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APPLICATION OF INDUCTION HEATING
TO HIGH TEMPERATURE
FATIGUE TESTING

by

Donald Lane Harper

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CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

29 May 1962
(Date)

Professor in Charge

Head of the Department
of Metallurgical Engineering

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Thanks are also due Mr. Martin Sheska and the machine shop staff for their assistance. Appreciation is also extended to Mr. W. Feilbach and Mr. D. Ritter for their assistance and contributions.

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INTRODUCTION

Background

Accelerated activity in the development of hypersonic aircraft and spacecraft has created new problems of materials testing. Testing equipment must be capable of simulating higher temperatures as well as severe thermal cycling superimposed upon the cyclic application of stress.

Among the materials under study requiring this testing equipment are the heavy refractory metals such as tungsten and molybdenum, which are capable of operating at very high temperatures while maintaining strength.

In order to evaluate materials for use in such applications, it is necessary to develop equipment for high temperature fatigue testing which is capable of rapid thermal pulsing or cycling, very high testing temperatures, convenient environmental control, and the cyclic application of stresses independent of temperature fluctuations sustained by the test specimen.

Purpose of the Investigation

The purpose of this investigation was to study the application of high frequency induction heating to fatigue testing at elevated temperatures and to develop an integrated system to perform such tests on A-286, a precipitation hardening stainless steel at testing temperatures of 1350°F, 1500°F and 1800°F.

DESCRIPTION OF THE EQUIPMENT

Arrangement of the System

Figure 1 and Figure 2 show the components and arrangement of the equipment.

The fatigue specimen is a constant stress, tapered cantilever approximately 1/10 of an inch in thickness and 6 inches in length.

The cyclic load is applied by a Wiedemann Sonntag SF-2 fatigue testing machine which can apply an alternating force up to 24 lbs., at a frequency of 1800 cycles per minute.

A portion of the fatigue specimen's constant stress section is heated by a four-turn induction heating coil energized by a Lepel 2-1/2 KW high frequency induction heating generator.

The temperature of the hottest portion of the heated specimen is sensed by a Barber-Colman radiation pyrometer. The pyrometer sights through a 1/4 inch spacing between the turns of the coil on the hottest portion which is called the target area.

The signal from the radiation pyrometer is interpreted by a temperature recorder into the actual temperature of the target area. The deviation of the sensed temperature from the control point temperature is translated into an error signal which feeds a proportional controller. The proportional controller sends an adjustment signal to a servo-motor which adjusts a power rheostat in the induction generator. A Barber-Colman Co. Wheelco 8000 Series Recorder and Magnetic Modulated Proportional Controller are utilized in the instrumentation described above.

Fatigue Machine

The Sonntag SF-2 fatigue testing machine is manufactured by the

Wiedemann Machine Co., King of Prussia, Penna. The SF-2 is capable of applying an alternating force of ± 24 lbs. to the free end of a cantilever beam fatigue specimen by means of an eccentric mass rotating at 1800 r.p.m. The maximum allowable deflection of the free end is ± 0.5 inches.

Once a fatigue specimen is designed, the equipment is carefully tuned for use with the designed specimen. The tuning and calibration can easily be verified by running the machine at several force settings and comparing the measured deflections with available formulas. An alternate method is to disconnect the loading fixtures from the free end of the cantilever beam and apply known loads by means of a spring scale. If this deflection-versus-load relationship corresponds to the deflection-versus-dynamically-applied-load relationship, then the calibration of the fatigue machine is correct.

An advantage of primary importance is that the Sonntag SF-2 is a constant force machine. Even though thermal cycles, during operation, may cause changes in the deflection of the specimen due to changes in the value of Young's Modulus, the applied load and resulting stress remains the same.

At high temperatures, surface material may be stressed beyond its yield stress, resulting in localized plastic deformation. The extent to which this takes place and its effect has not been investigated in the experimental program herein reported.

It is well known that fatigue cracks are initiated early in the fatigue life of a part. Once a fatigue crack has initiated, the effective stress propagating the crack to failure is the stress at the root of the fatigue crack destined to cause failure. The relationship of this stress to the depth of the crack and the radius of the root is varied, difficult to determine, and certainly dependent upon temperature.

High Temperature Fatigue Specimens

The fundamental task of the high temperature fatigue testing unit is to record the total number of cyclic applications of a selected stress required to cause failure of a reproducible specimen held at some controlled elevated temperature.

The fatigue crack must therefore initiate and propagate from a position on the specimen where the maximum fiber stress is known and the temperature is controlled.

There are two specimen designs which are capable of producing these conditions, but by different means. One is a constant stress specimen illustrated in Figure 3, which is so designed that the applied stress is constant over most of its length. In the case of this specimen, a failure occurs at a location where the heating pattern produces material having the lowest fatigue strength. For A-286, this invariably took place through the hottest portion of the specimen. The radiation pyrometer must therefore measure the temperature of this hottest zone and the temperature control must respond to this signal.

The second type of specimen is the maximum stress type illustrated in Figure 4. This type of specimen has a sharp reduction of its section modulus at some position along its length, causing this to be the position of maximum stress. The maximum stress position is made the target area for the radiation pyrometer, at which position the fatigue failure occurs. The maximum stress specimen has the advantage of being easier to machine than the constant stress specimen. A disadvantage of the maximum stress specimen is the notch effect of the suddenly reduced section which may be difficult to define.

Specimens must be proportioned appropriately to enable the maximum of 24 lbs. of force to produce the maximum stress levels desired, yet the specimens must also be short and stiff enough so that the maximum allowable deflection of ± 0.5 inches is not exceeded at the highest levels of stress.

Induction Heating Coil

Figure 5 shows one of the latter evolutions of coil design. It is evident from the side view of the coil that the minimum coil to work spacing is determined by the maximum deflection of the fatigue specimen. Also note that the number of coil turns is symmetrical about the 5/16" spacing required to expose the target area for the radiation pyrometer.

The major objective of the coil design is to produce the highest temperature in the target area which is uniform across and through the specimen. This objective was approached through a succession of coil re-designs. The results of a temperature survey produced by the coil design illustrated is represented in Figure 6.

The temperature variation of the specimen surface around a cross-section of the target zone indicates a maximum of ± 13°F deviation from the control temperature. The author feels that this can be reduced by further refinement of coil and specimen design. Figure 7 represents these temperature variations is a more detailed manner.

High Frequency Induction Heating Generator

The high frequency current required for induction heating was generated by a Lepel 2-1/2 KW tube oscillator. The generator proved to be highly dependable, simple to operate, and capable of very high rates of heating for the fatigue specimen. Figure 8 indicates the heating rate produced by the generator.

Since maximum power can be instantly applied with the flick of a dial, the time required to heat the specimen from 1350-1500°F is 1.2 seconds, 1350-1800°F is 4.3 seconds, and 1500-1800°F is 3.1 seconds.

Temperature Control Arrangement

Radiation Pyrometer

The temperature of the fatigue specimen at the location where the fatigue crack will occur must be accurately monitored during the duration of each test. The temperature device must further provide a primary signal to which temperature control may respond.

Measurement of the target zone temperature can be performed either by thermocouples percussion-welded to the neutral axis of the specimen, or by a radiation pyrometer sighting between the induction coils onto the target area.

Possible difficulties were anticipated with the thermocouple technique. One, the vibration might damage one of the percussion welds, or even cause it to break off entirely. The temperature control system would respond to this drop in signal and cause overheating of the specimen. Two, diffusion at the weld sites may cause a progressive variation in the output of the thermocouple.

Because of the lack of physical contact and its constancy over an extended period of time, a radiation pyrometer temperature measurement was selected and has proved to be satisfactory.

The instrument chosen was a Wheelco-Land radiation pyrometer, type R6. This instrument is positioned 6" away from the 1/4" square target area. The radiated energy emitted from the target area is optically focused upon a small block of aluminum in which 10 thermocouples, wired in series, are imbedded. The output of this radiation pyrometer versus temperature of a perfect radiator (black body) is plotted in Figure 9. The plot indicates that in the range of (1300°F-1800°F), the output increases very slowly at a low level. This undesirable situation is intensified by the fact that the emissivity of the oxidized specimen has a value of 0.660 when oxidized in still air at 1350°F, a value of 0.674 when oxidized in still air at 1500°F, and a value of 0.679 when oxidized in still air at 1800°F. Although this is an undesirable situation, the emissivity was fairly constant and compensation could be made for the low value.

