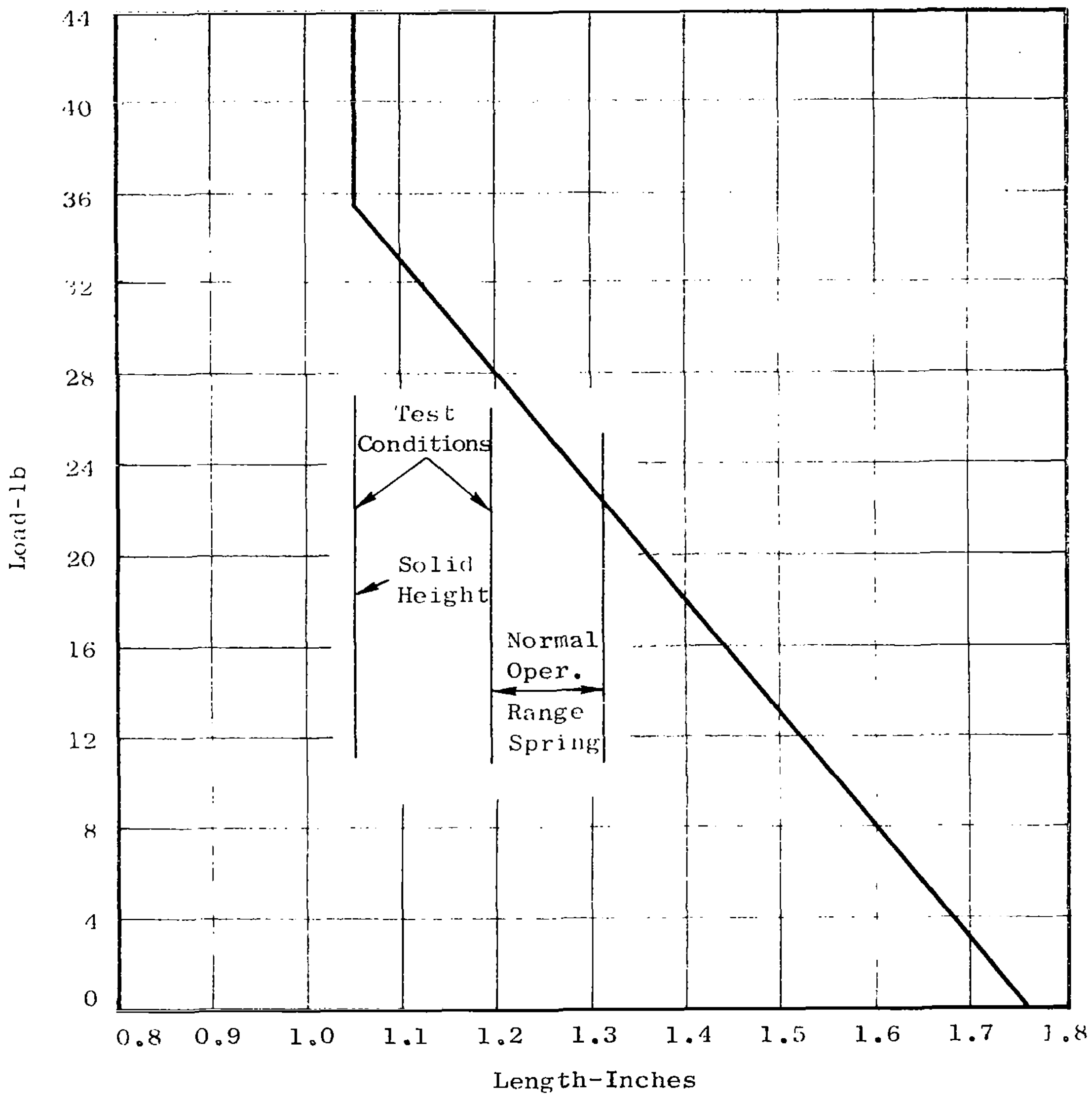


Figure 5. Load-Length Characteristics of Sample Springs Design B Prior to Start of Endurance Tests.

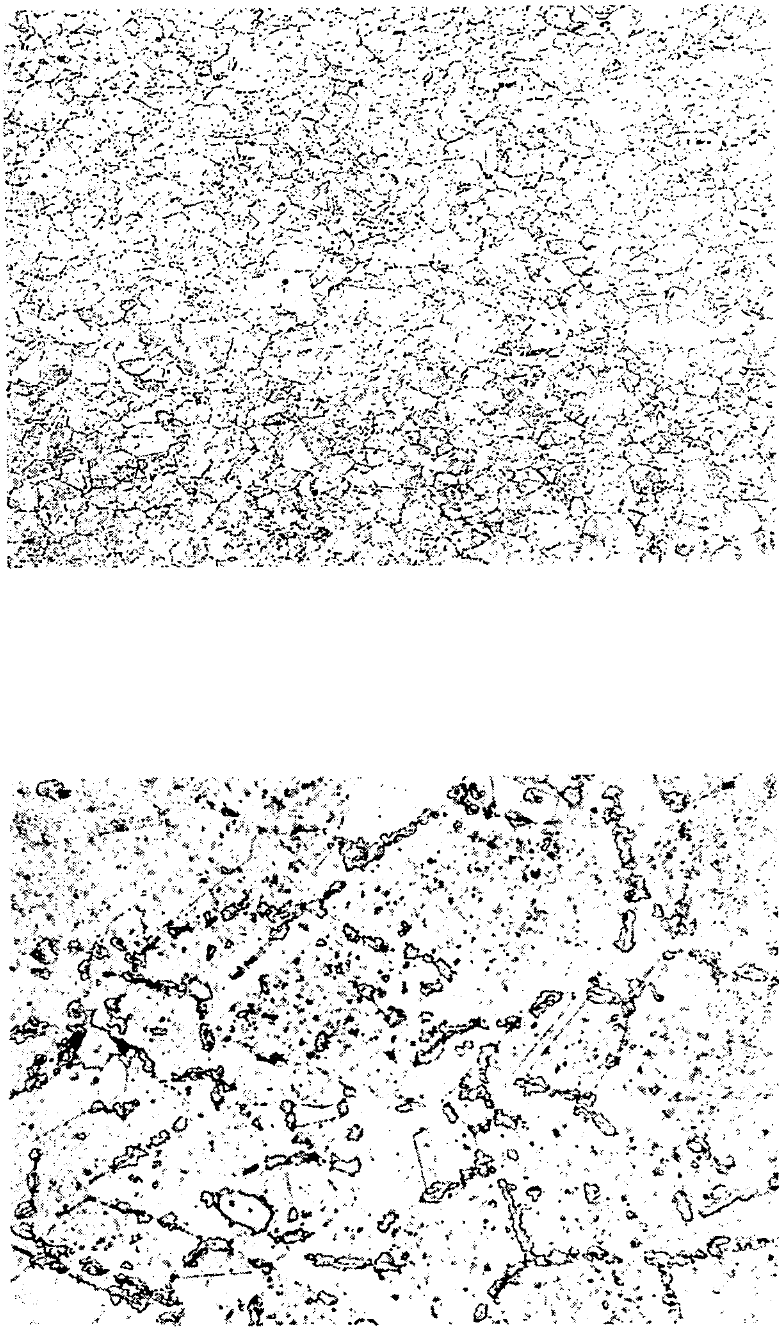
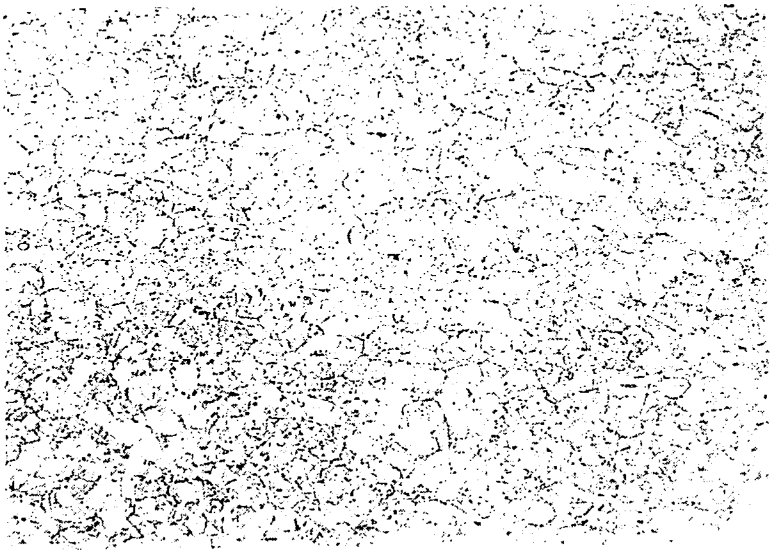


Figure 6. Photomicrographs (100X, Top and 1000X, Bottom) of Spring Design A, After Heat Treatment and Before Test.



