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Final Report

# A COMPARISON OF QUENCHING CHARACTERISTICS OF HIGH-TEMPERATURE AND SILICONE OILS

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## ABSTRACT

A Type-430 stainless-steel bar was used to obtain cooling curves at the center of the bar upon quenching in a silicone oil and a high-temperature oil at bath temperatures from 200° to 500°F.

From the cooling curves the severity of quench for each oil for a given test condition was computed, using Russell's Tables.

It has been shown that the high-temperature oil had superior quenching characteristics at all temperatures tested. The maximum H value for the high-temperature oil was 1.67 in.$^{-1}$, whereas for the silicone oil the maximum value was 1.1 in.$^{-1}$; both occurred at 500°F.


## OBJECTIVE

A comparative evaluation of the quenching characteristics of a silicone oil and a high-temperature oil.

## INTRODUCTION

In this investigation two oils were compared over a range of temperature as to the severity of quench achieved by each when a bar of 1-1/8-in. diameter was quenched in them. One of the quenching media was Park Chemical Thermo Quench Oil. The other was Dow-Corning Silicone 550 Oil.

At room temperature the viscosities of these oils are different, the high-temperature oil being more viscous than the silicone oil. However, above 200°F, at practical oil-bath temperatures, both oils were very fluid. Both oils tended to fume at high temperatures. It was noted that the silicome oil began to fume at 350°F, and this became very prominent at 500°F. The fumes were odorless, nonirritating, and appeared as steam. The high-temperature oil began to fume at 400°F and at 500°F fumed to a greater extent than the silicone oil. There was some irritating odor to the fumes of the darker high-temperature oil.

## EXPERIMENTAL METHOD

The technique used to evaluate the quenching characteristics of these two oils was to quench a bar of 1-1/8-in.-diameter steel in an agitated bath held at temperatures from 200° to 500°F. The center temperatures of this bar during quenching were recorded on a high-speed recorder with a chart speed of six in./min. From these data the severity of quench, H, was computed, using Russell's Tables.[1]

Material Tested.—In order to eliminate the effects of thermal arrests due to phase transformations on cooling, a stainless steel, Type 430, was used in this investigation. This steel has the beneficial property of a constant thermal conductivity over the temperatures used in this work.[2]

Method of Heating.—The test bar was heated in a vertical-tube furnace, 18 in. high, to a quenching temperature of 1600°F. The specimen was suspended from a stainless-steel tube of 3/8-in. diameter welded to the specimen. The tube in turn was fixed to a transite board so that the specimen was placed in the same position in heating and quenching for all runs.

The quench pot had a capacity of five gal and was heated by an immersion heater. After the test specimen had been quenched in the oil bath, it was found that the bath had increased in temperature a maximum of 20°F.

Test Method.—To eliminate end effects, the test specimen was made six in. long and had a diameter of 1-1/8 in. The steel had a machined finish. From one end of the specimen a 1/8-in. hole was drilled three in. deep. A chromel-alumel thermocouple, 24 gage, was threaded into spaghetti tubing and inserted into the hole and butt welded to the center of the specimen. A stainless-steel tube of 3/8-in. diameter was slipped over the thermocouple and welded to the end of the specimen. The stainless-steel tubing in turn was fastened to a transite board so that the specimen during quenching had 3-1/2 in. of oil above and below the ends of the specimen. By this means, the specimen was placed in the same position during each heating and quenching cycle.

Temperatures at the center of the specimen during quenching were recorded on a Brown Electronik Recorder with a chart speed of six in./min. The accuracy of this instrument was checked with a Brown potentiometer and was ± 5°F.

In making a test, the specimen, attached to the transite board and equipped with a thermocouple connected to the recorder, was suspended vertically into the vertical-tube furnace and allowed to come to a uniform temperature. This temperature varied slightly from run to run but was in the range from 1600°F ± 10°F. The oil bath, maintained at the desired temperature, from 200° to 500°F, was adjacent to the vertical furnace so that the specimen could be removed from the high-temperature furnace and quenched vertically in the oil in less than one second. The oil bath was agitated by an electrically driven propeller. Very slight agitation was accomplished at the low temperatures due to the high viscosity of the oils. At higher oil-bath temperatures, however, a moderate degree of stirring was achieved. Some deviations were encountered in the cooling curves on duplicate runs, but these occurred mainly in the lower temperature range. The data used for calculating the severity of quench were from the upper portion of the cooling curves where good reproducibility was obtained on duplicate runs.

## ANALYSIS OF DATA

The method used for computing H, the severity of quench, from the cooling curves is outlined by Austin.[3] The tables ~~taken~~ from Russell[1] found in Austin's book[3] were extrapolated and used in the form of a curve. These extrapolated data are shown in Fig. 1. In this figure, hL is plotted as a function of $\tau$, the relative time ratio, for a center position of the specimen. The value of $\tau$ is given by

$$\tau = \frac{a^2 t}{L^2}$$

where $a^2$ = thermal diffusivity (in.$^2$/min), t = time to 1/2 temp (min), and $L^2$ = radius of bar squared (in.$^2$).

The severity of quench, h, as defined by Russell, was used in Fig. 1 and is twice as large as Grossman's H. Both have units of in.$^{-1}$. In computing H, a value of thermal diffusivity must be obtained. For a Type-430 stainless steel a value of 0.007 to 0.0075 in.$^2$/sec has been reported.[2] In this investigation the thermal diffusivity was taken as 0.007 in.$^2$/sec.

The following calculation will serve to illustrate the method used to determine the severity of quench from cooling-curve data:

The cooling curve shown in Fig. 4 will be used in this example. From this curve the half temperature is determined.

$$\frac{(1605°F - 350°F)}{2} + 350°F = 977°F$$

The time required to reach this temperature was 25 sec or 0.417 min.

The relative time ratio, $\tau$, is

$$\tau = \frac{a^2 t}{L^2} = \frac{0.007 \text{ in.}^2}{\text{sec}} \quad \frac{60 \text{ sec}}{\text{min}} \quad \frac{0.417 \text{ min}}{(0.5625)^2 \text{ in.}^2}$$

$$\tau = 0.554$$

Referring to Fig. 1, at a value of $\tau = 0.554$ the corresponding hL value is 1.04.

The value of Russell's h then is

$$hL = 1.04$$

$$h = \frac{1.04}{(.5625) \text{ in.}} = 1.85 \text{ in.}^{-1}$$

or Grossman's H is

$$2H = h$$

$$H = \frac{1.85}{2} = 0.93 \text{ in.}^{-1}$$

The cooling curves obtained for the silicone oil are shown in Figs. 2-7 and those for the high-temperature oil in Figs. 8-13. The results of the calculations for the severity of quench are summarized in Tables I and II. A comparison of the quenching characteristics for the two oils is presented in Fig. 14. It can be seen that the high-temperature oil is superior in quenching characteristics to the silicone oil at all oil-bath temperatures tested. The difference appears to become greater as the temperatures of the oil baths increase.

It has been shown[4] that three definite stages of cooling exist when a metal surface is cooled in a liquid. The first stage is one of slow heat transfer due to the formation of vapor films that separate the liquid from the metal. This stage is prominent in liquids having low and sharp boiling points. The second stage is one of rapid heat transfer and is characterized by a bubble formation around the metal which continuously brings the liquid in contact with the metal as the bubble of vapor ascends through the liquid. This stage is the most effective. The third stage of cooling is by convection since the surface of the metal is below the boiling point of the liquid.

A possible explanation for the lower severity of quench obtained using the silicone oil as compared to the high-temperature oil lies in the stages of cooling. The Dow-Corning 550 Silicone Oil does not boil but passes directly from the liquid to the gel state. The lower severity of quench in the silicone oil is probably due to the fact that the most effective stage in cooling, the boiling stage, is absent in this oil.

In making a comparison between these two oils, the economic aspect must be considered. The cost of the silicone oil is about eighty times more than that of the high-temperature oil. This exceedingly high price will necessarily limit the use of silicone oil as a commercial quenching agent.

## CONCLUSIONS

A comparison of quenching characteristics of a silicone and a high-temperature oil at bath temperatures up to 500°F has shown:

1. Silicone oil begins to fume at 350°F; however, at 500°F it does not fume as much as the high-temperature oil. Both oils fume heavily at 500°F, but only the high-temperature oil exhibits an irritating odor.

2. The severity of quench obtained with the silicone oil was inferior to that of the high-temperature oil at oil-bath temperatures of 200°F and above. The difference became greater with higher bath temperatures. At 500°F the high-temperature oil gave an H value of 1.67 in.$^{-1}$ compared to 1.1 in.$^{-1}$ for the silicone oil.

