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Evaluation of quenching media using the end-quench hardenability test

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EVALUATION OF QUENCHING MEDIA USING THE END-QUENCH HARDENABILITY TEST

By

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A

THESIS

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CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

Table No. Page

INTRODUCTION

The purpose of the thesis was to evaluate the quenching speed of different quenching media by studying their behaviour in relation to hardenabilities of steels, using the standard A.S.T.M. End-quench Test.

At the outset an understanding of the term "Hardenability", so extensively used in industrial heat-treatment, is necessary. The property of a steel, of hardening on quenching to various depths beneath the surface is referred to as the "Hardenability". It may simply be called the "Susceptibility to hardening". Hardenability should be distinguished from the "Hardening capacity", which represents the magnitude of the hardness achieved. The chief factors which affect the inherent hardenability of a steel are:

1. Amount of carbon in the steel.
2. Nature and amount of alloying element.
3. Austenitic grain size.
4. Method of manufacture.

Besides these, there are other external factors which should be considered in performing any hardenability test. These are:

1. Previous heat-treatment of the steel before the final quenching test.

2. Surface finish of the bar to be hardened or of the face to be cooled.

3. Rate of heating

4. Scale formation and decarburisation

5. Temperature to which the specimen is heated

6. Temperature before the quenching operation

7. Cooling medium used

8. Temperature and agitation of the cooling medium

Hardenability is really a relationship between rates of cooling, hardness and microstructure. The basic information concerning the transformation is obtained from the diagram, as constructed by Davenport and Bain,[(1)] where transformation temperature is plotted against the time interval at that temperature in secs. usually expressed in logarithmic scale. The information furnished by the isothermal transformation diagram, is, however, not immediately applicable to the customary heat-treating practices, since these all involve continuous cooling. A continuous cooling diagram, depicting the transformation behaviour on cooling at a series of continuous cooling rates can be constructed.[(2)] Hardenability can be determined from a knowledge of transformation characteristics, particularly from continuous cooling rate diagrams. But it is too laborious

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(1) Davenport E.S. and E.C. Bain. Transformation of Austenite at constant subcritical temperatures. Trans. A.I. M.E., Vol. 3, 1930.

(2) Grange, R.A. and J.M. Keifer. Transformation of Austenite on continuous cooling and its relation to transformation at constant temperature. Trans. A.S.M. Vol. 29, 1941.

to be of any practical use. Consequently, for customary heat-treatment practice several methods of hardenability measurement have been sought for. Of these Shepherd P-F Test[3] has been used in tool steel industry. The test consists in quenching a 3/4" round bar into a 10% aqueous brine solution after heating to predetermined temperatures and then fracturing the bars and rating the fractures. Following this, one-half piece is polished and etched with 50% aqueous HCl at 180° F to show the depth of hardness. The steel is then rated according to its fracture and hardness depths when quenched from those temperatures. A test has been described by Burns, Moore and Archer.[4] The test is similar in principle to the Shepherd test except the sample is 1" round by 6" long and is quenched in water instead of brine. Instead of etching to determine hardness penetration they actually measure it. Hardness readings are taken at 1/16" interval from the surface to the center and plotted against distance from the surface. The area of this curve is then calculated. The rating includes the Rockwell C surface hardness, the area under the hardenability traverse curve and the Rockwell C center hardness, Grossmann[5] has

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(3) Shepherd, B.F. Trans. A.S.M., Vol. 22, pp. 979-1000, 1934

(4) Burns, J.Z., Moore, T.L., and Archer, R.S. Trans. A.S.M., Vol. 26, p. 1, 1938.

(5) Grossmann, M.A., Asimow, M.A. and Urban, S.F. Hardenability, its relation to quenching and some quantitative data. A.S.M. Publication, 1939

developed the conception of critical diameter of the specimen of a given steel at which the center hardness changes abruptly with small changes in diameter.

The most convenient and popular method in the United States accomplishing this result is the End-quench Test developed by W. E. Jominy and A. L. Boegehold of General Motor Works, Ford and Standardised by S.A.E. and A.I.S.I. This standard test has been described in A.S.T.M. Standards.(6) There are several reasons of the popularity of the End-quench Test. In a single test, hardness is developed in the steel in question with all rates of cooling from over 500^0 F per sec. to 4^0 F per sec. is obtained. The method is especially suited to alloy steels, whose critical cooling rates are in the range from about 150^0 F per sec. to 4^0 F per sec. However, for shallow hardening steels different types of bars have been used and found satisfactory. The end-quench method can be used to find the hardenability of a carburising steel in the carburised condition. In fact this method of end cooling is the only one suitable for carburised steels.

Hardenability is now an established factor. Because of the popularity of the end-quench test, the S.A.E. and A.I.S.I. jointly established minimum and maximum end-quench

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(6) End-quench Test for hardenability of steel, A.S.T.M. Standards, Part I-A, pp. 983, 1946.

hardenability curves known as hardenability bands, for most of the alloy steels. These steels are distinguished from the usual designation by the suffix 'H' to denote steels produced to hardenability specifications. On account of the several advantages the use of hardenability specifications or H-bands in the United States has considerably increased during the past few years.

In this connection it should be mentioned that M. A. Grossmann[7] of Carnegie-Illinois Steel Corporation and J. Field[8] have made it possible to predict the end-quench hardenability curve of a steel of known composition and grain size, though with some limited accuracy, by the use of hardenability multiplying factors.

Considering the importance of hardenability and the popularity of the end-quench test attempts have been made to utilize the end-quench test for purposes other than hardenability determinations. It has been mentioned in the introduction that in determining the hardenability of a specimen, the quenching medium and its agitation is a factor of vital importance. Thus it appears probable that using a steel specimen of standard hardenability and controlling the rate of agitation of the quenching medium

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(7) Grossman, M.A. Hardenability calculated from chemical composition. Trans. A.I.M.E., Vol. 150, 1942.

(8) Boyd, L.C. and J. Field. Calculation of standard end-quench hardenability curves from chemical composition and grain size. A.I.S.I. Contributions to the Metallurgy of Steel, No. 12, 1946.

the efficiency of a medium as regards quenching speed can be determined.

In customary quenching practice selection of the proper quenching medium for developing the best properties in the heat-treated part is still a problem. In the past several investigators have tried to evaluate quenching media in different ways. Direct measurement of the cooling rates at the center and the surface of a steel specimen has been tried. These will be discussed later. The A.S.T.M. End-quench test needs very simple apparatus and it is not much time consuming. Besides, by controlling the rates of agitation, it is possible to study the behaviour of quenching media under different rates of agitation and especially at very high rates, which cannot be obtained easily under usual quenching conditions. The behaviour of quenching media under such states of agitation has not yet been fully studied. It was hoped that the present investigations would reveal important facts in this line.

II

REVIEW OF LITERATURE

Under this heading, the important prior investigations, which have been very useful in forming a background for the carrying out of the present investigations and the interpretations of the resulting data, will be mentioned briefly:

Liquid Quenching Media

The problem of evaluating quenching media for the hardening of steel has been studied extensively by Howard Scott.[9] In discussing the general characteristics of quenching liquids, he mentions three stages of cooling, when a steel specimen is quenched in a liquid medium. These stages are Vapour Blanket, Vapour Transport and Final stages respectively as named by him. He has treated the problem of quenching liquids from almost all aspects and mentioned the dominant properties of different liquids affecting the cooling rates at different stages. Scott has also mentioned in his paper the basic properties on which a quenching medium is to selected.

Aqueous Solutions with Intermediate Cooling Rates between Water and Oil

The cooling rates of aqueous solutions of inorganic

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(9) Scott, H. The problem of quenching for the hardening of steel. Trans. A.S.M., Vol. 22, p. 577, 1934.

and organic materials have been studied by different investigators. As has been stated before, salt solutions generally increase the quenching speed. Thomas E. Hamill (10) has studied the behaviour of aqueous solutions of organic liquids like Ethelene Glycol, Glycerine and inorganic substance like Sodium Silicate extensively at different concentrations. The quenching characteristics of these solutions were studied by means of Temperature-Time Cooling curves on small cylinders of a 0.96 per cent carbon steel. Four concentrations of 1:4 Sodium Silicate having specific gravities corresponding to 4.6°, 9.5°, 13.2°, 16.7° Be' and two of 1:2.5 sodium silicate 12.4° and 28.8° Be' were found, which gave intermediate cooling rates between those obtained with water and with oil at room temperature. The results obtained with aqueous solutions of Ethelene Glycol and Glycerine are believed to justify the conclusions that these solutions cannot be used successfully as quenching media for intermediate cooling rates between water and oil. Some troubles were experienced with the instability of the sodium silicate solutions. The stabilities of these solutions were greatly increased by the addition of 2% solution

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(10) Hamill, T.E. Aqueous solutions of Ethelene Glycol, Glycerine and Sodium Silicate as quenching media for steels. Bureau of Standards Journal of Research, p. 555, July - Dec. 1931.

(by vol.) of Sodium Hydroxide of Sp.Gr. 1.065.

Oil as Quenching Media

Evaluation of oils as quenching media has been the subject of investigation over many years. The works of Spring, Landsdale and Alexander (11) on evaluation of quenching oils, articles on quenching oils by W. G. Forbes, (12) and G. W. Pressel (13) and a paper by W. I. Pumphrey and F. W. Jones (14) are of importance. It has been stated by Pressel that there is more to the selection of a quenching oil than the specification of such physical properties as fire point, flash point, viscosity, etc. That is only the beginning. Two other characteristics must be built into the oil, namely: oxidation stability and quenching speed. Forbes discusses the different sources of oils and their properties. Unstability and objectionable odour forbids the use of animal and fish oils as quenching media. Vegetable oil also are easily oxidized. Mineral oils with additives have been tried along this line. Some metallurgists believe that additions of about 3 to 5% of lard oil

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(11) Spring, E.K., P.T. Landsdale and C.W. Alexander. An evaluation of quenching oils. Trans. A.S.M., Vol. 33, p. 42, 1944.

(12) Forbes, W.G. What quenching oil to use. Iron Age, p. 50, Aug. 3, 1944.

(13) Pressel, G.W. What quenching oil not to use. Iron Age. Nov. 9, 1944.

(14) Pumphrey, W.I. and F.W. Jones. Some experiments on quenching media. Journal of the Iron and Steel Institute, Vol. 156, p. 37, 1947.

impart beneficial results. Pressel also reports that during the war period different oil companies and metallurgical laboratories worked independently improving the quenching speed of their oils in several ways. To attain superior speed the inhibited base oil is further treated by the addition of wetting agents which quickly eliminate the vapour phase, and dissipate heat faster. Experiments with compounded quenching oils revealed the superior hardening effect of some compounded oils.

The conclusions arrived at by Spring, Lansdale and Alexander as a result of their experiments are of interest. They concluded that: (1) quenching oils cannot be chosen solely on the basis of physical properties, (2) the greatest variations in quenching rates developed by the oils tested are but a minor factor in terms of steel hardenability, (3) the straight mineral oils in comparison to animal and vegetable oils exhibited the greatest change in quenching rate with continued use. In discussion of this paper A. P. Seasholtz of E. F. Houghton and Co., Philadelphia remarks that with the type of high alloy steel (18 : 8 Stainless) used by the authors any of the oils tested will have a sufficiently rapid quenching rate to exceed the critical cooling rate.

