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REPORT  
ON  
RELAXATION STRENGTHS FOR "17-22-A"V, A-286, INCONEL X  
AND INCONEL 700 ALLOYS  
(PHASE I)

by

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RELAXATION STRENGTHS FOR "17-22-A"V, A-286, INCONEL X  
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(PHASE I)

An investigation was conducted to determine the relaxation properties of "17-22-A"V alloy at 1100°F, A-286 at 1200°F, Inconel X at 1350°F and Inconel 700 at 1400°F. A major objective was to determine the optimum clamping stress at room temperature for maximum residual stress in 1000 hours. Solution treatments of both 1650° and 1800°F were evaluated for A-286 alloy. Tests were conducted on Inconel X solution treated at 2100°F, aged for 24 hours at 1550°F plus a second age of 20 hours at 1300°F or of 24 hours at 1350°F.

The tests were conducted by a step-down method using small steps in stress to give results equivalent to continuous relaxation. The conditions of testing gave relaxation strengths for the usual idealized conditions for a bolt at constant uniform temperature with no elastic follow-up and with no influence from thread or gasket efficiencies.,

SUMMARY

The maximum relaxation strengths observed were as follows:

Alloy	Temp. (°F)	Residual Stress at 1000 Hours (psi)	Equivalent Clamping Stress at 75°F (psi)
"17-22-A"V	1100	4,000	(~ 37,000)
A-286 (ST 1800°F)	1200	28,000	78,000
A-286 (ST 1650°F)	1200	22,000	82,000
Inconel X	1350	23,000-21,000	60,000-47,000
Inconel 700	1400	30,000	72,500

The relaxation strength at 1000 hours was not very sensitive to the initial stress.

Relaxation strength of the Inconel X at 1000 hours was independent of the aging temperatures of 1300° or 1350°F, although the material aged at 1300°F had somewhat higher relaxation strength at the shorter-time periods. The number of tests for "17-22-A"V and A-286 alloys was very limited due to lack of further interest in these alloys at the time preliminary test results became available. Two values of 1000-hour stress are given for Inconel X because the maximum residual stress of 23,000 psi occurred for a lower initial stress than is usually the case due to the opposition to relaxation arising from a volume decrease in the alloy. The second value given of 21,000 psi was obtained with an initial stress close to the proportional limit at 1350°F.

An initial stress close to the proportional limit at the test temperature appeared to give the highest relaxation strength for 1000 hours. This indicated that the optimum clamping stress at room temperature for bolts would be the stress which would result in a stress at temperature close to the proportional limit. Inconel X at 1350°F appeared to be a slight exception in that a volume decrease during early portions of the tests maintained stress and gave slightly higher residual stresses at 1000 hours for lower initial stresses.

Relaxation strength generally increases with initial stress for time periods up to 1000 hours until yielding occurs during application of the stress. The relaxation strength for comparatively short-time periods continues to increase when the initial stress is raised into the yield range. The relaxation rate is, however, increased by yielding so that the relaxation strength eventually falls below that of the unyielded material. Probably the cross-over in relaxation strength occurs at shorter and shorter times the higher the temperature (faster creep rate) and the greater the amount of yielding for a given alloy.

## RELAXATION PROPERTIES AND THEIR MEASUREMENT

As used in this report, relaxation means the replacement of an initial elastic strain by the plastic strain of creep, with consequent reduction in the stress level. Such relaxation of stress is involved in the performance of materials in a number of applications characterized by stresses maintained by elastic strain, but relaxation properties are most frequently employed in the design and selection of materials for bolts for elevated-temperature service.

In any assembly, such as a flanged joint, in which bolts offset a load tending to separate the members, the geometry and temperature pattern of the overall assembly and the type of coupling between members affect the rate of relaxation. Relaxation characteristics are normally measured experimentally for the hypothetical assembly of completely-rigid flanges held together by a bolt, with the entire assembly maintained at uniform temperature. Because the length of the bolt would then be held fixed, all creep which occurs must be accommodated within the bolt itself; that is, all the creep strain replaces elastic strain initially present in the heated bolt to give maximum lowering in the residual stress remaining in the bolt.

In actual practice some degree of elastic strain is always present in the flange and associated parts no matter how massive they may be made. As creep occurs in the bolt, a portion of the creep strain reduces the strain in the flange, so that part of the bolt's creep is used up by an increase in its length and is not available for stress relaxation in the bolt. This condition of "elastic follow-up" is intensified when an elastic member is in series with the heated bolt, so that its elastic strain can absorb a part of any creep strains. The non-creeping elastic member can be portions of the bolt at temperatures below that of the hot section where creep is taking place. The ratio of the total system

elasticity to that of the creeping section is commonly designated the "elasticity factor." Elastic follow-up always reduces relaxation rates and must be taken into account in design of bolts. In practice, other factors such as thread efficiencies, gasket creep, etc., have the opposite effect of increasing the amount of overall creep and thereby increasing the rate at which the clamping stress in the bolt relaxes with time.

### Experimental Methods

The tests were conducted in standard creep units. The necessary initial load was applied to the specimens already heated at the test temperatures. The load was applied in increments of approximately 1250 or 2500 psi and the deformation for each increment of load measured. Creep was then allowed to take place until the removal of the last weight applied would return the length to the value which existed when the full load was initially applied. This process was repeated until 1000 hours had elapsed to provide step-wise variations of stress with time while keeping the strain constant. Such data were plotted and an average curve drawn through the steps to define the continuous relaxation characteristics with time.