3. The high cost of the silicone oil, together with its inferior quenching properties, as compared to the high-temperature oil does not warrant its use as a commercial quenching medium.

## REFERENCES

1. Russell, T. F., "Some Mathematical Considerations on the Heating and Cooling of Steel," Iron and Steel Institute, Special Report No. 14, 1936, p. 149.

2. Sinnott, M. J., and J. C. Syhne, "An Investigation of the Quenching Characteristics of a Salt Bath," <u>Trans., Amer. Soc. for Metals</u>, vol. 44, 1952, p. 758.

3. Austin, J. B., <u>The Flow of Heat in Metals</u>, Amer. Soc. for Metals, 1941, p. 120.

4. Scott, H., "The Problem of Quenching Media for the Hardening of Steel," <u>Trans., Amer. Soc. for Metals</u>, vol. 22, 1934, p. 577.

TABLE I

SUMMARY OF COOLING DATA FOR CENTER OF BAR
SILICONE OIL

| Run No. | Bath Temp °F | 1/2 Temp °F | Time to 1/2 Temp Min | τ | hL | h | H |
|---|---|---|---|---|---|---|---|
| 1 | 200 | 911 | 0.484 | 0.642 | 0.81 | 1.45 | 0.73 |
| 2 | 200 | 902 | 0.483 | 0.641 | 0.81 | 1.45 | 0.73 |
| 3 | 300 | 950 | 0.450 | 0.598 | 0.91 | 1.62 | 0.81 |
| 4 | 350 | 977 | 0.417 | 0.554 | 1.04 | 1.85 | 0.93 |
| 5 | 400 | 1008 | 0.392 | 0.520 | 1.16 | 2.06 | 1.03 |
| 6 | 400 | 1000 | 0.412 | 0.547 | 1.07 | 1.90 | 0.95 |
| 7 | 450 | 1034 | 0.408 | 0.542 | 1.08 | 1.92 | 0.96 |
| 8 | 450 | 1026 | 0.402 | 0.534 | 1.11 | 1.98 | 0.99 |
| 9 | 500 | 1064 | 0.367 | 0.487 | 1.30 | 2.31 | 1.16 |
| 10 | 500 | 1058 | 0.400 | 0.531 | 1.12 | 1.99 | 1.00 |
| 11 | 500 | 1049 | 0.392 | 0.521 | 1.16 | 2.06 | 1.03 |

TABLE II

SUMMARY OF COOLING DATA FOR CENTER OF BAR
HIGH-TEMPERATURE OIL

| Run No. | Bath Temp °F | 1/2 Temp °F | Time to 1/2 Temp Min | τ | hL | h | H |
|---|---|---|---|---|---|---|---|
| 12 | 200 | 903 | 0.433 | 0.575 | 0.97 | 1.72 | 0.86 |
| 13 | 200 | 907 | 0.417 | 0.554 | 1.03 | 1.83 | 0.92 |
| 14 | 305 | 958 | 0.400 | 0.531 | 1.12 | 1.99 | 1.00 |
| 15 | 305 | 958 | 0.383 | 0.509 | 1.21 | 2.15 | 1.08 |
| 16 | 350 | 980 | 0.367 | 0.487 | 1.30 | 2.31 | 1.16 |
| 17 | 350 | 982 | 0.383 | 0.509 | 1.21 | 2.15 | 1.08 |
| 18 | 400 | 1008 | 0.333 | 0.442 | 1.53 | 2.72 | 1.36 |
| 19 | 400 | 1003 | 0.367 | 0.487 | 1.30 | 2.31 | 1.16 |
| 20 | 450 | 1030 | 0.317 | 0.421 | 1.68 | 3.00 | 1.50 |
| 21 | 450 | 1034 | 0.317 | 0.421 | 1.68 | 3.00 | 1.50 |
| 22 | 500 | 1058 | 0.300 | 0.398 | 1.88 | 3.34 | 1.67 |

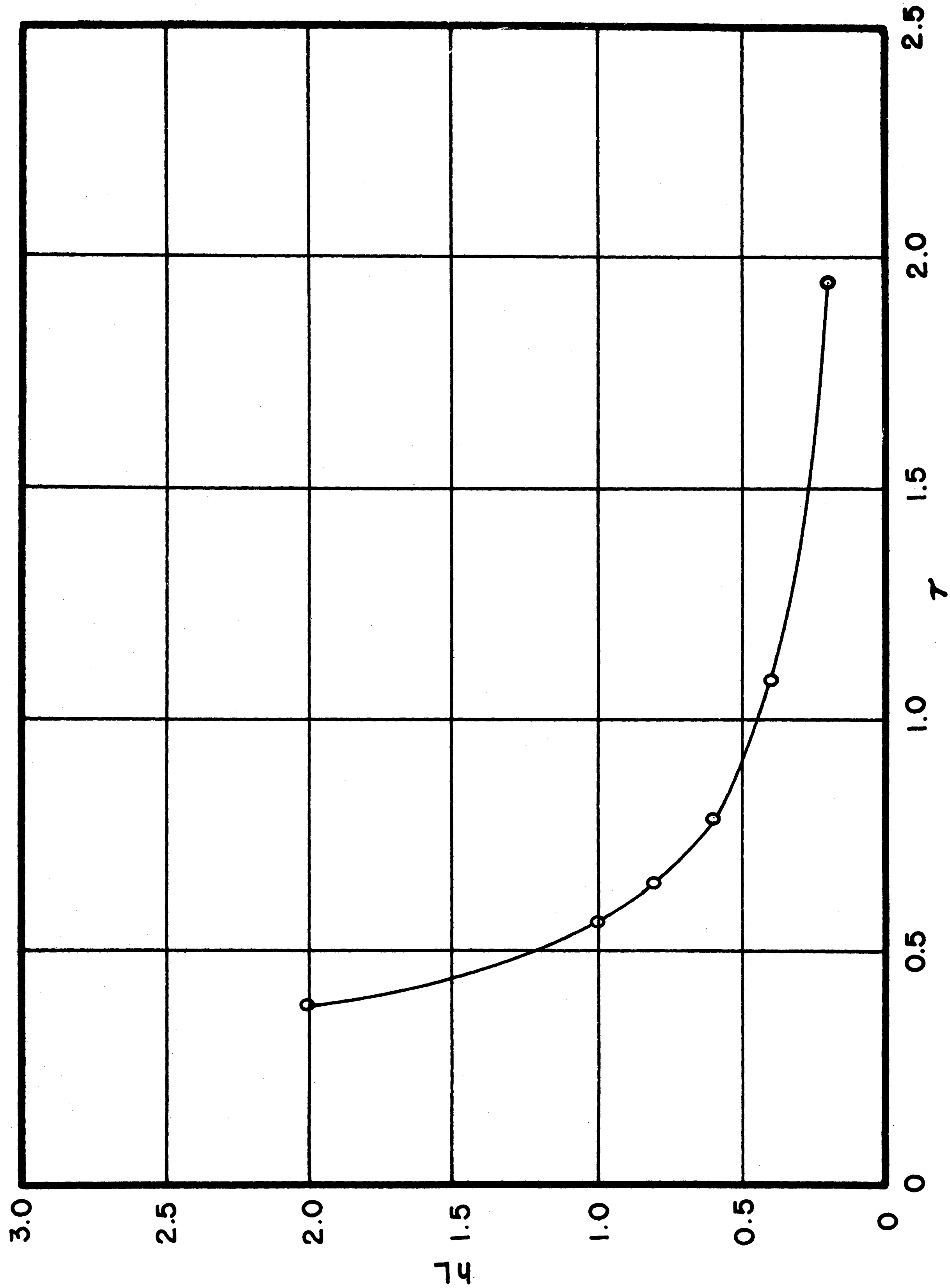


Fig. 1. Extrapolation of Russell's Tables for center bar position and unaccomplished temperature increment, U = 0.5.

