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FINAL REPORT ON

ELASTIC PROPERTIES OF METALS AT HIGH TEMPERATURES

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PURPOSE OF THE PROJECT

The purpose of the research was to determine the temperature dependance of

1. Young's modulus;
2. the modulus of rigidity; and
3. Poisson's ratio

for alloys commonly used in high-temperature service. An ultrasonic method has been used in order to make instantaneous measurements and at very low levels of stress and strain.

ABSTRACT

The temperature dependance of Young's modulus, the modulus of rigidity, and Poisson's ratio of nine different alloys has been determined from 80°F to 1600°F. They are N155, 16-25-6, 19-9 DL, S816, Inconel-X, Hastelloy alloys B and C, Haynes alloy 25, and Discaloy. These alloys are of the types used in high-temperature service in the range 1000°F to 1500°F. The effect of several types of heat treatment on their elastic properties at high temperatures has been determined.

The method of measurement used is an ultrasonic one. The elastic properties are calculated from measured values of the velocities of longitudinal and transverse ultrasonic waves in the specimen being tested. A pulse method is used in which only one end of the specimen is heated while the other is kept at room temperature. This arrangement is necessary because of the limitations of the piezoelectric crystals used as sources of the sound waves. The wave velocities in the heated region of the specimen are calculated from the difference in time for an echo to return from two different points within the heated region. One point is the end of the bar, while the other point is a slot cut partway through the bar.

At low temperatures, the results obtained ultrasonically are the same as those from the usual static stress-strain measurements. At high temperatures the ultrasonic results are slightly higher than the static ones, the difference being about 1 per cent at 1200°F.

A principal advantage of the method is that a measurement of the moduli is made instantaneously and the results apply to that instant.

In general, the moduli of the alloys decrease linearly with temperature. For most of the alloys, the rate of decrease of the modulus of rigidity is approximately 0.25 x 10^6 psi per 100°F and that of Young's modulus is about 0.6 x 10^6 psi per 100°F.

Poisson's ratio was observed to vary linearly from .29-.30 at room temperature to .34-.35 at 1600°F.

The factors primarily considered in studying the temperature dependance of the moduli are as follows:

1. solution-treatment temperature;
2. aging at the service temperature; and
3. hot-cold work at 1200°F.

The general effects of these factors on Young's modulus and the modulus of rigidity are:

1. Solution treatment lowers the moduli. The amount of lowering appears to be independant of the solution-treatment temperature.

2. Aging raises the moduli in some cases and produces no change in others. Where a change in the moduli occurs, Poisson's ratio decreases.

3. Hot-cold work decreases the moduli.

Departure from linearity of the temperature-vs-moduli curves is observed above 600°F in Hastelloy alloys B and C and above 1350°F in Inconel-X, N155, and 16-25-6. An anomaly was observed in Hastelloy C above 1475°F in that the moduli increased slightly above that temperature.

INTRODUCTION

Three general methods for measuring the elastic constants of a given metal are as follows: (1) by obtaining a stress-strain curve; (2) by exciting a specimen into a resonant mode of vibration; and (3) by measuring directly the velocity of pulses of sound waves passing through the material. This investigation uses the third method. It has the following advantages:

1) A measurement of the elastic constants is made instantaneously and the values measured pertain to that instant.

2) Heating time can be made short by use of a salt bath.

3) Very low amplitudes of stress and strain are used and hence any effects due to creep are eliminated.

4) No errors can result from mechanical slippage in the mounting, as in the stress-strain method.

5) No ambiguity arises as to the mode of vibration.

The principle disadvantage is that a bar at least 3/4 inch in diameter and 8 inches or more in length is needed. Preferably, it should be about 16 inches long.

The temperature dependance of Young's modulus, the modulus of rigidity, and Poisson's ratio has been determined from 80°F to 1600°F for nine different alloys. They are N155, 16-25-6, 19-9 DL, S816, Inconel-X, Hastelloy alloys B and C, Haynes alloy 25, and Discaloy. These alloys are of the type used in high temperature service in the range of 1000°F to 1500°F.

In particular it was desired to investigate the temperature dependance of the moduli of those alloys in the as-received and solution-treated conditions, and to study the effects of the following factors:

1. solution-treatment temperature;
2. aging at the service temperatures; and
3. hot-cold work at 1200°F.

Relationship between the Elastic Constants and the Velocities of Longitudinal and Transverse Sound Waves in Metals

The principle elastic constants for isotropic materials are related to the Lame constants, λ and μ, for an isotropic solid by the following equations:

$$E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu}$$

$$G = \mu$$

$$P.R. = \frac{\lambda}{2(\lambda + \mu)}$$

where E, G, and P.R. are respectively Young's molulus, the modulus of rigidity and Poisson's ratio.

In an isotropic polycrystalline material λ and μ have the following relationships to the usual tensor notation for the elastic constants of an anisotropic solid:

$$\lambda = C_{12} = C_{21} = C_{23} = C_{32} = C_{13} = C_{31}$$

$$\lambda + 2\mu = C_{11} = C_{22} = C_{33}$$

$$\mu = C_{44} = C_{55} = C_{66}$$

For an isotropic solid all the other "C's" are zero. The velocity of sound in an infinite medium is related to μ and λ by means of the following equations:

$$v_\ell = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

By simple rearrangement and substitution E, G, and P.R. may be expressed in terms of the velocity of sound as follows:

$$E = \frac{\rho v_t^2 (3v_\ell^2 - 4v_t^2)}{v_\ell^2 - v_t^2}$$

$$G = \rho v_t^2$$

$$P.R. = 1/2 \frac{v_\ell^2 - 2v_t^2}{v_\ell^2 - v_t^2} ,$$

where

ρ = density of the material

v_ℓ = longitudinal ultrasonic wave velocity

v_s = transverse ultrasonic wave velocity

Theoretical Relationships between the Elastic Constants and the Internal Forces of a Solid

The elastic properties of solids depend directly on their various internal cohesive and repulsive forces. These will vary widely in different types of solids and may be summarized as follows:

1. Heteropolar Forces. These are due mainly to the electrostatic attraction between charged spherical ions. Ionic crystals such as the alkali halides have this type of binding.

2. Homopolar Forces. These arise from the sharing of electrons between neighboring atoms. Diamond is a typical example, since each carbon atom shares its four valence electrons with the four nearest neighbors and thus completes an outer shell of eight electrons in each atom.

3. Van der Waals Attraction. This is a very weak force and comes from the mutual polarization of the atoms of a solid. It is responsible for the cohesion of the rare gases in the solid state and most molecular lattices.

4. Metallic Forces. Several factors contribute to these. There is a strong attractive force between the negatively charged cloud of "free" electrons and the positively charged metal ions. Opposing this attractive force are two repulsive forces: (1) the mutual repulsion of the electrons

in the electron cloud, and (2) the repulsion between ions that are in contact due to an overlapping of their closed shells.

The elastic constants are derived from the energies which give rise to these forces in the following manner:[1]

$$A = 1/2 \frac{\partial^2 W}{\partial \mathcal{E}^2} \qquad B = 1/2 \frac{\partial^2 W}{\partial \gamma^2} \qquad C = 1/2 \frac{\partial^2 W}{\partial \mathcal{E}_v^2}$$

where W = energy per atom of the crystal;

$\mathcal{E}$ = change in lattice distance;

γ = angle of distortion during shear; and

$\mathcal{E}_v = \frac{\Delta V}{V_o}$ = change in volume per unit volume.

The usual elastic constants are related to A, B, and C by the following equations:

$$\frac{A}{\Omega_o} = C_{11} - C_{12} \qquad \frac{2B}{\Omega_o} = C_{44} \qquad \frac{2C}{\Omega_o} = 1/3\,(C_{11} + 2C_{12}),$$

where Ω_o = volume per atom.

The theoretical calculation of the binding energies in metals is difficult; quantitative results have only been obtained for the alkali metals and for copper.[2] It is found that in the former the binding energy is almost entirely the energy of the valence electrons in the field of the ions. In copper there is more overlapping of the closed shells, so that the repulsive forces between the ions come into play. Their effect on the total lattice energy is not great, but since these forces increase very rapidly with decreasing atomic distance their effect on the elastic constants is large.

An explanation of temperature dependance of the elastic constants for pure materials requires a knowledge of the temperature dependance of the binding energies. This theory has yet to be worked out for the metallic state.

DESCRIPTION OF THE METHOD

The method used is that developed by J. R. Fredrick.[3] The following measurements are made on the material:

1. the density;
2. the velocity of the longitudinal ultrasonic waves; and
3. the velocity of the transverse ultrasonic waves.

The density is determined by taking the ratio of the weight of a small sample to its loss in weight when weighed in water. The velocities of the ultrasonic waves are measured by observing the time required for a pulse of the waves to traverse a known distance in the solid. An ultrasonic reflectoscope is used for these velocity measurements. This device electrically excites a piezoelectric quartz crystal attached to the end of the metal specimen being tested, thus causing it to send out the desired pulse of ultrasonic waves. An echo will be received by the same crystal at a later time, dependent on the path length and the velocity of propagation. The reflectoscope amplifies this echo and presents it on a cathode-ray tube along with the initial pulse. The time interval between the two can be measured directly in microseconds by means of time markers superimposed on the timing axis.

The frequency of the ultrasonic waves was 2.25 mc and the pulses were about 5 mc long.

At elevated temperatures only one end of the metal specimen is heated. This is because the quartz crystal needs to be kept at room temperature. The wave velocities in the heated region are determined by observing the time intervals between echoes from two different points in the heated region. One point is the end of the specimen; the other is a narrow slot cut part way through the bar at a distance of from six to ten inches from the end. Fig. 1 shows the experimental arrangement.

A factor that must be taken into account in the calculation of the elastic constants at high temperatures by the above method is the change in dimensions of the specimen due to thermal expansion. This increases the path length but also lowers the density. The net result is that both E and G must be multiplied by a factor $(1 - \alpha t)$, where α is the linear coefficient of thermal expansion and t is the temperature. Poisson's ratio is unaffected by changes in length or density, since the length appears in both the numerator and denominator. Any correction factor thus cancels out.

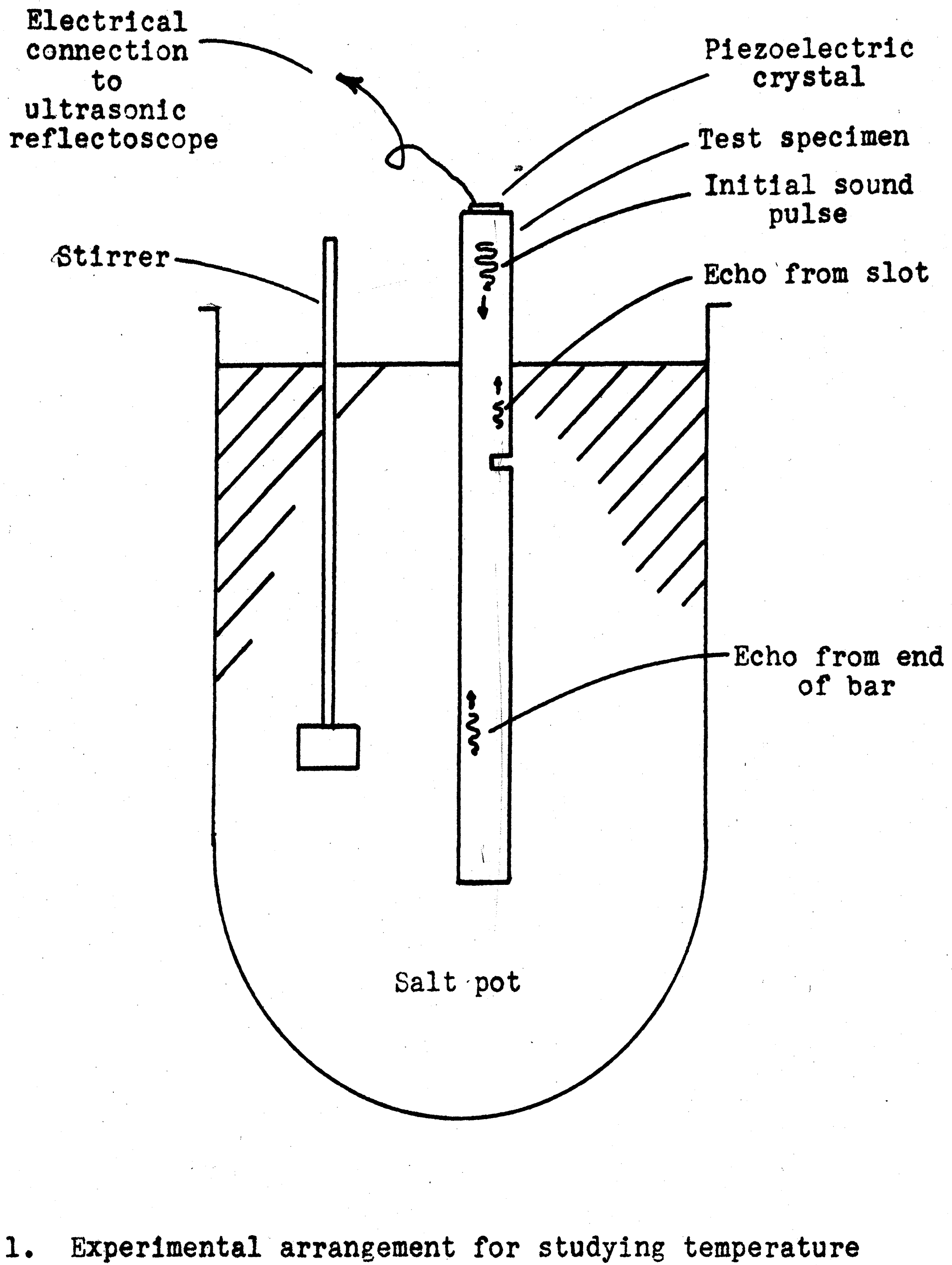

Fig. 1. Experimental arrangement for studying temperature dependance of elastic constants.

Heating of the specimens was done in a salt-bath type of furnace. Below 350°F, quenching oil was used instead of salt. Rapid heating and uniform temperature distribution were obtained by stirring vigorously with an electric mixer.

Each specimen was kept in the salt bath for from five to ten minutes before any measurements were made on the velocities of the ultrasonic waves. It was then allowed to air-cool.

The interval required for actually measuring the time between the echoes in the specimen is less than a minute.

The accuracy of the time measurement on the oscilloscope is the limiting factor in the accuracy of the final results. The error amounts to about a microsecond. For the acoustical path lengths used in this investigation this gives an error of 1 per cent in G, 1.5 per cent in E, and 3 per cent in P.R.

The dynamic method of measurement used here gives the "adiabatic" moduli, whereas static tests give isothermal moduli.

Dynamic methods have been shown by Gruneisen[4] to give the same results as static tests. The comparison is only valid at low temperatures, however. Lord Kelvin[5] shows that, due to thermal expansion under the conditions of adiabatic heating such as are obtained dynamically, the moduli as determined by the two methods will have the following relationship:

$$\frac{E_{ad}}{E_{iso}} = 1 - \alpha^2 T \frac{E_{ad}}{\rho C_p}$$

where E_{ad} is Young's modulus under dynamic conditions;

E_{iso} is Young's modulus under static or isothermal conditions;

α = coefficient of linear expansion;

C_p = heat capacity;

T = absolute temperature; and

ρ = density.

As long as T is small the difference between E_{ad} and E_{iso} is negligible. At about 1200°F, though, the static values will be of the order of magnitude of 1 per cent less than the dynamic ones.

Table X shows the densities and compositions of the materials tested.

RESULTS

1. N155

Figs. 2-18 show the temperature dependance of Young's modulus and the modulus of rigidity of N155 for various conditions of heat treatment.

Figs. 19-21 show similar curves for Poisson's ratio. The principal facts that can be deduced from these data may be summarized as follows:

1. The temperature dependance of the moduli is linear from room temperature to 1350°F. Above 1350°F there is some tendency for the moduli to decrease at a higher rate both before and after aging.

2. Aging solution-treated material several hours at temperatures of 1500°F raises Young's modulus by amounts varying from 0.4×10^6 psi to 1.0×10^6 psi at 1200°F. Similar effects occur in G, but the magnitude is half as great.

3. Solution-treatment of the as-received material reduces the low temperature moduli slightly, but the effect is not observed at high temperatures (Figs. 2 and 3).

4. The aging process is not complete after 16 hours at either 1350°F or 1500°F, since continuation of aging to 100 hours raises the moduli still more (Figs. 10 and 11).

5. There is no apparent difference between the elastic properties of material solution-treated 2 hours at 2050°F and that treated 1 hour at 2200°F (Figs. 4, 5, 8, and 9).

6. Aging 24 hours at 1350°F does not change the moduli of as-received material (Figs. 6 and 7).

7. In material solution-treated 1 hour at 2125°F there was little difference in the amounts by which the moduli increased due to aging in any of the following ways:

a) 24 hours at 1400°F;
b) 16 hours at 1475°F; and
c) 4 hours at 1500°F

(Figs. 12, 13, and 14).

8. Subjecting solution-treated material to 22 per cent hot-cold work at 1200°F lowers E and G uniformly at all temperatures by about 0.3 x 10^6 psi and 0.1 x 10^6 psi, respectively. Aging 16 hours at 1350°F then produces an increase in E and G. Loss of the specimen due to a furnace failure prevented a check at 100 hours to see if the effects of hot-cold work would be removed (Fig. 15).

9. Subjecting as-received material to 21 per cent hot-cold work at 1200°F lowers the moduli at low temperatures but not at high temperatures (Figs. 16, 2, and 3). Aging increases E and G by 0.5 x 10^6 psi and 0.3 x 10^6 psi, respectively.

10. Subjecting N155 solution-treated 1 hour at 2200°F to 15 per cent hot-cold work at 1600°F increases the moduli at room temperature, in contrast to hot-cold work at 1200°F but does not change their values at high temperatures, which is in agreement with results from hot-cold work at 1200°F (Figs. 17 and 18).

11. Poisson's ratio increases in a linear manner within the limits of experimental error from about .295 at room temperature to .34 at 1600°F (Figs. 19, 20, and 21).

Table I gives the values of Youngs modulus of N155 for different heat treatments and temperatures. These data are determined from the curves in Figs. 2-18.

2. Timken 16-25-6 Alloy

1. The temperature dependance of the moduli is linear over the range of temperatures measured, except that in the case of solution-treated material the rate of decrease is slightly greater above 1200°F.

2. Aging the as-received material at 1500°F and the solution-treated alloy at 1350°F raises the moduli but in different ways (Figs. 22 and 23). In the as-received material aging has a greater effect at room temperature. In the solution-treated material the high-temperature moduli are increased more than the room-temperature values.

3. Subjecting solution-treated material to 21.5 per cent hot-cold work at 1200°F uniformly reduces E and G by 0.7 x 10^6 psi and 0.25 x 10^6 psi, respectively (Fig. 24). Aging 100 hours at 1200°F removes the effects of the cold work on the moduli but does not result in moduli that are as large as the solution-treated-plus-aged condition only (Fig. 23).

TABLE I

YOUNG'S MODULUS OF N155
(Units are 10^6 psi)

Fig.	Condition of Material	80°F	400°F	800°F	1200°F	1350°F	1500°F	1600°F
2	As Received	30.4	28.5	26.1	23.6	22.55	21.5	
	S.T. 2 Hrs. at 2050°F	30.0	28.2	25.9	23.4	22.45	21.4	20.6
4	S.T. 1 Hr. at 2200°F							
	same +10Hr. at 1400°F	30.1	28.3	26.0	23.5	22.5	21.4	20.6
		30.6	28.8	26.4	23.85	22.8	21.7	20.85
6	As received, aged 24 Hrs. at 1350°F S.T. 2200°F 1 Hr. W.Q. aged 1400°F 24 Hr.	30.6	28.6	26.15	23.7	22.45	21.85	
8	S.T. 2 Hr. at 2050°F	29.95	28.15	25.9	23.4	22.4	21.3	20.5
	same +10 Hr. at 1400°F	30.55	28.75	26.4	23.9	22.8	21.7	20.8
10	S.T. 1 Hr. at 2200°F	30.2	28.3	25.8	23.2	22.5	20.9	
	same +100 Hr. at 1500°F	30.7	28.9	26.55	24.15	23.5	22.15	21.35
11	S.T. 2 Hr. at 2050°F	29.95	28.2	26.0	23.5	22.5	21.9	
	same +100 Hr. at 1350°F	30.9	29.0	26.65	24.1	23.0		
12	S.T. 1 Hr. at 2125°F	29.6	27.7	25.15	22.7	21.8	20.9	20.3
	same +16 Hr. at 1475°F	30.2	28.25	25.85	23.45	22.6		
13	S.T. 1 Hr. at 2125°F +24 Hr. at 1400°F	30.3	28.2	25.7	23.2	22.3	21.35	20.8
14	S.T. 1 Hr. at 2125°F +4 Hr. at 1500°F +HCW at 1200°F	30.0	28.0	25.6	23.1	22.15	21.2	20.6
15	S.T. 2 Hr. at 2050°F	29.8	27.9	25.5	23.1	22.2		
	same +16 Hr at 1350°F	30.3	28.45	26.05	23.65	22.7		
16	As received +HCW at 1200°F	30.3	28.35	25.95	23.6	22.7		
	same +16 Hr. at 1350°F	30.85	28.9	26.5	24.1	23.1		
17	S.T. 1 Hr. at 2200°F	30.05	28.2	25.85	23.35	22.35	21.3	20.6
	same +15°to HCW at 1600°F	31.0	28.8	26.1	23.45	22.45	21.45	20.8

4. Subjecting the as-received alloy to 20 per cent hot-cold work does not change E or G (Fig. 25). Aging 100 hours at 1500°F increases E and G at high temperatures by the same amount whether the material has been hot-cold worked or not. At room temperatures, however, the increases due to aging are only half as much in the hot-cold worked condition (Fig. 22).

5. There is no difference at 1200°F in the moduli of as-received material aged 100 hours at 1200°F and material hot-cold worked 20 per cent at 1200°F and aged 100 hours at 1500°F.

6. Poisson's ratio varies linearly from .29-.30 to .33-.34 (Fig. 27).

Table II presents a tabulation of the data on Young's modulus for 16-25-6.

TABLE II

YOUNG'S MODULUS OF TIMKEN 16-25-6 ALLOY
(Units are 10^6 psi)

Fig.	Condition of Material	80°F	400°	800°	1200°	1350°	1500°	1600°
22	As received	28.0	26.25	24.15	22.0	21.2	20.4	
	same +100 Hr. at 1500°F	29.5	27.5	25.1	22.75	21.85	21.0	20.4
23	S.T. 1 Hr. at 2100°F	28.2	26.4	24.05	21.7	20.55		
	same +100 Hr at 1350°F	28.5	26.75	24.6	22.45	21.65	20.7	20.0
24	S.T. at 2100°F 1 Hr. +21.5 per cent HCW at 1200°F	27.5	25.5	23.15				
	same +100 Hr. at 1200°F	28.2	26.35	24.0	21.7	20.85	20.0	19.5
25	As received +20 per cent HCW at 1200°F	28.15	26.3	24.0	21.7	20.85	20.0	
	same +100 Hr. at 1500°F	28.5	26.75	24.6	22.45	21.65	20.9	
26	As received +20 per cent HCW at 1200°F	28.35	26.4	23.9				
	same +100 Hr. at 1200°F	28.7	26.75	24.35	21.95	21.1	20.2	19.6

3. 19-9 DL

1. The temperature dependance of the moduli is linear from room temperature to 1600°F.

2. Aging at 1350°F does not affect the moduli of the as-received material (Fig. 28).

3. Solution-treatment for 1 hour at 2150°F uniformly decreases E and G by 1.0×10^6 psi and 0.45×10^6 psi respectively. Aging 100 hours at 1350°F increases the moduli to the values in the as-received condition (Fig. 29).

4. Solution-treatment at 2050°F instead of 2150°F gives values of E and G that are higher by 0.3×10^6 psi and 0.1×10^6 psi, respectively (Fig. 30). Aging 100 hours at 1500°F raises the moduli by the same amount as at the higher solution-treatment temperature.

5. Subjecting the as-received material to 9 per cent hot-cold work at 1200°F reduces E and G by 0.7×10^6 psi and 0.3×10^6 psi, respectively (Fig. 31). Aging 100 hours at 1500°F restores the original low-temperature values of the moduli but gives a value of E at 1600°F that is 0.4×10^6 psi higher than the original as-received material.

6. The effects of hot-cold work at 1200°F on solution-treated material are nonuniform. Subjecting alloy solution-treated at 2050°F to 21 per cent hot-cold work lowers E uniformly by 0.4×10^6 psi (Fig. 32). Subjecting 2150°F solution-treated material to 11 per cent hot-cold work at 1200°F increases E by 0.5×10^6 psi at room temperature but not at 1350°F (Fig. 34). Subjecting 2150°F solution-treated alloy to 30 per cent hot-cold work at 1200°F produces no change in E or G (Fig. 33).

The effects of aging the various hot-cold worked alloys also vary. Aging the 21 per cent hot-cold worked bar 100 hours at 1200°F does not change the room-temperature values of E or G but does raise E and G at 1200°F by 0.8×10^6 and $.45 \times 10^6$ psi, respectively (Fig. 32). In the specimen that is hot-cold worked 30 per cent, the properties after aging 100 hours at 1350°F are changed in that the room-temperature values of E and G do not increase as much as in a bar that has not been hot-cold worked (Fig. 33). In the 11 per cent hot-cold worked specimen, aging gives the same results as in a bar not hot-cold worked.

7. Poisson's ratio varies linearly from about .295 at room temperature to about .345 at 1600°F (Figs. 35 and 36). Any dependance on heat treatment produces changes within the experimental error of the equipment.

Table III summarizes the data for Young's modulus of 19-9 DL.

TABLE III

YOUNG'S MODULUS OF 19-9 DL

(Units are 10^6 psi)

Fig.	Condition of Material	80°F	400°F	800°F	1200°F	1350°F	1500°F	1600°F
28	As received or same after 100 Hr. at 1350°F	29.3	27.15	24.4	21.75	20.7	19.7	18.95
29	S.T. 1 Hr. 2150°F	28.0	25.95	23.3	20.65	19.6		
	same after 100 Hr. 1350°F	29.0	26.95	24.35	21.8	20.8	19.85	19.25
30	S.T. at 2050°F	28.65	26.5	23.65	20.9	19.85	18.9	
	same after 100 Hr. 1350°F	29.6	27.4	24.75	22.1	21.1	20.1	19.45
31	As received +9 per cent HCW at 1200°F	28.4	26.3	23.65	21.05	20.1	19.0	
	Same after 100 Hrs. at 1500°F	29.3	27.2	24.55	22.0	21.0	20.0	19.35
32	S.T. at 2050°F 2 Hr; 21 per cent HCW at 1200°F	28.3	26.1	23.2	20.4			
	Same after 100 Hrs. at 1200°F	28.4	26.4	23.9	21.4	20.5	19.5	18.8
33	S.T. at 2150°F 1 Hr; 30 per cent HCW at 1200°F	28.1	25.9	23.0	20.2	19.1		
	Same after 100 Hrs. at 1350°F	28.4	26.4	23.7	21.0	20.0	19.0	18.6
34	S.T. at 2150°F 1 Hr; 11 per cent HCW at 1200°F	28.5	26.3	23.6	20.9	19.9		
	Same after 100 Hr. at 1350°F	28.9	26.8	24.2	21.7	20.7	19.8	19.2

4. Discaloy

1. The moduli of this alloy are linearly dependant on temperature and do not change during aging for 100 hours at 1500°F (Fig. 37).

2. Poisson's ratio is linear and varies from .295 at room temperature to .34 at 1600°F (Fig. 42).

A summary of the data for Young's modulus is found in Table IV.

TABLE IV

YOUNG'S MODULUS OF DISCALOY
(Units are 10^6 psi)

Fig.	Condition of Material	80°F	400°	800°	1200°	1350°	1500°	1600° F
37	S.T. at 1800°F, 1 Hr.; +20 Hr. at 1350°F, +20 Hr. at 1200°F. Same after 100 Hr. at 1500°F	28.5	26.6	24.3	21.9	21.0	20.1	19.5

5. Inconel-X

1. The temperature dependance of the moduli of this alloy is linear up to about 1200°F. Above this temperature there is a greater decrease with increasing temperature.

2. Aging the as-received material 100 hours at 1500°F increases E and G by 0.9 x 10^6 and 0.45 x 10^6 psi, respectively at room temperature but gives no increase at 1500°F (Fig. 38).

3. Solution-treatment at 2100°F for 1 hour followed by recommended aging raises the value of E 0.4 x 10^6 psi above that of the as-received material (Fig. 39). Solution-treatment at 2050°F with no aging gives values of E and G only slightly less than those of the as-received material. Aging the 2050°F solution-treated specimen 100 hours at 1600°F yields values of E at room temperature equal to those obtained by optimum aging, but the value at 1350°F is less. Effects of aging 2050°F solution-treated material are confined to lower temperatures. Little change is produced above 1200°F (Figs. 40 and 41).

4. Poisson's ratio varies linearly from .30 at room temperature to .33 at 1600°F (Fig. 43).

A summary of the data for Young's modulus of Inconel-X is found in Table V.