A considerable amount of experimentation in this laboratory has resulted in the described procedure for the tests. It is recognized that the method approximates continuous relaxation only when the increments of load are small. Experience has indicated that the increments used are about as small as is practical when consideration is given to the experimental variables.

For example, Inconel X has an elastic modulus of about  $23 \times 10^6$  psi/in. /in. at 1350°F and the thermal expansion is about  $11.4 \times 10^{-6}$  inch per inch per °F at 1350°F. A change in temperature of 1°F would cause an apparent change of stress of about  $(11.4 \times 10^{-6})(23 \times 10^6) = 260$  psi. The sensitivity of the extensometer used

was about  $5 \times 10^{-6}$  inch per inch for the two-inch gage length of the specimens. Thus  $0.5^\circ\text{F}$  variation in temperature would cause as much change in length as the minimum value the extensometer was capable of measuring. Additional experimental conditions can further affect the extensometer reading, such as vibrations and small changes in ambient room temperature. Experience has shown that the best way to conduct the tests, in view of these experimental facts, is to choose an increment of stress permitting sufficient creep to define a curve which can be plotted to average the influence of the variables in determining the time at which an increment of stress should be relieved. As previously mentioned this turns out to be 1000 to 2000 psi for many materials. Results from a test with steps this size come very close to the actual experimental results from a continuous relaxation machine. The extensometer used in the present tests is as sensitive as experimental conditions warrant. The variations in temperature and other experimental variations would make it difficult to control the required stress changes much closer with a continuous relaxation machine.

In practice, the raw extensometer readings are immediately plotted as in Figure 1 for the test on Inconel X at  $1350^\circ\text{F}$  with an initial stress of 60,000 psi. In this test stress increments of about 2500 psi were used. These caused a change in extensometer units of about 2. Extensometer units were used to save the time of converting to inches per inch during the early portions of the tests when relaxation was very rapid. Some variation from the ideal curves is evident. However, it has been found that the actual curves can be corrected for small experimental variations in strain and time by computing the correct time for each increment from the creep data. The hash marks on the curves indicate these values. The derived continuous stress-time relaxation curve is shown in the upper portion of Figure 1 as an average curve through the stress-time steps. Reported relaxation strengths are based on the continuous curve.

The results of the tests are reported as the derived continuous relaxation curves in every case. The experimental stepwise values are also shown unless this caused undue confusion when a number of relaxation curves were shown on the same figure. The creep data used to determine the time to remove stress increments were not included in the report.

#### Equivalent Clamping Stress at Room Temperature

The basic condition of the relaxation tests as they were conducted was the maintenance of constant strain after the load was applied. If it is assumed that this also holds during heating to the test temperature for the case where the stress was applied at room temperature, then the stress-strain curves at the two temperatures define the relationship between the initial stress at test temperature and the clamping stress at room temperature. The following calculations were involved:

1. If no yielding occurred at either the test temperature or at 75°F, the clamping stress can be computed as:  $(\text{Initial Stress at Test Temperature}) \times (\text{E at 75°F} / \text{E at Test Temperature})$ .

Modulus values were taken from the stress-strain data obtained during loading of the tests, or from the literature.

2. If yielding occurred, then the clamping stress was considered to be the stress on the room temperature stress-strain curve which gave the same strain as the strain developed by applying the initial stress at the test temperature.

Stress-strain curves at 75°F were not available, except for Inconel 700 alloy. Estimates were, therefore, based on nominal properties for the other alloys at room temperature.

It is important to recognize that the equivalent clamping stresses reported are idealized values, as are the residual-stress relaxation strengths. To meet the assumptions involved a bolt and flange would have to be heated uniformly

from 75°F to the test temperature with no relaxation during heating. Both would have to have the same coefficient of expansion, or else differential expansion would influence the results. Elastic follow-up is assumed to be zero for the heating period as well as for the test period.

No special attempts were made to establish accurate modulus values. The values from the stress-strain curves are considered to be reliable at best to  $\pm 1 \times 10^6$ .

## EXPERIMENTAL MATERIALS

Machined specimens were supplied from fully heat-treated bar stock by the Wright Aeronautical Division. The specimens had a gage section approximately 2-inches long by 0.357-inch in diameter with 9/16-12 threads.

The information given in the following sections was supplied regarding each of the alloys investigated.