External Factors Affecting the Quenching Speed

Among the external factors, temperature of the medium is a factor controlling the quenching speed to a variable extent in different media. Scott in his paper (mentioned before) discussed the effect with different liquids. Forbes has reported that the best temperature for oils lie between 75° F to 120° F.

The agitation of the bath is the most important external factor determining the cooling rate of a quenching media. It has been mentioned by Scott that agitation has the general effect of increasing in general the speed of all three stages of cooling. It is an important factor even in the vapour phases of cooling. Cooling rates at the center of a sphere of unstated composition were observed by French,(15) during quenching in still water and under a water spray at several water pressures. The curves obtained showed that the cooling time from the quenching temperature to say 600° C, diminished more rapidly with increasing spray pressure than was consistent with the increase in cooling rate.

The use of oils in the end-quench test was made originally by D. S. Eppelsheimer (and co-workers, A. S. Harding, Q. O. Therous, F. I. Wakefield and V. B. Wilkins in their joint thesis at the University of New Hampshire).(16)

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(15) French, H. J. Quenching of steels. Trans. A.S.S.T. Vol. 17, p. 646, May; p. 798, June 1930.

(16) Harding, A. S., Q.O. Therous, F.I. Wakefield and V.B. Wilkins. Jominy Hardenability test modified. A thesis submitted at the Univ. of New Hampshire in partial fulfillment of Bachelor of Science Degree in Mechanical Engineering. September 1944.

The authors main idea was to find out whether water could be replaced by oils as quenching media in the end-quench test. In course of their experiments they noticed the peculiar behaviour of Gulf Super Quench and Regular (#684 Gulf) oils under the high agitation of the end-quench test. The reported superior Gulf Super Quench oil, according to usual quenching practice, was found to have a lower quenching speed when used on a fine grained steel specimen in the above described test. The peculiar behaviour may have been due to the removal of vapour phases of cooling during the high agitation of the test.

In some recent works by Sandoz and Siebert,[17] the evaluation of quenching oils was studied, using an end-quench test. A few commercial oils with more or less different physical properties and of different origins were used in place of water as quenching media. They used four different steels, N.E. 9450, 8740, 3312 and 4340. As the results obtained on the latter three steels confirmed those obtained on the first steel, the authors mentioned the results of the N.E. 9450 steel only. Besides the standard agitation of the end-quench test, effects of various agitations caused by changing the stream height and also the diameter of the orifice for the liquid flow were studied. Effects of increasing the initial temperature of the oil

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(17) Siebert, C. A. and G. Sandoz. An evaluation of quenching oils by means of End-quench Test, Metals Technology, TP No. 2353, April, 1948.

also were investigated. The important findings were: (1) increasing the orifice size and stream height increased the hardening power, although the difference was not proportionate; (2) increasing the oil temperature resulted in a decrease in the hardening power of one of the oils tested. This was contrary to the data reported by Spring, Landsdale and Alexander. However, the data were obtained here with still oil. It was also concluded that with high rates of agitation such as those encountered in tests, there was little, if any, advantage to be gained byusing a proprietory compounded oil in place of a straight mineral oil.

III

THEORY

In discussing the theoretical background of the investigation under consideration an understanding of the different stages of cooling is necessary. In the section on the review of the literature, three stages of cooling as reported by Scott have been mentioned.

First Stage or Vapour Blanket Stage. This is the stage a steel specimen encounters when just immersed in the quenching liquid. A vapour blanket is formed and maintained around the metal. Here the temperature is so high that the quenching medium is vapourised at the surface of the metal. Cooling is by radiation and conduction through vapour film. The dominant property is the boiling point of the liquid. The nearer the liquid temperature approaches its boiling point the more it maintains the vapour blanket stage. Cooling at this stage is very slow, becauseof the thermal insulation offered by the vapour blanket and its duration is very important. Here heat is carried away by large masses of vapour and deposited at a distance by recondensing.

"B' Stage or Vapour Transport Stage. When the metal has cooled to such a temperature that a continuous vapour film is no longer maintained, the quenching medium wets the surface of the metal by disruption of the vapour film and violent boiling ensues. This is the fastest and most important stage of cooling. The cooling capacity in this stage is usually taken to be representative of the liquid concerned. Here heat is carried away by large masses of vapour and deposited at a distance by recondensing. Physical properties as Heat of Vaporisation and viscosity of the medium is important at this stage. It may be said that high speed photographs taken has proved the existence of these phases of cooling.

'C' Stage. This stage begins when the surface temperature of the metal approaches the boiling point of the liquid. This is the final stage, in which cooling again is comparatively slow. The cooling proceeds by liquid conduction and convection. Thermal conductivity is the dominant factor here. The figure below shows the duration and nature of the different stages of cooling in a typical cooling curve for the center of a small cylinder during quenching in a still liquid.

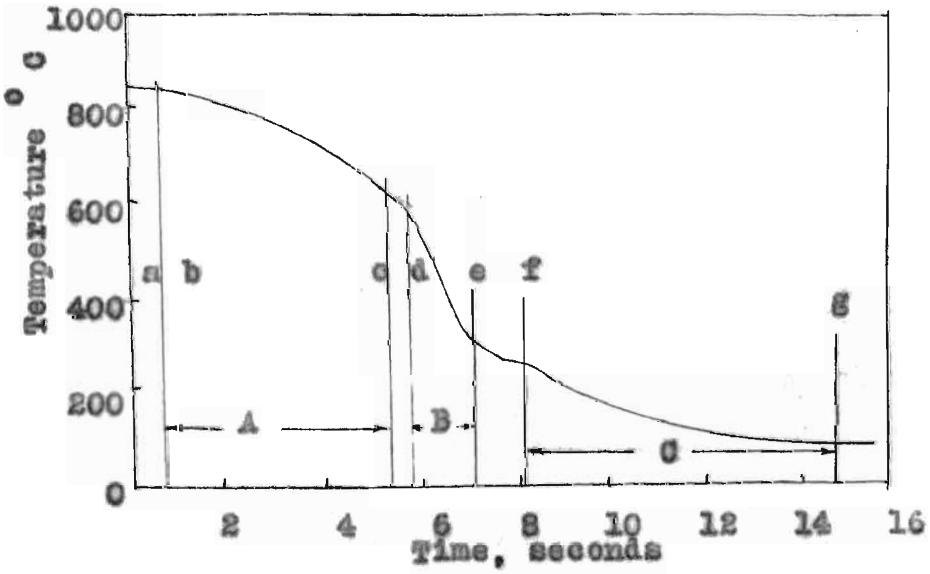

Fig. 1

Typical cooling curve for the center of a small cylinder during quenching in still water at 137° F, illustrating the stages of surface cooling.

The two universally used liquid media for quenching are water and oil. Water provides the fastest cooling rate attainable in practice. The first stage in water is important because of the lower boiling point of water. But its duration is short. The duration of the first stage may be further shortened by the addition of salt as might be expected from the increase of the boiling point. On the other hand, a solution of soap in water increases greatly the duration of vapour phase. A rise in temperature affects the cooling power of water, mainly by prolonging the vapour blanket stage. The second stage in water is very rapid and the unique cooling power of the water quench is realised. Water and aqueous solutions retain this initial quenching speed through the lower temperatures that lie in the range where distortion and cracking occur. Thus the field of usefulness of water quenching is restricted to simple shapes and shallow hardening steels.

In oil quenching, in ordinary oils, the duration of the vapour blanket stage is longer but the vapour blanket is much thinner and the cooling is better than water. The rate of cooling in the 'B' stage is considerably slower than in the corresponding stage in water and the duration of the stage is less. Mineral oils are composed of various hydrocarbons, each of which has its definite boiling point. For this reason in oils there is a gradual transition into 'C' stage cooling as contrasted to the comparatively abrupt demarkation between the 'B' and 'C' stage in water quenching. The problem of developing an ideal quenching oil was to reduce the duration of 'A' stage cooling to the minimum and increase the 'B' stage cooling rate. The oils show little or no change of duration of the vapour blanket with a small rise in bath temperature, because of their very high boiling point. On the contrary the lowering of viscosity by smaller rise in liquid temperature improves the second stage of cooling.

The mechanism of cooling in case of sodium silicate solution presents somewhat different picture than the other aqueous solutions. Sodium silicate forms a jelly-like solution with water, commercially known as water glass. On quenching a steel specimen in such a solution it has been said that a thin coating of silica is formed on the surface of the metal. This coating of silica acts as an insulation throughout the process of cooling. This has been ascribed to be the probable reason of retardation of cooling rate.

It has been already been reported that a very high rate of agitation has unusual effects on the quenching speed of a liquid, specially oils. Effect on the second stage of cooling is most prominant. As the removal of bubbles from the surface of the steel will no longer be entirely dependent upon gravity and convection currents, vapour transport stage of cooling will be most affected. The first stage of cooling also will be considerably affected.

Under very high state of agitation a small rise in initial temperature of oil in a quenching bath has been found to decrease thequenching speed slightly. In still oil, increase in temperature of the oil to a small extent will decrease the viscosity of the medium, which permits the vapour bubbles to escape more readily from the surface than is the case when oil temperature is low. However it would appear that a very high degree of agitation would minimise the effect of viscosity, and the temperature difference between the surface of steel and the oil would be very important.

IV

EQUIPMENT, EXPERIMENTAL PROCEDURE, RESULTS AND DISCUSSION

A standard A.S.T.M. end-quench test as devised by W. E. Jominy was utilized, though with modifications, in all the present series of tests with the idea of studying the behaviour of different quenching media under different quenching conditions.

Several oils and a solution of sodium silicate in water were substituted for water as quenching media. The various experiments can be divided into four series:

1. A study of comparative quenching speed under standard end-quench test agitation.

2. Effect of different quenching speeds on steels of similar hardenability but of different chemical composition.

3. Effect of austenitic grain sizes on relative speeds of quenching media.

4. A study of the effect of different rates of agitation on the depth of hardening.

Comparative Quenching Speed under Standard End-Quench Test Agitation.

A few different quenching media were selected for evaluating quenching properties under usual conditions. Four of these were oils from two different commercial oil companies, a solution of sodium silicate and finally water as a standard for comparison. The liquids used were:

1. Gulf #372 oil
2. Gulf super-quench oil
3. Houghton #2 soluble quenching oil - F-8197
4. Houghto-quench oil - F-8458
5. Solution of sodium silicate in water of specific gravity 16° Be' (2% caustic soda solution by vol. of specific gravity 1.065 was added to increase the stability of the solution without affecting the quenching speed).
6. Water

The first two oils were obtained from the Gulf Oil Corporation, Pittsburgh, Pa., and the other two from E. F. Houghton and Co., Philadelphia, Pa. The physical properties of the oils are given below:

Table I

Tests	#372 Gulf	Gulf Super-Quench	Houghton #2 Soluble	Houghto-Quench
Viscosity, SUV 100° F	102.2	87.4	100-110	100-110
Gravity °A.P.I.	27.0	31.0	28.3	
Flash Point °F	355	345	355	355
Fire Point °F	410	390	410	410

An approximate idea of the quenching speeds under usual conditions of the oils can be obtained from the attached "center cooling rate" and "quenching speed" curves for the different oils, as supplied by the oil companies concerned. (Figs. 2, 3 and 4).

It has been claimed by the Gulf Oil Corporation in their bulletin "Gulf Super-quench" that this oil surpasses conventional oils in quenching speed. It is further mentioned that the increased quenching power of Gulf Super-quench results from the shortening of the 'First' stage cooling and increasing the cooling rate in the 'second' stage.