A problem might be anticipated if a brightly polished specimen were to be tested in a controlled atmosphere which prevents oxidation of the specimen. In this case, the very low emissivity of the bright surface (approximately 0.08) would not be raised to a reasonable level by the oxidation of the surface.

It is doubtful that low target area emissivity will be a serious problem in most investigations as long as it is a recognized phenomenon. The procedure adopted in this investigation was to standardize the temperature recording equipment, using blank specimen with thermocouples attached. Care was taken to use a blank specimen oxidized in air at a temperature no higher than the temperature for which standardization was intended.

Fatigue specimens to be tested at temperatures of 1000°F to

1325°F may be momentarily heated to the aging temperature to assure maximum tarnishing.

Another approach would be to apply a thin coating of some material such as a colloidal dispersion of graphite in a vehicle such as water or aromatic solvent. When dry, these coatings provide a uniformly high emissivity. It must be cautioned that the thickness of the coating is very critical. If too thin, the coating lacks effectiveness, and if too thick, the coating may not be adherent to the metallic surface.

Temperature Recorder

The temperature of the fatigue specimen target area was continuously measured and recorded by a 8000 Series Wheelco Recorder which translated the voltage signal from the radiation pyrometer into a temperature reading. When this instrument is used with a radiation pyrometer, the scale has an exponential form corresponding to the output of the pyrometer. A typical scale would be 1000°F-2500°F.

The indicating scale, radiation pyrometer, and internal parts and adjustments must all be matched and standardized if true temperatures are to be indicated. Standardization is easily accomplished by applying a thermocouple immediately adjacent to the target area of a specimen heated to the testing temperature according to the thermocouple. The Wheelco Recorder is then adjusted to read that temperature by means of an emissivity compensating adjustment.

If the effects of low specimen temperature and low emissivity combine to produce radiation pyrometer potentials so low that they cannot be brought into the range of the indicating scale, a device described in Figure 10 is capable of compensating for this difficulty.

Controller and Servo Mechanism

The temperature control is accomplished by a Wheelco Recorder and a Wheelco Magnetic Modulator Positioner, which operates through a servo to control the output of the high frequency induction generator. The MMP Controller interprets an error signal from the recorder in terms of an appropriate change in power with fast response and little overshoot.

EXPERIMENTAL WORK

Material

A-286 is a precipitation hardening, stainless steel, developed by the Allegheny Ludlum Steel Corporation for high strength and resistance to corrosion up to 1300°F. Properties of A-286 are attained through heat treatment which generally consists of a solution treatment at 1650°F-1800°F, followed by an aging treatment at 1325°F for 16 hours.

The normal ranges of chemical analysis for A-286 and the analysis of the heat studied are tabulated in Table 1.

A-286 contains enough nickel (24-28%) to stabilize austenite at all temperatures.

Ni_3Ti or Ni_3Al is the equilibrium phase of coherent precipitation responsible for the precipitation hardening of the solution treated material. Ni_3Ti does not form above 1650°F and dissolves readily at 1700°F, if formed by overaging.

Emphasis has been placed upon the careful control of the Boron content between 0.0010-0.010%. If Boron is absent, a weak lamellar precipitate is formed upon age-hardening. Boron contents as high as 0.20% can give rise to a low melting point, grain boundary segregate.

Cold-working of the solution treated material may result in overaging or the formation of the soft lamellar precipitate, if the Boron content is excessive. For this reason, it was decided to machine and grind the fatigue specimens after precipitation hardening, since these processes result in some cold-working of the surface.

Preparation of Fatigue Specimens

The alloy A-286 was received in the form of 2" wide by 1/8" thick strips in lengths of approximately 9 feet. The material was solution treated at the mill which consisted of heating the material to 1800°F for 14 minutes, followed by fan cooling.

Since cold-working of solution treated A-286 is reported to influence the aging kinetics of the alloy, it was decided to machine the test specimens from the 2" x 1/8" strips after the aging heat treatment. At an aged hardness of 280 Brinell, the material can be machined, using high-speed tooling.

The strips were cut into 6" specimen blanks and aged at 1325 ± 12°F for 16 hours. Aging increased the hardness from 173 Brinell to 272 Brinell, as indicated by Figure 11.

After the specimen blanks were aged, they were carefully machined to the profile of the fatigue specimen. Following machining, the specimens were surface ground with a Norton 32A80 - M5B grinding wheel, at a speed of 5400 SFPM. A free flow application of coolent was applied to obtain (1) the best surface finish, (2) a minimum of subsurface metallurgical damage, and (3) the lowest possible residual stresses.

To relieve residual grinding stresses that were produced, the fully machined and ground fatigue specimens were stress relieved at 1325°F for 1 hour. This is the aging temperature and little effect is produced by this stress relief.

Fatigue Testing Results

The results of fatigue tests performed at 1350°F, 1500°F and 1800°F are plotted in Figure 12. These curves clearly indicate that in the range of 1350°F to 1800°F, the fatigue life is improved by decreasing testing temperatures. It should be recalled that aged

A-286 will overage in several hours at a temperature of 1500°F. Also, the equilibrium phase of coherent precipitation is rapidly re-dissolved at 1500°F and 1800°F. Specimens were not stress relieved after the surface grinding operation. It is evident that any residual stresses formed during grinding are rapidly relieved at the testing temperature and do not appreciably influence the results. Specimens tested at 1350°F, without stress relieving, exhibited greatly reduced fatigue strengths.

For purposes of comparison, the data referred to above is plotted with other available fatigue data on A-286 in Figure 13. Study of this figure indicates that the agreement is good and reasonable.

CONCLUSIONS

1. The application of induction heating to high temperature fatigue testing offers some real advantages. Among these advantages are:

   a. unlimited testing temperatures over extended periods

   b. rapid heating and cooling of only a small portion of the test specimen

   c. dissipation of heat to the laboratory is a minimum

   d. adaptation of environmental control to the heated fatigue specimen may be simplified

2. A maximum stress type fatigue specimen may be preferable to a constant stress type for several reasons:

   a. the maximum stress specimen is easier to machine.

   b. there is a most likely position for the specimen to fail.

3. The possibility of the interaction of electromagnetic heating with the propagation of a fatigue crack should be further investigated. Nothing has indicated the presence of this effect nor has it been proven not to exist.

4. The fatigue properties of A-286 are as follows:

Fatigue Strength, 1000 psi

Test Temperature	10^5 Cycles	10^6 Cycles	10^7 Cycles	10^8 Cycles
1350°F	54.0 est.	45.0	41.1	39.5 est.
1500°F	34.0	28.5	25.7	24.0 est.
1800°F	16.0	12.8	10.6 est.	9.0 est.

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TABLE I

Chemical Analysis of Alloy A-286

	Normal Range	Heat Tested 22909
Carbon	0.08 max.	0.08
Manganese	1.00 - 2.00	1.25
Silicon	0.40 - 1.00	0.86
Chromium	13.50 - 16.00	14.85
Nickel	24.00 - 28.00	24.92
Molybdenum	1.00 - 1.50	1.26
Titanium	1.75 - 2.25	2.03
Vanadium	0.10 - .50	0.24
Aluminum	0.35 max.	0.28
Iron	Bal.	Bal.
Sulphur	0.04 max.	0.009
Phosphorus	0.04 max.	0.016
Boron	0.0010 - .010	0.007

TABLE II

Fatigue Testing Data

Testing Temperature	Max. Stress (psi)	No. of Cycles to Failure
1350°F (SR)	48,000	400,000
1350°F (SR)	45,000	912,000
1350°F (SR)	42,000	4,115,000
1350°F (SR)	41,000	10,111,000
1350°F (SR)	40,000	28,000,000 +
1500°F (SR)	35,000	73,000
1500°F	35,000	114,000
1500°F (SR)	30,000	480,000
1500°F	27,000	1,084,000
1500°F (SR)	26,000	9,113,000
1800°F	25,000	3,800
1800°F	20,000	16,000
1800°F (SR)	19,600	30,000
1800°F	16,000	99,000
1800°F (SR)	14,000	347,000 ~
1800°F	12,000	1,519,000