### "17-22-A"V Steel (WAD 7823)

The specimens, marked G1 through G14, were obtained from bar stock heated 1 hour at 1850°F, air cooled, and tempered at 1200°F for 6 hours to a hardness of RC 26-32. The stock was from Heat Lot Number D-16654 having the following reported chemical composition:

<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>S</u>	<u>P</u>
0.31	0.65	0.84	1.55	0.51	0.79	0.007	0.011

### A-286 Alloy (AMS 5735)

Two sets of specimens were supplied. Those marked F1 through F8 had been solution treated at 1800°F for 1 hour, oil quenched and aged at 1350°F for 16 hours. Those marked F9 through F15 had been solution treated at 1650°F and aged at 1350°F. The stock used was reported to be from Heat B8949 with the following chemical composition:



<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Cr</u>	<u>Ni</u>	<u>Mo</u>	<u>V</u>	<u>Ti</u>	<u>Al</u>	<u>S</u>	<u>P</u>
0.01	0.11	0.05	15.05	25.1	1.27	0.47	1.99	0.1	0.008	0.006

#### Inconel X (AMS 5668)

Specimens D1 through D9 were supplied from stock solution treated at 2100°F for 2 hours, air cooled and double aged at 1550°F for 24 hours plus 1300°F for 20 hours. Specimens D1-1 through D1-9 were similarly heat treated except that the final age was 24 hours at 1350°F. The object was to determine if the difference in aging materially affected relaxation properties. The specimens were reported to have been taken from Heat T7925X having the following chemical composition:

<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Cr</u>	<u>Ni</u>	<u>Ti</u>	<u>Al</u>	<u>Fe</u>	<u>Cb+Ta</u>	<u>S</u>	<u>Cu</u>
0.04	0.34	0.8	15.15	72.57	2.73	0.81	6.63	0.84	0.007	0.04

#### Inconel 700 (WAD 7827)

Specimens C1 through C9 were supplied from 11/16 inch diameter stock solution treated at 2160°F for 2 hours, air cooled, and aged at 1600°F for 4 hours. The stock was reported to have been taken from Heat Y7952 having the following chemical composition:

<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>Cr</u>	<u>Ni</u>	<u>Co</u>	<u>Mo</u>	<u>Ti</u>	<u>Al</u>	<u>S</u>	<u>Fe</u>
0.12	0.24	0.07	15.7	46.25	28.69	3.08	2.02	3.13	0.007	0.65

## RESULTS AND DISCUSSION

The stress-time relaxation curves obtained are shown graphically. The residual stress values for time periods of 1, 10, 30, 100, 500 and 1000 hours were read from the relaxation curves and tabulated. The data are evaluated in terms of initial stress applied at the test temperature and the relation of these stresses to the equivalent clamping stress at room temperature.

"17-22-A"V Alloy (WAD 7823)

Two tests were conducted at 1100°F which gave the curves of Figure 2 and the following relaxation strengths:

Equivalent Clamping Stress at 75°F (psi)	Actual Initial Stress at 1100°F (psi)	Residual Stress (psi) at Indicated Time Periods					
		1-hr	10-hr	30-hr	100-hr	500-hr	1000-hr
118,000	60,000	35,000	22,500	17,000	11,500	5,500	3,000
37,000	25,000	19,500	14,500	12,000	9,000	5,500	4,000

The residual stress for time periods of 100 to 1000 hours at 1100°F were low and apparently nearly independent of the equivalent clamping stress at 75°F. A stress of 25,000 psi at 1100°F was above the proportional limit. Because appreciable yielding usually lowers long time strength, it is doubtful that there would have been much gain in relaxation strength for 1000 hours from increasing the initial stress to values between 25,000 and 60,000 psi.

It should be noted that the test started under 60,000 psi at 1100°F yielded to a considerable extent during loading. Even 25,000 psi was slightly above the proportional limit.

When these low relaxation strengths of the experimental material were reported to WAD representatives, it was decided to drop further testing of the alloy.

Yield characteristics indicated by the stress-strain data for loading the relaxation tests were as follows:

Initial Stress (psi)	Proportional Limit (psi)	Elastic deformation (inch/inch)	Plastic deformation (inch/inch)	Total Loading Deformation (inch/inch)
60,000	17,500	0.00285	0.00108	0.00393
25,000	22,500	0.00119	0.00005	0.00124

The properties of the test stock were not measured at 75°F. However, other data available indicate that the modulus should be  $30 \times 10^6$  psi, proportional limit about 135,000 psi and 0.1% offset yield strength about 155,000 psi. Using these values, the following equivalent clamping stresses at 75°F were computed.

60,000 psi Initial Stress at 1100°F. Equivalent Clamping Stress =  $(30 \times 10^6)$  (0.00393) = 118,000 psi. This appears to be below the expected proportional limit at 75°F. Consequently it appears that the clamping stress would have been about 118,000 psi. It should be noted that while yielding would not occur during loading at 75°F it would occur during heating to 1100°F.

25,000 psi Initial Stress at 1100°F. The equivalent clamping stress would be:  $(30 \times 10^6)$  (0.00124) = 37,200 psi. This is well below the proportional limit at 75°F and the test was conducted under conditions approximating a clamping stress of 37,000 psi at 75°F. Yielding during heating would be expected to be quite small even though 25,000 psi was above the proportional limit at 1100°F.