The bulletin "Houghton on Quenching" issued by the E. F. Houghton & Co. claims the superiority of Houghton #2 soluble oil over other conventional oils up to the period of the last World War. It is stated that Houghton #2 is a combined processed oil developed after considerable research by the E. F. Houghton & Co. Later on they developed a still faster quenching oil in 1941 named "Houghto-quench". The Houghto-quench oil is stated to contain certain wetting agents for prevention of gas pockets.

The sodium silicate solution selected should have an quenching speed between water and oil under ordinary immersion quenching conditions.

The liquids were selected from several different types to obtain more comparative results, as the origin of the liquid in case of oils has appreciable effects on the quenching properties.

The steel specimens used in making the standard A.S.T.M.

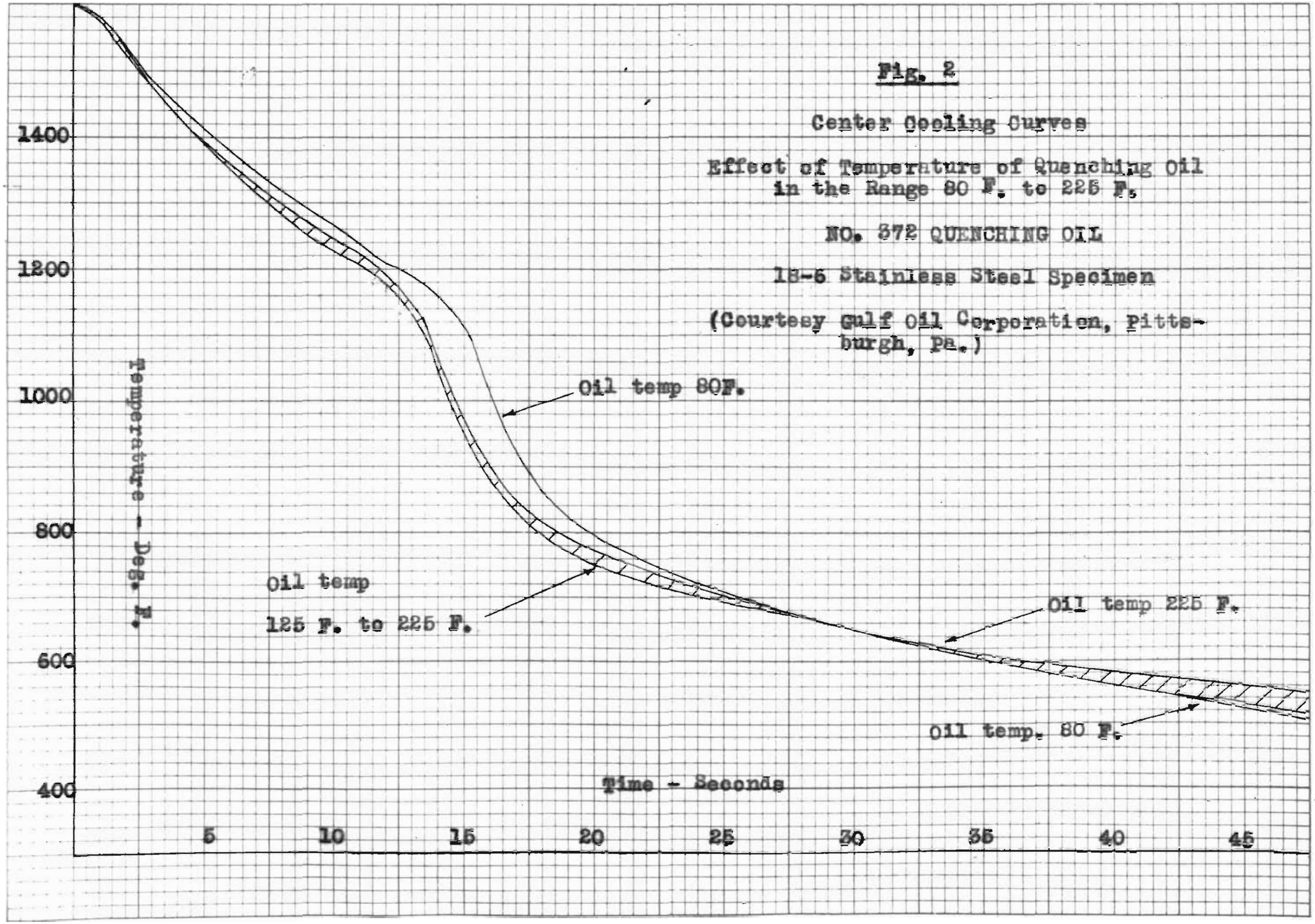
Fig. 2
Center Cooling Curves
Effect of Temperature of Quenching Oil in the Range 80 F. to 225 F.
NO. 372 QUENCHING OIL
18-8 Stainless Steel Specimen
(Courtesy Gulf Oil Corporation, Pittsburgh, Pa.)
Oil temp 80F.
Oil temp
125 F. to 225 F.
Oil temp 225 F.
Oil temp. 80 F.
Temperature - Deg. F.
1400
1200
1000
800
600
400
Time - Seconds
5
10
15
20
25
30
35
40
45

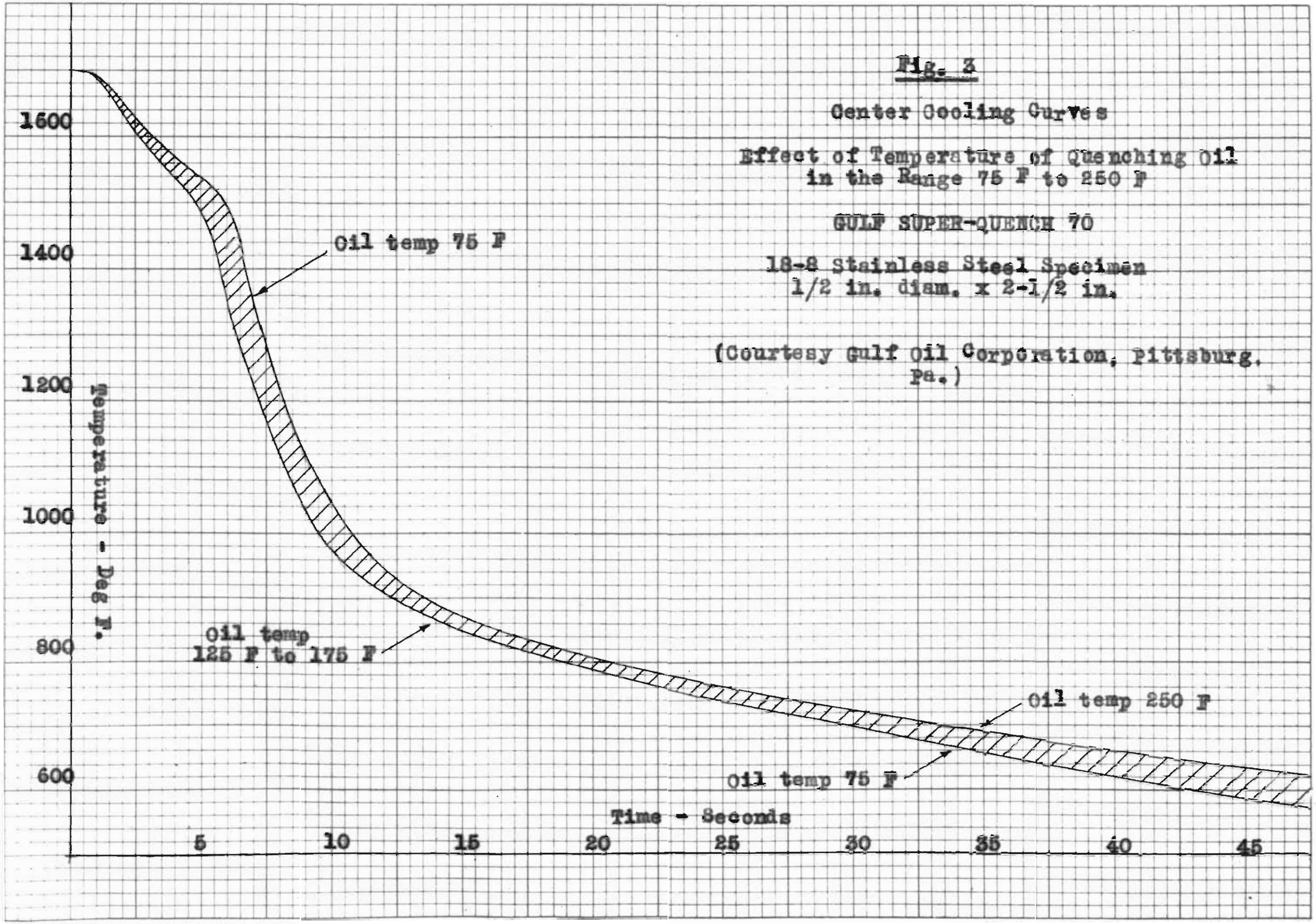
Fig. 3
Center Cooling Curves
Effect of Temperature of Quenching Oil in the Range 75 F to 250 F
GULF SUPER-QUENCH 70
18-8 Stainless Steel Specimen 1/2 in. diam. x 2-1/2 in.
(Courtesy Gulf Oil Corporation, Pittsburg, Pa.)
Oil temp 75 F
Oil temp 125 F to 175 F
Oil temp 250 F
Oil temp 75 F
Temperature - Deg F.
Time - Seconds
1600
1400
1200
1000
800
600
5
10
15
20
25
30
35
40
45

