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PLASTIC STRAIN ABSORPTION AS A CRITERION FOR HIGH TEMPERATURE DESIGN

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ABSTRACT

The development of isothermal strain reversal data as an aid to high-temperature design is proposed. A test apparatus capable of mechanically cycling a specimen in tension and compression within set strain limits is described. Data are presented which confirms Coffin's theory that total plastic strain per cycle can be used to predict the number of cycles to failure. Evidence that Inconel strain weakens at the test temperature is noted and grain size is found to be the most important variable affecting the behavior of materials subjected to strain reversals.

INTRODUCTION

The advent of high-performance mechanisms such as jet and rocket motors, gas turbines, and nuclear reactor components has created a necessity for obtaining the high-temperature properties of metals. The structural problems which arise in high-temperature design are in general problems of plastic flow, such as creep, stress relaxation, and strain cycling. This discussion deals primarily with the strain-cycling characteristics of ductile alloys.

Strain-cycling and stress-relaxation phenomena arise principally from changes in operating conditions. Such changes generally involve adjustments in pressures, temperatures, flow conditions, radiation levels, etc. The number, magnitude, and frequency of these depend on the particular application and the physical constants of the metal. These factors, not all of which are independent, may be listed as: (1) coefficient of thermal expansion, (2) thermal conductivity, (3) stress-strain characteristics, (4) design geometry, (5) time-rate of change of temperature, and (6) time under constraint (longer time, lower stress due to relaxation, but greater plastic strain).

In designing for cyclic conditions, three basic types of information are required. First, the designer must establish the complete operating program of the system; second, he must obtain data on the strain-cycling and relaxation properties of the material to be used; third and finally, he must devise suitable methods for applying this data to the design of complex structures. The problem is in general to assess each operating condition to determine the loss of the metals' useful life.

TEST APPARATUS

The problem is one which only recently has received serious attention and very little data are available. Conventional fatigue data, either axial or bending, involve stress cycling of a frequency which is not always related to service conditions. Therefore, a test program was conceived which would evaluate the effect of frequencies measured in minutes or hours instead of merely milliseconds and the controlled variable was strain rather than stress. To accomplish this end, a test apparatus was developed at the Oak Ridge National Laboratory which will permit axial strain-cycling of a metal specimen at elevated temperatures in controlled environments.

A simplified schematic drawing of this apparatus is shown in Fig. 1 (Y-20821). The specimen shown in this drawing is a 3/4-in. OD tubular specimen which is machined to have a gage length of 1 in. with a 0.060-in. wall. The top shoulder of the specimen is welded to the casement and the bottom shoulder is welded to the piston pull rod which runs through the specimen. The specimen is stressed to produce a designated total strain, in tension and compression, by means of controlled gas pressure either on top or bottom of the piston. The strain is sensed by extending the pull rod through pressure seals at the top of the cylinder to the dial gage and motion transmitter. The motion transmitter, which converts small movements into pressure changes, is connected to two pressure switches which are set to operate at pressures corresponding to the desired strain limits. When the strain limit in one direction is reached, the pressure switch will actuate appropriate solenoid valves to apply controlled pressure to the other side of the piston. In this manner one can apply an alternating load to a specimen while maintaining fixed strain limits. The magnitude of the alternating stress is set for each test to obtain the desired strain in a

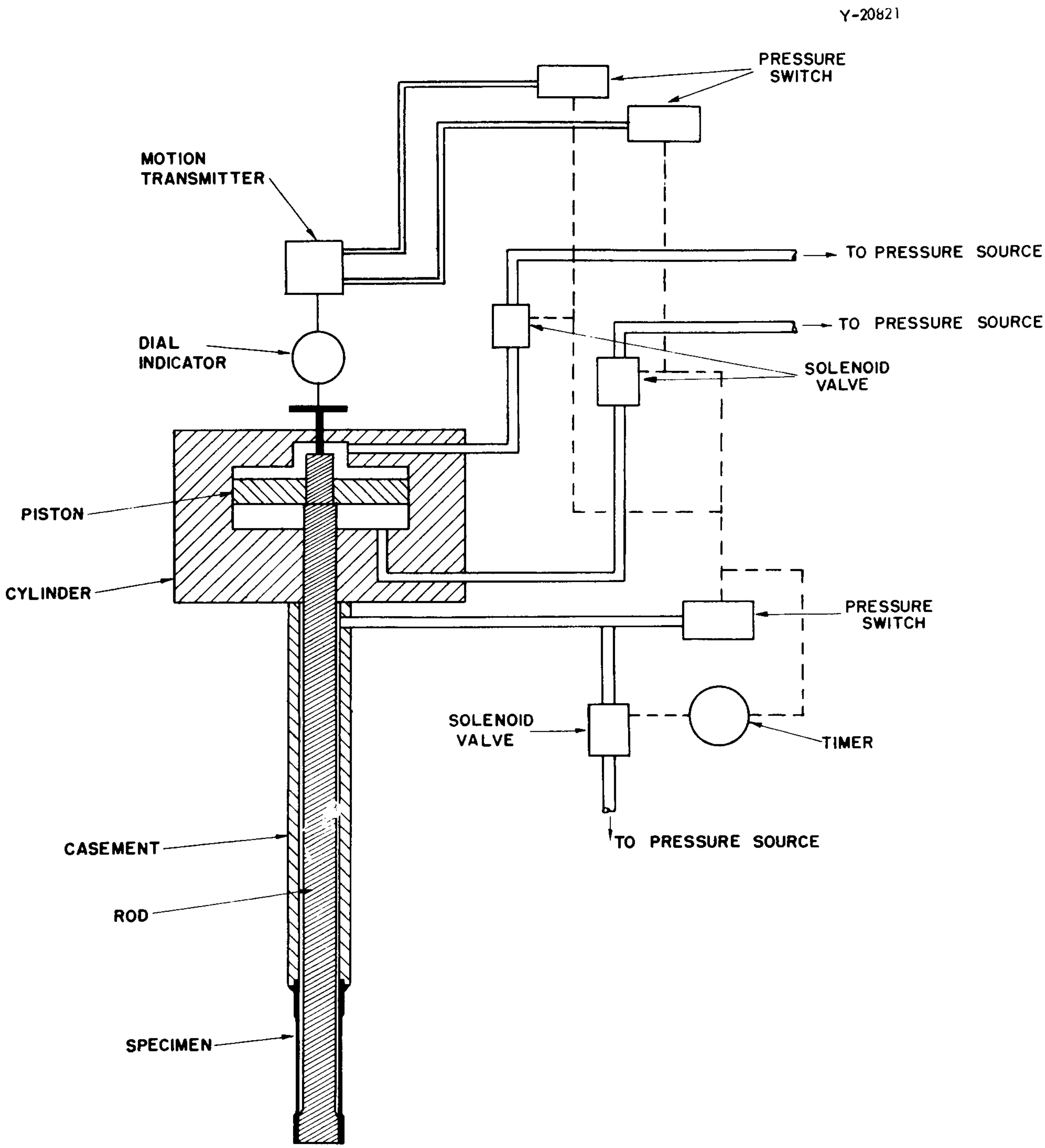

Fig. 1 Strain Cycle Apparatus

2-min cycle; however, it will be shown later that the cycle time does vary somewhat with the number of cycles. To determine failure, the specimen is internally pressurized at a very low pressure which drops at the first complete crack in the wall of the specimen. A pressure switch senses the drop and actuates the proper solenoids to bleed the pressure from the piston and cut off the pressure source. This, in essence, gives an exact measure of the specimens' useful life.

The time and expense necessary to affix a new tubular test specimen for each test created a desire to modify the test rig to accept a threaded rod specimen. This was accomplished and to date the majority of data have been produced by the modified rigs. There is one point to consider; wherein the tubular specimen's failure is defined as the first complete crack, the rod specimen's failure is by complete rupture. The type of strain cycle obtained from this type of rig is shown in Fig. 2 (ORNL-LR-DWG 20330). It can be seen that the relationship of strain-time obtained in the mechanical device is not quite the same as the type of strain-time curve which is obtained from a thermal cycle. In order to more exactly simulate this square type of cycle some further modifications were made. As shown in Fig. 3 (ORNL-LR-DWG 20331), a slight change was made in the pull rods and cylinder head design. The head was made to furnish structurally rigid reference surfaces so that the strain limits could be set on the pull rod by threaded nuts which can be locked in place and act as stops. The total strain can therefore be adjusted to the desired limit per cycle. The time per cycle is regulated by a timer which actuates solenoid valves to apply pressure to either the top or bottom of the piston. The pressure in this test is not critical and must only be of a magnitude to strain the specimen to the strain limits of the test. In this type of test, the time per cycle is held constant; however, the plastic strain per cycle varies with the number of cycles.