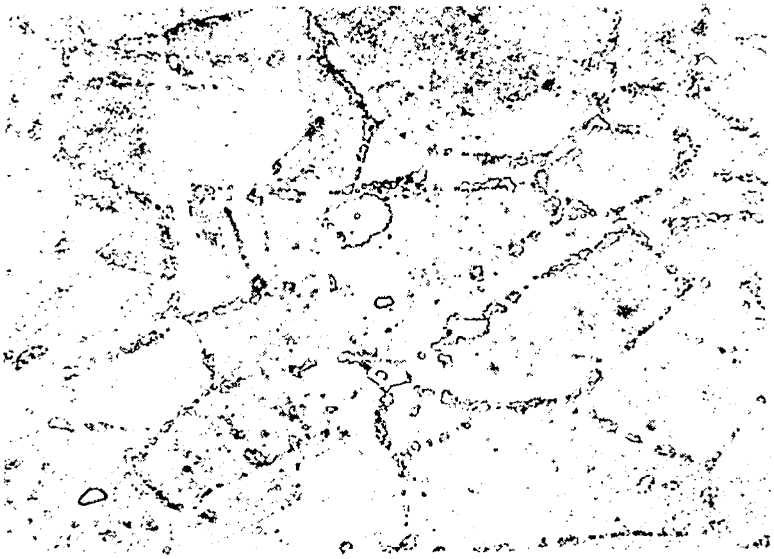
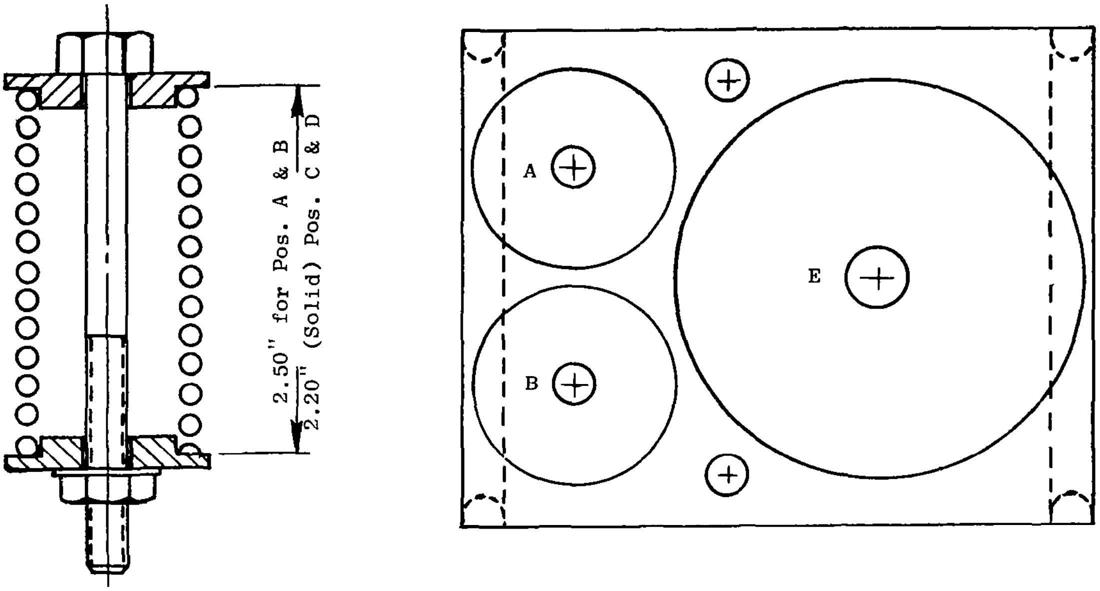
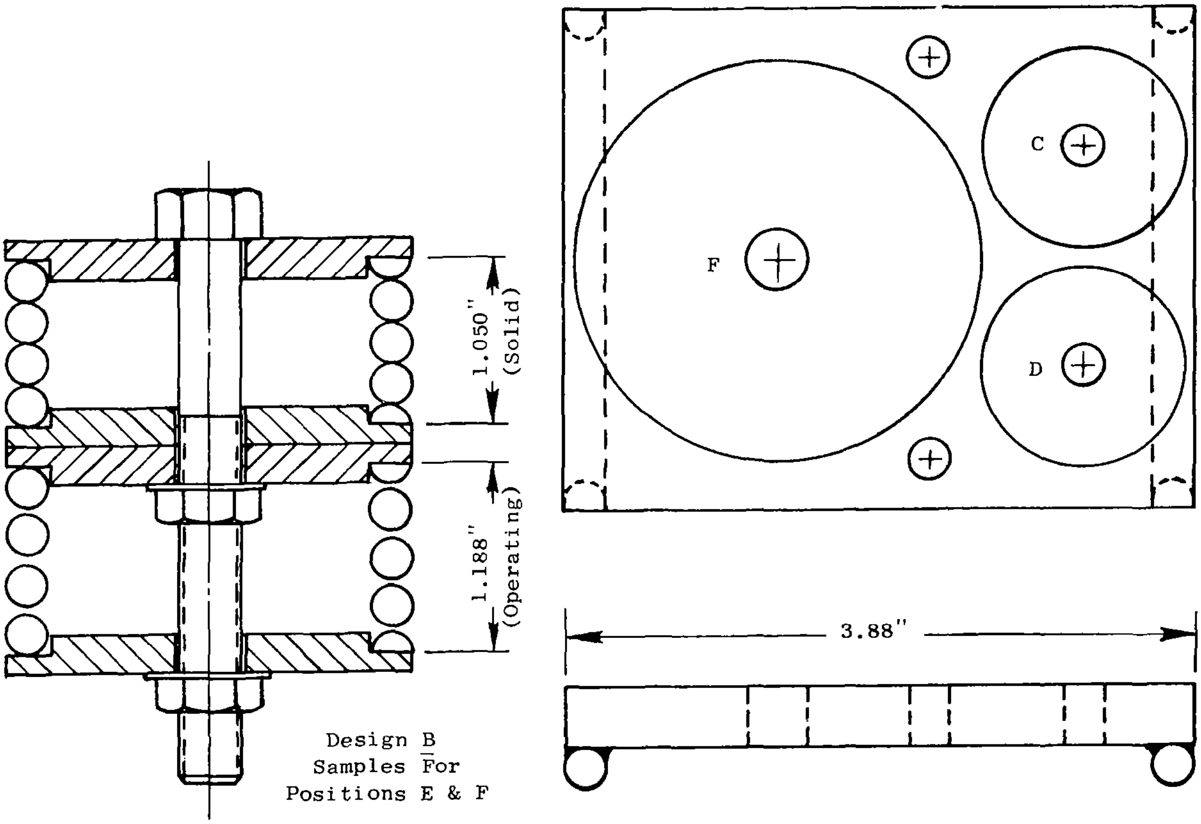