TABLE V

YOUNG'S MODULUS OF INCONEL-X
(Units are 10^6 psi)

Fig.	Condition of Material	80°F	400°	800°	1200°	1350°	1500°	1600°
38	As received	30.1	28.5	26.6	24.7	24.0	23.3	22.5
	same after 100 Hr. at 1500°F	31.0	29.3	27.3	25.2	24.3	23.3	
39	S.T. 1 Hr. at 2100°F +24 Hr. at 155°F, +20 Hr. at 1300°F	30.4	28.9	27.0	25.2	24.3	23.2	
	same after 16 Hrs. at 1500°F	30.8					22.7	
40	S.T. 4 Hrs. at 2050°F	29.7	28.2	26.3				
	same 100 Hrs. at 1600°F	30.7	28.95	26.8	24.55	23.6	22.55	21.8

6. S-816

1. The as-received moduli of this alloy do not change appreciably with solution-treatment at either 2150°F or 2250°F nor with aging 16 hours at 1400°F (Figs. 44 and 45). Aging the 2250°F solution-treated specimen 16 hours at 1500°F appears to increase the moduli slightly, but this should be checked with more data before drawing any definite conclusions.

2. Poisson's ratio varies from .29 to .33 (Fig. 46).

TABLE VI

YOUNG'S MODULUS OF S-816
(Units are 10^6 psi)

Fig.	Condition of Material	80°F	400°	800°	1200°	1350°	1500°F
44	As received	33.95	31.9	29.3	26.75	25.8	24.85

7. Hastelloy B Alloy

This alloy shows a nonlinear dependance of the moduli on temperature above 600°F (Fig. 48). Aging 16 hours at 1475°F has negligible effect on the moduli but continued aging for one week increases E and G at 1475°F by 0.6×10^6 psi and 0.2×10^6 psi, respectively.

Poisson's ratio varies linearly from .31 at room temperature to .35 at 1600°F (Fig. 52b).

TABLE VII

YOUNG'S MODULUS OF HASTELLOY B ALLOY
(Units are 10^6 psi)

Fig.	Condition of Material	80°	400°	800°	1200°	1350°	1500°	1600°F
48	S.T. 1 Hr at 2125°F	31.65	30.3	28.35	26.2	25.1	24.05	23.2

8. Haynes Alloy 25

The moduli of this alloy have a linear dependance on temperature up to 1600°F (Fig. 49). The moduli are insensitive to aging 16 hours at 1475°F.

TABLE VIII

YOUNG'S MODULUS OF HAYNES ALLOY 25
(Units are 10^6 psi)

Fig.	Condition of Material	80°	400°	800°	1200°	1350°	1500°	1600° F
49	S.T. 1 Hr. at 2225°F	33.5	31.4	28.8	26.2	25.2	24.25	23.6

9. Hastelloy C

The moduli of this alloy change very rapidly with aging at 1475°F and 1600°F. The change occurs at such a rate as to be readily followed by the reflectoscope. Since the change was the same at room temperature as at the aging temperatures, it was followed by heating the specimens for varying lengths of time in an air furnace, and then cooling to room temperature for a determination of Young's modulus. Two different specimens, A and B, were tested successively. Fig. 47 shows the variation with time of the room-temperature value of Young's modulus as a result of aging at 1600°F.

Figs. 50 and 51 show the net change of the moduli over the temperature range of 80°F to 1600°F due to aging 16 hours at 1600°F. The increases in E and G are 2.7 x 10^6 psi and 1.1 x 10^6 psi, respectively. The change in slope between 1475°F and 1600°F is reversible and not due to aging effects.

Poisson's ratio decreases with aging. Before aging it varies linearly from .32 to .35 over the range of temperature of 80°F to 1600°F. After aging the variation is from .31 to .33 over the same temperature range (Figs. 52 c and d).

TABLE IX

YOUNG'S MODULUS OF HASTELLOY C
(Units are 10^6 psi)

Fig.	Condition of Material	80°	400°	800°	1200°	1350°	1500°	1600°F
51	S.T. 1 Hr. at 2225°F	30.1	28.75	26.95	24.45	23.25	22.1	22.0
	S.T. 1 Hr. at 2225°F +16 Hr. at 1600°F	32.8	31.3	29.4	27.0	25.9	24.85	24.9

General Results

1. In order to determine whether or not the effects due to hot-cold work at 1200°F are the result of anisotropy due to rolling, measurements were made of the moduli in a direction at right angles to the direction of rolling on three different alloys. No orientation effect was apparent in any of the specimens measured.

2. The velocities of longitudinal and transverse waves were measured in specimens of N155 and 1020 steel while they were being statically stressed at room temperature. Stresses up to 50,000 psi were used on the 1020 steel and 70,000 psi on the N155, but no changes in the velocities were noted.

For all alloys in which the moduli are increased by aging the value of Poisson's ratio is decreased slightly.

DISCUSSION OF RESULTS

A characteristic shown by all the materials whose moduli change as a result of aging is that the moduli are increased. The principal structural change occurring is usually some sort of migration of solute atoms with the formation of precipitates, either at grain boundaries or within the grains themselves. This indicates that, as might be expected, the presence of the solute atoms alters the force fields in the grains in such a way as to lower the moduli.

Changes in the elastic properties due to migration of precipitate particles to grain boundaries or to the presence of the precipitate particles within the grains will be small unless the new phase occupies a considerable portion of the volume of the alloy. This is because the measured elastic constants are macroscopic rather than microscopic.

Slight changes in composition have negligible effect on the moduli, as indicated by the fact that values for the two heats of N155 are in good agreement. This fact was also verified in a series of tests in which the amounts of molybdenum, tungsten, and columbium in N155 were varied individually by a few per cent. No significant changes were observed in the moduli.

The abrupt change in slope in Hastelloy alloy C at 1475°F could be due to a phase transformation. It coincides with an abrupt change in slope on the ultimate tensile strength vs temperature graph supplied by the manufacturer for this alloy.

The decrease in the moduli as a result of hot-cold work at 1200°F is difficult to understand, since strain energy introduced into the lattice should increase the moduli as is observed for hot-cold work on N155 at 1600°F. More tests should be run before any firm conclusions can be drawn or the mechanism completely understood.

CONCLUSIONS

In general, the moduli of elasticity of the alloys tested decrease linearly from 80°F to 1600°F except for Hastelloy alloy C, which shows an anomalous behavior at 1500°F. Poisson's ratio increases linearly over the same range of temperature.

Solution treatment lowers the moduli of the as-received specimens. No differences were found due to different solution-treatment temperatures.

Aging raises the moduli in some cases and produces no change in others. Where a change in the moduli occurs, Poisson's ratio decreases.

Hot-cold work at 1200°F decreases the moduli of N155, 19-9 DL, and 16-25-6.

The method is not as sensitive as might be desired for detecting small effects, but it is satisfactory for gross effects. If the errors could be reduced to 0.1 per cent, it is likely that more changes in the moduli resulting from changes in the strain energy in the lattice would be detected. These changes in strain energy might result from either precipitation effects or hot-cold work.

APPENDIX A

TEST MATERIALS

The composition of the alloys on which moduli measurements were made are given in Table X. The available history of the bar stock used is as follows:

Low-Carbon N155

Heat A-1726 was in the forms of 7/8-inch broken-corner square bars which had been hot rolled in one heat from a 2-inch square billet with an initial temperature of 2050°F and a finishing temperature of 1910°F. The billets were produced from a 13-inch square ingot in fifteen heats working from 2070° to 1730°F. The bar-stock hardness was 228 Brinell and the grain size was 7-8.

Heat M127 stock was supplied by the Haynes Stellite Company as 3/4-inch round bars which had been commercially produced and heat treated. The heat treatment after hot rolling was 1 hour at 2125°F followed by rapid air cooling.

Inconel-X

The Inconel-x bar stock was in the form of 1-inch rounds produced by hot-rolling 2-inch square billets between 2200°F and 1800° to 1900°F. The billets were produced from 18 x 18-inch 4400-pound ingots from a 9400-pound induction furnace heat. The grain size was 6-8.

16-25-6 (Timken Alloy)

The 16-25-6 test material wasfurnished in the form of 1-inch round hot-rolled bars commercially produced from a 19-ton electric-furnace heat. The 19-inch round floated ingots were press forged to 4-inch square billets starting at 1975°F. The billets were hot-rolled to 1-inch rounds.

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Commercially produced 3/4-inch round bar stock in the hot-rolled condition was supplied by the Allegheny Ludlum Steel Corporation.

TABLE X

COMPOSITION OF ALLOYS USED IN TESTS

	Heat Number	Density	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Other
N155	A1726 M127	8.29 8.25	0.13 0.12	1.63 1.60	0.42 0.54	21.22 21.24	19.00 20.10	19.70 19.39	2.90 3.14	2.61 2.47	0.84 1.07	N:0.13 N:0.14
Inconel-X	Y3724-X	8.19	0.04	0.56	0.38	14.97	73.22				1.02	Al:0.78 Ti:2.38 Cu:0.03
16-25-6	17310	8.10	0.58	1.82	0.54	16.84	26.18		6.60			Cu:0.162
S816	61858	8.64	0.38	1.28	0.23	19.51	19.91	43.20	3.82	4.15	3.84	
Hastelloy B	Lot-2754	9.21	0.03- 0.05	0.56- 0.76	0.11- 0.62	0.15- 0.84	balance		27.84 29.14			V:0.33-0.45
Hastelloy C	C1040	8.82	0.08	0.56	0.48	16.33	balance	1.51	16.77	4.56		
Haynes 25	L-14	9.08	0.09	1.40	0.48	19.90	10.64	balance		14.60		Ti:0.16
19-9 DL	B10810	7.90	0.30	1.09	.38	18.97	9.18		1.24	1.50	.52	Ti:0.32
Discaloy	43103	8.03	0.03			15.	26.		3.0			

Hastelloy Alloy B

Commercially produced 3/4-inch round bar stock was supplied by the Haynes Stellite Company. The bars had been solution treated for 1 hour at 2125°F and rapidly air cooled.

Hastelloy Alloy C

Commercially produced 3/4-inch round bar stock was supplied by the Haynes Stellite Company. The bars had been solution treated 1 hour at 2225°F and rapidly air cooled.

Haynes 25

Commercially produced 3/4-inch round bar stock was supplied by the Haynes Stellite Company. The bars had been solution treated 1 hour at 2225°F and rapidly air cooled.

19-9 DL

Commercially produced 7/8-inch broken-corner square-bar stock from 12-ton arc-furnace heats was used. The bars were hot rolled with a finishing temperature of 1650°F and stress relieved for 2 hours at 1200°F at the mill.

Discaloy

Rolled-bar stock, 1-1/16-inch round, from a commercial arc-furnace heat was used. The hot-rolled bars were heat treated by oil quenching after 1 hour at 1800°F and aging for 20 hours at 1350°F plus 20 hours at 1200°F.

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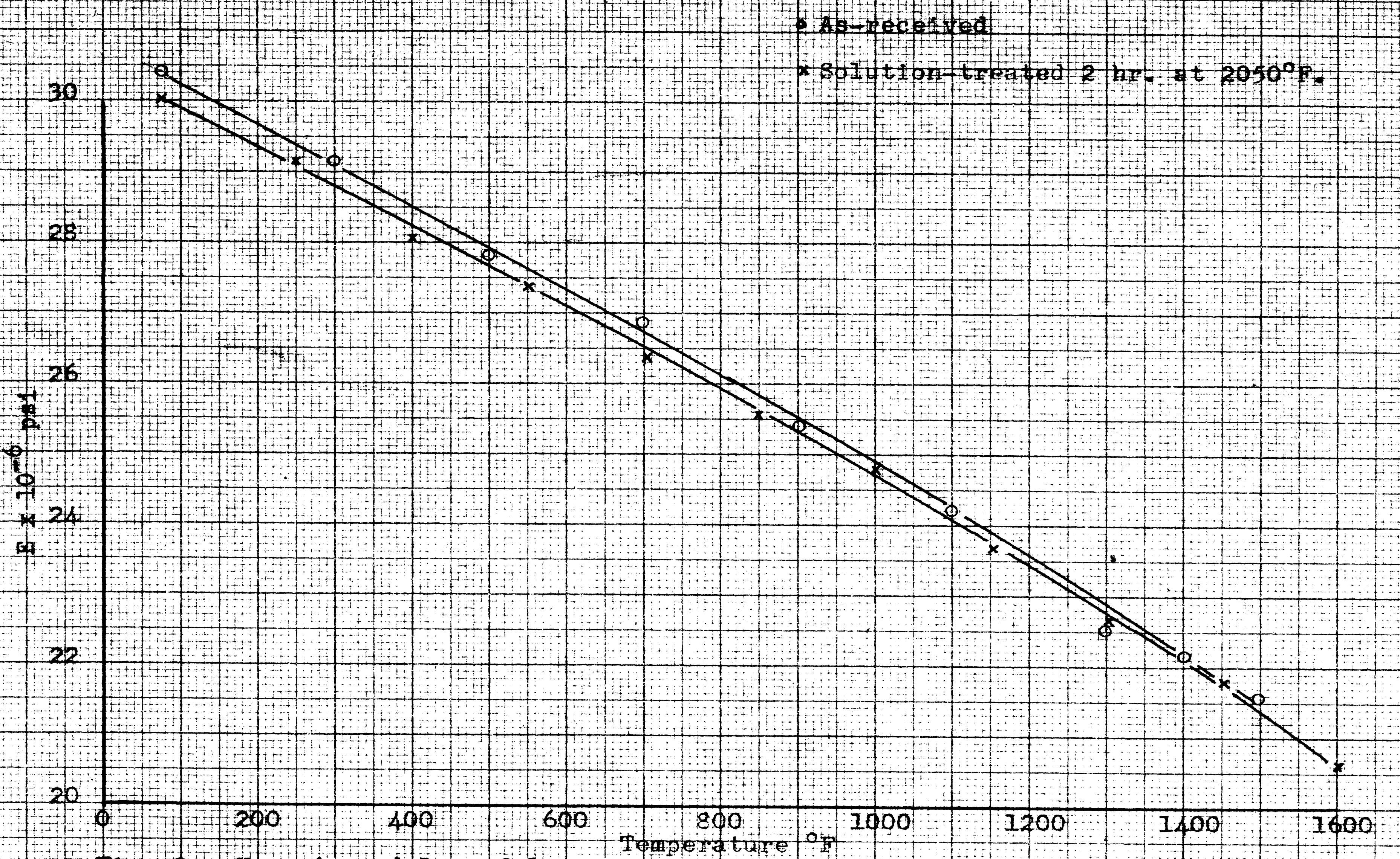

Fig. 2. Young's modulus of low-carbon N155 as-received end after solution-treatment 2 hr. at 2050°F, heat A1726.

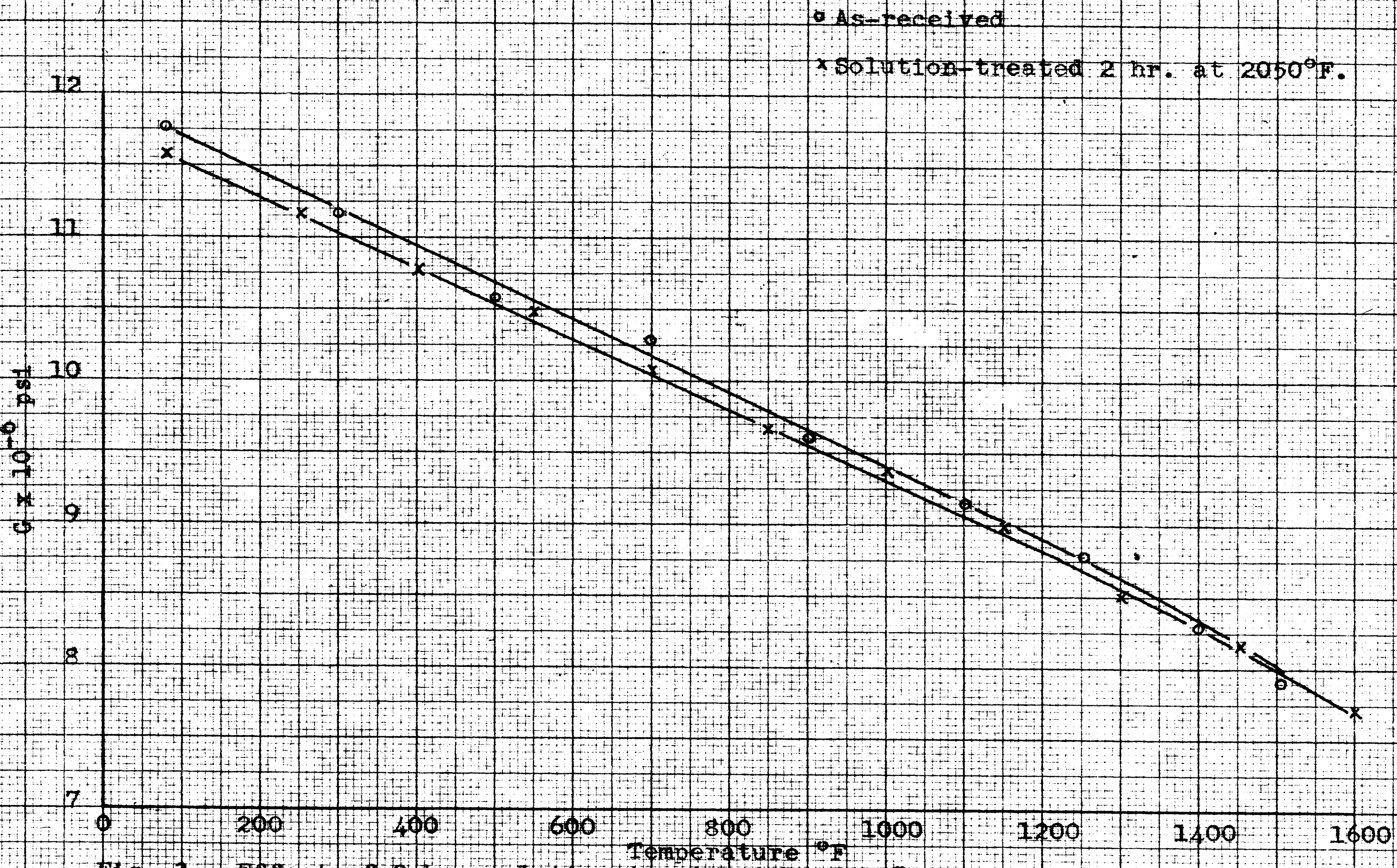

Fig. 3. Effect of 2 hr. solution-treatment at 2050°F on the modulus of rigidity of N155, heat A1726.

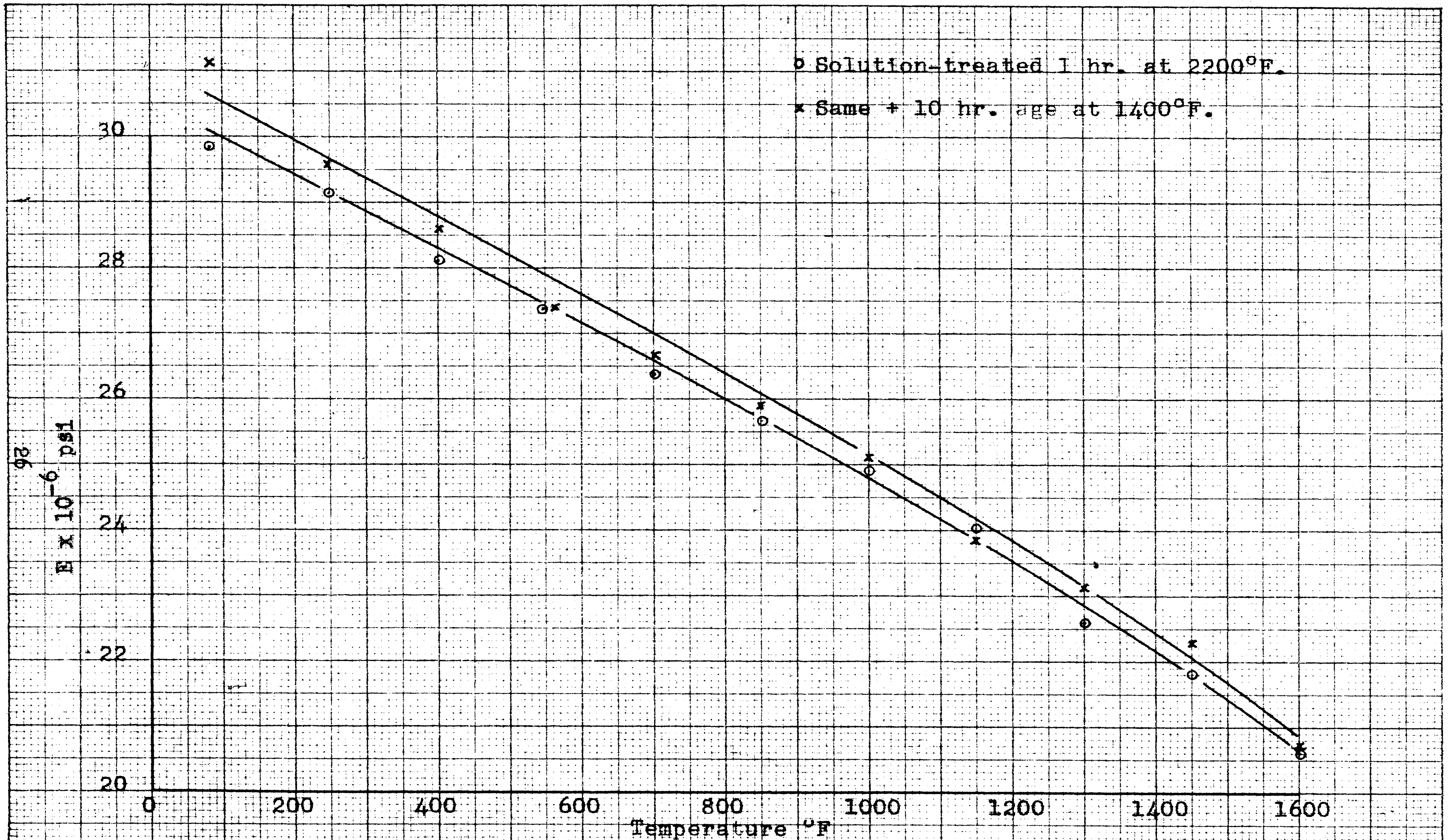

Fig. 4. Effect of aging on Young's modulus at low-carbon N155 solution-treated at 2200°F, heat A1726, aged at 1400°F.

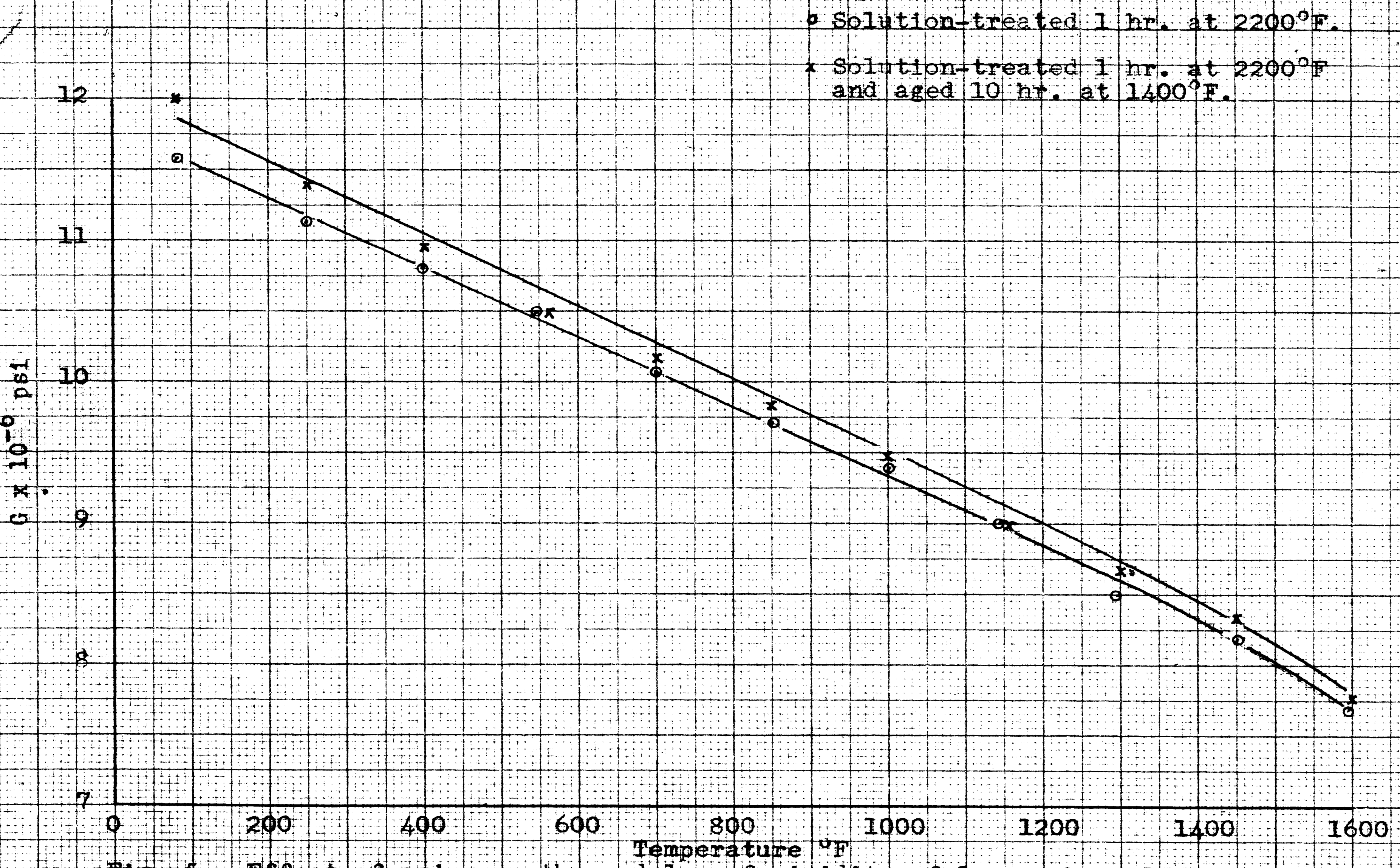

Fig. 5. Effect of aging on the modulus of rigidity of low-carbon N155 solution-treated at 2200°F, heat A1726, aged at 1400°F.

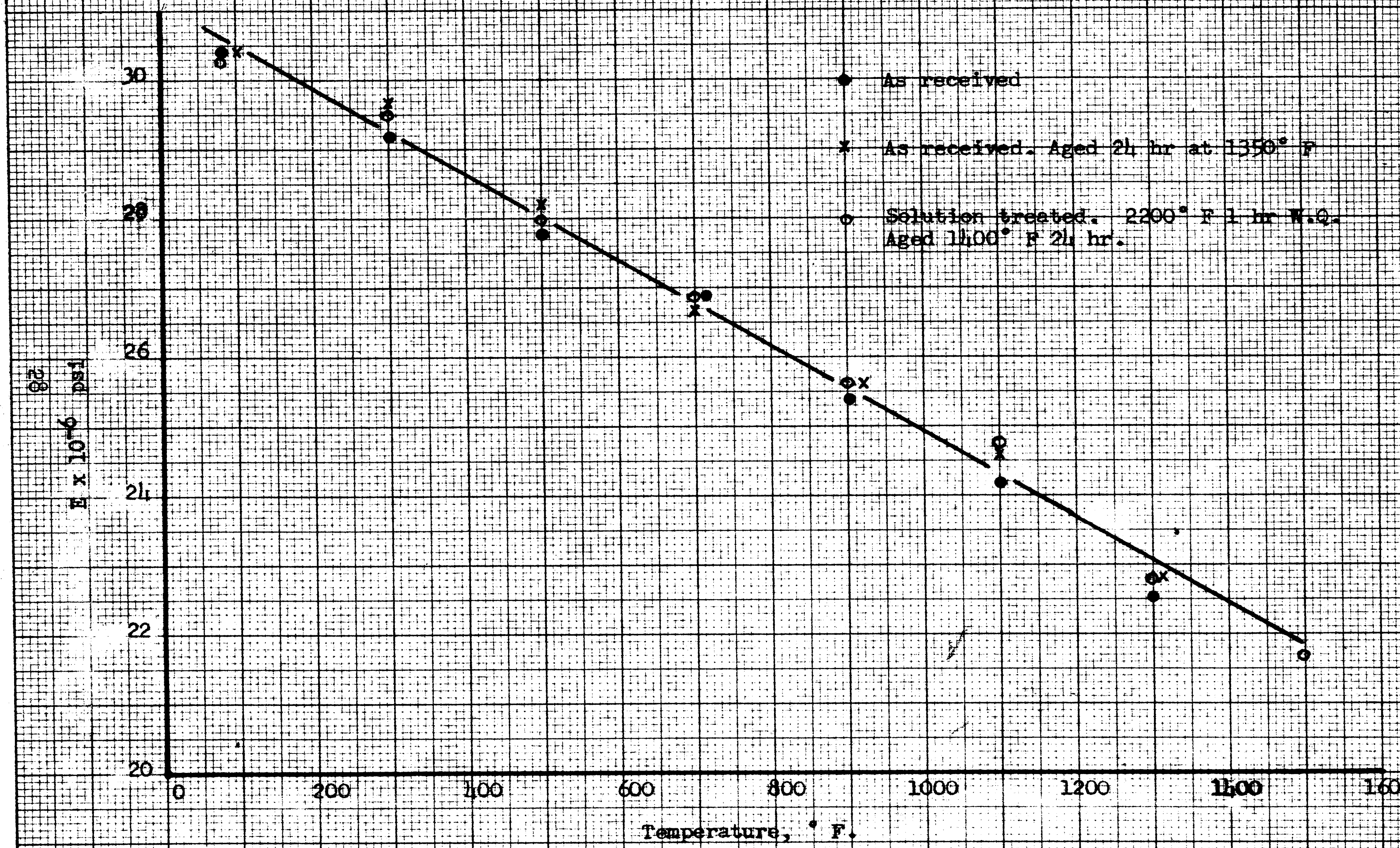

Fig. 6. - Young's modulus of N155, Heat A1726 as a function of temperature. Effect of aging at 1350°F on as-received material and and of aging at 1400°F on material S.T. 1 hr at 2200°F.