The test program that was initiated was one to investigate the high-temperature strain-cycling behavior of Inconel, a common high-temperature Ni-Cr-Fe alloy, considering the following variables:

1. Temperature
2. Grain Size
3. Specimen Geometry-Fabrication History

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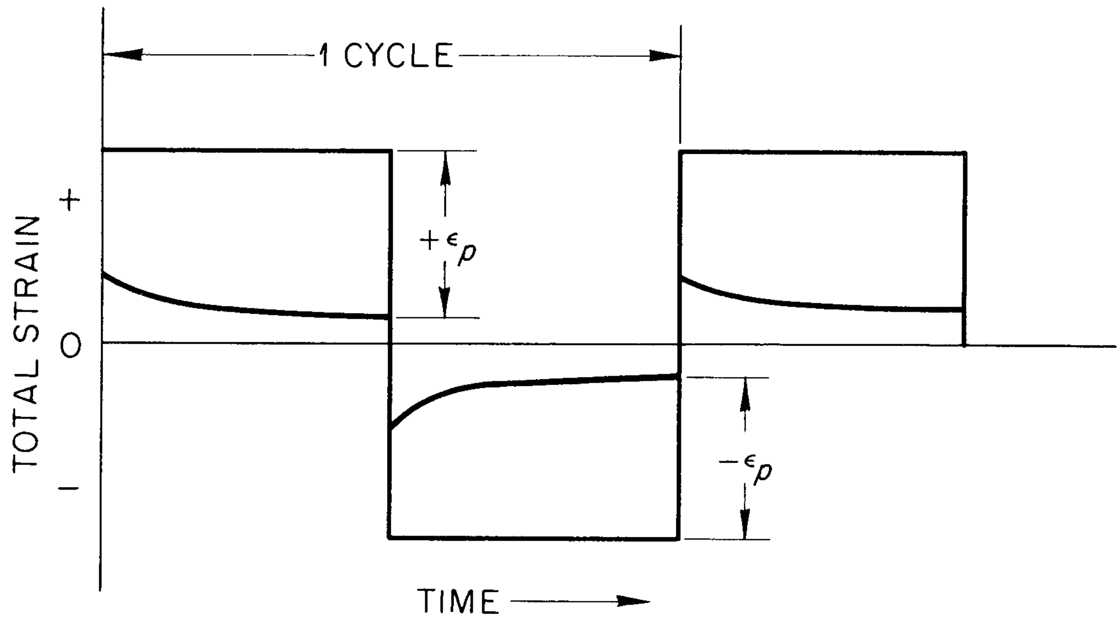

Typical Thermal Cycle

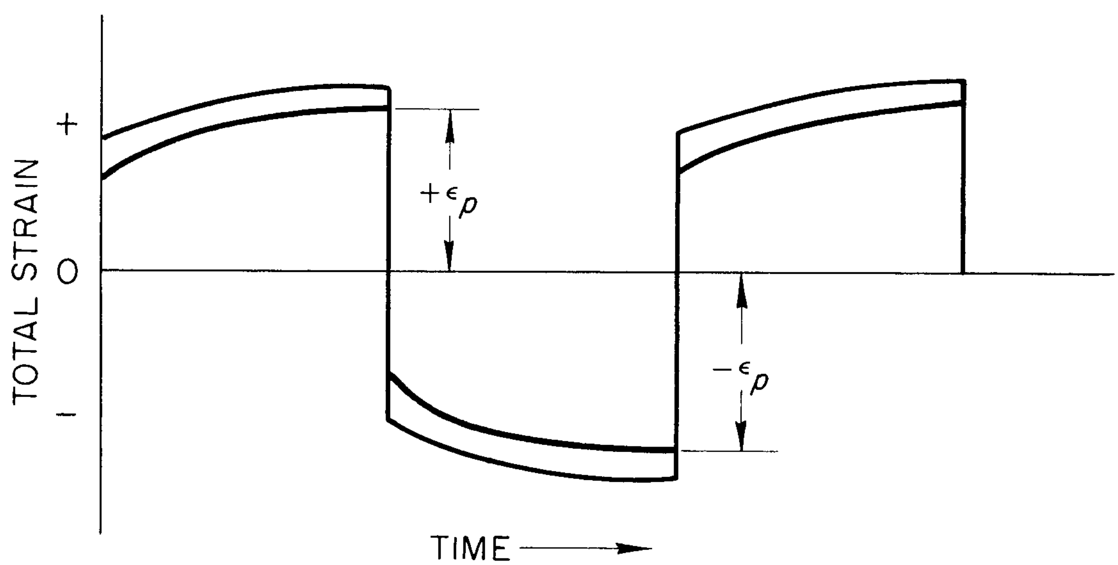

Fig. 2 Comparison of Thermal Strain-Cycle to Strain-Cycle Produced by Apparatus.

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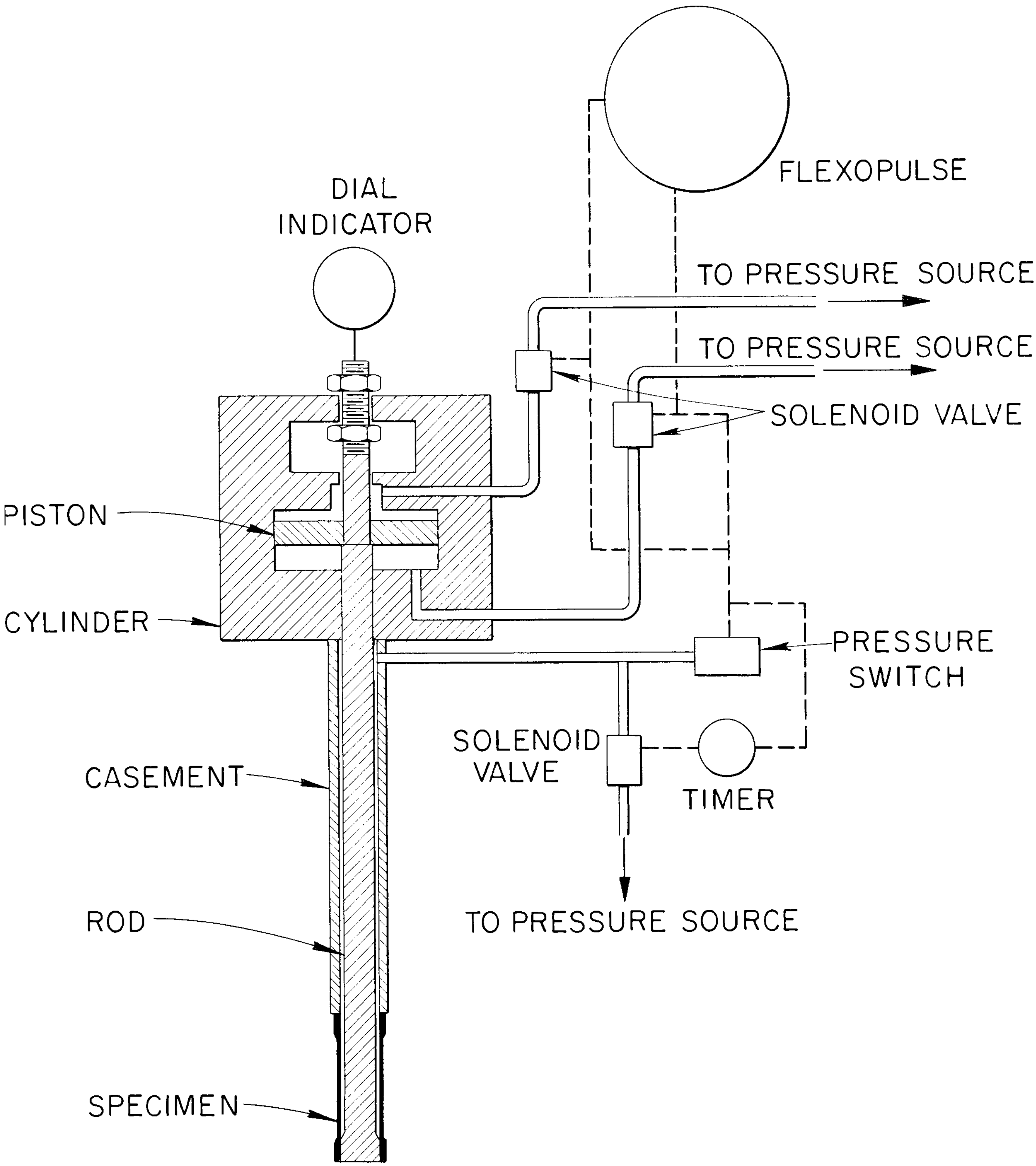

Fig. 3. Strain Cycle Apparatus (Modified).

This test program is actually a segment of an over-all investigation of high-temperature dynamic load properties. The temperature range in this study was chosen so as to be above the work hardening range but below that temperature where other metallurgical instabilities might occur. This permitted a testing range from 1300 to 1600°F.

The effect of the second variable, grain size, was determined by comparing results of material tested after a 1650°F anneal with that of tests performed on the same heat after a 2050°F anneal for two hours. The grain size of the two types of specimens are shown in Figs. 4 (Y-22523) and 5 (Y-22522). All tests were run in argon to exclude any effect that environment may contribute.

RESULTS AND DISCUSSION

Coffin,[1] in his study of the problem of thermal strain cycling, used equipment where one could thermal cycle a tubular specimen with restrained ends. Characteristic fatigue curves were obtained by plotting the ΔT of the specimen versus the log of the number of cycles to failure. From this data it was then possible to separate the plastic strain per cycle from the total strain and obtain an empirical relation of the form

$$N^{\alpha} \epsilon p = C \qquad (1)$$

where N is the number of cycles to failure, ϵp is the plastic strain per cycle, and α and C are experimental constants. However, due to the fact that the greatest magnitude of plastic strain per cycle obtainable from his rig was one per cent, Coffin used the ultimate tensile strain as his high-strain point.

Using this as a basis, the first study at ORNL was to determine the effect of the magnitude of isothermal strain cycles on the number of cycles to failure. Results have been obtained from testing fine and coarse-grain Inconel rod at 1300, 1500, and 1600°F in argon and are shown in Figs. 6 (ORNL-LR-DWG 20332), 7 (ORNL-LR-DWG 20333), and 8 (ORNL-LR-DWG 20334). The log ϵp is plotted versus log N where ϵp is the measured plastic strain per cycle and N is the number of cycles to failure. The type of strain cycle used to obtain these plots is shown in the corner of each plot.

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[1] Coffin, L. F., "A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal," Trans. ASME, 1954, p. 931.