Figure 7. Photomicrographs (100X, Top and 1000X, Bottom) of Spring Design B, After Heat Treatment and Before Test



Spring Samples (Design A)
For Positions A, B, C, & D

Stainless Steel Test Fixtures



Design B
Samples For
Positions E & F

Figure 8. Arrangement of Springs and Fixtures for Endurance Test

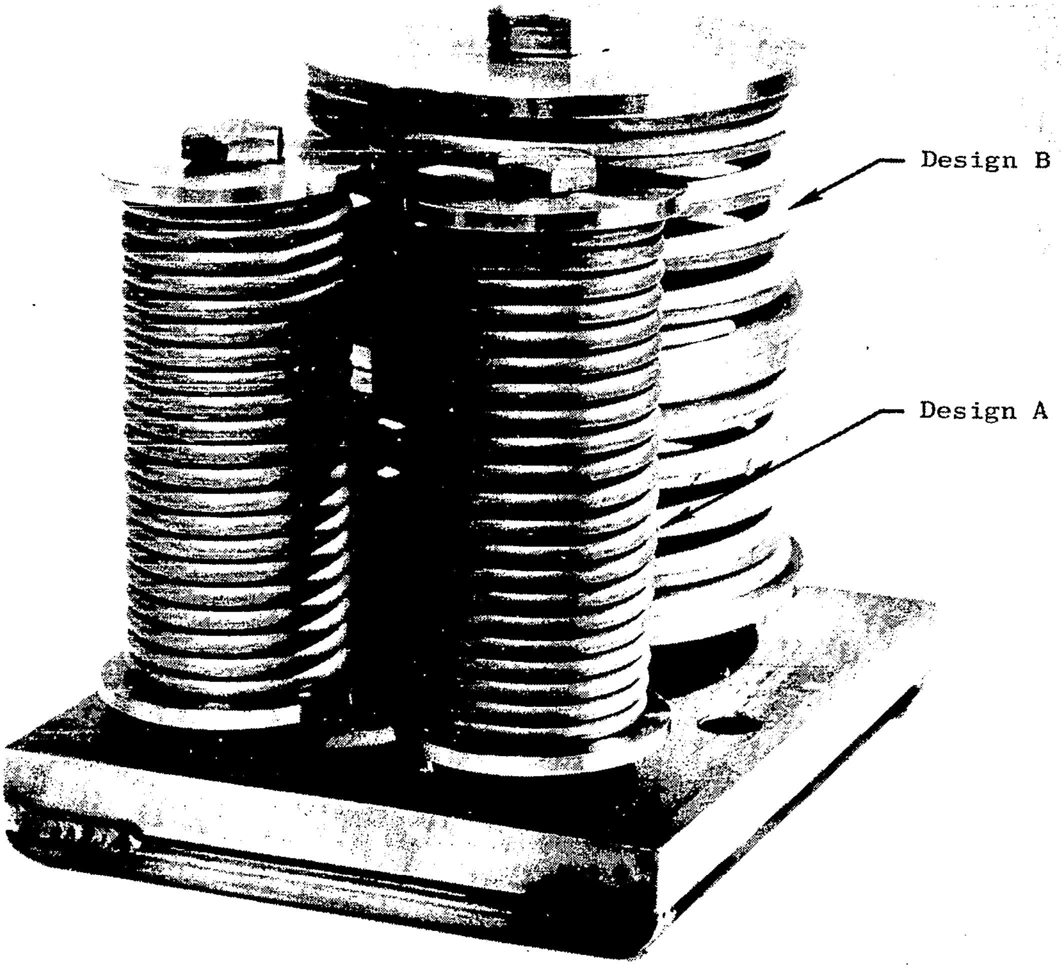


Figure 9. Sample High Temperature Springs Mounted on Test Fixture for Placement in Oven for Endurance Test.

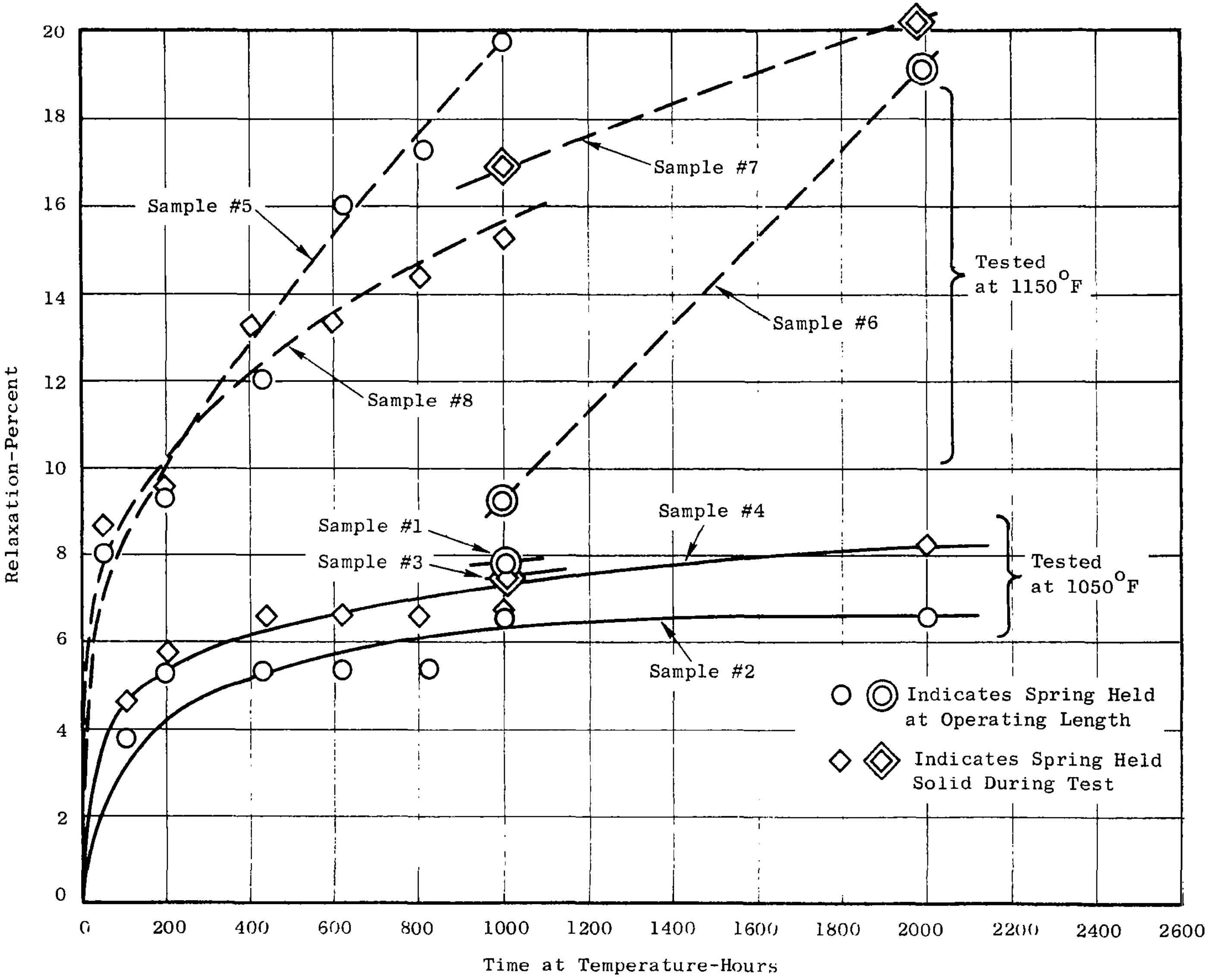


Figure 10. Load-Relaxation Characteristics of Spring Design A.

