FINAL REPORT

TO

WRIGHT AIR DEVELOPMENT CENTER, MATERIALS LABORATORY

ON

PROPERTIES AT 1000°, 1100°, AND 1200°F FOR TURBINE WHEELS OF FOUR LOW-ALLOY STEELS

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FOREWORD

This report was prepared by the Engineering Research Institute of the University of Michigan under Contract Number: AF33(038)-13496. The work authorized under this contract involved the determination of the properties of eleven turbine wheels, as covered by this report, together with a study of the relationships between structures of the alloys as controlled by heat treatment and properties at high temperatures. The latter study was carried out using bar stock and was planned to help explain the influence of heat treatment on the turbine wheels.

This report covers the properties of the turbine wheels. Another report is being prepared which covers the results of structural studies on the wheels and bar stock and correlates the two studies

PROPERTIES AT 1000°, 1100°, AND 1200°F FOR TURBINE WHEELS OF FOUR LOW-ALLOY STEELS

SUMMARY

Properties at 1000°, 1100°, and 1200°F are reported for jet-engine turbine wheels made from four low-alloy hardenable steels. The steels were SAE 4340, 1.25 Cr-Mo-Si-V ("17-22A"S), 3 Cr-Mo-W-V (H-40), and 12 Cr-Mo-W-V (C-422). The wheels were contour forged from commercial heats. Wheels of each alloy were heat treated by normalizing, oil quenching, and by an interrupted quench. All were tempered to an aim hardness of 280 to 320 Brinell.

All wheels were surveyed for hardness and tensile properties at room temperature and rupture properties at 1100°F. The wheel of each alloy having the best properties in these tests was used for more extensive surveys of properties. These included tensile and rupture tests at 1000°, 1100°, and 1200°F, and determination of curves of stress - time for total deformation of 0.1, 0.2, 0.5 and 1.0 per cent at 1100°F. Less extensive total deformation data were obtained at 1000° and 1200°F.

The objective of the investigation was to define the range of high temperature properties available in turbine wheels made from commercially available low-alloy creep resistant steels. The low-alloy steels would have the very important advantages of low requirements in strategic and costly alloying elements, together with relatively simple production characteristics. The data reported are sufficient to define quite closely the service conditions under which the alloys could be operated as turbine wheels for jet engines.

There was very little difference in strength between the alloys for the wheels with the best heat treatment at short time periods. The 4340 steel fell off rapidly in strength with time. The "17-22A"S steel had the highest strength at 1000°F, but fell off with time at 1100° and 1200°F. The H-40 and C-422 steels maintained their strength better with time and temperature. Heat treatments which produced intermediate transformation products in the structures of the steels resulted in highest strength, except for C-422 alloy. The latter 12 Cr alloy could not be heat treated to such structures. The treatments producing the best properties were normalizing for 4340 steel, oil quenching for "17-22A"S steel, oil quenching for H-40, and oil quenching for C-422 alloy.

INTRODUCTION

Tensile, rupture and total-deformation data at 1000°, 1100°, and 1200°F are reported for forged and heat treated turbine wheels of four low-alloy "ferritic" steels. The four steels are SAE 4340, 0.3C-1.25Cr-0.5Mo-0.60Si-0.25V ("17-22A"S), 0.3C-3Cr-0.5Mo-0.5W-0.8V (H-40), and 0.2C-13Cr-1Mo-0.8W-0.25V (C-422). The influence of heat treatment was first surveyed by rupture tests at 1100°F on normalized and tempered, oil-quenched and tempered, and interrupted quench and tempered wheels. The wheel of each alloy appearing to have the best properties was used to obtain tensile, rupture, total-deformation and creep data at 1000°, 1100°, and 1200°F.

The investigation was undertaken to supply information which could be used to evaluate low-alloy hardenable steels for service as turbine wheels for jet engines. Suitable properties for the low temperature - high stress service at the center of the wheels can easily be developed with such alloys. Their ability to withstand the high stresses and temperatures at the rims of the wheels is limited by the decrease in creep and rupture strength of the type of alloy with increasing temperature. Therefore, the main value of this report is to indicate the relationships between temperature and stress as a function of service life for typical commercially available low-alloyed steels in the form of commercially produced and heat treated turbine wheels.

Low-alloyed hardenable ferritic steels would have two important advantages for turbine wheel service. They require relatively small amounts of such scarce elements as nickel, chromium and molybdenum. Secondly, their production and fabrication characteristics are far superior to the high-alloy austenitic steels commonly used. Both of these characteristics would be of considerable strategic importance, provided properties were adequate for turbine wheel service or if service life and temperatures were limited to the capabilities of the low-alloy steels.

DESCRIPTION OF TURBINE WHEELS

The turbine wheels were made from commercial heats of steel having the reported compositions in Table I. The wheels were contour forged in dies to the approximate dimensions shown in Figure 1 by an experienced forging company. Figure 1 does not show the stub shaft and boss which were cut off prior to cutting the wheels into test coupons. The forging company also heat treated the wheels as summarized in Table II. The forged and heat treated wheels were furnished to the University by the Materials Laboratory, Wright Air Development Center.

The properties of low-alloy steels are dependent on the types of metal structure developed by heat treatment. These structures are dependent in part on temperatures at which transformation occurs on cooling, a factor controlled by the cooling rate. In addition, structural conditions established by processing prior to hardening probably influence the final structures. Such effects are difficult to predict for large size forgings with varying section size. For this reason, two common cooling rates for hardening were used, oil quenching and air cooling. In addition, an attempt to develop a high strength structure was made by using an interrupted quench selected to cause transformation to occur at intermediate temperatures. The interrupted quench was omitted for C-422 alloy because the available trans formation data indicated that necessary transformation times could not be obtained by the interrupted quench method.

Temperatures of heat treatment used were those established by the manufacturers for the alloys. Tempering conditions after hardening were selected to established a hardness range of 280 to 320 Brinell in the wheels. This hardness range is representative of that usually required to provide adequate strength at the centers of turbine wheels to withstand the high stresses at low temperatures at that point. The hardness values in Table II were those reported by the heat treaters for surface measurements before the wheels were shipped to the University.

There were certain unexpected responses to the original heat treatments which required additional heat treatments, as indicated in Table II and discussed below:

1. The oil quenched and normalized forgings of 4340 steel were initially tempered at too high a temperature to meet the hardness requirements. The second treatments used were usual commercial practice for the steel for the desired hardness. It should be recognized that the tempering temperature of the oil-quenched forging had to be restricted to 1050°F and no tempering could be used for the normalized forging. The retention of hardness of the interrupted quench wheel after tempering at 1200°F was unexpected. Either there are stable intermediate transformation products, or some unknown deviation from reported tempering conditions occurred.

2. The interrupted quench forging of "17-22A"S steel required a second temper to reduce the hardness to the desired range.

3. The initial tempering of the H-40 forgings was inadequate. Additional tempering at 1200°F reduced the surface hardness to the upper limit of the desired range. Subsequently, it was determined that the internal hardness of the forgings was too high for useful properties, and additional tempering at 1250°F was used on coupons cut from the forgings to reduce the hardness to the specified range.

4. The surface hardness indicated that the C-422 forgings apparently responded properly to the initial heat treatments. However, hard spots were found during attempts to cut the forgings into test coupons. The Crucible Steel Company, producers of the steels, reheat treated the wheels to eliminate this difficulty. They used a full anneal at 1600°F before heating for hardening. A double temper of two hours at 1200°F was used to produce the proper hardness.

5. Due to tempering difficulties, it was necessary to accept the wheels from the producer with surface hardnesses higher than 320 Brinell.

RESULTS

Three general types of results are presented: (1) quality tests, (2) survey tests of the influence of type of heat treatment, and (3) extensive properties for the wheel of each alloy with the best heat treatment. Check tests were made to study the variation in properties with location in the wheels. The location of each test specimen can be determined by checking the code numbers with Figure 1.

Quality Tests

The central slice (1-2-3 of Figure 1) from all wheels was magnafluxed and macroetched. All of the forgings, except the normalized and tempered C-422, were free from indications of defects. The slice from the C-422 forging gave two small magnaflux indications and showed inhomogeneity on macroetching near the center. Photographs of the macroetched surfaces are shown in Figures 2a, 3a, 4a, and 5a.

Each center slice was surveyed for hardness variations with the results shown in Figures 2b, 3b, 4b, and 5b. The location of principle ranges in hardness are indicated by coding of the locations of the hardness impressions. The following tabulation summarizes the hardness surveys:

Steel	Treatment	Principle Ranges in Brinell Hardness
4340	Normalized	300-320 near center; 321-345 at rim
4340	Oil Quenched	260-280 at center; 281-300 at flange; 301-320 at rim
4340	Interrupted Quench	280-300 except at rim; 301-320 in center of of rim and 321-340 at rim surface
"17-22A"S	Normalized	235-260 except at rim; rim center 260-290; rim surface 321-330
"17-22A"S	Oil Quenched	280-300 at center, mainly 290-320 except 321-340 at rim
"17-22A"S	Interrupted Quench	301-320 at central portion; 321-345 in flange and rim
H-40	Normalized	Mixed 315 to 380
H-40	Oil Quenched	Mixed 315 to 390
H-40	Interrupted Quench	Mixed 327 to 393
C-422	Normalized	283-290 at center; 290 to 323 in flange and rim
C-422	Oil Quenched	275-290 at center; remainder 290-310 except for one location on flange of 321-352

It will be noted that:

1. The normalized "17-22A"S wheel was softer than specified over a considerable portion of the cross section.

2. A major portion of all the H-40 wheels was harder than 340 Brinell.

3. The centers of the 4340 and "17-22A"S wheels tended to be the softest, while the hardness of the wheels of the other two steels varied over the entire cross section.

4. The surface hardness measurements made by the forging company did not show the high hardness of the H-40 wheels.

In general, the ranges in hardness were about those to be expected in large forgings with the section size variation involved. The more uniform values for C-422 wheels was probably due, at least in part, to the conditioning involved in the prior heat treatments and annealing applied before hardening.

The tensile properties at room temperature of specimens taken from the forgings are included in Tables IIIa, IVa, Va, Vb, and VIa. Emphasis was placed on specimens from the centers of the wheels because poor center properties, particularly low ductility, are a common problem in turbine wheel forgings. It will be noted that:

1. The tensile and yield strengths generally reflect the hardness. Those steels and treatments which resulted in high hardness generally gave the highest strengths and lowest ductility. The specimens from the normalized 4340 steel wheel had unusually low proportional limits, due to the lack of tempering.

2. Specimens taken from the center of wheels in general had adequate ductility, except for H-40 wheels.

3. All of the H-40 wheels had very high tensile and yield strengths in accordance with their high hardness. Those specimens taken from the center of the wheels had very low elongation. Retempering coupons at 1250°F to reduce hardness of the oil-quenched wheel reduced strengths and improved ductility. Test material was not available to determine if the additional tempering improved the low center ductility.

4. The C-422 wheels also tended to have somewhat low center ductility. It is uncertain whether the lower values from the normalized than from the oil-quenched wheel reflects heat treatment or variation of individual specimens.

Survey of Effect of Heat Treatment on Elevated Temperature Properties of Wheel Forgings

Rupture tests at 1100°F were used to evaluate the influence of heat treatment on the turbine wheels and to select the best wheel for extensive testing.

4340 Wheel Forgings

The stress - rupture time curves obtained are shown in Figure 2c, and the test data are included in Table IIIb. Testing was stopped at 100 hours at 1100°F, due to low strength, and the major evaluation carried out at 1000°F. The rupture strengths and interpolated ductilities were as follows:

Treatment	Temp (°F)	10-Hour Strength (psi)	10-Hour Elong. (%)	100-Hour Strength (psi)	100-Hour Elong. (%)	1000-Hour Strength (psi)	1000-Hour Elong. (%)
N. 1750°F	1000	--	--	48,000	3	24,000	3
O.Q. 1550°F + T. 1050°F	1000	58,000	28	38,000	16	15,000	12
Interrupted Quench + T. 1200°F	1000	--	--	48,000	2	22,000	--
N 1750°F	1100	36,000	6	18,000	5	--	--
O.Q 1550°F + T. 1050°F	1100	28,000	20	16,000	40	--	--
Interrupted Quench + T. 1200°F	1100	33,000	3	19,000	5	--	--

There was little difference between the normalized and the interrupted-quench wheels. The oil-quenched wheel was weaker and had higher elongation in the rupture tests.

The normalized wheel was selected for more extensive testing on the basis that its strength and ductility were equal to the interrupted-quench wheel with a much simpler heat treatment. The low elongation of the normalized wheel was admittedly an undesirable characteristic. The oil-quenched wheel was judged, however, to have too low strength to be of interest.

"17-22A"S Wheel Forgings

The stress - rupture time curves at 1100°F for the three heat treatments are shown in Figure 3c, and the test data are included in Table IVb. The rupture strengths and interpolated ductilities were as follows:

Heat Treatment	10-Hour Strength (psi)	10-Hour Elong. (%)	100-Hour Strength (psi)	100-Hour Elong. (%)	1000-Hour Strength (psi)	1000-Hour Elong. (%)
N. 1750°F + T. 1200°F	(64,000)	--	35,000	3	15,000	--
O.Q. 1750°F + T. 1200°F	(68,000)	--	41,000	3	19,000	(2)
Interrupted Quench + T. 1200°F	--	--	41,000	3	22,000	3

The interrupted-quench wheel had slightly higher strength than the oil-quenched. The normalized wheel was the weakest. All three treatments resulted in low elongation in the tests.

The oil-quenched wheel was selected for more extensive testing. The higher strength of the interrupted-quench wheel was not sufficient to offset the problems of the more difficult heat treatment. The normalized wheel was too soft, as well as being too weak in the rupture tests.

H-40 Wheel Forgings

The stress - rupture time curves at 1100°F for the three heat treatments are shown in Figure 4c, and the test data are included in Tables Vc and Vd. The rupture strengths and interpolated ductilities were as follows:

Heat Treatment	10-Hour		100-Hour		1000-Hour	
	Strength (psi)	Elong. (%)	Strength (psi)	Elong. (%)	Strength (psi)	Elong. (%)
Wheels Tempered at 1200°F						
N. 1950°F	(64,000)	(<1)	48,000	(<1)	(36,000)	--
O.Q. 1750°F	(72,000)	(2)	52,000	(1-2)	(37,000)	--
Interrupted Quench	(74,000)	(<1)	50,000	(2)	34,000	--
Coupons Re-Tempered for 4 Hours More at 1250°F						
Normalized	56,000	7	44,000	3	32,000	(2)
Oil Quenched	59,000	17	47,000	7	31,000	--
Interrupted Quench	56,000	7	48,000	4	31,500	--

All of the wheels, as supplied, gave very erratic rupture-test data and low ductility. Reduced diameter specimens with enlarged fillets were required to avoid fracture in the threads and fillets. None of the forgings, as furnished, were judged suitable for further testing.

Because the hardness surveys had shown all the wheels to be excessively hard, tests were made to determine the additional tempering required to reduce the hardness to the proper range. Four hours at 1250°F produced the proper hardness and alleviated the brittleness in the rupture tests. There was very little difference in rupture properties at 1100°F (Figure 4c and Table Vc) between the various initial treatments. Coupons cut from the oil-quenched wheel retempered at 1250°F were selected as having the best combination of properties and heat treatment procedure for more extensive testing.

C-422 Wheel Forgings

The stress - rupture time curves at 1100°F for the two heat treatments are shown in Figure 5c, and the test data are included in Table VIb. The rupture strengths and interpolated elongations were as folows:

Heat Treatment	10-Hour		100-Hour		1000-Hour	
	Strength (psi)	Elong. (%)	Strength (psi)	Elong. (%)	Strength (psi)	Elong. (%)
N. 1900°F + T. 1200°F	48,000	25	39,000	18	32,000	9
O.Q. 1900°F + T. 1200°F	51,000	36	43,000	31	36,000	14

The oil-quenched wheel was selected for further testing on the basis of higher strength and ductility.

Tensile, Rupture, Total - Deformation and Creep Properties of Selected Turbine Wheels at 1000°, 1100°, and 1200°F

Specimens from those wheels selected on the basis of the survey rupture tests, as described in the previous section, were subjected to more extensive testing. The rupture strengths were established out to 1000 hours for 1000° and 1100°F and to 100 hours at 1200°F, except for the 4340 wheel, where the testing time was limited to 100 hours at 1100°F. Curves of stress versus time for total deformations(1) of 0.1, 0.2, 0.5 and 1.0 per cent were established fairly completely for time periods of 1000 hours at 1100°F for the "17-22A"S, H-40 and C-422 wheels. The testing of the 4340 wheel was most extensive at 1000°F. Lower stress creep tests, which were discontinued at about 1000 hours, were used to established some of the lower deformation values.

The total deformation values at 1000° and 1200°F were limited to those available from the time - elongation curves for the rupture tests. Similar data for the survey tests have been included in the tables for all the wheels.

Tensile tests were carried out at 1000°, 1100°, and 1200°F on the selected wheels. The minimum creep rates were measured for all rupture and creep tests. The creep rates were generally sufficiently slow for the lower stress creep tests at 1100°F, so that the creep strength for a creep rate of 0.0001-per cent per hour could be established.

Specimens having a 0.505 inch diameter and a 2 inch gage length taken radially near the rim were used for the majority of the tests. Single specimens taken from three other locations, as indicated below, were used to indicate the variability of properties:

1. A specimen taken tangentially at the rim.

2. A small specimen (0.250 inch diameter by 1 inch gage length) taken radially as near the rim as possible. This test was run because the gage lengths of the larger specimens were further from the rim than the normal depth of blade root fastenings.

3. A small specimen taken at the center of the wheels to indicate center properties.

These variable location specimens were limited to the wheels selected for extensive testing, and to rupture tests at 1100°F for the "17-22A"S, H-40, and C-422 wheels and to 1000°F for the 4340 wheel.

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(1) Total deformation as used in this report includes both the deformation on loading and the creep deformation.

The results of the tests are presented as follows:

4340 Wheels

1. Tensile data - Table IIIa.

2. Rupture data - Table IIIb and Figure 2d.

3. Total-deformation data - Table IIIb and Figures 2e and 2f. The stress - time for total-deformation curves were shown for all three heat treatments.

4. Available stresses for rupture and total deformations of 1.0, 0.5, 0.2 and 0.1 per cent in 1, 10, 100, 500 and 1000 hours are summarized in Table IIIc for all three wheels.

5. Figure 2g summarizes tensile, rupture and total-deformation strengths at 1000°, 1100°, and 1200°F for the normalized wheel.

6. Minimum creep rates - Table IIIb and Figure 2h. No tests were made at sufficiently low stresses to define the 0.0001-per cent per hour creep strength.

"17-22A"S Wheels

1. Tensile data - Table IVa.

2. Rupture data - Table IVb and Figure 3d.

3. Total - deformation data - Table IVb and Figure 3e. Graphical presentation of the total-deformation data was limited to the oil-quenched wheel. Table IVb, however, contains the available data from the rupture tests on the other two wheels.

4. Available stresses for rupture and total deformations of 1.0, 0.5, 0.2 and 0.1 per cent in 1, 10, 100, 500 and 1000 hours for the oil-quenched wheel are summarized in Table IVc.

5. The tensile, rupture and 1.0-per cent total-deformation strengths at 1000°, 1100°, and 1200°F for the oil-quenched wheel are summarized graphically in Figure 3f.

6. Minimum creep rates for all rupture and creep tests are included in Table IVb. The stress - creep rate curves for the oil-quenched wheel are shown as Figure 3g. The indicated stress for a rate of 0.0001-per cent per hour at 1100°F is included in Table IVc.

H-40 Wheels

1. Tensile data - Table Vb.

2. Rupture data - Table Vd and Figure 4d.

3. Total-deformation data - Table Vd and Figure 4e. The data for all tests are included in Tables Vc and Vd, while the stress - time for total-deformation curves of Figure 4e are limited to the retempered

oil-quenched wheel selected for extensive testing.

4. Available stresses for rupture and for total deformation of 1.0, 0.5, 0.2 and 0.1 per cent in 1, 10, 100, 500 and 1000 hours for the oil-quenched and retempered wheel are summarized in Table Ve.

5. Figure 4f summarizes the tensile, rupture and 1.0-per cent total-deformation strengths for the retempered oil quenched wheel.

6. Minimum creep rates for all tests are included in Tables Vc and Vd. The stress - creep rate curves for the retempered oil-quenched wheel are shown in Figure 4g. The stress for a creep rate of 0.0001-per cent per hour at 1100°F indicated by Figure 4g is included in Table Ve.

C-422 Wheels

1. Tensile data - Table VIa.

2. Rupture data - Table VIb and Figure 5d.

3. Total-deformation data - Table VIb and Figure 5e.

4. Available rupture and total-deformation strengths for 1, 10, 100, 500 and 1000 hours for the oil-quenched wheel are summarized in Table VIc.

5. Tensile, rupture and 1.0-per cent total-deformation strengths at 1000°, 1100°, and 1200°F for the oil-quenched wheel are summarized in Figure 5f.

6. Creep data are included in Table VIb. Figure 5g shows the stress - creep rate curves for the retempered oil-quenched wheel and the indicated stress for a creep rate of 0.0001-per cent per hour at 1100°F is included in Table VIc.

As would be expected, there was some scatter in the data for the tests on each wheel. The scatter was due to specimens being taken from fairly large forgings with variable response to heat treatment at different points in the forging, as evidenced by the hardness variations.

Specimens taken radially at the rim, tangential to the rim, and at the center of the wheels in general gave about the same rupture test properties as the radial 0.505 inch diameter specimens used for establishing properties. The points did not deviate from the stress - rupture time curves appreciably more than the specimens used to establish the curves. In only one case, the H-40 wheel, did the elongation of the specimen taken at the center fall appreciably below that of the rim specimens. It will be recalled (Table Va) that this was also true for room temperature tensile tests for this alloy. Tangential specimens had about the same properties as the radial specimens. Thus, the majority of tests indicate that there was no great variation in rupture properties at 1100°F throughout the wheels. More tests would possibly show small consistent differences.

DISCUSSION

Data are presented in this report which define the rupture properties of turbine wheels made from four low-alloy steels at 1000°, 1100°, and 1200°F. This is supplemented by the relationships between stress and time for total deformations of 0.1, 0.2, 0.5 and 1.0 per cent at 1100°F. Less extensive total-deformation data are reported at 1000° and 1200°F. In addition, information is supplied regarding the response of the four alloys in the form of turbine wheels to three types of heat treatment. The data also present the opportunity to compare the properties of the four alloys.

The comparisons of properties can be relied upon with certain reservations. As will be discussed in a forthcoming report, and as was demonstrated in this report, the properties of the alloys vary with heat treatment. Essentially, this means that the properties are dependent on the hardening temperatures and on cooling rates as they control temperatures of transformation. Since cooling rate is a function of the size of the wheel and the particular cooling conditions, the data are limited to the particular heat treatment conditions and should be applied to other sizes and treatment conditions with the fundamentals of heat treatment clearly in mind. Recognitions should be further given to the well known tendency for response to heat treatment to vary between heats of such alloys.

As is well known in the metallurgy of such materials, the necessary restriction of tests to one wheel for each condition is perhaps the most severe limitation. Almost invariably it is necessary to develop forging procedures and heat treatments by experience to obtain optimum properties for a particular alloy. Thus, a small lot of wheels made experimentally is always subject to uncertainty. Such effects were evident in this investigation in that treatments had to be repeated and modified.

These limitations should not be allowed to obscure the value of the data in this report. All experimental applications of alloys are subject to similar limitations. The data do indicate the level of properties obtainable in the form of actual turbine wheels and are sufficient to make a choice of material and to proportion parts with the usual safety factors of engineering design. In actual use of the alloys, the metallurgists would develop suitable practices and checks to insure uniform and as nearly optimum properties as possible for any particular alloy through experience.

Influence of Heat Treatment

The metallurgical principles controlling properties of low-alloy hardenable steels at high temperatures have not been well established in the literature. It has been recognized in work on bar stock that normalizing and tempering of bar stock generally gives higher strength above some limiting temperature, but lower ductility, than liquid quenching and tempering. This essentially means that tempered martensite has inferior strength to intermediate temperature transformation products, but superior hot ductility.

The test temperatures considered in this investigation were all in the range in which the normalized structure in bar stock develops superior properties. It should further be recognized that 12 Cr steel (C-422) is considered to transform to martensite on either liquid quenching or normalizing. A strong possibility also exists for vanadium bearing steels that cooling rate affects a secondary hardening reaction which is also important to properties at high temperatures.

Varying treatments were used for the wheels to establish the influence of the heat treatment conditions in the large size wheels. The interrupted quench was used to develop intermediate transformation products to determine if superior properties would be obtained. The latter type of treatment, in theory, offers considerable promise if structures with better properties could be obtained than those usually resulting from liquid quenching or normalizing.

With this background, the results obtained are considered for the individual alloys.

<u>4340 Turbine Wheels</u>

The oil-quenched wheel had the lowest rupture strength and highest ductility because the structure was largely tempered martensite. Both normalizing and the interrupted quench developed the higher strength intermediate transformation products in the structure.

The hardening characteristics of 4340 steel are marginal for normalizing the size of wheel used in this investigation. The hardenability of 4340 steel varies widely with normal composition variation within the specification. The composition of the heat used for this investigation indicates that it represents the higher hardenability heats of 4340 steel. Apparently, it barely hardened to the specified hardness range on normalizing.

The tempering characteristics of 4340 steel are also marginal for service at 1000° to 1200°F. In general, it is considered desirable to temper considerably above the service temperature to reduce structural instability during service. Such instability generally is reflected in the strength values falling off rapidly with increasing time of testing or service. To maintain the necessary hardness, the tempering temperature of the oil quenched wheel had to be limited to 1050°F and the normalized wheel could not be tempered at all. The omission of a temper for the normalized wheel probably contributed to the rapid decrease in rupture and total-deformation strength with time.