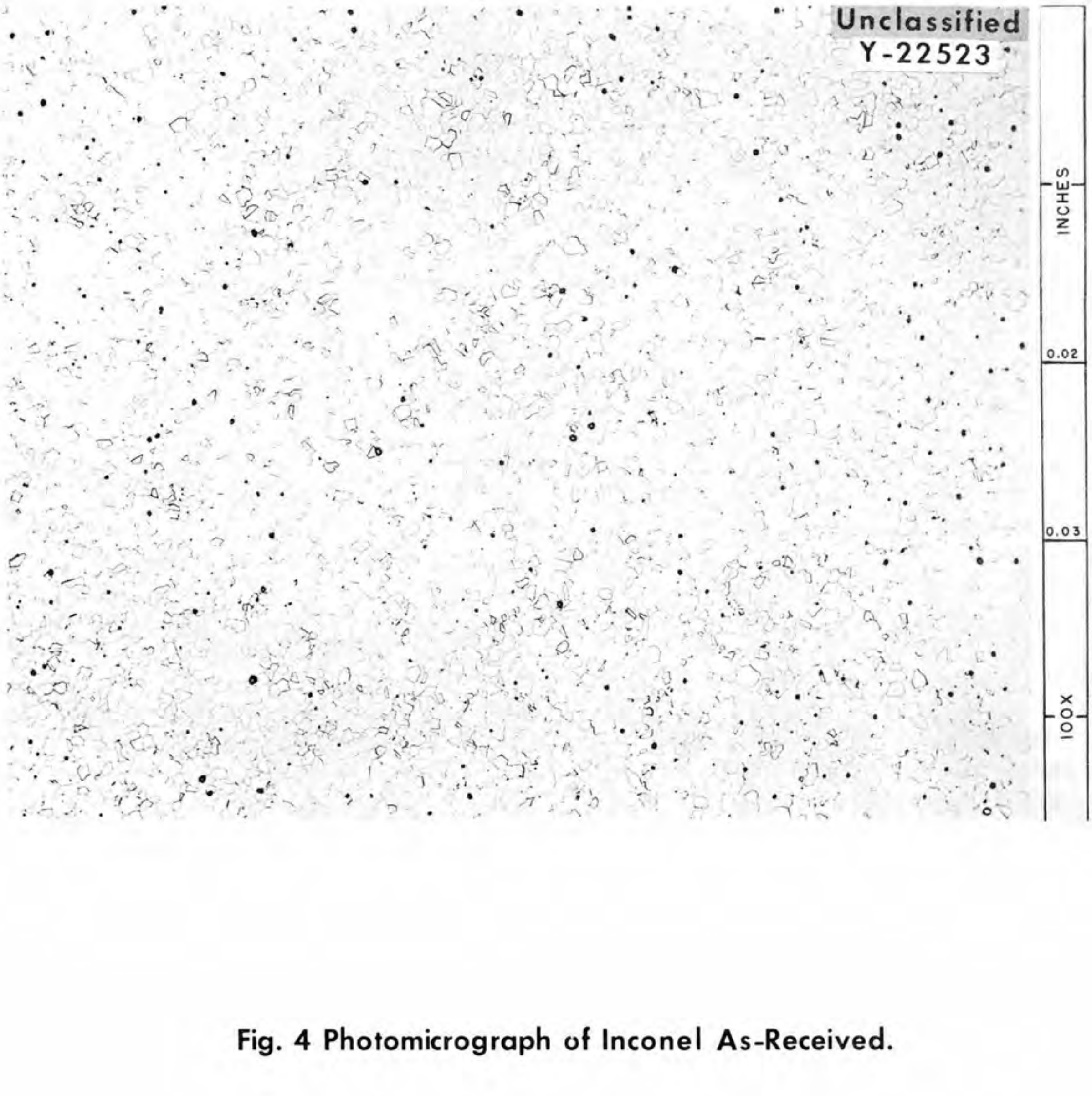

Fig. 4 Photomicrograph of Inconel As-Received.

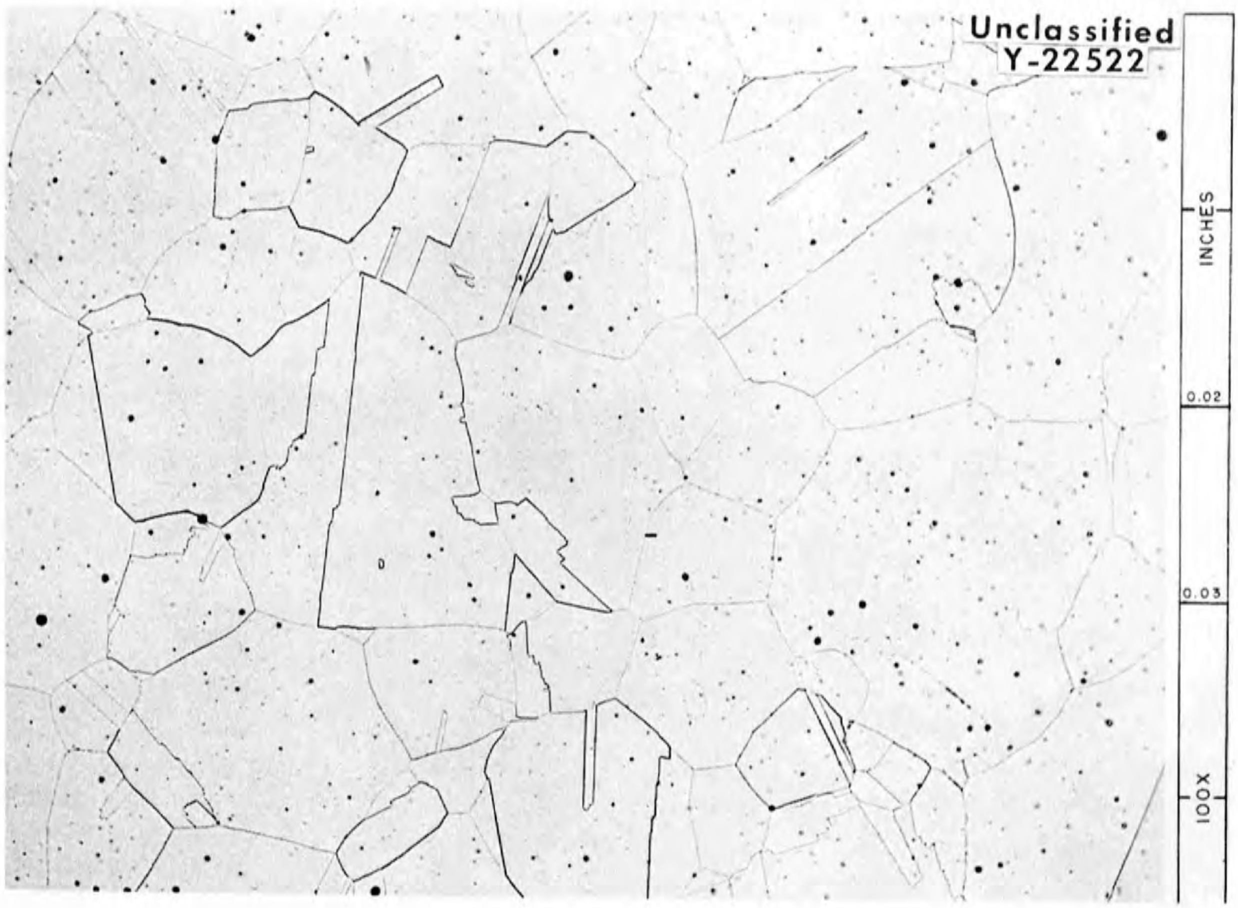

Fig. 5 Photomicrograph of Inconel After a 2050 F Anneal for 2 hr.

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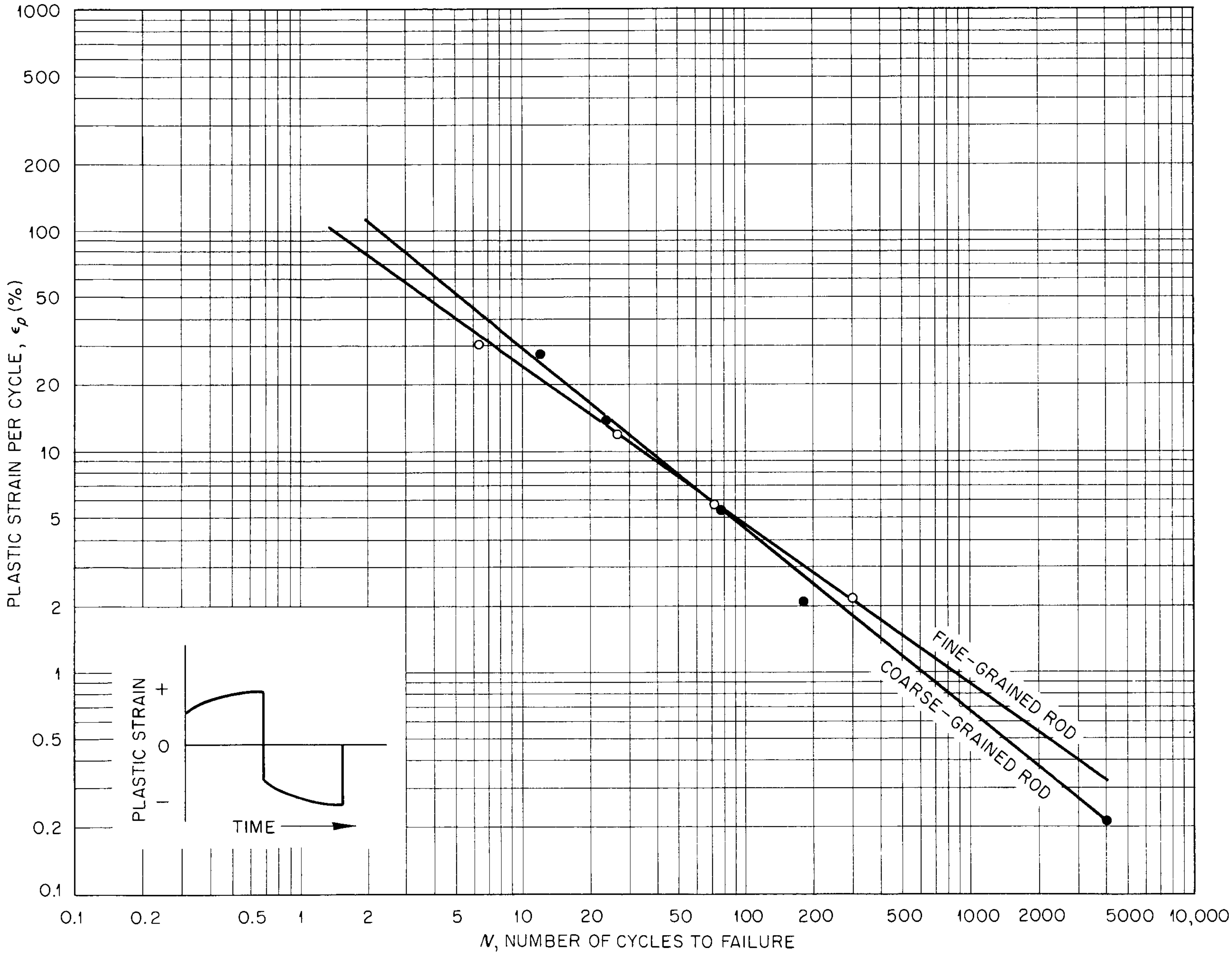