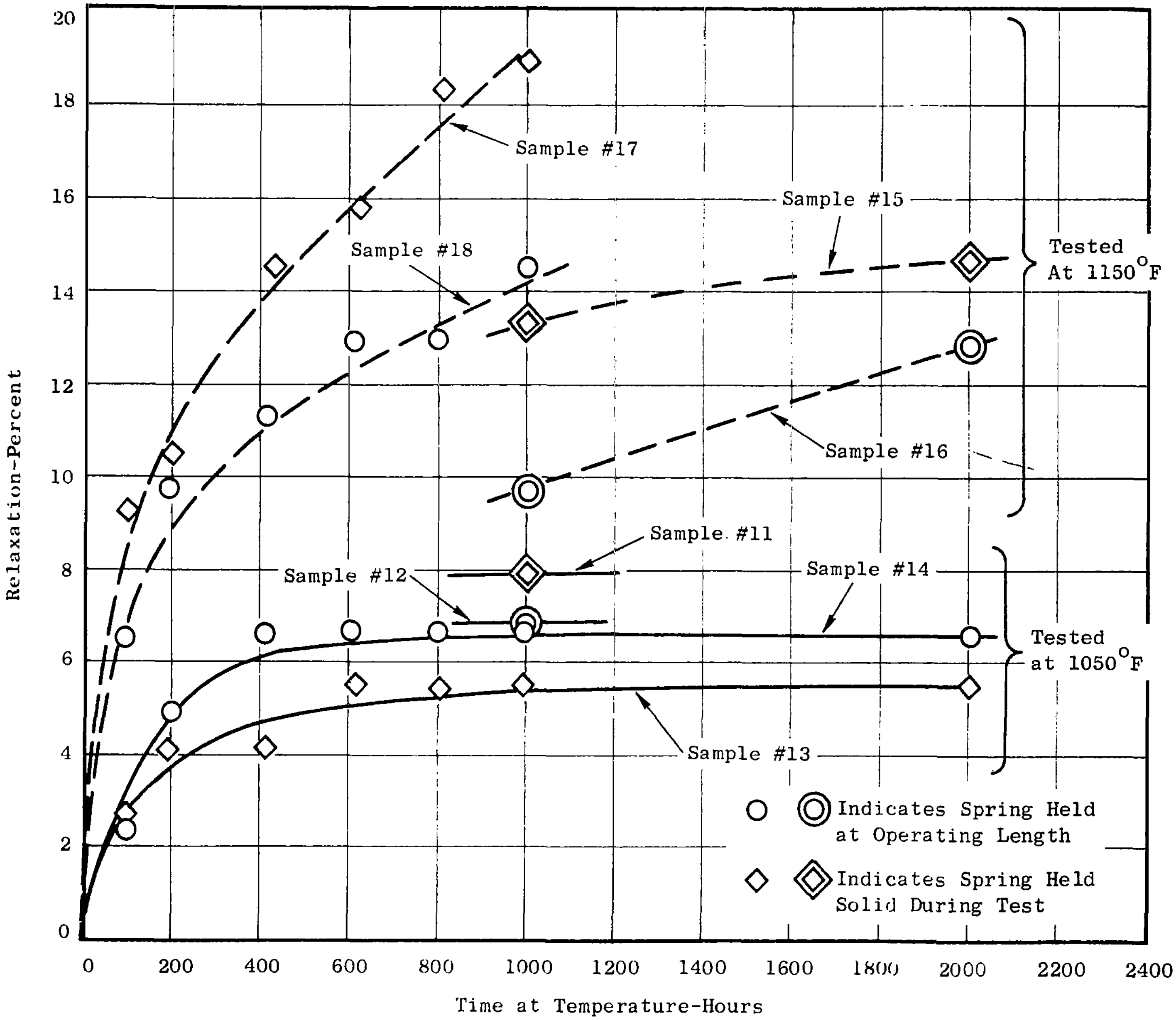


Figure 11. Load-Relaxation Characteristics of Spring Design B.

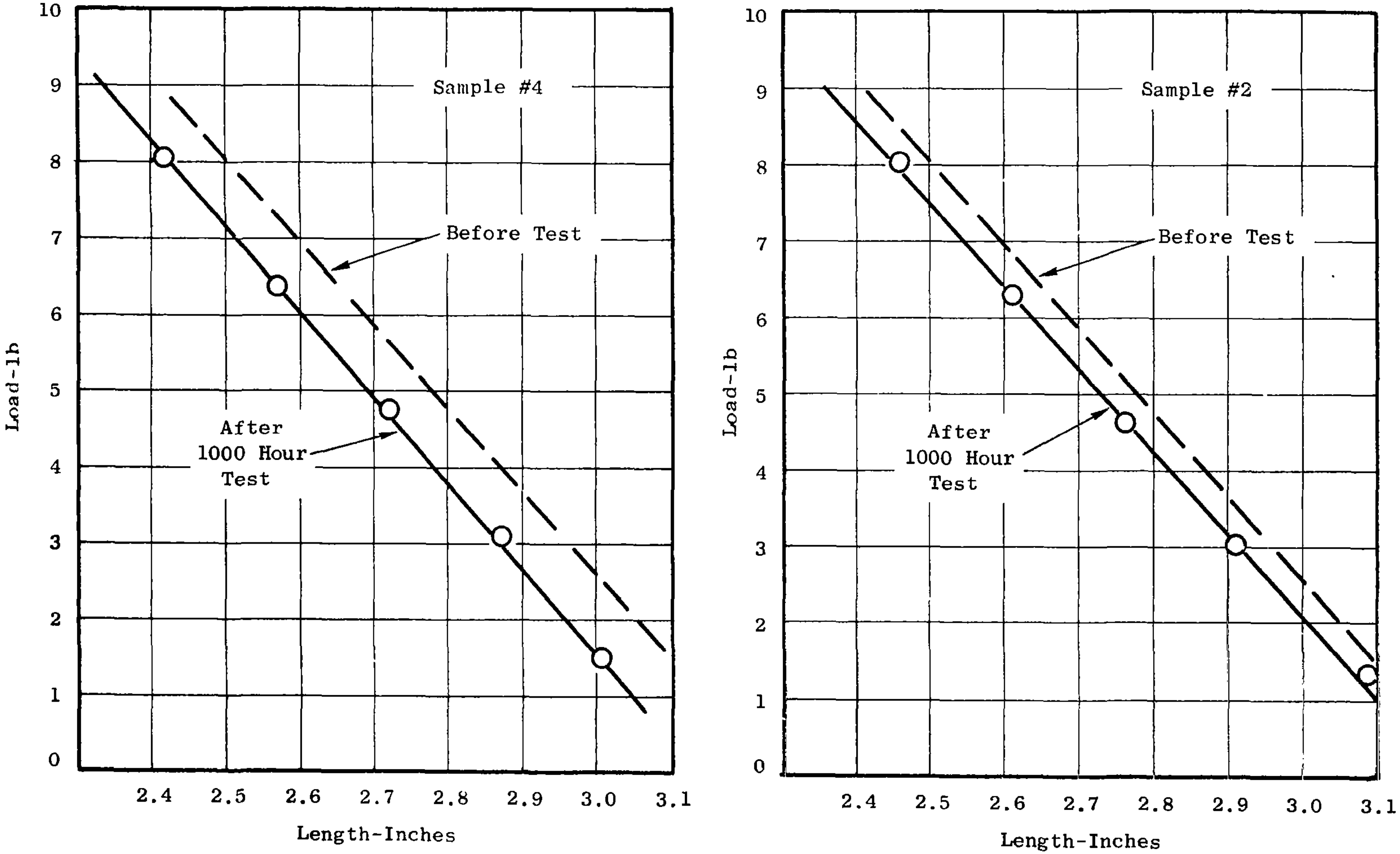


Figure 12. Load-Length Characteristics of Spring Design A for Sample #4 (Left) Kept Solid and #2 (Right) at Operating Length During Test at 1050°F.