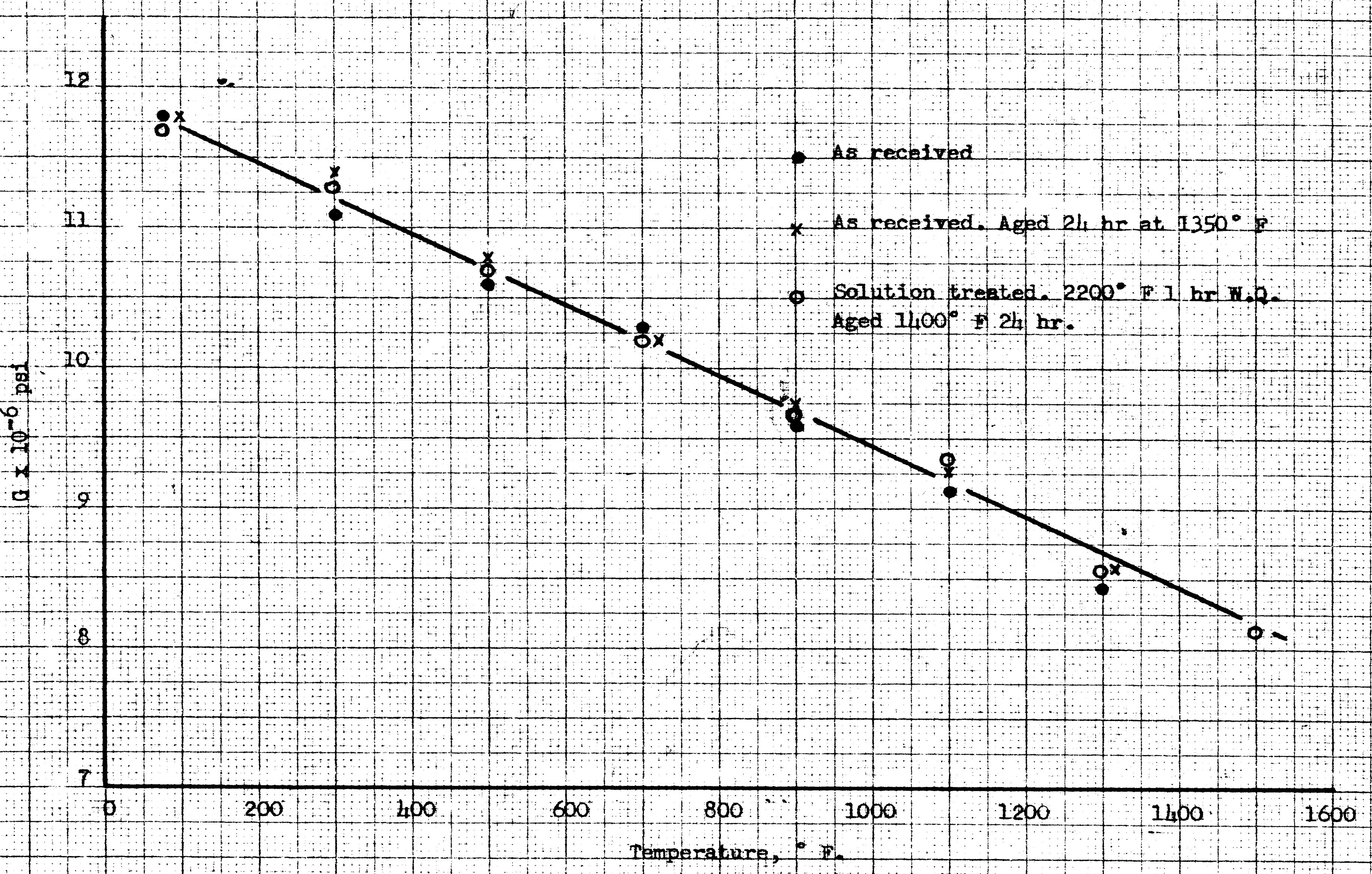

Figure 7. - Modulus of rigidity of N155, Heat A1726, as a function of temperature. Effect of aging at 1350°F on as-received material and of aging at 1400°F on material S.T. 1 hr at 2200°F.

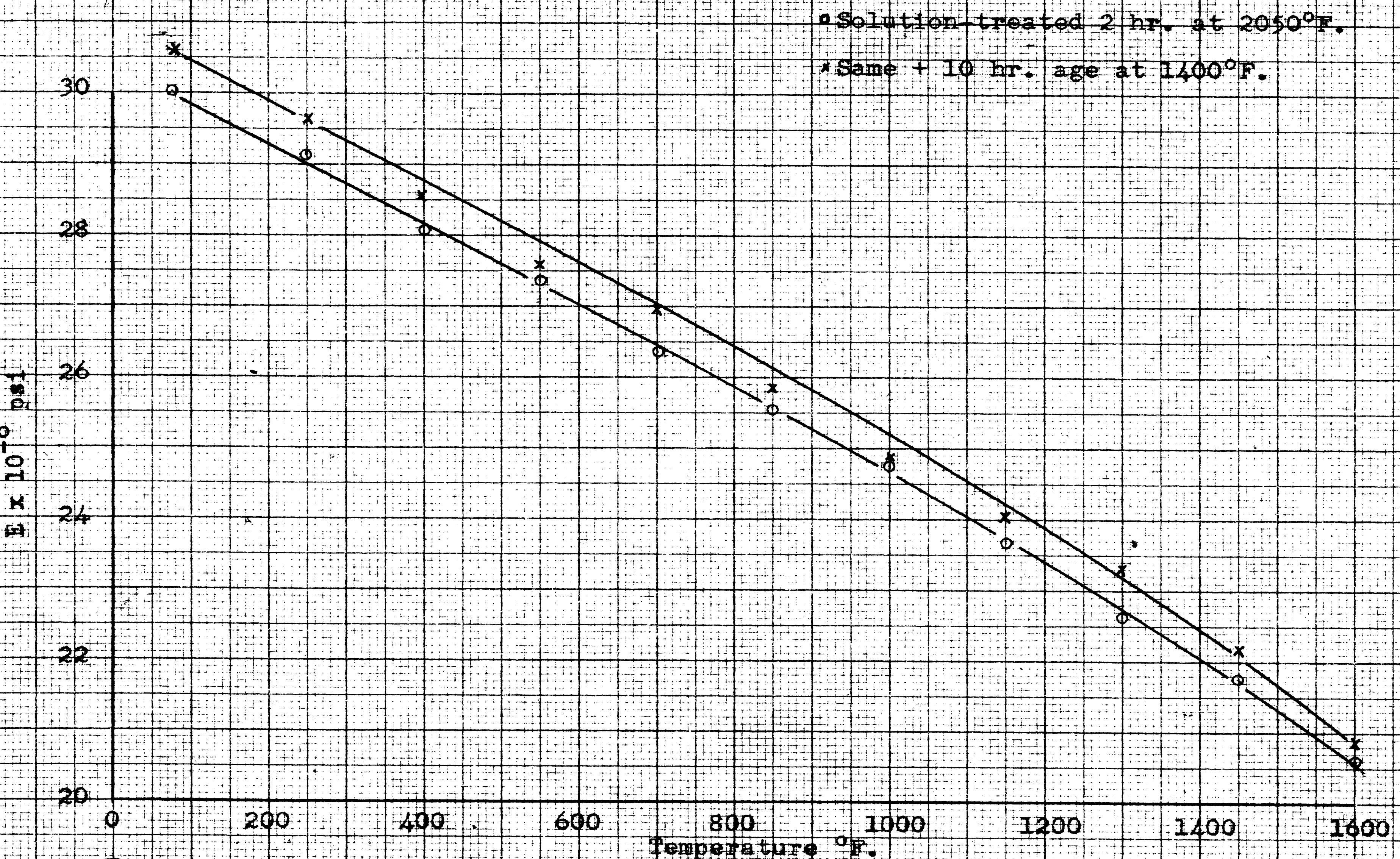

Fig. 8. Effect of aging on the Young's modulus of low-carbon N155 S.T. at 2050°F, heat A1726, aged at 1400°F.

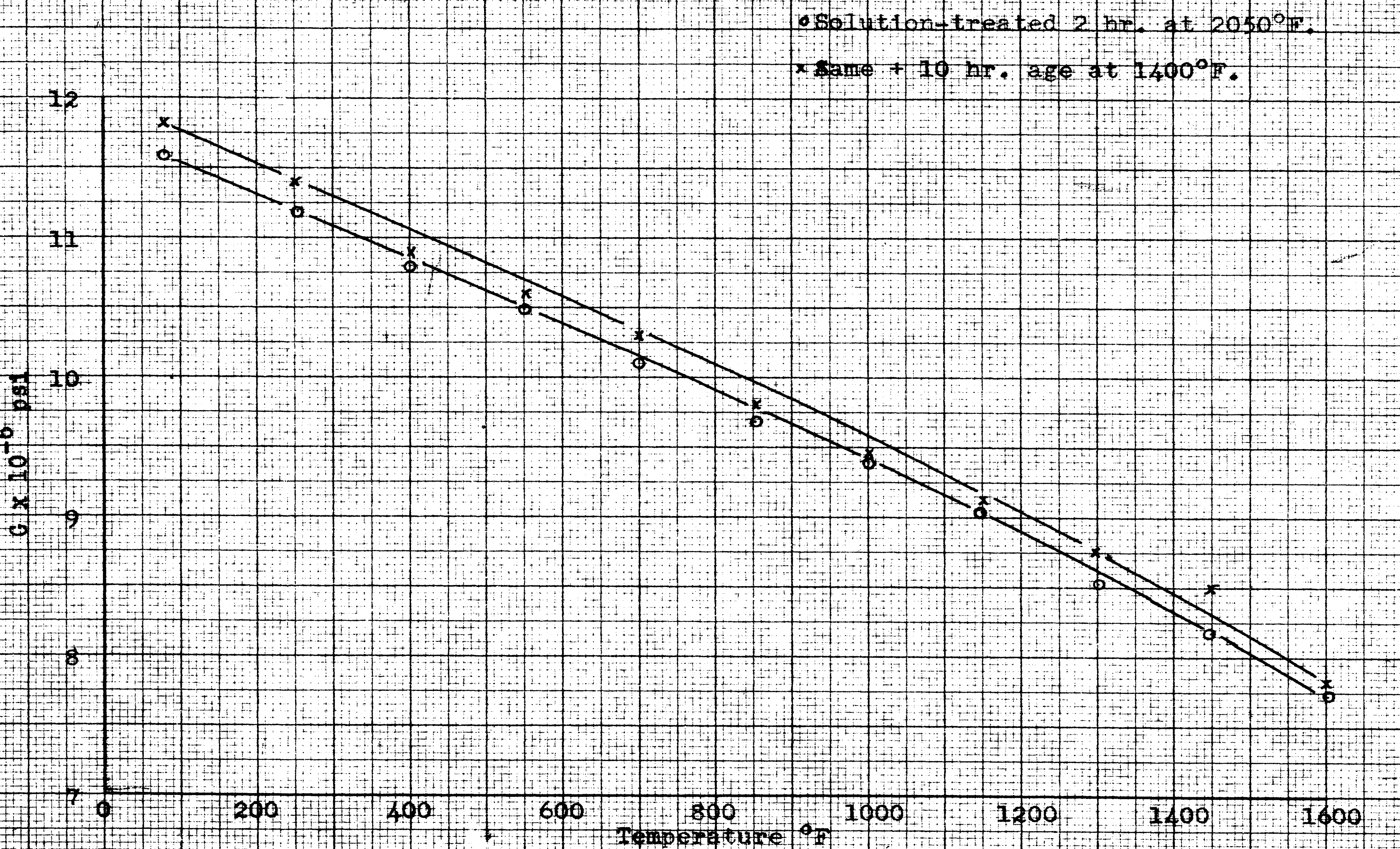

Fig. 9. Effect of aging on the modulus of rigidity of low-carbon N155 S.T. at 2050°F heat A1726, aged at 1400°F.

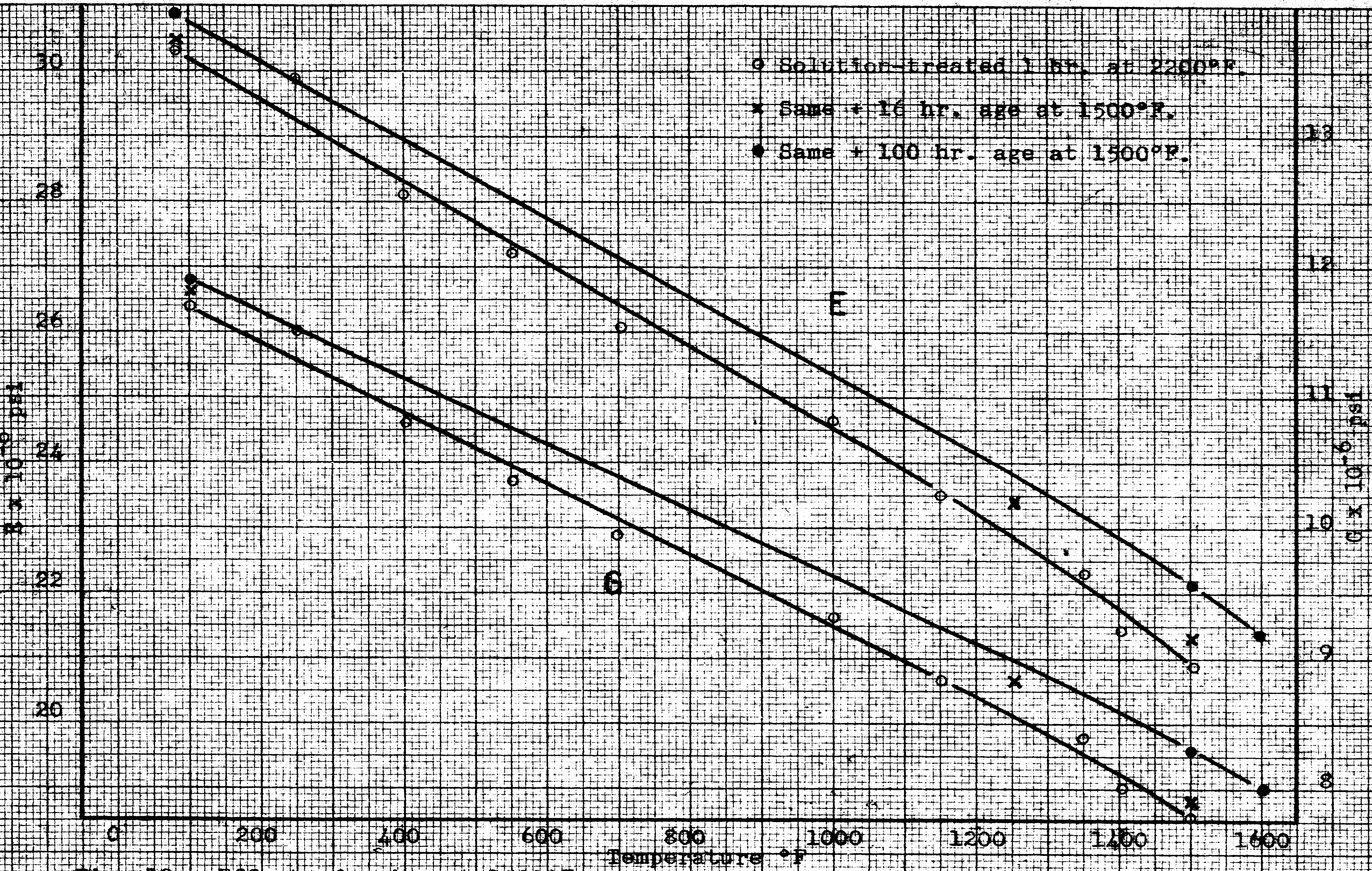

Fig. 10. Effect of aging at 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of N155, heat A1726, S.T. 1 hr. at 2200°F.

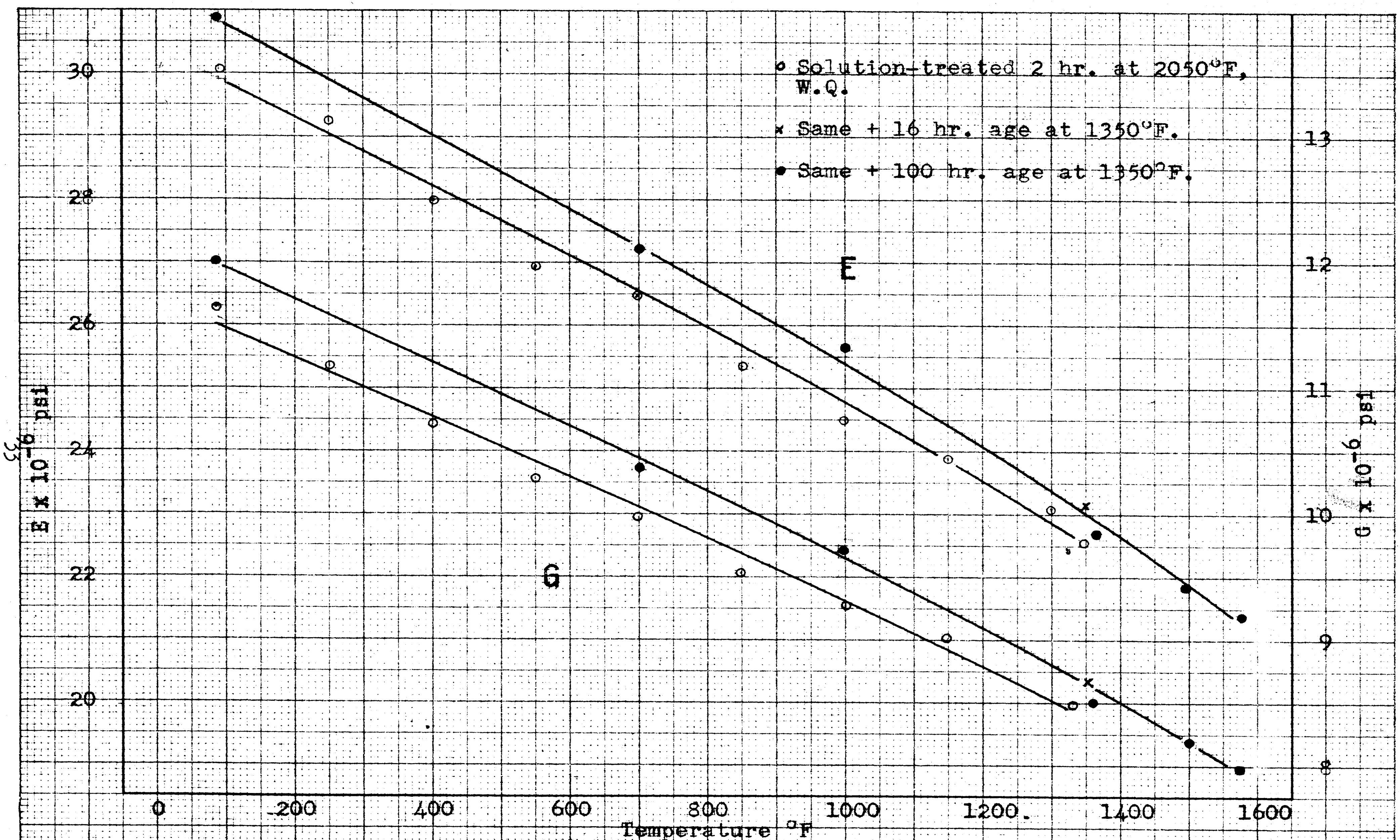

Fig. 11. Effect of aging at 1350°F on the temperature dependance of Young's modulus and the modulus of rigidity of N155, heat A1726, S.T. 2 hr. at 2050°F.

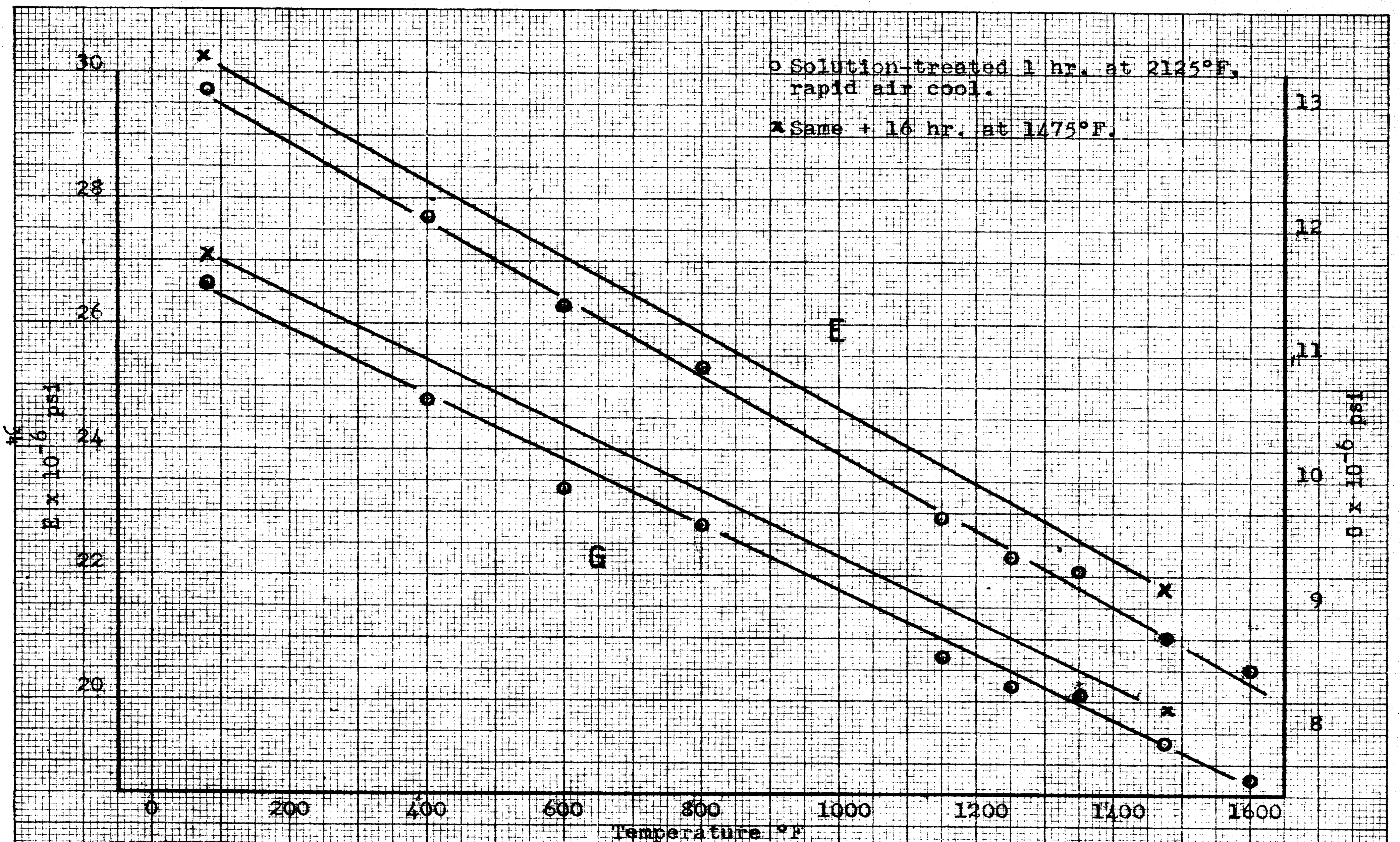

Fig. 12. Effect of aging at 1475°F on the temperature dependance of Young's modulus and modulus of rigidity of N155, heat No. M127, S.T. 1 hr. at 2125°F.

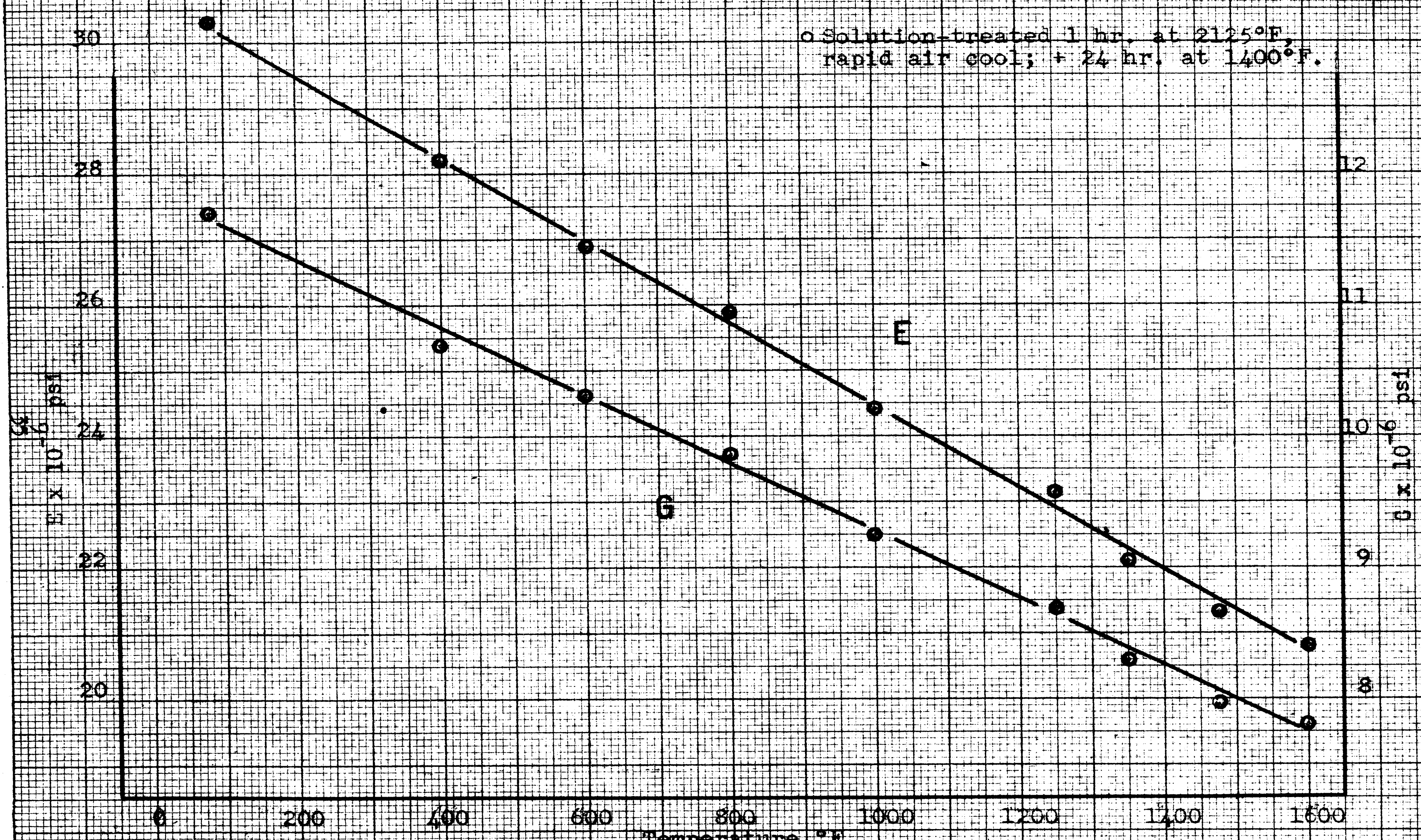

Fig. 13. Temperature dependance of Young's modulus and the modulus of rigidity of N155, heat No. M127, S.T. 1 hr. at 2125°F, aged 24 hr. at 1400°F.

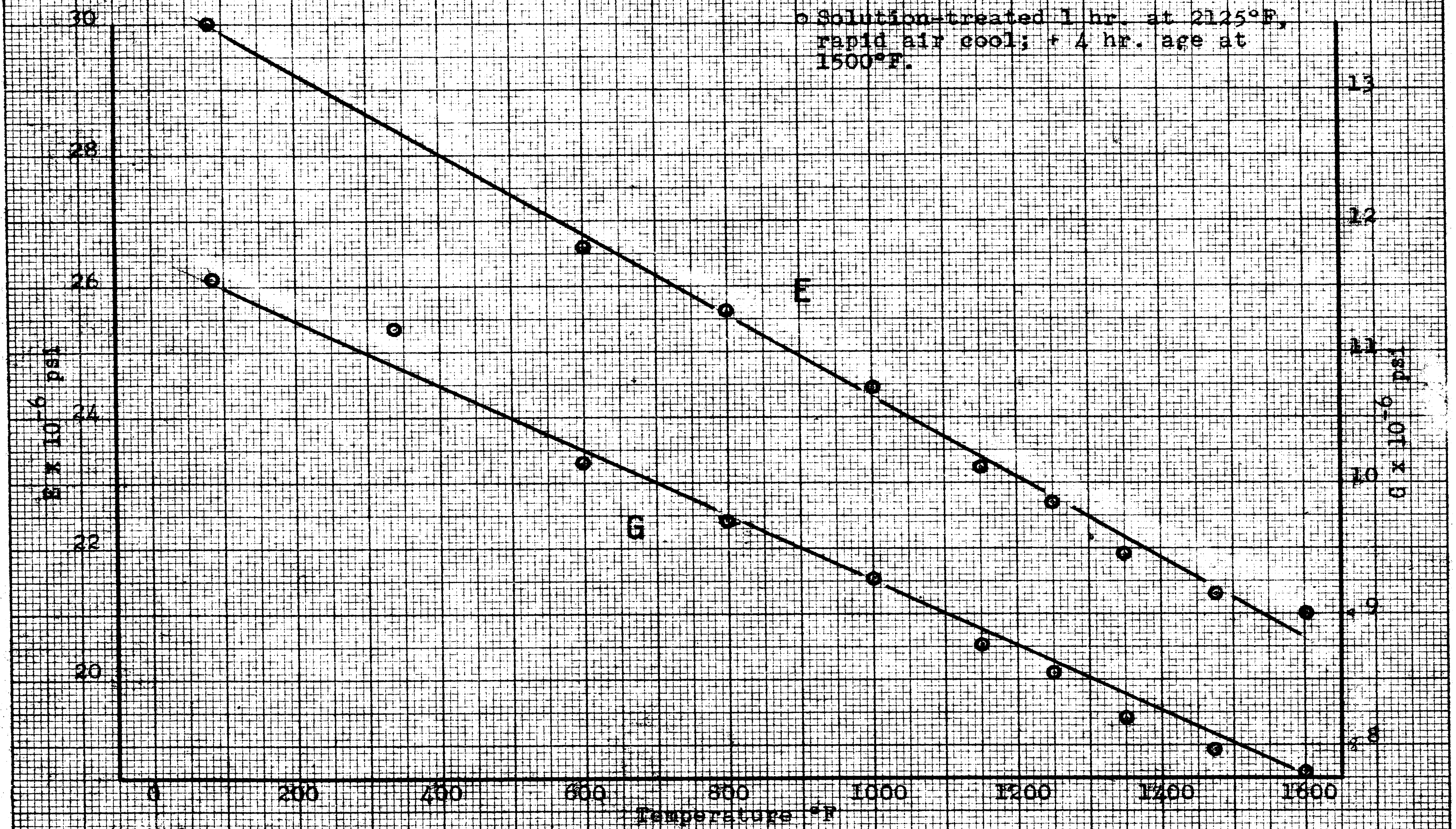

FIG. 14. Temperature dependance of Young's modulus and the modulus of rigidity of N155, heat M127, S.T. 1 hr. at 2125°F, aged 4 hr. at 1500°F.