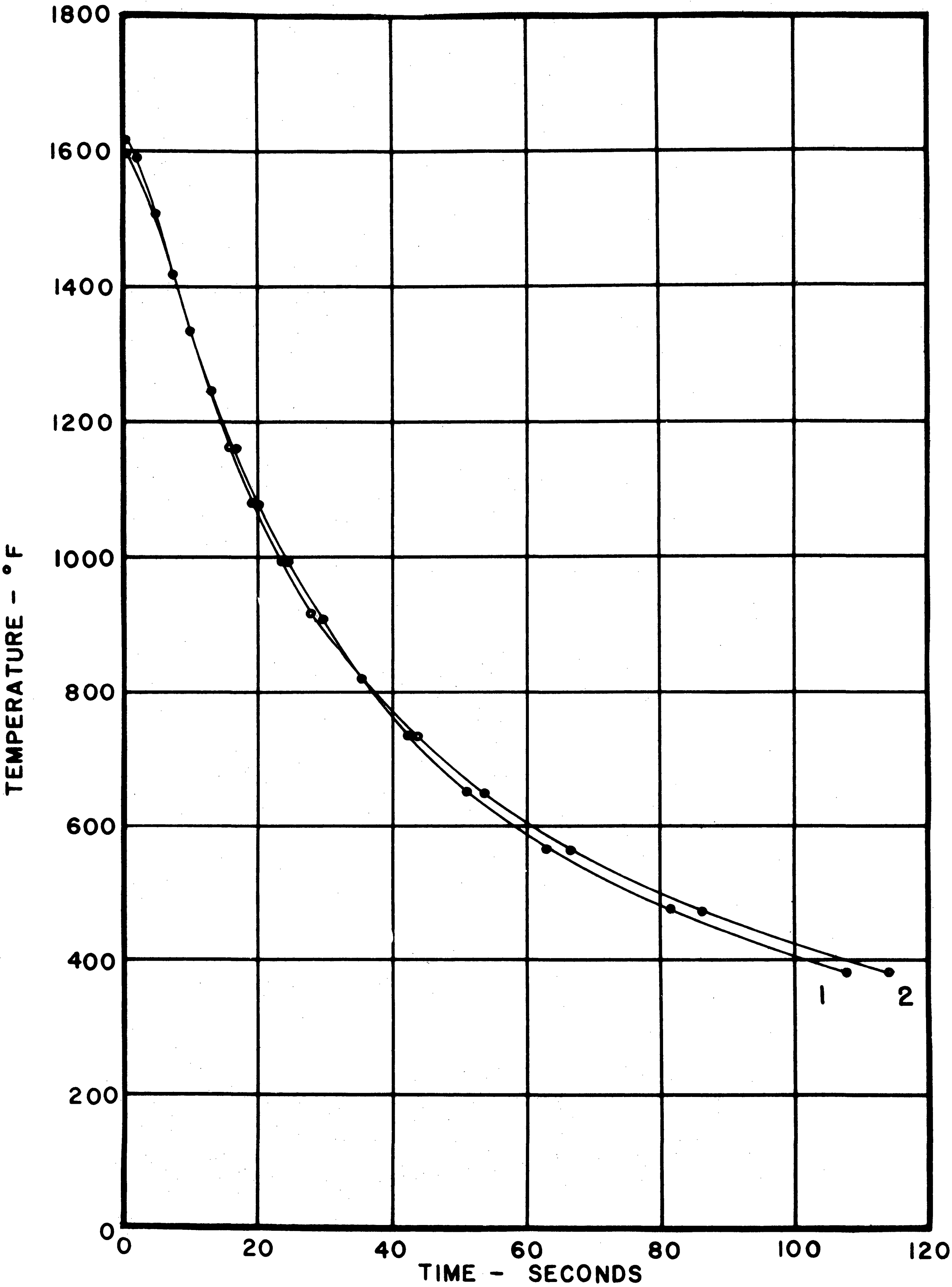


Fig. 2. Cooling curves obtained with silicone oil at 200°F.

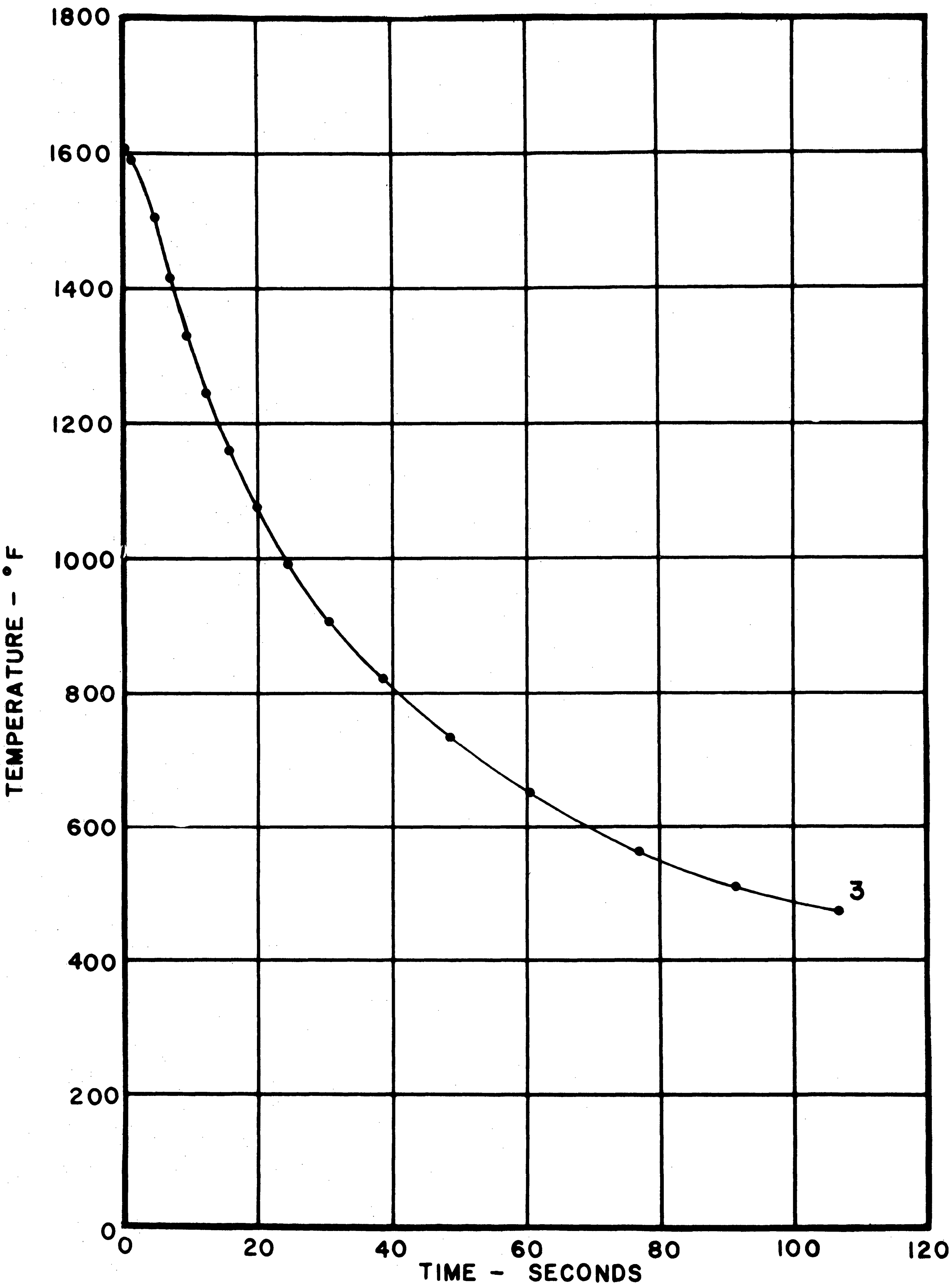


Fig. 3. Cooling curve obtained with silicone oil at 300°F.