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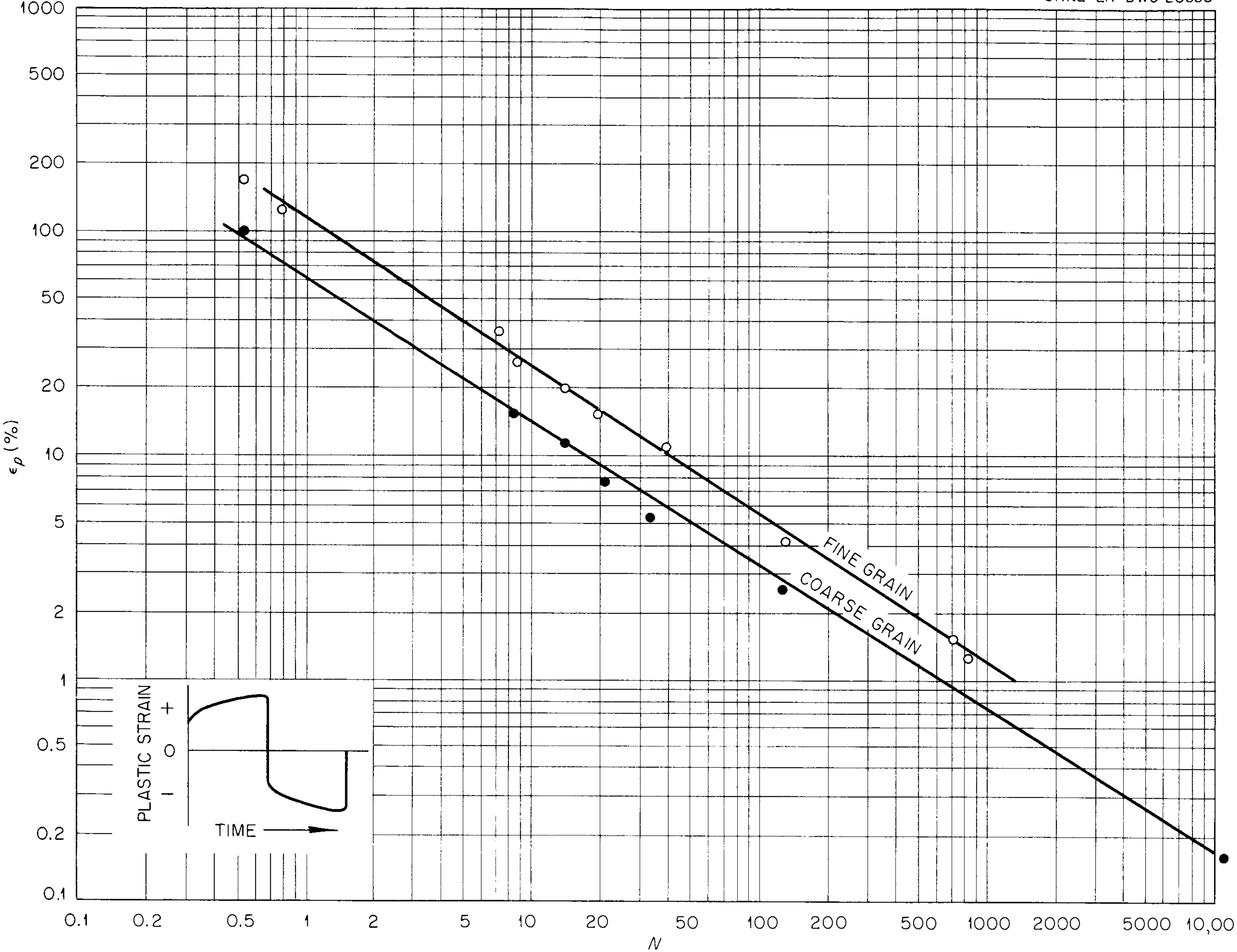

Fig. 7. Strain Cycle Properties of Inconel Rod Tested at 1500°F.

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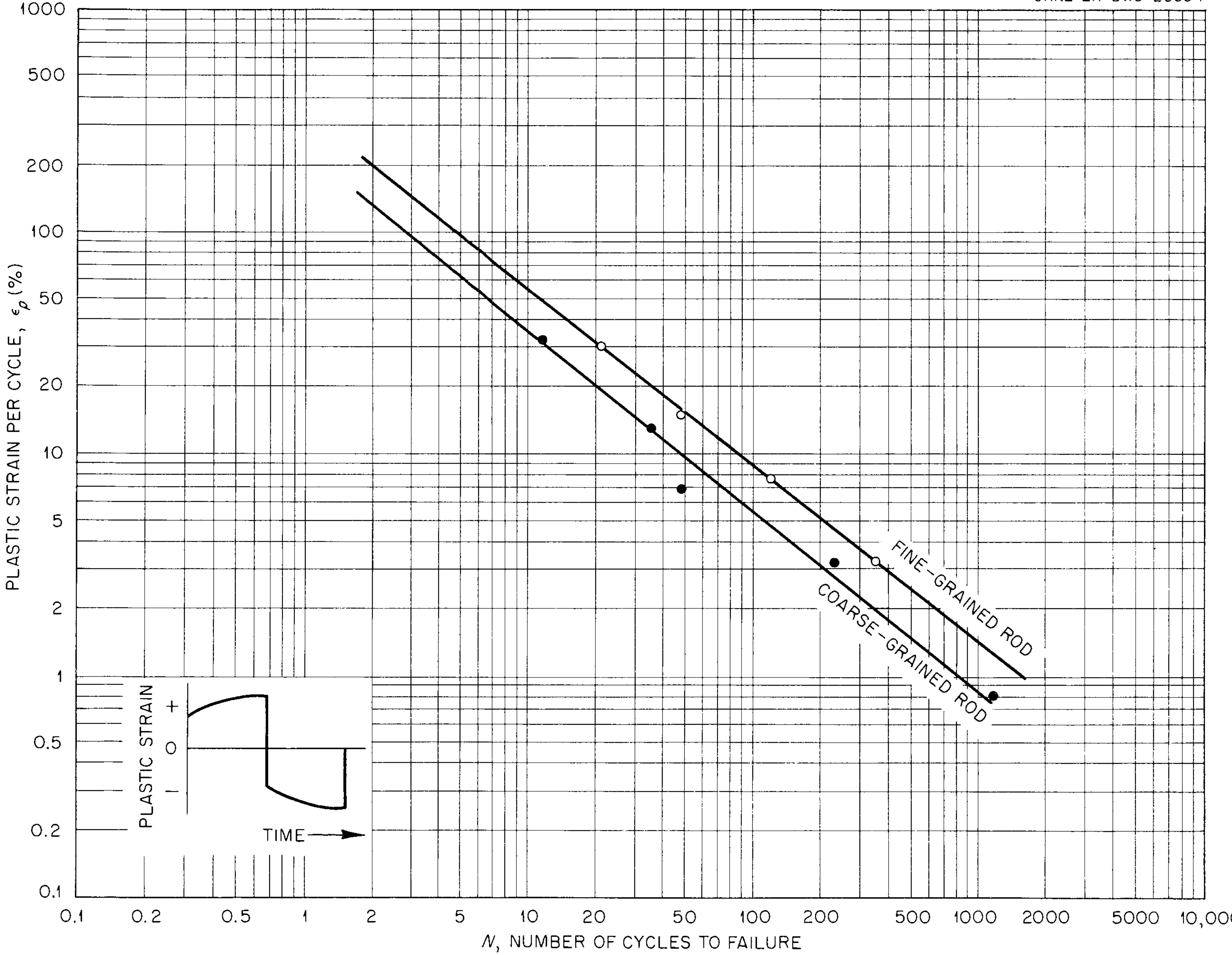

Fig. 8. Strain Cycle Properties of Inconel Rod Tested at 1600°F.

A comparison of the fine and coarse-grain data shows that at both the elevated temperatures, coarse-grain material exhibited fewer cycles to failure. The logical conclusion one could make from this is that a fine-grain size is more desirable than a coarse-grain size in component parts subjected to thermal cycles. A comparison of the plastic strain properties at the three temperatures are shown in Figs. 9 (ORNL-LR-DWG 20335) and 10 (ORNL-LR-DWG 20336). There appears to be anomalous effects produced by temperature for tests with high plastic strains per cycle. However, for low plastic strain per cycle, the effect of temperature seems to be quite small. Metallographic examination of both fine- and coarse-grain specimens disclosed that all failures were intergranular and that cracks were initiated at the surface. As in all types of fatigue failures, there seems to be two stages of failure, the initiation of cracks then their propagation. This second stage might be affected by the magnitude of the strain and the test temperature.