(SR) Stress relieved - 1325°F, 1 hour

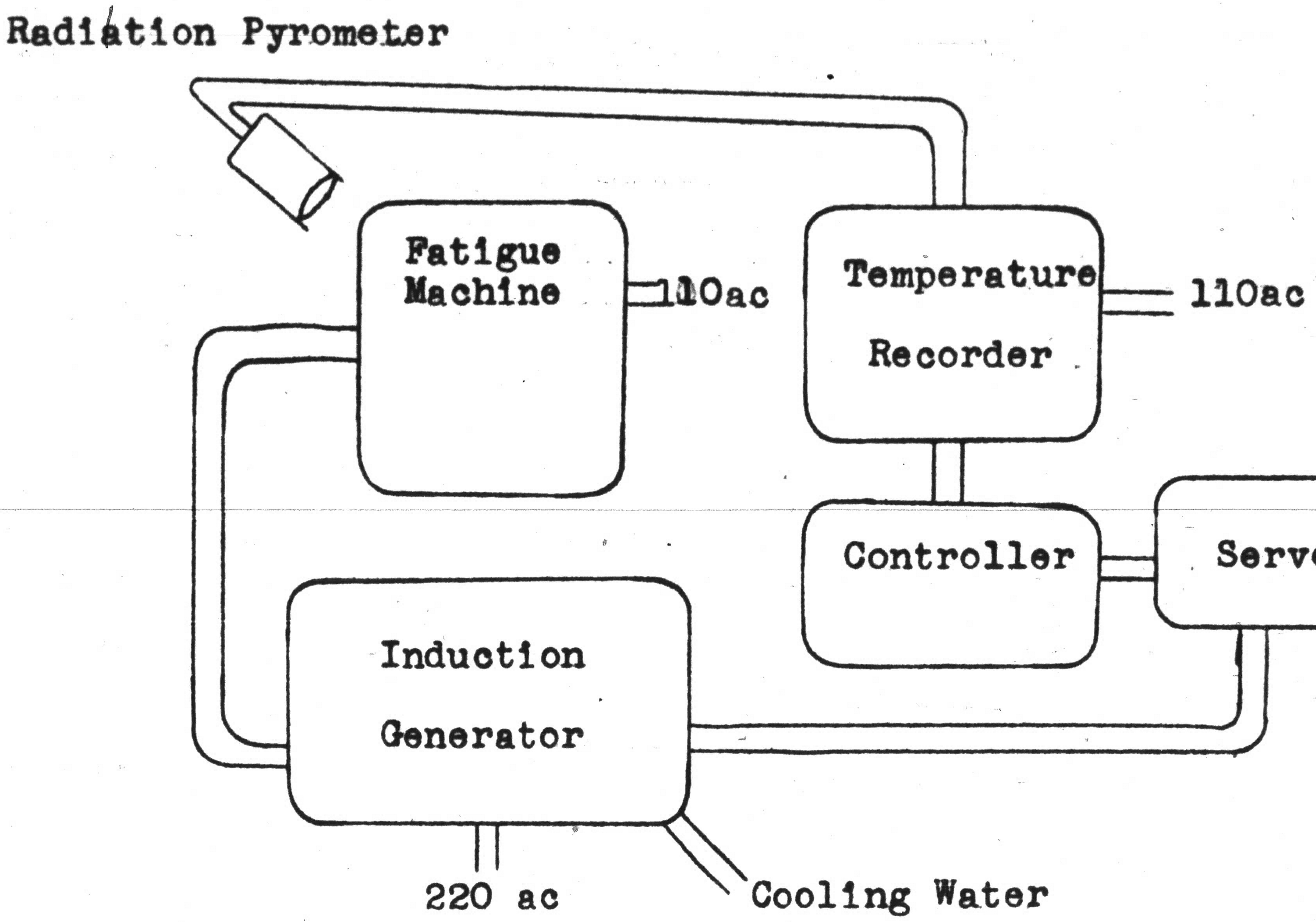

Figure 1 - High Temperature Fatigue Testing Unit.

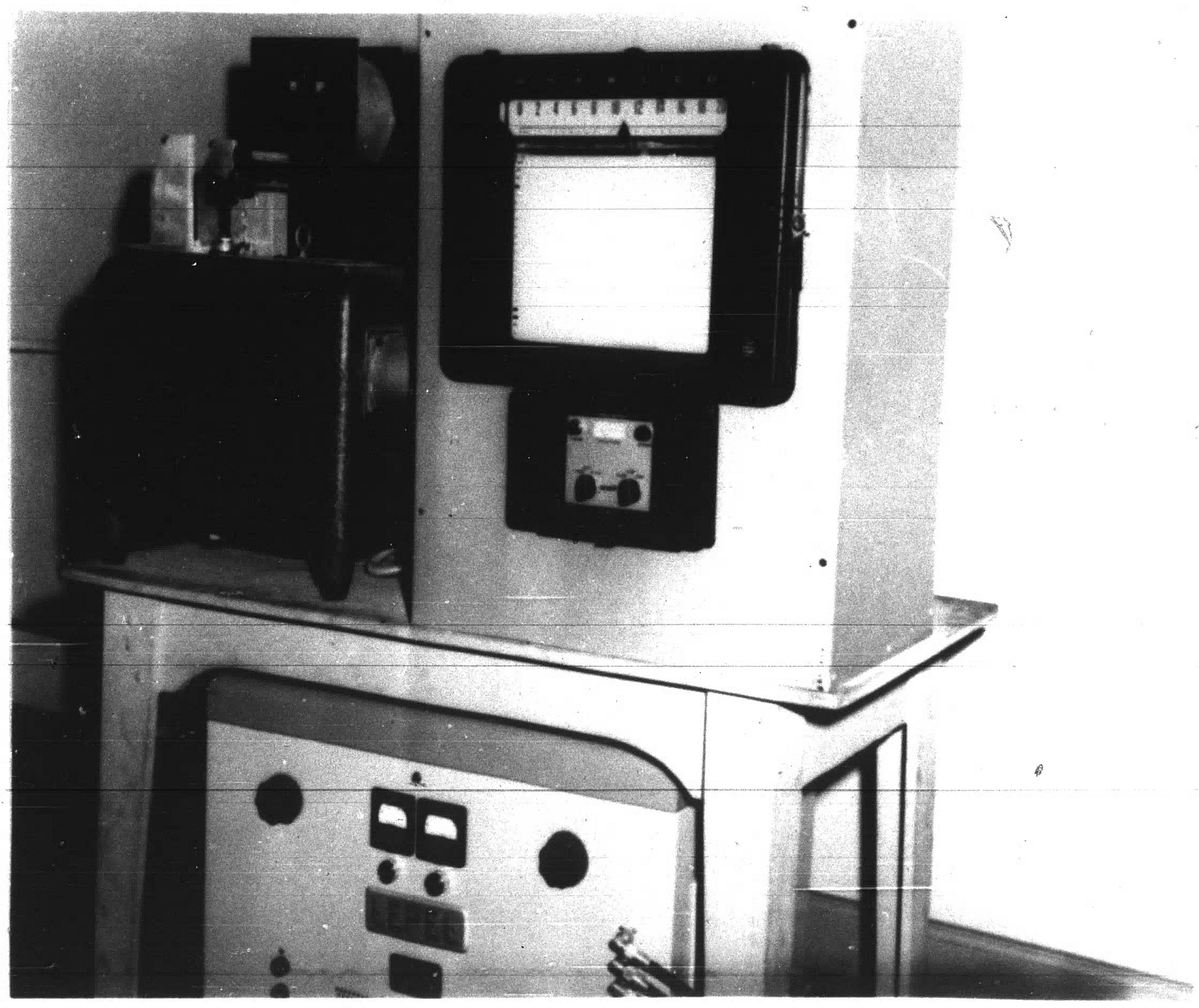

Figure 2 - High Temperature Fatigue Testing Unit.