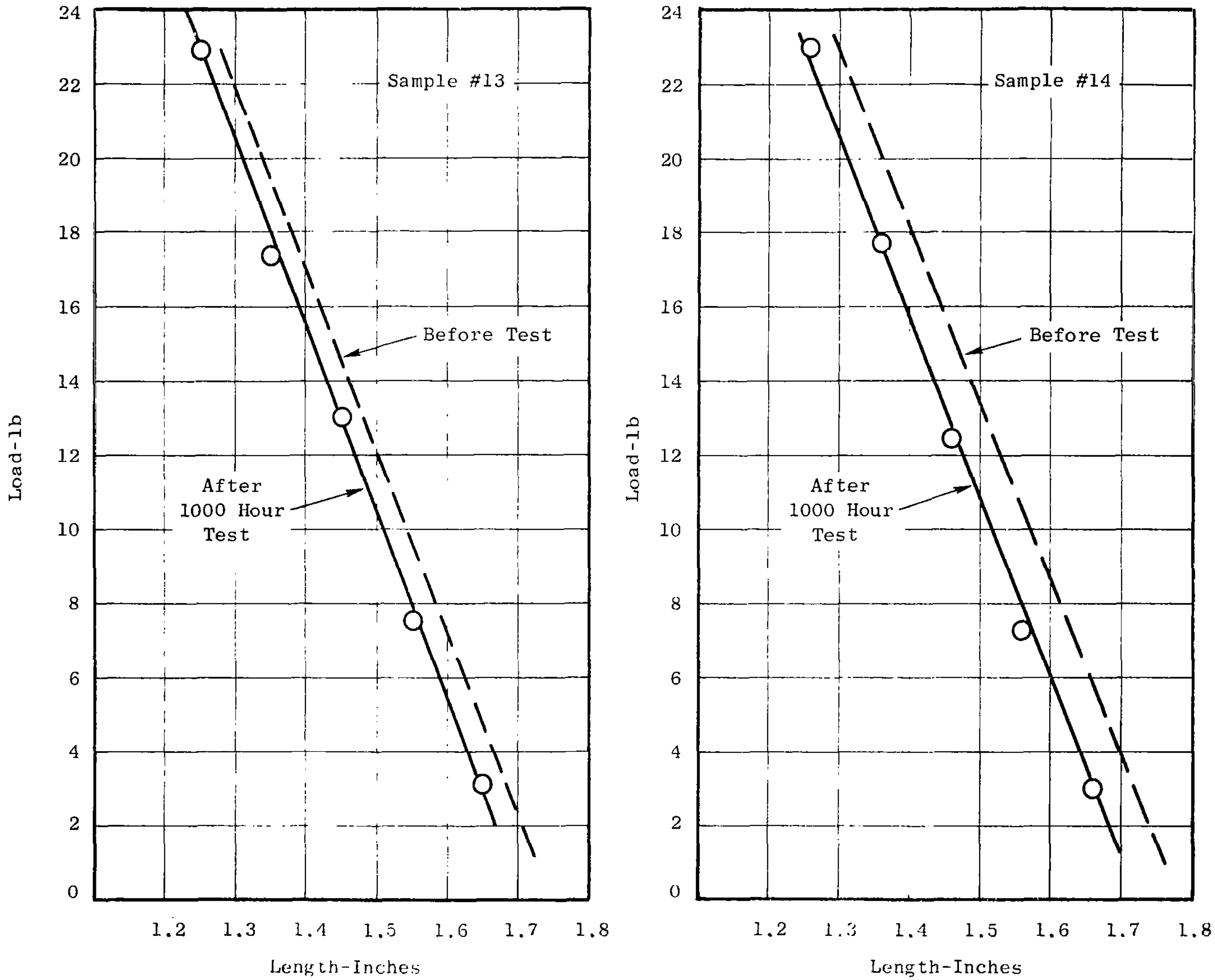


Figure 13. Load-Length Characteristics of Spring Design B for Sample #13 (Left) Kept Solid and #14 (Right) at Operating Length During Test at 1050°F.

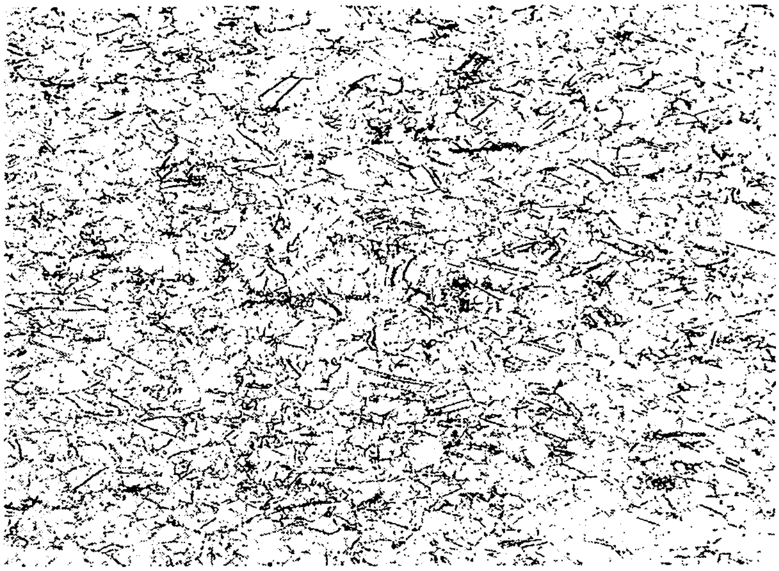


Figure 14. Photomicrographs of Spring Sample #4 (Design A) (100X Top; 500X Bottom) After Relaxation Test for 1000 Hours at 1050°F.