#### A-286 Alloy (AMS 5735)

The tests conducted at 1200°F gave the curves of Figure 3 which indicate the following relaxation strengths:

Equivalent Clamping Stress at 75°F (psi)	Actual Initial Stress at 1100°F (psi)	Residual Stress (psi) at Indicated Time Periods					
		1-hr	10-hr	30-hr	100-hr	500-hr	1000-hr
		<u>Solution Treated at 1650°F and Aged at 1350°F</u>					
82,000	60,000	55,000	51,000	47,000	42,000	29,000	22,000
		<u>Solution Treated at 1800°F and Aged at 1350°F</u>					
(~97,500)	80,000	64,000	55,000	51,500	46,000	31,000	24,000
78,000	60,000	58,000	54,000	51,000	46,500	34,000	28,000

Solution treating at 1800°F resulted in a higher relaxation strength at 1200°F for an initial stress of 60,000 psi at 1200°F than did solution treating at 1650°F. The difference in residual stress was 3000 psi at 1 hour and 6000 psi at 1000 hours. An initial stress of 60,000 psi at 1200°F resulted in higher residual stresses than an initial stress of 80,000 psi for time periods longer than 60 hours for the material solution treated at 1800°F. At 1000 hours the residual stress of the specimen

started under 80,000 psi had fallen 4000 psi below that for the material started under 60,000 psi.

The stress of 60,000 psi was fairly close to the proportional limit at 1300°F. Because residual stresses generally increase with initial stress up to the point where yielding occurs and then decrease, the optimum clamping stress at 75°F was, therefore, probably not far from 80,000 psi for either solution treatment. When the results presented were reported to WAD representatives, however, it was requested that no further testing be done on this alloy to define the relation of clamping stress to relaxation strength.

Equivalent clamping stresses at 75°F were computed on the basis that the modulus was  $22.5 \times 10^6$  psi at 1200°F and  $30 \times 10^6$  psi at 75°F. The stress strain curves indicated that the material solution treated at 1650°F had a proportional limit of about 40,000 psi at 1200°F with elastic plus plastic strain at 60,000 psi of 0.00281 inch per inch. The material solution treated at 1800°F had a proportional limit of 55,000 psi with total strains of 0.00269 for an initial stress of 60,000 psi and 0.00403 inch per inch for 80,000 psi.

Data were not available for the particular material tested at room temperature but, the literature indicates that the modulus would be about  $29.1 \times 10^6$  psi. Yield strengths for the material ought to be about as follows:

Solution Treatment (°F)	0.02% Offset Yield Strength (psi)	0.2% Offset Yield Strength (psi)
1650	95,000	105,000
1800	82,500	100,000

Using this information the following equivalent clamping stresses at room temperature were estimated:

60,000 psi Initial Stress at 1200°F for Material Solution Treated at 1650°F.  
 $(29.1 \times 10^6)(0.00281) = 81,800$  psi. This is sufficiently below the probable 0.02-percent offset yield strength to indicate that little or no yielding would occur at 75°F, so that the equivalent clamping stress at 75°F was probably close to 82,000 psi.

Material Solution Treated at 1800°F with Initial Stresses at 1200°F of 80,000 and 60,000 psi. For 80,000 psi at 1200°F:  $(29.1 \times 10^6)(0.00403) = 111,750$  psi. This is well above the probable yield strength so that yielding would have occurred. The probability is that the strain of 0.00403 inch per inch would have been attained at a stress below 100,000 psi and the clamping stress would probably be of the order of 97,500 psi.

For 60,000 psi at 1200°F:  $(29.1 \times 10^6)(0.00269) = 78,250$  psi. This is below the probable 0.02 percent offset yield strength at 75°F so that the equivalent starting stress would be about 78,000 psi.

#### Inconel X Alloy (AMS 5668)

The relaxation curves for the tests conducted at 1350°F are shown in Figure 4. The specimens had been solution treated at 2100°F for 2 hours, air cooled and then aged at 1550°F for 24 hours plus aged at 1300°F for 20 hours or at 1350°F for 24 hours. The steps in stress were omitted from the curves for the sake of clarity and only the derived relaxation curves are shown. The relaxation strengths defined by these curves follow:

Equivalent Clamping Stress at 75°F (psi)	Actual Initial Stress at 1350°F (psi)	Residual Stress (psi) at Indicated Time Periods						Aging Temp. (°F)
		1-hr	10-hr	30-hr	100-hr	500-hr	1000-hr	
(~90,000)	70,000	58,000	50,000	46,000	39,500	24,000	16,000	1300
(~90,000)	70,000	53,000	48,000	45,000	39,000	24,000	16,000	1350
(~81,000)	60,000	55,000	50,000	46,500	40,500	28,000	18,000	1300
(~81,000)	60,000	53,000	47,500	44,000	40,000	28,000	18,000	1350
60,000	45,000	44,000	42,000	40,000	38,000	29,500	21,000	1300
60,000	45,000	44,500	41,000	38,500	35,000	28,500	21,000	1350
54,000	40,000	-----	38,000	36,500	34,000	26,500	20,000	1350
47,000	35,000	39,000	38,000	36,500	34,000	27,500	23,000	1300
47,000	35,000	-----	36,500	36,000	34,000	27,500	23,000	1350

Note: Yielding would occur at 75°F for a clamping stress of 90,000 psi and possibly for 81,000 psi.

The residual stress at 1000 hours increased from 16,000 to 23,000 psi as the initial stress at 1350°F was reduced from 70,000 to 35,000 psi. A decrease in volume during the early stages of the tests with initial stresses of 40,000 and 35,000 psi slightly complicated results. The volume decrease offset creep and caused a reduction in gage length which delayed the first reduction of stress for specimens D1-5 and D1-3. When the test on specimen D-9 was conducted, the stress was raised during the period of volume decrease to simulate the rise in stress which would occur in a tightened bolt undergoing the volume decrease. The volume decrease also delayed the reduction in stress for specimens D1-2 and D-8. Its effect was apparently masked for the specimens tested with higher initial stresses due to the more rapid creep.