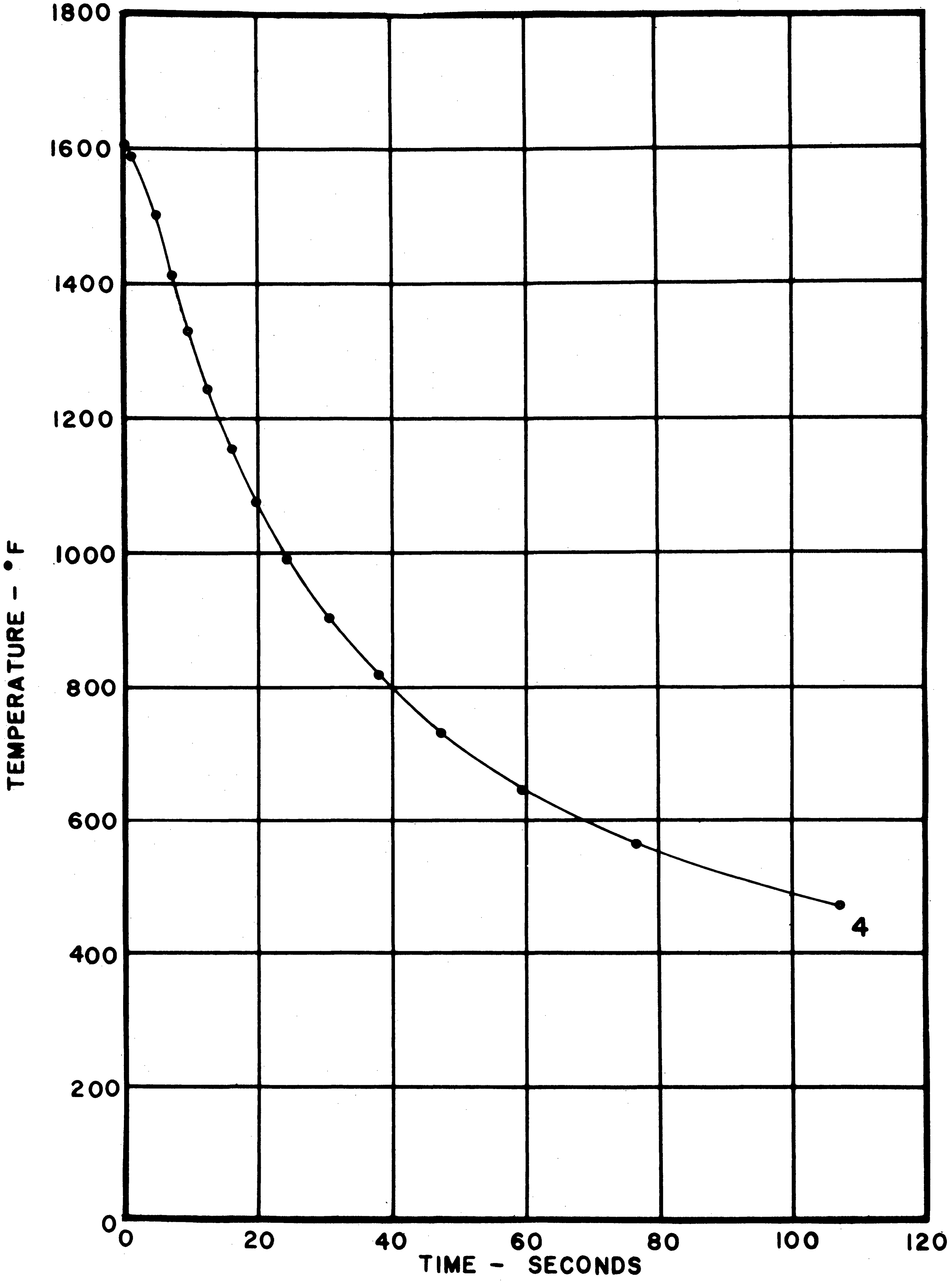


Fig. 4. Cooling curve obtained with silicone oil at 350°F.

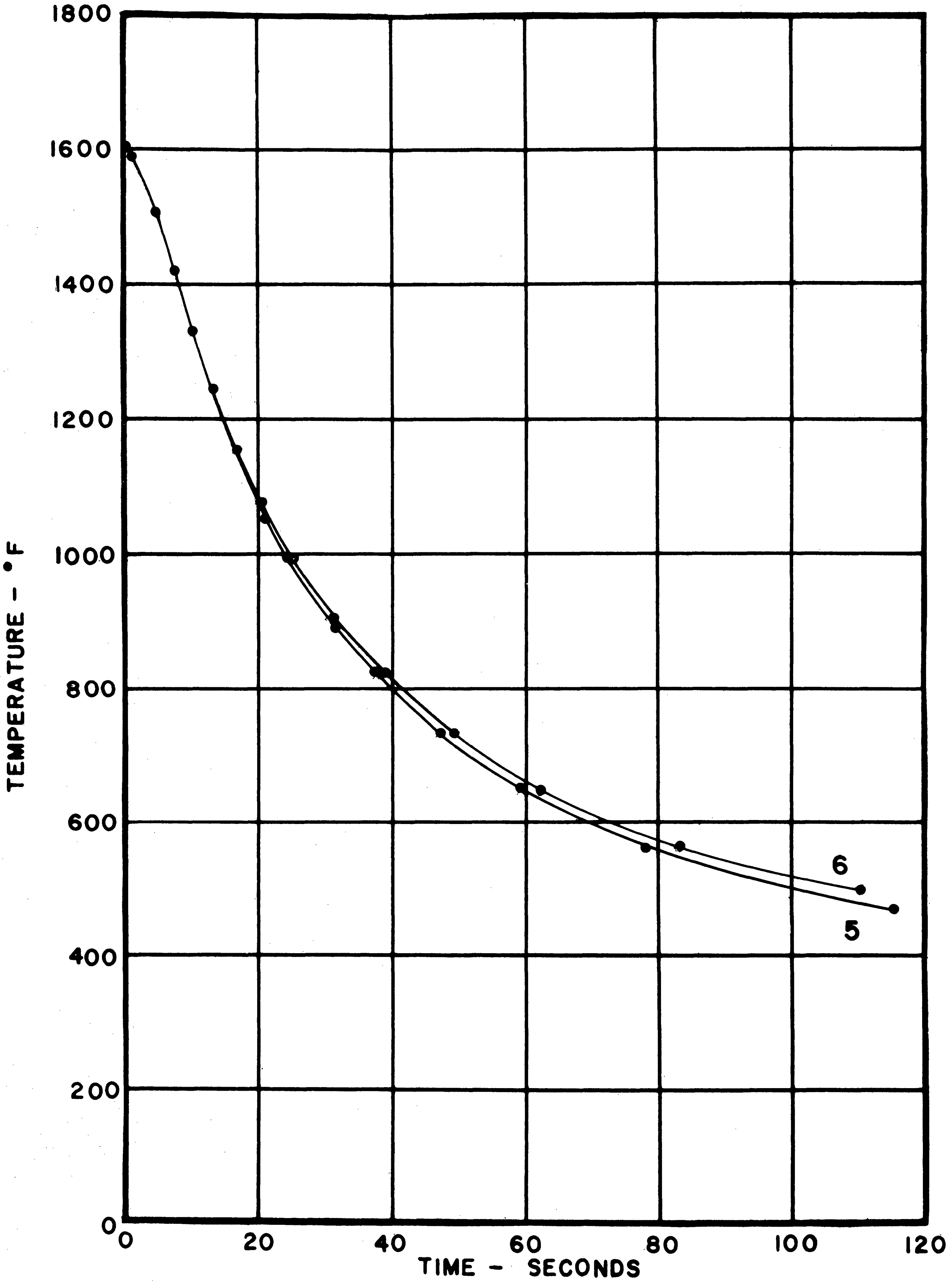


Fig. 5. Cooling curves obtained with silicone oil at 400°F.