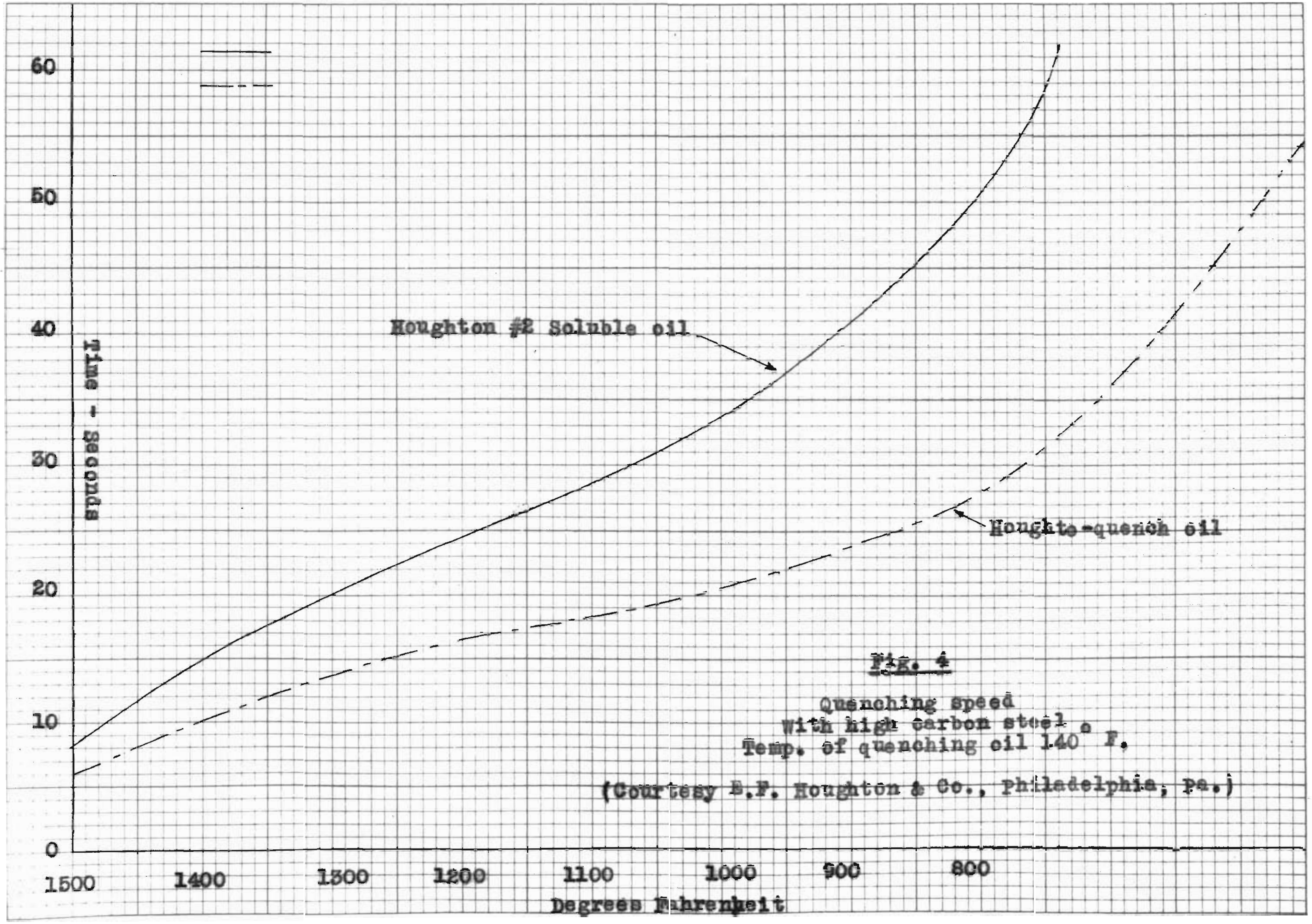

Fig. 4

Quenching speed
With high carbon steel
Temp. of quenching oil 140° F.

(Courtesy E.F. Houghton & Co., Philadelphia, Pa.)

Jominy test pieces were from A.I.S.I. 8742 and 8640 steels, chemical analysis of which are given below:

	C	Mn	P	S	Si	Ni	Cr	Mo	Heat No.*
AISI 8742	.43	.86	.016	.027	.30	.46	.53	.28	211101
AISI 8640	.39	.82	.014	.020	.29	.52	.48	.22	102959

Grain coarsening temperature - above 1900° F for both.

Grain size No. 7 for both.

* Carilloy steels

Hardenabilities of the steels under standard end-quench test are quite different, that of 8640 steel being much lower.

The test pieces were machined to the dimension of 4" long standard test piece from bars normalised at about 1650° F for one hour as recommended for the steels under consideration. Specimens were heated to 1550° F in a stainless steel box under cover of cast iron turnings to prevent scaling and decarburisation, kept for one-half hour at temperature and end-quenched according to recommended A.S.T.M. practice using the different liquids. All the heatings were done in a Multiple Unit Resistence Electric Furnace with Micromax Automatic Control and a Calibrated Chromel-alumel Thermocouple. A 3/8" orifice for liquid flow with a 3" stream height was used in all the tests of this series. Initial temperature of the media was always maintained between 85° - 95° F. Photographs of the set up showing the end-quench apparatus, furnace with accessories has been given in the figures 5 and 6. The hardness determinations were made at standard distances from the quenched end at two diametrically opposite places on the surface after grinding off o.015" material from the surface by means of a precision surface grinder. Precautions were taken not to over heat the specimen to the extent of tempering. Hardnesses at different distances from the end were measured by fixing the specimen in a standard Equitron apparatus. This is a device for conveniently measuring the hardness on the ground surface of the specimen at an interval of 1/16". The apparatus with the specimen in place can be fitted on the anvil of a Rockwell Hardness Tester.

Results and Discussion

Hardness results are given in the tables on pages 28, 29, 30. The values mentioned are the mean of the two readings. In most of the cases the hardness tests were repeated to obtain more accuracy. Curves were then plotted showing Rockwell "C" scale hardness against distance from the quenched end of the specimen on standard A.S.T.M. hardenability graph sheets.

Discussion of Results

The curves obtained with the different media and specimens of steel have been shown in a comparative way by sup-

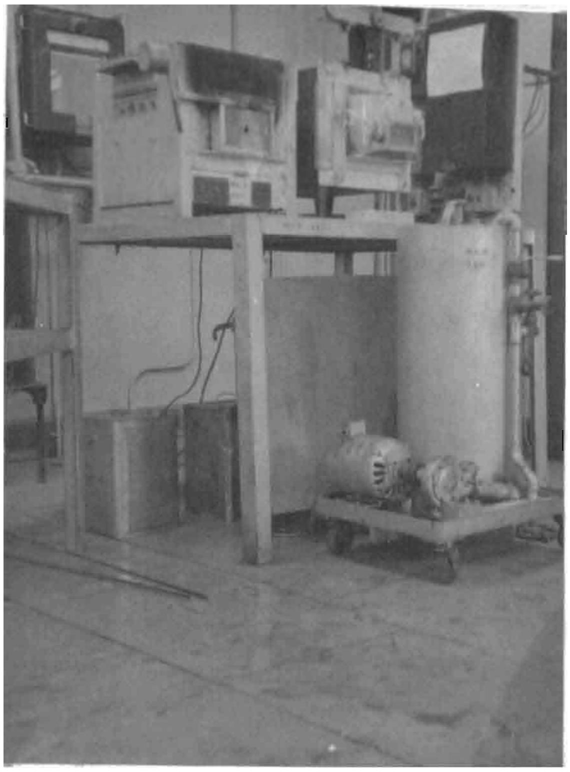

Fig. 5

End-quenching apparatus and furnace with accessories

Fig. 6

End-quenching apparatus showing actual quenching operation.

TABLE I

Distance from end in sixteenths of an inch	Rockwell Hardness 'C' Scale			
	Water		Sodium silicate soln.	
	AISI 8742	AISI 8640	AISI 8742	AISI 8640
1	58.0	57.0	57.5	56.0
2	57.5	56.5	57.5	55.5
3	56.5	55.5	57.0	54.5
4	56.0	54	56.5	54
5	55.0	52.5	56	51.5
6	55.0	50	55	49
7	53.5	46.5	53	45
8	53.0	43	50.5	41
9	51.0	39.5	47.5	37
10	48.5	37	44.5	35
11	46	34.5	42.5	34
12	45	33.5	40.5	32.5
13	42	--	39.5	--
14	40.5	31.5	38.5	30.5
16	38	30.5	36.5	29.5
18	37	--	35	28.5
20	35.5	28	34.5	28
24	33.5	27	33	27
28	32.5	27	32	26.5
32	31.5	26.5	31.5	26.5
36	30	26.5	31	26.5
40	30	26.5	31	26.5

TABLE II

Distance from end in sixteenths of an inch	Rockwell Hardness 'C' Scale			
	Gulf Super-quench		Gulf #372	
	AISI 8742	AISI 8640	AISI 8742	AISI 8640
1	56	51.5	56	52
2	54.5	46	55	48
3	53	42.5	54	43
4	50	39	52	39
5	48	37.5	50	36
6	45.5	35.5	47	34.5
7	44	34	44	33.5
8	41.5	33	42.5	32.5
9	40.5	32	41	--
10	39.5	31.5	39.5	31
11	38.5	--	38.5	--
12	37.5	30.5	37.5	30
14	36	29.5	36	29
16	35	28.5	35	28.5
18	34.5	28	34	28
20	34	27.5	33	27.5
24	32.5	27.5	32	27.5
28	32	27	31	27.5
32	32	27	30.5	27
36	31.5	27	30.5	27
40	31.5	26.5	30.5	26.5

TABLE III

Distance from end in sixteenths of an inch	Rockwell Hardness 'C' Scale			
	Houghto-quench		Houghton #2 Soluble	
	AISI 8742	AISI 8640	AISI 8742	AISI 8640
1	55	52	56	54.5
2	55	46.5	55.5	52.5
3	54	41.5	55	46
4	52.5	38	54	42
5	50.5	36	52	38.5
6	47.5	34.5	49	36
7	45	33	46	34
8	43.5	32	44.5	32
9	42	31.5	42	31.5
10	41	30.5	40	31
11	39	--	38.5	--
12	38.5	30	37.5	29
14	37	29	36.5	28
16	35	28.5	35.5	28
18	33.5	28	34.5	27.5
20	33	28	33	27
24	32.5	27.5	32	26.5
28	32	26.5	31.5	27
32	31	26	31.5	26.5
36	31	26	31	26
40	31	26	31	26

erimposing in one sheet of paper the curves for quenching media of similar origin and also for the two steels, (Figs. 7, 8, and 9). The quenching liquids are divided into groups of (1) water and sodium silicate solution, (2) Gulf #372 and Gulf Super-quench oils, (3) Houghton #2 soluble and Houghto-quench oils, and each group plotted on same paper.

The most interesting thing about the curves is that Gulf Super-quench and Houghto-quench oils, which are reported to have higher quenching speeds than Gulf #372 and Houghton #2 soluble oils respectively, have shown lower speeds than the latter oils in all the cases, up to a certain distance from the quenched end. The differences in case of Gulf oils are small in comparison with the Houghton oils. Again, in case of Houghton oils the difference is far more pronounced when A.I.S.I. 8640 steel was used. The different stages of cooling encountered by a hot piece of steel, when quenched in a liquid medium, has been mentioned already. It has been stated that in the end-quench test, the very high agitation of the medium seems to affect the different stages of cooling in different ways. It is true that rate of cooling is much increased in all the stages. But the first and second stages, specially the second stage, are affected in a more pronounced way. It is quite possible that disruption of the vapour blanket formed at the first stage of cooling takes place, partially, if not completely, under this high state of agitation.