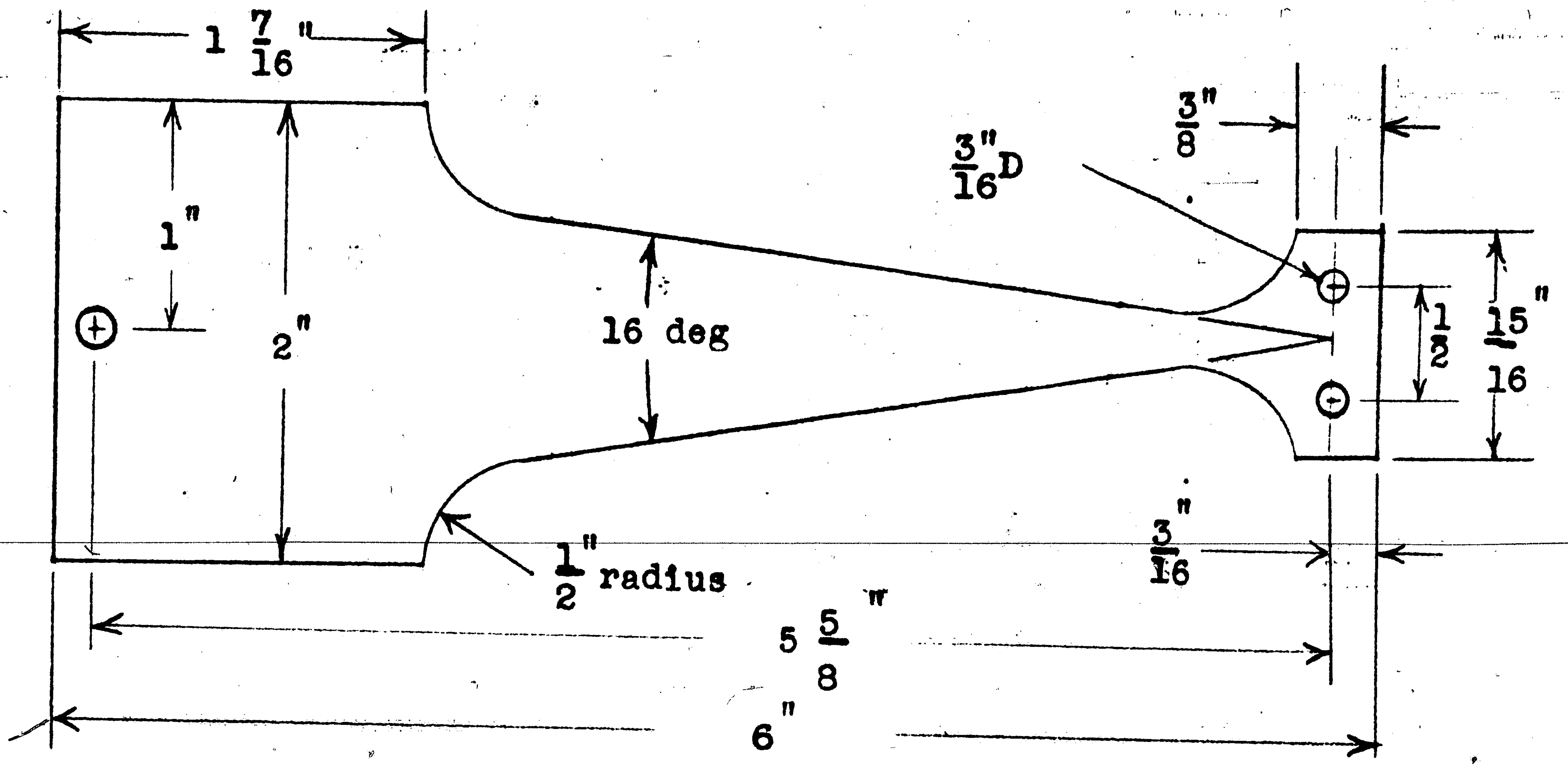

Figure 3 - Constant Stress Cantilever Fatigue Specimen.

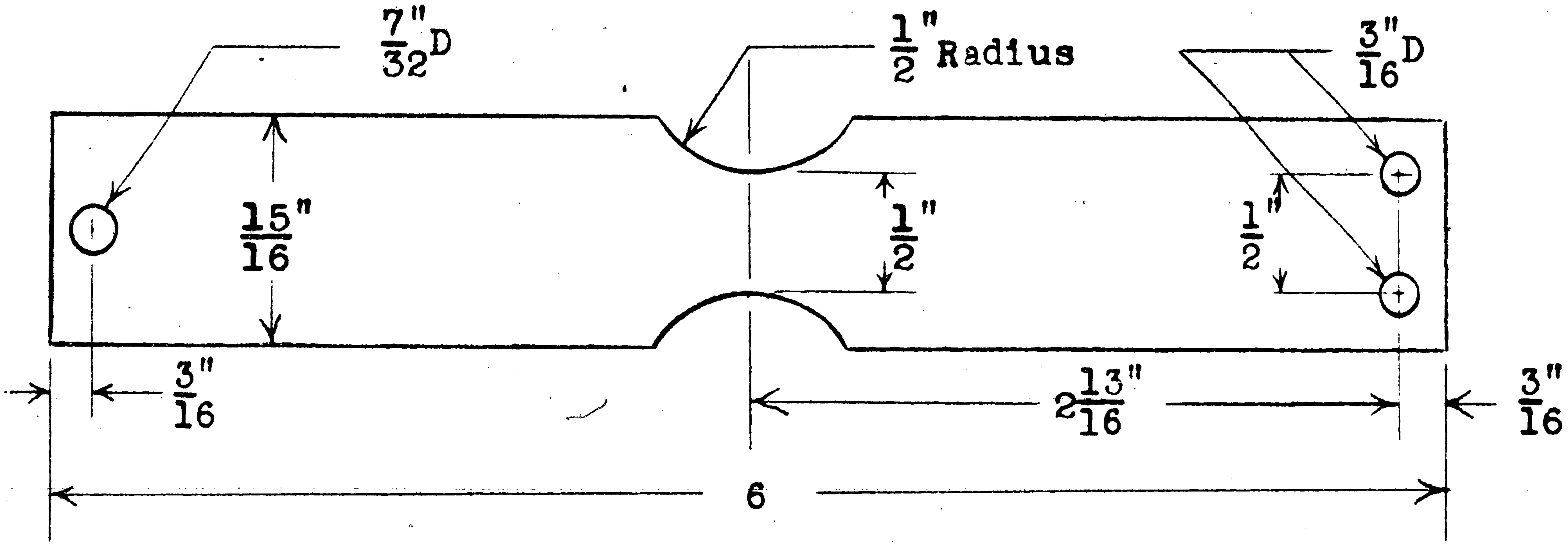

Figure 4 - Maximum Stress Cantilever Fatigue Specimen.