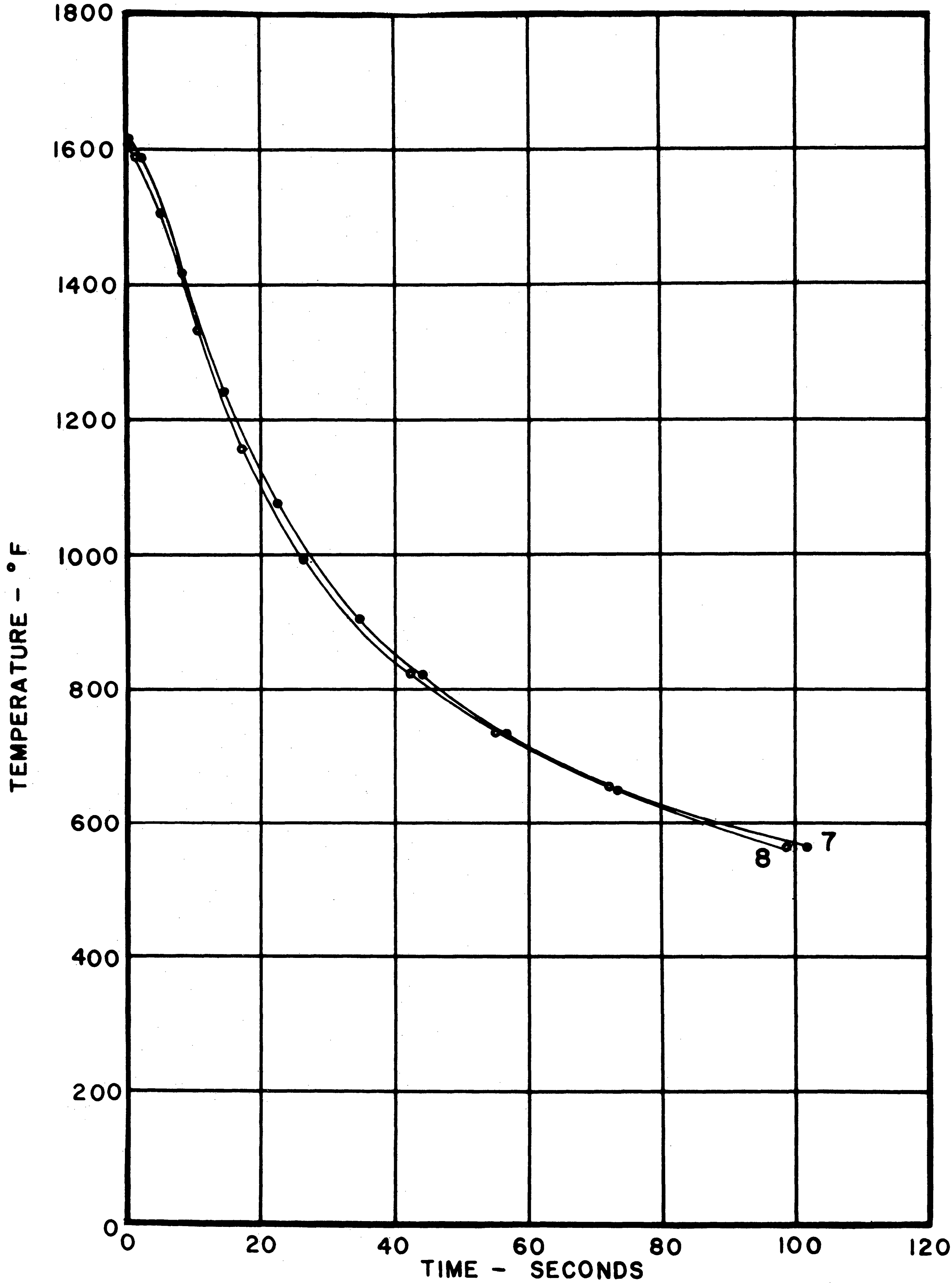


Fig. 6. Cooling curves obtained with silicone oil at 450°F.

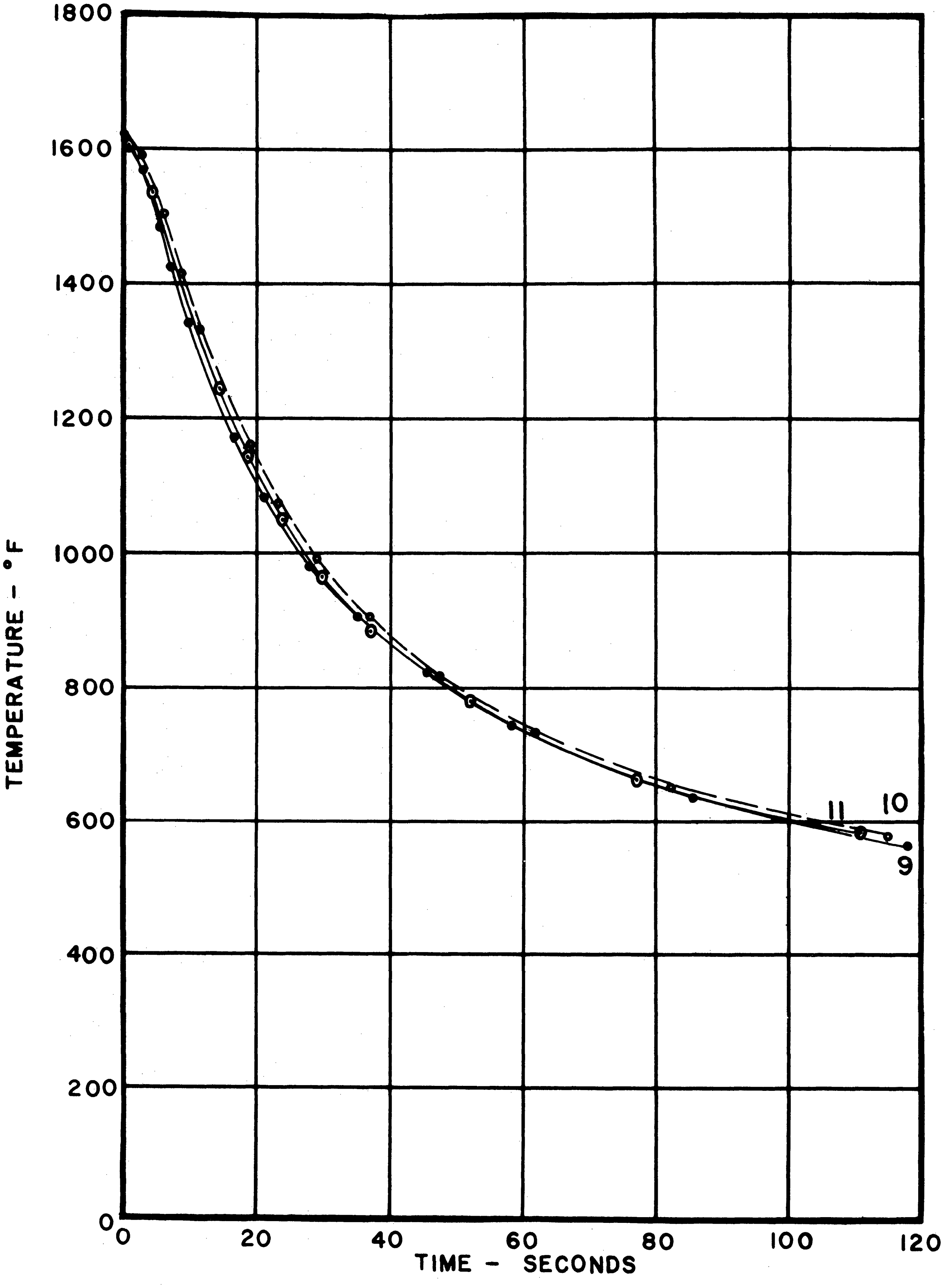


Fig. 7. Cooling curves obtained with silicone oil at 500°F.