Those specimens aged for 24 hours at 1350°F had slightly lower relaxation strengths at the shorter time periods than those aged at 1300°F for 20 hours. In general, however, there was little difference at 100 hours and no difference at 1000 hours.

The data indicate that the optimum clamping stress at 75°F for time periods of 1000 hours would be 47,000 psi or lower. The increase in residual stress as the initial stress was reduced to such low values was probably due to the effective maintenance of residual stress by the volume decrease. Normally it would be expected that residual stress would increase with initial stress up to a limiting value and then fall off with higher initial stresses. The data suggest that the optimum initial stress at 1350°F would have been about 60,000 psi if it had not been for the effectiveness of the volume decrease for lower initial stress. Thus the optimum clamping stress would have been close to the proportional limit, if the volume decrease had not altered relaxation behavior for lower initial stresses.

The clamping stresses were estimated with the following data:

Modulus,  $E$ , at  $1350^{\circ}\text{F}$  of  $23 \times 10^6$  psi taken from the stress-strain curves for the loading of the relaxation tests. These curves gave a proportional limit of 57,500 psi with no difference between the specimens aged at  $1300^{\circ}$  and  $1350^{\circ}\text{F}$ .

The literature indicated  $E$  at  $75^{\circ}\text{F}$  to be  $31 \times 10^6$  psi and the yield strength for 0.2 percent to be about 92,000 psi. Sufficiently reliable data were not found to justify the differentiation between the yield characteristics of the material finally aged at  $1300^{\circ}\text{F}$  from that aged at  $1350^{\circ}\text{F}$  for the purposes of these calculations.

The strains during the application of the initial stresses at  $1350^{\circ}\text{F}$  used in the following calculations were taken from the stress-strain curves for the load application. The equivalent clamping stress at  $75^{\circ}\text{F}$  was computed as: ( $E$  at  $75^{\circ}\text{F}$ ) (strain from the initial stress application at  $1350^{\circ}\text{F}$ ).

Initial Stress at $1350^{\circ}\text{F}$ (psi)	Strain During Application of Initial Stress			(E $75^{\circ}\text{F}$ ) (Total Strain) (psi)	Equivalent Clamping Stress at $75^{\circ}\text{F}$ (psi)
	Elastic (in/in)	Plastic (in/in)	Total (in/in)		
70,000	0.00305	0.00012	0.00317	(98,000)	( $\sim 90,000$ ) <sup>a</sup>
60,000	0.00261	0.00002	0.00263	(81,500)	( $\sim 80,000$ ) <sup>b</sup>
45,000	0.00195	-----	0.00195	60,500	60,500
40,000	0.00174	-----	0.00174	54,000	54,000
35,000	0.00152	-----	0.00152	47,250	47,250

- (a) Because the yield strength at  $75^{\circ}\text{F}$  was probably only about 92,000 psi, the equivalent clamping stress would have had to be kept below 98,000 psi to keep the initial strain down to 0.00317 inch per inch. The value of 90,000 psi represents an estimate of the magnitude of this stress.
- (b) Some yielding would probably occur during the application of 81,500 psi at  $75^{\circ}\text{F}$  so that the equivalent clamping stress would have to be slightly lower to maintain the initial strain at 0.00263 inch per inch.

### Inconel 700 Alloy (WAD 7827)

The curves of Figure 5 show the following relaxation strengths for three initial stresses at 1400°F:

Equivalent Clamping Stress at 75°F (psi)	Actual Initial Stress at 1400°F (psi)	Residual Stress (psi) at Indicated Time Periods					
		1-hr	10-hr	30-hr	100-hr	500-hr	1000-hr
100,500	80,000	60,000	49,000	44,000	38,500	29,500	26,000
72,500	60,000	58,000	48,500	44,000	40,000	33,000	30,000
54,500	45,000	45,000	42,500	41,000	37,500	31,500	28,000

The highest residual stress at 1000 hours resulted from the initial stress of 60,000 psi at 1400°F. Apparently the clamping stress for maximum residual stress at 1000 hours would, therefore, be close to 72,500 psi. A slightly higher value might result from either a somewhat higher or lower clamping stress. It is perhaps more important that the residual stress at 1000 hours would be quite insensitive to a wide range of initial stresses.

While an actual volume decrease was not observed in the early portions of the tests, it appears that the effect was present to delay the time at which relaxation required the removal of load in the tests started at 1400°F under 60,000 and 45,000 psi.