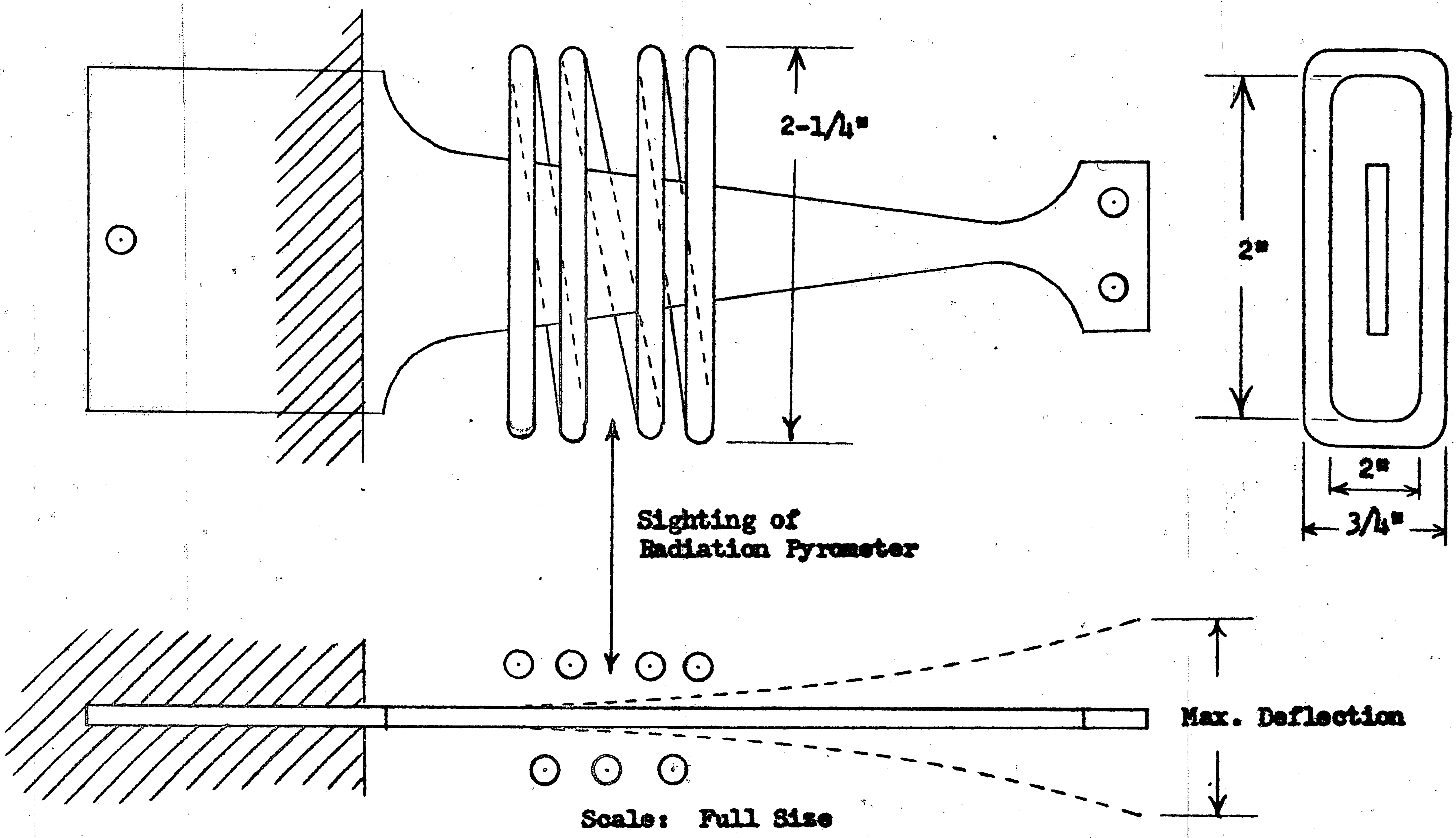

Figure 5: Constant Stress Fatigue Specimen
With Induction Heating Coil Shown in Operating Position.

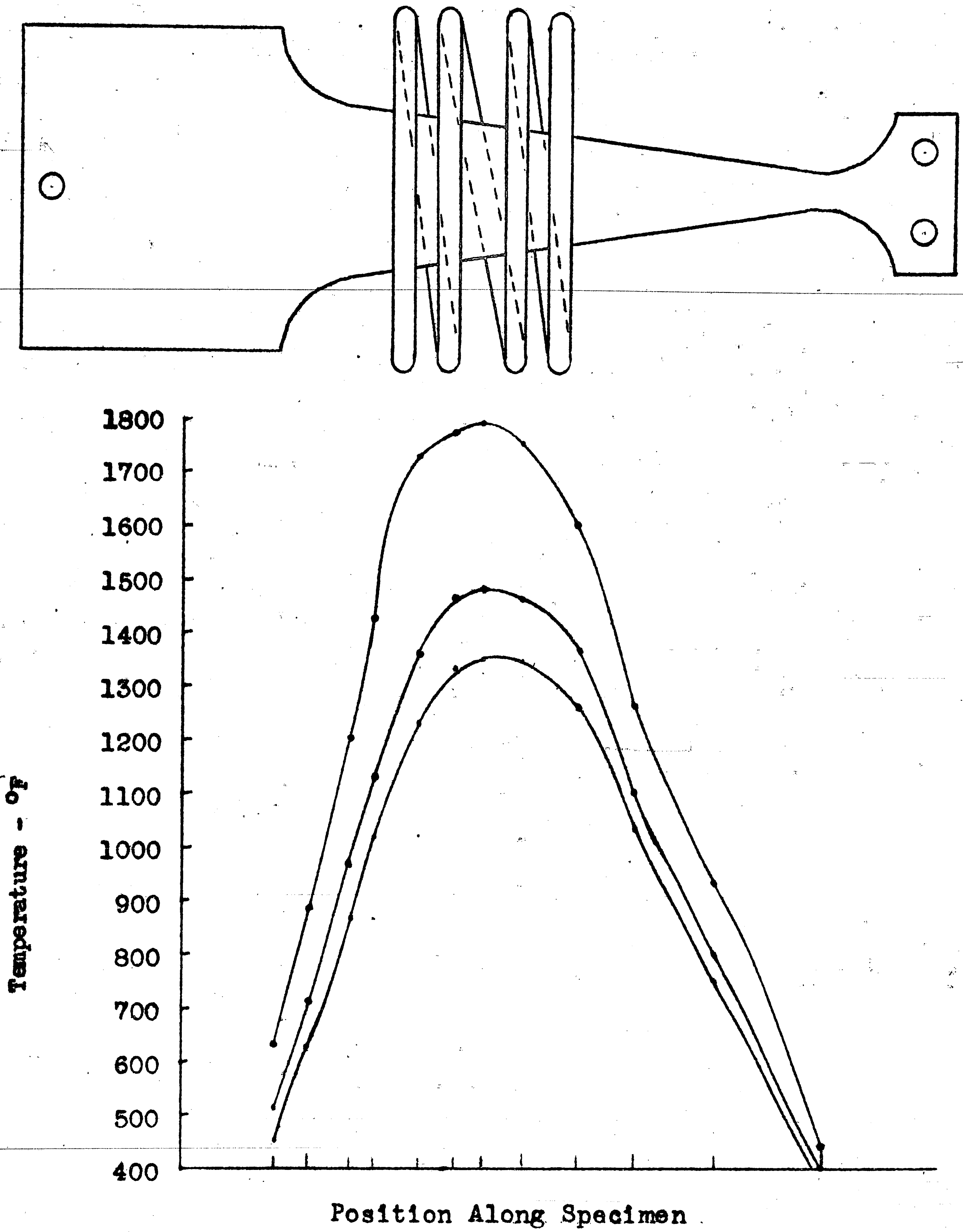

Figure 6 - Temperature Profile Along Length of High Temperature Fatigue Specimen For Target Area Temperatures of 1350°F, 1500°F, and 1800°F.

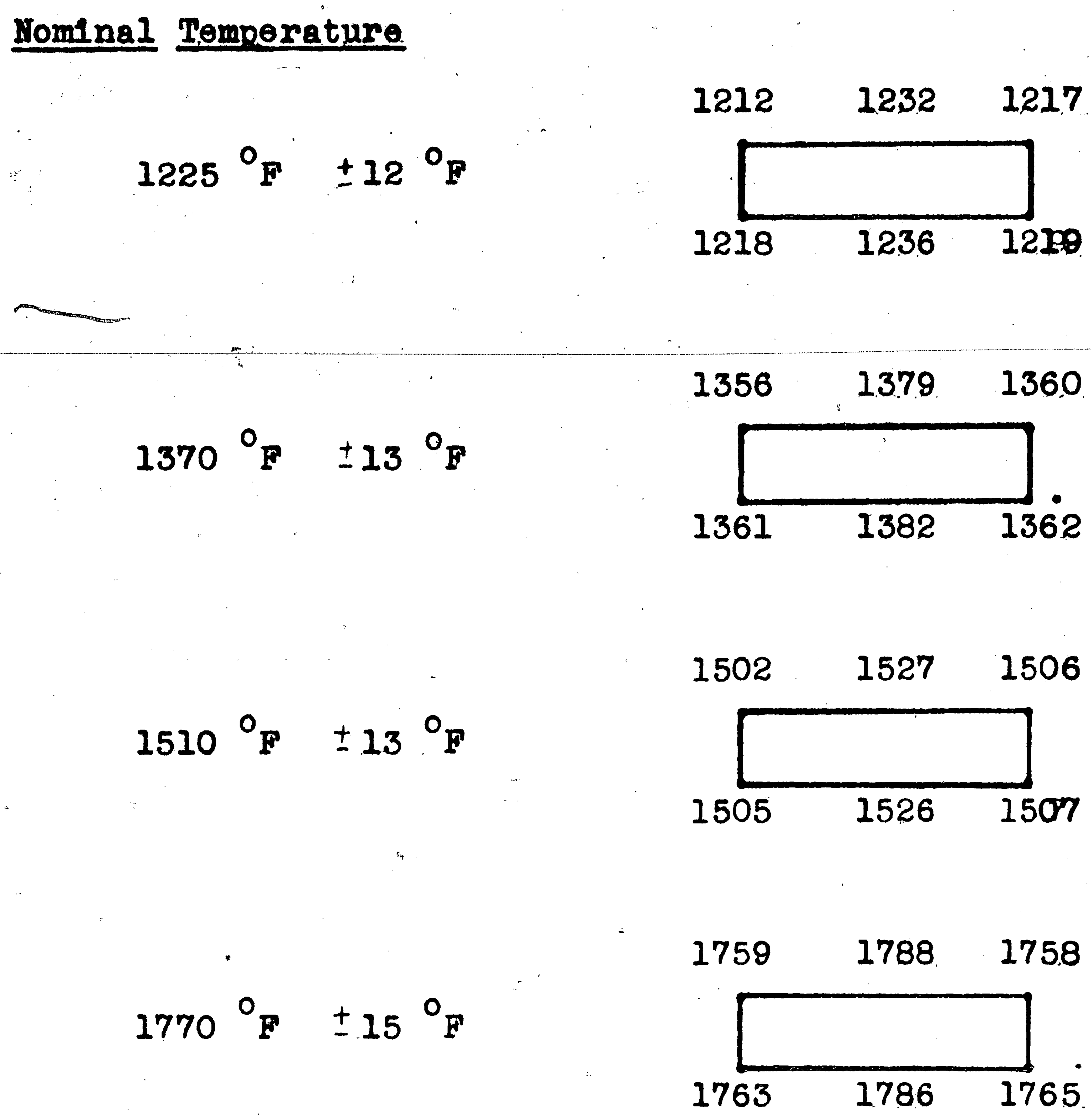

Figure 7 - Temperatures of Specimen Surface Across Top and Bottom in the Target Zone.