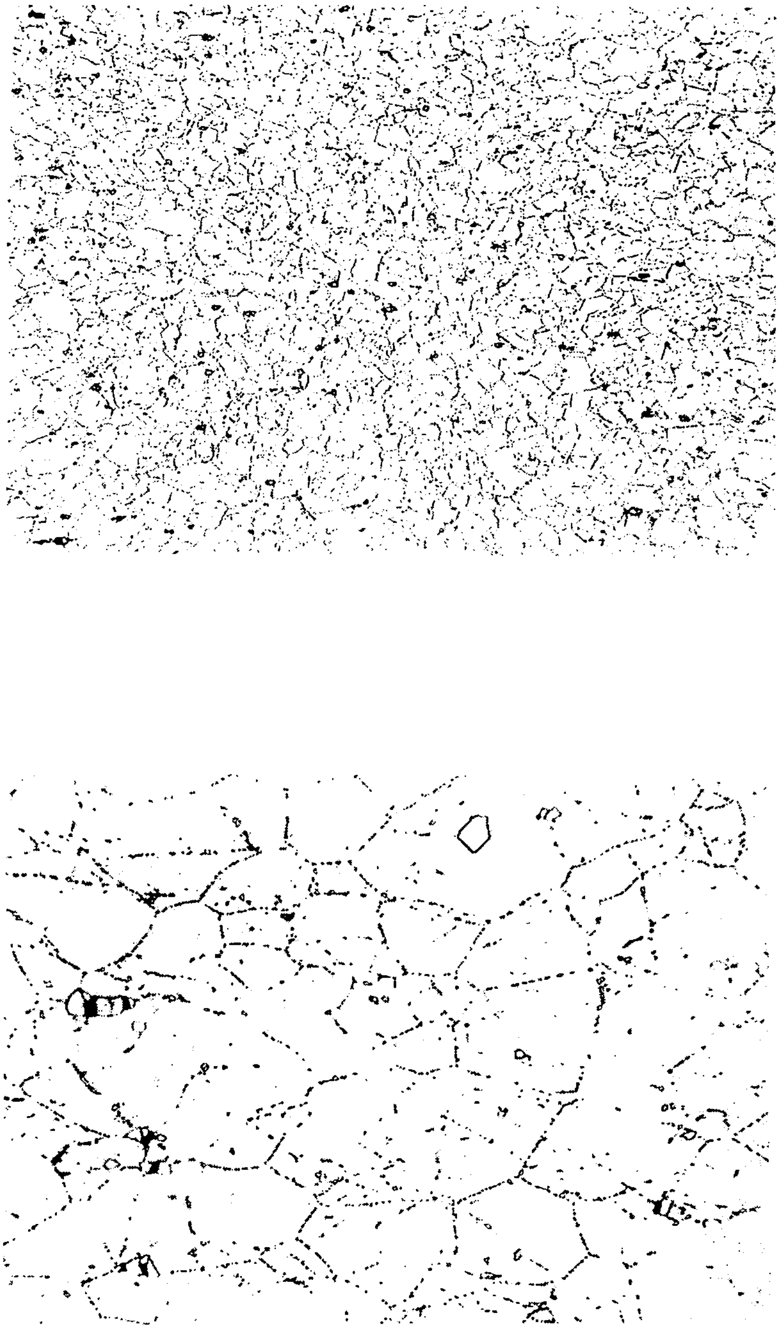


Figure 15. Photomicrographs of Spring Sample #14 (Design B) (100X Top; 500X Bottom) After Relaxation Test for 1000 Hours at 1050°F.

TABLE I

TYPICAL CHEMICAL COMPOSITION OF MATERIALS FOR HIGH TEMPERATURE SPRINGS

		Elements - Percent (Nominal)													
REF.#	MATERIAL	C	Cr	Co	Fe	Ti	Cb	Al	Mo	Mn	W	Ni	Cu	Si	Other
1	Inconel X-750	-	15.0	-	7.0	2.5	1.0	0.9	-	0.5	-	73.1	-	-	
2	Inconel 718	-	18.4	-	19.2	0.9	5.3	0.5	3.1	0.2	-	52.0	0.1	0.3	
3	Rene'41	0.1	19.0	11.0	5.0	3.1	-	1.5	9.8	-	-	50.5	-	-	Boron 50 ppm
4	Udimet 500	0.1	17.5	16.5	4.0	2.9	-	2.9	4.0	0.5	-	51.1	-	0.5	
5	Udimet 700	0.1	15.0	18.5	-	3.2	-	4.2	5.0	0.4	-	53.6	-	-	Boron .03
6	Stellite L605	0.1	19.5	51.9	2.5	-	-	-	-	1.4	14.5	10.0	-	0.1	
7	A286 Stainless	0.1	15.0	-	53.5	2.0	-	0.3	1.3	1.5	-	25.0	-	1.0 MAX	Vanadium 0.3

TABLE II

MECHANICAL PROPERTIES OF CANDIDATE MATERIALS FOR HIGH TEMPERATURE SPRINGS

	Material (Alloy)	Mfg. Recommended Max. Service Temp. °F	Elastic Modulus, psi x 10^{-6}			
			Torsion (G)		Tension (E)	
			At Room Temp.	At Max Temp.	At Room Temp.	At Max Temp.
1.	Inconel X750	1100	11.5	8.5	31.0	25.5
2.	Inconel 718	1200	11.2	8.0	29.6	24.5
3.	Rene'41	1300	12.1	9.0	31.6	25.0
4.	Udimet 500	1200	11.7	9.6	31.0	25.7
5.	Udimet 700	1200	12.3	10.3	32.5	27.0
6.	L-605	1300	12.5	9.0	32.6	23.0
7.	Stainless A286	950	10.5	8.4	29.1	25.0

TABLE III

RELAXATION OF ALLOY SPRINGS WITH VARIOUS STRESSES AT 1000°F(2)

Temper(1)	Hardening or Stabilizing Treatment	Stress	Relaxation, % Load Loss					
			5 Hr	10 Hr	20 Hr	50 Hr	100 Hr	140 Hr
		A286						
15%	16 hr., 1350°F	10,000 psi	5.0	5.0	5.0	5.0	5.0	5.0
		20,000	5.0	5.1	5.5	5.5	6.0	6.0
		40,000	5.8	6.3	6.4	6.8	7.5	7.5
		60,000	4.7	5.5	6.0	6.4	7.2	7.5
		80,000	6.0	6.8	8.2	9.0	10.0	10.0
		Inconel X-750						
15%	16 hr., 1350°F	10,000	7.0	8.0	9.0	10.0	12.0	13.0
		20,000	7.0	8.0	10.0	13.0	14.0	15.0
		40,000	9.3	10.5	12.5	15.5	20.0	21.7
		60,000	8.3	10.5	13.0	17.3	19.8	21.6
		80,000	10.0	12.0	15.5	21.0	25.0	41.0
		L605						
15%	16 hr., 1300°F	10,000	6.0	7.0	9.0	11.0	15.0	17.0
		20,000	6.5	7.0	9.0	12.5	15.0	17.5
		40,000	6.8	7.75	9.0	12.5	15.8	18.0
		60,000	5.0	6.7	8.6	12.5	16.0	18.3
		80,000	5.4	7.3	9.6	13.5	18.0	30.8
		Rene'41						
Annealed	16 hr., 1350°F	10,000	6.0	7.0	8.0	9.0	9.0	9.5
		20,000	6.5	6.5	8.0	9.0	10.0	10.0
		40,000	7.5	8.0	8.8	9.5	10.5	10.7
		60,000	6.3	6.7	7.7	8.6	9.3	9.3
		80,000	6.5	6.9	7.75	8.7	9.5	9.75
15%	16 hr., 1400°F	10,000	10.0	11.0	12.0	14.0	15.0	15.0
		20,000	9.5	10.0	11.5	13.5	15.0	15.0
		40,000	10.5	11.0	12.5	14.7	15.7	16.5
		60,000	9.15	10.3	12.5	15.0	16.3	17.0
		80,000	8.3	9.3	11.5	14.0	15.6	16.8

(1) Percentages refer to reductions in area.

(2) Information from Besemer and Stanton Paper -(Reference #3.)

TABLE IV

SUMMARY OF SPRING STRESS RELAXATION TEST RESULTS(1)

	Material	1000°F Initial Stress (psi)	Average Percent Stress Relaxation in 100 Hours
1.	Inconel X-750	42,500	7.3
		40,000	5.8
2.	Inconel 718	53,500	3.3
		42,000	3.3
		41,300	4.2
		40,000	2.9
3.	Rene'41	47,000	3.7
		40,000	3.9
4.	U-500	48,400	3.7
		40,000	3.3
5.	U-700	53,400	10.7
		40,000	9.9
6.	L-605	51,600	20.4
		39,000	19.3

(1) Tests made at General Electric Company, Aircraft Engine Group Materials Laboratory as part of their material investigation work and data made available for review in connection with the study work on this program.

TABLE V

STRESS RELAXATION TEST RESULTS(1)

HELICAL COMPRESSION SPRINGS MADE OF INCONEL 718

Spec. No.	Temp °F	Stress psi	Percent Stress Relaxation at Indicated Time, Hour									
			1	10	25	50	100	delay 90 days(2)	100	250	500	1000
1	1000	41,300	3.9	4.1	4.3	4.9	4.9		4.3	4.5	4.5	4.5
2	1000	41,300	3.1	3.1	3.1	3.5	3.5		3.0	3.9	3.4	3.4
7	1000	40,000	2.4	2.4	2.9	2.9	3.1		2.5	2.9	3.4	3.4
8	1000	40,000	2.1	2.2	2.5	2.5	2.7		2.1	2.5	2.9	2.9
11	1100	40,000	2.8	2.9	3.1	4.0	4.2					
12	1100	40,000	2.9	3.1	3.5	3.8	3.9					
9	1200	40,000	3.8	4.7	5.7	7.2	9.2					
10	1200	40,000	3.1	5.0	6.8	8.6	10.6					

(1) Tests made at General Electric Company, Aircraft Engine Group Materials Laboratory, as part of their material investigation work and data made available for review in connection with the study work on this program.