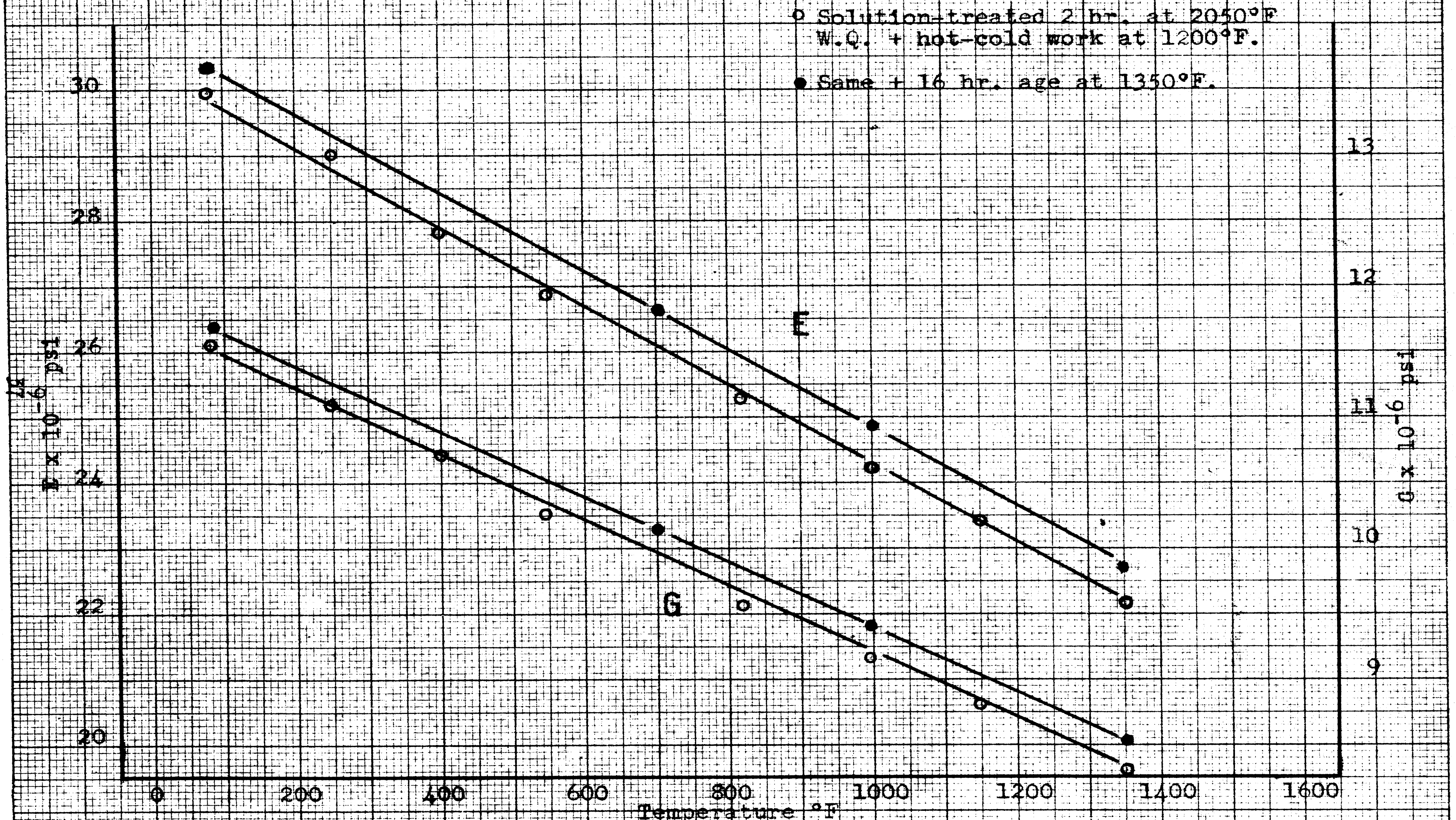

Fig. 15. Effect of aging at 1350°F on the temperature dependance of Young's modulus and the modulus of rigidity of N155, heat A1726, S.T. 2 hr. at 2050°F, + 22% H.C.W. at 1200°F.

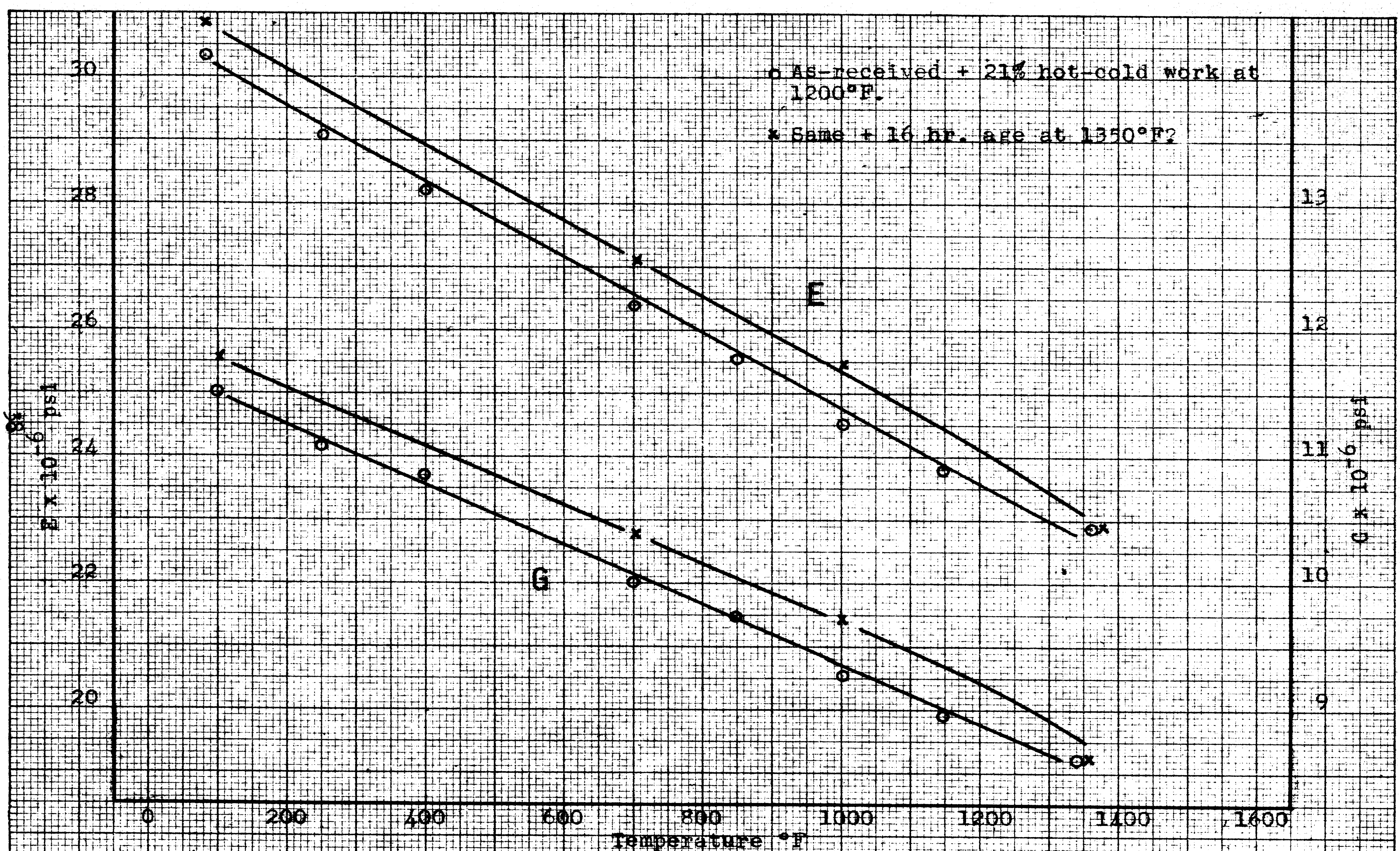

Fig. 16. Effect of aging at 1350°F on the temperature dependance of Young's modulus and the modulus of rigidity of N155, heat A1726, as-received + 21% H.C.W. at 1200°F.

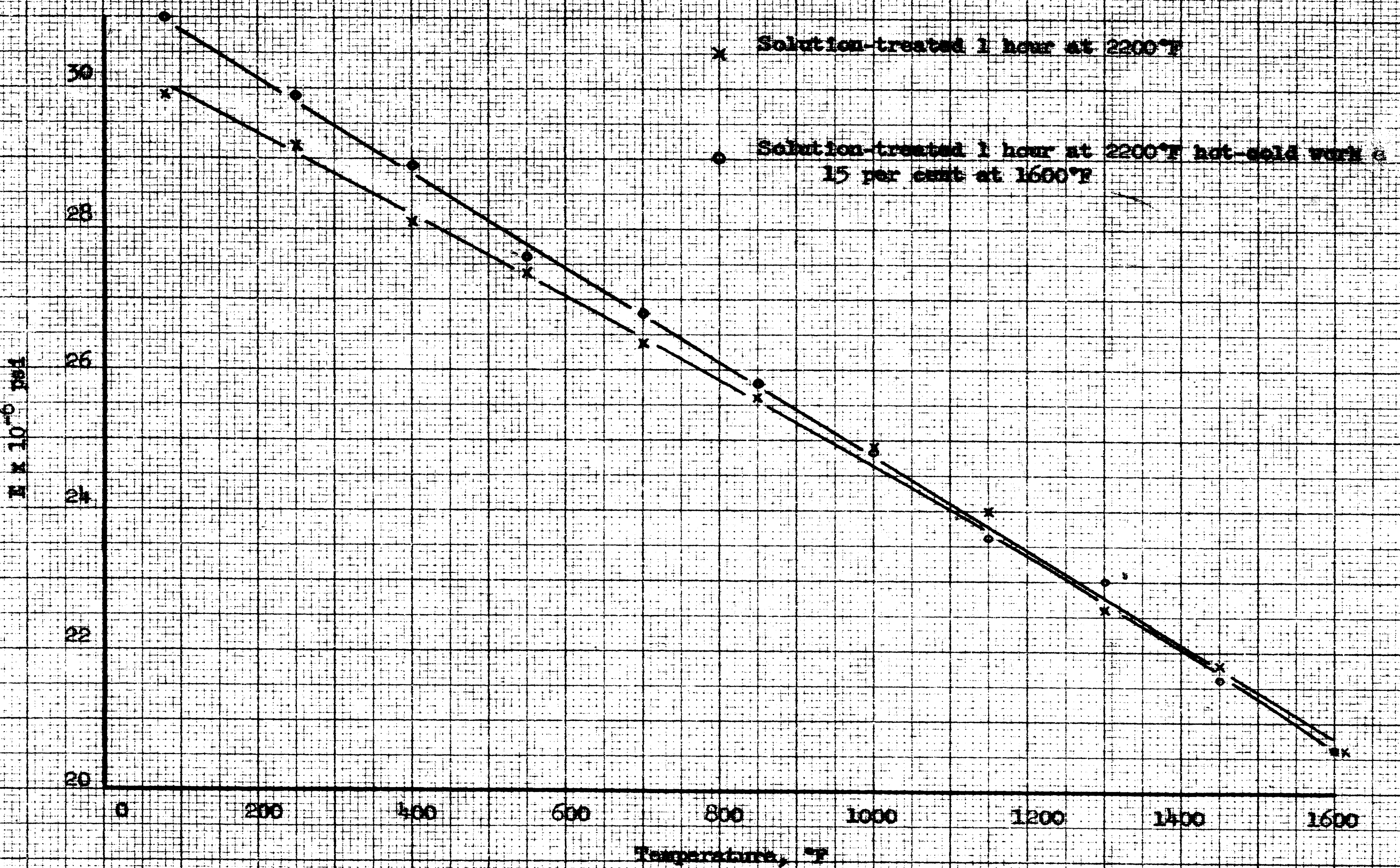

Fig. 17. Effect of hot-cold work on Young's modulus of low-carbon N155, Heat A1726, as a function of temperature. S. T. 1 hr at 2200° F.

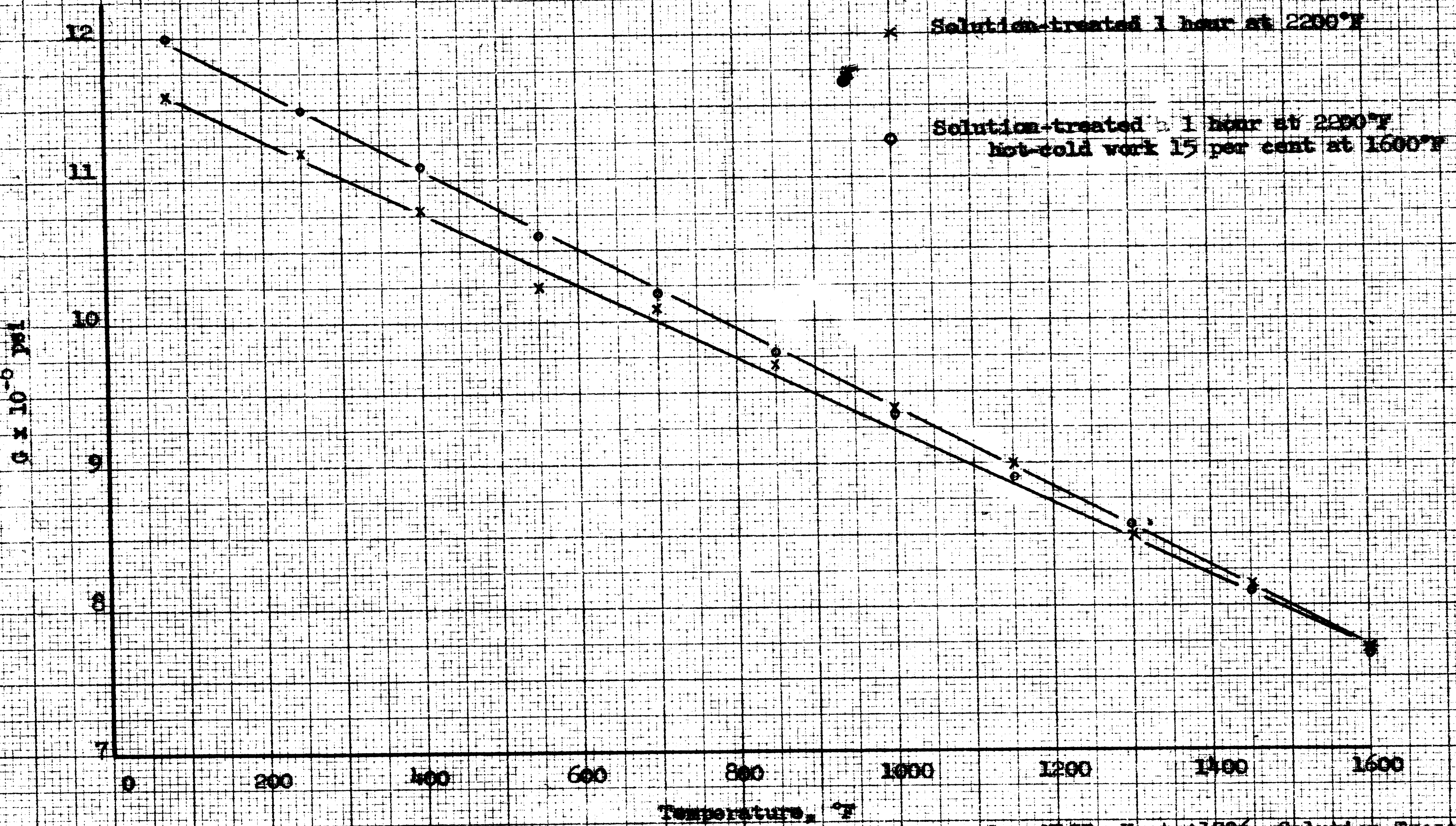

Fig. 18. Effect of hot-cold work on modulus of rigidity of low-carbon N155, Heat A1726, Solution-Treated 1 hr at 2200° F.

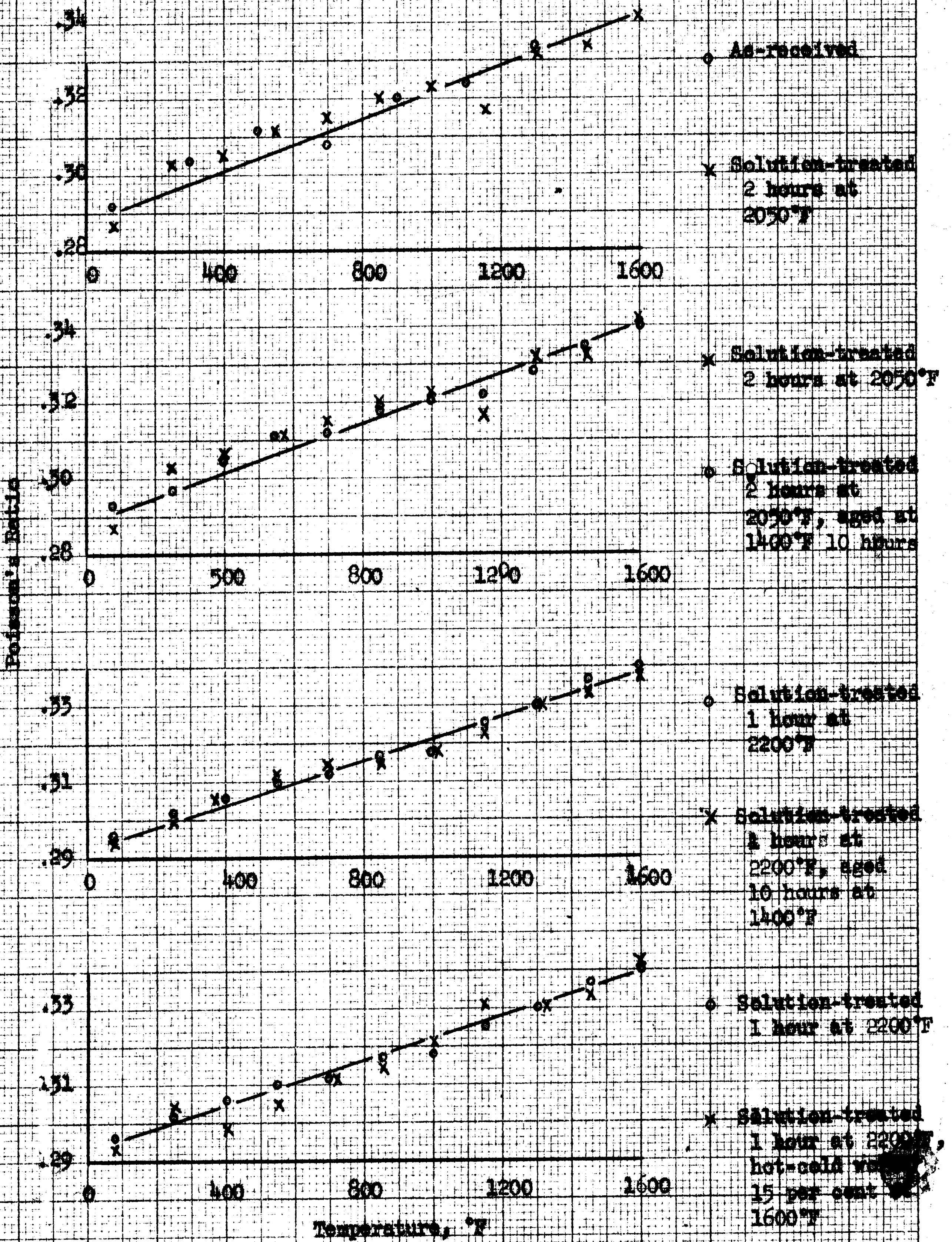

Fig. 9. Poisson's ratio for low-carbon N155.

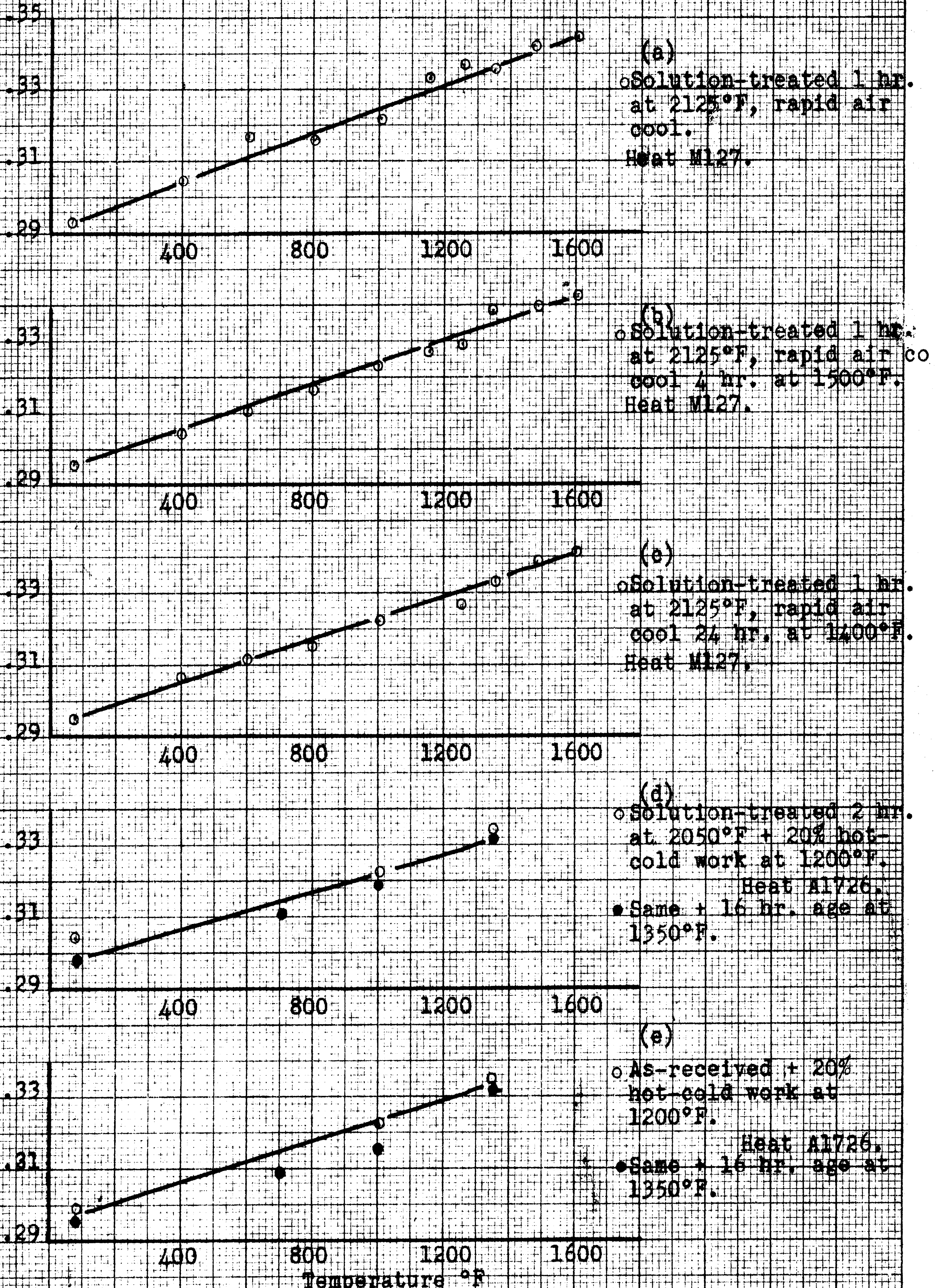

Fig. 20. Effect of S.T. at 2125°F and 2050°F and of aging at 1350°F, 1400°F, and 1500°F on Poisson's ratio of N155.

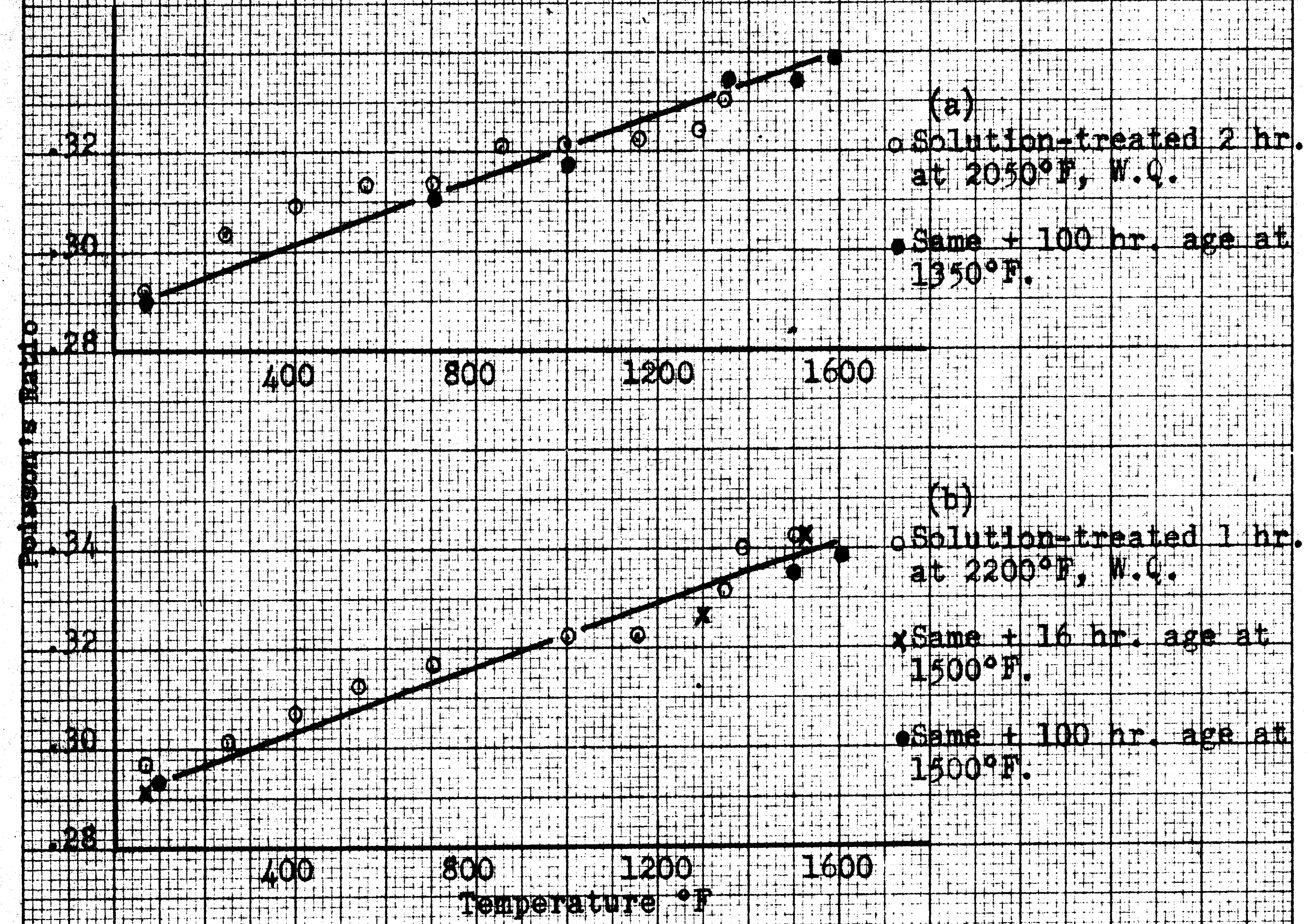

Fig. 21. Effect of aging at 1350°F with S.T. 2 hr. at 2050°F and aging at 1500°F with S.T. 1 hr. at 2200°F on Poisson's ratio of N155, heat A1726.