The test results just discussed were obtained from the rig where the stress and plastic strain per cycle are held constant. However, the time per cycle decreases as shown in Fig. 11 (ORNL-LR-DWG 20337) where the time per cycle is plotted versus the number of cycles. Tests of both fine-and coarse-grain material show this typical behavior at all three temperatures. This is an indication that the elastic properties of the material changes with each strain reversal. In many applications, a component part which is thermally strain cycled will have a superimposed stress. While this stress is usually well within design limits based upon creep tests, the material may weaken to such a degree that the load no longer is within the design limits for the component part.

A similar series of tests have been run on tubular specimens at 1500°F in argon. The results are shown in Fig. 12 (ORNL-LR-DWG 20338) for fine- and coarse-grain specimens. The grain-size effect is similar to that seen in the case of rod data. Also shown in Fig. 12 is the fine-grain rod data for comparison to the tube data and indicates that for lower strains, tubular specimens fail in fewer cycles. However, this difference seems to be caused by the method of sensing failure, for if the tube specimen test is failed in the same manner as rod tests (test points shown in Fig. 12 as stars), the data are very similar. We can, therefore, conditionally postulate that the strain cycle properties are very similar between heats, fabrication histories, and specimen geometries, if these variables do not tend to cancel one another.

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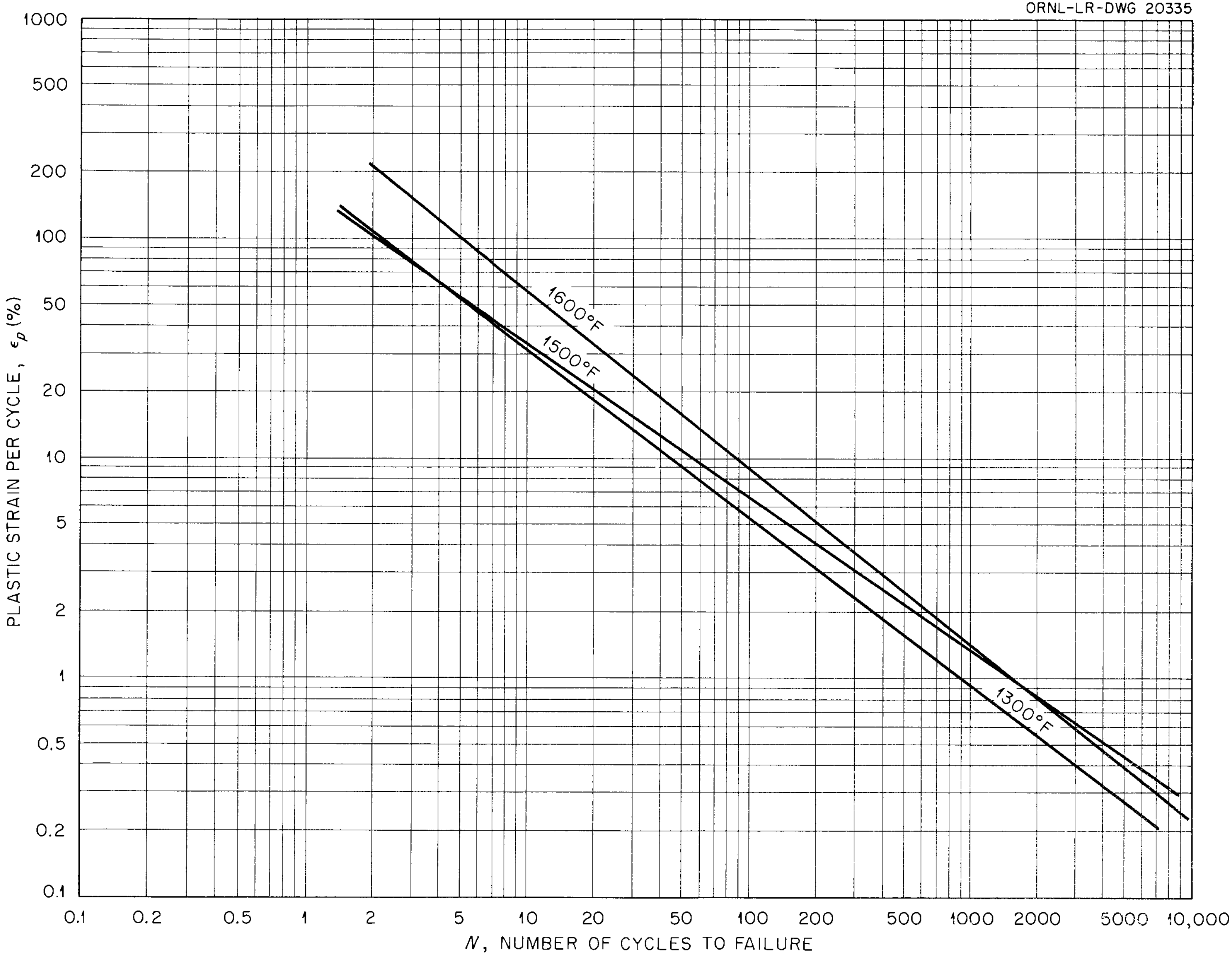

Fig. 9. Comparison of the Strain Cycles Properties of Inconel Rod Tested at 1300, 1500, and 1600°F. Material in the As–Received Condition.

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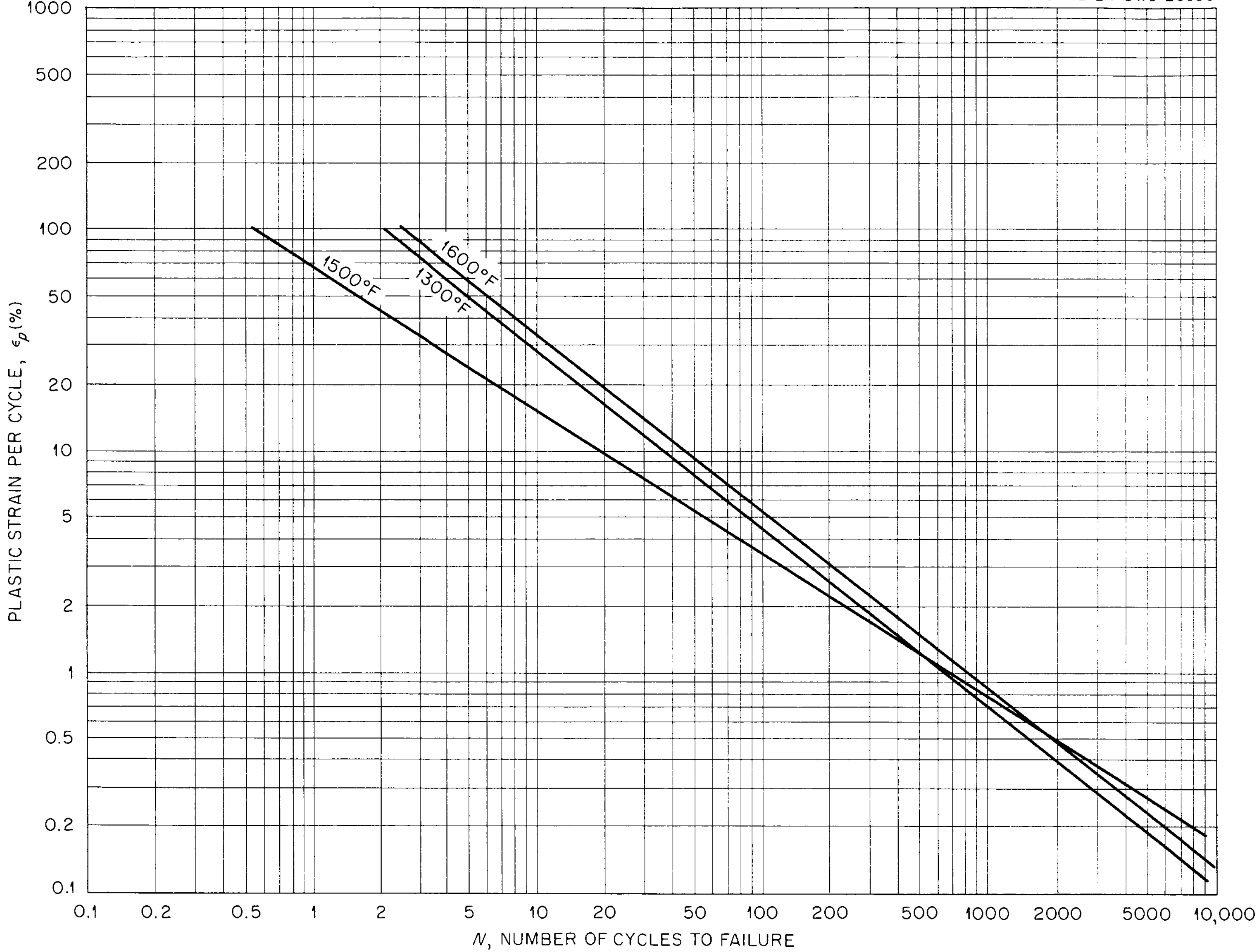

Fig. 10. Comparison of the Strain Cycle Properties of Inconel Rod Tested at 1300, 1500, and 1600°F. Material in the Annealed Condition 2050°F for 2 hr.