The stress-strain data for loading of the relaxation tests indicated a modulus value of  $24.8 \times 10^6$  psi at 1400°F. The proportional limit appeared to be 65,500 psi. The deviation from proportionality between 65,000 and 80,000 was, however, quite small so that the strain was only increased 0.000118 inch per inch (from 0.00323 to 0.00335 inch per inch) at 80,000 psi. A tensile test at 75°F gave a modulus value of  $30 \times 10^6$  psi. The equivalent clamping stresses for the three tests were computed as follows:



$$\underline{80,000 \text{ psi Initial Stress at } 1400^{\circ}\text{F: } (30 \times 10^6) \times (0.00335) = 100,500 \text{ psi}}$$

This assumes no yielding at room temperature. If there would be any, it apparently would be slight. Any error would be less than uncertainty in the modulus values.

$$\underline{60,000 \text{ psi Initial Stress at } 1400^{\circ}\text{F: } 60,000 \times 30.0/24.8 = 72,500 \text{ psi}}$$

$$\underline{45,000 \text{ psi Initial Stress at } 1400^{\circ}\text{F: } 45,000 \times 30/24.8 = 54,500 \text{ psi}}$$

The proportional limit at room temperature was definitely known to be more than 70,000 psi so the lower two clamping stresses do not involve yielding.

### General Discussion

Results of this investigation indicated that the optimum initial stress for maximum relaxation strength at the longer time periods was close to the proportional limit of each alloy at the test temperature. The one exception was Inconel X which underwent a volume decrease during the early portions of the tests. This volume change appeared to be effective in offsetting the creep causing relaxation and lowered the initial stress for maximum 1000-hour relaxation strength.

The influence of initial stress observed agree with the general trends in the literature for relaxation. In most cases, the relaxation strength increases with the initial stress. However, very few relaxation tests are conducted under conditions where yielding occurs during loading. Other work in this laboratory and a few cases in the literature, indicates that when yielding occurs, the relaxation strengths will be high at the shorter time periods but at longer time periods will fall below those for the case where little or no yielding occurs. Thus it appears that in most cases the usual observation of increasing relaxation strength with increasing initial stress holds for extended times of relaxation only up to the point where appreciable yielding occurs. Theoretically it would appear that this should hold only when the creep resistance is reduced by cold work.

However, the authors have observed the same behavior in relaxation tests for such alloys as S816 which normally are considered to be improved by cold work.

So far as the authors are aware, very little data are available regarding the relation of yielding during clamping at room temperature and yielding during application of an initial stress at the relaxation test temperature. It would seem that this might vary between alloys and test conditions depending on the effect of cold work on creep resistance. Certainly it appears that yielding resulting from a decrease in yield strength with increasing temperature would be detrimental to relaxation strengths even though there was no yielding during clamping at room temperature. It, therefore, appears that in most cases the proportional limit at the relaxation temperature is the controlling factor in determining the optimum clamping stress at room temperature.

It was pointed out in the description of relaxation test methods that the conditions of conducting the tests for this investigation were considerably idealized. In bolting practice some degree of elastic follow-up usually exists to maintain the residual stress at a higher level than shown by the tests. Thread efficiencies are also involved and may show more rapid rates of relaxation than is indicated by the tests. If gaskets are involved in the joint, relaxation of the gaskets must also be considered.

It should further be recognized that if appreciable elastic follow-up is involved in the bolting system, appreciable elongation by creep can occur. In cases where the deformation to rupture is low, rupture can occur under relaxation conditions. For instance, the previous report submitted under this investigation, 2536-24-F, "Rupture and Total Deformation Characteristics of M252, (VM), Udimet 500, Inconel 700, Inconel 713 and Stellite 31 Alloys (Phase VII)" showed that the Inconel 700 alloy investigated had very low elongation in rupture tests at 1350°F.

It could be susceptible to rupture in the presence of elastic follow-up. This problem would be intensified by retightening of bolts. In addition, notch effects of threads might also reduce rupture strength.

The observed relaxation strength were in reasonable agreement with those published for the alloys. The only exception was the unduly low values for "17-22-A"V alloy. Otherwise, the relaxation strengths were within the range of variation which would be expected between various lots of the alloys.