The interrupted quench wheel was reported to have been tempered at 1200°F while maintaining proper hardness. This appeared to be so questionable that, when no great difference in rupture properties was observed at 1000° and 1100°F, it was a contributing factor for selecting the normalized wheel for extensive testing. If subsequent experience substantiates that controlled isothermal types of transformation treatments do result in more stable structures for 4340 steel, its utility for high temperatures may be considerably improved.

The oil quenched and normalized wheels had to be rehardened due to overtempering after the first heat treatment. The double treatments may have resulted in different characteristics than would have resulted from a single treatment.

"17-22A"S Turbine Wheels

In the case of this steel, the normalized wheel did not harden adequately. Furthermore, it appeared as if the oil quenching produced a cooling rate which gave structures with properties very near those characteristic of normalized bar stock of this alloy. The interrupted-quench wheel developed structures and properties similar to the oil-quenched wheel.

This behavior is difficult to understand. Experience with the alloy indicated that it should have hardened satisfactorily by normalizing. Secondly, oil quenching should have developed martensite with inferior strength. There is no evident reason in the available information to explain this behavior. It seems necessary to conclude that:

1. The oil-quenched wheel had the structures and properties ordinarily considered characteristic of intermediate transformation structures and not of tempered martensite. The properties obtained were those normally expected for "normalized" material.

2. Care should be exercised to make certain that some unknown factor did not disturb the normal response to heat treatment before the properties reported are accepted as typical of oil-quenched wheels of the size tested.

Even though the hardening characteristics of "17-22A"S appear to be marginal in the size considered, it could be tempered at 1200°F. This is a characteristic of vanadium bearing steels and probably is related to their secondary hardening characteristics.

H-40 Turbine Wheels

Apparently all three heat treatments gave about the same initial structures and properties. The microstructures were mixed martensite, bainites and acicular ferrite. In a subsequent report, it will be shown that bar stock does respond differently to oil quenching and normalizing. It appears, therefore, the size effect restricted cooling rates during oil quenching to the point where some high temperature transformation occurred. On the other hand, normalizing and interrupting the quench apparently caused only about the same amount of transformation, in spite of longer times for transformation.

The response of the wheels to heat treatment probably reflects the restricted temperature range and sluggishness of transformation of this higher alloyed steel. These features greatly limit variation in response to heat treatment. It will be noted that it was doubtful if there was a real difference between the three wheels--certainly the choice of the oil-quenched wheel for extensive testing was based on small differences insofar as properties are concerned.

A good deal of difficulty was encountered in tempering the H-40 wheels. Limited available information at the time indicated that 1200°F should have reduced the hardness to the desired range.

C-422 Turbine Wheels

In theory, the hardening power of this 12 Cr steel ought to be sufficient to remove differences between oil quenching and normalizing. In actual practice, the quenching treatment gave better properties. In spite of transformation to martensite in both cases some additional metallurgical variable involved in cooling rate influenced properties. This is also characteristic of bar stock. The properties obtained were practically identical with those established for the alloy by the manufacturer on bar stock.

The exact cause of the hard spots observed after the initial heat treatment was not established. The manufacturer used an equalizing heat treatment prior to hardening. Apparently this alloy can show variable response to heat treatment as a result of variations in prior hot working conditions, unless such variations are eliminated by intermediate heat treatments.

Comparative Properties of Turbine Wheels of the Four Alloys

The stress - rupture time and stress - time for 1.0-per cent total deformation curves for the wheels selected for extensive testing are compared in Figures 6 and 7. It will be noted that:

1. All four alloy wheels had similar rupture strengths up to about 20 hours at 1000°F and to one hour at 1100°F. The strength of the 4340 steel wheel fell below the other alloys for longer time periods at these temperatures and for all time periods considered at 1200°F.

2. The "17-22A"S wheel maintained rupture strengths higher than or equal to the other alloys for time periods out to 1000 hours at 1000°F, to 100 hours at 1100°F, and to 10 hours at 1200°F.

3. There was little difference in rupture strength between the H-40 and C-422 wheels at 1000° and 1100°F. The H-40 wheel, however, gave substantially higher strengths at 1200°F.

4. The elongation in the rupture tests of all alloys except C-422 dropped to values in the range of 2 to 5 per cent with increasing time for rupture. There were two exceptions to this:

(a) The elongation of the H-40 samples stayed up to values between 6 and 10 per cent at 1000°F.

(b) The 4340 samples had high elongation at 1200°F.

5. The relative strengths for a total deformation of 1.0-per cent compared similarly to the rupture strengths. The C-422 steel in general had slightly lower total deformation strengths in comparison to the other steels than indicated by the stress - rupture strengths. This was due to relatively fast creep rates during first-stage creep for the C-422 material. Consequently, 1.0-per cent total deformation was obtained in a rather small fraction of the time to rupture for the C-422 alloy, whereas the other materials were usually in third-stage creep, at least for the longer time tests, before 1.0-per cent deformation was obtained.

The semilog stress - time for total deformation curves of Figure 7 suggest greater differences between steels than the log stress - time for rupture curves of Figure 6. This, however, is mainly due to the condensing of the stress axis by the logarithmic scale for the rupture tests.

The comparative total-deformation strengths for 0.5-per cent were similar to those for 1.0-per cent. However, at 0.2-per cent and 0.1-per cent, the differences tended to disappear for all except the 4340 steel, which was still weak in comparison to the other steels. This is due to the deformation on loading largely controlling these low total deformations. The 4340 remained low due to lower yield strengths, as well as low creep strength.

6. The creep strengths for 0.0001-per cent per hour given in Table IVc, Ve and VIc show a considerably higher strength for the C-422 wheel. Reference to the creep curves will, however, show that this difference only appears for the creep rates lower than 0.001-per cent per hour. Therefore, the creep resistance follows the pattern of other strengths in that the differences between the steels tended to disappear at high stresses. The 4340 steel became weaker than the others at relatively short time periods, probably mainly due to low creep resistance. "17-22A"S fell off with time before H-40 steel, and C-422 maintained strength for long time periods, except at 1200°F, where H-40 seemed to maintain strength better.

The relative strengths of the alloys suggests that:

1. At short time periods the strengths are mainly dependent on the hardness. Thus, there was little difference between the four alloys, and such differences as did exist were probably mainly due to hardness variations.

2. The loss in strength with increasing time for 4340 steel in comparison to the other steels was probably due both to lower inherent creep resistance and to an unstable structure which tempered during testing. The same factors probably apply to the "17-22A"S steel, but to a lesser degree.

3. Apparently the main difference between H-40 and C-422 steels was inherent creep resistance. It may well be, however, that the maintainance of strength of the H-40 steel at 1200°F also reflects a greater resistance to loss of strength by tempering.

4. There does not appear to be a complete explanation of the loss in elongation with time for rupture for the three lower alloy steels. High ductility in the rupture test is characteristic of 12 Cr steels and was therefore to be expected for the C-422 steel.

5. Oxidation was extensive for 4340 steel in the longer tests at 1200°F. The same was true for "17-22A"S and H-40 steels to a lesser degree. This means that their use at temperatures above 1100°F would be limited to rather short time periods. Oxidation was also sufficiently advanced at 1100°F for these same three steels in the longer tests so that

their use for periods prolonged beyond the time periods used in these tests might require protection from oxidation.

So far as could be determined, the comparative strengths of the alloys were reasonably typical. The superiority of H-40 to C-422 at 1200°F is a possible exception to this. Some adjustments in actual levels of properties could be obtained by improvement of heat treating conditions to develop more favorable structures. This would probably show up mainly in the prolonging of the time at which properties tend to fall off with time and in reducing the rate at which properties decrease with time. It would also shift the relative strengths at the shorter time periods to a slight extent.

For these reasons, the rupture and total deformation data should be considered as mainly showing how the strength tends to fall off more rapidly for the lower alloyed materials. The differences in elongation and reduction of area in the rupture tests mainly show the superiority of the 12 Cr type steels. Minor improvements in this characteristic probably could be achieved for the lower alloyed steels. This, however, apparently will be small so long as the higher strengths characteristic of intermediate transformation products is developed by restriction of the cooling rate. The greater ductility possible by quenching to martensite and tempering would necessarily be accompanied by a considerable sacrifice in strength.

CONCLUSIONS

Commercially produced contour forged turbine wheels for a jet engine made from for low-alloy hardenable steels were examined for properties at both room temperature and 1000°, 1100° and 1200°F. The more important results were as follows:

1. With one possible exception, all of the forged wheels were sound and free from defects.

2. The wheels were to be produced to a hardness range of 280 to 320 Brinell. Some difficulty in obtaining this hardness range was encountered. This unquestionably could be corrected through experience in producing and heat treating the alloys in the section sizes considered.

3. Some evidence of low center ductility was encountered. Because this is probably mainly a function of manufacturing techniques, considerable improvement could be expected with production experience.

4. Normalized, oil-quenched and an interrupted quench wheels were compared by rupture tests at 1100°F. Except for the 12 Cr (C-422) alloy, the treatments which produced mixed transformation products had the highest strength at the elevated temperatures. The oil-quenched 12 Cr wheel had better strength than the normalized wheel, although both had tempered martensitic structures. The interrupted quench produced properties in the three other steels as good as, but no better than, normalizing or oil quenching. The better of the latter two treatments appeared

to be a function of both composition and unidentified heat treatment conditions.

5. The wheel of each alloy having the best rupture test properties at 1100°F was also subjected to rupture tests at 1000°F and 1200°F. Curves of stress versus time for total deformations of 0.1, 0.2, 0.5 and 1.0 per cent were developed at 1100°F. Less extensive total deformation data were established at 1000° and 1200°F.

6. The wheels all had similar strengths at short time periods, except that lower strength was obtained from the 4340 wheel at 1200°F for all time periods considered. The 4340 steel gave the lowest strengths for the longer time periods at 1000°, 1100°, and 1200°F. The strength-time curves for the 1.25Cr-Mo-Si-V ("17-22A"S) steel increased in slope at 1100° and 1200°F, so that it had lower strengths at these temperatures for the longer time periods. The 3Cr-Mo-W-V (H-40) steel was strongest at 1200°F. Only the 12 Cr (C-422) steel gave high elongation in the rupture tests at all three temperatures.

7. The 4340 and the "17-22A"S steels had marginal hardenability for normalizing wheels of the size tested to a minimum Brinell of 280. The 4340 steel also has marginal tempering characteristics for service at 1000° to 1200°F. All of the other steels, however, could be tempered at 1200°F or higher.

TABLE I

Chemical Composition of Forged Turbine Wheels

Type Steel	C (%)	Mn (%)	Si (%)	P (%)	S (%)	Cr (%)	Ni (%)	Mo (%)	V (%)	W (%)	Cu (%)	Manufacturer's Heat Number
4340	0.40	0.76	0.29	0.010	0.015	0.74	1.91	0.50	--	--	--	656601
"17-22A"S	0.30	0.57	0.60	0.018	0.019	1.22	0.23	0.49	0.24	--	0.13	38516
H-40	0.29	0.48	0.26	0.012	0.018	3.05	0.49	0.49	0.85	0.55	0.15	K-2509
C-422	0.23	0.81	0.16	0.011	0.012	13.19	0.65	1.03	0.25	0.84	--	W-3561

TABLE II

Heat Treatments of Forged Turbine Wheels

4340 Steel

All forgings were isothermally annealed for 15 hours at 1200°F directly from the forging operation.

	Surface Brinell Hardness Rim	Surface Brinell Hardness Hub
Disk No. 1 - Normalized Forging		
1st Treatment: Air cooled from 1750°F and tempered 2 hours at 1200°F	217	229
2nd Treatment: Renormalized from 1750°F (no tempering)	285	285
Disk No. 3 - Oil Quenched Forging		
1st Treatment: Oil quenched from 1750°F and tempered 8 hours at 1200°F	269	255
2nd Treatment: Oil quenched from 1550°F and tempered at 1050°F	302	285
Disk No. 4 - Interrupted Quench Forging		
Water quenched from 1750°F until black, then withdrawn until glow returned. This was repeated until glow did not return upon withdrawal from water. It was then transferred to a furnace at 700°F and held for 8 hours. It was then tempered for 2 hours at 1200°F.	302	293

"17-22A"S Steel

All forgings were isothermally annealed for 8 hours at 1200°F directly from the forging operation.

	Surface Brinell Hardness Rim	Surface Brinell Hardness Hub
Disk No. 1 - Normalized Forging		
(a) Air cooled from 1750°F and tempered 2 hours at 1200°F	302	285
Disk No. 3 - Oil Quenched Forging		
(a) Oil quenched from 1750°F and tempered 8 hours at 1200°F	302	302

TABLE II, Continued.

"17-22A"S Steel

	Surface Brinell Hardness Rim	Hub
Disk No. 4 - Interrupted Quench Forging		
(a) Quenched in water until black, withdrawn until glow returned, requenched until black, and process repeated until glow did not return. The forging was then placed directly in a furnace at 700°F for 8 hours, then tempered at 1200°F for 2 hours	399	399
(b) Retempered for 2 more hours at 1200°F	341	331

H-40 Steel

All forgings were isothermally annealed for 8 hours at 1200°F directly from forging.

	Surface Brinell Hardness Rim	Hub
Disk No. 1 - Normalized Forging		
(a) Air cooled from 1950°F and tempered 2 hours at 1200°F	429	444
(b) Retempered 3 more hours at 1200°F	341	341
Disk No. 3 - Oil Quenched Forging		
(a) Oil quenched from 1950°F and tempered 8 hours at 1200°F	415	415
(b) Tempered 3 more hours at 1200°F	341	352
Disk No 4 - Interrupted Quench Forging		
(a) Interrupted quench from 1950°F in water as previously described for other steels; then tempered at 1200°F for 2 hours	389	363
(b) Retempered for 3 more hours at 1200°F	341	331
Final Treatments for All Forgings		
Subsequently, bars cut from all three forgings were retempered for 4 more hours at 1250°F	287 to 322	

TABLE II, Concluded.

C-422 Steel

All forgings were isothermally annealed for 8 hours at 1200°F directly from forging.

	Surface Brinell Hardness Rim	Surface Brinell Hardness Hub
Disk No. 1 - Normalized Forging		
1st Treatment: Air cooled from 1900°F and tempered for 2 hours at 1200°F	321	331
2nd Treatment: Full annealed for 6 hours at 1600°F and furnace cooled; then air cooled from 1900°F and double tempered 2 + 2 hours at 1200°F	285	293
Disk No. 4 - Oil Quenched Forging		
1st Treatment: Oil quenched from 1900°F and tempered 8 hours at 1200°F	285	285
2nd Treatment: Full annealed at 1600°F for 6 hours and furnace cooled; then oil quenched from 1900°F and double tempered 2 + 2 hours at 1200°F	302	311

Note: Second treatments required due to hard spots after first treatment.

TABLE IIIa

Tensile Properties of 4340 Turbine Wheels

Specimen Number	Specimen Location (1)	Brinell Hardness	Test Temp. (°F)	Tensile Strength (psi)	Offset Yield Strengths (psi) 0.02%	Offset Yield Strengths (psi) 0.1%	Offset Yield Strengths (psi) 0.2%	Proportional Limit (psi)	Elongation in 2-in. (%)	Reduction of Area (%)
	Wheel No. 1.	Heat Treatment: First Treatment - N. 1750°F + T. 2 hrs. at 1200°F. Second Treatment - N. 1750°F.								
1W	SRR	328	75	163,500	69,500	97,000	112,000	46,000	15.0	45.5
1X	CRR	331	75	163,500	72,000	102,500	119,000	43,000	12.5	40.3
2W	SRC	316	75	156,500	62,000	92,000	106,500	37,000	6.5	9.3
2X	CRC	316	75	155,000	58,500	87,000	101,500	40,000	10.5	25.5
2Y	CRC	308	75	155,250	70,500	96,500	110,000	46,000	12.0	32.8
2Z	SRC	304	75	151,000	65,250	92,500	105,500	44,000	11.5	30.2
1Y	CRR	325	1000	99,000	56,500	77,250	86,500	46,000	16.0	48.7
3W	SRR	334	1000	98,750	65,500	80,250	87,500	48,000	21.0	58.5
14Z	STR	-	1000	100,000	57,250	77,500	85,750	37,500	16.0	44.8
3X	CRR	331	1100	71,500	46,750	57,000	64,000	25,000	14.0	35.0
1Z	SRR	313	1100	64,250	34,000	51,000	57,750	18,500	24.5	56.8
14Y	CTR	-	1100	72,500	31,000	47,250	58,000	19,500	14.0	26.7
3Z	SRR	320	1200	38,000	11,750	23,750	29,000	10,000	25.0	41.3
3Y	CRR	328	1200	38,500	15,500	24,500	31,000	9,000	30.5	37.0
14X	CTR	-	1200	34,500	15,500	22,750	27,500	8,500	30.5	28.8

(concluded on following page)

Table IIIa (concluded)

Specimen Number	Specimen Location (1)	Brinell Hardness	Test Temp. (°F)	Tensile Strength (psi)	Offset Yield Strengths (psi)			Proportional Limit (psi)	Elongation in 2-in. (%)	Reduction of Area (%)
					0.02%	0.1%	0.2%			
Wheel No. 3. Heat Treatment: First Treatment: O.Q. 1750°F + T. 8 hrs. at 1200°F. Second Treatment: O.Q. 1550°F + T. at 1050°F.										
1W	SRR	-	75	136,500	112,500	115,750	116,000	73,000	18.5	62.2
1X	CRR	-	75	129,000	107,000	109,250	110,750	78,000	17.0	58.3
2W	SRC	-	75	125,500	96,750	98,750	99,250	79,000	15.5	39.2
2X	CRC	-	75	123,750	91,750	94,750	95,250	82,000	17.0	44.6
2Y	CRC	-	75	122,750	89,750	94,000	94,500	74,500	18.0	48.6
2Z	SRC	-	75	123,750	92,500	95,750	96,250	74,500	18.5	47.7
Wheel No. 4. Heat Treatment: Int.-quench from 1750°F + T. 2 hrs. at 1200°F.										
1W	SRR	288	75	141,250	90,500	104,750	109,250	64,500	17.0	49.5
1X	CRR	289	75	140,250	87,000	101,250	106,250	63,000	17.0	48.8
2W	SRC	290	75	137,750	79,000	97,500	103,750	47,000	11.0	23.4
2X	CRC	292	75	137,750	86,250	99,500	105,250	65,000	12.0	29.8
2Y	CRC	286	75	137,750	91,250	102,250	106,500	68,000	14.0	26.1
2Z	SRC	287	75	136,250	85,750	98,500	103,250	60,500	12.0	31.7

(1) SRR - Surface plane radial specimen at rim of wheel
CRR - Central plane radial specimen at rim of wheel
SRC - Surface plane radial specimen at center of wheel
CRC - Central plane radial specimen at center of wheel
STR - Surface plane tangential specimen at rim of wheel
CTR - Central plane tangential specimen at rim of wheel

TABLE IIIb

Rupture, Total Deformation, and Creep Data for 4340 Turbine Wheels

Specimen Number	Specimen Location (a)	Test Temp. (°F)	Stress (psi)	Time to Fracture (hours)	Elongation in 2-in. (%)	Reduction of Area (%)	Time to Reach Specified Total Deformations (hours) 0.1%	0.2%	0.5%	1.0%	Time at Start of Third Stage Creep (hours)	Minimum Creep Rate (%/hr.)	Deformation on Loading (In./In.)
Disk No. 1 Heat Treatment: (a) N. 1750°F + T. 2 hrs. at 1200°F. (b) N. 1750°F.													
10W	SRR	1000	65,000	35	3.5	5.9	(c)	(c)	1.4	13	20	--	0.00310
4Y	CRR	1000	50,000	88(e)	2.2	1.2	(c)	(c)	22	68	63	0.0055	0.00200
6W	SRR	1000	45,000	163	2.8	1.8	(c)	1	35	118	95	0.005	0.00180
4Z	SRR	1000	39,000	146	2.7	1.7	(c)	0.8	40	122	98	0.0045	0.00160
6Y	CRR	1000	34,000	292	2.3	4.0	(c)	11	108	250	185	0.0025	0.00140
9Z	SRR	1000	34,000	277	2.2	2.8	(c)	4	88	213	170	0.0033	0.00140
7A(b)	SRR	1000	34,000	165(d)	--	--	(c)	(c)	--	--	--	0.0045	--
5A(b)	SRC	1000	34,000	200	4.2	4.0	(c)	3	68	180	170	0.0037	0.00163
6Z	SRR	1000	24,000	957	3.3	1.3	(c)	21	339	683	390	0.00086	0.00097
14W	STR	1000	24,000	635	3.5	2.4	1	30	220	470	320	0.0015	0.00094
9X	CRR	1100	44,000	3.9	6.8	12.0	(c)	(c)	0.1	0.8	--	--	0.00275
6X	CRR	1100	25,000	37(f)	5.5	7.8	(c)	0.4	2.8	12	5	0.0365	0.00129
4W	SRR	1100	20 000	67	6.2	7.0	0.2	1.6	9.2	22	17	0.035	0.00090
4X	CRR	1100	17,000	130	5.3	3.9	(c)	1.6	14	41	64	0.0186	0.00095
9Y	CRR	1200	20,000	2.5	15.0	19.1	(c)	(c)	(c)	0.25	--	2.3	0.00290
10Y	CRR	1200	14,000	12(f)	20.0	14.9	(c)	0.2	1.3	3.3	4	0.26	0.00150
10X	CRR	1200	8 000	139	27.5	25.5	(c)	0.6	5.5	14	--	0.061	0.00066
10Z	SRR	1200	7.000	157(g)	30.0	--	--	--	--	--	--	--	--
Disk No. 3. Heat Treatment: (a) O.Q. 1750°F + T. 8 hrs. at 1200°F. (b) O.Q. 1550°F + T. at 1050°F.													
4Z	SRR	1000	50,000	23	28.0	48.7	(c)	(c)	0.5	2	--	--	0.00215
6W	SRR	1000	40,^00	77	16.5	30.8	(c)	(c)	2.5	8.5	--	--	0.00265
6X	CRR	1000	32,500	247	11.5	14.5	(c)	1.5	11	40	68	0.019	0.00130
6Y	CRR	1000	27,500	372	11.5	17.8	(c)	2	18	68	110	0.0095	0.00120
6Z	SRR	1000	20,000	604	14.0	26.8	1	6	42	124	120	0.0055	0.00079
4W	SRR	1100	25,000	17	20.5	39.1	(c)	(c)	0.2	2(h)	--	--	0.00190
4X	CRR	1100	20,000	31	23.0	34.4	(c)	0.2	0.8	2.6(h)	--	--	0.00134
4Y	CRR	1100	13,000	212	57.0	41.0	0.2	1.2	8.5	20	73	0.017	0.00085
Disk No. 4. Heat Treatment: Int. -quench 1750°F + T. 2 hrs. at 1200°F.													
4Z	SRR	1000	50,000	88	2.2	3.5	(c)	0.4	28	81	63	0.0076	0.00190
6W	SRR	1000	40,000	185	3.1	3.5	(c)	1	55	140	120	0.005	0.00160
6X	CRR	1000	34,000	278	1.8	2.2	(c)	7	123	256	150	0.0024	0.00135
6Y	CRR	1000	28,000	377	1.8	2.4	(c)	18	181	355	210	0.0018	0.00118
6Z	SRR	1000	19 000	Off 1150(j)	--	--	2	82	560	1228(h)	960	0.00063	0.00090
4X	CRR	1100	30,000	17	3.5	5.9	(c)	0.2	2	4	--	--	0.00173
4W	SRR	1100	25,000	29	4.7	8.1	(c)	0.5	3.6	11.2	19	0.066	0.00137
4Y	CRR	1100	16,000	199	5.6	7.0	0.6	9	39	84	90	0.011	0.00073

(a) SRR - Surface plane radial specimen at rim of disk
CRR - Central plane radial specimen at rim of disk
SRC - Surface plane radial specimen at center of disk
STR - Surface plane tangential specimen at rim of disk

(b) 0.250-inch diameter specimens
(c) Specimen reached this deformation on loading
(d) Broke in threads
(e) Broke in fillet
(f) Broke in gage mark
(g) Very badly scaled
(h) Extrapolated value
(i) Creep test
(j) Test discontinued at this time

TABLE IIIc

Rupture and Time - Deformation Strengths of 4340 Turbine Wheels

Total Deformation (%)	Stress to Cause Total Deformations at Indicated Times (psi) 1 hour	10 hours	100 hours	500 hours	1000 hours
Wheel No. 1.	Heat Treatment:	First Treatment - N. 1750°F + T. 2 hours at 1200°F Second Treatment - N. 1750°F			
		1000°F			
0.2	42,000	31,000	--	--	--
0.5	67,000	54,000	34,000	19,000	--
1.0	--	69,000	43,000	25,000	17,000
Rupture	--	--	48,000(3%)	29,000 (3%)	24,000 (3%)
		1100°F			
0.2	20,000	--	--	--	--
0.5	31,000	19,000	--	--	--
1.0	42,000	27,000	11,000	--	--
Rupture	--	36,000 (6%)	18,000(5%)	--	--
		1200°F			
0.5	~15,000	6,000	--	--	--
1.0	17,000	9,000	--	--	--
Rupture	25,000(15%)	14,000(22%)	7,800(27%)	--	--
Wheel No. 3.	Heat Treatment:	First Treatment - O.Q. 1750°F + T. 8 hours at 1200°F Second Treatment - O.Q. 1550°F + T. at 1050°F			
		1000°F			
0.2	34,000	16,000	--	--	--
0.5	46,000	32,000	~12,000	--	--
1.0	54,000	40,000	23,000	--	--
Rupture	--	58,000(28%)	38,000 (16%)	22,500(12%)	15,000 (12%)
		1100°F			
0.2	15,000	--	--	--	--
0.5	20,000	12,000	--	--	--
1.0	26,000	16,000	--	--	--
Rupture	--	28,000 (20%)	16,000(40%)	--	--
Wheel No. 4.	Heat Treatment:	Interrupted-quench from 1750°F + T. 2 hours at 1200°F			
		1000°F			
0.2	44,000	31,000	19,000	--	--
0.5	--	--	35,000	18,000	--
1.0	--	--	46,000	25,000	17,000
Rupture	--	--	48,000 (2%)	28,000 (2%)	22,000 (-)
		1100°F			
0.2	24,000	16,000	--	--	--
0.5	--	22,000	--	--	--
1.0	--	26,000	15,000	--	--
Rupture	--	33,000 (3%)	19,000 (5%)	--	--

NOTE: Estimated elongation at fracture given in parentheses with rupture strengths.