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE ______
LABORATORY ______
TYPE SPECIMEN ______
TEST NO. ______

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

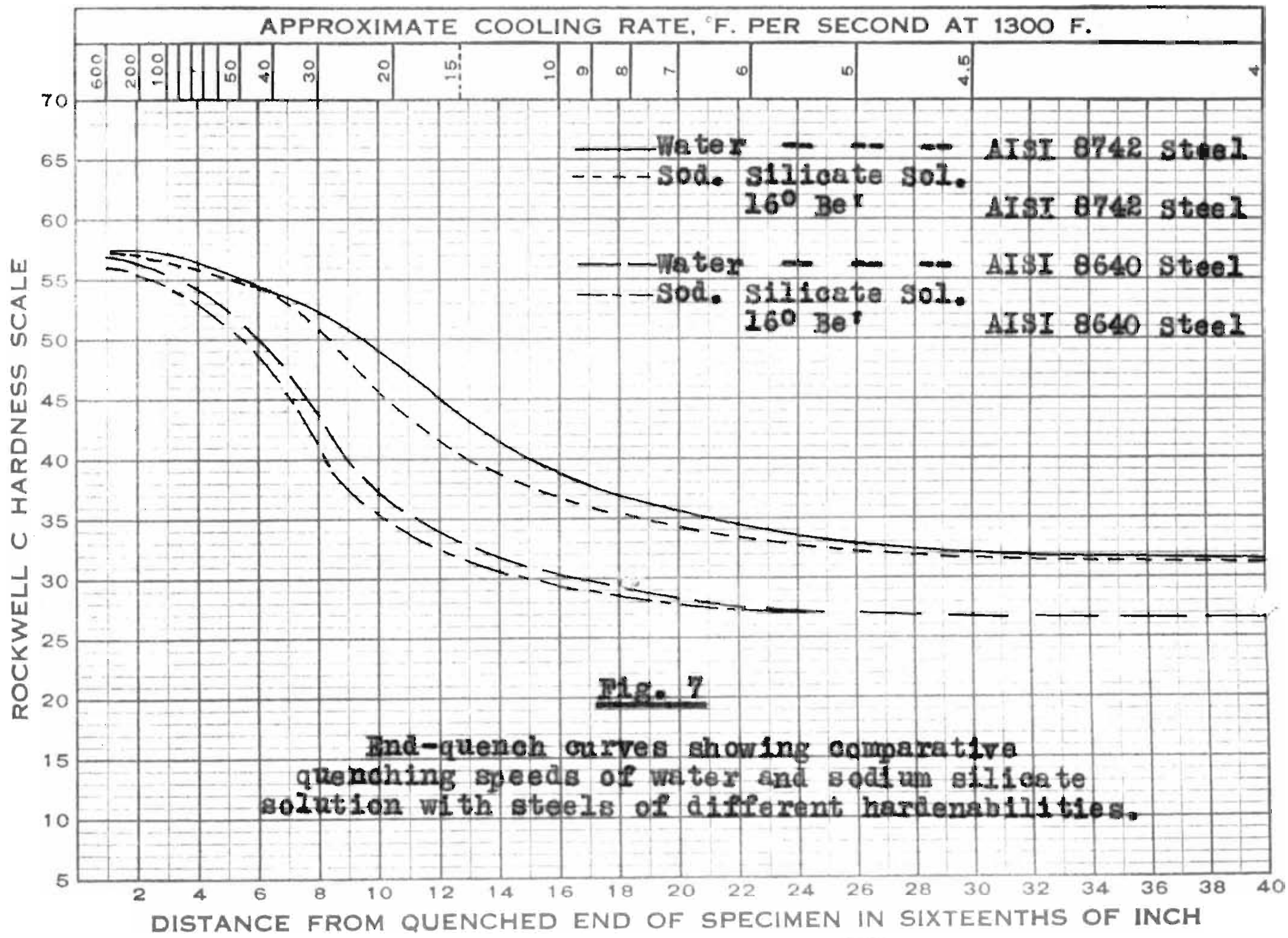

Fig. 7

End-quench curves showing comparative quenching speeds of water and sodium silicate solution with steels of different hardenabilities.

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE
LABORATORY
TYPE SPECIMEN
TEST NO.

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

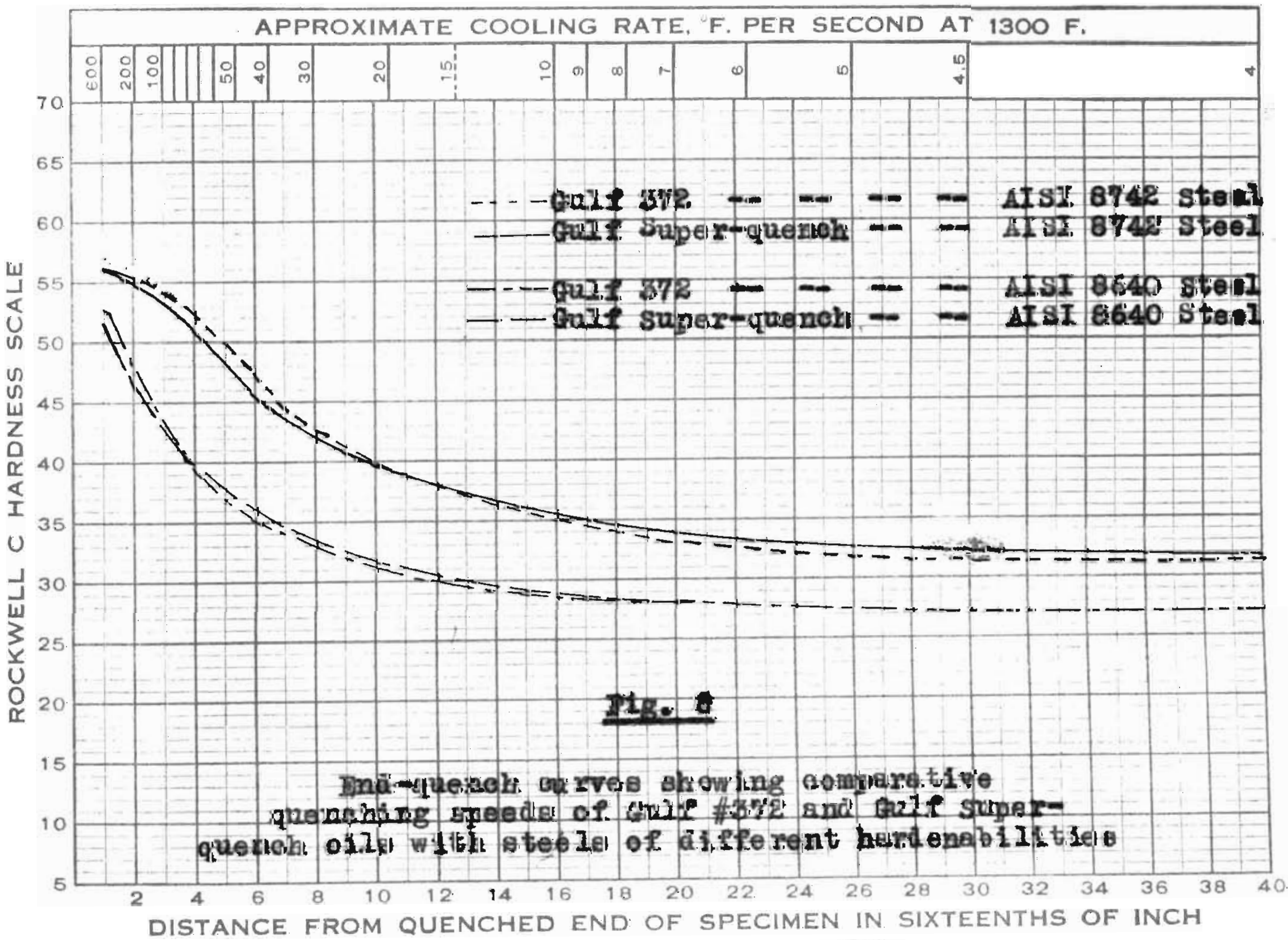

Fig. 8

End-quench curves showing comparative quenching speeds of Gulf #372 and Gulf Super-quench oils with steels of different hardenabilities

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE ______
LABORATORY ______
TYPE SPECIMEN ______
TEST NO. ______

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

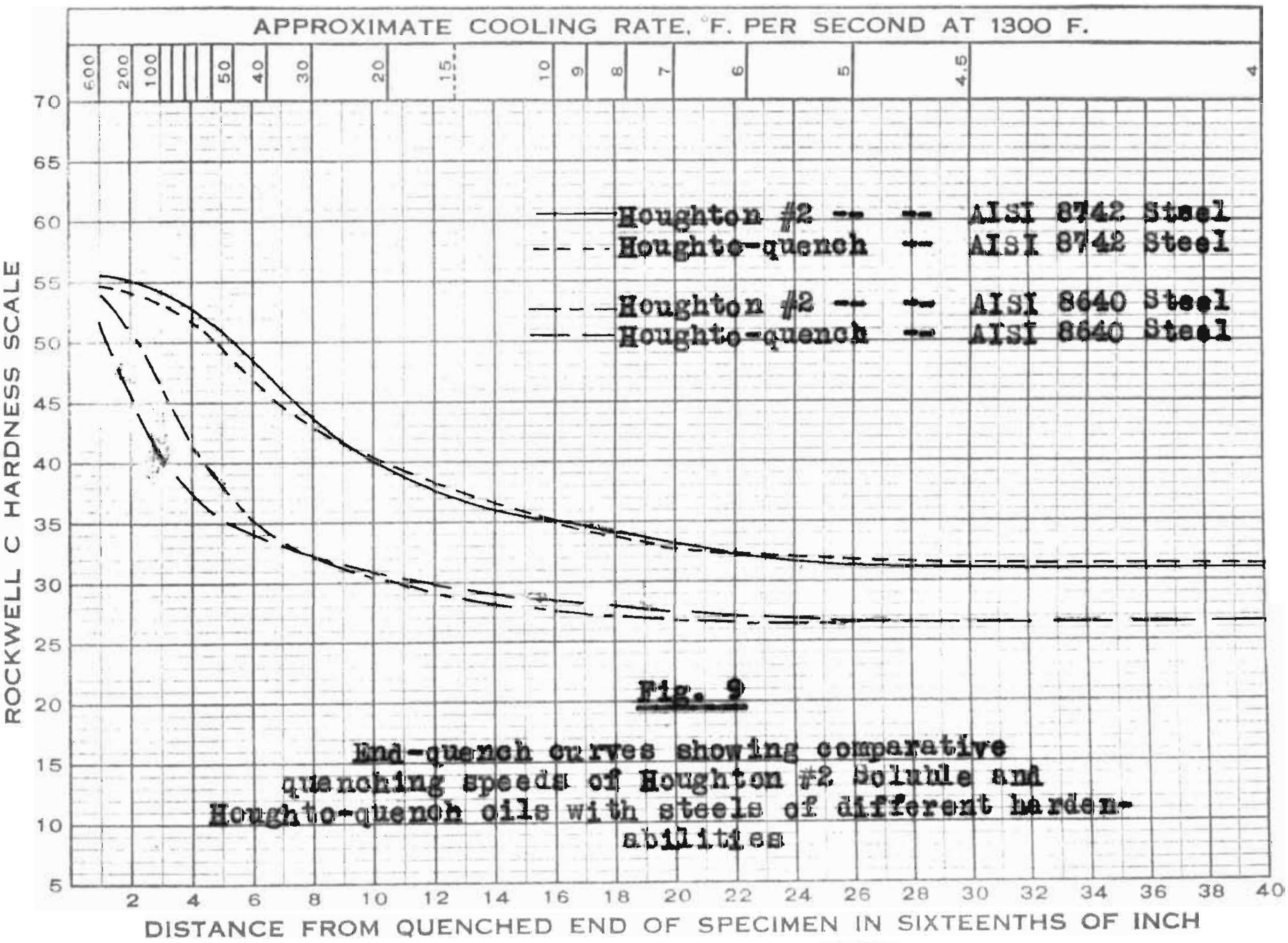

Fig. 9

End-quench curves showing comparative quenching speeds of Houghton #2 Soluble and Houghto-quench oils with steels of different hardenabilities

Transportation of the vapour in the second stage takes place almost immediately as it is formed at the surface of the metal. In ordinary immersion quenching vapour transportation takes place by convection currents set up in the liquid. Thus the viscosity of the medium plays a great role in the second stage of cooling. Here the usual convection current is not at all necessary and the transporting of heat is far quicker than that obtained with usual convection currents. The viscosity of the medium plays a minor part in affecting the quenching speed at this stage. It seems also that the addition agents used with certain oils for wetting out (as Houghto-quench oil) the surface of the metal and hastening the disruption of the vapour phase will have no significant effect under these conditions. It is very reasonable to suggest that the superior quenching properties of Gulf super-quench and Houghto-quench oils over the other respective oils in ordinary immersion quenching operation is related to one or more of the above factors and principally limited to the first and second stages of cooling. The most possible explanation of the discrepancy in quenching speeds observed is the partial or complete absence of the vapour phases of cooling and lack of opportunity for the development of the superior qualities (affecting the first and second stages of cooling mainly) of the Gulf Super-quench and Houghto-quench oils, thereby <u>indirectly</u> increasing the quenching speeds of the Gulf #372 and

Houghton #2 soluble oils respectively, especially in the case of the latter oil. The greater difference in the case of Houghton #2 soluble oil, when used for the AISI 8640 steel may be due to the fact that the critical cooling rates for transformation in the portions of the specimen under consideration, were such that a comparatively small rise in the rate of quenching affected the hardness of AISI 8640 steel considerably, while having less effect in the case of the AISI 8742 steel.