(2) Note the 1/2% recovery that occurred after 90 days. This behavior is not uncommon.

TABLE VI

SUMMARY OF DATA FROM SPRING DESIGN A

	(1) Initial Design with Inconel 718	(2) Force Too Low, Length Increased	(3) Increased Wire Diameter d and Mean Diameter D	(4) Increase P/f, as Stresses Very Low	(5) Check Values Column (4) At 1200°F
G	11.0	11.0	11.0	11.0	9.0
O.D.	1.039	1.044	1.105	1.045	1.045
d	.094	.094	.105	.105	.105
I.D.	.851	.856	.895	.835	.835
D	.945	.950	1.00	.940	.940
N	19	22	19	19	19
P/f	6.0	6.0	8.67	10.6	8.67
L_{free}	2.917	3.583	3.250	3.245	3.245
L_1	2.750	2.875	2.875	2.875	2.875
L_2	2.375	2.500	2.500	2.500	2.500
L_{solid}	1.974	2.256	2.205	2.205	2.205
P_1	1.0	4.25	3.25	3.92	3.21
P_2	3.25	6.5	6.5	7.90	6.46
P_s	5.65	7.96	9.06	11.0	9.02
f_1	.167	.708	.375	.370	.370
f_2	.542	1.083	.750	.745	.745
f_s	.614	1.327	1.045	1.040	1.040
D/d	10.05	10.01	9.5	8.95	8.95
S_1	4.3	14.0	8.2	9.4	7.8
S_2	13.1	21.5	16.5	19.0	15.5
S_s	18.7	26.5	23.0	26.5	22.0
T	Room	Room	Room	Room	1200°F

TABLE VII

SUMMARY OF DATA FOR SPRING DESIGN B

	(1) Initial Design with Inconel 718	(2) Modified Dimensions for Preferred Design	(3) Adjust Turns and Length to Reduce Stress	(4) Met Goals, Check at 1200°F
G	11.0	11.0	11.0	9.0
O.D.	1.968	2.322	2.4	2.4
d	.192	.192	.192	.192
I.D.	1.584	1.938	2.008	2.008
D	1.776	2.130	2.200	2.200
N	5	4	3.6	3.6
P/f	67	48.5	48.4	39.6
L_{free}	2.153	1.955	1.777	1.777
L_1	1.680	1.450	1.312	1.312
L_2	1.556	1.326	1.188	1.188
L_{solid}	1.344	1.152	1.075	1.075
P_1	31.7	24.0	22.5	18.4
P_2	40.0	30.5	28.5	23.3
P_s	54.3	39.0	34.0	27.8
f_1	.473	.505	.465	.465
f_2	.597	.629	.589	.589
f_s	.809	.803	.702	.702
D/d	9.25	11.1	11.5	11.5
S_1	23	21	20	19
S_2	29	26	25	20
S_s	40	34	30	25
T	Room	Room	Room	1200°F

TABLE VIII

LOAD, DEFLECTION, AND LENGTH DATA FOR SPRINGS DESIGN A

(PRIOR TO ENDURANCE TESTS)

		Load (lb.) for Deflection (and Length) Shown*				
Spring #	Free Length	0.15"	0.30"	0.45"	0.60"	0.75"
1	3.26	1.44 (3.11)	3.06 (2.96)	4.69 (2.81)	6.31 (2.66)	7.94 (2.51)
2	3.26	1.38 (3.11)	3.03 (2.96)	4.66 (2.81)	6.31 (2.66)	7.97 (2.51)
3	3.24	1.63 (3.09)	3.25 (2.94)	4.84 (2.79)	6.50 (2.64)	8.12 (2.49)
4	3.26	1.41 (3.11)	3.03 (2.96)	4.66 (2.81)	6.28 (2.66)	7.91 (2.51)
5	3.25	1.53 (3.10)	3.16 (2.95)	4.78 (2.80)	6.41 (2.65)	8.03 (2.50)
6	3.26	1.41 (3.11)	3.03 (2.96)	4.66 (2.81)	6.28 (2.66)	7.91 (2.51)
7	3.26	1.44 (3.11)	3.06 (2.96)	4.72 (2.81)	6.34 (2.66)	8.00 (2.51)
8	3.25	1.50 (3.10)	3.16 (2.95)	4.81 (2.80)	6.44 (2.65)	8.06 (2.50)

*Numbers in parenthesis in Table are actual measured lengths.

TABLE IX

LOAD, DEFLECTION, AND LENGTH DATA FOR SPRINGS DESIGN B

(PRIOR TO ENDURANCE TESTING)

Spring #	Free Length	Load (lbs.) for Deflection (and Length) Shown*				
		0.10"	0.20"	0.30"	0.40"	0.50"
11	1.81	2.88 (1.71)	7.56 (1.61)	12.38 (1.51)	17.12 (1.41)	22.00 (1.31)
12	1.78	4.06 (1.68)	8.88 (1.58)	13.62 (1.48)	18.50 (1.38)	23.38 (1.28)
13	1.79	2.81 (1.69)	7.50 (1.59)	12.25 (1.49)	17.06 (1.39)	22.12 (1.29)
14	1.80	3.56 (1.70)	8.38 (1.60)	13.38 (1.50)	17.88 (1.40)	22.88 (1.30)
15	1.80	2.94 (1.70)	7.44 (1.60)	12.19 (1.50)	17.00 (1.40)	21.75 (1.30)
16	1.81	3.31 (1.71)	7.50 (1.61)	12.00 (1.51)	16.88 (1.41)	21.94 (1.31)
17	1.81	3.31 (1.71)	7.75 (1.61)	12.38 (1.51)	17.12 (1.41)	22.19 (1.31)
18	1.81	2.94 (1.71)	7.44 (1.61)	12.00 (1.51)	16.88 (1.41)	21.88 (1.31)

*Numbers in parenthesis in Table are actual measured lengths.

TABLE X

SPRING SAMPLE DATA AND TEST ARRANGEMENTS

		Initial Characteristics					Test Conditions		
			Pos. 1(2)		Pos. 2(3)		Located In	Test Load	
Sample Number		Free Length(1)	Test Length	Force,(4) lb.	Test Length	Force,(4) lb.	Fixture #(5)	Solid	Working
1	Design A	3.26"	2.80	4.7	2.50	7.9	I		X
2		3.26	↑	4.6		8.0	II		X
3		3.24		4.8		8.1	I	X	
4		3.26		4.6		7.9	II	X	
5		3.25		4.7		8.0	IV		X
6		3.26		4.6		7.8	III		X
7		3.26	↓	4.7		8.0	III	X	
8		3.25	2.80	4.8	2.50	8.1	IV	X	
11	Design B	1.81	1.31	23.8	1.19	29.8	I	X	
12		1.78	↑	23.2		29.0	I		X
13		1.79		23.5		28.4	II	X	
14		1.80		22.9		28.7	II		X
15		1.80		23.5		29.1	III	X	
16		1.81		23.4		29.1	III		X
17		1.81	↓	23.8		29.4	IV	X	
18		1.81	1.31	23.7	1.19	29.2	IV		X

(1) Measured by comparator or vernier calipers, on center line between spring ends.

(2) Position 1 - Initial operating position.