TABLE IVa

Tensile Properties of "17-22A"S Turbine Wheels

Specimen Number	Specimen Location (1)	Brinell Hardness	Test Temp. (°F)	Tensile Strength (psi)	Offset Yield Strengths (psi) 0.02%	0.1%	0.2%	Proportional Limit (psi)	Elongation in 2-in. (%)	Reduction of Area (%)
Wheel No. 1. Heat Treatment: N. 1750°F + T. 2 hrs. at 1200°F.										
1W	SRR	314	75	142,750	98,500	109,500	114,500	76,500	15.0	50.3
1X	CRR	282	75	137,000	98,000	107,000	111,500	89,000	14.5	47.1
2W	SRC	242	75	117,000	72,000	79,500	81,000	47,000	9.0	13.4
2X	CRC	238	75	116,000	73,500	78,500	80,000	66,000	15.5	38.5
2Y	CRC	238	75	117,000	73,500	77,000	79,000	62,500	20.5	48.9
2Z	SRC	241	75	119,000	74,000	79,500	81,500	61,500	19.0	48.0
Wheel No. 3. Heat Treatment: O.Q. 1750°F + T. 8 hrs. at 1200°F.										
1W	SRR	326	75	151,000	123,000	132,000	134,000	93,000	18.0	56.4
1X	CRR	313	75	145,000	123,500	130,500	133,000	94,000	16.5	50.9
2W	SRC	313	75	145,000	122,000	126,500	128,500	109,500	11.0	23.8
2X	CRC	311	75	145,000	120,500	126,000	128,000	103,000	12.0	29.2
2Y	CRC	295	75	145,000	119,000	125,500	128,000	99,500	17.5	46.6
2Z	SRC	294	75	146,000	121,000	126,500	129,000	106,000	15.0	40.7
14X	CTR	-	1000	97,500	65,000	83,000	90,000	38,000	21.5	71.0
3W	SRR	-	1000	96,250	64,500	83,250	89,000	45,500	23.0	73.0
3X	CRR	-	1000	96,500	72,500	84,750	90,000	50,000	26.0	72.5
14Y	STR	-	1100	83,500	49,500	68,250	76,000	24,500	27.0	72.5
1Z	SRR	-	1100	90,500	48,500	65,250	72,000	29,000	29.5	71.6
1Y	CRR	-	1100	83,250	46,000	67,000	74,250	25,000	23.5	73.5

(concluded on following page)

Table IVa (concluded)

Specimen Number	Specimen Location (1)	Brinell Hardness	Test Temp. (°F)	Tensile Strength (psi)	Offset Yield Strengths (psi) 0.02%	0.1%	0.2%	Proportional Limit (psi)	Elongation in 2 in. (%)	Reduction of Area (%)
(continued) Wheel No. 3. Heat Treatment: O.Q. 1750°F + T. 8 hrs. at 1200°F.										
3Y	CRR	-	1200	62,500	32,000	46,750	54,000	16,000	24.0	44.8
3Z	SRR	-	1200	63,000	28,500	44,500	51,000	12,500	22.5	48.3
14W	STR	-	1200	62,500	33,500	44,000	54,000	19,000	22.0	41.6
Wheel No. 4. Heat Treatment: Interrupted-quench 1750°F + T. 2 hrs. at 1200°F + T. 2 hrs. at 1200°F.										
1W	SRR	332	75	158,500	137,500	142,500	143,500	126,000	16.0	51.1
1X	CRR	321	75	155,500	125,500	135,500	138,000	93,000	16.5	49.8
2W	SRC	320	75	148,500	121,000	131,000	134,000	98,000	5.0	6.4
2X	CRC	317	75	149,000	124,000	130,500	133,000	104,000	8.0	9.3
2Y	CRC	318	75	149,000	119,500	128,000	131,500	101,000	15.0	41.0
2Z	SRC	312	75	149,500	124,000	131,000	133,000	108,000	15.5	41.9

(1) SRR - Surface plane radial specimen at rim of wheel
CRR - Central plane radial specimen at rim of wheel
CTR - Central plane tangential specimen at rim of wheel
STR - Surface plane tangential specimen at rim of wheel
SRC - Surface plane radial specimen at center of wheel
CRC - Central plane radial specimen at center of wheel

TABLE IVb

Rupture, Total Deformation, and Creep Data for "17-22A"S Turbine Wheels

Specimen Number	Specimen Location (a)	Test Temp. (°F)	Stress (psi)	Time to Fracture (hrs.)	Elongation in 2-in. (%)	Reduction of Area (%)	Time to Reach Specified Total Deformations (hrs.) 0.1%	0.2%	0.5%	1.0%	Time at Start of Third Stage Creep (hrs.)	Minimum Creep Rate (%/ hr.)	Deformation on Loading (In./In.)
	Disk No. 1.	Heat Treatment: N. 1750°F + T. 2 hrs. at 1200°F											
4W	SRR	1100	50,000	26	12.3	7.0	(b)	(b)	0.6	6	5.5	0.095	0.0029
4X	CRR	1100	45,000	36	5.7	3.9	(b)	(b)	3.5	13	14	0.046	0.0023
4Y	CRR	1100	40,000	60	5.6	7.0	(b)	(b)	8	24	--	0.025	0.0021
4Z	SRR	1100	30,000	175	1.7	0.8	(b)	3	62	134	46	0.0035	0.00135
6W	SRR	1100	20,000	519	2.6	2.8	(b)	35	216	406	238	0.0016	0.00113
	Disk No. 3.	Heat Treatment: O.Q. 1750°F + T. 8 hrs. at 1200°F.											
7Z	SRR	1000	90,000	1.8	15.0	67.0	(b)	(b)	(b)	0.2	-	-	0.00470
9Z	SRR	1000	80,000	66	13.1	51.0	(b)	(b)	1	14.5	32	0.030	0.00340
7W	SRR	1000	70,000	171(c)	5.6	15.4	(b)	(b)	6	60	75	0.009	0.00297
7Y	CRR	1000	60,000	487	2.5	4.5	(b)	(b)	92	350	270	0.0016	0.00260
9X	CRR	1100	80,000	0.2	16.0	70.3	(b)	(b)	(b)	-	-	-	--
4Z	SRR	1100	47,500	51	2.6	5.1	(b)	(b)	6	29	20	0.0172	0.00220
4X	CRR	1100	42,500	94	3.5	8.2	(b)	(b)	10	47	48	0.0135	0.00200
4W	SRR	1100	38,500	86(c)	3.0	3.5	(b)	1	19	45	64	0.018	0.00190
4Y	CRR	1100	32,500	219	3.0	1.6	(b)	2	49	156	116	0.0043	0.00147
9W	SRR	1100	32,500	165	3.2	3.1	(b)	2	44	97	74	0.0065	0.00138
7A(d)	SRR	1100	32,500	171	3.0	3.2	(b)	(b)	29	98	94	0.0068	0.00148
5A(d)	SRC	1100	32,500	244	3.2	4.7	(b)	(b)	--	--	--	0.0057	--
6W	SRR	1100	25,000	489	2.6	3.2	(b)	21	199	402	280	0.0015	0.00108
6X	CRR	1100	20,500	792	1.7	2.8	3	57	441	774	575	0.0008	0.00082
14Z	STR	1100	19,500	1112	3.6	2.8	1.5	48	374	728	380	0.0009	0.00095
6Y(e)	CRR	1100	15,500	Off 1120	-	-	5	109	896	2460(f)	-	0.00032	0.00065
6Z(e)	SRR	1100	12,500	Off 1120	-	-	26	227	1210(f)	-	-	0.00032	0.00060
9Y(e)	CRR	1100	7,000	Off 1085	-	-	630	1805(f)	-	-	-	0.00009	0.00031
10W	SRR	1200	35,500	5.2	7.0	8.5	(b)	(b)	0.4	1.9	2	0.33	0.0026
10Y	CRR	1200	32,000	6.2	5.5	4.8	(b)	(b)	1	3	3	0.24	0.0022
10X	CRR	1200	22,000	33	3.0	6.2	(b)	2	7	16	12	0.054	0.0015
10Z	SRR	1200	16,000	73	1.4	4.3	(b)	3	19	38	19	0.016	0.0011
	Disk No. 4.	Heat Treatment: Interrupted-quench 1750°F + T. 2 hrs. at 1200°F + T. 2 hrs. at 1200°F.											
4X	CRR	1100	45,000	69	2.3	4.0	(b)	(b)	7	36	44	0.018	0.0021
4W	SRR	1100	37,500	151	4.0	1.6	(b)	1	20	79	91	0.0086	0.00176
4Y	CRR	1100	32,500	287(c)	3.0	2.0	(b)	2	77	186	77	0.0033	0.00150
4Z	SRR	1100	26,000	479	3.9	1.6	(b)	9	156	337	167	0.0018	0.00117
6W	SRR	1100	20,500	1233	3.0	3.6	2	55	490	964	677	0.00071	0.00085

(a) SRR - Surface plane radial specimen at rim of disk
CRR - Central plane radial specimen at rim of disk
SRC - Surface plane radial specimen at center of disk
STR - Surface plane tangential specimen at rim of disk
(b) Specimen reached this deformation on loading
(c) Broke in gage mark
(d) 0.250-inch diameter specimen
(e) Creep test
(f) Extrapolated value.

TABLE IVc

Rupture, Time - Deformation, and Creep Strengths of the "17-22A"S Turbine Wheel

(Heat Treatment: O.Q. 1750°F + T. 8 hours at 1200°F)

Total Deformation (%)	Stress to Cause Total Deformations at Indicated Times (psi)					0.0001% per Hour Creep Strength (psi)
	1 hour	10 hours	100 hours	500 hours	1000 hours	
			1000°F			
0.5	80,000	69,000	59,000	--	--	
1.0	86,000	81,000	67,000	56,000	51,000	
Rupture	90,000(15%)	84,000(14%)	75,000(10%)	60,000(2.5%)	54,000(-)	—
			1100°F			
0.1	21,000	15,000	10,000	7,000	5,000	7,500
0.2	37,000	27,000	18,000	10,000	8,000	
0.5	--	43,000	29,000	19,000	14,000	
1.0	--	~50,000	36,000	22,000	17,000	
Rupture	67,000(10%)	53,000(6%)	41,000(3%)	24,500(2.5%)	19,000(2%)	
			1200°F			
0.5	32,000	20,000	--	--	--	
1.0	39,000	25,000	10,000	--	--	
Rupture	50,000(13%)	29,000(5%)	14,000(1.5%)	--	--	—

NOTE: Estimated elongation at fracture given in parentheses with rupture strengths.

TABLE Va

Room Temperature Tensile Properties of As-Received H-40 Turbine Wheels

Specimen Number	Specimen Location (1)	Brinell Hardness	Tensile Strength (psi)	Offset Yield Strengths (psi)			Proportional Limit (psi)	Elongation in 2-in. (%)	Reduction of Area (%)
				0.02%	0.1%	0.2%			
Wheel No. 1.	Heat Treatment: N. 1950°F + T. 2 hrs. at 1200°F + T. 3 hrs. at 1200°F								
1W	SRR	352	168,500	129,250	147,000	153,500	102,000	12.0	40.5
1X	CRR	350	167,500	128,750	145,500	151,750	104,000	11.0	31.2
2W	SRC	363	163,250	126,500	145,500	154,000	96,000	1.0	4.3
2X	CRC	350	165,500	125,000	144,000	151,750	104,000	1.5	3.9
2Y	CRC	356	169,250	130,500	148,000	154,250	105,000	5.0	9.6
2Z	SRC	345	169,000	129,000	145,750	152,500	104,000	7.0	13.4
Wheel No. 3.	Heat Treatment: O.Q. 1950°F + T. 8 hrs. at 1200°F + T. 3 hrs. at 1200°F								
1W	SRR	364	182,000	139,250	160,750	166,000	113,000	9.5	23.5
1X	CRR	364	183,500	137,000	158,500	164,250	108,000	10.0	23.7
2W	SRC	362	175,250	131,000	155,750	163,750	104,000	2.0	2.8
2X	CRC	365	172,500	124,000	150,250	159,750	95,000	2.0	2.8
2Y	CRC	346	177,000	125,500	150,750	159,500	96,000	5.0	7.8
2Z	SRC	341	178,750	127,750	150,500	159,750	99,000	8.5	16.0
Wheel No. 4.	Heat Treatment Int.-quench 1950°F + T. 2 hrs. at 1200°F + T. 3 hrs. at 1200°F								
1W	SRR	351	173,000	133,500	150,000	156,500	108,000	10.5	33.7
1X	CRR	361	176,000	130,000	149,250	157,750	101,000	10.0	23.4
2W	SRC	357	169,250	137,000	157,750	164,000	109,500	1.5	1.2
2X	CRC	367	171,500	129,750	150,250	158,250	102,000	2.0	4.7
2Y	CRC	357	174,750	131,000	150,750	158,750	101,000	2.5	7.4
2Z	SRC	355	175,000	129,250	149,000	156,750	102,000	9.0	19.5

(1) SRR - Surface plane radial specimen at rim of wheel
CRR - Central plane radial specimen at rim of wheel
SRC - Surface plane radial specimen at center of wheel
CRC - Central plane radial specimen at center of wheel

TABLE Vb

Tensile Properties of Retempered H-40 Turbine Wheel

Heat Treatment: O.Q. 1950°F + T. 8 hrs. at 1200°F + T. 3 hrs. at 1200°F + T. 4 hrs. at 1250°F

Specimen Number	Specimen Location (1)	Brinell Hardness	Test Temp. (°F)	Tensile Strength (psi)	Offset Yield Strengths (psi)			Proportional Limit (psi)	Elongation in 2-in. (%)	Reduction of Area (%)
					0.02%	0.1%	0.2%			
3W	SRR	295	75	146,500	113,500	126,500	130,000	90,000	15.5	50.5
3X	CRR	to	75	145,250	113,000	125,500	129,000	98,000	16.5	51.5
1Z	SRR	320	75	155,000	120,000	133,500	139,000	102,500	13.5	44.0
1Y	CRR	305 -	1000	99,750	68,500	87,000	94,000	47,000	15.0	50.5
14W	STR	320	1000	96,750	70,000	86,500	92,250	50,000	19.0	61.0
3Y	CRR	295 -	1100	80,250	54,500	68,500	74,500	37,000	21.0	61.0
14X	CTR	320	1100	80,000	54,000	68,500	74,500	34,000	16.5	48.8
3Z	SRR	295 -	1200	65,500	39,000	50,500	55,500	26,000	15.0	53.5
14Y	CTR	320	1200	63,750	39,750	52,000	58,000	25,000	16.0	47.8

(1) SRR - Surface plane radial specimen at rim of wheel
CRR - Central plane radial specimen at rim of wheel
STR - Surface plane tangential specimen at rim of wheel
CTR - Central plane tangential specimen at rim of wheel

TABLE Vc

Rupture, Total Deformation, and Creep Data for As-Received H-40 Turbine Wheels

Specimen Number	Specimen Location (a)	Test Temp. (°F)	Stress (psi)	Time to Fracture (hours)	Elongation in 2-in. (%)	Reduction of Area (%)	Time to Reach Specified Total Deformations (hours) 0.1%	0.2%	0.5%	1.0%	Time at Start of Third Stage Creep (hrs)	Minimum Creep Rate (%/hr.)	Deformation on Loading (In./In.)
Disk No. 1. Heat Treatment: N. 1950°F + T. 2 hrs. at 1200°F + T. 3 hrs. at 1200°F.													
4W	SRR	1100	55,000	28(g)	--	--	(c)	(c)	12	--	--	0.011	--
4X	CRR	1100	55,000	48(b)	--	--	(c)	(c)	19	40(e)	30	0.011	0.00285
4Z	SRR	1100	55,000	97	1.4	0.9	(c)	(c)	14	93(e)	90	0.0039	0.00342
4Y	CRR	1100	45,000	164(g)	--	--	(c)	(c)	121	--	--	--	0.00195
6W	SRR	1100	45,000	242	8.3	14.1	(c)	(c)	22	97	100	0.0067	0.00215
6X	CRR	1100	37,000	518	5.0	4.0	(c)	2	118	336	300	0.0022	0.00177
Disk No. 3. Heat Treatment: O.Q. 1950°F + T. 8 hrs. at 1200°F + T. 3 hrs. at 1200°F.													
6W	SRR	1100	60,000	35	2.2	2.8	(c)	(c)	13	26(e)	21	0.011	0.00270
4Y	CRR	1100	50,000	136	1.8	3.9	(c)	(c)	44	106(e)	96	0.00465	0.00229
4W	SRR	1100	45,000	298	1.8	3.9	(c)	(c)	76	262(e)	218	0.0019	0.00213
4Z	SRR	1100	39,000	456(b)	2.2	4.3	(c)	1	141	455(e)	400	0.0013	0.00175
6Y	CRR	1100	38,000	189(b)	1.0	0	(c)	2	185	188	180	0.00084	0.00178
Disk No. 4. Heat Treatment: Int. -quench 1950°F + T. 2 hrs. at 1200°F + T. 3 hrs. at 1200°F.													
4X	CRR	1100	60,000	34(g)	--	--	(c)	(c)	3	28	22	0.014	0.00322
6W	SRR	1100	55,000	67	1.9	5.8	(c)	(c)	14	63(e)	40	0.0065	0.00291
4W	SRR	1100	50,000	108	2.6	8.1	(c)	(c)	18	73	73	0.0088	0.00238
4Y	CRR	1100	45,000	243(g)	--	--	(c)	(c)	75	228	156	0.0025	0.00214
4Z	SRR	1100	39,000	407(g)	--	--	(c)	1	142	400(e)	200	0.0014	0.00170
6X	CRR	1100	40,000	457(b)	1.4	3.1	(c)	(c)	170	451	408	0.0012	0.00197
6Y	CRR	1100	35,000	697	2.3	7.0	(c)	5	326	690	688	0.00084	0.00168

(a) SRR - Surface plane radial specimen at rim of disk
CRR - Central plane radial specimen at rim of disk
(b) Broke in fillet
(c) Specimen reached this deformation on loading
(d) Test discontinued at this time
(e) Extrapolated value
(f) Broke in gage mark
(g) Broke in threads

TABLE Vd

Rupture, Total Deformation, and Creep Data for Retempered H-40 Turbine Wheels

Specimen Number	Specimen Location (a)	Test Temp. (°F)	Stress (psi)	Time to Fracture (hrs.)	Elongation in 2-in. (%)	Reduction of Area (%)	Time to Reach Specified Total Deformations (hrs.) 0.1%	0.2%	0.5%	1.0%	Time at Start of Third Stage Creep (hrs.)	Minimum Creep Rate (% / hr.)	Deformation on Loading (in. /in.)
	Disk No. 1. Heat Treatment: N. 1950°F + T. 2 hrs. at 1200°F + T. 3 hrs. at 1200°F + T. 4 hrs. at 1250°F.												
9W	SRR	1100	60,000	2.7	10.5	37.4	(d)	(d)	0.04	0.5	-	0.66	0.00440
9X	CRR	1100	50,000	43(b)	3.0	7.8	(d)	(d)	0.3	11	25	0.026	0.00305
9Y	CRR	1100	45,000	81	2.7	6.2	(d)	(d)	5	53	68	0.0096	0.00265
9Z	SRR	1100	34,000	735(c)	2.3	4.3	(d)	1	219	652	520	0.001	0.00169
	Disk No. 3. Heat Treatment: O.Q. 1950°F + T. 8 hrs. at 1200°F + T. 3 hrs. at 1200°F + T. 4 hrs. at 1250°F												
8X	CRR	1000	75,000	3.3	20.0	58.3	(d)	(d)	0.1	0.7	1.3	0.67	0.00383
8Y	CRR	1000	70,000	8.7	19.3	60.0	(d)	(d)	0.2	2	3.5	0.24	0.00350
8W	SRR	1000	65,000	130	6.3	14.7	(d)	(d)	1	26	68	0.01	0.00300
8Z	SRR	1000	60,500	256(b)	10.0	29.5	(d)	(d)	4	43	146	0.0078	0.00285
10W	SRR	1000	57,000	443	9.0	31.4	(d)	(d)	10	116	222	0.0033	0.00281
9W	SRR	1100	60,000	10	17.0	50.0	(d)	(d)	0.1	1.4	-	0.285	0.00333
9Y	CRR	1100	50,000	80	8.0	22.0	(d)	(d)	1.5	23	30	0.02	0.00262
9X	CRR	1100	42,000	175(b)	5.0	8.8	(d)	(d)	13	84	100	0.0066	0.00254
5A(e)	SRC	1100	40,000	313	2.0	7.0	(d)	(d)	94	304(f)	282	0.0016	0.00254
9A(e)	SRR	1100	39,350	354	5.1	9.4	(d)	(d)	2	140	120	0.0036	0.00256
9Z	SRR	1100	36,000	514	4.5	10.0	(d)	2	71	280	280	0.0024	0.00199
6X	CRR	1100	36,000	566	4.0	9.0	(d)	1	156	507	285	0.0011	0.00185
14Z	STR	1100	33,000	1032	4.5	9.2	(d)	2	248	616	400	0.0011	0.00157
10Y(g)	CRR	1100	28,000	Off 1120	-	-	(d)	16	810	2477(f)	-	0.0003	0.00142
10Z(g)	SRR	1100	20,000	Off 1120	-	-	1	256	2396(f)	-	-	0.00014	0.00096
7Z(g)	SRR	1100	12,000	Off 1100	-	-	235	1725(f)	-	-	-	0.000064	0.00057
7Y	CRR	1200	42,000	7.8	7.0	23.7	(d)	(d)	0.4	3.1	3	0.16	0.00267
7W	SRR	1200	35,000	36	5.5	8.1	(d)	(d)	5.5	18	22	0.039	0.00236
7X	CRR	1200	30,000	74	5.5	12.3	(d)	0.1	12.2	37	28	0.019	0.00197
	Disk No. 4. Heat Treatment: Interrupted-quench 1950°F + T. 2 hrs. at 1200°F + T. 3 hrs. at 1200°F + T. 4 hrs. at 1250°F												
9W	SRR	1100	60,000	2.9	10.5	40.2	(d)	(d)	0.03	0.8	1	0.38	0.00323
9X	CRR	1100	50,000	70	4.5	8.2	(d)	(d)	1.5	26	55	0.02	0.00285
9Y	CRR	1100	45,000	144	2.5	7.4	(d)	(d)	13	94	44	0.0084	0.00240
9Z	SRR	1100	39,000	273	6.5	12.6	(d)	(d)	14	100	100	0.0056	0.00200

(a) SRR - Surface plane radial specimen at rim of disk
CRR - Central plane radial specimen at rim of disk
SRC - Surface plane radial specimen at center of disk
STR - Surface plane tangential specimen at rim of disk
(b) Broke in gage mark
(c) Broke in fillet
(d) Specimen reached this deformation on loading
(e) 0.250-inch diameter specimen
(f) Extrapolated value
(g) Creep test

TABLE Ve

Rupture, Time - Deformation, and Creep Strengths of Retempered H-40 Turbine Wheel

(Heat Treatment: O.Q. 1950°F + T. 8 hours at 1200°F + T. 3 hours at 1200°F + T. 4 hours at 1250°F)

Total Deformation (%)	Stress to Cause Total Deformations at Indicated Times (psi)					0.0001% per Hour Creep Strength (psi)
	1 hour	10 hours	100 hours	500 hours	1000 hours	
			1000°F			
0.5	65,000	56,000	--	--	--	
1.0	73,000	67,000	57,000	--	--	——
Rupture	78,000(20%)	70,000(19%)	64,000(10%)	56,000(9%)	52,000(-)	
			1100°F			
0.1	20,000	17,000	13,000	~ 11,000	~ 10,000	16,000
0.2	37,000	30,000	22,000	17,000	15,000	
0.5	51,000	44,000	36,000	29,000	26,000	
1.0	61,000	52,000	42,000	34,000	31,000	
Rupture	--	60,000(17%)	48,000(7%)	36,000(4%)	32,000 (4%)	
			1200°F			
0.5	40,000	31,000	--	--	--	
1.0	--	37,000	25,000	--	--	——
Rupture	--	40,000(6%)	30,000(5%)	--	--	

NOTE: Estimated elongation at fracture given in parentheses with rupture strengths.