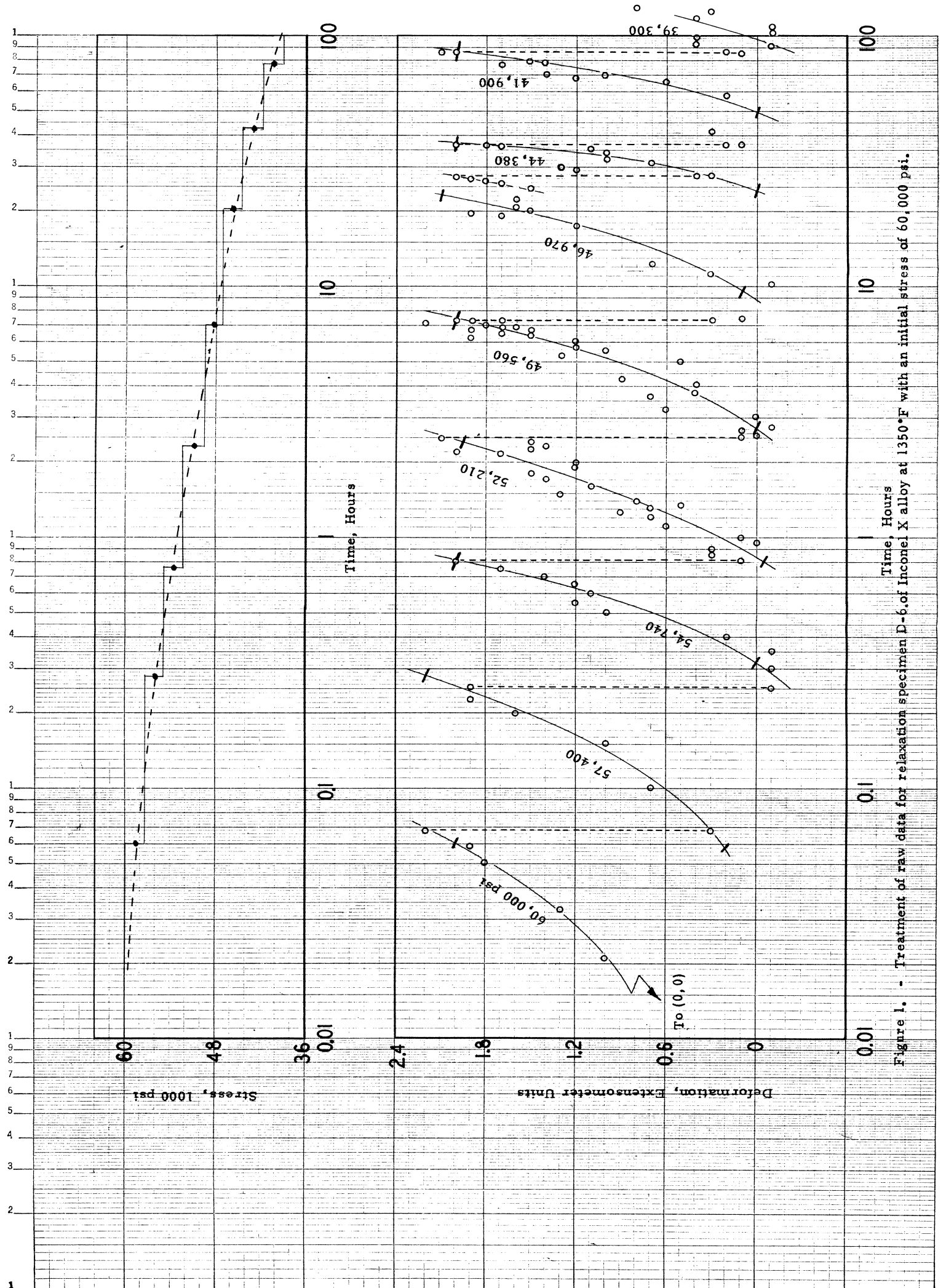


Figure 1. - Treatment of raw data for relaxation specimen D-6 of Inconel X alloy at 1350°F with an initial stress of 60,000 psi.