The usual quenching speeds of the oils seems to be regained towards the latter portions of the curves, the exact positions slightly varying with different oils and steels. The superior quenching properties obtained due to the unusual cooling condition could not exist at the lower cooling rates, thus the original and usual properties of the oils were predominant.

The curves for water and sodium silicate solutions for the same two steels, show the superiority of water at all the parts of the different curves, in spite of the unusual conditions of the test. It is of interest that towards the beginning, specially in cases of AISI 8742 steel, the curves of the two liquids, water and sodium silicate solution, show similar nearly equal quenching speeds. In these cases also, the far superior speed of water which appears to be absent, may be due to the reasons suggested for the case of the oils.

Steels with Different Chemical Composition but Similar Hardenability

In this set of experiments another steel specimen, A.I.S.I. 3140 of following chemical composition was used using the same quenching media under similar conditions:

	C	Mn	P	S	Si	Ni	Cr	Heat No.*
AISI 3140	.41	.79	.016	.027	.33	1.29	.73	22.327

* Carilloy Steels

Austenitic grain size of the steel - No. 7

Grain Coarsening Temperature -- above 1900° F.

The steel has very similar hardenability with the A.I.S.I. 8742 steel in the standard end-quench test.

Results and Discussion

Hardness values are given in the Tables IV and V on pages 38 and 39. Curves for hardness values against distance from end have been drawn in the same way as before. In the figures 10 and 11, the curves for 8742 and 3140 AISI steels, respectively, for all the media have been superimposed. The idea is to show the change in the nature of the curves, if any, with the three sets of liquids, while two different steels, with almost identical hardenabilities under standard conditions, are used. The two steel specimens selected showed very similar hardenabilities under standard A.S.T.M. end-quench tests.

The curves show some interesting results. First, the

TABLE IV

Distance from end in sixteenths of an inch	Rockwell Hardness 'C' Scale — A.I.S.I. 3140 Steel			
	Water	Sod. Sil.	Gulf #372	Gulf Sup. Quench
1	57.5	57.5	55	55
2	57	56.5	54	53.5
3	56.5	55	52.5	51.5
4	56.5	54	50.5	49.5
5	55	53.5	49	47
6	54.5	52	46	44.5
7	53.5	50.5	44.5	42.5
8	53	48.5	42.5	41
9	51.5	47	41	39.5
10	49.5	45	40	38.5
11	47.5	43	39	37.5
12	46	41	38	36.5
14	42	38.5	36.5	34.5
16	40	36	35	34
18	38.5	35.5	34	33
20	36.5	34.5	33	32.5
24	34.5	33.5	32	32.5
28	33.5	32.5	32	32
32	32.5	32.5	31.5	32
36	32	32	31.5	31.5
40	32	32	31.5	31.5

TABLE V

Distance from end in sixteenths of an inch	Rockwell Hardness 'C' Scale A.I.S.I. 3140 Steel	
	Houghton #2 Soluble	Houghto-quench
1	55	54
2	54	53
3	52.5	50.5
4	50.5	48.5
5	48.5	46
6	46.5	44
7	44.5	42
8	42.5	41
9	41	40
10	39.5	39
11	39	38
12	38	37.5
14	36.5	36
16	35.5	35
18	34.5	34.5
20	34	34
24	33	33
28	33	32.5
32	32	32.5
36	32.5	32
40	32	32

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE________
LABORATORY________
TYPE SPECIMEN________
TEST NO.________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

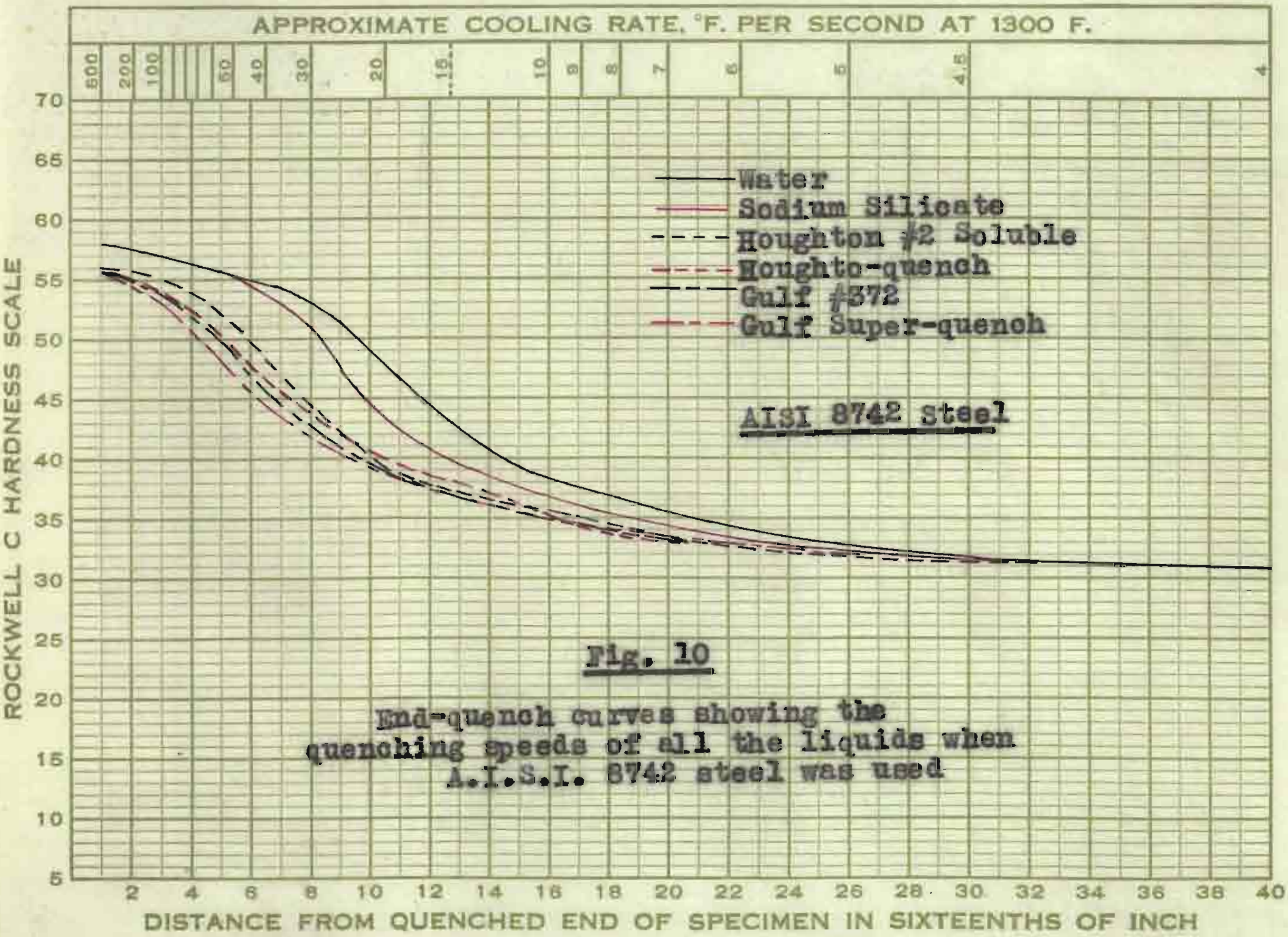

Fig. 10

End-quench curves showing the quenching speeds of all the liquids when A.I.S.I. 8742 steel was used

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE
LABORATORY
TYPE SPECIMEN
TEST NO.

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

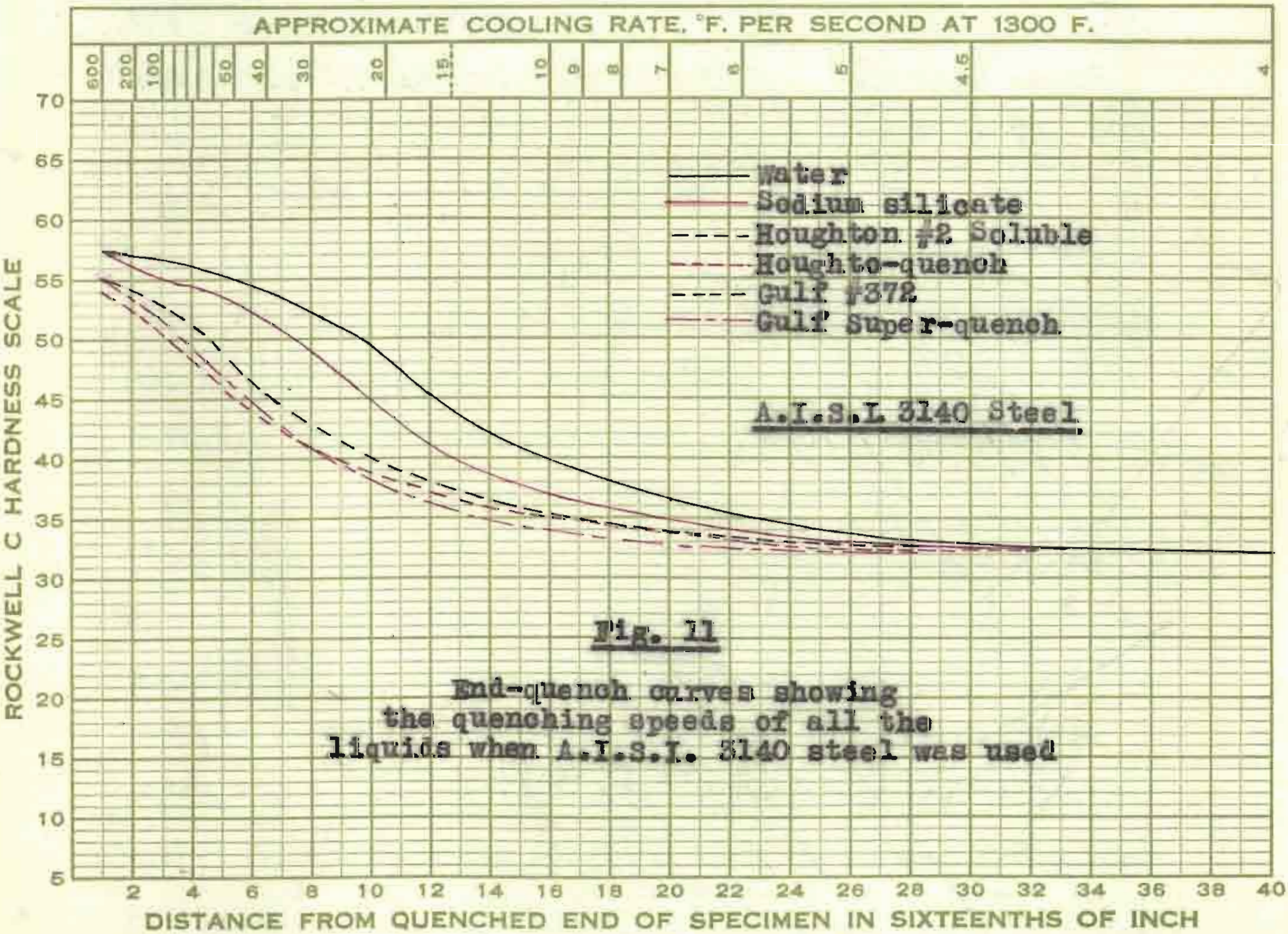

Fig. 11

End-quench curves showing
the quenching speeds of all the
liquids when A.I.S.I. 3140 steel was used

water and sodium silicate solution curves for A.I.S.I. 8742 steel coincide up to a short distance, about 3/8", from the end. This was not observed in case of A.I.S.I. 3140 steel curves with the same liquids. Second, Gulf #372 and Houghton #2 soluble oil curves coincide in case of A.I.S.I. 3140 steel, but there is good variation in case of A.I.S.I. 8742 steel. Again, if water and sodium silicate curves are compared separately for the two different steels, the curves for sodium silicate solution are dissimilar. In case of A.I.S.I. 3140 steel, a lowering of hardness figures is more prominent. Similarly, by superimposing curves of A.I.S.I 8742 and A.I.S.I. 3140 steels for all the oils, it can be shown that the hardness figures for A.I.S.I. 3140 steel are slightly lower than those of A.I.S.I. 8742 in all other cases, though to varying degrees.