TABLE VIa

Tensile Properties of C-422 Turbine Wheels

Specimen Number	Specimen Location (1)	Brinell Hardness	Test Temp. (°F)	Tensile Strength (psi)	Offset Yield Strengths (psi) 0.02%	0.1%	0.2%	Proportional Limit (psi)	Elongation in 2-in. (%)	Reduction of Area (%)
Wheel No. 1. Heat Treatment: (a) N. 1900°F + T. 2 hrs. at 1200°F. (b) Full anneal 6 hrs. at 1600°F. N. 1900°F + T. 2 + 2 hrs. at 1200°F.										
1W	SRR	301	75	145,500	105,500	117,250	122,750	87,500	16.0	35.0
1X	CRR	308	75	145,500	95,000	112,500	118,250	67,000	16.0	33.8
2W	SRC	300	75	133,500	88,500	102,500	107,250	70,500	5.5	7.4
2X	CRC	295	75	133,250	92,250	102,250	107,000	77,000	5.5	8.1
2Y	CRC	288	75	135,250	93,250	104,750	110,250	77,000	8.0	12.2
2Z	SRC	294	75	134,000	94,000	105,250	109,500	75,500	7.5	22.7
Wheel No. 4. Heat Treatment: (a) O.Q. 1900°F + T. 8 hrs. at 1200°F. (b) Full anneal 6 hrs. at 1600°F. O.Q. 1900°F + T. 2 + 2 hrs. at 1200°F.										
1W	SRR	291	75	141,500	98,500	108,500	113,000	83,000	16.0	40.1
1X	CRR	299	75	141,000	96,500	107,500	112,500	82,500	16.5	37.9
2W	SRC	294	75	135,500	94,250	104,000	108,750	80,000	7.5	8.9
2X	CRC	287	75	133,000	89,750	101,000	106,000	69,000	7.5	13.0
2Y	CRC	285	75	132,500	91,000	101,500	105,500	71,000	12.5	30.2
2Z	SRC	282	75	130,750	86,000	100,000	104,500	66,000	17.0	41.8
14Y	CTR	-	1000	83,500	54,500	70,250	75,500	38,500	30.0	70.0
1Y	CRR	298	1000	84,000	55,500	69,250	74,000	36,000	29.0	66.7
3W	SRR	299	1000	78,000	52,500	65,750	70,750	38,000	34.5	78.8
1Z	SRR	305	1100	66,250	45,500	55,500	60,250	35,500	37.0	79.8
14W	STR	-	1100	64,500	42,500	53,250	58,250	30,500	39.0	81.4
3Y	CRR	305	1100	67,000	37,500	54,500	60,000	22,000	31.5	76.8
3X	CRR	313	1200	49,500	28,500	39,250	43,750	13,500	40.5	86.8
14X	CTR	-	1200	48,500	28,000	36,250	41,500	19,500	39.0	83.8
3Z	SRR	299	1200	50,000	26,250	39,250	44,250	15,500	45.5	87.5

(1) SRR - Surface plane radial specimen at rim of wheel
CRR - Central plane radial specimen at rim of wheel
SRC - Surface plane radial specimen at center of wheel
CRC - Central plane radial specimen at center of wheel
CTR - Central plane tangential specimen at rim of wheel
STR - Surface plane tangential specimen at rim of wheel

TABLE VIb

Rupture, Total Deformation, and Creep Data for C-422 Turbine Wheels

Specimen Number	Specimen Location (a)	Test Temp. (°F)	Stress (psi)	Time to Fracture (hrs.)	Elongation in 2-in. (%)	Reduction of Area (%)	Time to Reach Specified Total Deformations (hrs.) 0.1%	0.2%	0.5%	1.0%	Time at Start of Third Stage Creep (hrs.)	Minimum Creep Rate (%/hr.)	Deformation on Loading (In./In.)
Disk No. 1. Heat Treatment: (a) N. 1900°F + T. 2 hrs. at 1200°F. (b) Full anneal 6 hrs. at 1600°F. N. 1900°F + temper 2 + 2 hrs. at 1200°F.													
4W	SRR	1100	55,000	2	26.5	69.5	(b)	(b)	(b)	-	-	-	0.00555
4X	CRR	1100	45,000	15	23.5	73.0	(b)	(b)	(b)	1	-	-	0.00326
4Y	CRR	1100	35,000	318	15.0	36.3	(b)	(b)	4	26	216	0.0069	0.00220
4Z	SRR	1100	32,000	1055	9.5	20.4	(b)	1	45	225	550	0.0017	0.00180
Disk No. 4. Heat Treatment: (a) O.Q. 1900°F + T. 8 hrs. at 1200°F. (b) Full anneal 6 hrs. at 1600°F. O.Q. 1900°F + temper 2 + 2 hrs. at 1200°F													
9W	SRR	1000	67,500	12	26.0	70.4	(b)	(b)	0.10	0.8	-	0.35	0.00415
9X	CRR	1000	62,000	72	15.0	64.0	(b)	(b)	3.0	12.0	38	0.041	0.00340
9Y	CRR	1000	58,000	116	21.5	68.5	(b)	(b)	0.8	8.5	40	0.0342	0.00310
10X	CRR	1000	54,000	Off 1150(c)	-	-	(b)	(b)	4.0	184	-	0.00079	0.00272
4W	SRR	1100	50,000	14	36.0	80.5	(b)	(b)	0.2	1.1	5	0.39	0.00312
4Z	SRR	1100	44,000	81	28.0	77.0	(b)	(b)	3	11	-	-	0.00249
4X	CRR	1100	40,000	399	29.5	69.3	(b)	(b)	2	19	160	0.0055	0.00207
10Z	SRR	1100	40,000	119	33.8	72.8	(b)	(b)	2.5	16	-	-	0.00230
7A(d)	SRR	1100	40,000	175	27.0	69.5	(b)	(b)	5	15	100	0.021	--
5A(d)	SRC	1100	40,000	258	20.2	57.0	(b)	(b)	5	23	130	0.0097	--
4Y	CRR	1100	35,000	1001	14.5	56.9	(b)	0.5	16	234	394	0.0015	0.00190
14Z	STR	1100	35,000	730	14.5	57.9	(b)	0.5	17	199	448	0.0024	0.00190
10W(e)	SRR	1100	28,000	Off 1120	-	-	(b)	4	318	1790(f)	-	0.00033	0.00150
6X(e)	CRR	1100	22,000	Off 1104	-	-	1	58	2300(f)	-	-	0.0001	0.00099
10Y(e)	CRR	1100	13,000	Off 1085	-	-	40	1090	-	-	-	0.00007	0.00070
6Y	CRR	1200	45,000	0.2	31.5	81.0	(b)	(b)	(b)	-	-	-	0.0055
6Z	SRR	1200	30,000	15	26.0	74.3	(b)	(b)	0.9	4.2	6	0.15	0.00183
6W	SRR	1200	25,000	53	28.5	77.0	(b)	0.3	8.4	19.6	20	0.041	0.00159
9Z	SRR	1200	20,000	134	18.0	65.8	(b)	0.5	25	50	40	0.015	0.00121

(a) SRR - Surface plane radial specimen at rim of disk
CRR - Central plane radial specimen at rim of disk
SRC - Surface plane radial specimen at center of disk
STR - Surface plane tangential specimen at rim of disk

(b) Specimen reached this deformation on loading

(c) Test discontinued at this time

(d) 0.250-inch diameter specimen

(e) Creep test

(f) Extrapolated value

TABLE VIc

Rupture, Time - Deformation, and Creep Strengths of C-422 Turbine Wheel

(Heat Treatment: (a) O.Q. 1900°F + T. 8 hours at 1200°F. (b) Full anneal 6 hours at 1600°F O.Q. 1900°F + T. 2 + 2 hours at 1200°F)

Total Deformation (%)	Stress to Cause Total Deformation at Indicated Times (psi)					0.0001% per Hour Creep Strength (psi)
	1 hour	10 hours	100 hours	500 hours	1000 hours	
			1000°F			
0.5	58,000	50,000	--	--	--	
1.0	67,000	60,000	55,000	~ 52,000	--	—
Rupture	--	66,000(26%)	60,000(20%)	57,000 (-)	56,000 (-)	
			1100°F			
0.1	22,000	16,000	10,000	--	--	22,000
0.2	33,000	26,000	20,000	15,000	13,000	
0.5	44,000	37,000	31,000	26,000	24,000	
1.0	50,000	43,000	36,000	31,000	29,000	
Rupture	--	51,000(36%)	43,000 (31%)	38,000 (20%)	36,000 (14%)	
			1200°F			
0.5	31,000	23,000	15,000	--	--	
1.0	--	27,000	17,000	--	--	—
Rupture	37,500(31%)	30,000(27%)	21,000(20%)	--	--	

NOTE: Estimated elongation at fracture given in parentheses with rupture strengths.

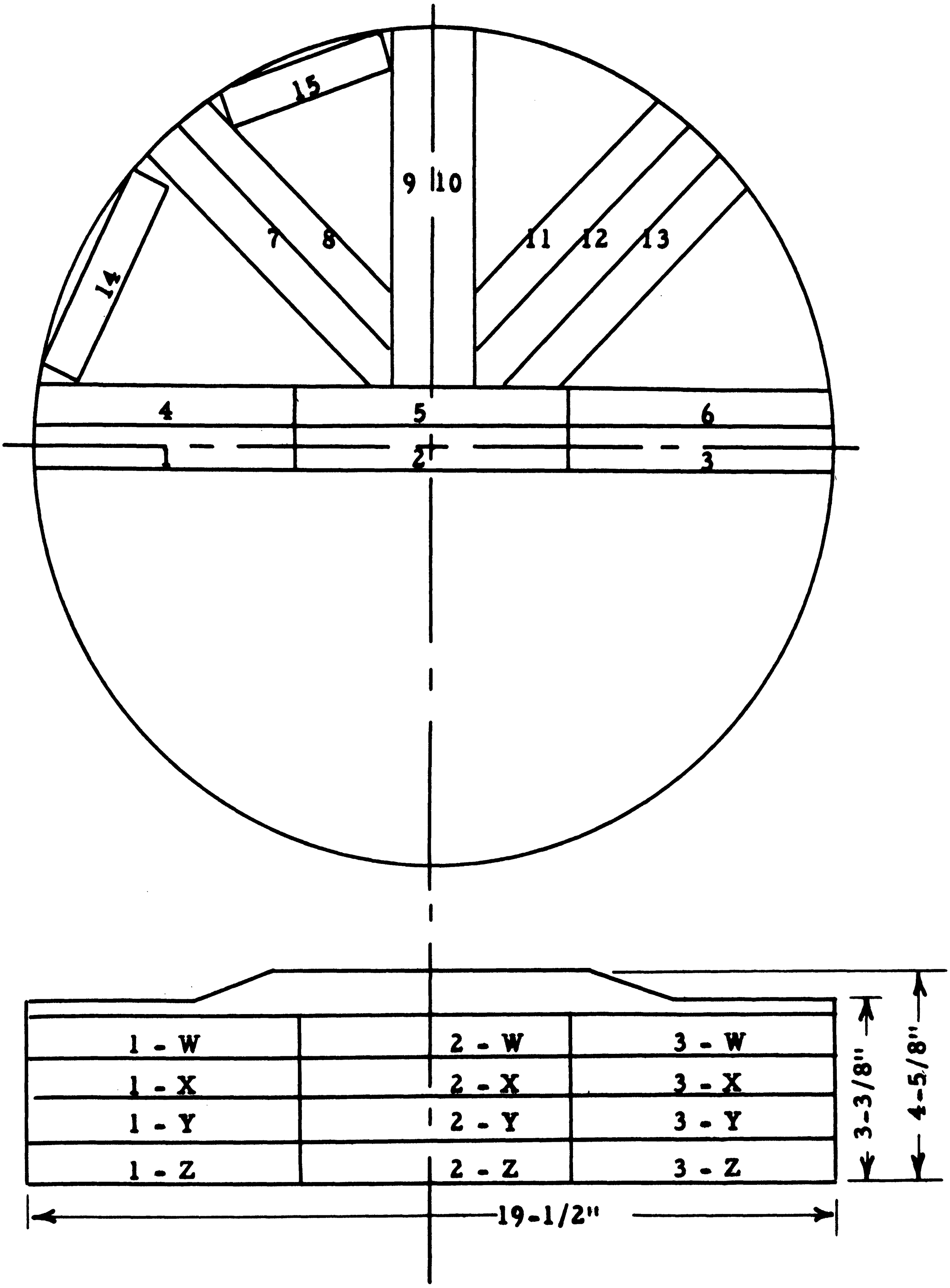
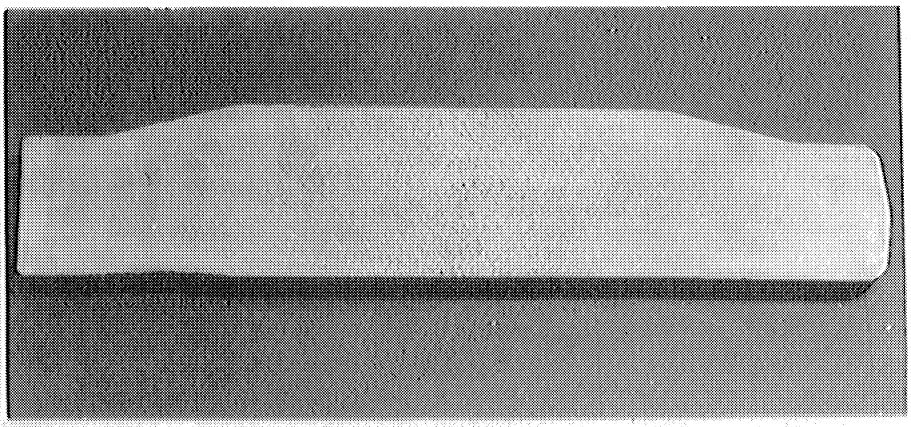
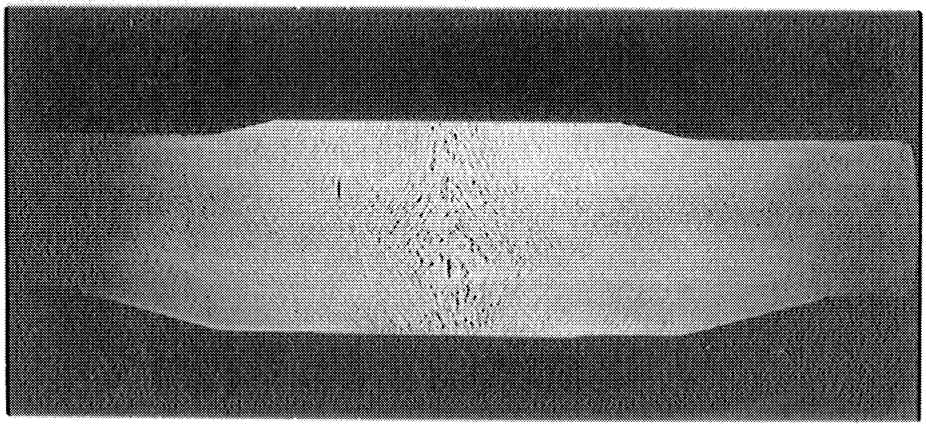


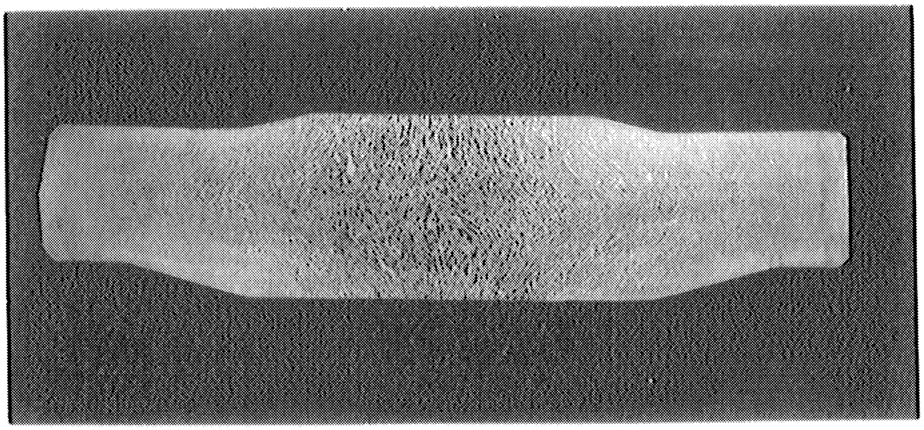
Figure 1. Method Used for Sectioning and Coding of Test Specimens from Forged Turbine Wheels



4340 Disk No. 1. Heat Treatment: (a) Normalize 1750°F + temper 2 hrs. at 1200°F. (b) Normalize 1750°F. BHN=297/345.



4340 Disk No. 3. Heat Treatment: (a) Oil quench 1750°F + temper 8 hrs. at 1200°F. (b) Oil quench 1550°F + temper at 1050°F. BHN=260/320.



4340 Disk No. 4. Heat Treatment: Interrupted-quench 1750°F + temper 2 hrs. at 1200°F. BHN=280/340.

Figure 2a. Macroetched Center Sections of 4340 Disks Nos, 1, 3, and 4.

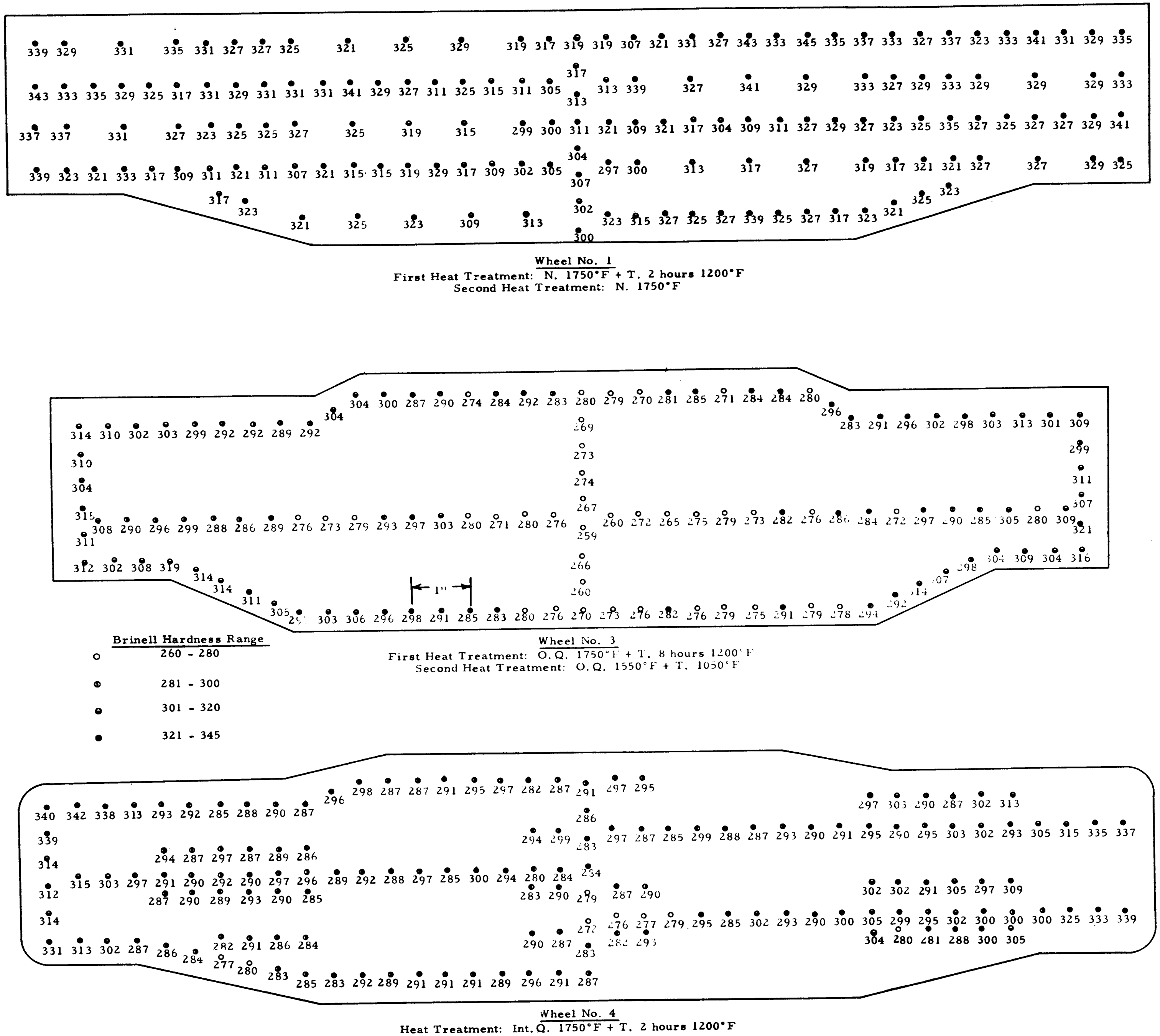


FIGURE 2b. - BRINELL HARDNESS SURVEY OF CENTER SECTION OF 4340 STEEL TURBINE WHEELS

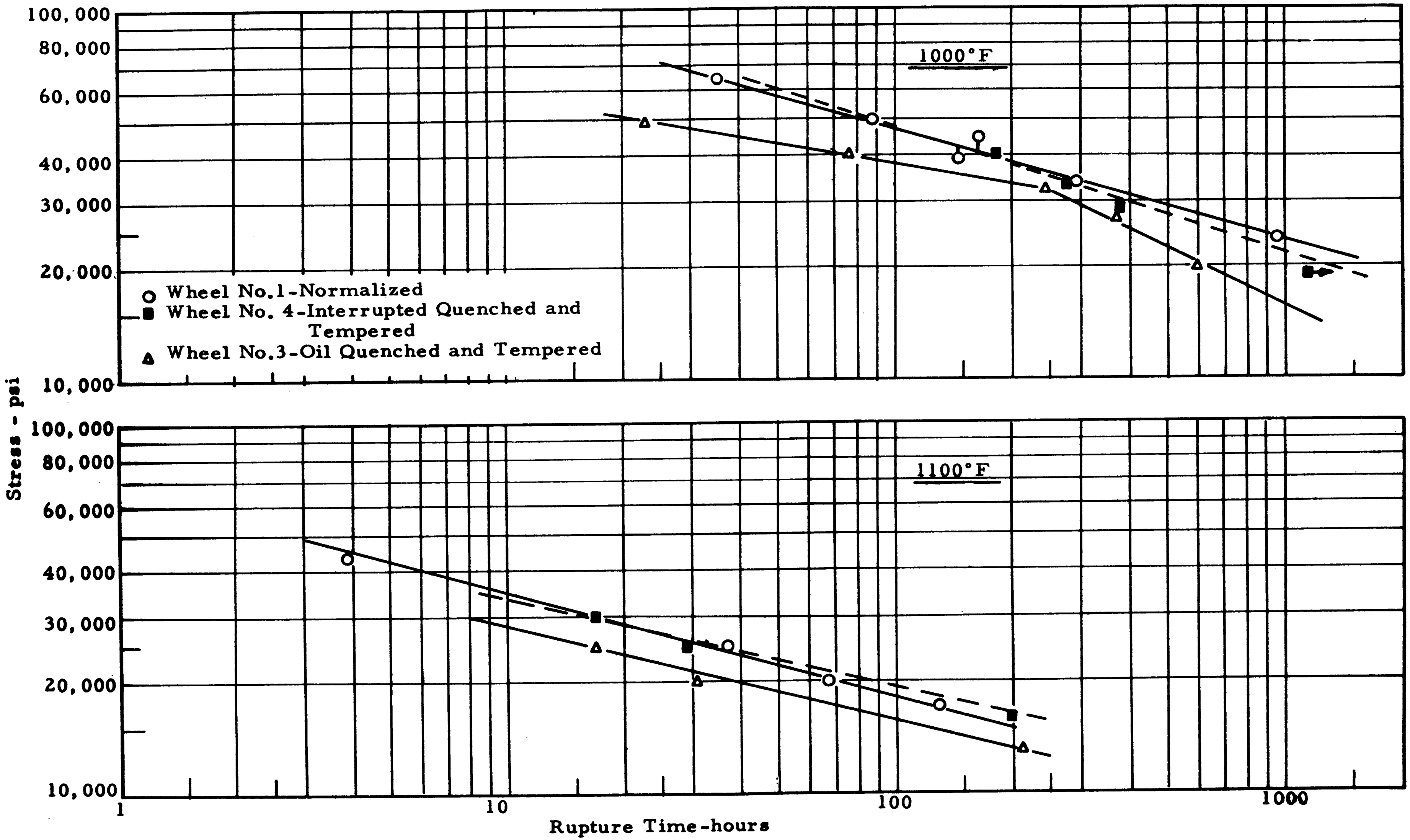


Figure 2c. - Survey Stress-Rupture Time Curves for the 4340 Turbine Wheels at 1000° and 1100°F.
(Wheel No. 1: First Heat Treatment, N. 1750°F + T. 2 hours at 1200°F; Second Heat Treatment, N. 1750°F.
Wheel No. 3: First Heat Treatment, O.Q. 1750°F + T. 8 hours at 1200°F; Second Heat Treatment, O.Q. 1550°F + T. at 1050°F.
Wheel No. 4: First Heat Treatment, Int. Q. 1750°F + T. 2 hours at 1200°F.)