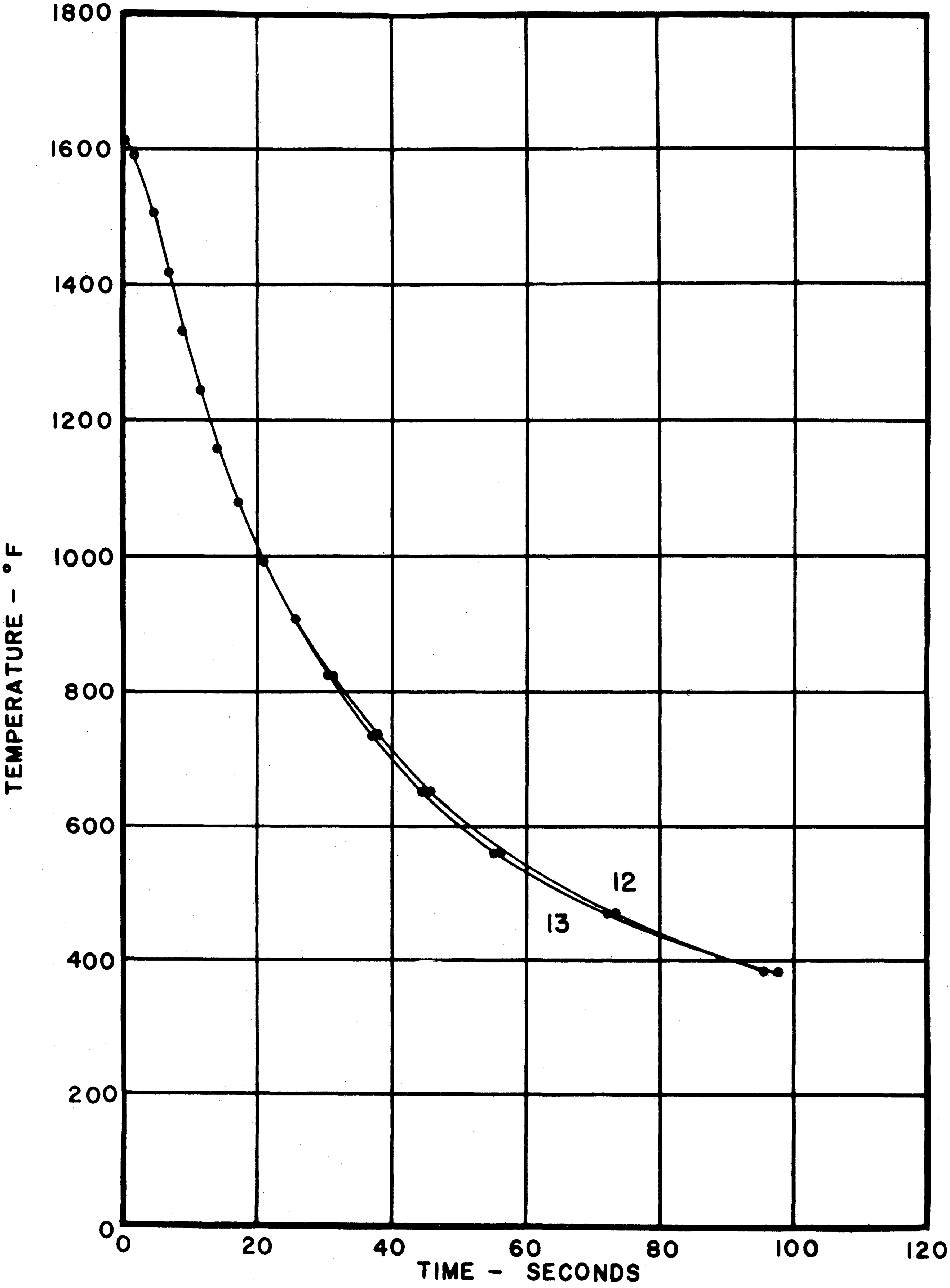


Fig. 8. Cooling curves obtained with high-temperature oil at 200°F.

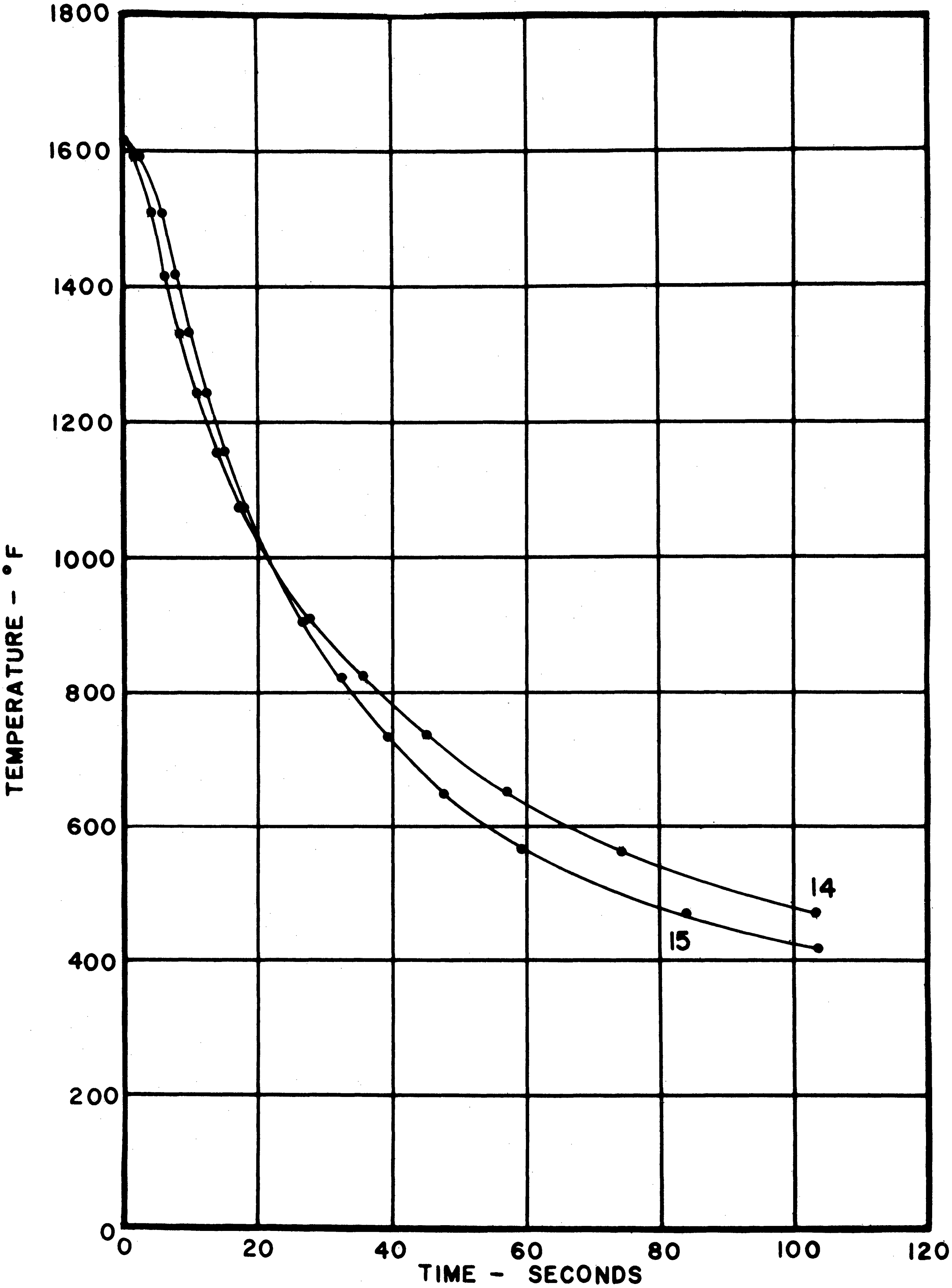


Fig. 9. Cooling curves obtained with high-temperature oil at 305°F.

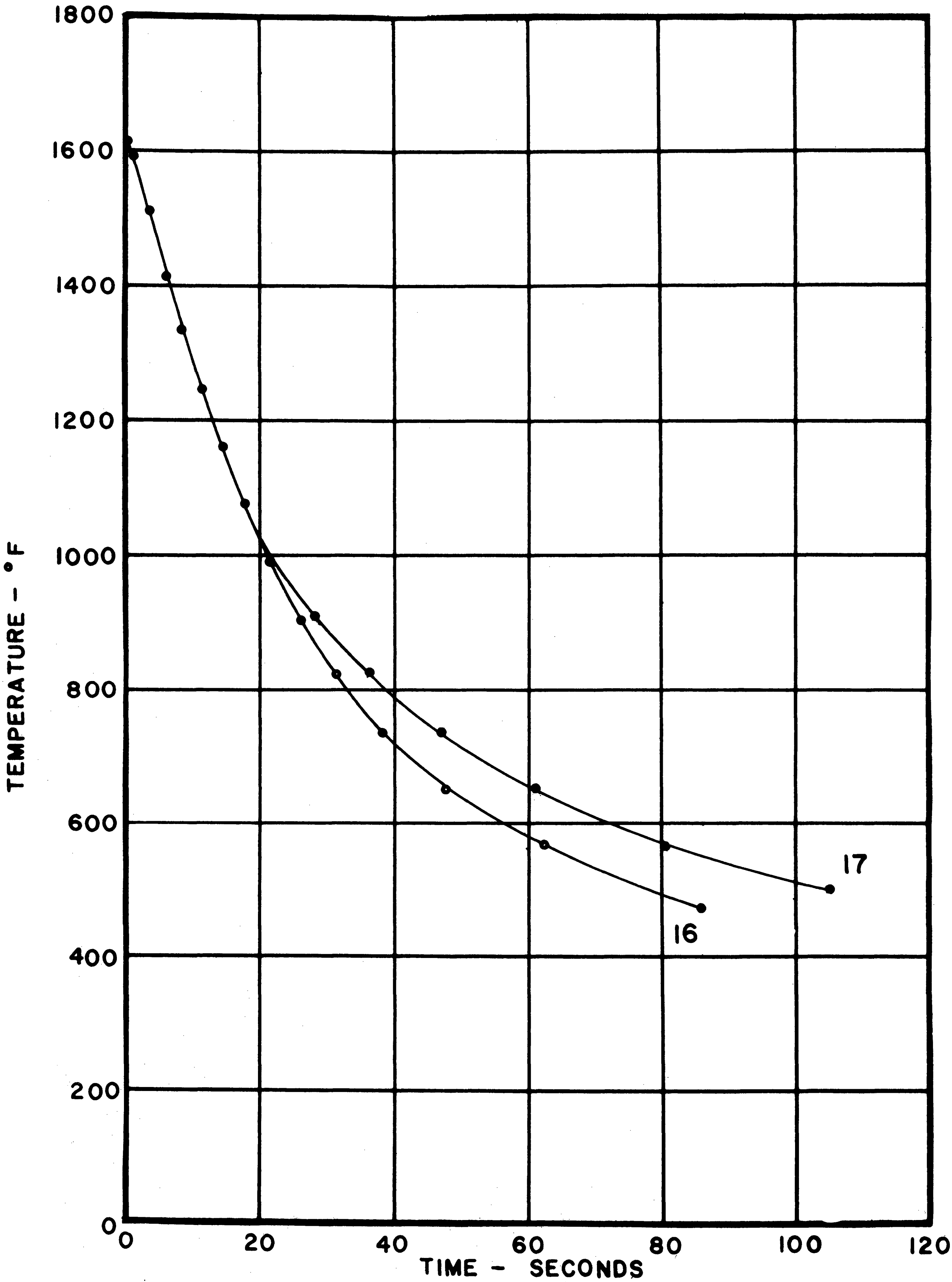


Fig. 10. Cooling curves obtained with high-temperature oil at 350°F.