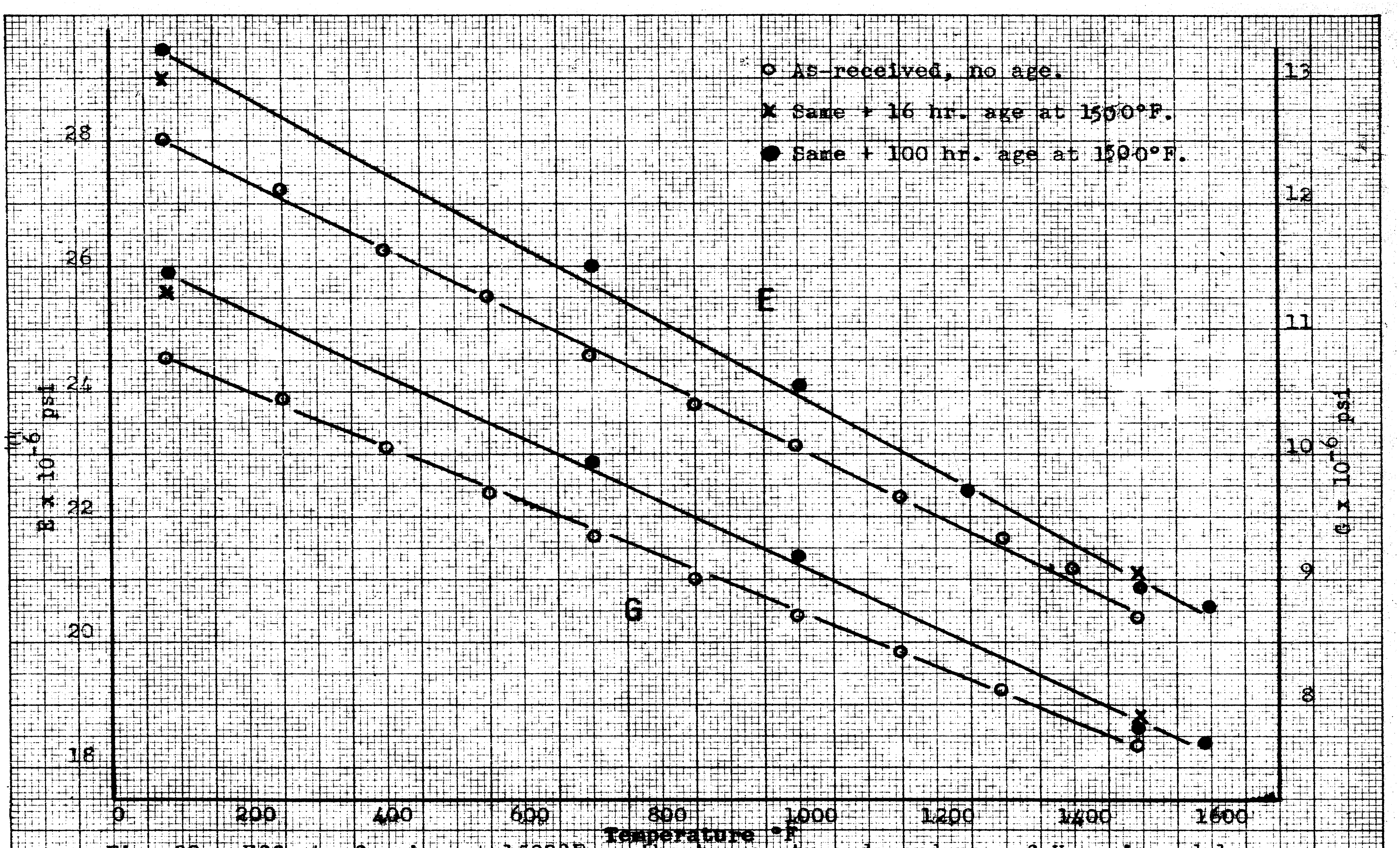

Fig. 22. Effect of aging at 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of 16-25-6, as received.

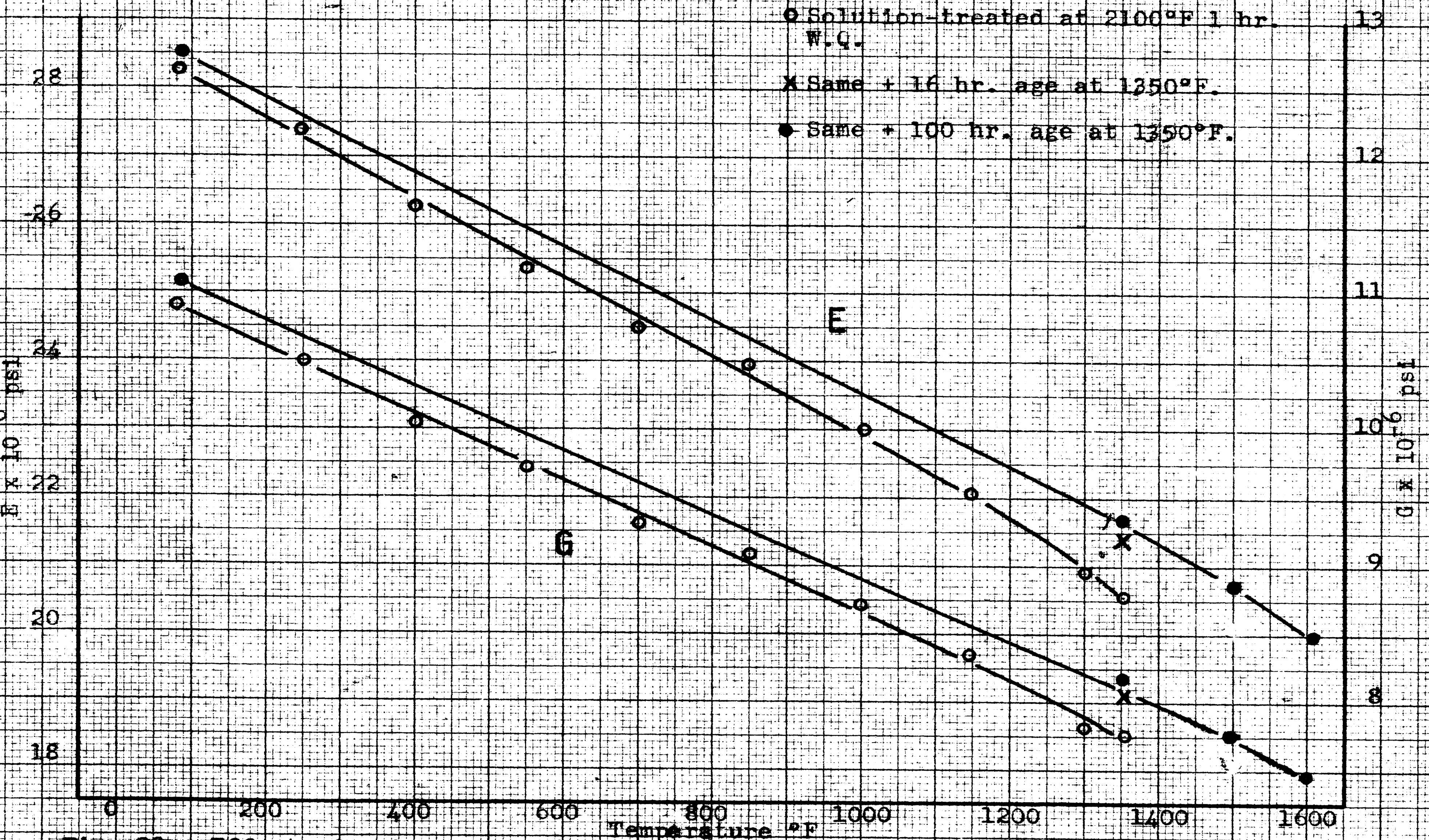

Fig. 23. Effect of aging at 1350°F on the temperature dependance of Young's modulus and the modulus of rigidity of 16-25-6, solution-treated 1 hr. at 2100°F.

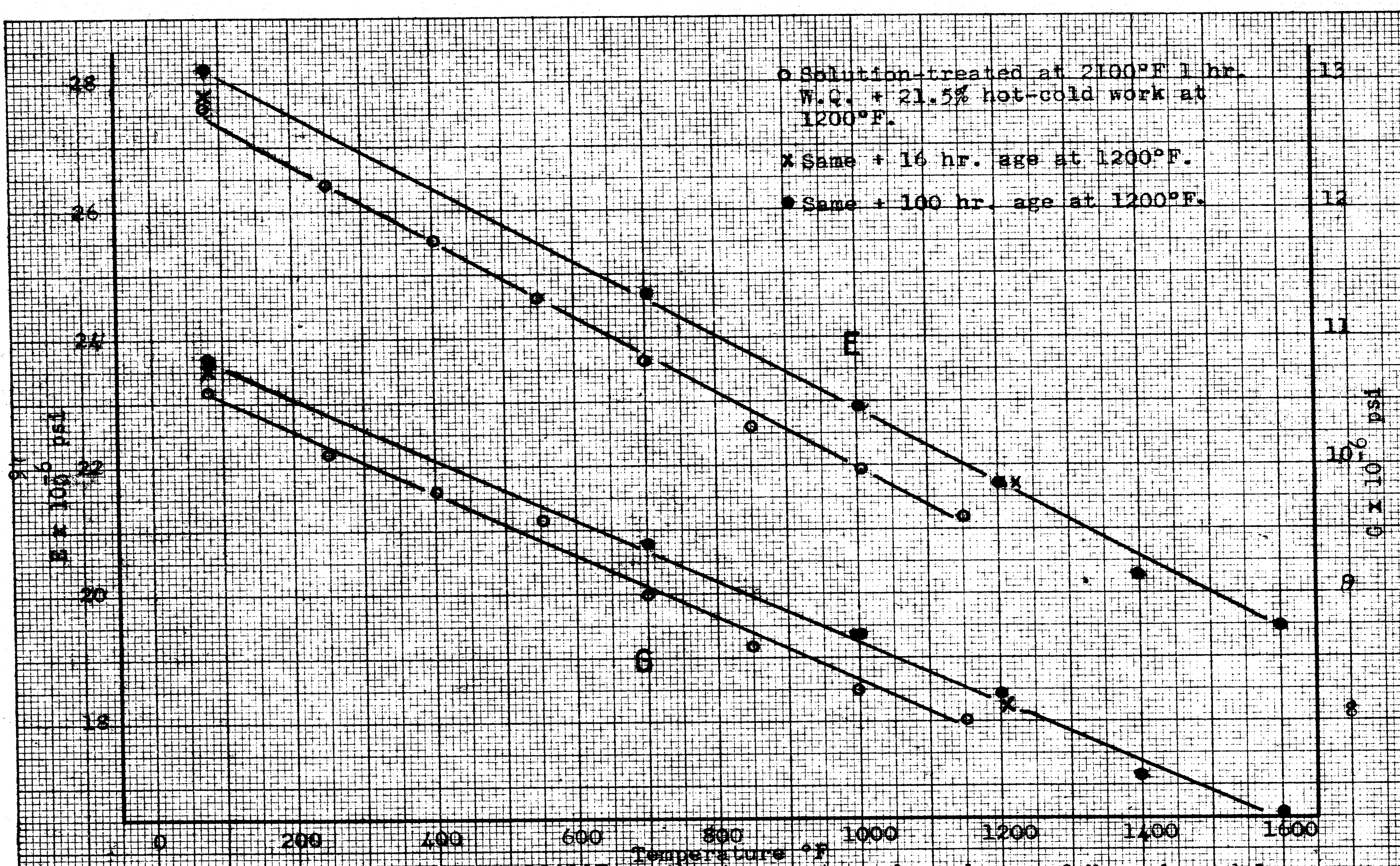

Fig. 24. Effect of aging at 1200°F on the temperature dependance of Young's modulus and the modulus of rigidity of 16-25-6, S.T. 1 hr. at 2100°F + 21.5% H.C.W. at 1200°F.

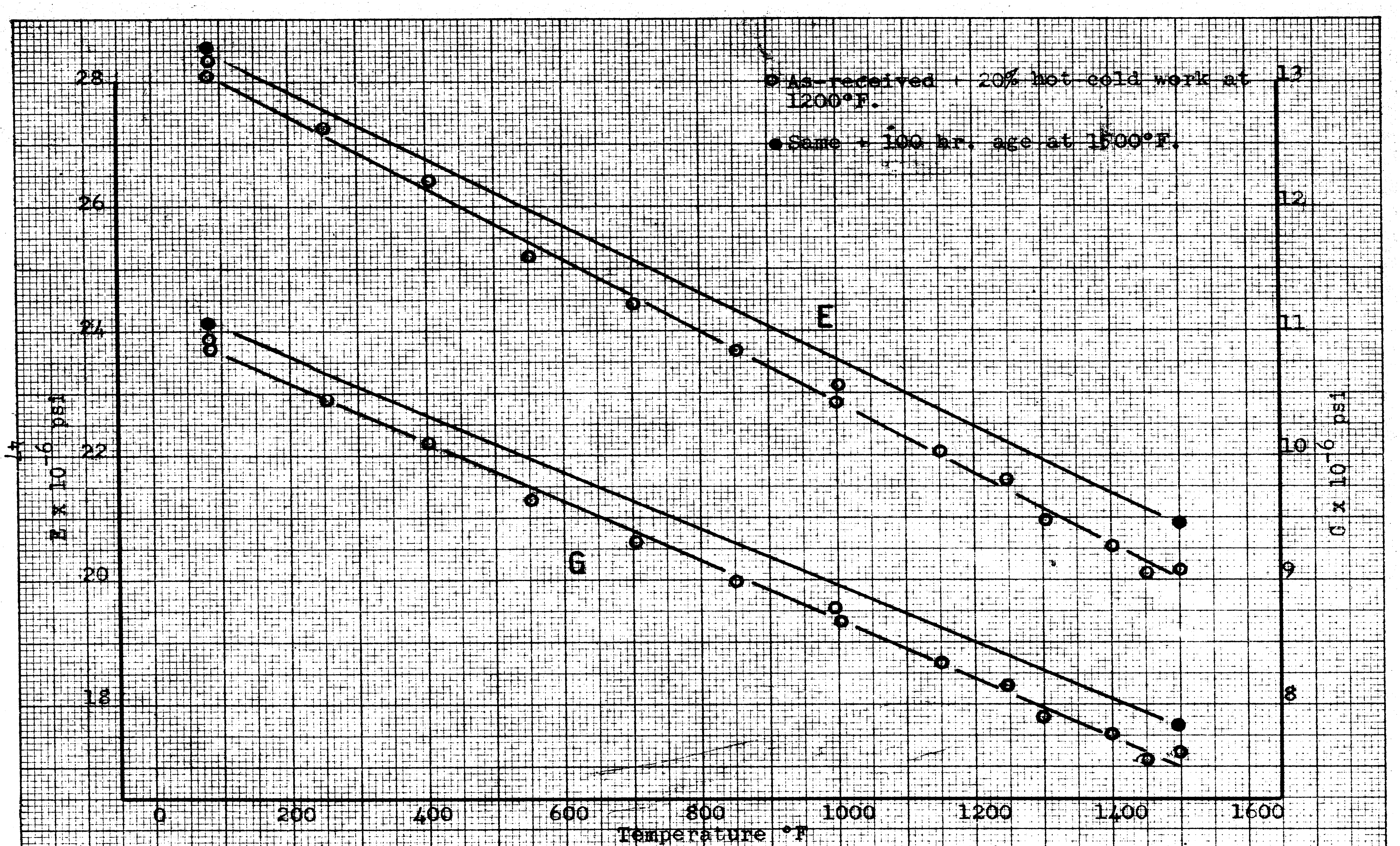

Fig. 25. Effect of aging at 1200°F on the temperature dependance of Young's modulus and the modulus of rigidity of 16-25-6, as-received + 20% H.C.W. at 1200°F.

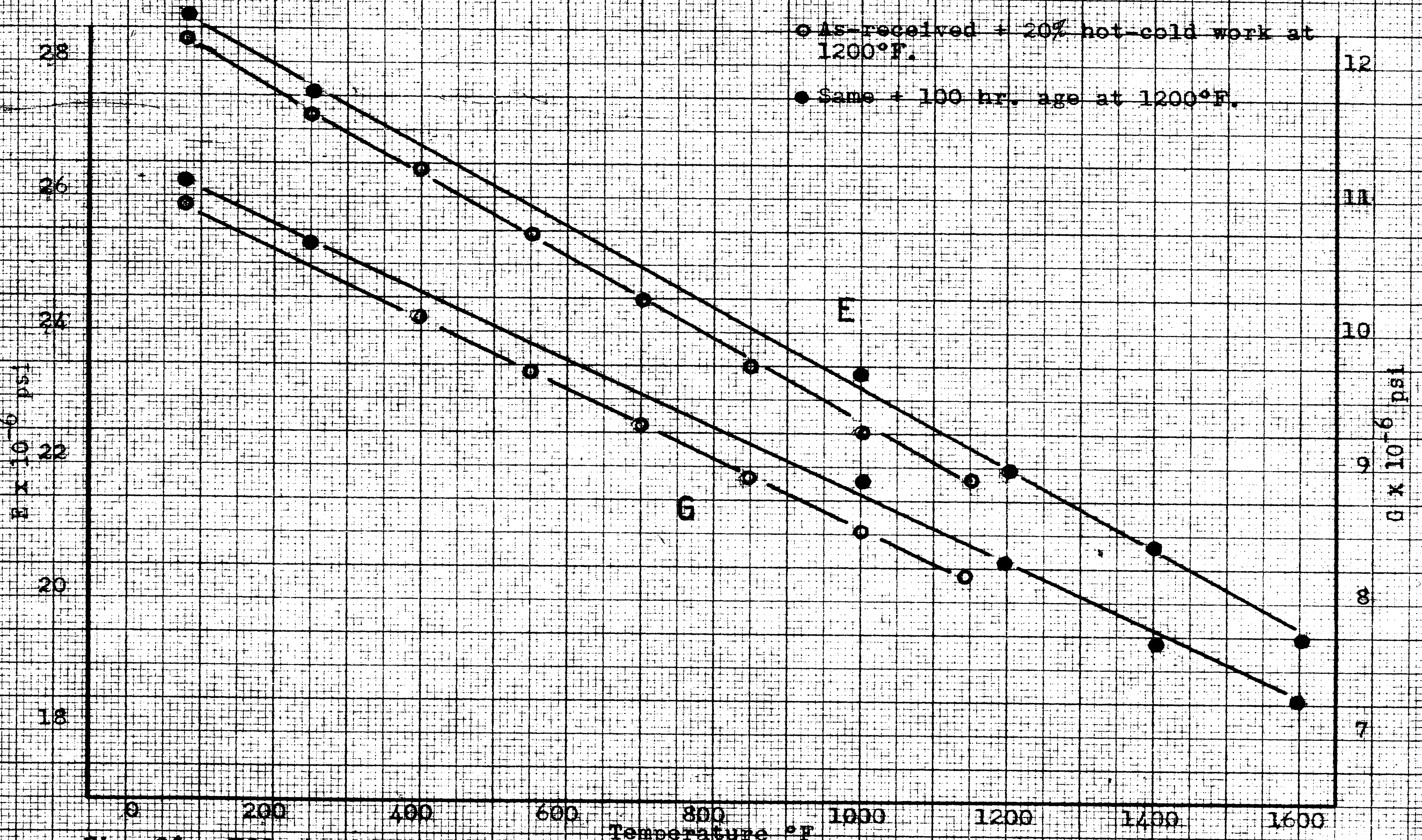

Fig. 26. Effect of aging at 1200°F on the temperature dependance of Young's modulus and the modulus of rigidity of 16-25-6, as-received + 20% H.C.W. at 1200°F.

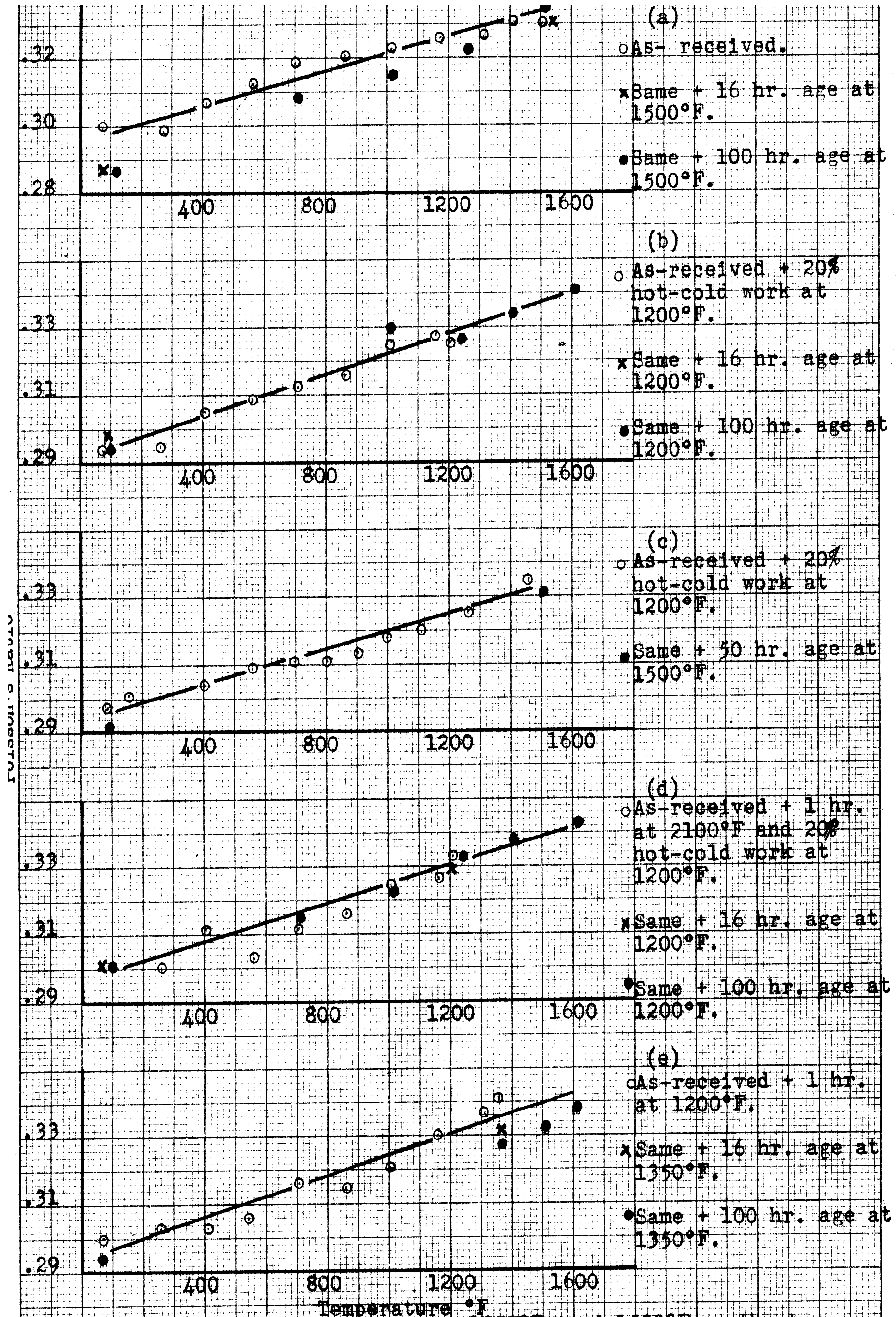

Fig. 17. Effect of aging at 1200°F, 1350°F, and 1500°F on the temperature dependance of Poisson's ratio of 16-25-6 with variation of S.T. and H.C.W.

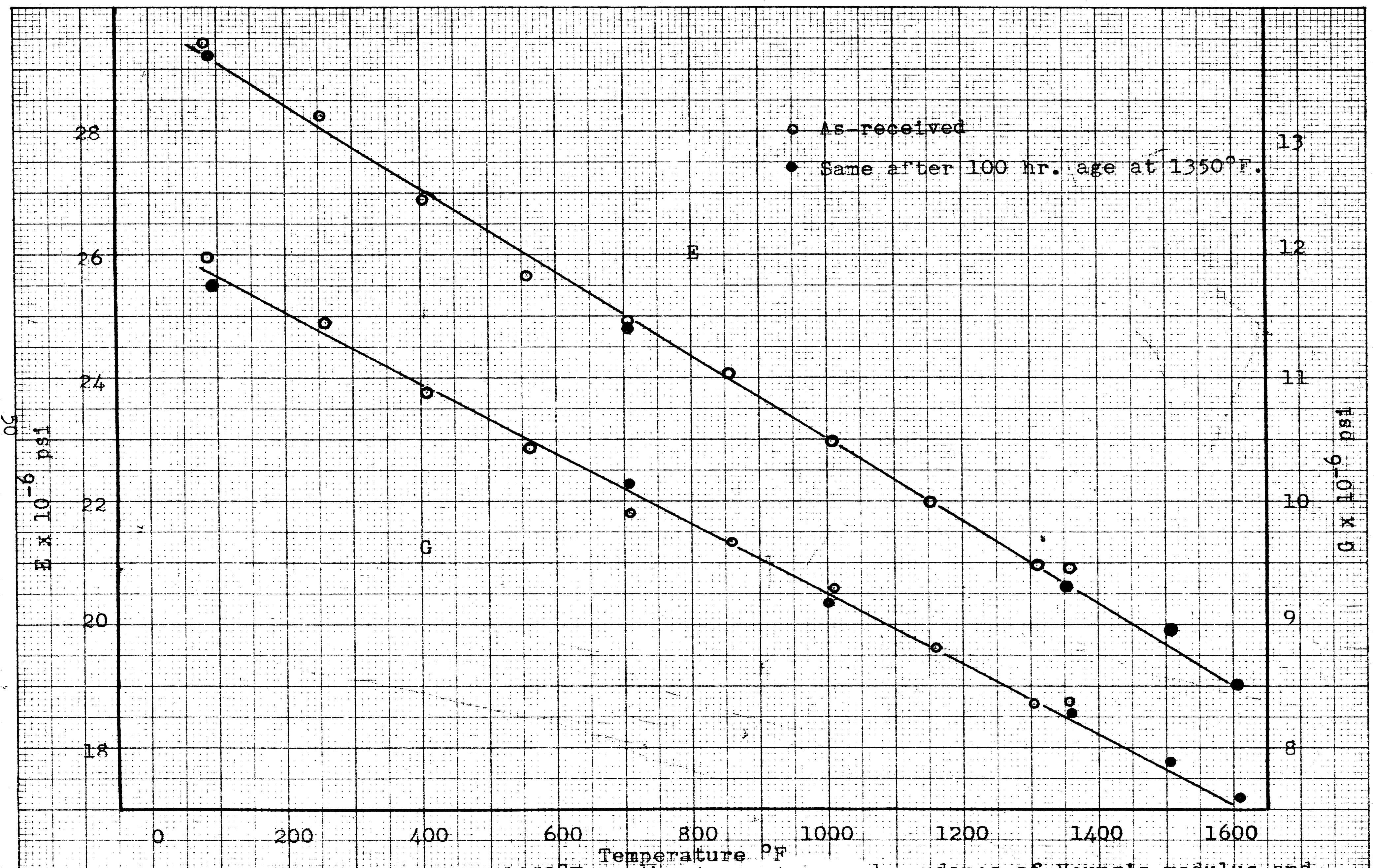

Fig. 28. Effect of aging at 1350°F on the temperature - dependance of Young's modulus and the modulus of rigidity of 19-9-DL, as received.

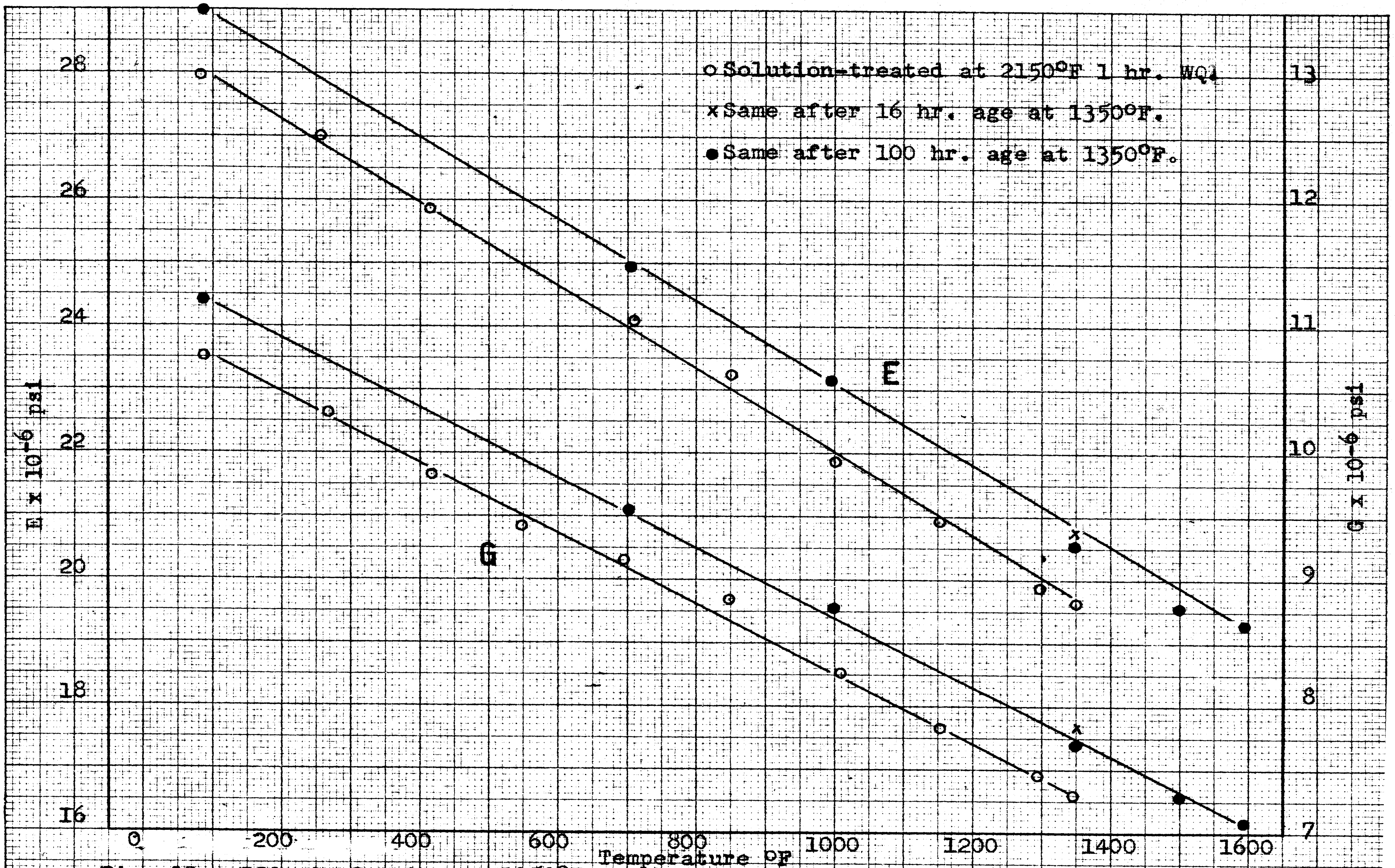

Fig. 29. Effect of aging at 1350°F on the temperature dependance of Young's modulus and the modulus of rigidity of 19-9-DL, S.T. 1 hr. at 2150°F.