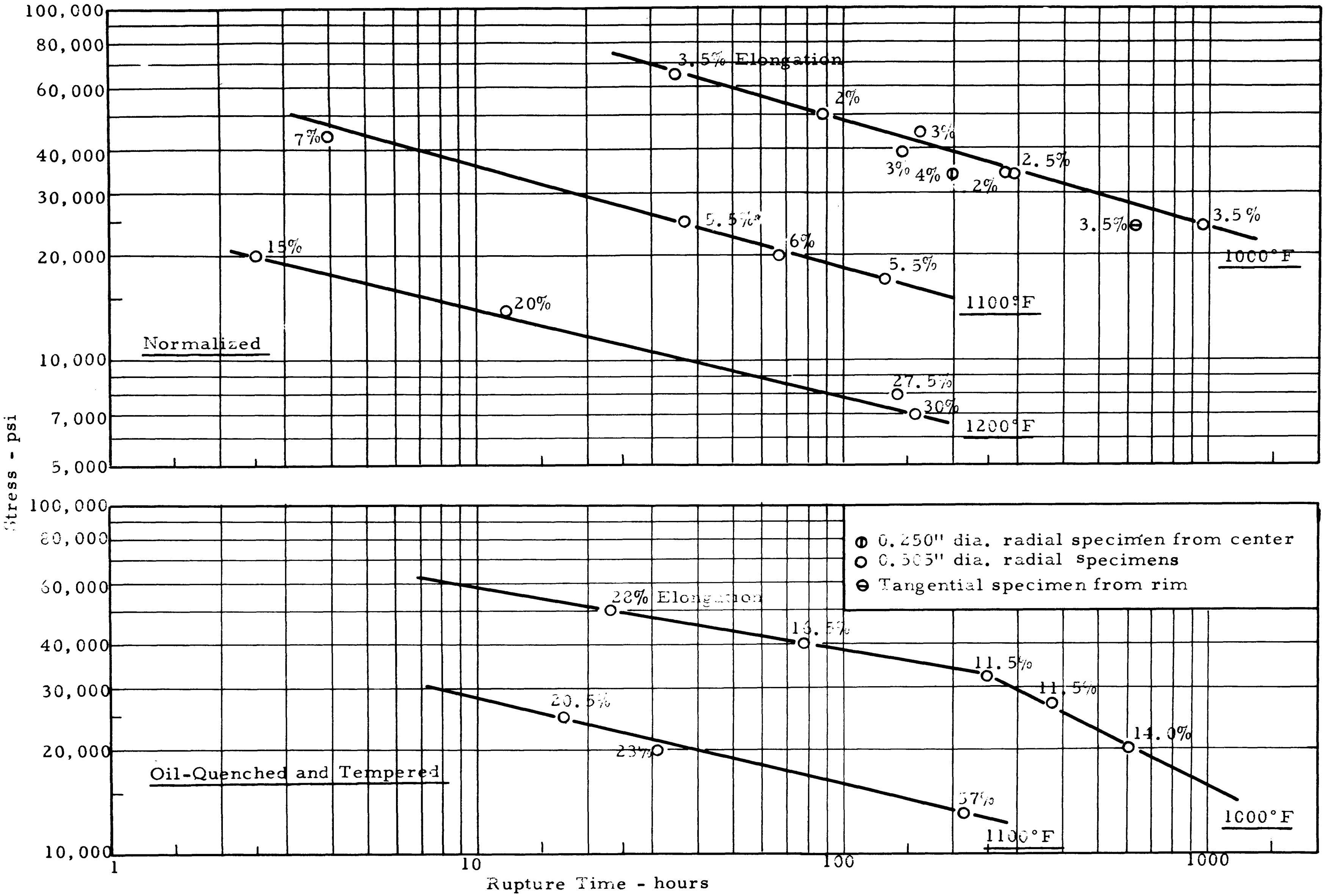


Figure 2d. - Stress-Rupture Time Curves for the Normalized 4340 Turbine Wheel at 1000°, 1100°, and 1200°F, and the Oil-Quenched and Tempered Wheel at 1000° and 1100°F.
(Normalized Wheel: First Heat Treatment, N. 1750°F + T. 2 hours at 1200°F; Second Heat Treatment, N. 1750°F.
Oil-Quenched Wheel: First Heat Treatment, O.Q. 1750°F + T. 2 hours at 1200°F; Second Heat Treatment, O.Q. 1550°F + T. at 1050°F.)

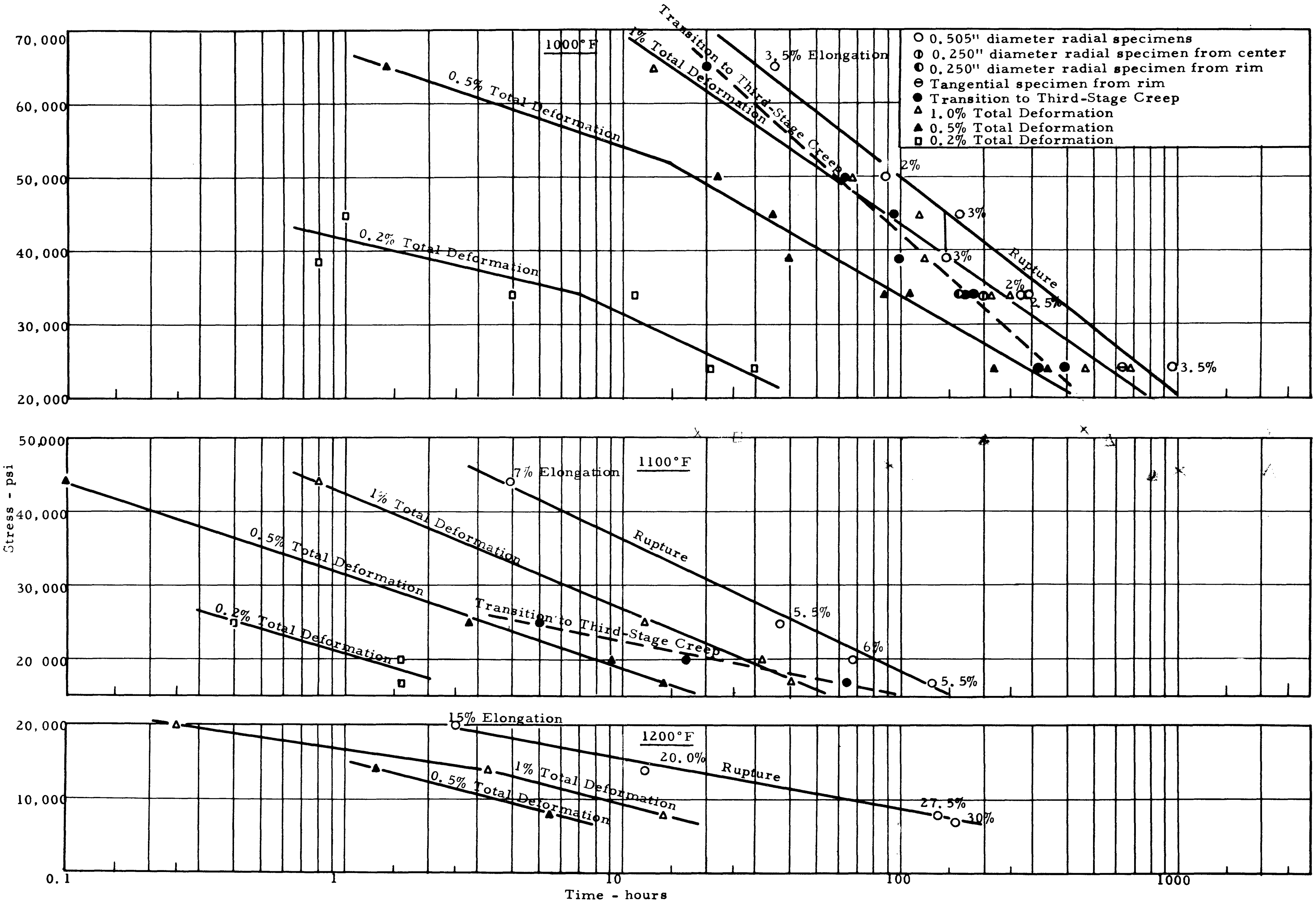


Figure 2e. - Stress-Rupture and Total Deformation Curves Obtained for the Normalized 4340 Turbine Wheel at 1000°, 1100°, and 1200°F.
(First Heat Treatment: N. 1750°F + T. 2 hours at 1200°F.
Second Heat Treatment: N. 1750°F.)

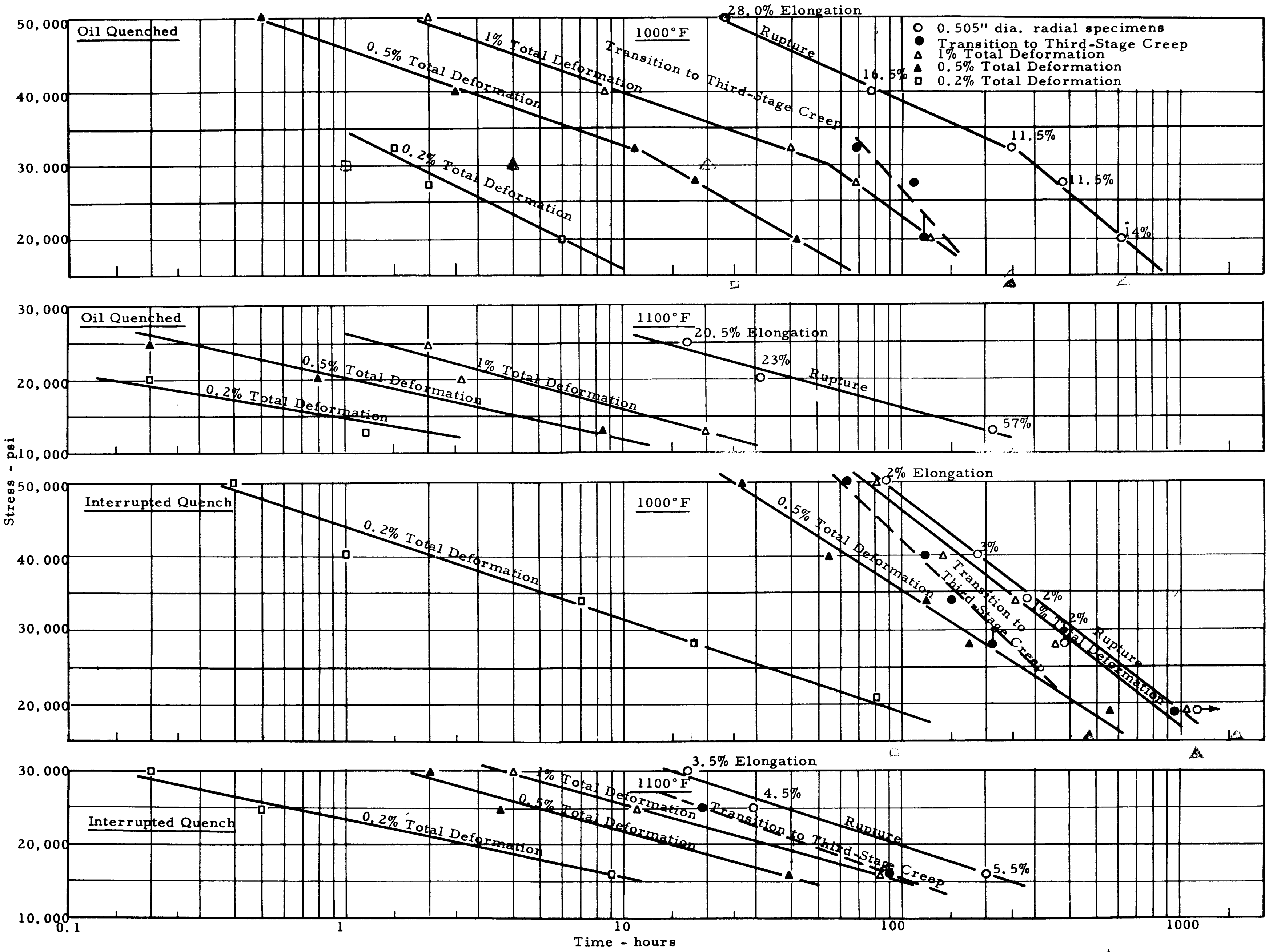


Figure 2f. - Stress-Rupture and Total Deformation Curves Obtained for the Oil-Quenched and Tempered and the Interrupted Quenched 4340 Turbine Wheels at 1000° and 1100°F.
(Oil-Quenched Wheel: First Heat Treatment, O.Q. 1750°F + T. 8 hours at 1200°F; Second Heat Treatment, O.Q. 1550°F + T. at 1050°F. Interrupted Quenched Wheel: Int.Q. from 1750°F + T. 2 hours at 1200°F.)

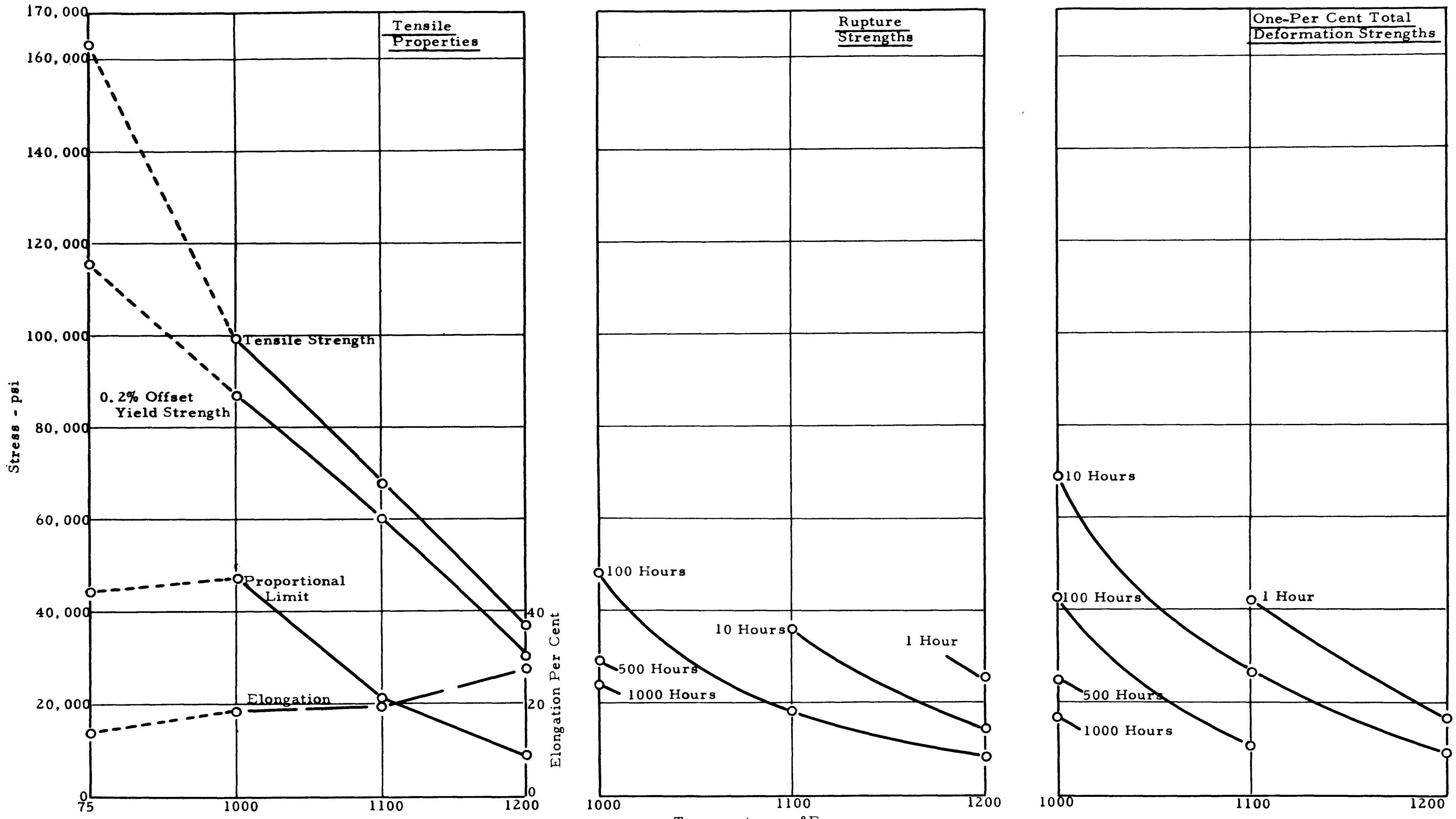


Figure 2g. - Summary of Short-Time Tensile Properties and Rupture and One-Per Cent Total Deformation Strengths of the Normalized 4340 Turbine Wheel. (First Heat Treatment: N. 1750°F + T. 2 hours at 1200°F. Second Heat Treatment: N. 1750°F.)

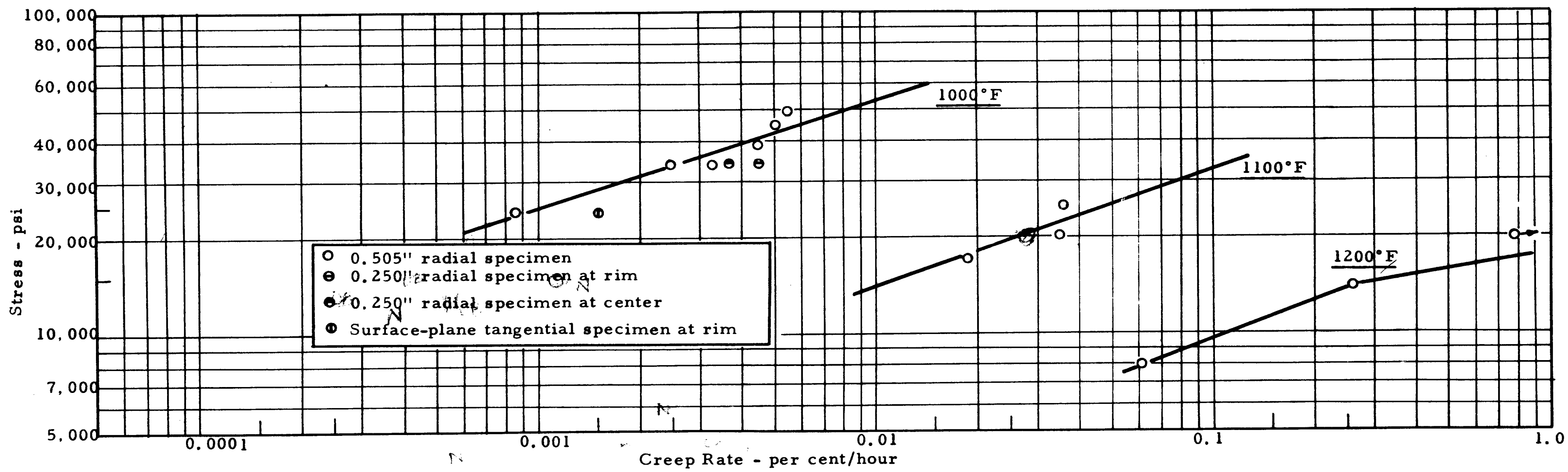
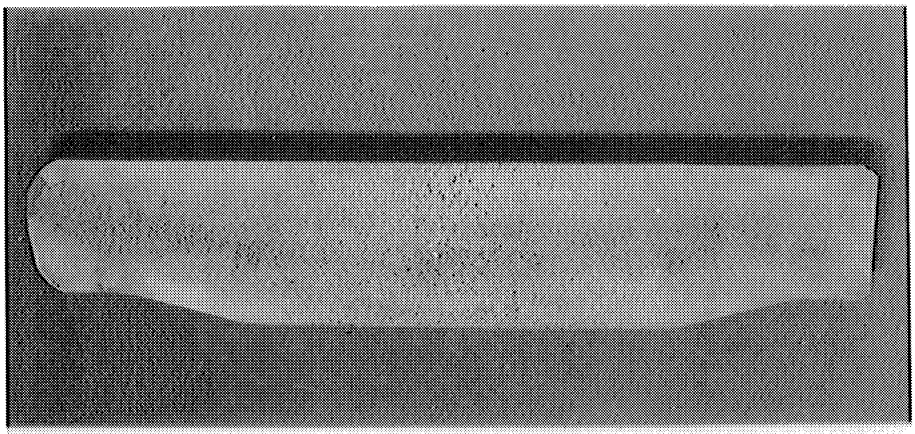
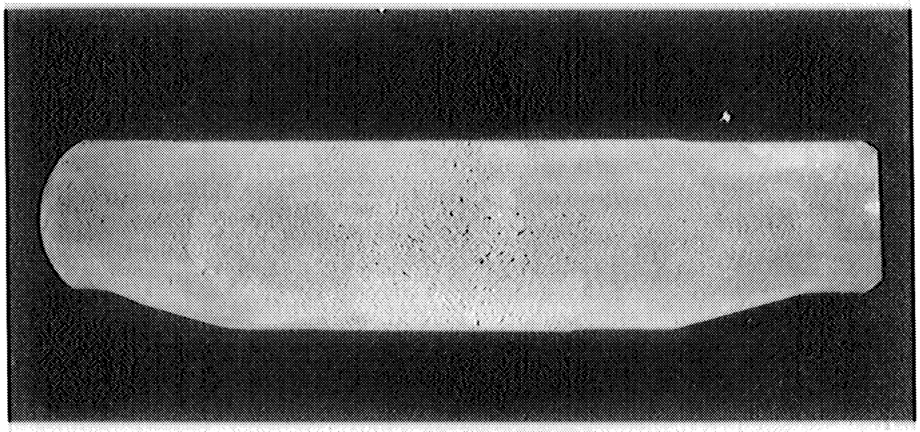


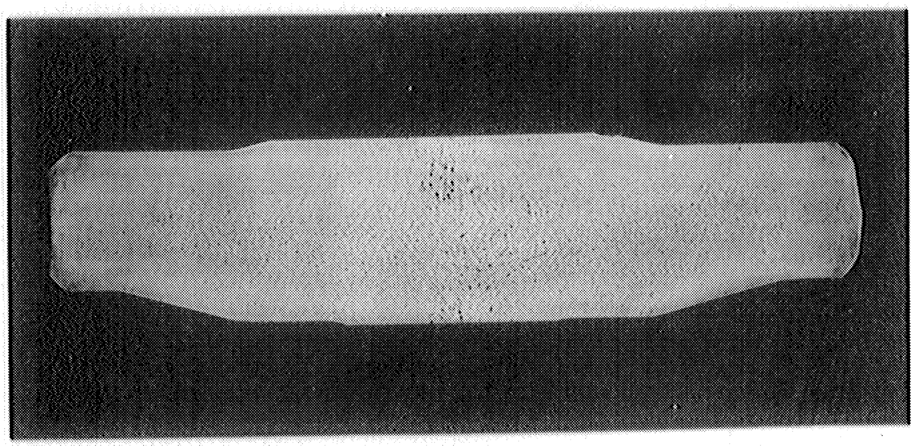
Figure 2h. - Stress-Creep Rate Curves for the Normalized 4340 Turbine Wheel at 1000°, 1100°, and 1200°F.
(First Heat Treatment: N. 1750°F + T. 2 hours at 1200°F.
Second Heat Treatment: N. 1750°F.)



"17-22A"S Disk No. 1. Heat Treatment: Normalize 1750°F + temper 2 hrs. at 1200°F. BHN=235/330.



"17-22A"S Disk No. 3. Heat Treatment: Oil quench 1750°F + temper 8 hrs. at 1200°F. BHN=281/340.



"17-22A"S Disk No. 4. Heat Treatment: Interrupted-quench 1750°F + temper 2 hrs. at 1200°F + temper 2 hrs. at 1200°F. BHN=300/360.

Figure 3a. Macroetched Center Sections of "17-22A"S Disks Nos. 1, 3, and 4.