It is therefore apparemt, that steels with different chemical composition but similar hardenabilities according to standard end-quench hardenability test may behave differently to different media with different quenching speeds. A probable explanation is proposed. The hardness figure obtained at any position on the specimen of steel is the average of the hardness figures for different products of transformation of Austenite. Different proportions of the transformation products may result in the same hardness value. Thus, similar hardness figures obtained with different steels does not indicate that the constituents supplying the hardness observed are the same. Now, it is known that different transformation products will have different cooling rates for their formation. It is thus quite evident that variation of cooling rate has altered the proportions of the transformation products (accounting for the hardness values at different positions) differently with the two different steels, though they had similar hardness figures at similar positions along the bar in the standard end-quench test. Looked at from another angle, it maybe said that increasing the quenching speed from the lowest quenching speeds, observed with the Gulf Super-quench and Gulf #372 to the highest speed observed with water, increased the hardness figures of A.I.S.I. 8742 steel at slower rate than those of A.I.S.I. 3140 steel and ultimately with the water quench they nearly coincided.

The results of further increasing the speed beyond water quench were not studied. It is difficult to say whether there will be any further change in the comparative hardness figures of the two steels. It may also be true that a so-called set of limiting hardness values under the present test conditions has been attained. It is suggested that the investigation be carried out further along this line, using more steels and higher quenching rates.

Effect of Austenitic Grain Sizes on Relative Speeds of Quenching Media

In this series, the purpose of the experiment was to observe the behaviour of curves of hardness figures plotted against distances from the quenched end with the same steel, at different austenitic grain sizes, when different quenching media were used. The specimens could be selected from different steels with similar hardenabilities but different grain sizes. As this type of property cannot possibly be in steels of the same composition, another factor, chemical composition, enters into the field. The picture thus gets quite complicated. To avoid this difficulty the same steel was heated to two different temperatures to obtain different grain sizes. The steel specimen used for this purpose conformed to the specification C-1045 and the chemical analysis is as follows:

	C	Mn	P	S	Heat No.*
C-1045	.44	.77	.013	.045	842521

* Carilloy steel

The oils, Houghton #2 and Houghto-quench, and sodium silicate solution of 16° Be' sp. gr. as used in the previous experiments were used as quenching media. To obtain the different grain sizes, (A) one specimen was heated to 1550° F., kept for one-half hour at temperature, and (B) the other to 1900° F. and kept for one hour at temperature. Both were then quenched from the same temperature of 1550° F. The quenching from the same temperature was necessary as cooling rates are slightly different if quenched from higher temperature. Hence equalisation of quenching temperatures was necessary. The other experimental conditions and procedure were similar to previous experiments.

The grain sizes of the specimens were measured on the same quenched bars by polishing and etching with 3% Nital. The grain boundaries were outlined clearly by the formation of ferrite at the grain boundaries, at a certain distance from the quenched end. Photo-micrographs of the two structures at 100 dia. magnification are shown in Figures 12 and 13 on page 46. The grain sizes measured according to A.S.T.M. charts are No. 3 - 4 at 1550° F., and No. 1 at 1900° F.

Results and Discussion:

The hardness values are given in the Tables VI and VII, pages 47 and 48. Hardness values were plotted as usual on two plots separately for each grain size, superimposing curves for different media (Figs. 14 and 15, pages 49 and 50).

From the plots it is clear that in cases of all the quenching media, the hardness figures with the larger grain sized specimen are always higher than those of the smaller grain size. This behaviour has been explained earlier by several investigators. The larger grain sizes have smaller surface area per unit volume of steel. Thus in larger grain sizes transformation takes place more slowly and hardenability is increased.

In the curves for the two different grain sizes it is

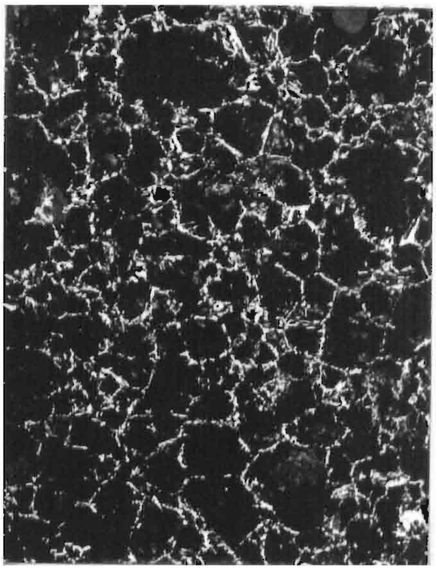

Fig. 12

Photomicrograph showing outlines of grain boundary developed in the C-1045 steel heated to 1550° F. for one-half hour.

Etchant: 3% Nital
Magnification: 100 X

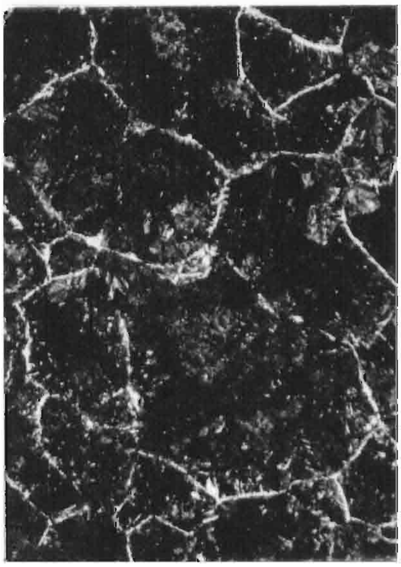

Fig. 13

Photomicrograph showing outlines of grain boundary developed in the C-1045 steel heated to 1900° F. for one hour.

Etchant: 3% Nital
Magnification: 100 X

TABLE VI

Distance from end in sixteen-ths of an inch	Rockwell Hardness 'C' Scale C-1045 Steel Heated to 1550° F		
	Soc. Silicate	Houghton #2 Sol.	Houghto-quench
1	51	35	31
2	49	31	29
3	44	28.5	28
4	33	27	27
5	31	--	25.5
6	30.5	25	24.5
7	--	--	--
8	29	24	23
9	--	--	--
10	28	22.5	22
11	--	--	--
12	26.5	21	20
14	25.5	20	18.5
16	24.5	18.5	--
18	23.5	16.5	15.5
20	22.5	16	14
24	19	13	12
28	16	11.5	10.5
32	?	9.5	9
36	?	8.5	8
40	?	8.5	8

TABLE VII

Distance from end in sixteenths of an inch	Rockwell Hardness 'C' Scale — C-1045 Steel Heated to 1900° F		
	Sod. Silicate	Houghton #2 Sol.	Houghto-quench
1	53	42.5	34.5
2	51.5	35.5	31.5
3	47	30.5	30.5
4	38	29.5	--
5	33.5	--	28.5
6	32	28.5	--
7	--	--	28
8	30.5	28.5	--
9	--	--	--
10	29	27	26.5
11	--	--	--
12	29	27	25.5
14	27	26.5	25
16	27.5	25	24
18	25.5	23.5	22.5
20	25	23	20.5
24	24	21	20
28	20.5	18.5	17
32	?	16	15
36	?	14.5	13.5
40	?	14	13.5

A. S. T. M. END QUENCH TEST FOR HARDENABILITY OF STEEL (A 255 - 46 T)

DATE__________
LABORATORY__________
TYPE SPECIMEN__________
TEST NO.__________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

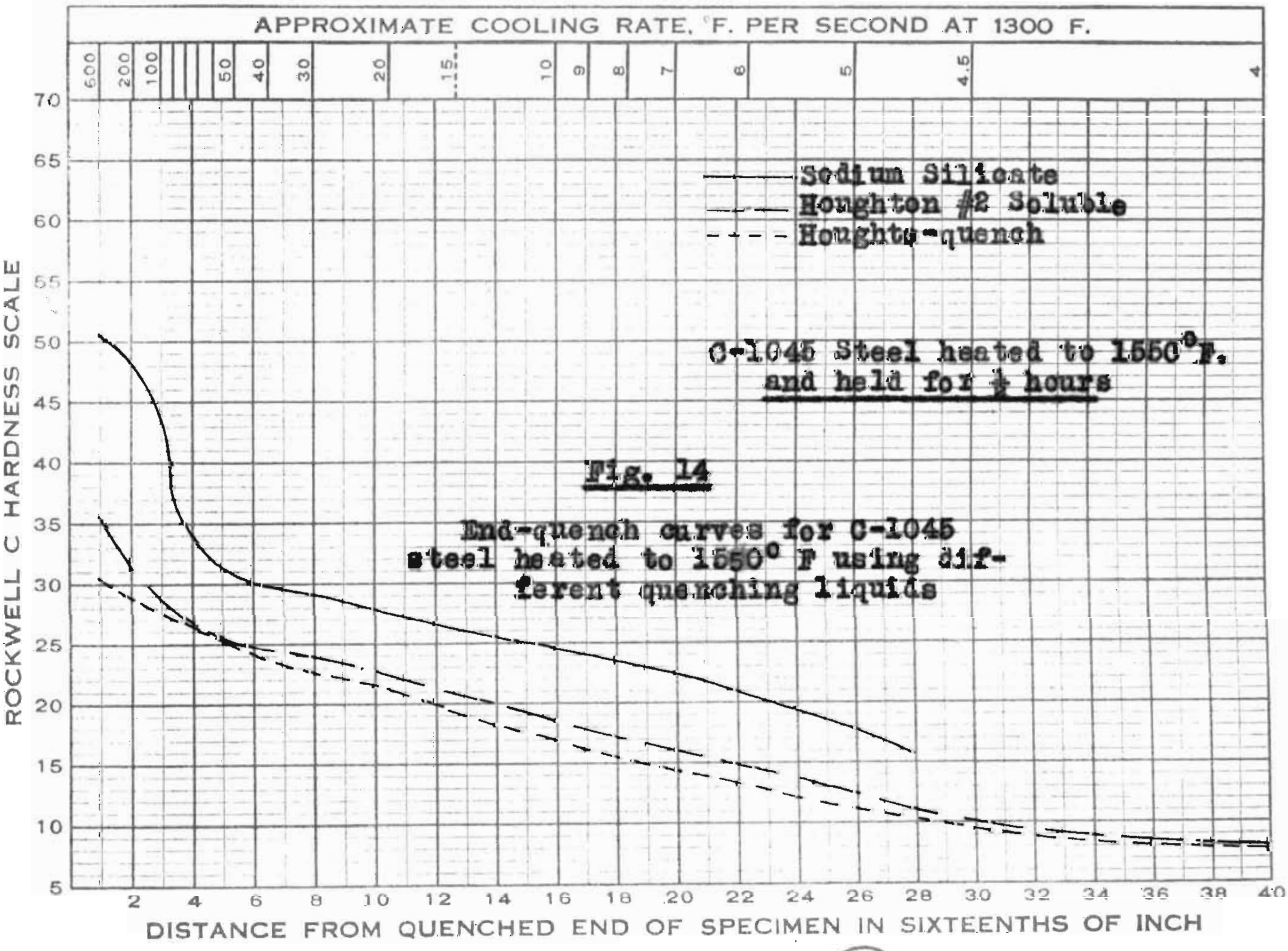

Fig. 14

End-quench curves for C-1045 steel heated to 1550° F using different quenching liquids