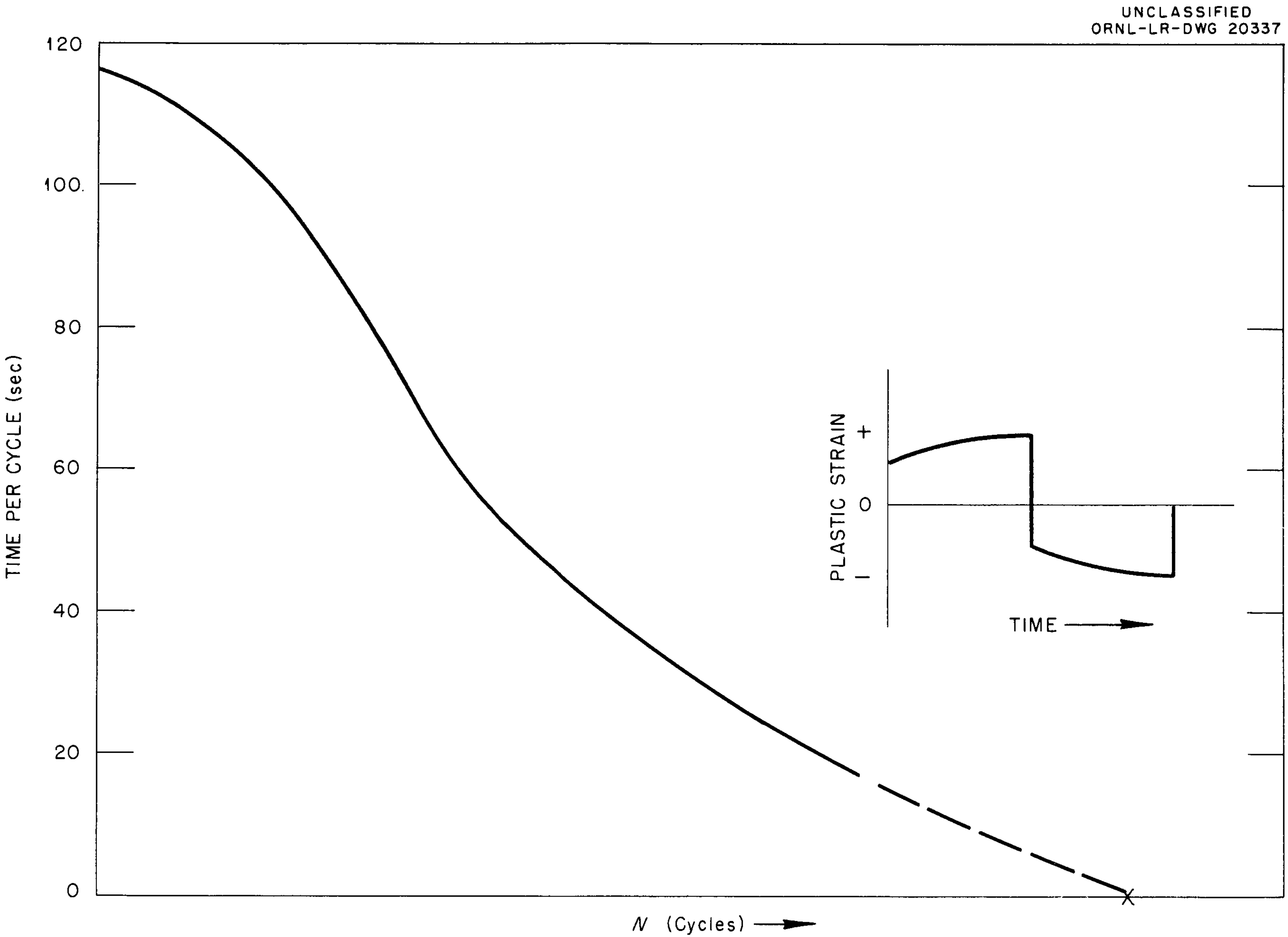

Fig. 11. Typical Plot of Time Per Cycle vs. No. of Cycles. Plastic Strain Held Constant.

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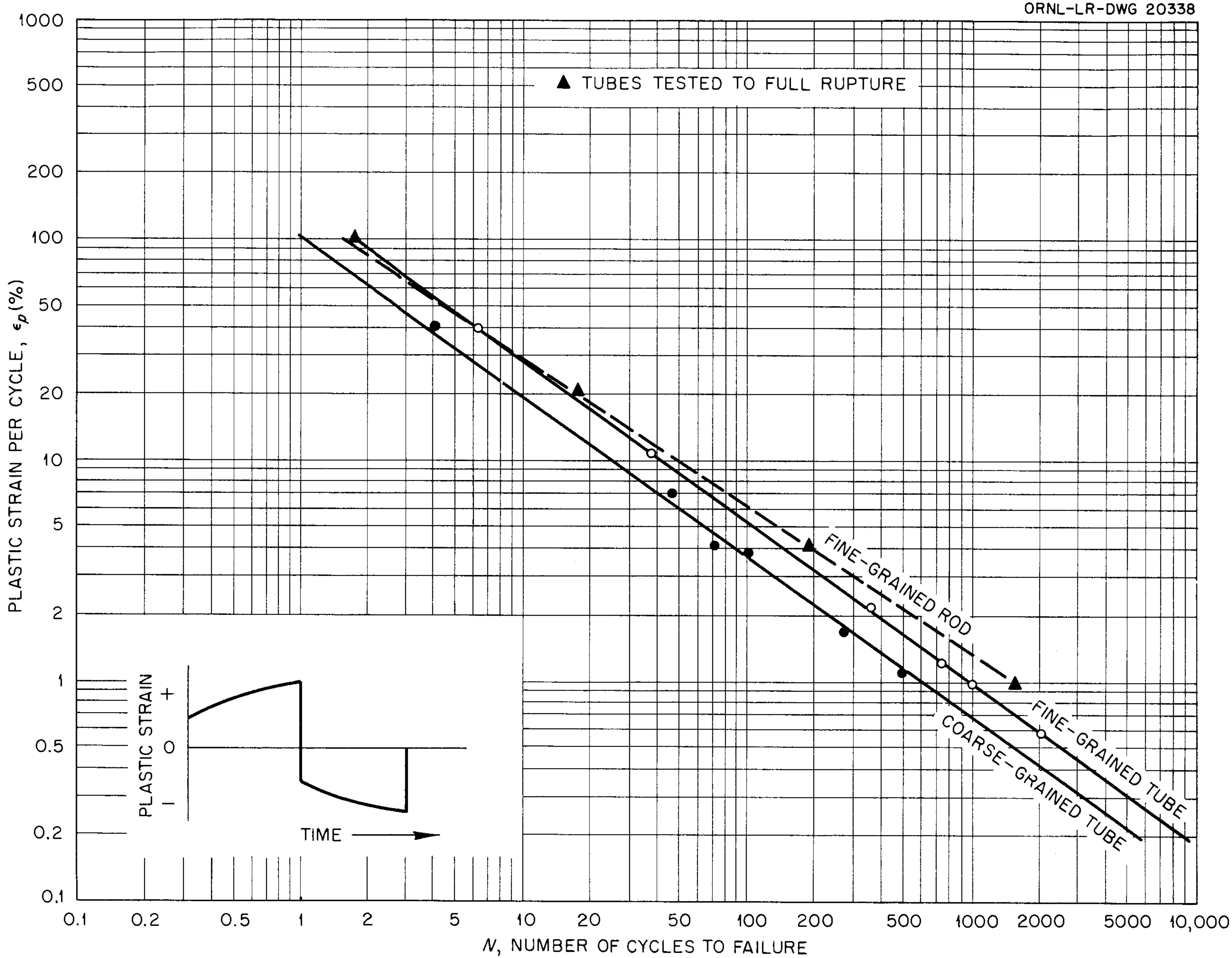

Fig. 12. Strain Cycle Properties of Inconel Tubes Tested at 1500°F.

The effect of the square wave form of total strain was determined by testing tubular specimens in the modified rig. In this type of test, the total strain and cycle time are held constant and stress and plastic strain vary with the number of cycles. The cycle frequency for these tests was 2-min per cycle. Figure 13 (ORNL-LR-DWG 20339) shows the plastic strain per cycle plotted versus the number of cycles for one typical low strain test. Here again evidence of a decrease in elastic properties is exhibited by the increase in plastic strain per cycle. Since there is not a constant plastic strain per cycle, the data cannot truly be plotted on the log ϵp versus log N chart. However, by using Coffin's log total plastic strain, which is the integrated area under the plot in Fig. 13, versus the number of cycles to failure, one can see the comparison. Figure 14 (ORNL-LR-DWG 20340) is a log $N\epsilon p$ versus log N plot for Inconel tubular specimens tested at 1500°F in argon. The line is the data taken from the constant plastic strain tests and the points are tests obtained by the 2-min cycle test with increasing plastic strain per cycle. These test points show clearly that the empirical equation

$$N^{\alpha} \epsilon p = C \qquad (1)$$

holds true for plastic strain cycling at elevated temperatures with approximately the same cycle frequency. Therefore, since this total plastic strain correlation holds true, the Inconel rod tests at 1300, 1500, and 1650°F are shown in Figs. 15 (ORNL-LR-DWG 20341), 16 (ORNL-LR-DWG 20342), and 17 (ORNL-LR-DWG 20343) where log $N\epsilon p$ is plotted versus log N.

SUMMARY

A study of isothermal strain-cycle properties has been accomplished for Inconel at elevated temperatures by means of a new type of test apparatus. The apparatus consists of a means to mechanically strain-cycle a specimen, either tubular or rod, within set strain limits at elevated temperatures in a controlled environment.

The effects of four variables were studied in relation to strain-cycling design criteria. These were: (1) temperature, (2) grain size, and (3) specimen geometry and (4) fabrication history. Significant results obtained from this investigation are as follows:

1) When log plastic strain per cycle is plotted versus log number of cycles to failure, a straight line results to 10,000 cycles.