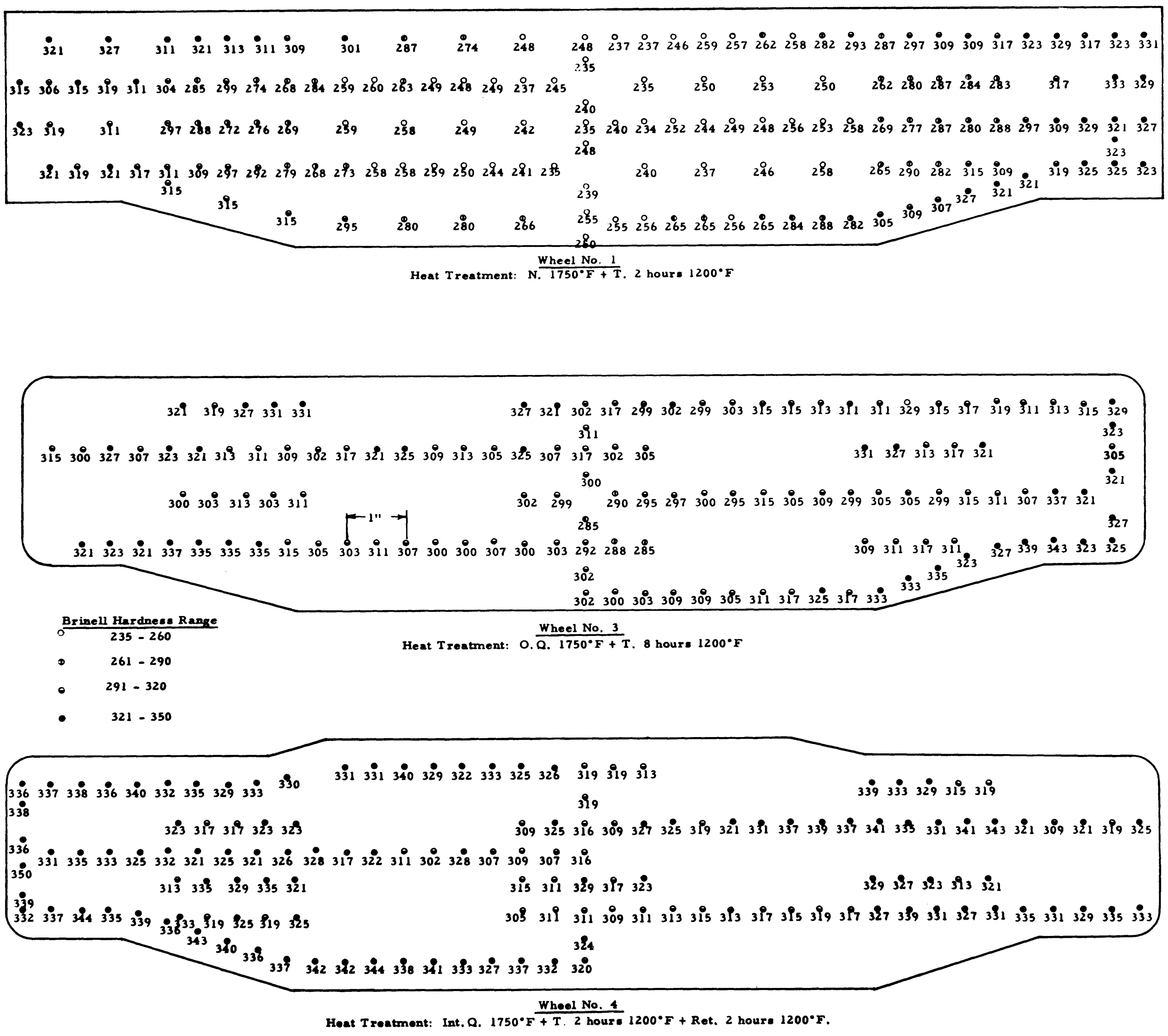


FIGURE 3b. - BRINELL HARDNESS SURVEY OF CENTER SECTION OF "17-22A"S STEEL TURBINE WHEELS

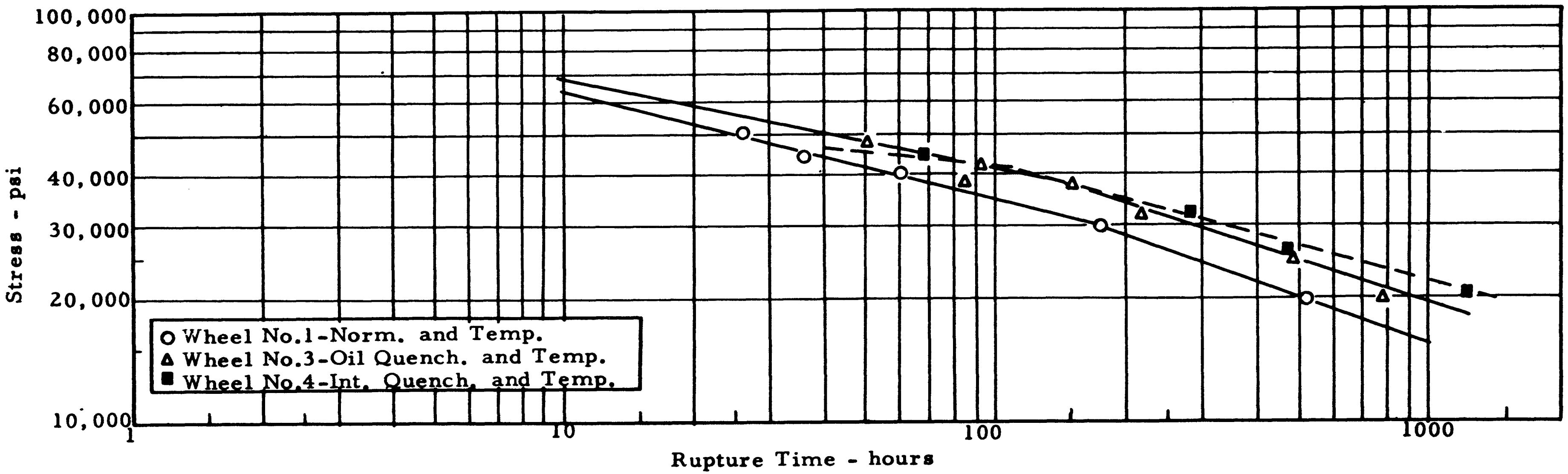


Figure 3c. - Survey Stress-Rupture Time Curves for the "17-22A"S Turbine Wheels at 1100°F.
(Heat Treatment: Wheel No. 1 - N. 1750°F + T. 2 hours at 1200°F.
Wheel No. 3 - O.Q. 1750°F + T. 8 hours at 1200°F.
Wheel No. 4 - Int.Q. 1750°F + T. 2 hours at 1200°F + Ret. 2 hours at 1200°F.)

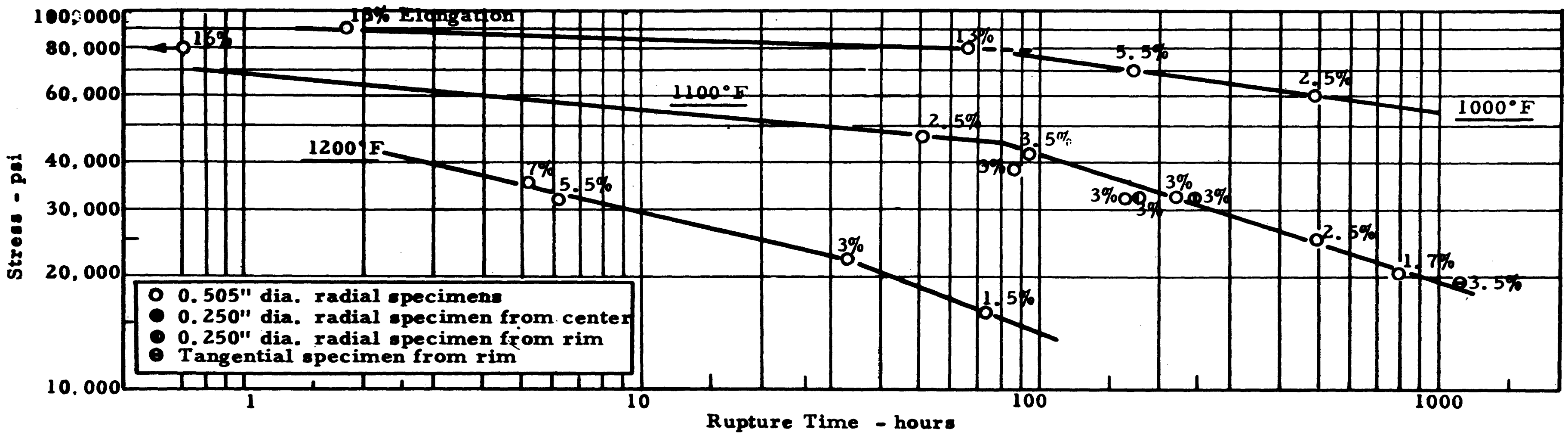


Figure 3d. - Stress-Rupture Time Curves for Oil-Quenched and Tempered "17-22A"S Turbine Wheel at 1000°, 1100°, and 1200°F. (Heat Treatment: O.Q. 1750°F + T. 8 hours at 1200°F.)

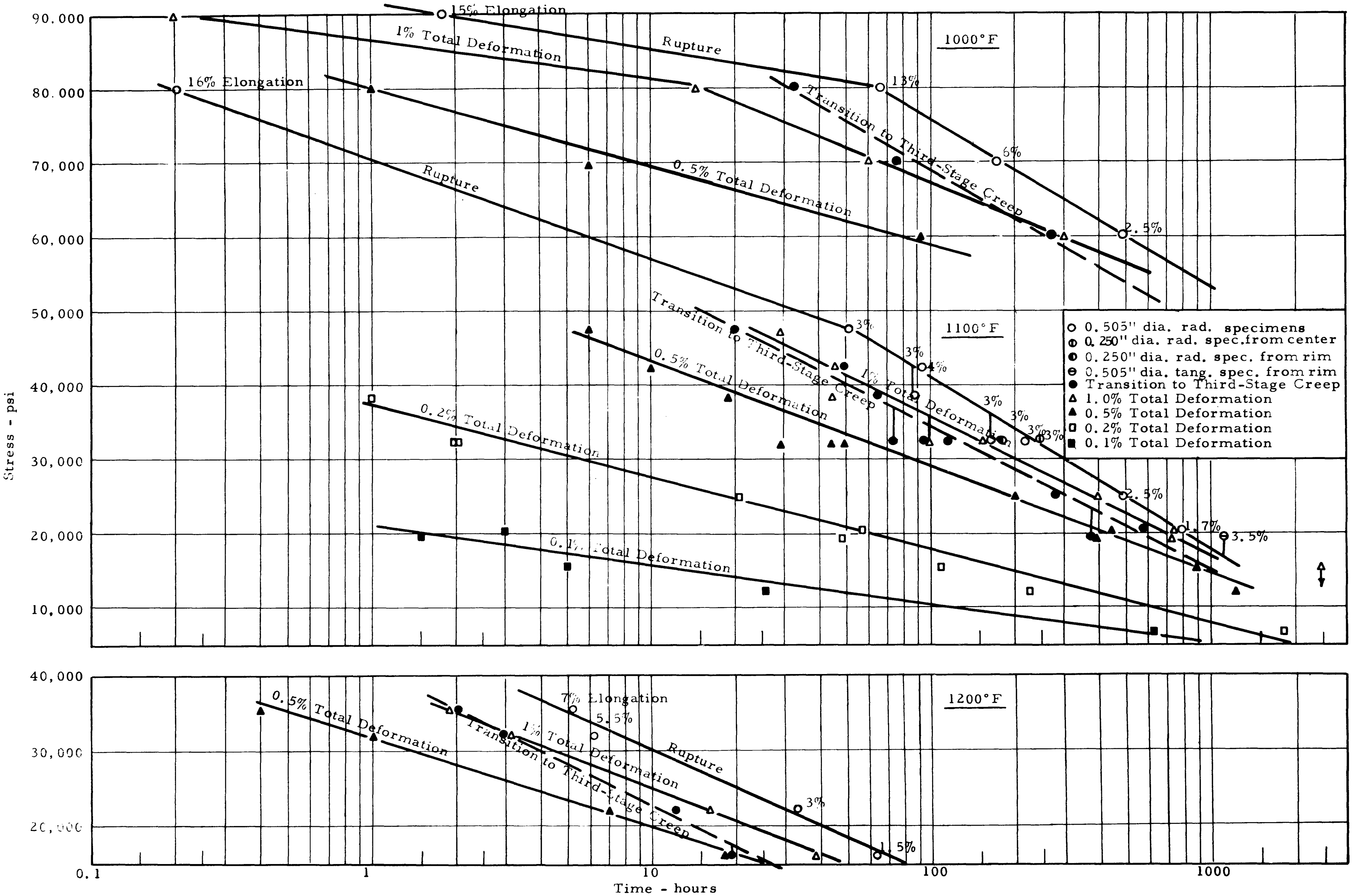


Figure 3e. - Stress-Rupture and Total Deformation Curves Obtained from Oil-Quenched and Tempered "17-22A"S Turbine Wheel at 1000°, 1100°, and 1200°F. (Heat Treatment: O.Q. 1750°F + T. 8 hours at 1200°F.)

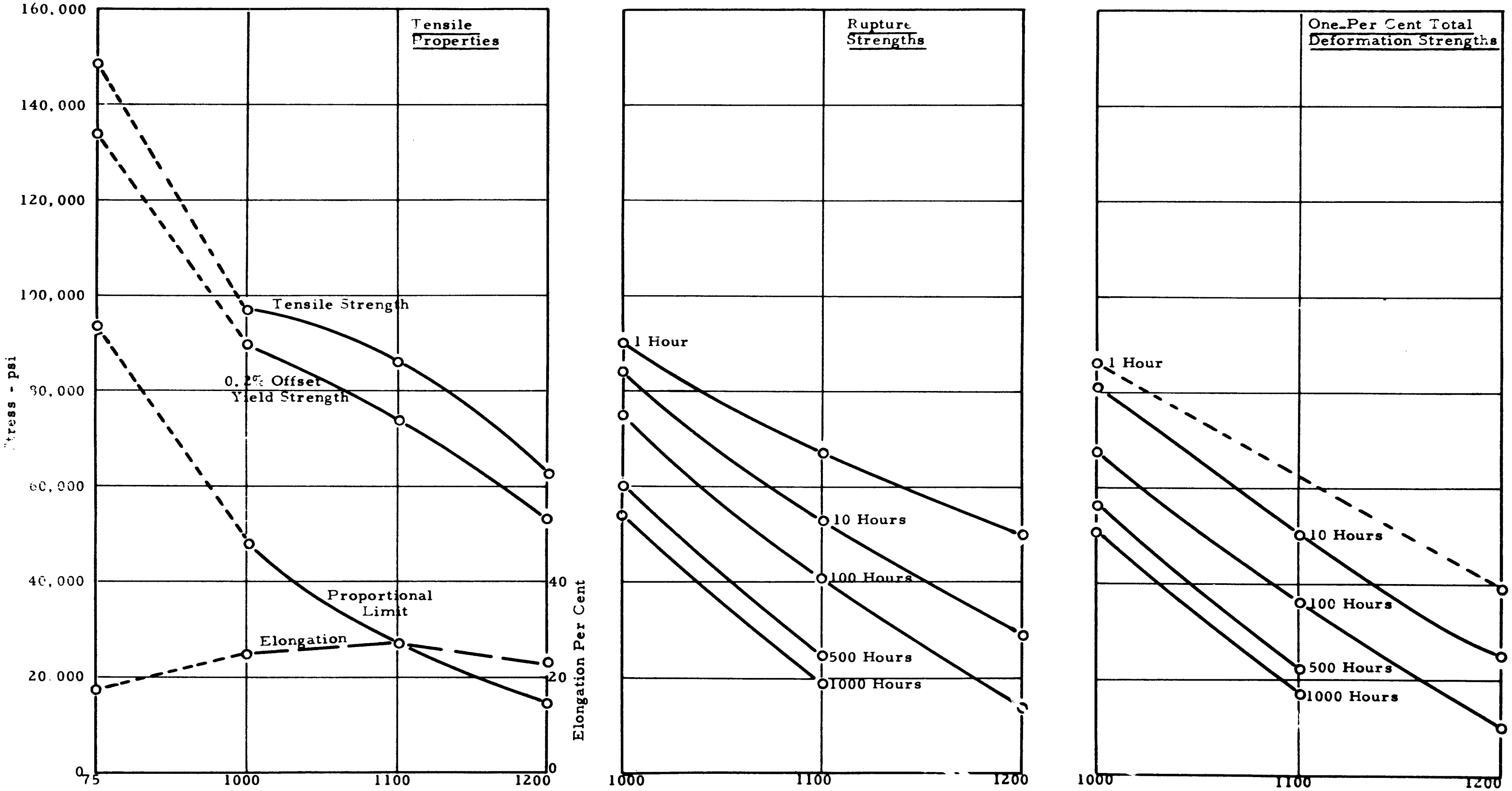


Figure 3f. - Summary of Short-Time Tensile Properties and Rupture and One-Per Cent Total Deformation Strengths of the Oil-Quenched and Tempered "17-22A"S Turbine Wheel.
(Heat Treatment: O.Q. 1750°F + T. 8 hours at 1200°F.)

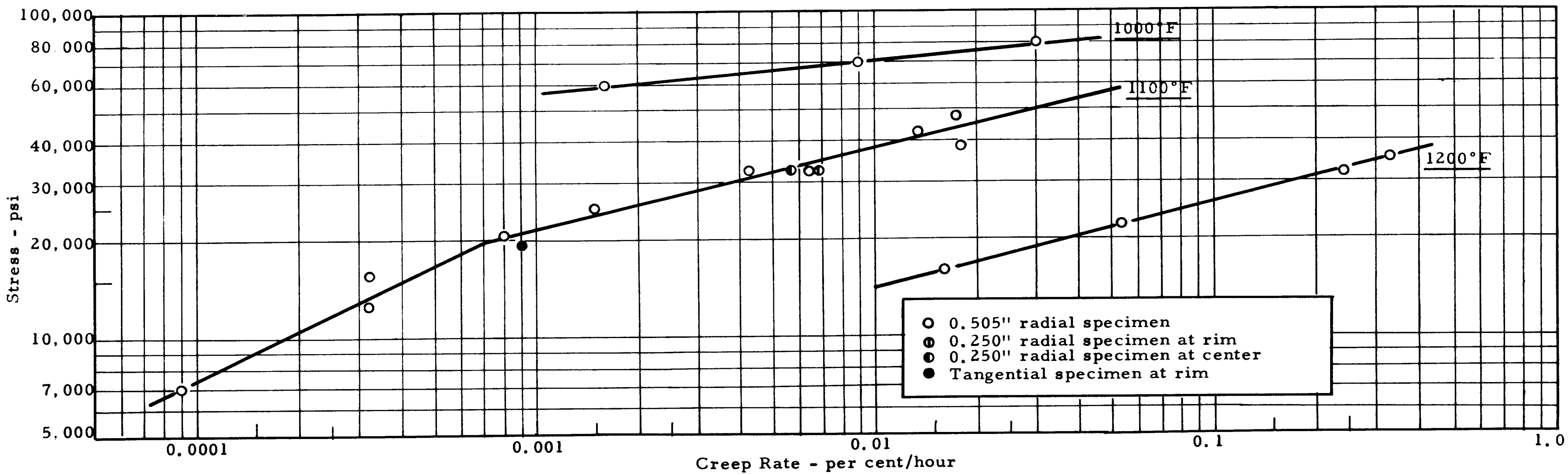
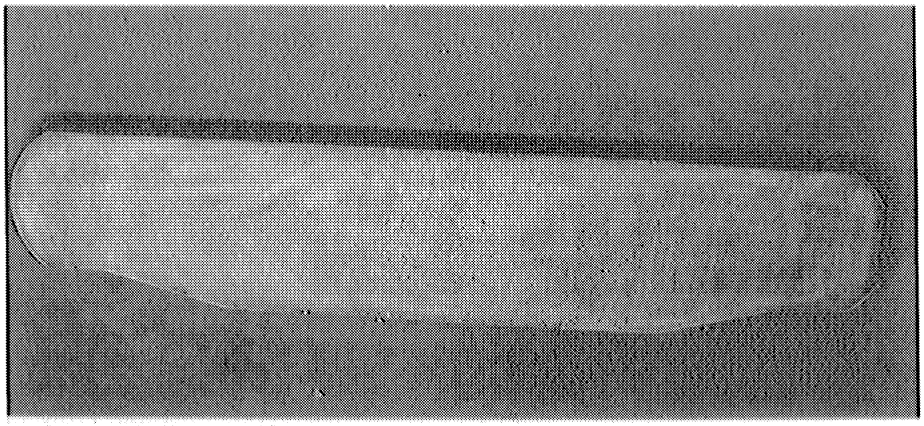
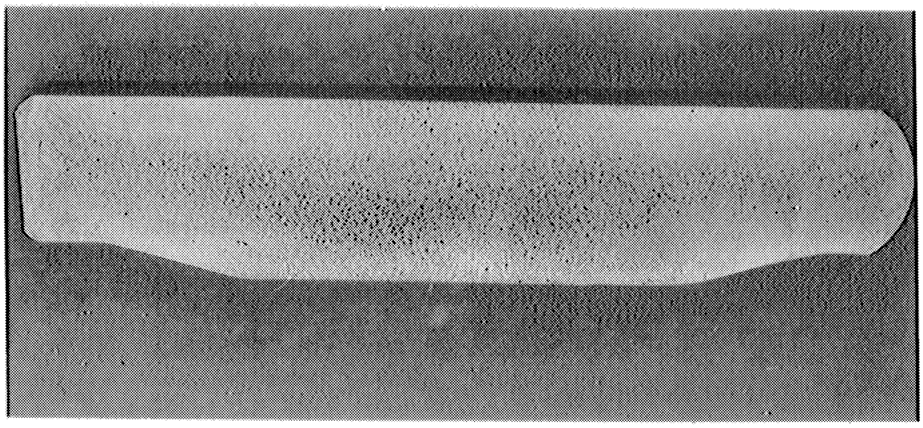


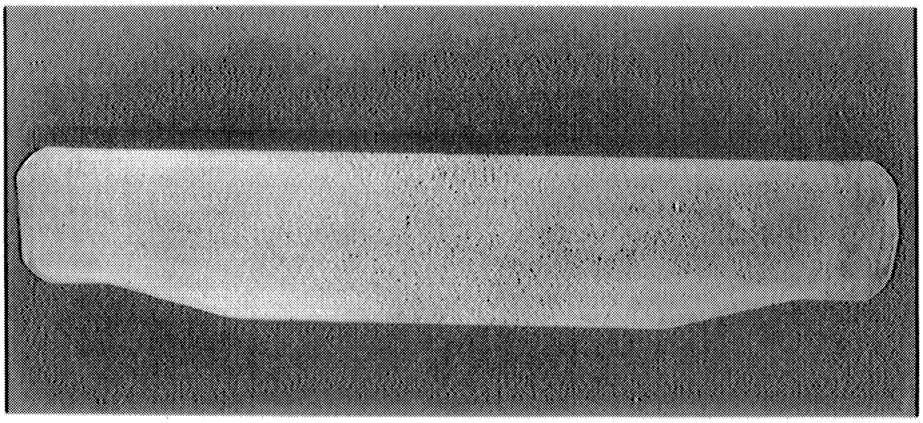
Figure 3g. - Stress-Creep Rate Curves for the Oil-Quenched and Tempered "17-22A"S Turbine Wheel at 1000°, 1100°, and 1200°F. (Heat Treatment: O.Q. 1750°F + T. 8 hours at 1200°F.)



H-40 Disk No. 1. Heat Treatment: Normalize 1950°F + temper 2 hrs. at 1200°F + temper 3 hrs. at 1200°F. BHN=315/380.

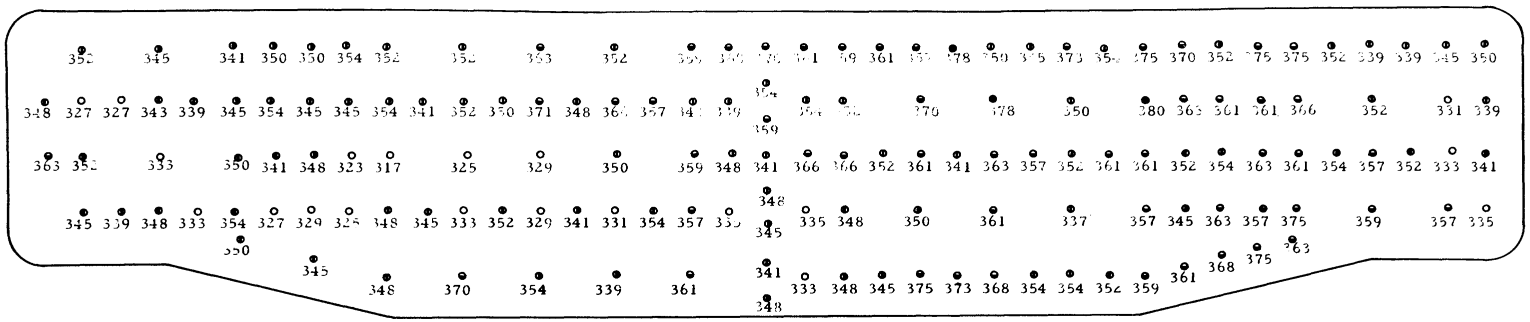


H-40 Disk No. 3. Heat Treatment: Oil quench 1950°F + temper 8 hrs. at 1200°F + temper 3 hrs. at 1200°F. BHN=315/390.



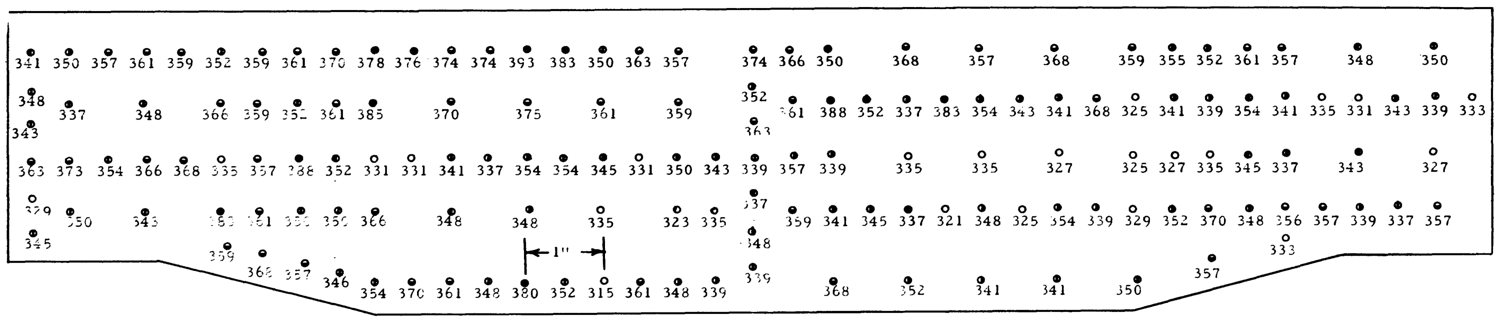
H-40 Disk No. 4. Heat Treatment: Interrupted-quench 1950°F + temper 2 hrs. at 1200°F + temper 3 hrs. at 1200°F. BHN=327/393.

Figure 4a. Macroetched Center Sections of As-Received H-40 Disks Nos. 1, 3, and 4.