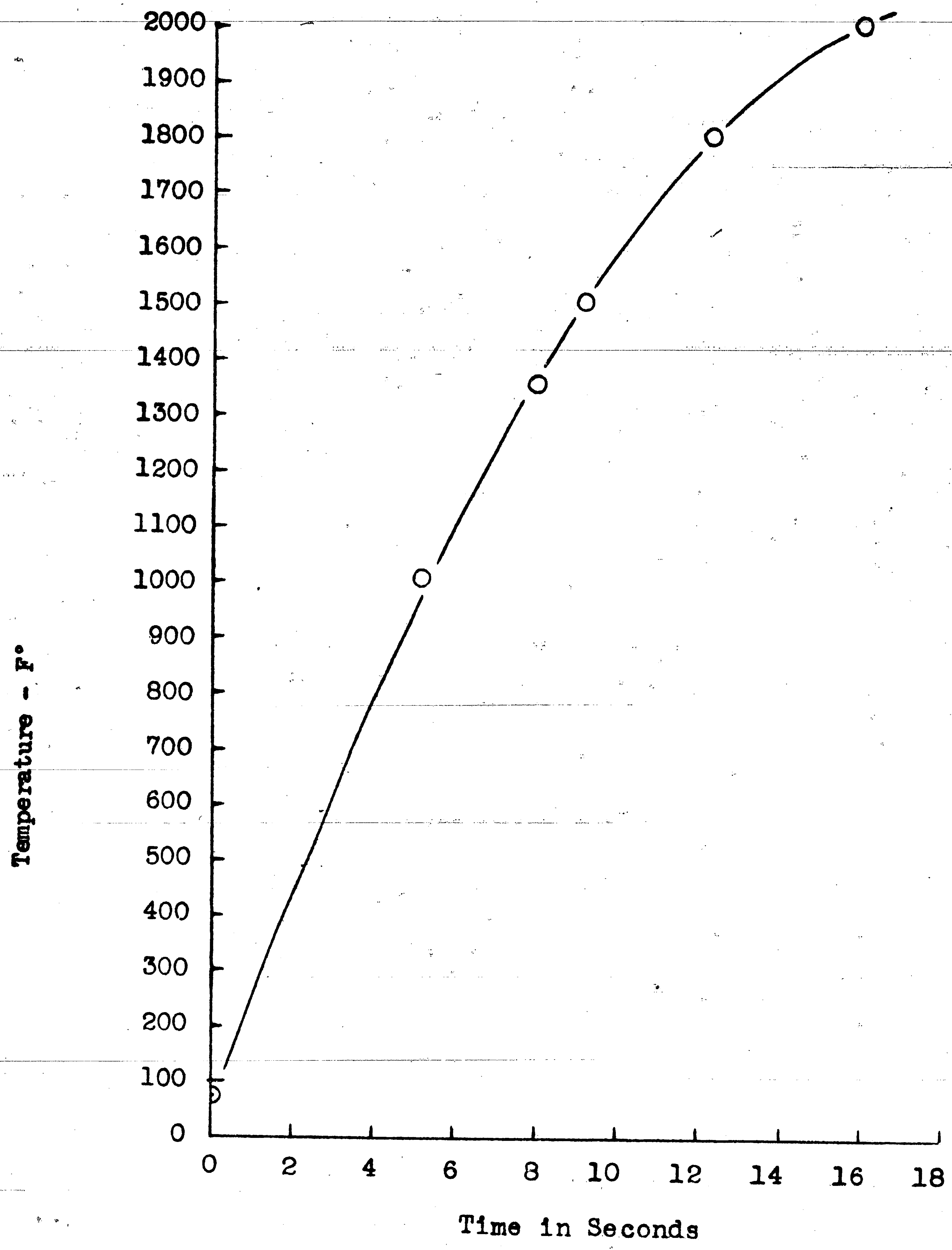

Figure 8 - The Heating Rate Attainable by the Equipment Described.

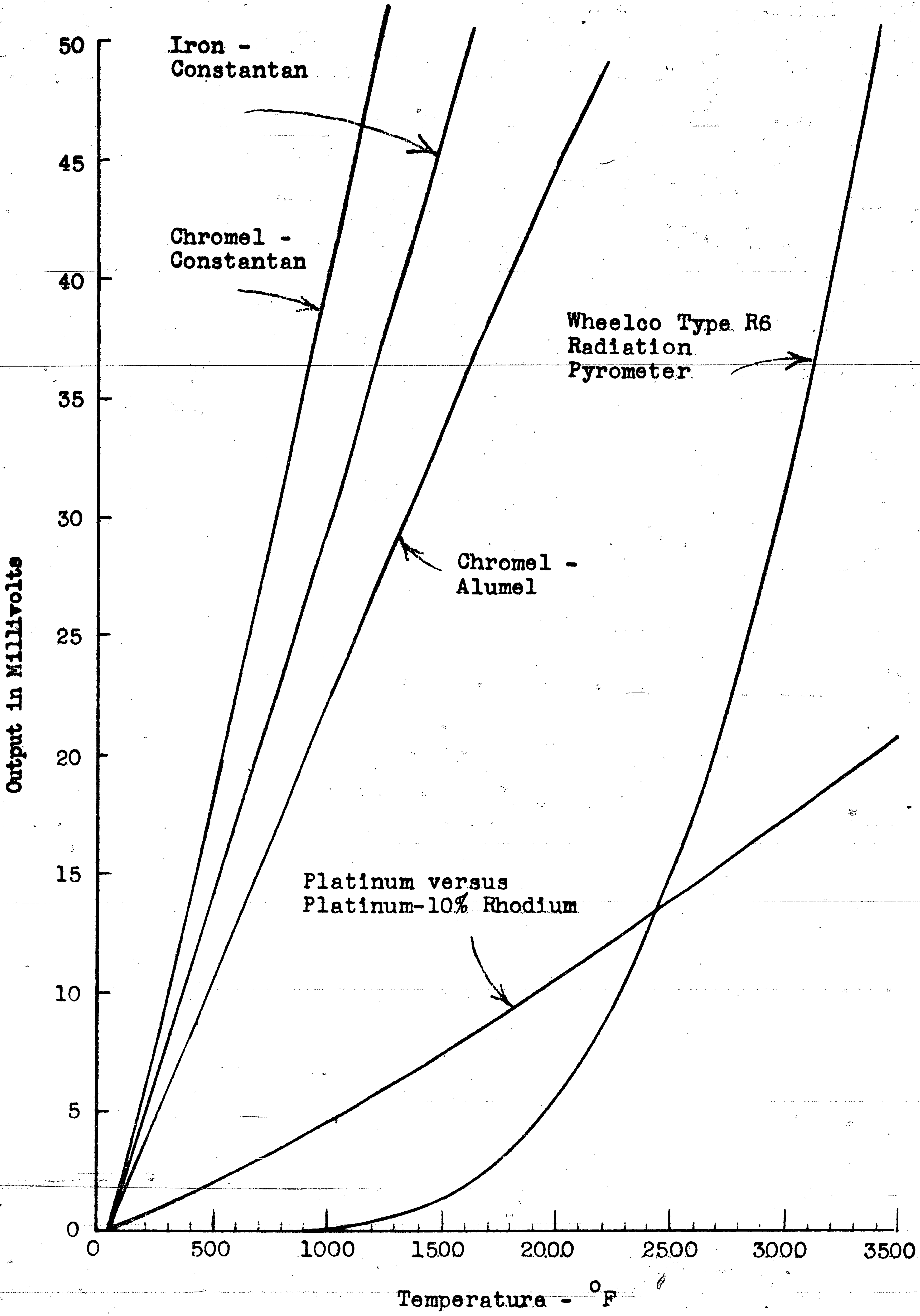

Figure 9 - Signal Output Versus Temperature for a Radiation Pyrometer Compared with Various Thermocouples.