(3) Position 2 - Final operating position, used for one of endurance test conditions. NOTE: Other test condition was with spring essentially solid. Length was 2.20" and 1.05", respectively.

(4) All values of force determined (based on straight line) from load/deflection data.

(5) Fixture I - for 1050°F - Long time test; i.e., springs at temperature for 1000-hour periods.

Fixture II - for 1050°F - Interrupted tests; i.e., springs removed from heat for periodic measurements.

Fixture III - for 1150°F - Long time test.

Fixture IV - for 1150°F - Interrupted tests.

TABLE XI

SUMMARY OF DATA FROM "INTERRUPTED" ENDURANCE TEST AT 1050°F TEMPERATURE

Sample No.	2	4	13	14
Initial Free Length	3.26	3.26	1.79	1.80
Test Condition - Load	Wkg.	Solid	Solid	Wkg.
Length	2.50	2.20	1.05	1.19
Temp. °F	1050	1050	1050	1050
Deflection Under Load	0.76	1.06	0.74	0.61
After 101 Hours				
Free Length	3.23	3.21	1.77	1.78
Length Reduction	.03	.05	.02	.02
(1) Relaxation %	3.9	4.7	2.7	3.3
After 195 Hours				
Free Length	3.22	3.20	1.76	1.77
Length Reduction	.04	.06	.03	.03
Relaxation %	5.3	5.7	4.1	4.9
After 427 Hours				
Free Length	3.22	3.19	1.76	1.76
Length Reduction	.04	.07	.03	.04
Relaxation %	5.3	6.6	4.1	6.6
After 619 Hours				
Free Length	3.22	3.19	1.75	1.76
Length Reduction	.04	.07	.04	.04
Relaxation %	5.3	6.6	5.4	6.6
After 808 Hours				
Free Length	3.22	3.19	1.75	1.76
Length Reduction	.04	.07	.04	.04
Relaxation %	5.3	6.6	5.4	6.6
After 1000 Hours				
Free Length	3.21	3.19	1.75	1.76
Length Reduction	.05	.07	.04	.04
Relaxation %	6.6	6.6	5.4	6.6
After 2000 Hours				
Free Length	3.21	3.17 (2)	1.75	1.76 (2)
Length Reduction	.05	.09	.04	.04
Relaxation %	6.6	8.3	5.4	6.6

(1) $$\text{Relaxation (\%)} = \frac{\text{Free Length Reduction}}{\text{Deflection Under Load}} \times 100$$

(2) Spring had a piece cut off the end of the last turn which could have affected the length measurement enough to alter the active relaxation data.

TABLE XII

SUMMARY OF DATA FROM "INTERRUPTED" ENDURANCE TEST AT 1150°F TEMPERATURE

Sample No.		5	8	17	18
Initial Free Length		3.25	3.25	1.81	1.81
Test Condition	Load	Wkg.	Solid	Solid	Wkg.
	Length	2.50	2.20	1.05	1.19
	Temp.°F	1150	1150	1150	1150
Deflection Under Load		0.75	1.05	0.76	0.62
After 101 Hours					
	Free Length	3.19	3.16	1.74	1.77
	Length Reduction	.06	.09	.07	.04
(1)	Relaxation %	8.0	8.6	9.2	6.5
After 195 Hours					
	Free Length	3.18	3.15	1.73	1.75
	Length Reduction	.07	.10	.08	.06
	Relaxation %	9.3	9.5	10.5	9.7
After 427 Hours					
	Free Length	3.16	3.11	1.70	1.74
	Length Reduction	.09	.14	.11	.07
	Relaxation %	12.0	13.3	14.5	11.3
After 619 Hours					
	Free Length	3.13	3.11	1.69	1.73
	Length Reduction	.12	.14	.12	.08
	Relaxation %	16.0	13.3	15.8	12.9
After 808 Hours					
	Free Length	3.12	3.10	1.67	1.73
	Length Reduction	.13	.15	.14	.08
	Relaxation %	17.3	14.3	18.4	12.9
After 1000 Hours					
	Free Length	3.10	3.09	1.66	1.72
	Length Reduction	.15	.16	.15	.09
	Relaxation %	20.0	15.2	19.7	14.5
After 2000 Hours					
	Free Length	--	--	--	--
	Length Reduction	--	--	--	--
	Relaxation %	--	--	--	--

(1) $$\text{Relaxation (\%)} = \frac{\text{Free Length Reduction}}{\text{Deflection Under Load}} \times 100$$

TABLE XIII

SUMMARY OF DATA FROM LONG TIME (1000 HOUR PERIOD) TESTS AT 1050°F TEMPERATURE

Sample No.	1	3	11	12
Unit Free Length	3.26	3.24	1.81	1.78
Test Condition - Load	Wkg.	Solid	Solid	Wkg.
Length	2.50	2.20	1.05	1.19
Temp. °F	1050	1050	1050	1050
Deflection Under Load	.76	1.04	.76	.59
After 1000 Hours				
Free Length	3.20	3.17	1.75	1.74
Length Reduction	.06	.07	.06	.04
Relaxation %(1)	7.9	6.7	7.9	6.8
After 2000 Hours				
Free Length	(2)	(2)	(2)	(2)
Length Reduction				
Relaxation %				

(1) $$\text{Relaxation (\%)} = \frac{\text{Free Length Reduction}}{\text{Deflection Under Load}} = 100$$

(2) During final 1000-hour test period the furnace temperature for the 1050°F test apparently went above set point for some limited time, causing complete relaxation but not annealing of the spring material.

TABLE XIV

SUMMARY OF DATA FROM LONG TIME (1000 HOUR PERIOD) TESTS AT 1150°F TEMPERATURE

Sample No.	6	7	15	16
Unit Free Length	3.26	3.26	1.80	1.81
Test Condition - Load	Wkg.	Solid	Solid	Wkg.
Length	2.50	2.20	1.05	1.19
Temp. °F	1150	1150	1150	1150
Deflection Under Load	.76	1.06	.75	.62
After 1000 Hours				
Free Length	3.19	3.08	1.70	1.75
Length Reduction	.07	.18	.10	.06
Relaxation %(1)	9.2	17.0	13.3	9.7
After 2000 Hours				
Free Length	3.11	3.03	1.69	1.73
Length Reduction	.15	.23	.11	.08
Relaxation %	19.7	21.7	14.7	12.9

(1) $$\text{Relaxation (\%)} = \frac{\text{Free Length Reduction}}{\text{Deflection Under Load}} = 100$$

TABLE XV

LOAD, DEFLECTION DATA FOR FOUR SPRINGS BEFORE AND AFTER 1000 HOURS AT 1050°F

Spring Sample Number	Deflection	Before Test		After Test	
		Load	Length	Load	Length
2	0.150"	1.38	3.11	1.40	3.09
	0.300	3.03	2.96	3.03	2.91
	0.450	4.66	2.81	4.66	2.76
	0.600	6.31	2.66	6.34	2.61
	0.750	7.97	2.51	8.03	2.46
4	0.150"	1.41	3.11	1.47	3.02
	0.300	3.03	2.96	3.09	2.87
	0.450	4.66	2.81	4.75	2.72
	0.600	6.28	2.66	6.37	2.57
	0.750	7.91	2.51	8.06	2.42
13	0.100	2.81	1.69	3.06	1.65
	0.200	7.50	1.59	7.75	1.55
	0.300	12.25	1.49	12.50	1.45
	0.400	17.06	1.39	17.37	1.35
	0.500	22.12	1.29	22.44	1.25
14	0.100	3.56	1.70	3.00	1.66
	0.200	8.38	1.60	7.37	1.56
	0.300	13.38	1.50	12.50	1.46
	0.400	17.88	1.40	17.75	1.36
	0.500	22.88	1.30	23.00	1.26

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