Wheel No. 1

Heat Treatment: N. 1950°F + T. 2 hours 1200°F + T. 3 hours 1200°F

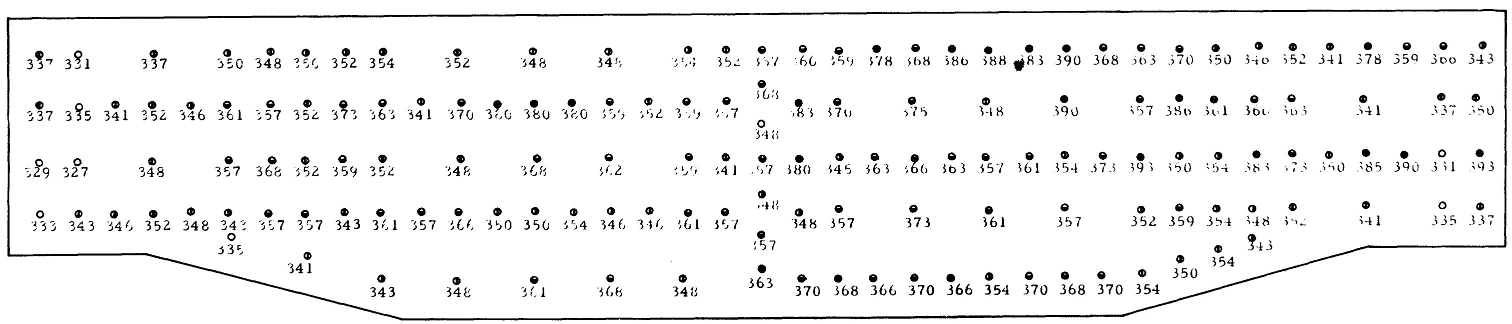


Brinell Hardness Range

○	317 - 335
⊕	336 - 355
◉	356 - 375
●	376 - 393

Wheel No. 3

Heat Treatment: O. Q. 1950°F + T. 3 hours 1200°F + T. 3 hours 1200°F



Wheel No. 4

Heat Treatment: Int. Q 1950°F + T. 2 hours 1200°F + T. 3 hours 1200°F

FIGURE 4b. - BRINELL HARDNESS SURVEY OF CENTER SECTION OF H-40 STEEL TURBINE WHEELS

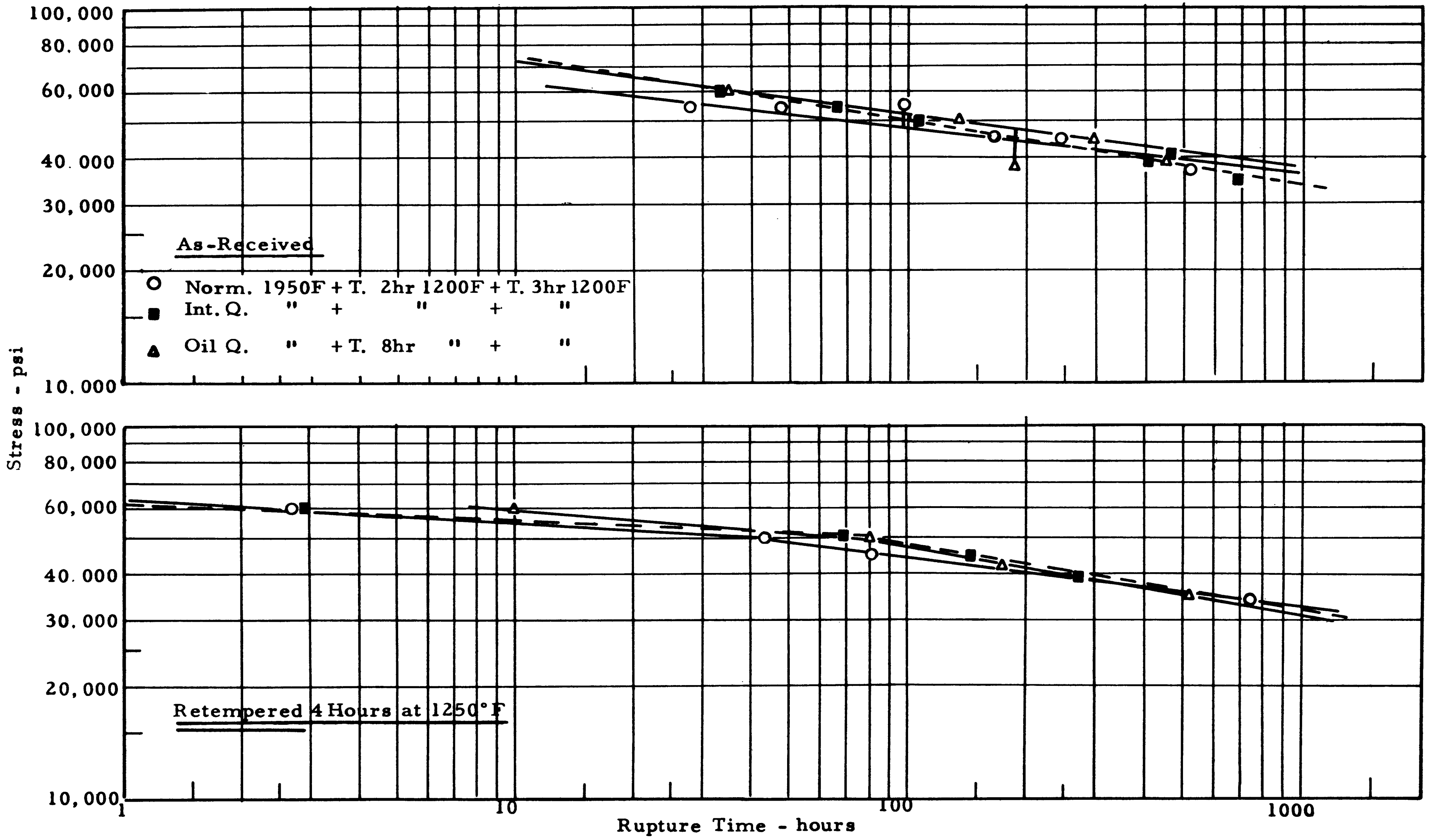


Figure 4c. - Survey Stress-Rupture Time Curves for the As-Received and Retempered H-40 Turbine Wheels at 1100°F

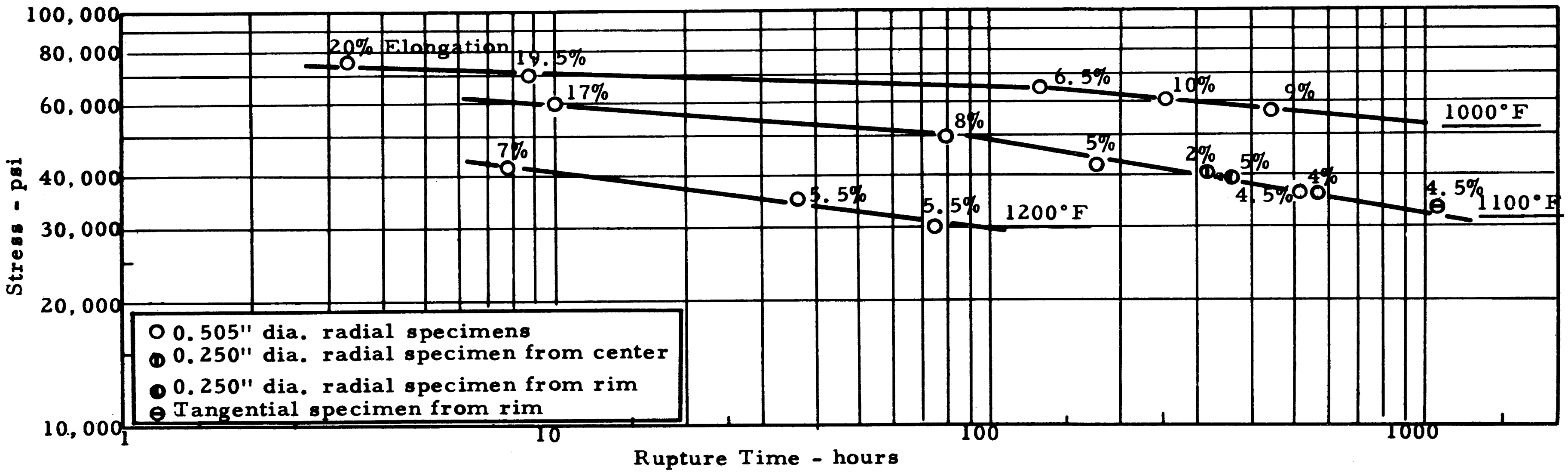


Figure 4d. - Stress-Rupture Time Curves for Oil-Quenched and Tempered H-40 Turbine Wheel at 1000°, 1100°, and 1200°F. (Heat Treatment: O.Q. 1950°F + T. 8 hours at 1200°F + 3 hours at 1200°F + Ret. 4 hours at 1250°F.)

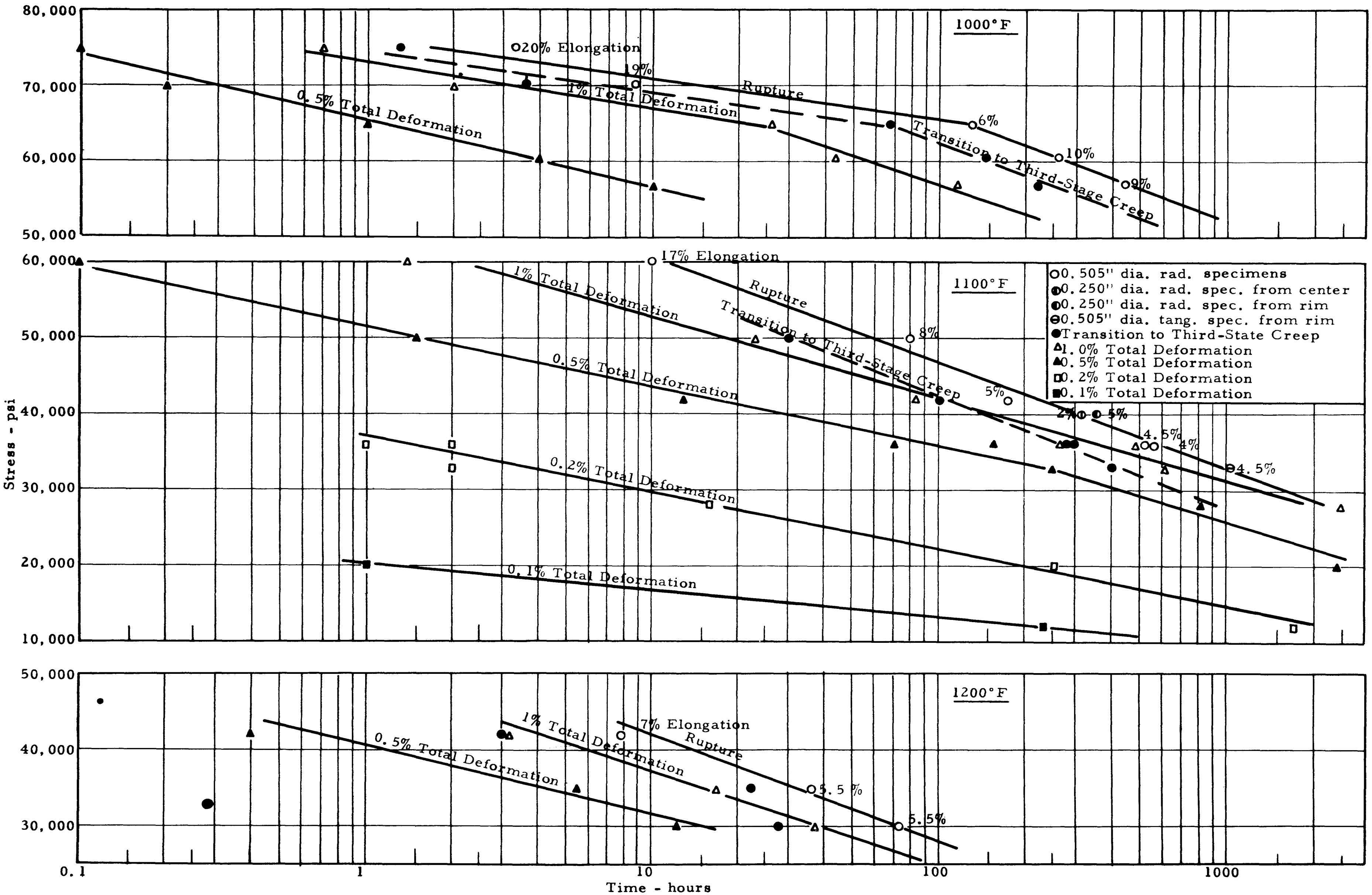


Figure 4e. - Stress-Rupture and Total Deformation Curves Obtained from the Oil-Quenched and Tempered H-40 Turbine Wheel at 1000°, 1100°, and 1200°F. (Heat Treatment: O.Q. 1950°F + T. 8 hours at 1200°F + Ret. 3 hours at 1200°F + T. 4 hours at 1250°F.)

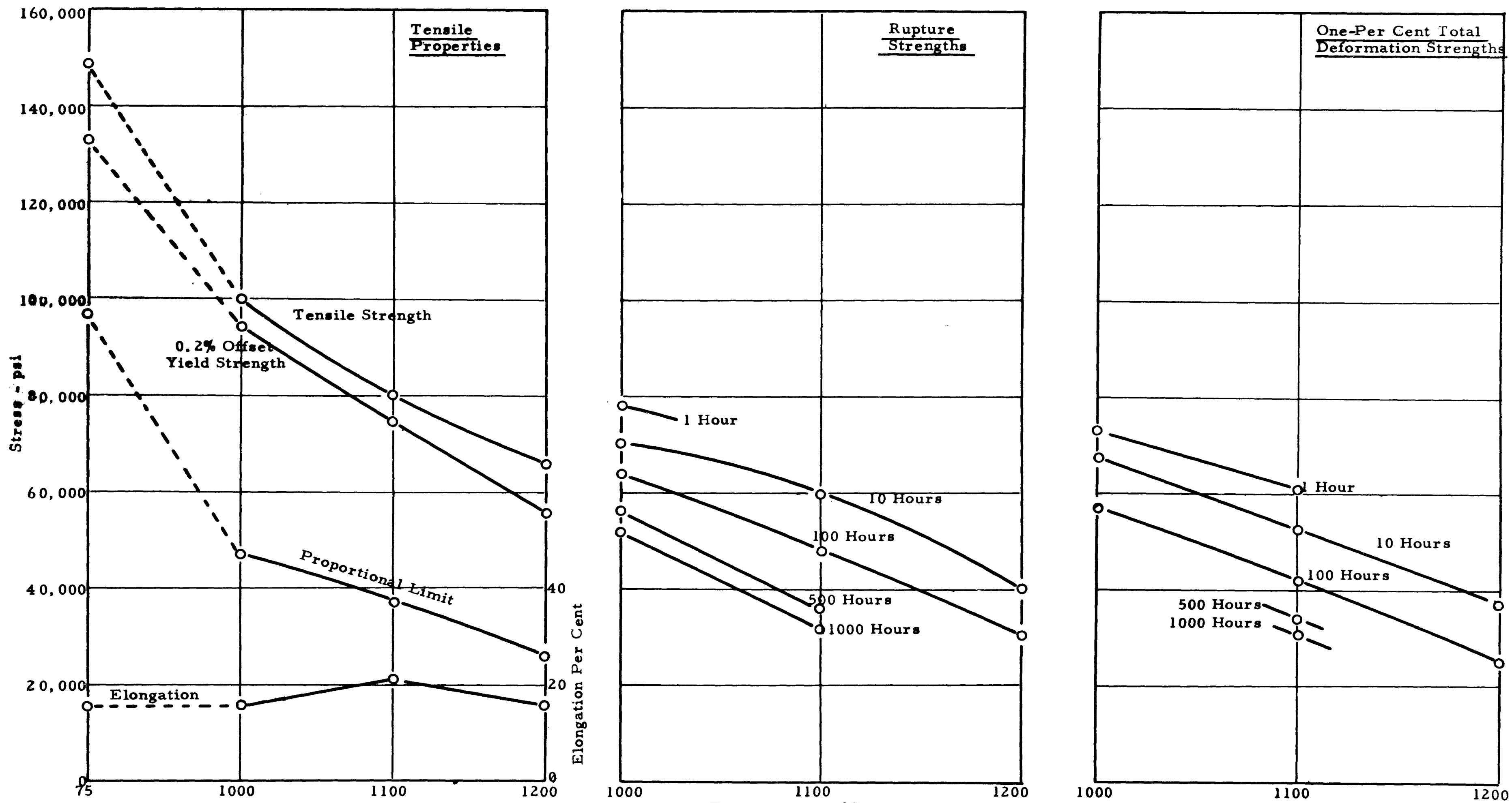


Figure 4f. - Summary of Short-Time Tensile Properties and Rupture and One-Per Cent Total Deformation Strengths of the Oil-Quenched and Tempered H-40 Turbine Wheel.
(Heat Treatment: O.Q. 1950°F + T. 8 hours at 1200°F + T. 3 hours at 1200°F and Ret. 4 hours at 1250°F.)

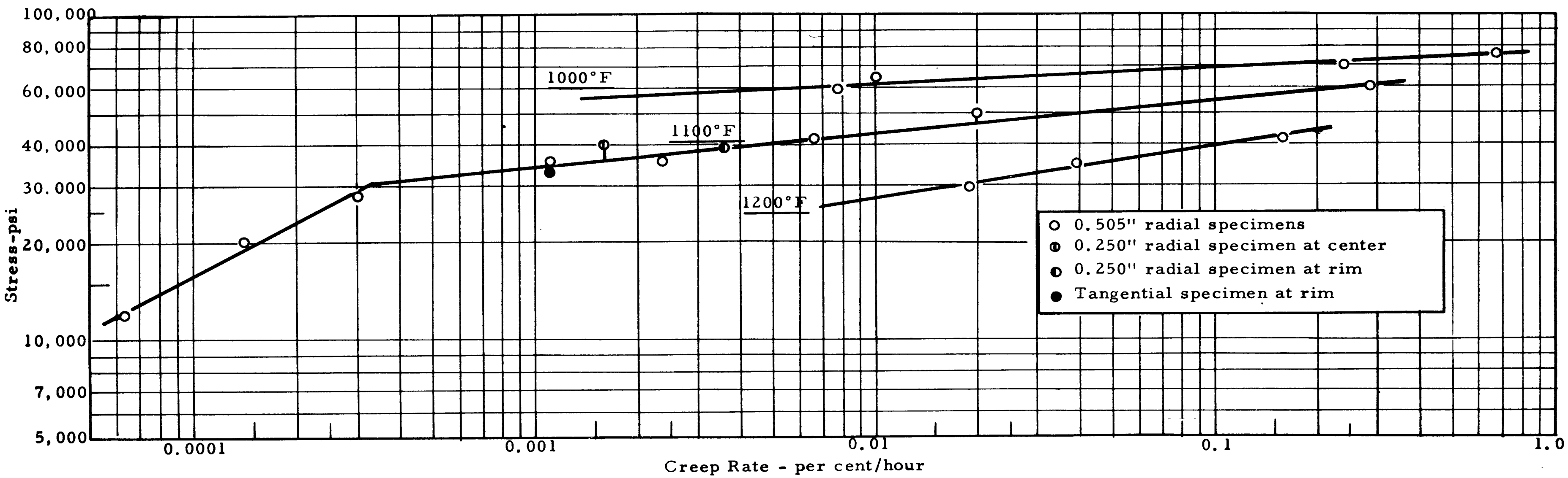
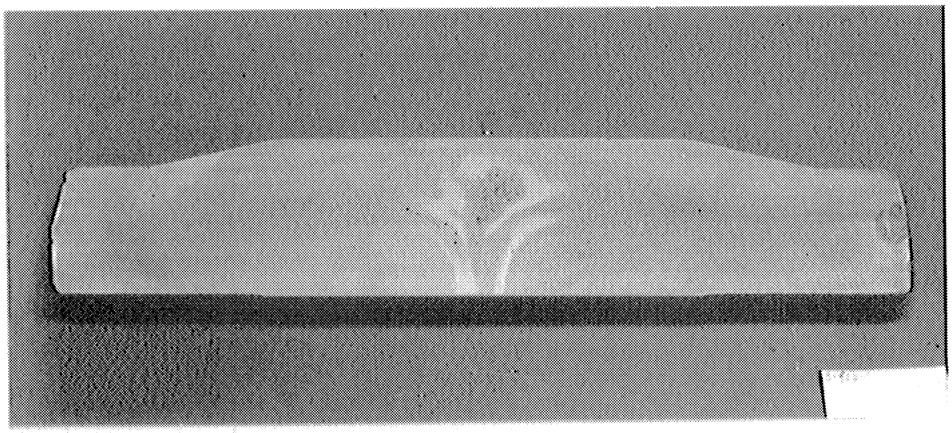
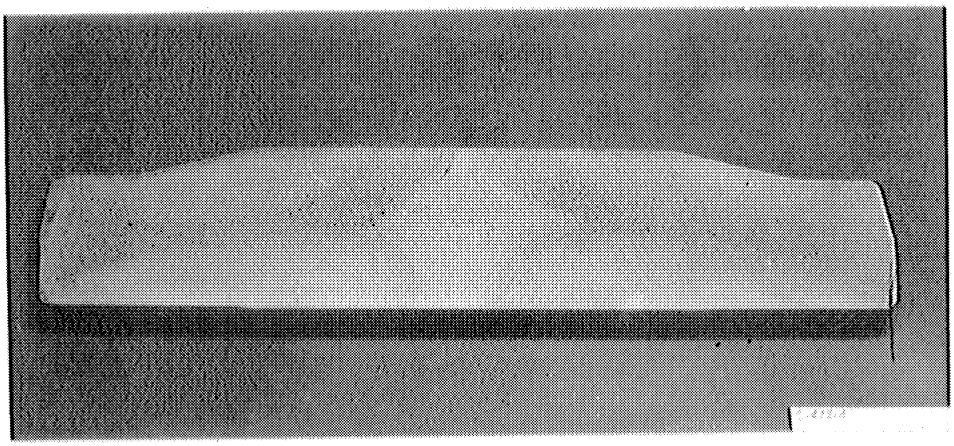


Figure 4g. - Stress-Creep Rate Curves for the Oil-Quenched and Tempered H-40 Turbine Wheel at 1000°, 1100°, and 1200°F. (Heat Treatment: O.Q. 1950°F + T. 8 hours at 1200°F + 3 hours at 1200°F + Ret. 4 hours at 1250°F.)

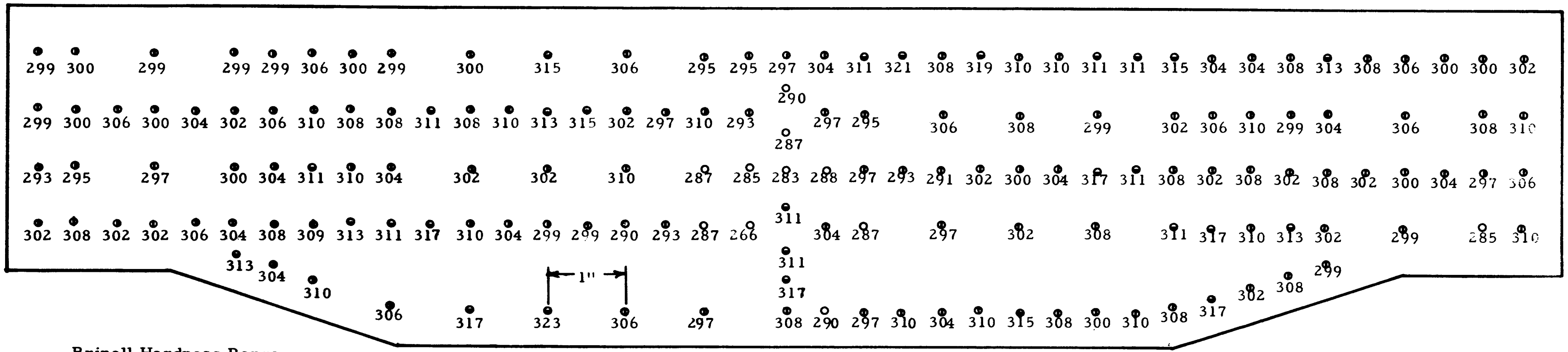


C-422 Disk No. 1. Heat Treatment: (a) Normalize 1900°F + temper 2 hrs. at 1200°F. (b) Full anneal 6 hrs. at 1600°F. Normalize 1900°F + temper 2 + 2 hrs. at 1200°F. BHN=283/323



C-422 Disk No. 4. Heat Treatment: (a) Oil quench 1900°F + temper 8 hrs. at 1200°F. (b) Full anneal 6 hrs. at 1600°F. Oil quench 1900°F + temper 2 + 2 hrs. at 1200°F. BHN=275/352.

Figure 5a. Macroetched Center Sections of C-422 Disks Nos. 1 and 4.