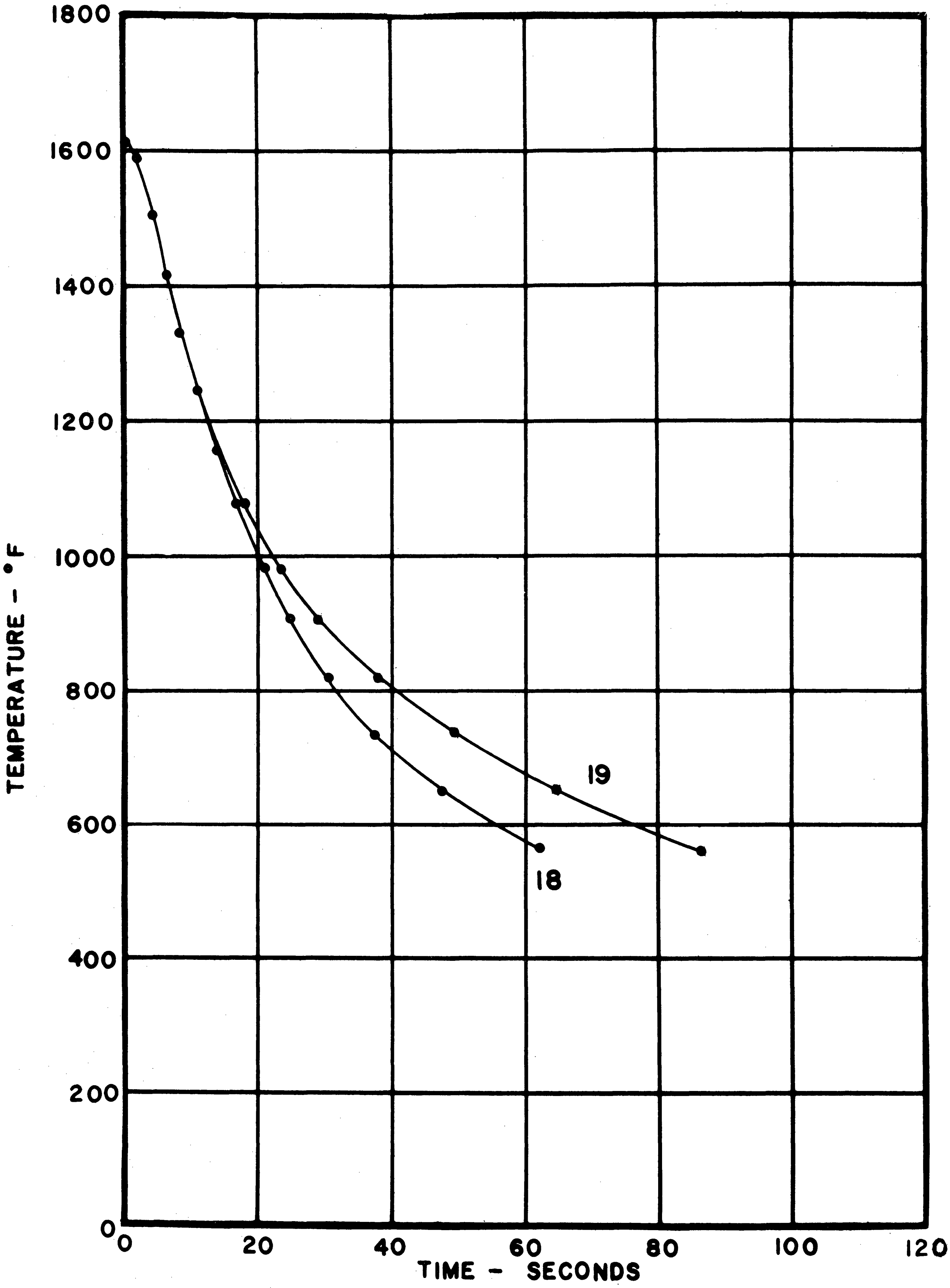


Fig. 11. Cooling curves obtained with high-temperature oil at 400°F.

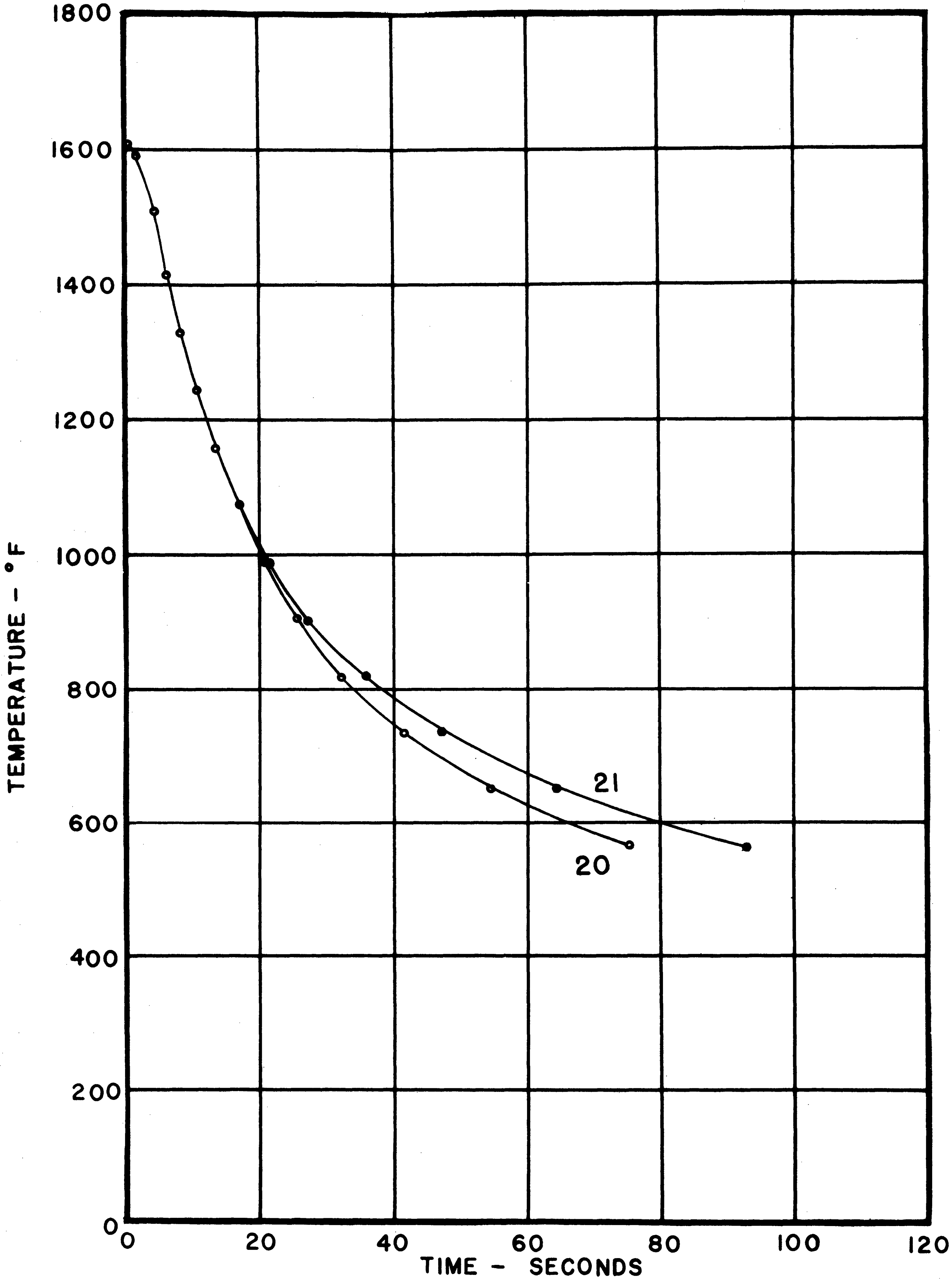


Fig. 12. Cooling curves obtained with high-temperature oil at 450°F.