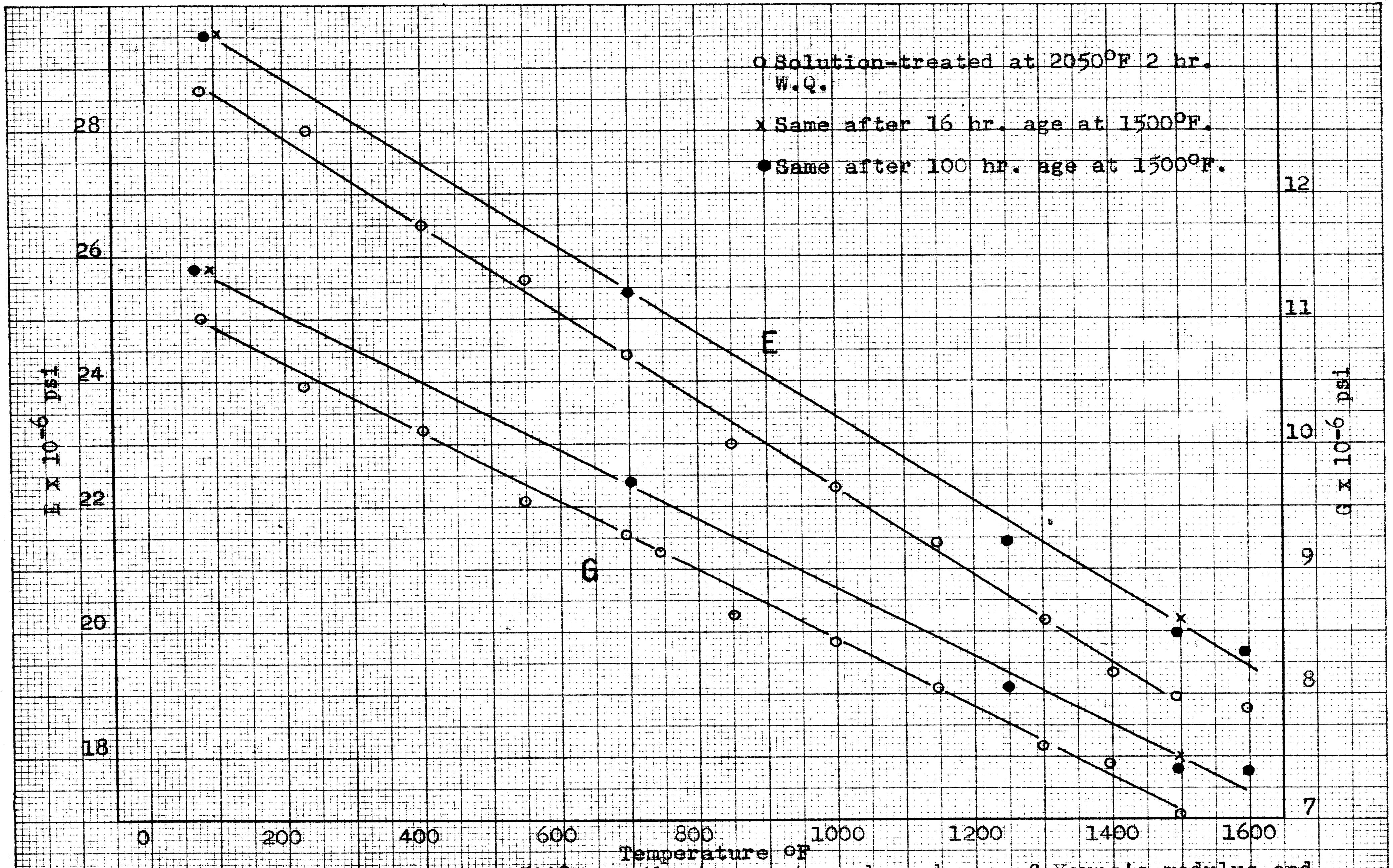

Fig. 30. Effect of aging at 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of 19-9-DL, S.T. 2 hr. at 2050°F.

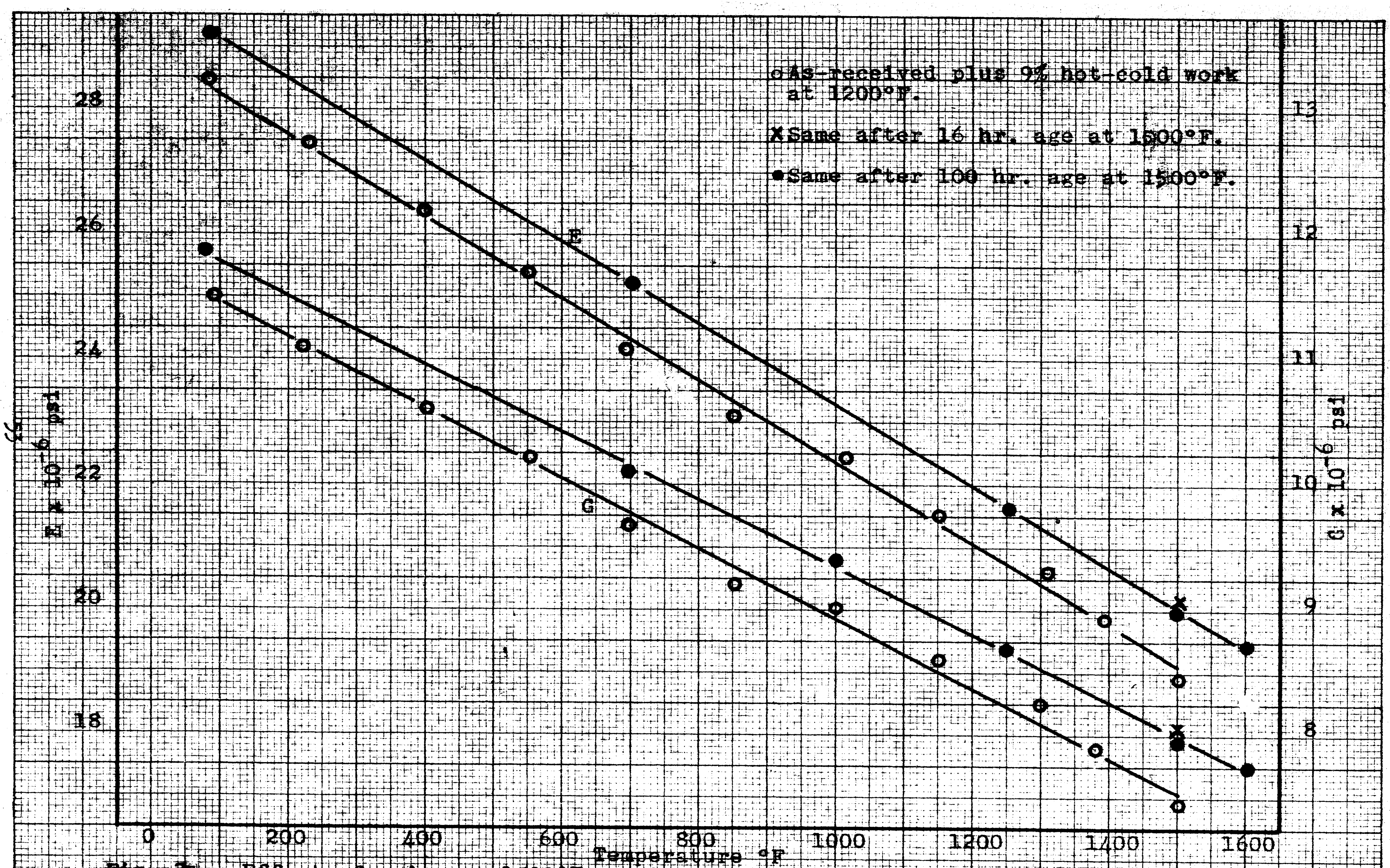

Fig. 31. Effect of aging at 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of 19-9-DL, as-received + 9% H.C.W. at 1200°F.

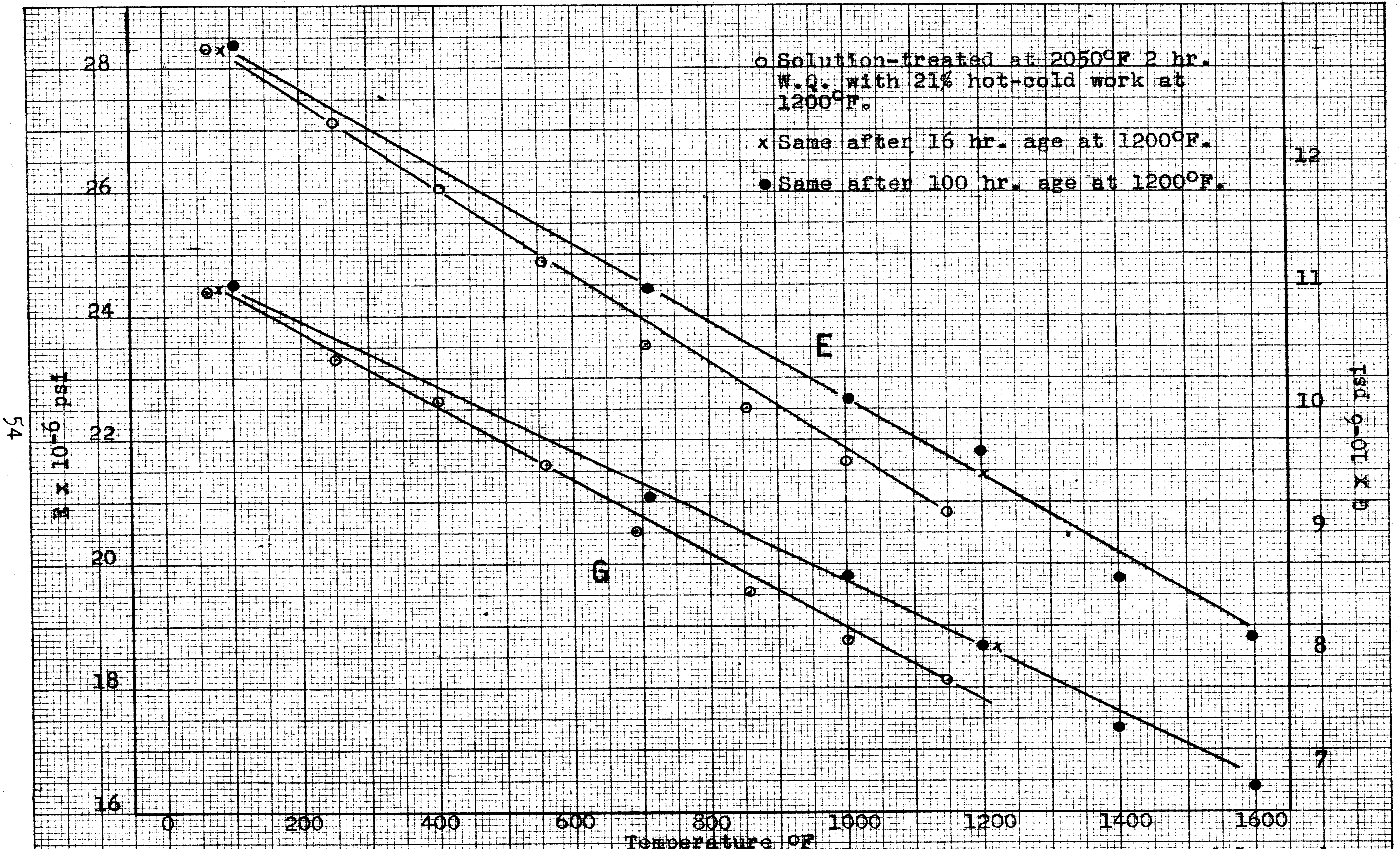

Fig. 32. Effect of aging at 1200°F on the temperature dependance of Young's modulus and the modulus of rigidity of 19-9-DL, S.T. 2 hr. at 2050°F + 21% H,C.W. at 1200°F.

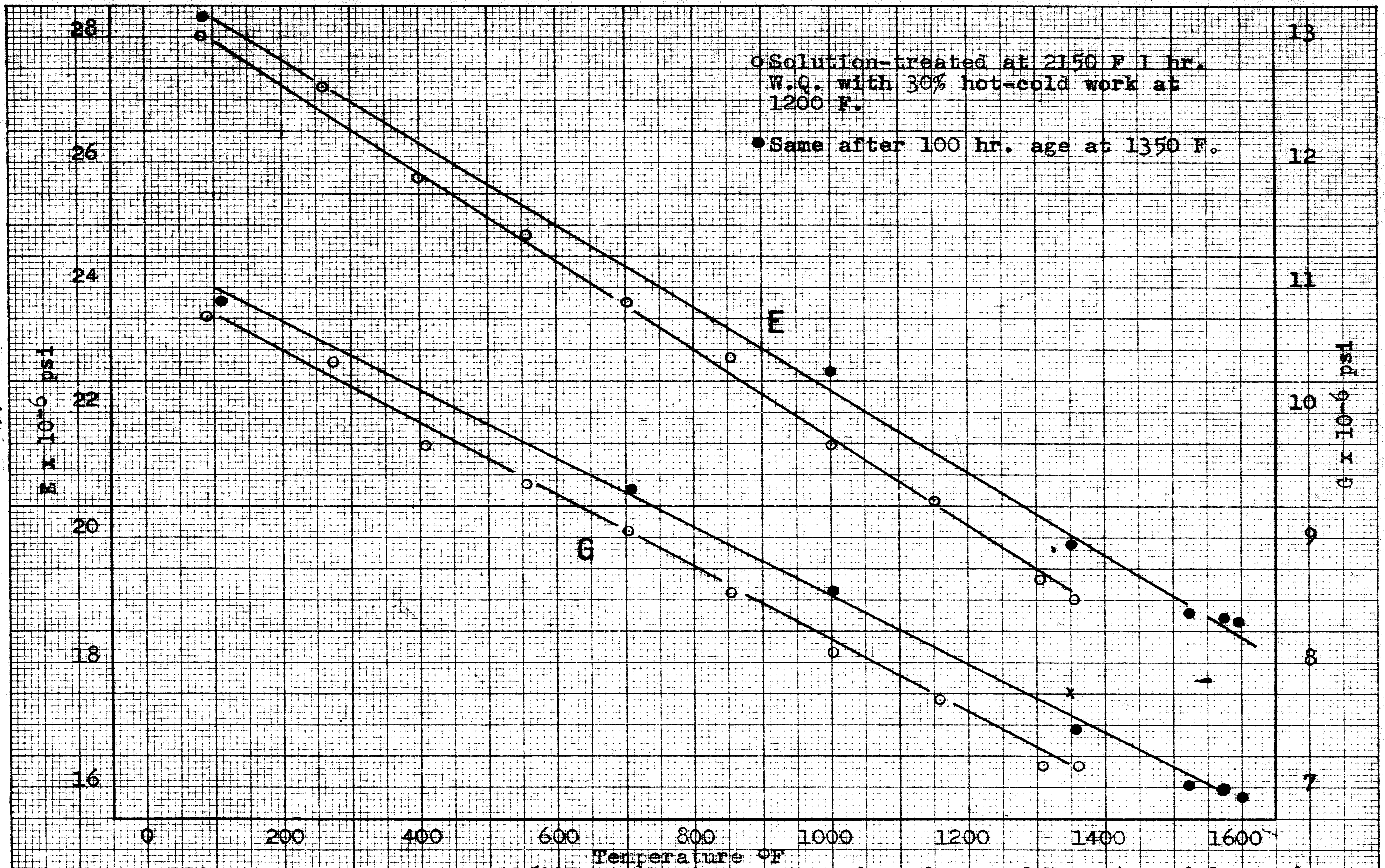

Fig. 33. Effect of aging at 1350°F on the temperature dependance of Young's modulus and the modulus of rigidity of 19-9-DL, S.T. 1 hr. at 2150°F + 30% H.C.W. at 1200°F.

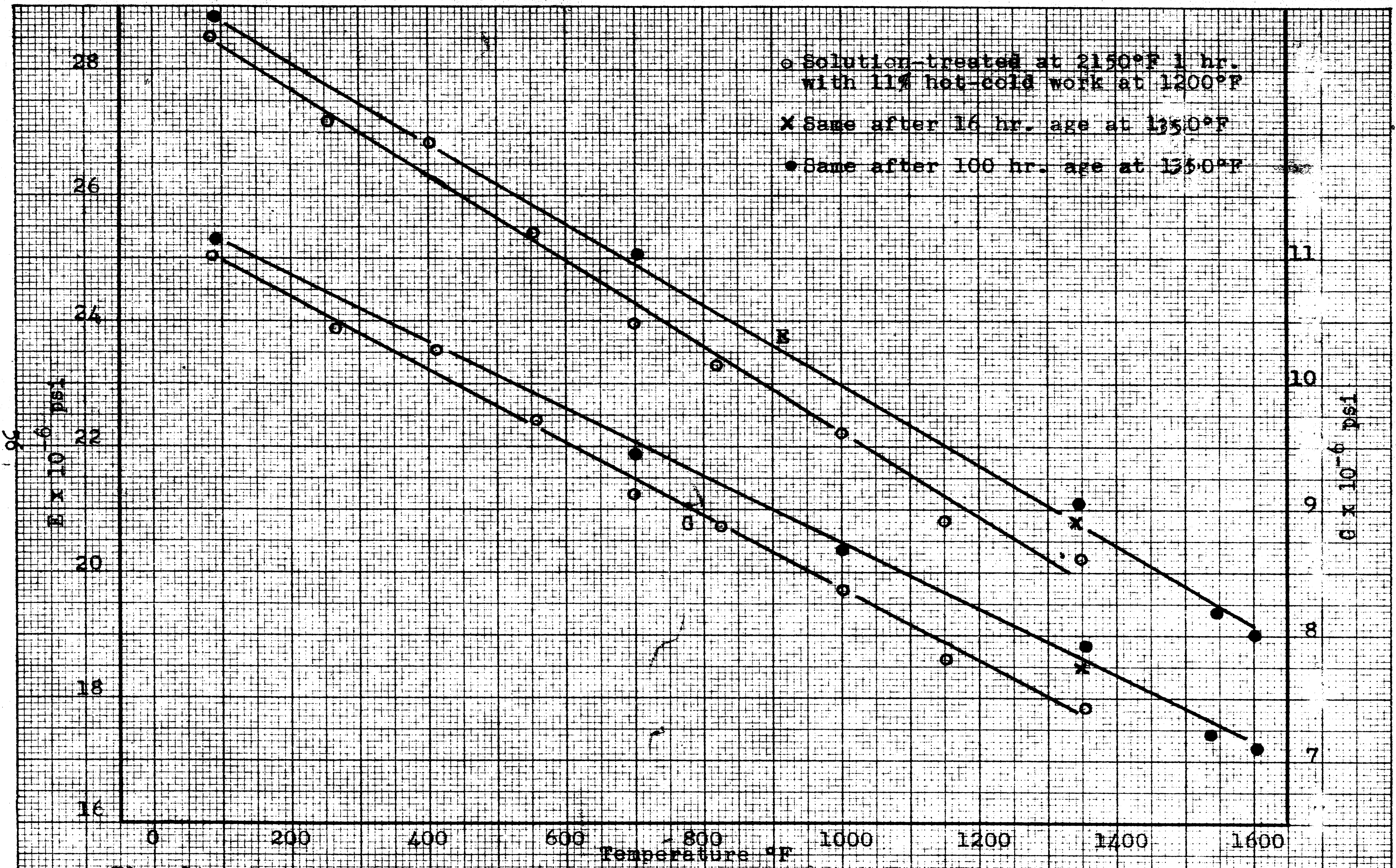

Fig. 34. Effect of aging at 1350°F on the temperature dependance of Young's modulus and the modulus of rigidity of 19-9-DL, S.T. 1 hr. at 2150°F + 11% H.C.W. at 1200°F.

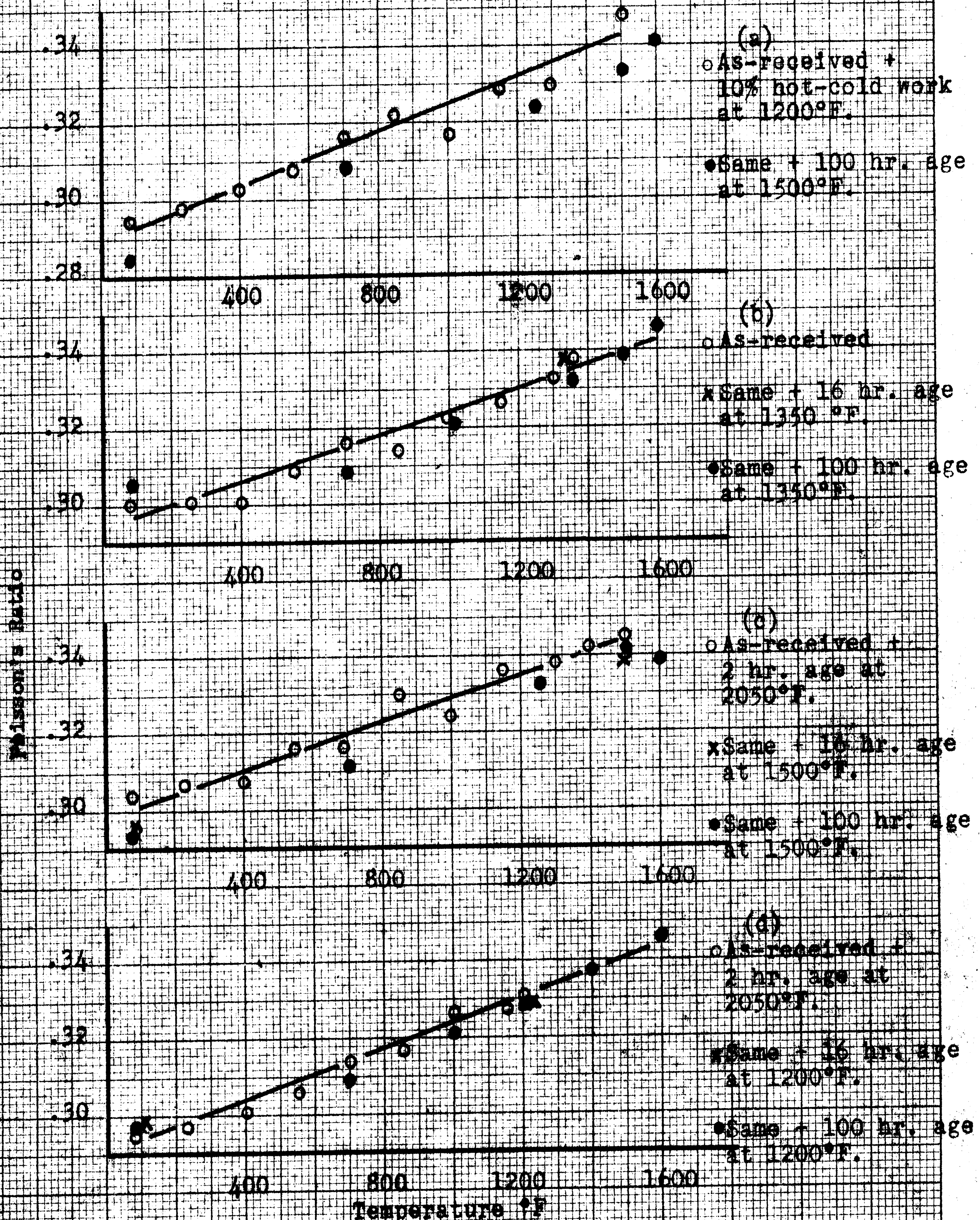

Fig. 35. Effect of aging at 1200°F, 1350°F, or 1500°F on the temperature dependance of Poisson's ratio of 19-9-DL with variations of S.T. and H.C.W.

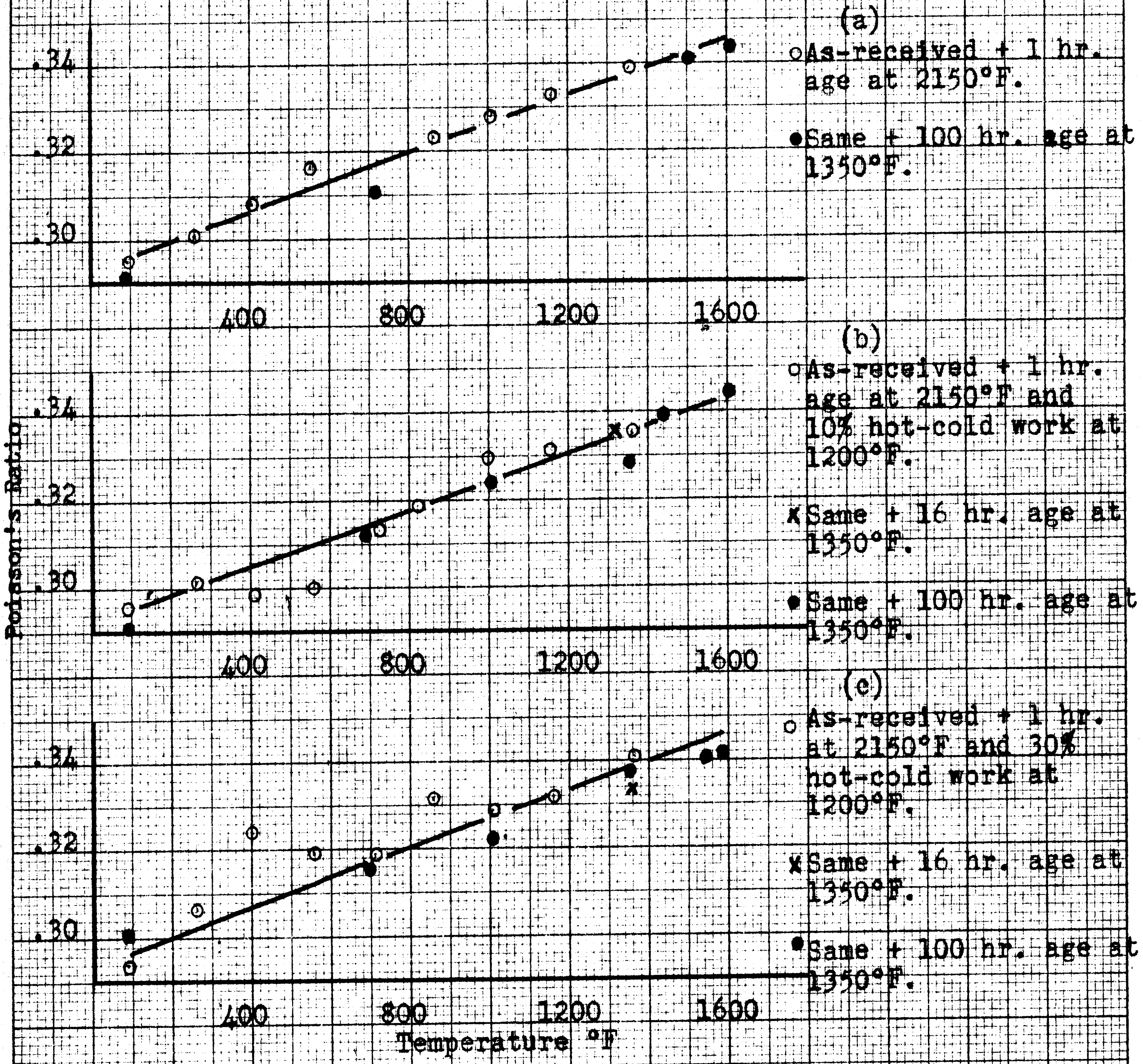

Fig. 36. Effect of aging at 1350°F on the temperature dependance of Poisson's ratio of 19-9-DL, S.T. 1 hr. at 2150°F + varying % H.C.W. at 1200°F.