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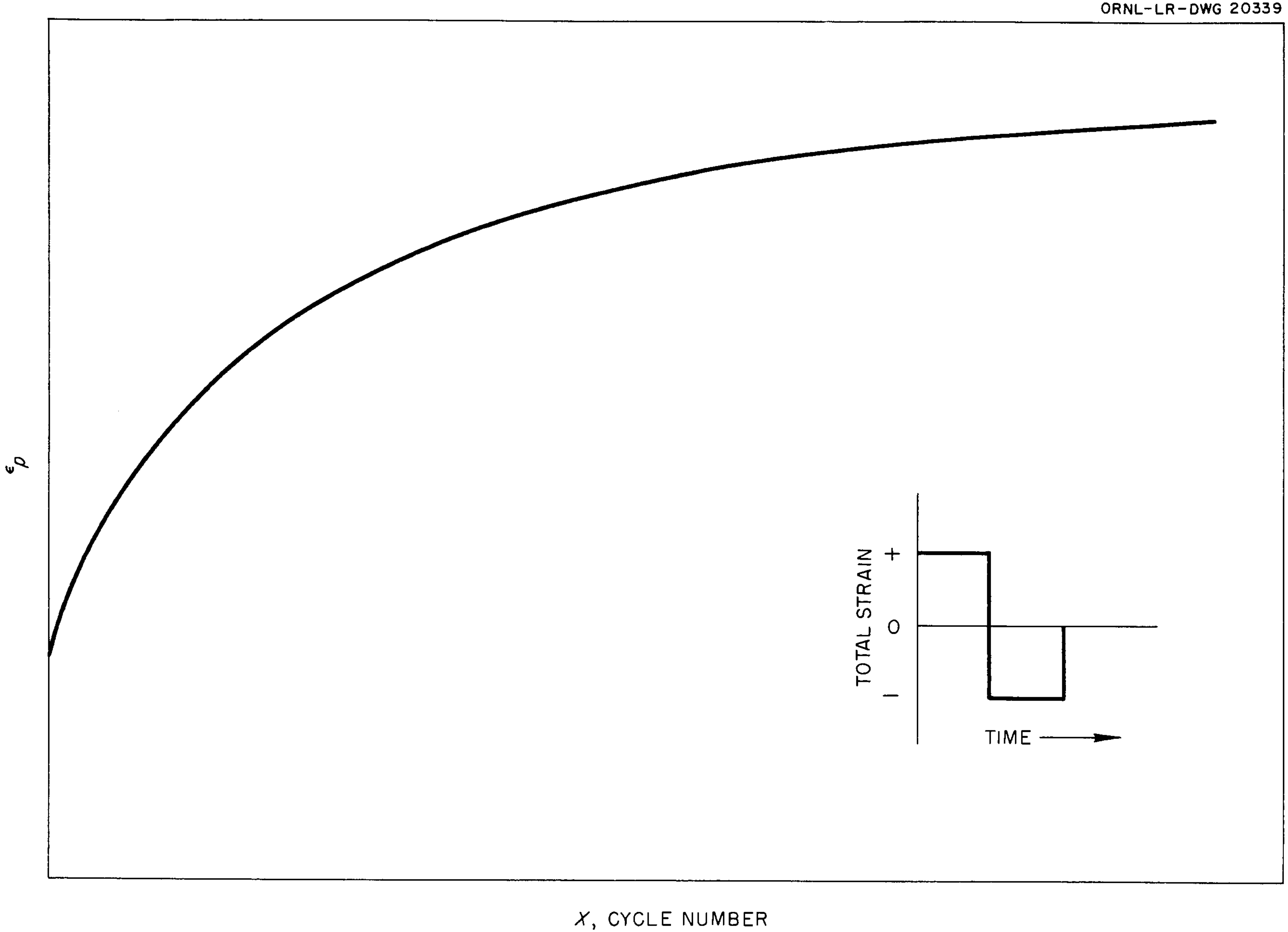

Fig. 13. Typical Plot for Plastic Strain Per Cycle vs. No. of Cycles.

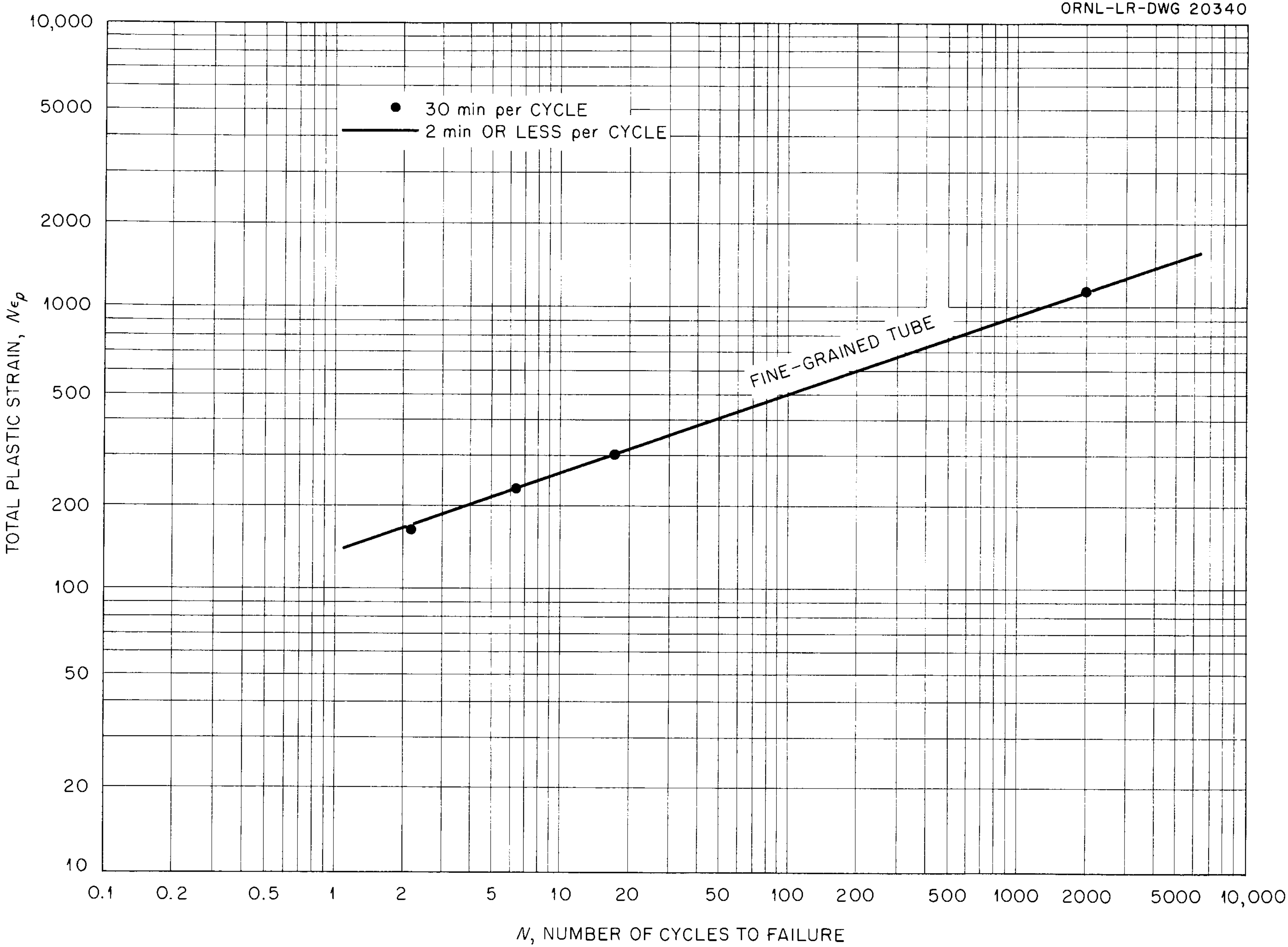

Fig 14. Comparison of Tube Tests Run With Different Cycle Frequencies

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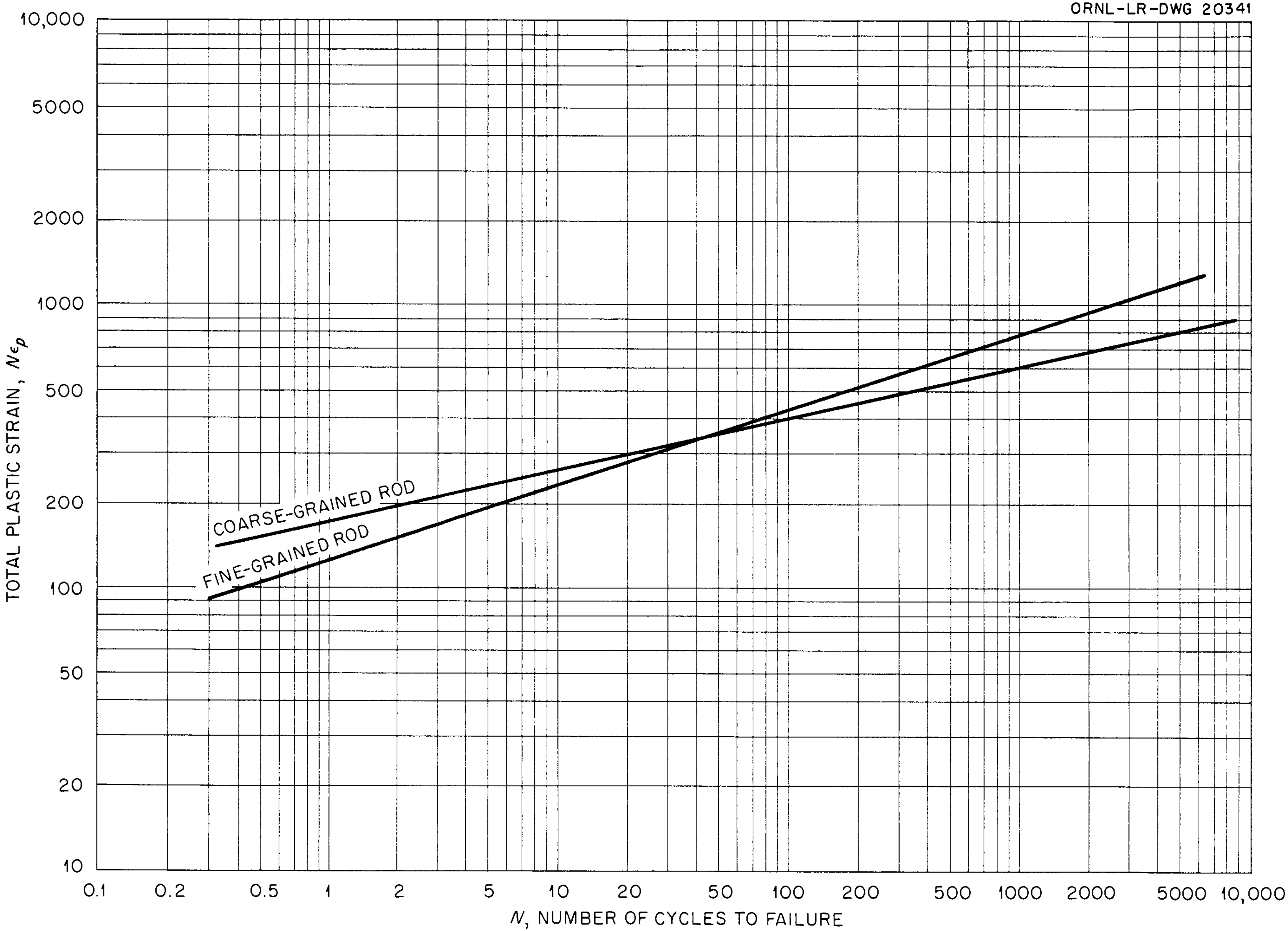