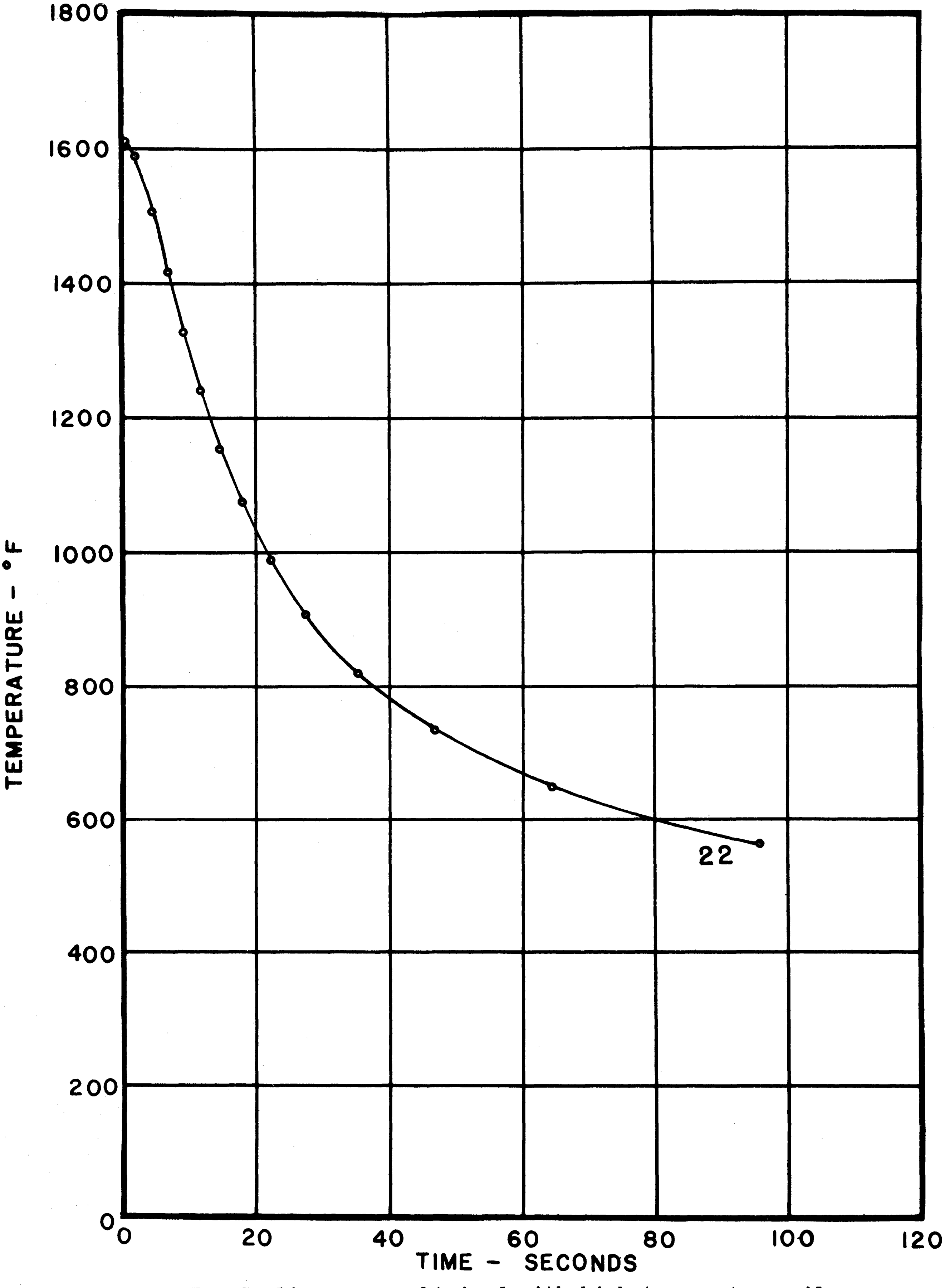


Fig. 13. Cooling curve obtained with high-temperature oil at 500°F.

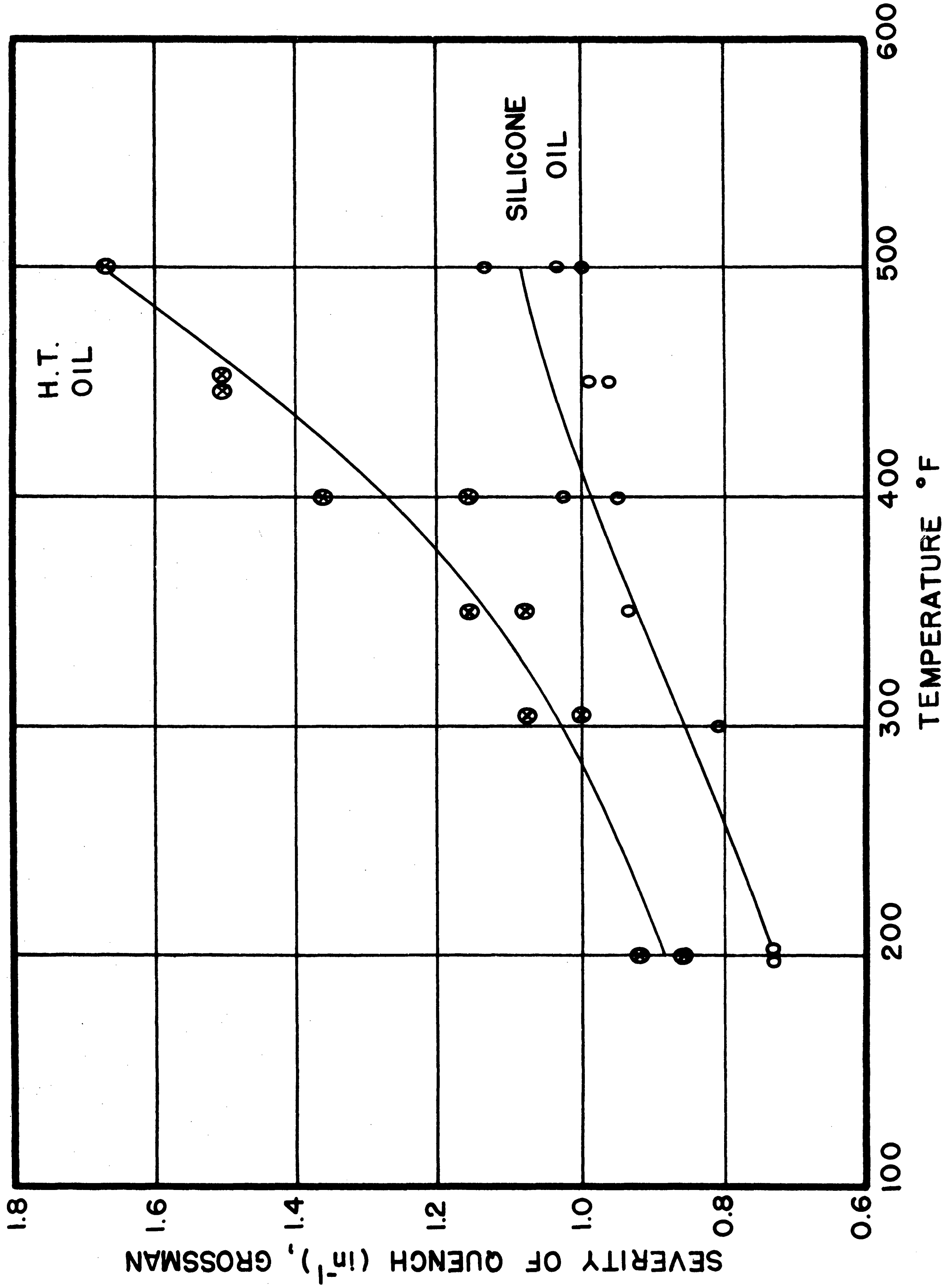


Fig. 14. Effect of oil-bath temperature on the severity of quench obtained with two oils.