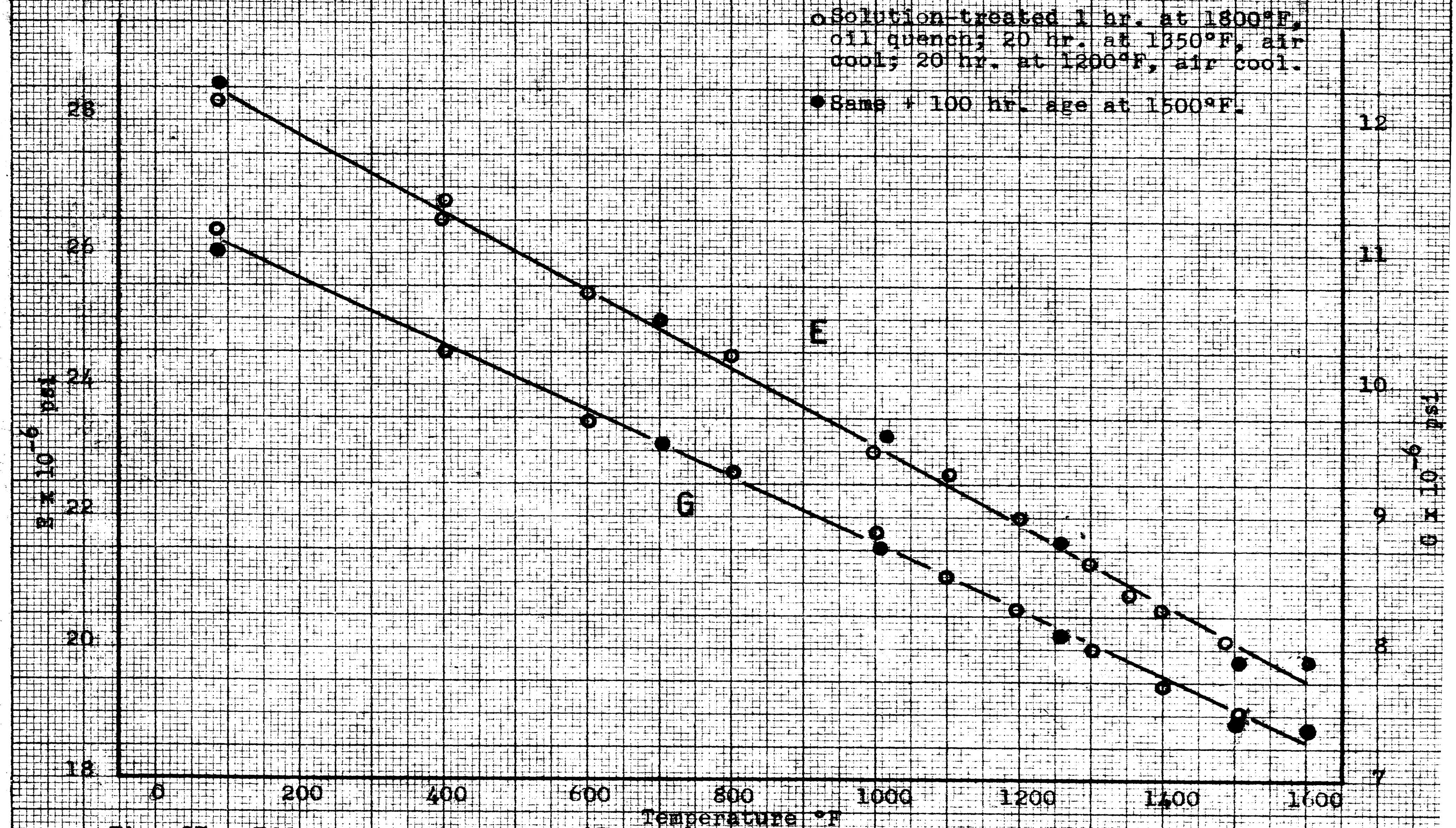

Fig. 37. Effect of aging at 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of Discaloy, S.T. 1 hr. at 1800°F, + 20 hr. at 1350°F, + 20 hr. at 1500°F.

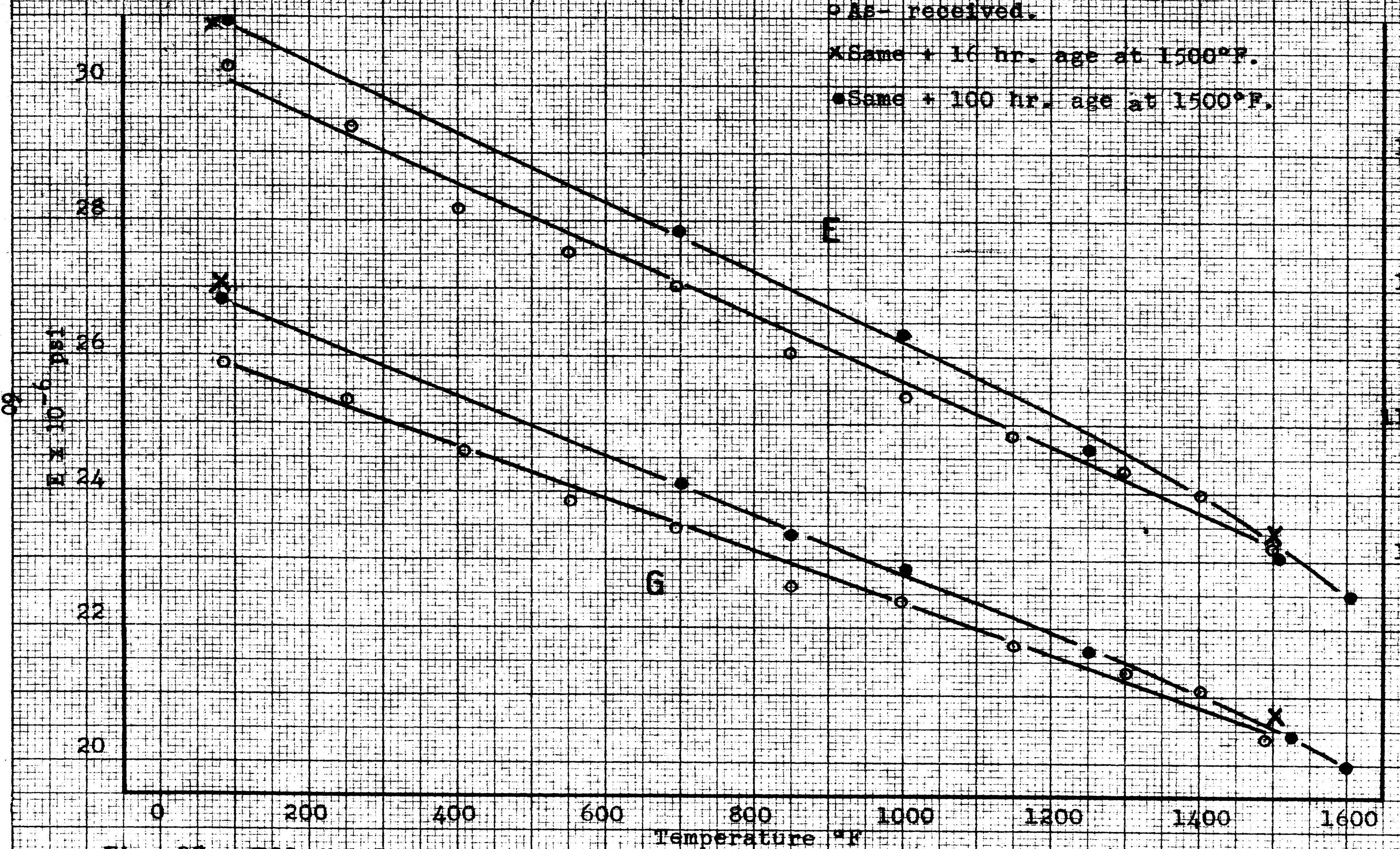

Fig. 38. Effect of aging at 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of Inconel-X, as-received.

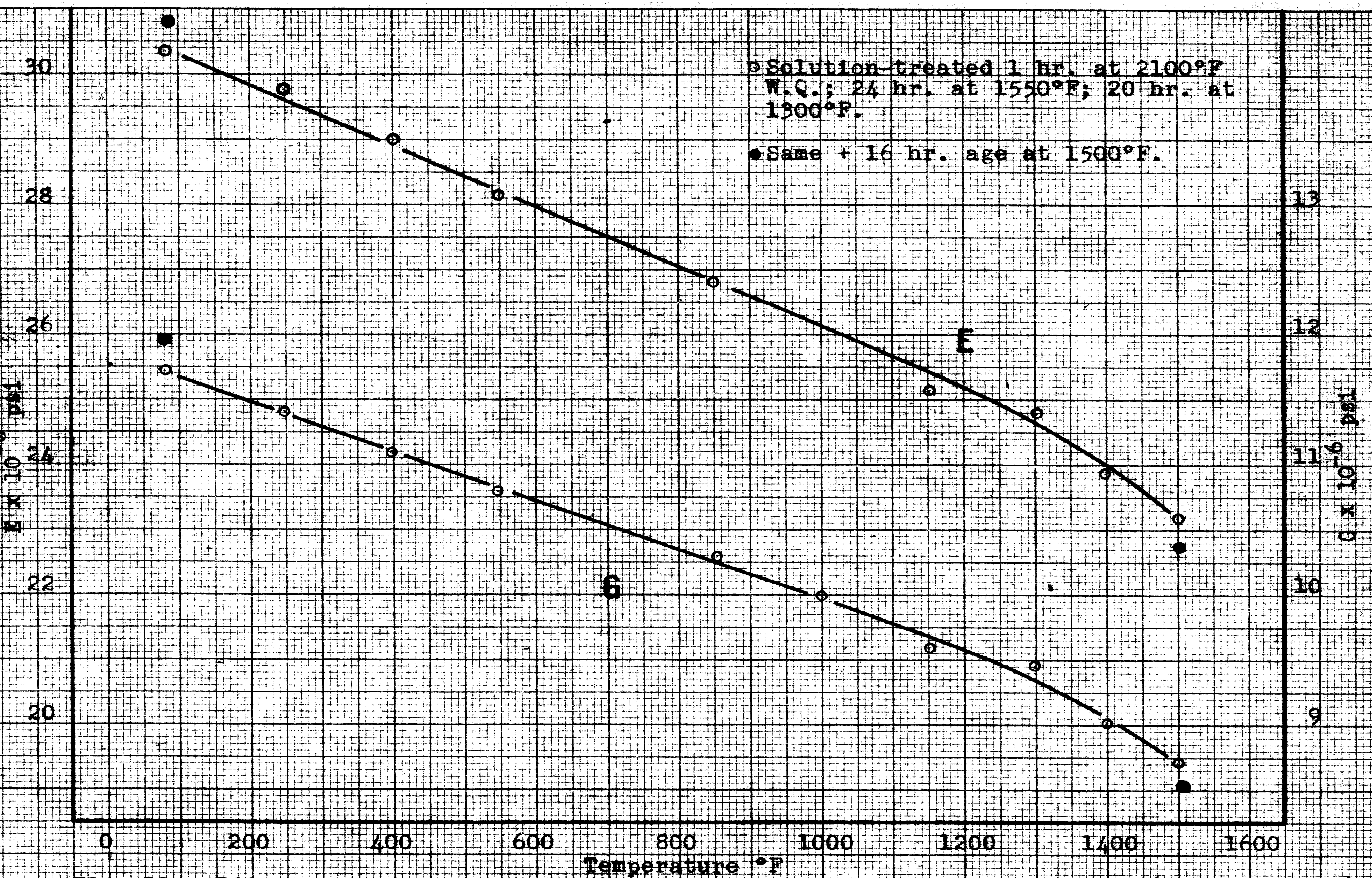

Fig. 39. Effect of aging at 1550°F, 1300°F, and 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of Inconel-X, S.T. 1 hr. at 2100°F.

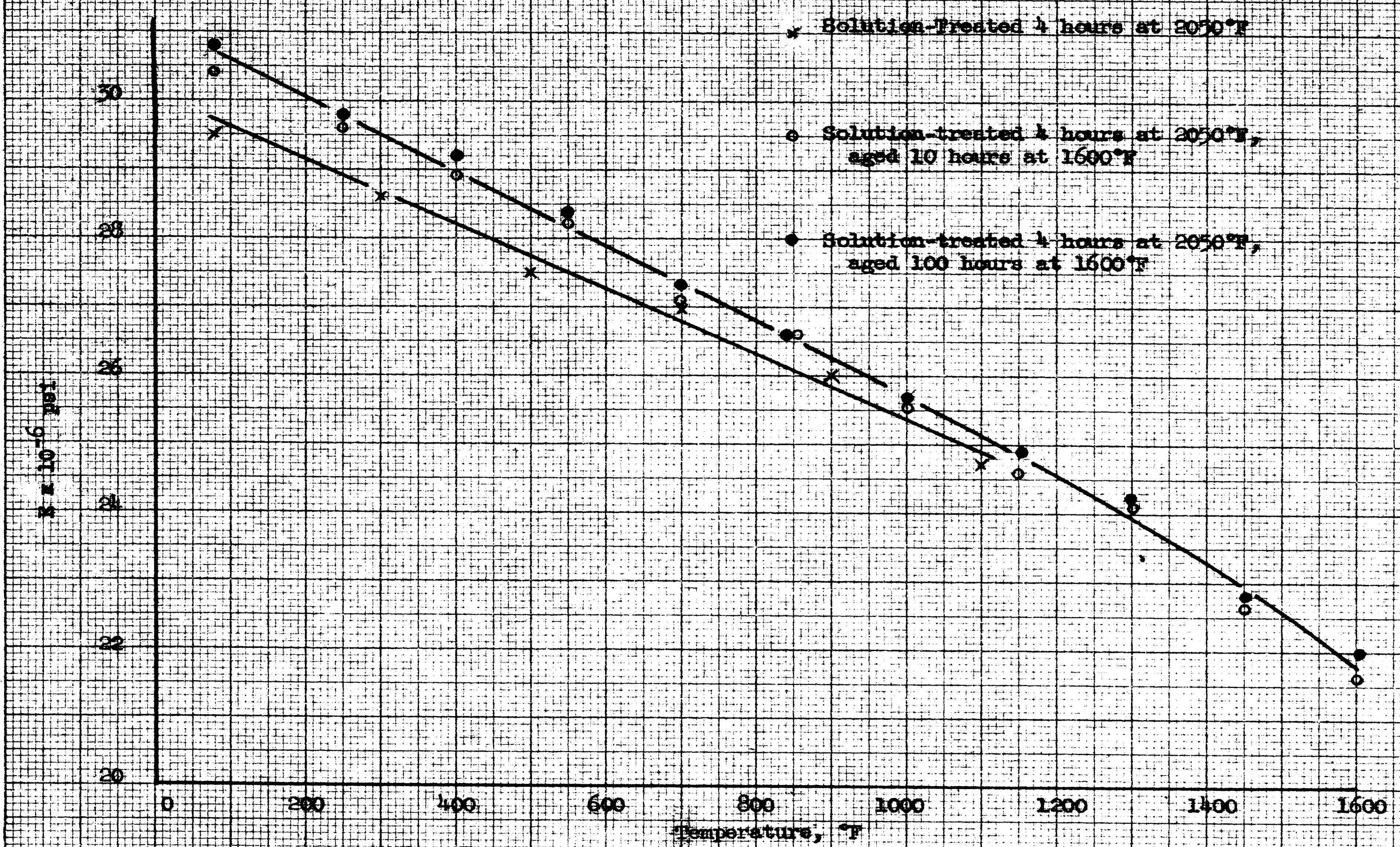

Fig. 40. Effect of aging on Young's modulus of Inconel-X, S. T. 4 hrs at 2050° F.

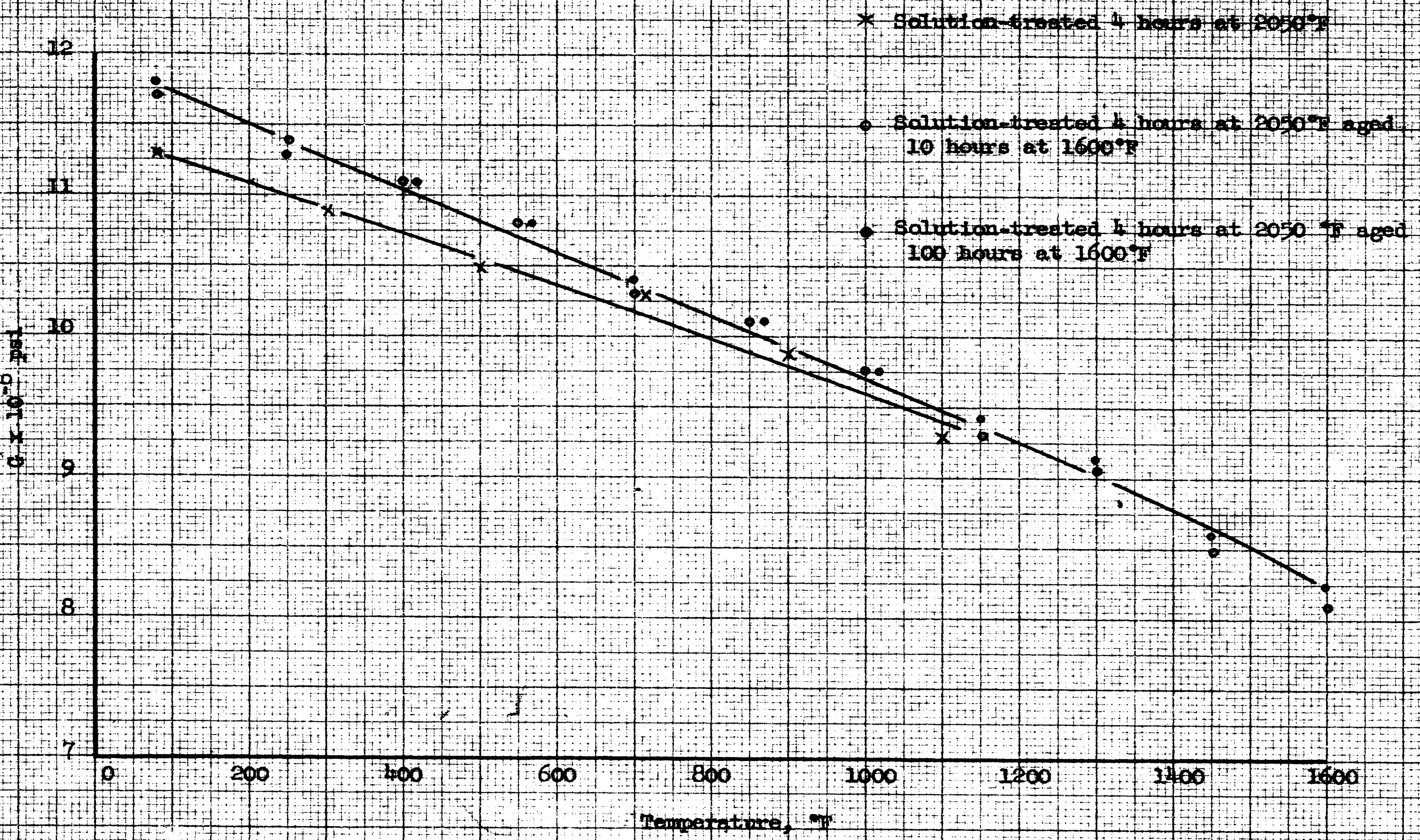

Fig. 41. Effect of aging on modulus of rigidity of Inconel-X, S. T. 4 hrs at 2050°F.

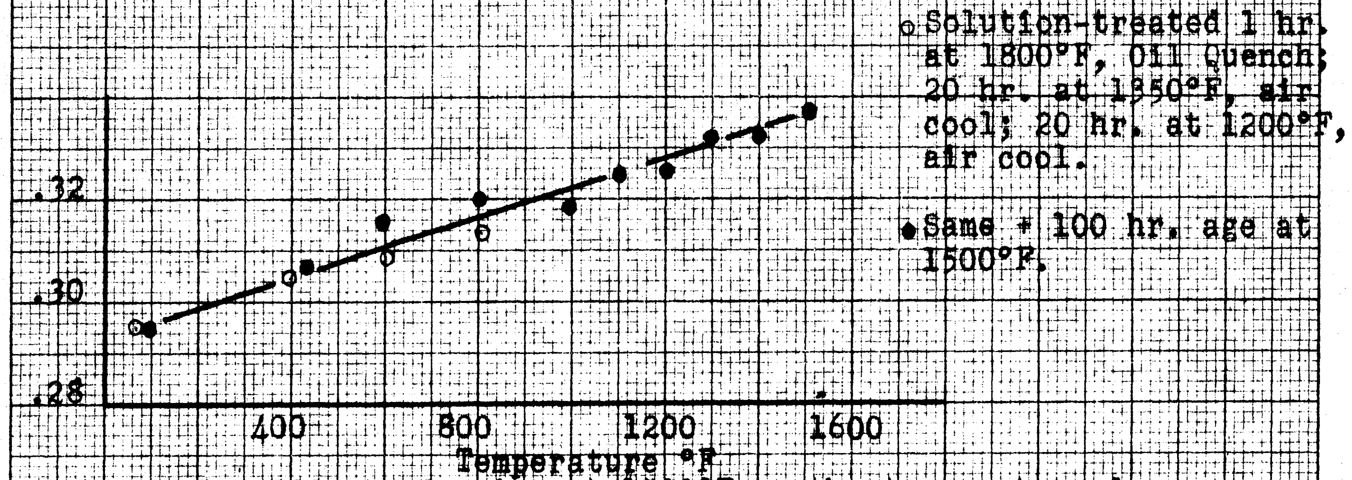

Fig. 42. Effect of aging at 1500°F on the temperature dependance of Poisson's ratio of Discaloy, S.T. 1 hr. at 1800°F, + 20 hr. at 1350°F, + 20 hr. at 1500°F.

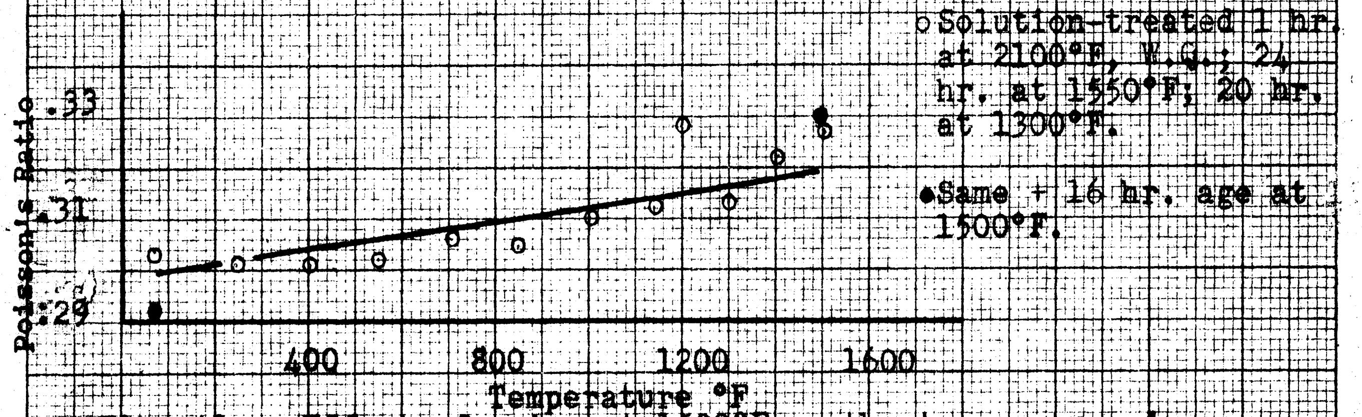

Fig. 43a. Effect of aging at 1500°F on the temperature dependance of Poisson's ratio of Inconel-X, S.T. 1 hr. at 2100°F, + 24 hr. at 1550°F, + 20 hr. at 1300°F.

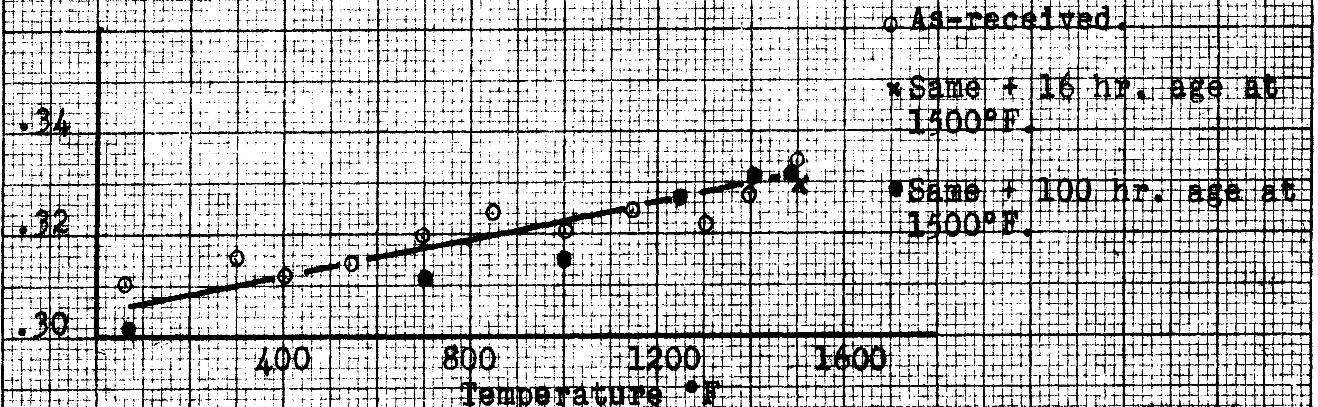

Fig. 43b. Effect of aging at 1500°F on the temperature dependance of Poisson's ratio of Inconel-X, as-received.

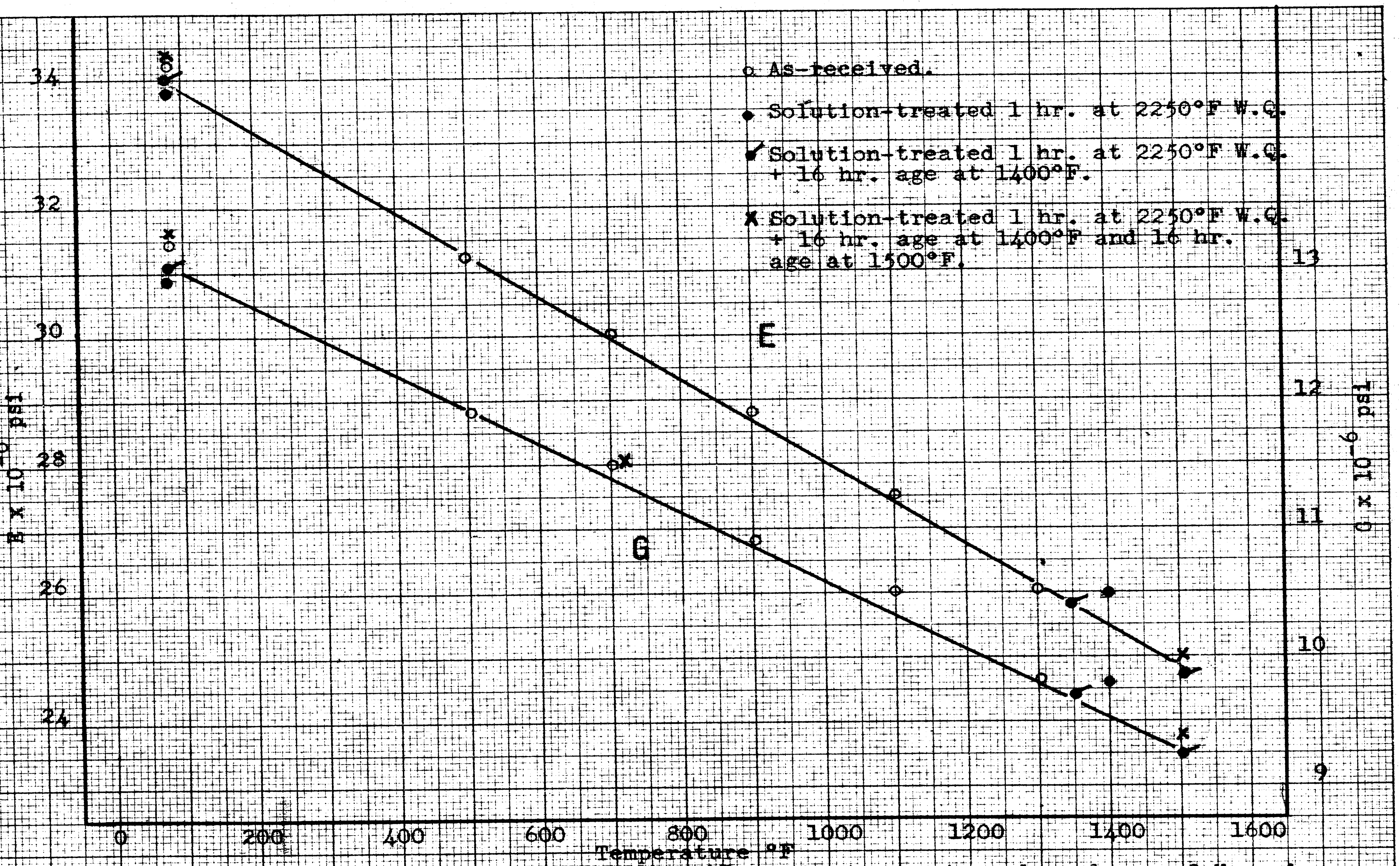

Fig. 44. Effect of aging at 1400°F and 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of S816, as-received or S.T. 1 hr. at 2250°F.