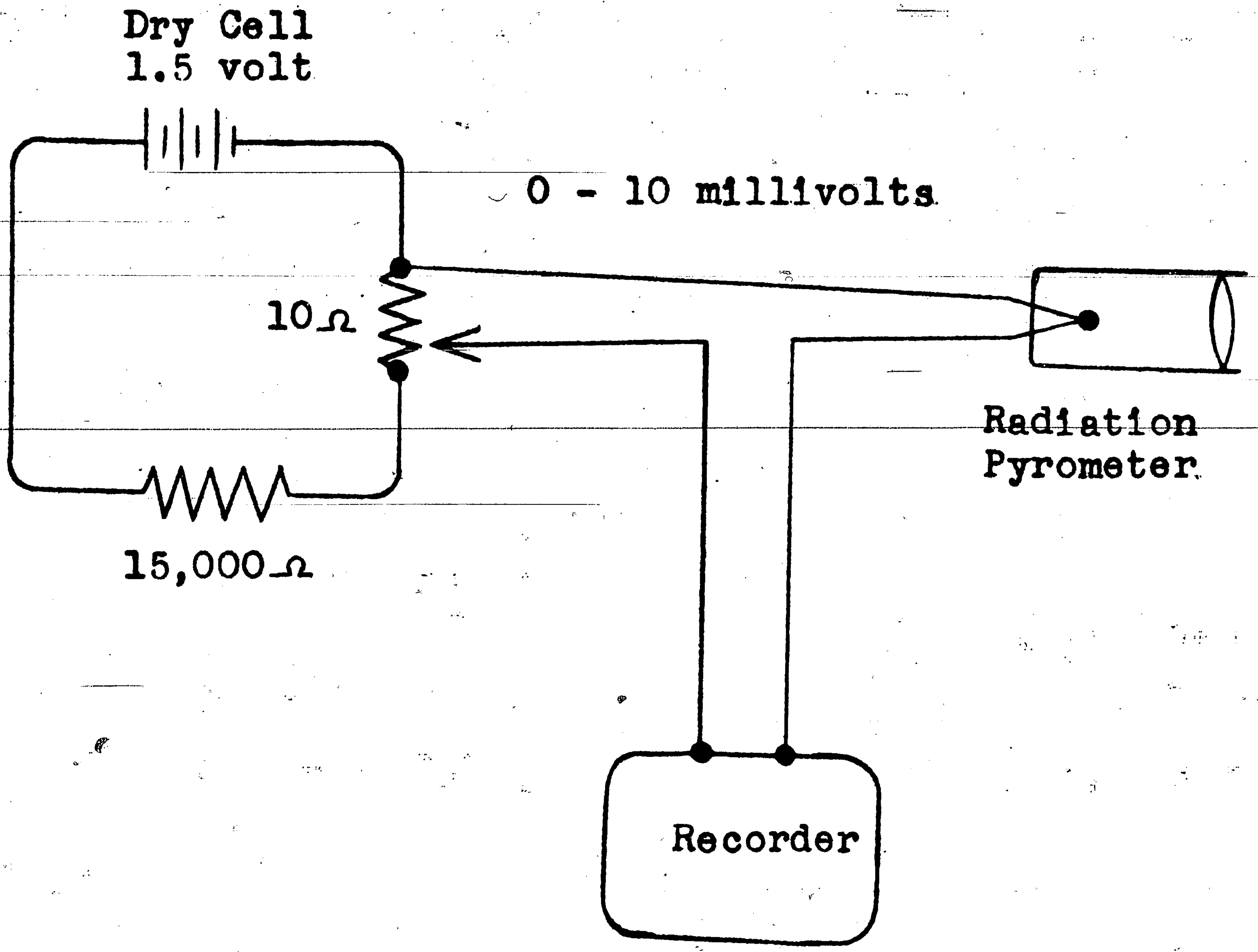

Figure 10 - Device for Boosting The Output of a Radiation Pyrometer.

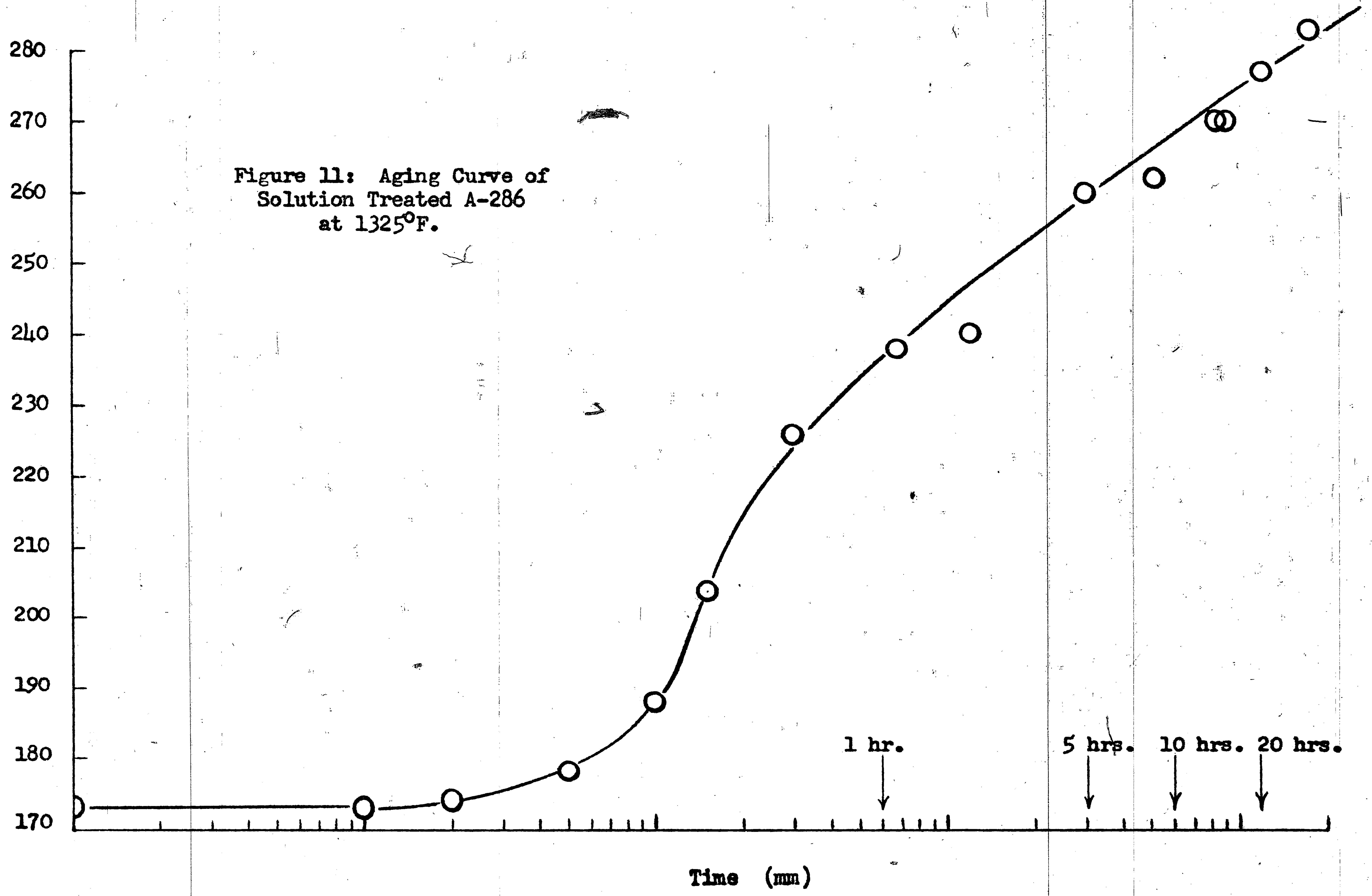

Figure 11: Aging Curve of Solution Treated A-286 at 1325°F.