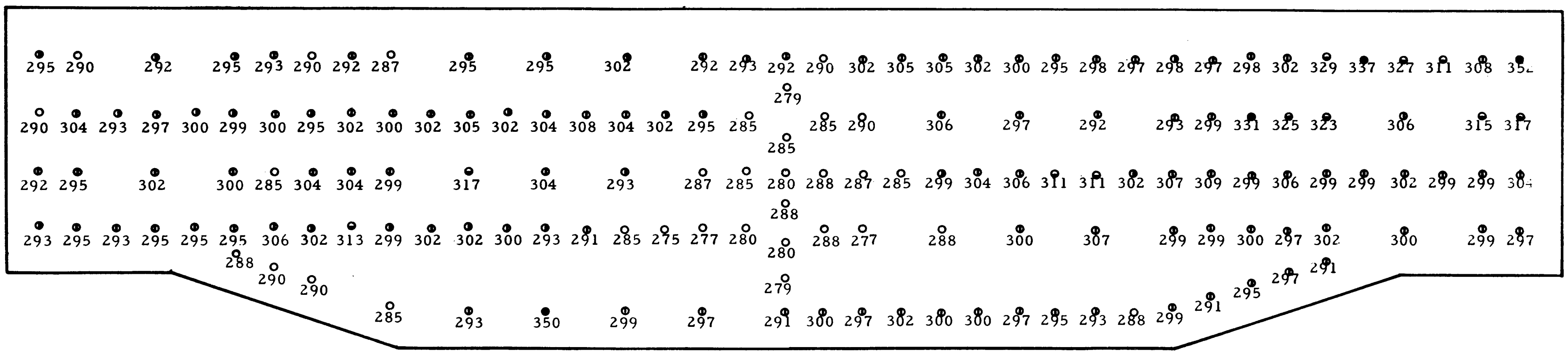
Brinell Hardness Range

○	266 - 290
◉	291 - 310
● (small)	311 - 330
●	331 - 352

Wheel No. 1

First Heat Treatment: N. 1900°F + T. 2 hours 1200°F

Second Heat Treatment: Full anneal 1600°F 6 hours; N. 1900°F + T. 2 + 2 hours 1200°F



Wheel No. 4

First Heat Treatment: O.Q. 1900°F + T. 8 hours 1200°F

Second Heat Treatment: Full anneal 1600°F 6 hours; O.Q. 1900°F + T. 2 + 2 hours 1200°F

FIGURE 5b. - BRINELL HARDNESS SURVEY OF CENTER SECTION OF C-422 STEEL TURBINE WHEELS

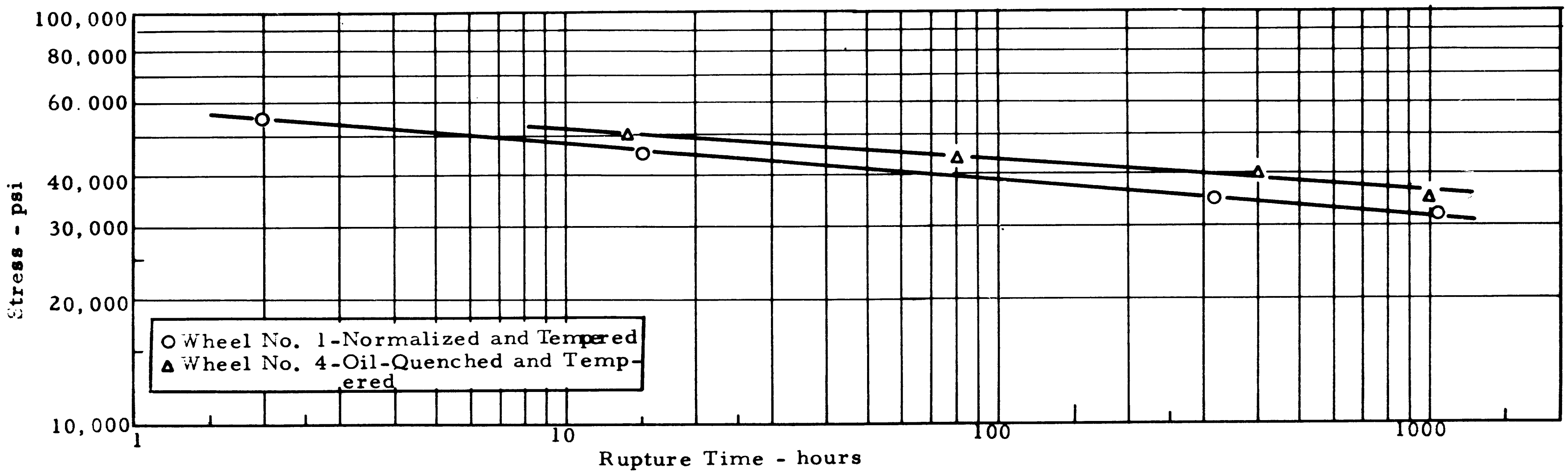


Figure 5c. - Survey Stress-Rupture Time Curves for the C-422 Turbine Wheels at 1100°F.
(Wheel No. 1 - Heat Treatment: N. 1900°F + T. 2 hours at 1200°F.
Second Heat Treatment: Full anneal at 1600°F for 6 hours. N. 1900°F + T. 4 hours at 1200°F.
Wheel No. 4 - First Heat Treatment: O.Q. 1900°F + T. 8 hours at 1200°F.
Second Heat Treatment: Full anneal at 1600°F for 6 hours. O.Q. 1900°F + T. 4 hours at 1200°F.)

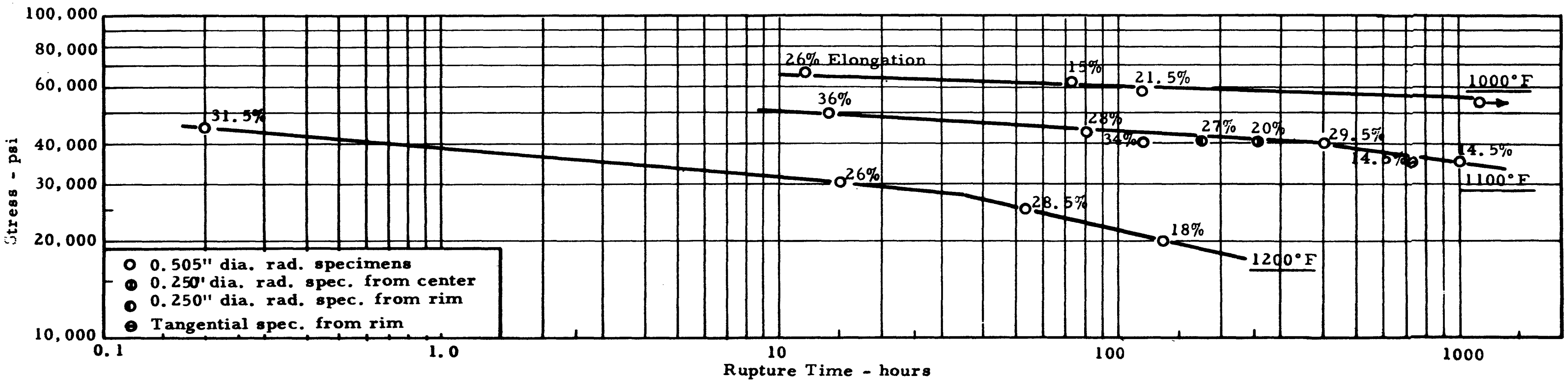


Figure 5d. - Stress-Rupture Time Curves for Oil-Quenched and Tempered C-422 Turbine Wheel at 1000°, 1100°, and 1200°F. (First Heat Treatment: O.Q. 1900°F + T. 8 hours at 1200°F. Second Heat Treatment: Full anneal 6 hours at 1600°F. O.Q. 1900°F + T. 4 hours at 1200°F.)

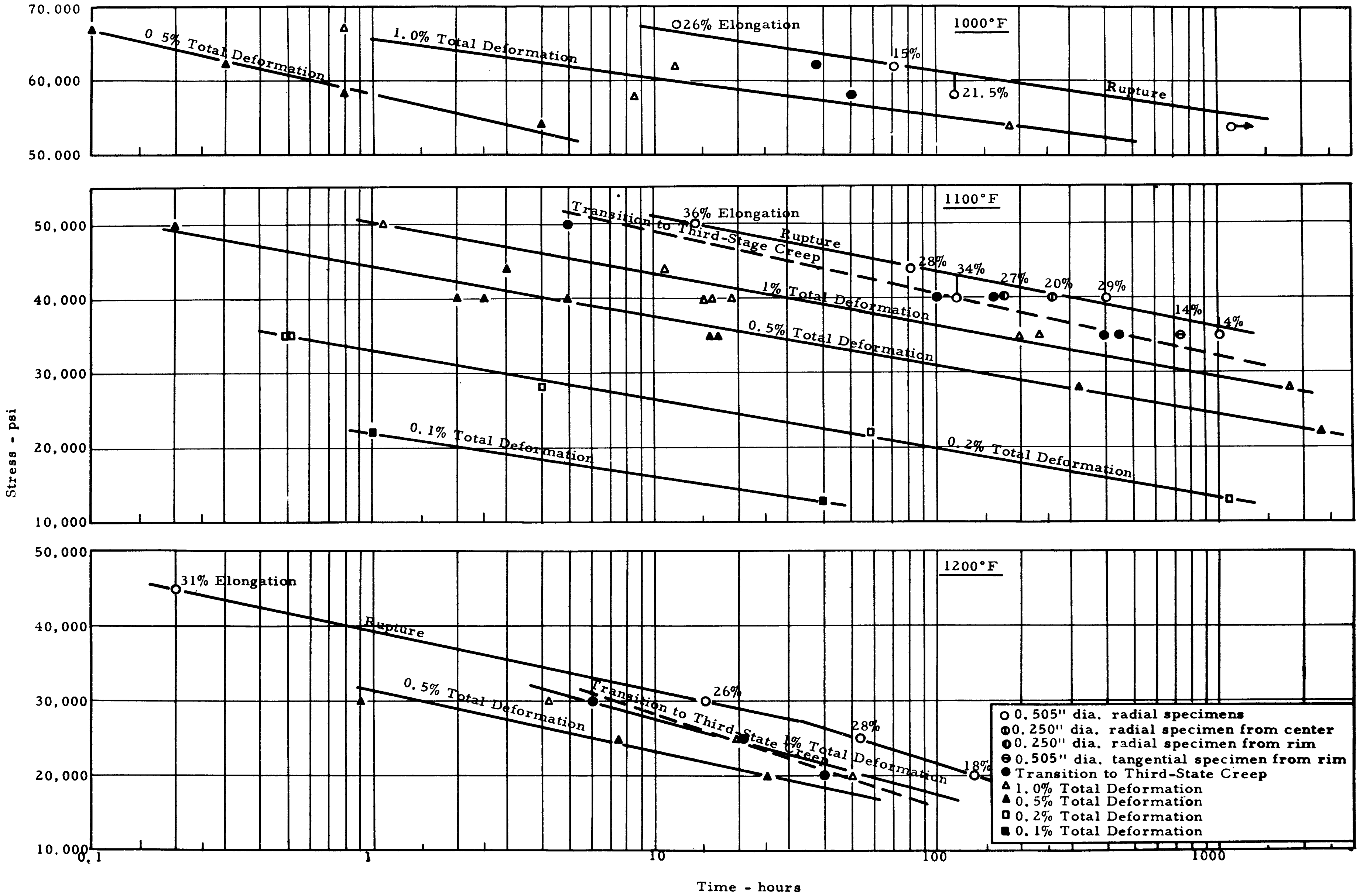


Figure 5e. - Stress-Rupture and Total Deformation Curves Obtained from the Oil-Quenched and Tempered C-422 Turbine Wheel at 1000°, 1100°, and 1200°F. (First Heat Treatment: O.Q. 1900°F + T. 8 hours at 1200°F. Second Heat Treatment: Full anneal 6 hours at 1600°F, O.Q. 1900°F + T. 2 hours at 1200°F.)

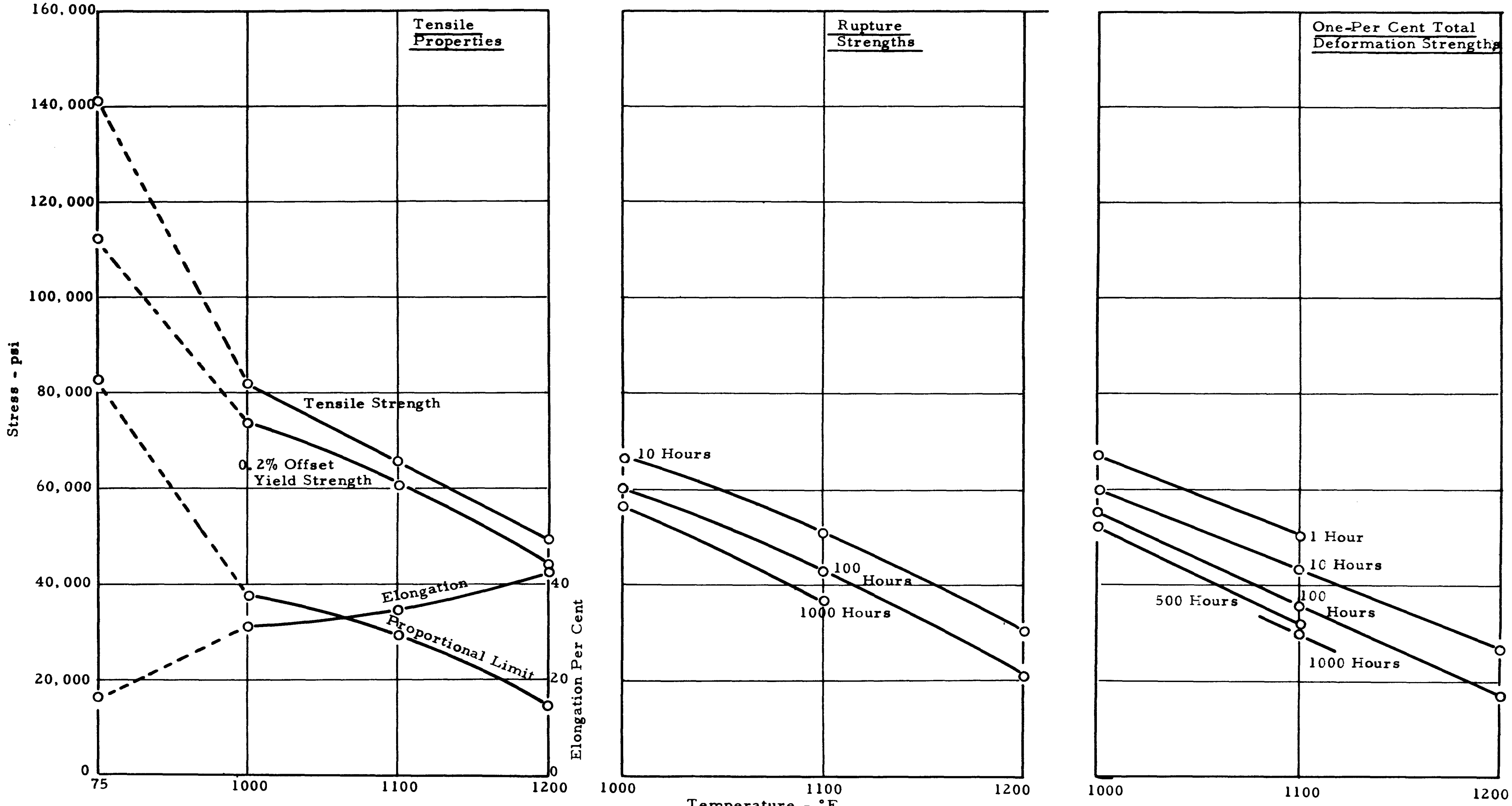


Figure 5f. - Summary of Short-Time Tensile Properties and Rupture and One-Per Cent Total Deformation Strengths of the Oil-Quenched and Tempered C-422 Turbine Wheel.
(First Heat Treatment: O.Q. 1900°F + T. 8 hours at 1200°F.
Second Heat Treatment: Full anneal 6 hours at 1600°F. O.Q. 1900°F + T. 4 hours at 1200°F.)

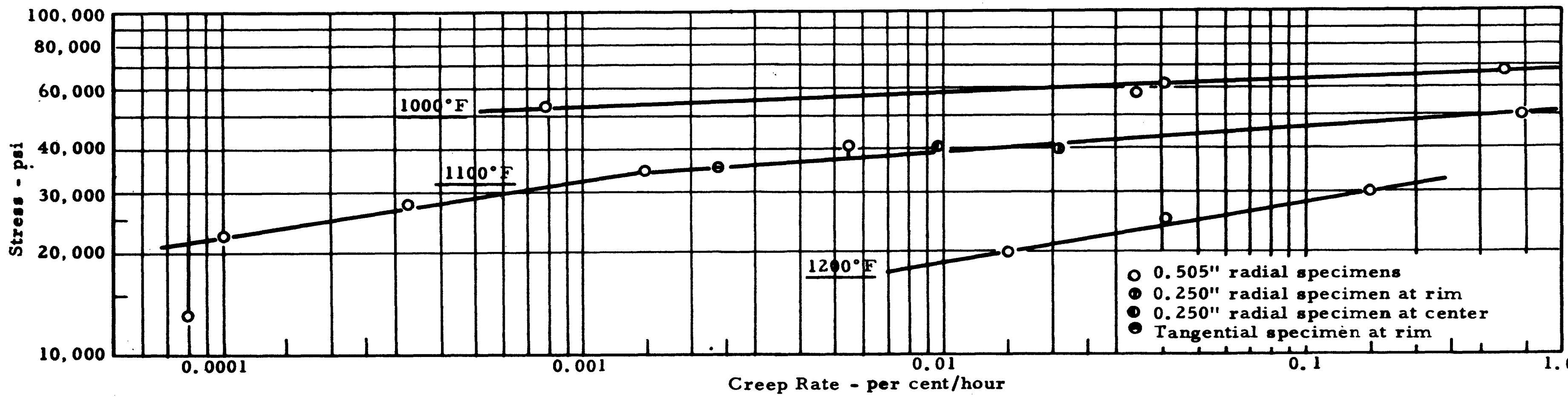


Figure 5g. - Stress-Creep Rate Curves for the Oil-Quenched and Tempered C-422 Turbine Wheel at 1000°, 1100° and 1200°F.
(First Heat Treatment: O.Q. 1900°F + T. 8 hours at 1200°F.
Second Heat Treatment: Full anneal 6 hours at 1600°F. O.Q. 1900°F + T. 4 hours at 1200°F.)

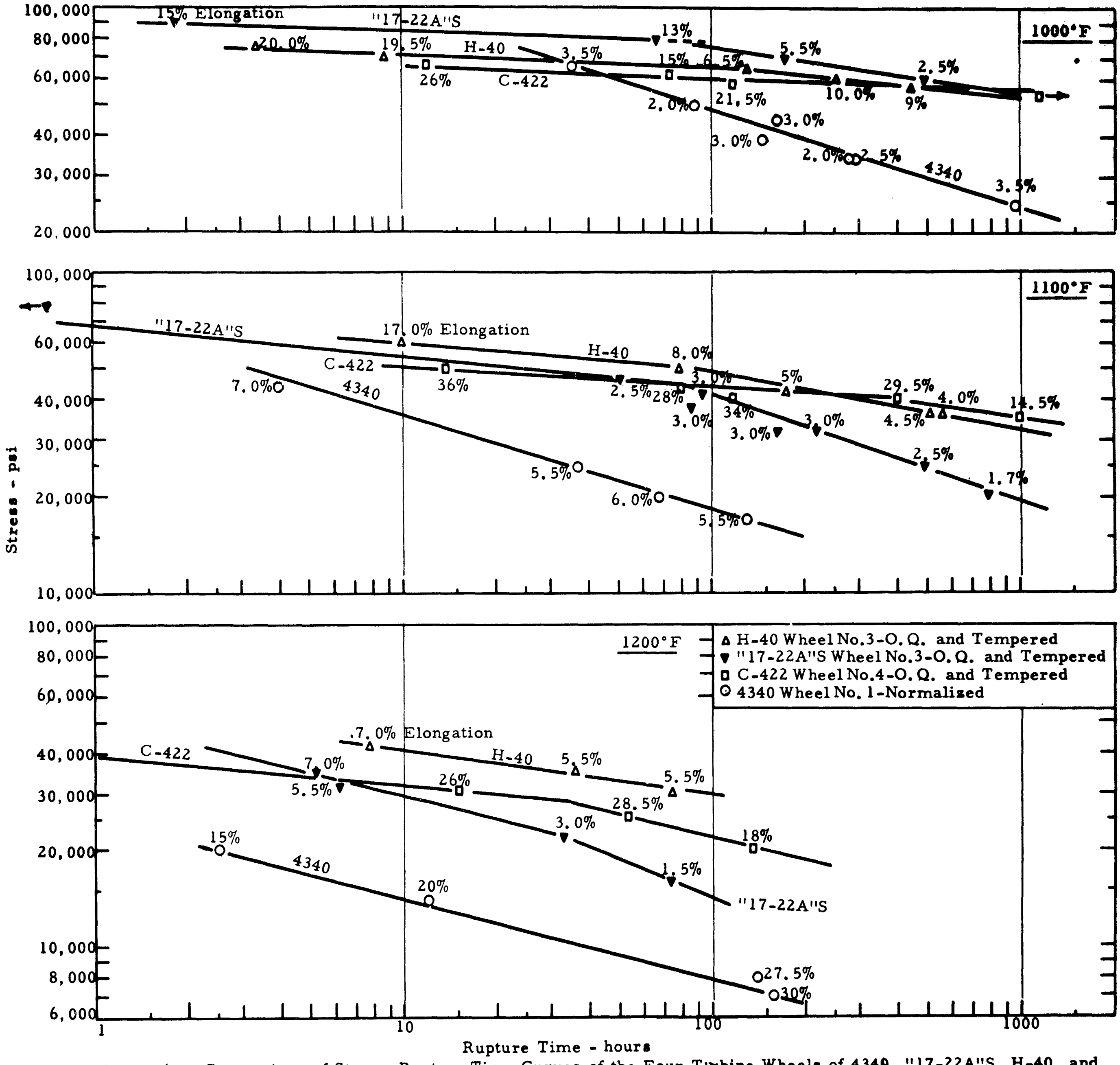


Figure 6. - Comparison of Stress-Rupture Time Curves of the Four Turbine Wheels of 4340, "17-22A"S, H-40, and C-422 Selected for More Extensive Testing at 1000°, 1100°, and 1200°F.
(Heat Treatment: 4340 Wheel No. 1-First Treatment, N. 1750°F + T. 2 hours at 1200°F; Second Heat Treatment, N. 1750°F.

"17-22A"S Wheel No. 3- O.Q. 1750°F + T. 8 hours at 1200°F.
H-40 Wheel No. 3-O.Q. 1950°F + T. 8 hours at 1200°F + Ret. 3 hours at 1200°F + Ret. 4 hours at 1250°F.
C-422 Wheel No. 4-First Treatment, O.Q. 1900°F + T. 8 hours at 1200°F; Second Treatment, Full anneal 1600°F for 6 hours, O.Q. 1900°F + T. 4 hours at 1200°F.)

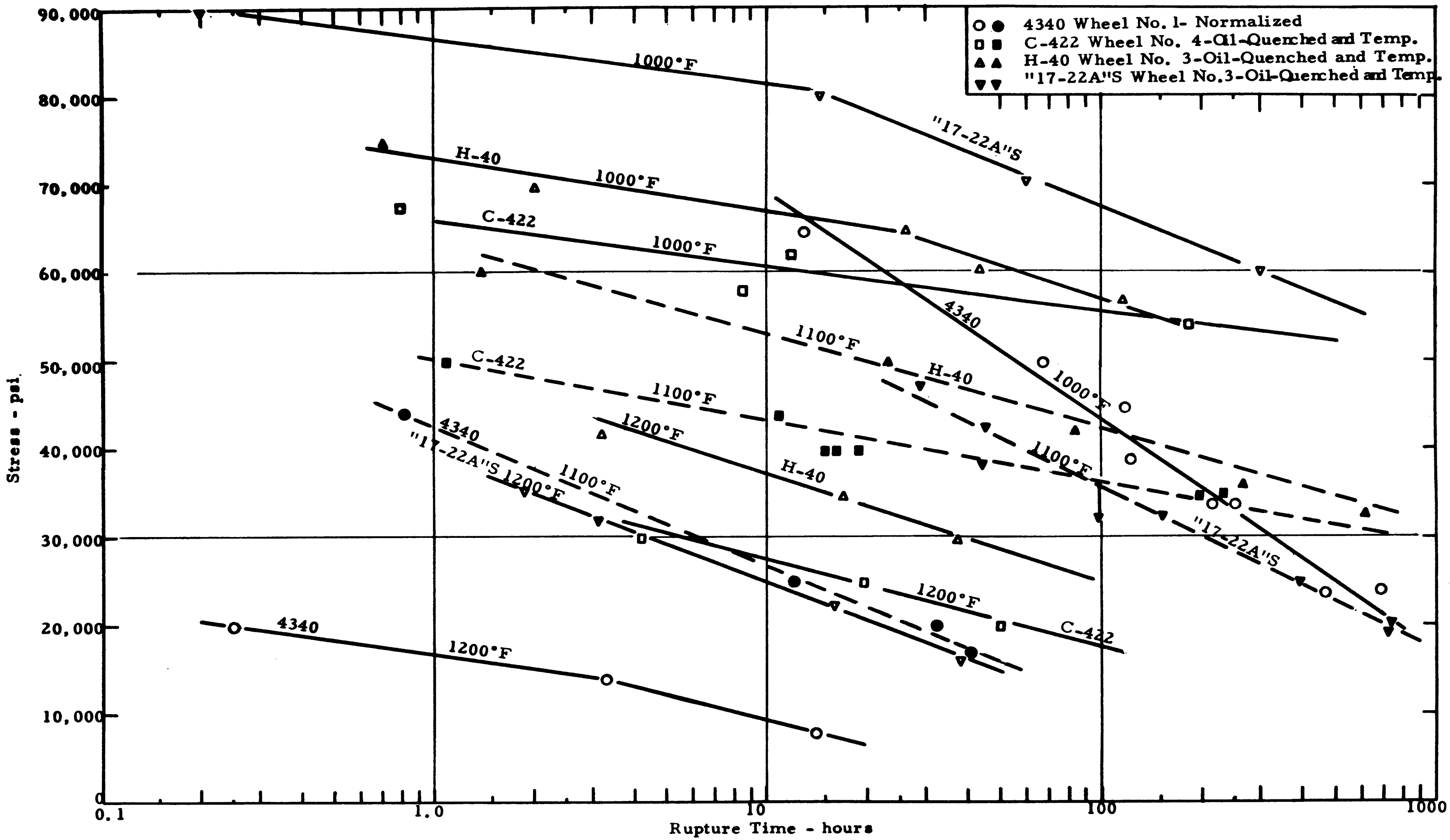


Figure 7. - Comparison of One Per Cent Total Deformation Curves for the Four Turbine Wheels of 4340, "17-22A"S, H-40, and C-422 Selected for More Extensive Testing at 1000°, 1100°, and 1200°F.

(Heat Treatment: 4340 Wheel No. 1-First Treatment, N. 1750°F + T. 2 hours at 1200°F; Second Treatment, N. 1750°F.
"17-22A"S Wheel No. 3-O.Q. 1750°F + T. 8 hours at 1200°F.
H-40 Wheel No. 3- O.Q. 1950°F + T. 8 hours at 1200°F + Ret. 3 hours at 1200°F + Ret. 4 hours at 1250°F.
C-422 Wheel No. 4-First Treatment, O.Q. 1900°F + T. 8 hours at 1200°F; Second Treatment, Full anneal 1600°F for 6 hours, O.Q. 1900°F + T. 4 hours at 1200°F.)