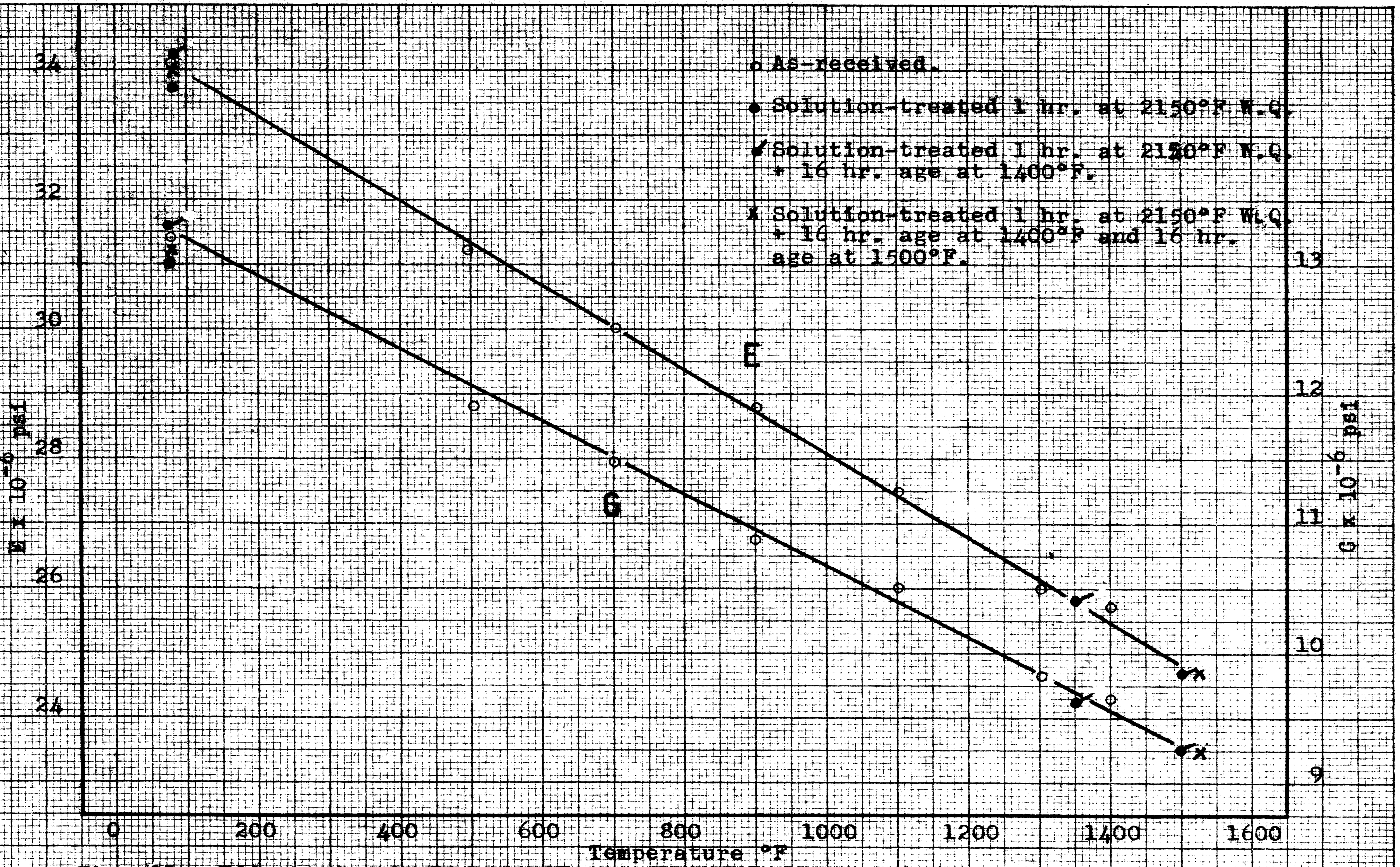

Fig. 45. Effect of aging at 1400°F and 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of S816, as-received or S.T. 1 hr. at 2150°F.

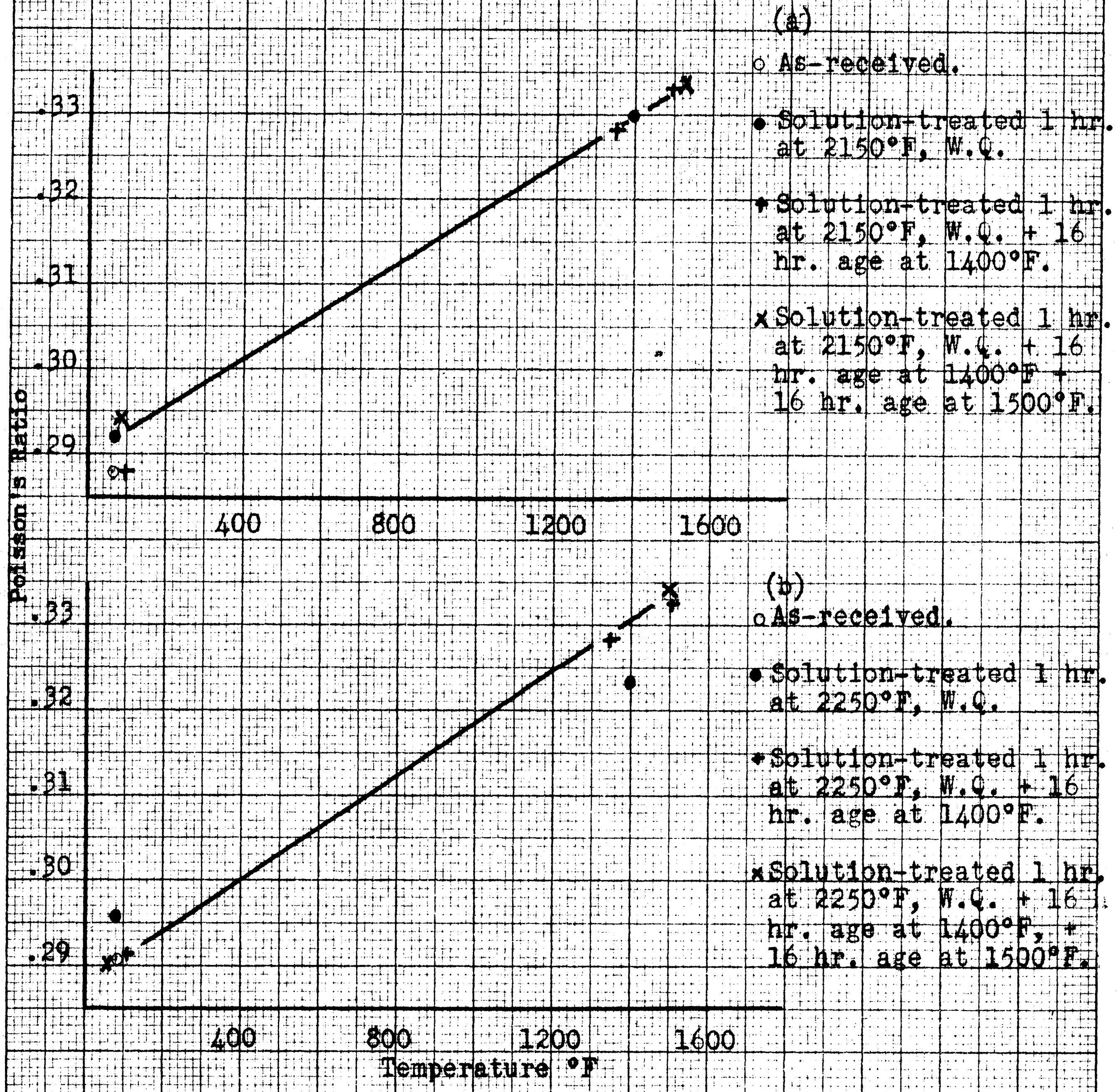

Fig. 46. Effect of aging at 1400°F and 1500°F on the temperature dependance of Poisson's ratio of S816; as-received, S.T. at 2150°F, or S.T. at 2250°F.

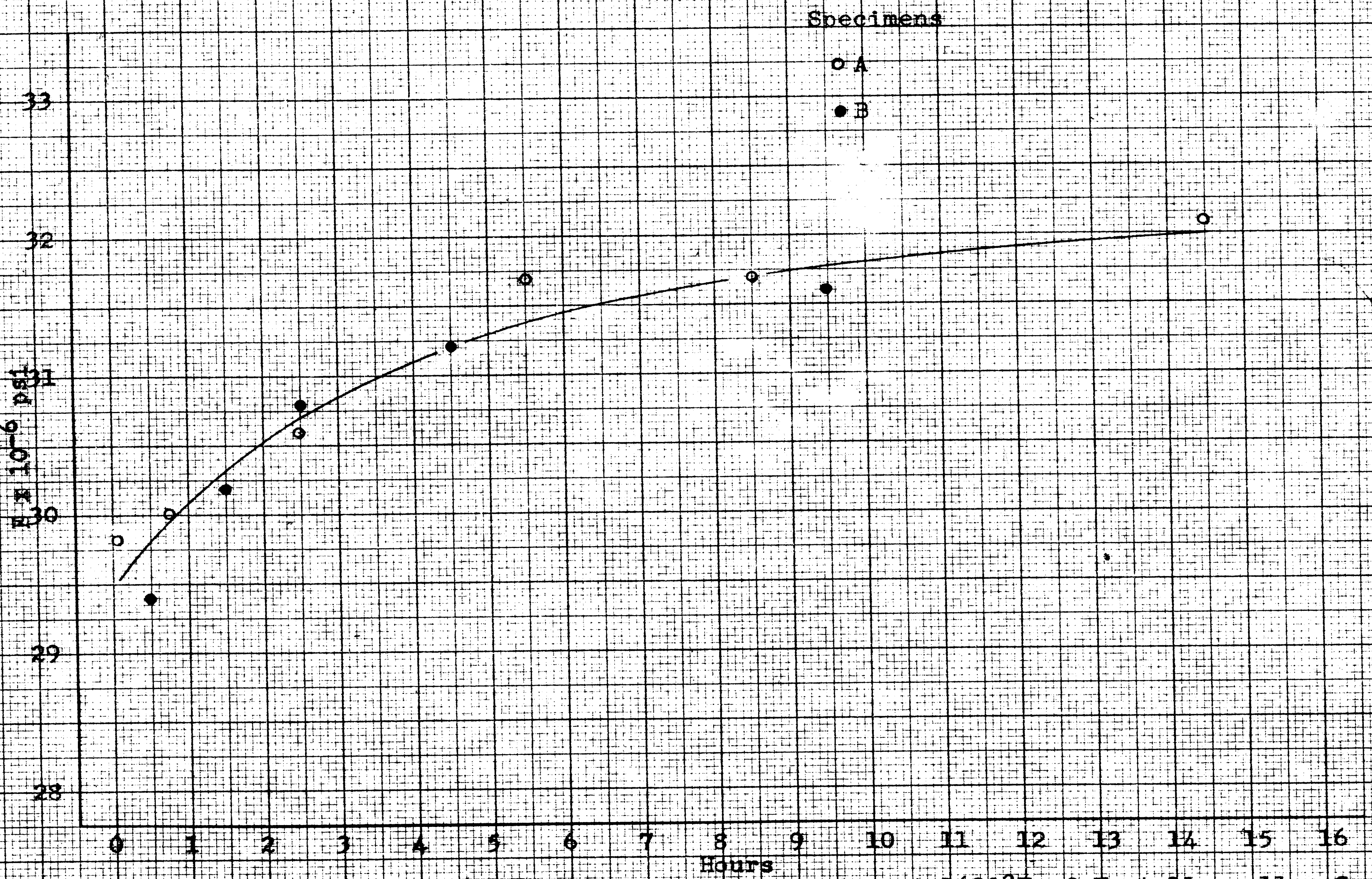

Fig. 47. Time dependance of Young's modulus on aging at 1600°F of Hastelloy alloy C, S.T. 1 hour at 2225°F, rapid air cooled.

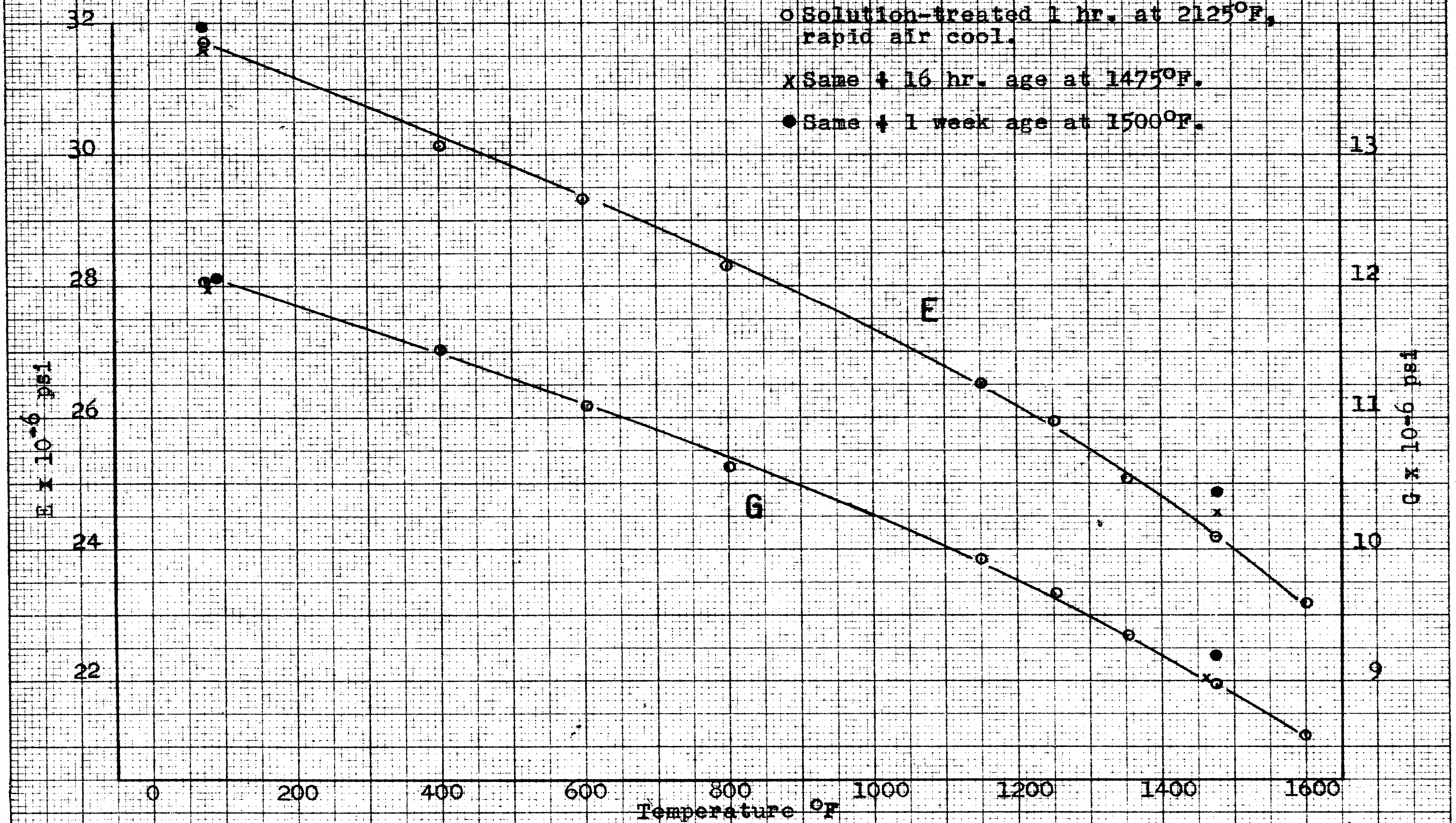

Fig. 48. Effect of aging at 1475°F and 1500°F on the temperature dependance of Young's modulus and the modulus of rigidity of Hastelloy alloy "B", S.T. 1 hr. at 2125°F.

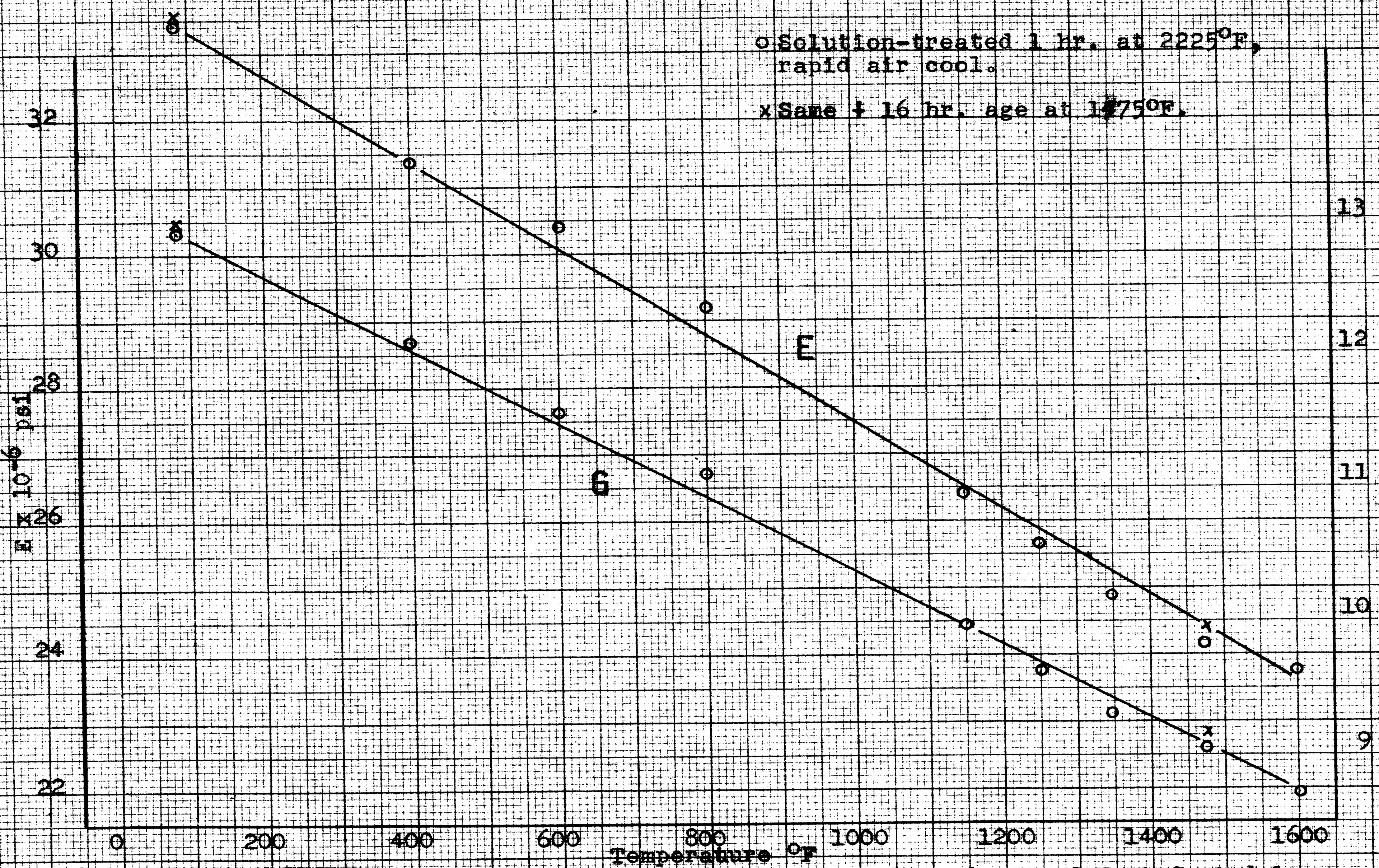

Fig. 49. Effect of aging at 1475°F on the temperature dependance of Young's modulus and the modulus of rigidity of Haynes alloy "25", S.T. 1 hr. at 2225°F.

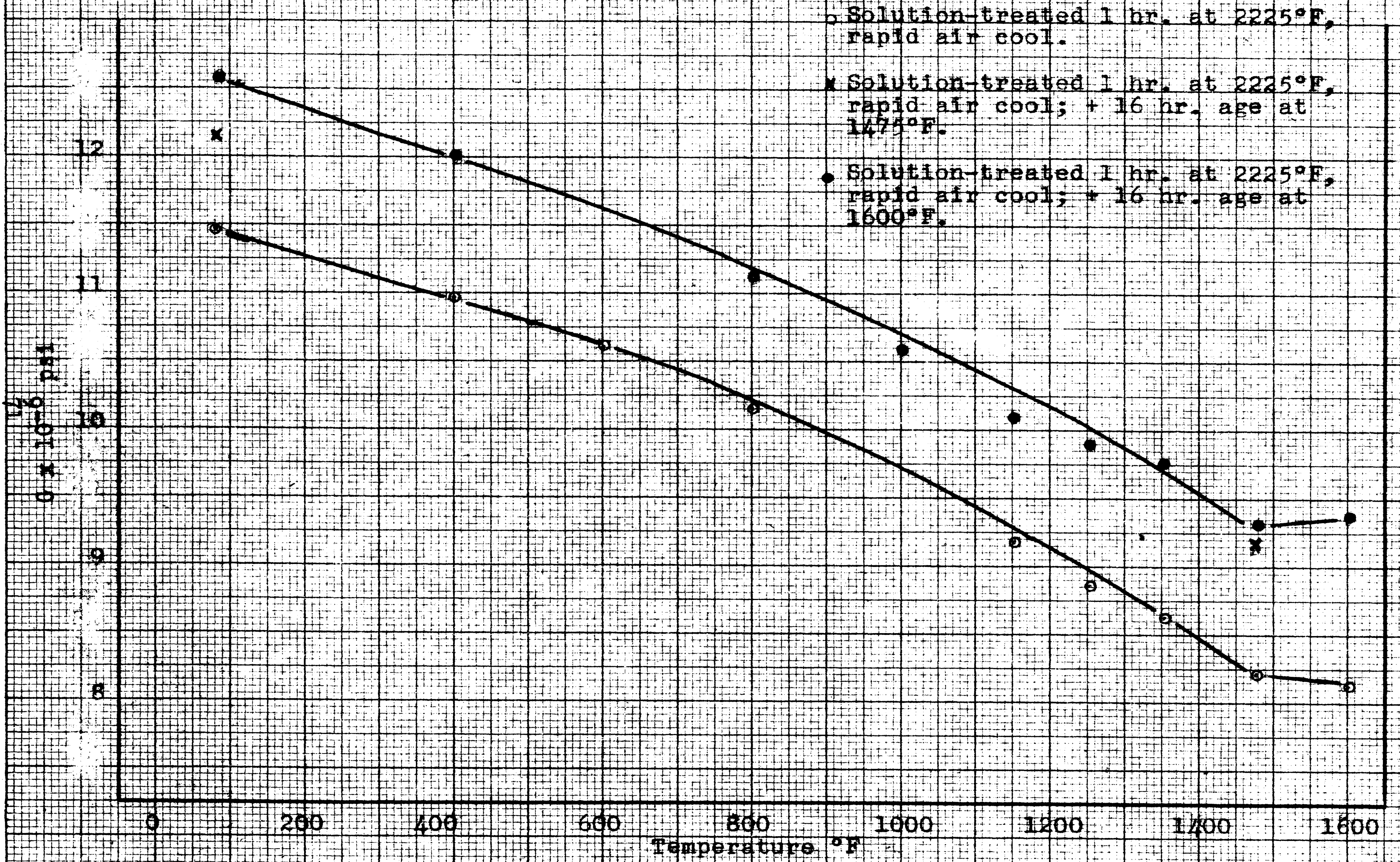

Fig. 50. Temperature dependance of modulus of rigidity of Hastelloy alloy "C", S.T. 1 hr. at 2225°F.

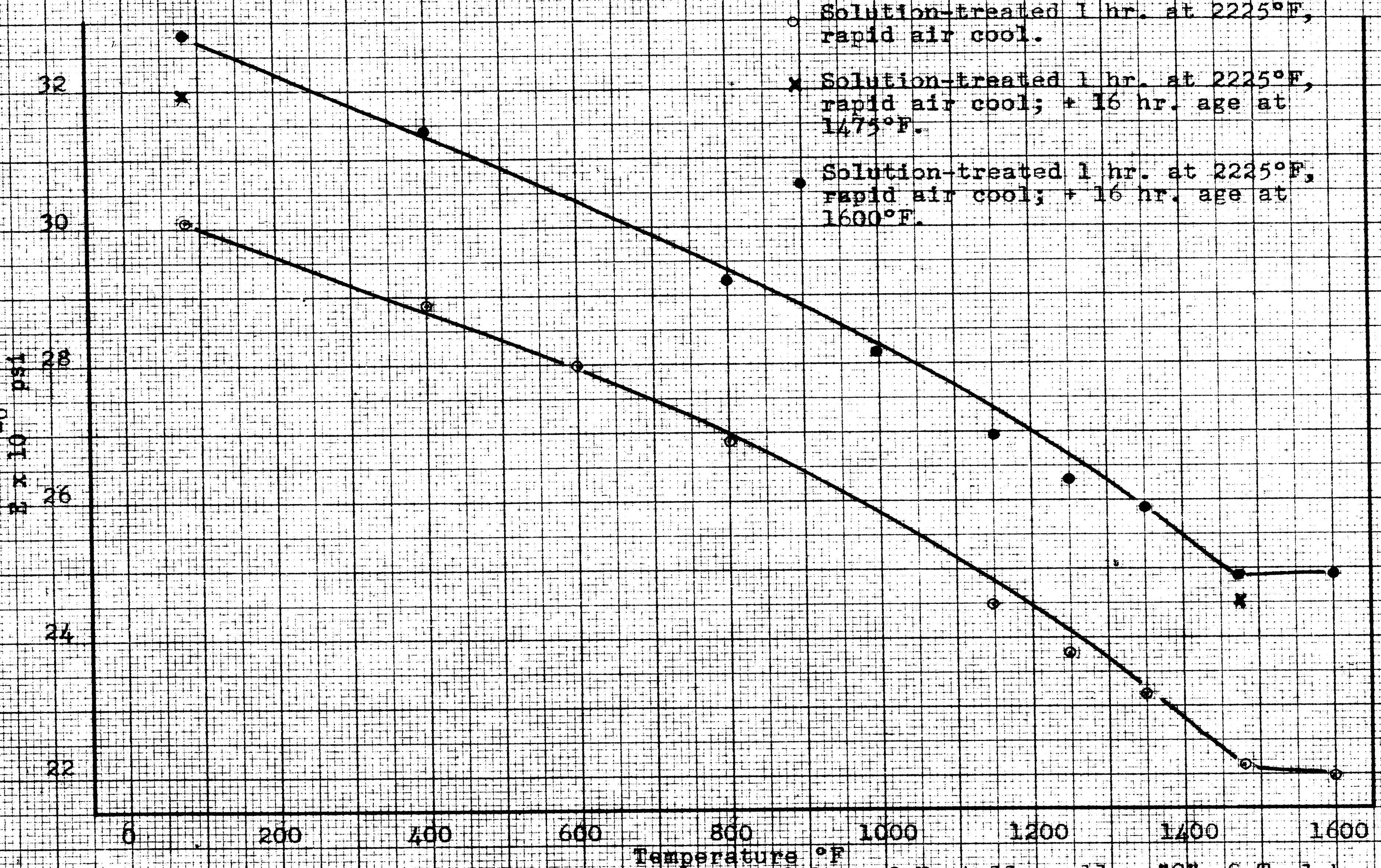

Fig. 51. Temperature dependance of Young's modulus of Hastelloy alloy "C", S.T. 1 hr. at 2225°F.

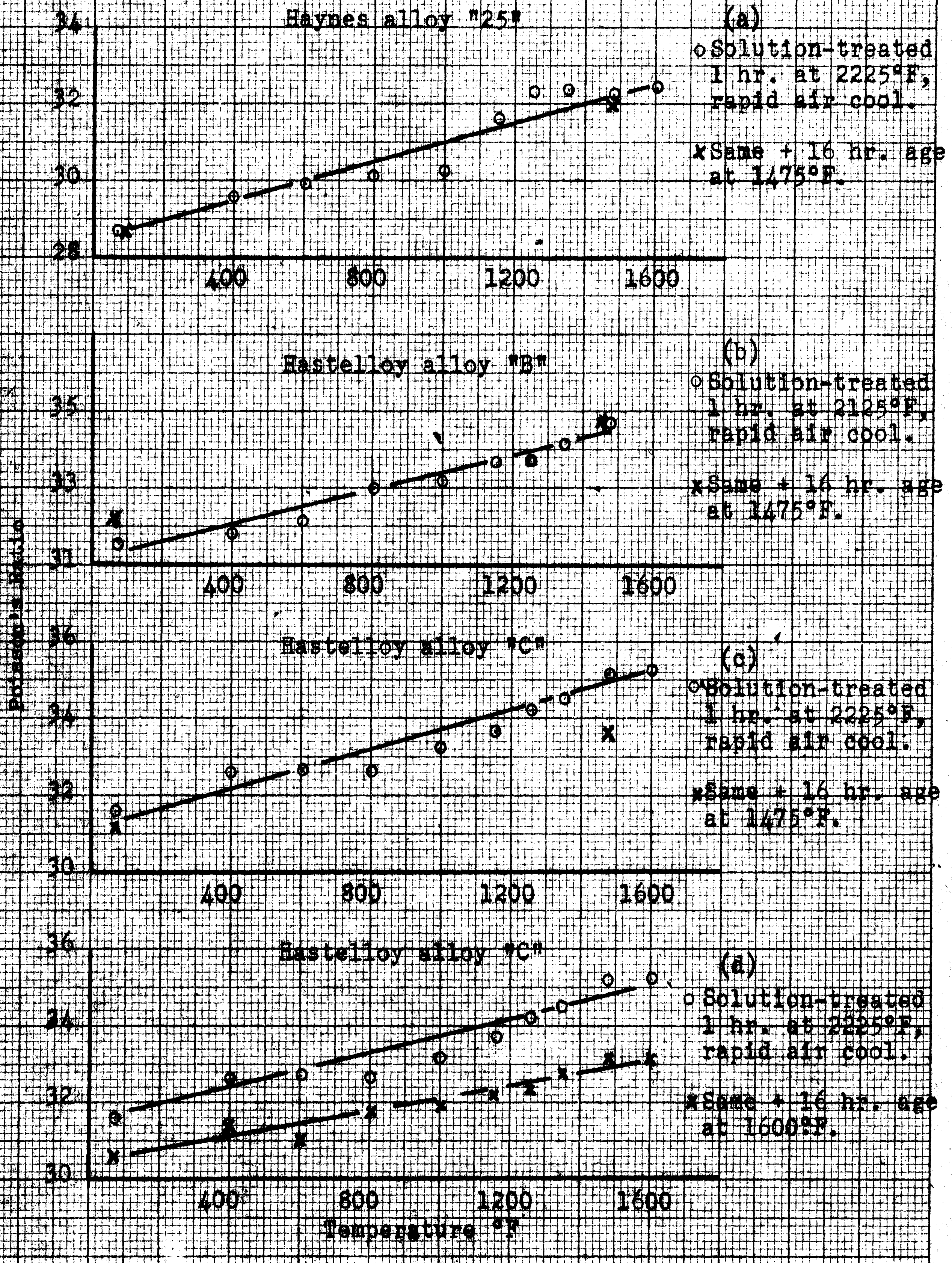

Fig. 52. Poisson's ratio of one Haynes alloy and two Hastelloy alloys.

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