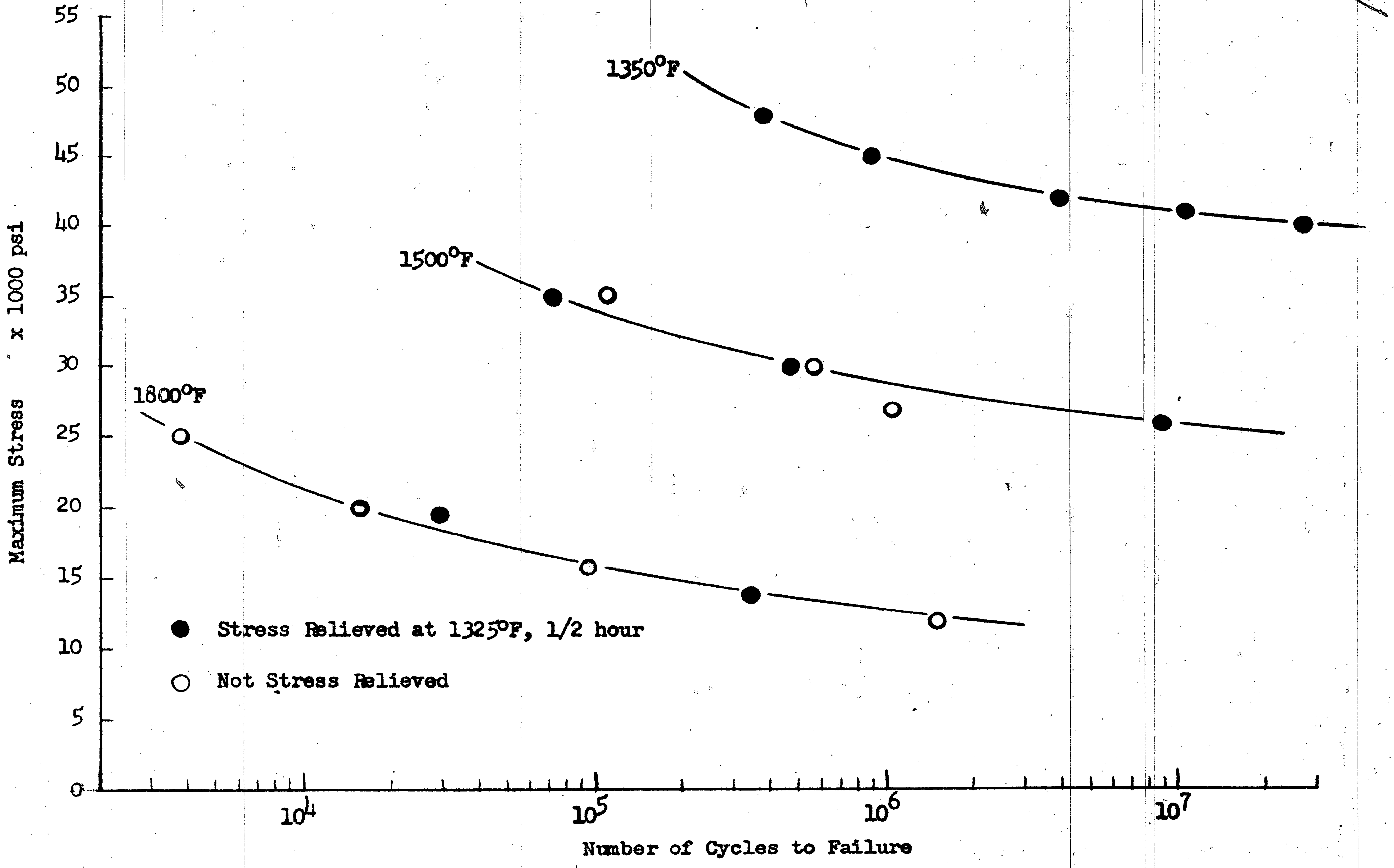

Figure 12: S-N Diagram for Aged A-286 at Temperatures of 1350°F, 1500°F, and 1800°F.

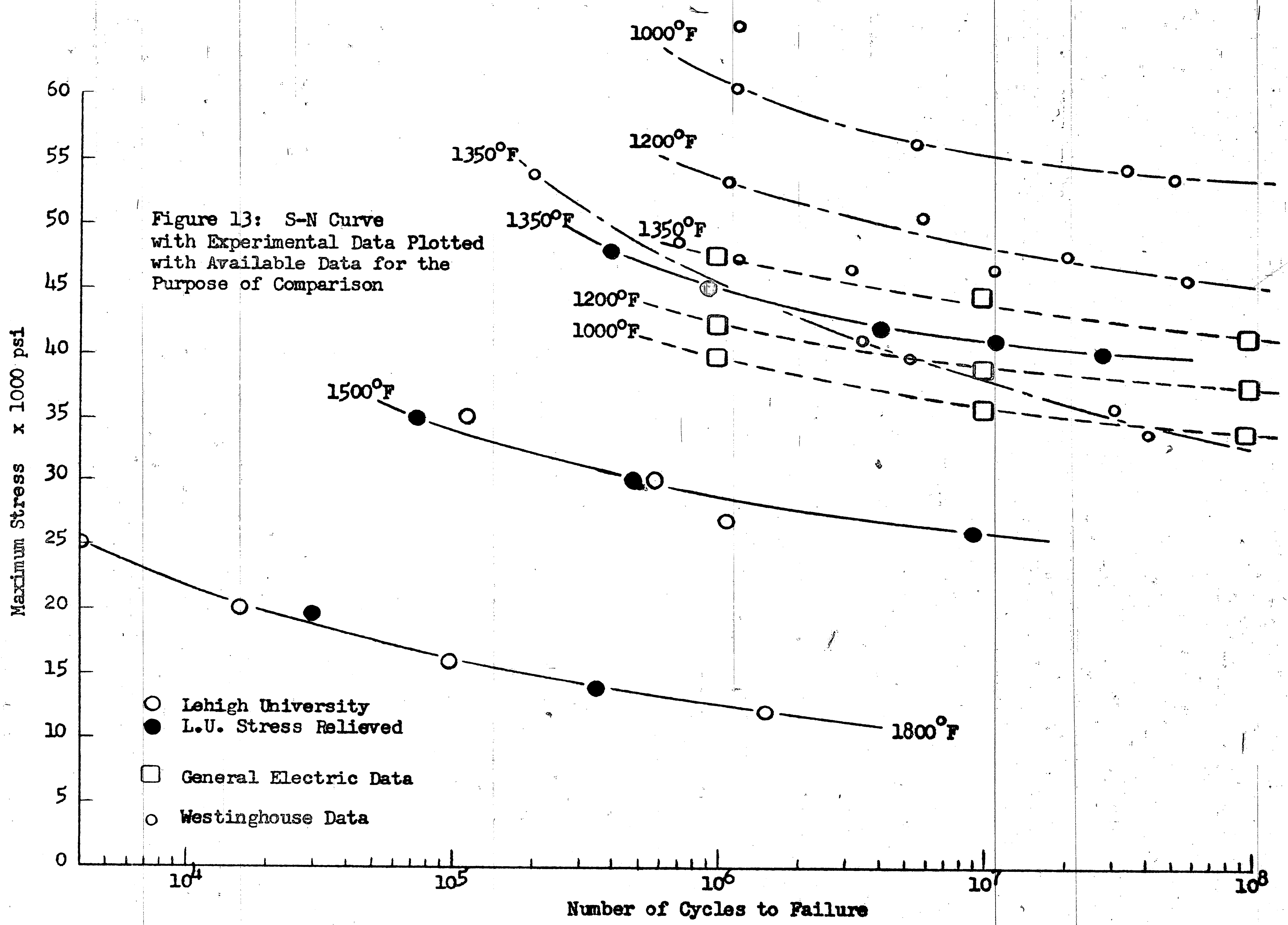

Figure 13: S-N Curve with Experimental Data Plotted with Available Data for the Purpose of Comparison

VITA

Donald Lane Harper was born to Samuel and Mary Harper in Plainfield, New Jersey, on April 25, 1934. He attended Watchung Borough Grammar School and went on to graduate from North Plainfield High School, North Plainfield, New Jersey, in June 1953. The author enrolled in Lafayette College, Easton, Pennsylvania, in the following fall and graduated with a degree of Bachelor of Science in Metallurgical Engineering in June of 1957. Immediately following graduation, the author joined the General Electric Company on a Chemical-Metallurgical Training Program and stayed with the Company for six months.

In January of 1958, the author accepted a position as instructor in mechanics of machinery and manufacturing processes in the Mechanical Engineering Department, Lafayette College, where he has been since that time. In addition to his teaching responsibilities, the author has carried on research investigations for the New Jersey Silica Sand Company of Millville, New Jersey.