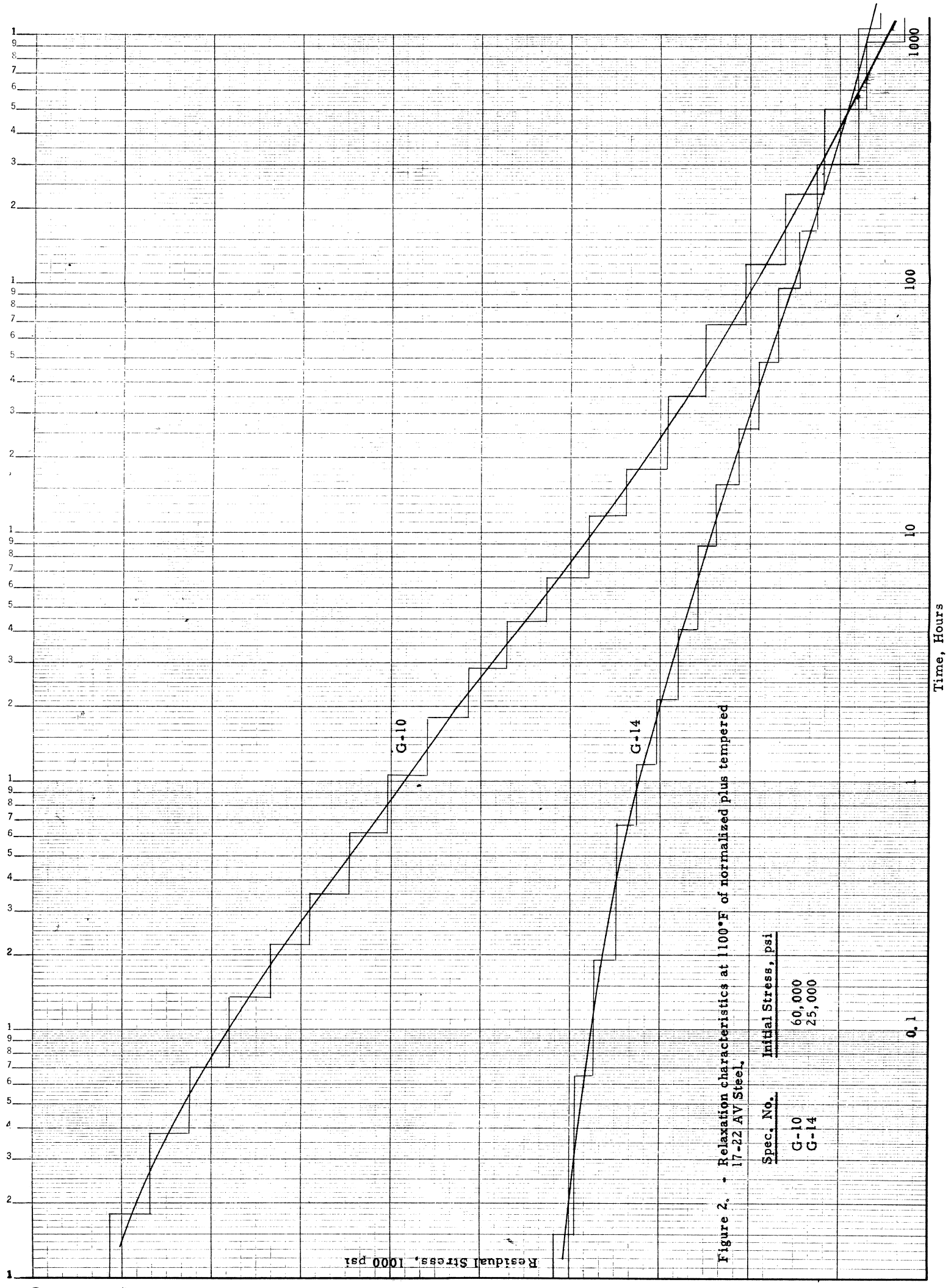


Figure 2. - Relaxation characteristics at 1100°F of normalized plus tempered 17-22 AV Steel.

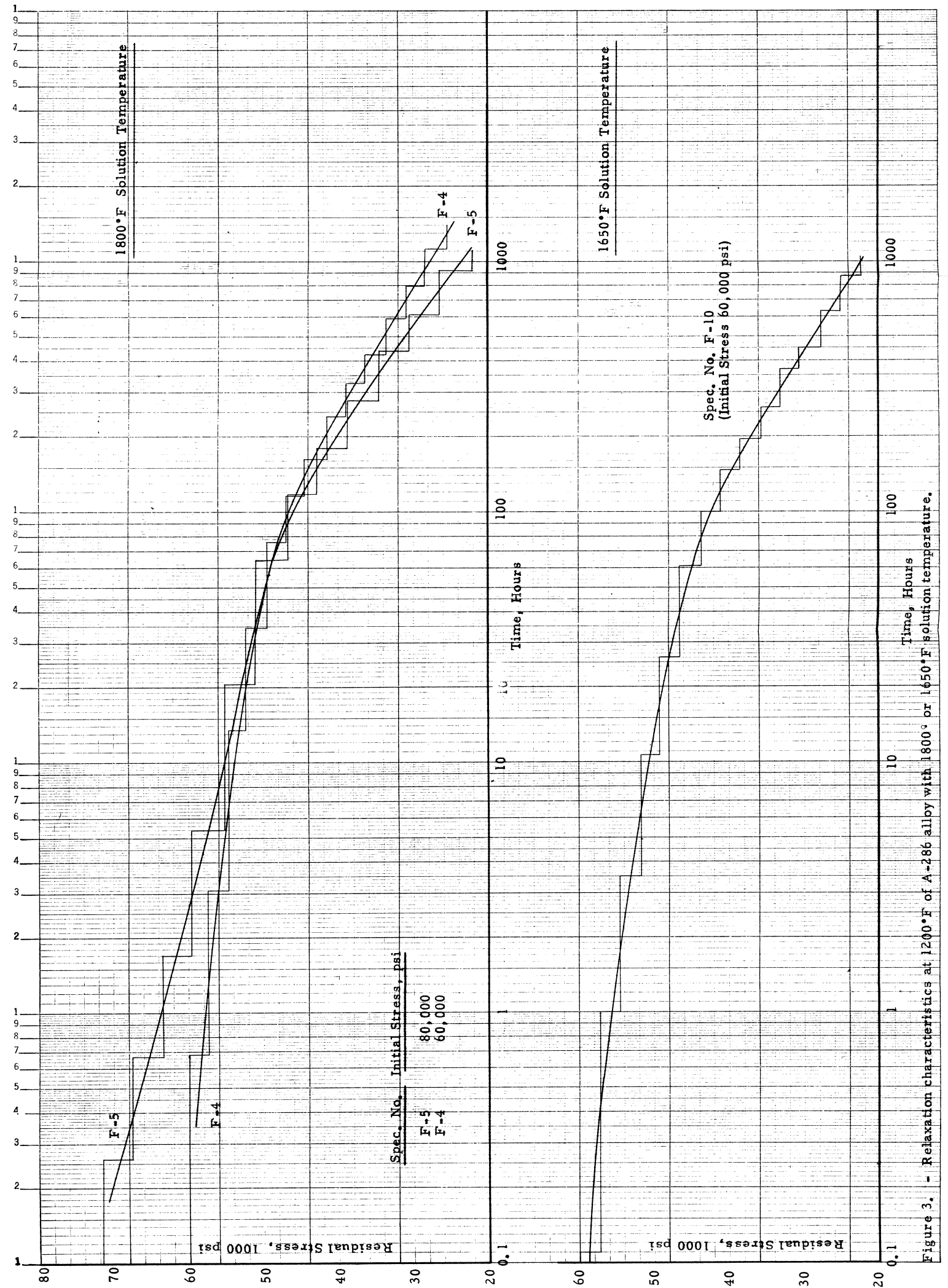


Figure 3. - Relaxation characteristics at 1200°F of A-286 alloy with 1800° or 1650°F solution temperature.