Fig. 15. Plastic Strain Absorption for Fine and Coarse Grain Inconel Rod Tested at 1300°F.

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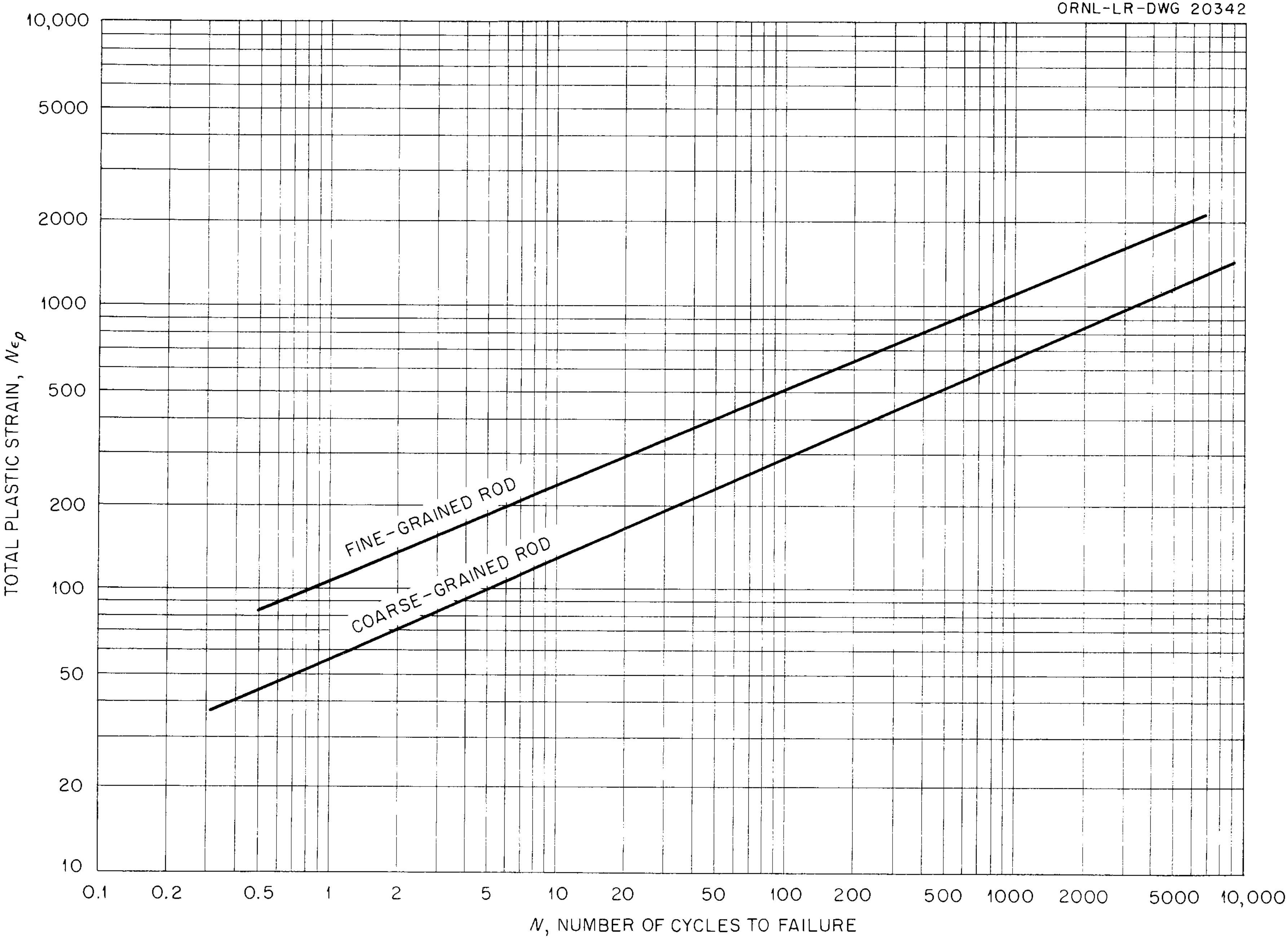

Fig. 16. Plastic Strain Absorption for Fine and Coarse Grain Inconel Rod Tested at 1500°F.

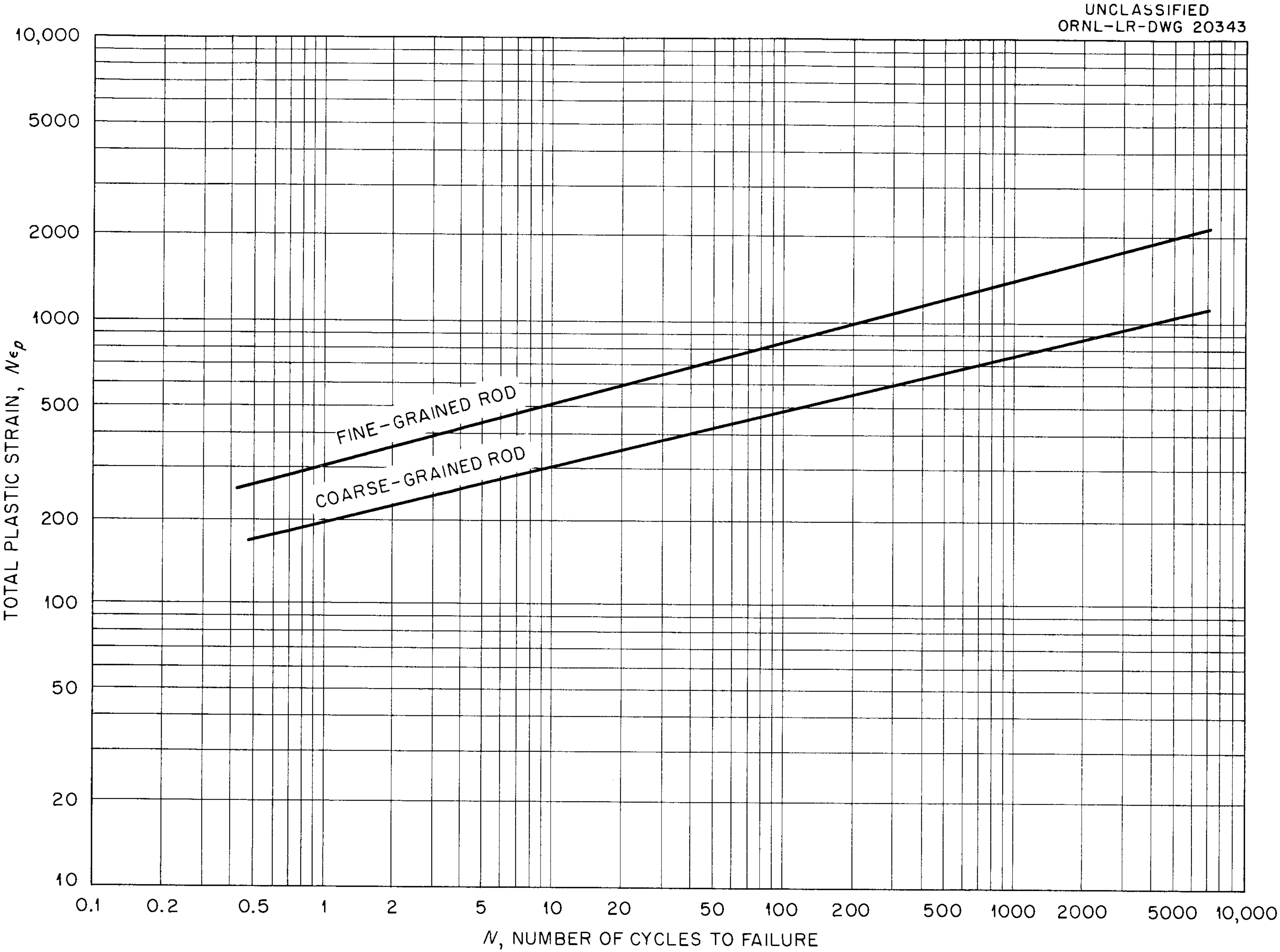

Fig. 17. Plastic Strain Absorption for Fine and Coarse Grain Inconel Rod Tested at 1600°F.

2) Within the test range of 1300–1600°F there appears to be little or no temperature effect on the cycles to failure for any given plastic strain per cycle.
3) Coffin's concept of total plastic strain was found to hold true for tests with the same cycle frequency.
4) Grain size was found to be the most significant factor affecting strain-cycle properties.
5) Strong evidence is furnished that Inconel strain weakens at elevated temperatures.

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