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE ______
LABORATORY ______
TYPE SPECIMEN ______
TEST NO. ______

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

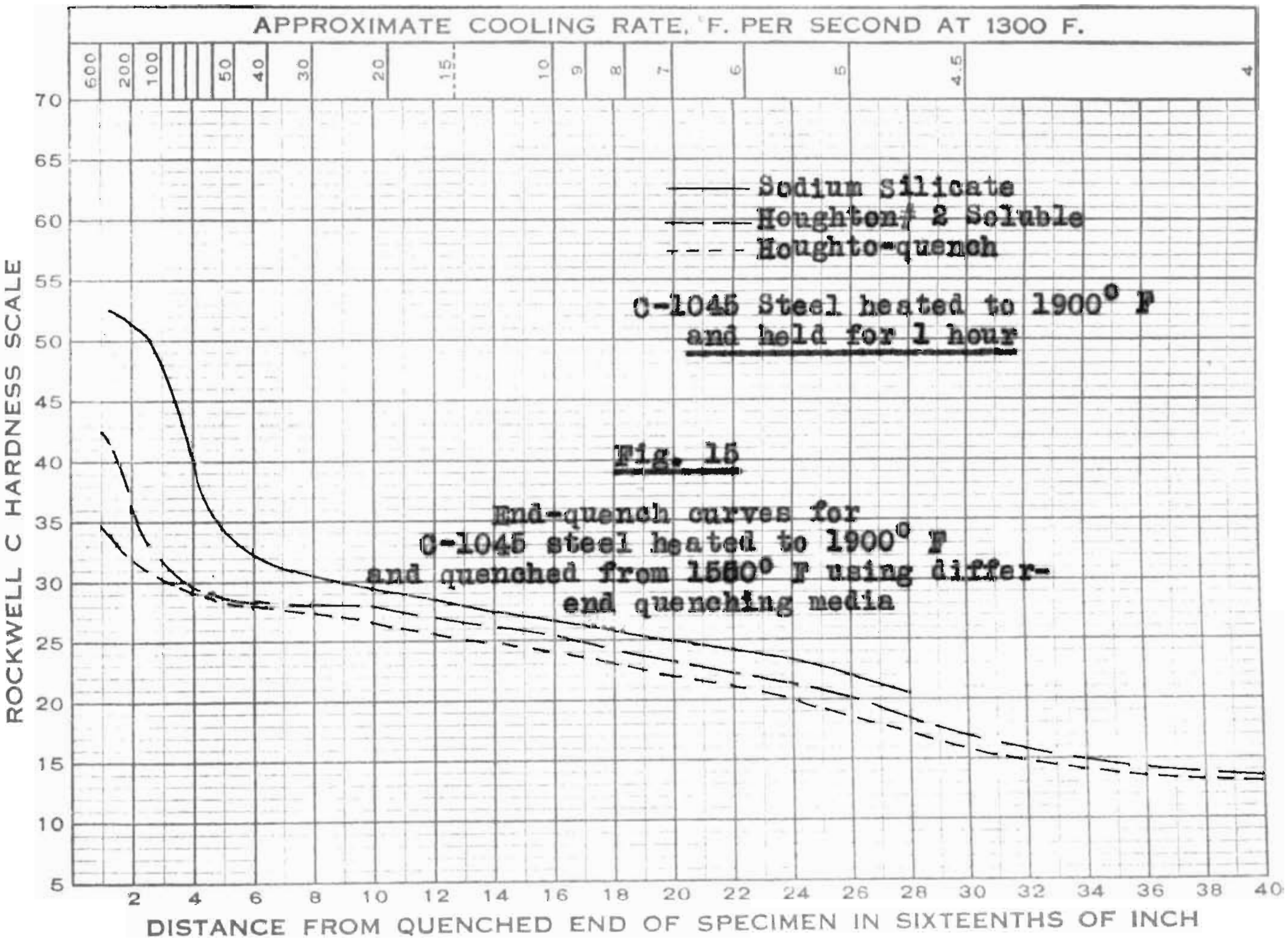

Fig. 15

End-quench curves for
C-1045 steel heated to 1900° F
and quenched from 1560° F using differ-
end quenching media

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also observed that the difference in the increase of hardness figures specially in case of the sodium silicate solution compared with the other two media is much less pronounced with the larger grain sized specimen than with the smaller grain sized one. It is also true that the curves with sodium silicate solution for the larger grain sized specimen has moved upward very little due to increased grain size, whereas the curves for the other liquids have considerably changed. Equal amount of decrease of critical cooling rate of transformation (on account of larger grain size) has not the same proportionate increase of hardness value due to different quenching speeds. Probably, the higher cooling rate as with sodium silicate solution has reached almost a certain optimum value, so that equal degree of increased sluggishness in the steel as regards transformations (due to increased grain size) did not respond to the desired extent.

Study of the Effects of Different Rates of Agitation

In the first series of experiments it was assumed that the unusual behaviour of the Gulf #372 and Houghton #2 Soluble oils showing superior quenching speeds than those of Gulf Super-quench and Houghto-quench oils is due to partial or complete elimination of Vapour blanket and Vapour Transport phases of cooling. If the assumption is true there must be a critical rate of agitation below which the usual character of the oils is still retained. On this assumption several quenching tests were run with different liquids, using different steels, under varying states of agitation.

The quenching media used in these tests were Houghton #2 soluble and Houghto-quench oils and sodium silicate solution, as used before. Steel specimens used were from A.I.S.I. 8742 and 8640 steels. The rate of agitation was changed by controlling the heights of the liquid stream above the top of the orifice without the specimen being in position. In this way four different heights at 6", 3" (previous height), 2" and 1" were obtained. Besides, a still lower rate of agitation was tried for by minimizing the usual distance of ½", between the orifice and the end of the specimen (when placed in position) as much as possible and at the same time lowering the height of the stream further. But the pressure of the liquid in this condition was found to be insufficient to cover the whole surface of the end of the specimen. This later idea was therefore abandoned.

Results and Discussion

Hardness results are given in the Tables VIII, IX, X, XI and XII on pages 53 to 57. Figures 16 thru 20, pages 58 thru 59, show, respectively, the curves for A.I.S.I 8742 steel with different heights on the stream of Houghton #2 Soluble and Houghto-quench oils and the curves for A.I.S.I. 8640 steel with different heights of stream of sodium silicate solution, Houghton #2 Soluble and Houghto-quench oils,

TABLE VIII

Distance from end in Sixteenth of an inch	Rockwell Hardness 'C' Scale AISI 8640 Steel - Sodium Silicate Soln.		
	1" height	2" height	6" height
1	56.5	57	56.5
2	56	55.5	55
3	54.5	54.5	55
4	53.5	54	54
5	52	51.5	51.5
6	47.5	49	49
7	43	45	45
8	38.5	40.5	39
9	36.5	37.5	36
10	34	35	34
11	--	32.5	--
12	32	31.5	32
14	31	30	30.5
16	29.5	29	29
18	29	29	29
20	28	28.5	28.5
24	27	27.5	27.5
28	26	26.5	26.5
32	26	26.5	26
36	26	26.5	26.5
40	26	26	26.5

TABLE IX

Distance from end in Sixteenths of an Inch	Rockwell Hardness 'C' Scale		
	AISI 8742 Steel - Houghton #2 Soluble		
	1" height	2" height	6" height
1	--	55.5	55.5
2	53.5	55	55.5
3	48	54	55
4	45	53.5	53.5
5	43	51	52
6	40.5	48.5	49.5
7	39.5	46.5	47.5
8	38	45.5	44.5
9	36.5	42.5	43
10	35.5	40.5	41
11	34.5	39.5	40
12	34	38.5	39
14	32	36.5	37.5
16	31.5	35.5	36
18	31	34.5	34.5
20	30.5	34.5	34
24	31	33	33
28	31	31.5	31.5
32	30.5	32	31.5
36	30.5	31	31
40	30.5	31	31

TABLE X

Distance from end in Sixteenths of an inch	Rockwell Hardness 'C' Scale AISI 8640 Steel - Houghton #2 Soluble		
	1" height	2" height	6" height
1	52	53	54
2	51	52.5	52.5
3	46	47.5	48
4	40	42	42.5
5	36	38	39
6	33.5	36	36
7	32	34	34
8	31.5	32	33
9	--	--	--
10	29.5	30	31
11	--	--	--
12	28.5	28.5	29
14	27.5	27.5	28.5
16	27	27	28
18	27	27	27.5
20	26.5	26	27.5
24	26.5	26.5	27
28	26	26	26.5
32	26	26.5	26
36	26	26	26
40	26	26	26

TABLE XI

Distance from end in Sixteenths of an inch	Rockwell Hardness 'C' Scale AISI 8742 Steel - Houghto-quench		
	1" height	2" height	6" height
1	54	52	54.5
2	51.5	53.5	54
3	48	53	53
4	45.5	50	51.5
5	43.5	47.5	50
6	41.5	45.5	48
7	40.5	43.5	45.5
8	39.5	41.5	43.5
9	38.5	40	41.5
10	38	38.5	40
11	37.5	37.5	38
12	37	36.5	36.5
14	36	35.5	35
16	34.5	34	34
18	33.5	33	33
20	33	32.5	32.5
24	32	31.5	31.5
28	31.5	31.5	31
32	31	31	31
36	31	31	30.5
40	31	31	30.5

TABLE XII

Distance from end in Sixteenths of an inch	Rockwell Hardness 'C' Scale AISI 8640 Steel - Hought-quench		
	1" height	2" height	6" height
1	47	50	53
2	42	45	50
3	37	40	46
4	34	36.5	42
5	32	34.5	38.5
6	31	33.5	36.5
7	--	32.5	34.5
8	30	32	33.5
9	--	--	33
10	29.5	31	32
11	--	--	--
12	29	30	31
14	28.5	29.5	29.5
16	28	28.5	29
18	--	28	28.5
20	27	27.5	28
24	26.5	27	27.5
28	26.5	27	26.5
32	26	27	26.5
36	26	26.5	27
40	26	26.5	26.5

A. S. T. M. END QUENCH TEST FOR HARDENABILITY OF STEEL (A 255 - 46 T)

DATE __________
LABORATORY __________
TYPE SPECIMEN __________
TEST NO. __________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

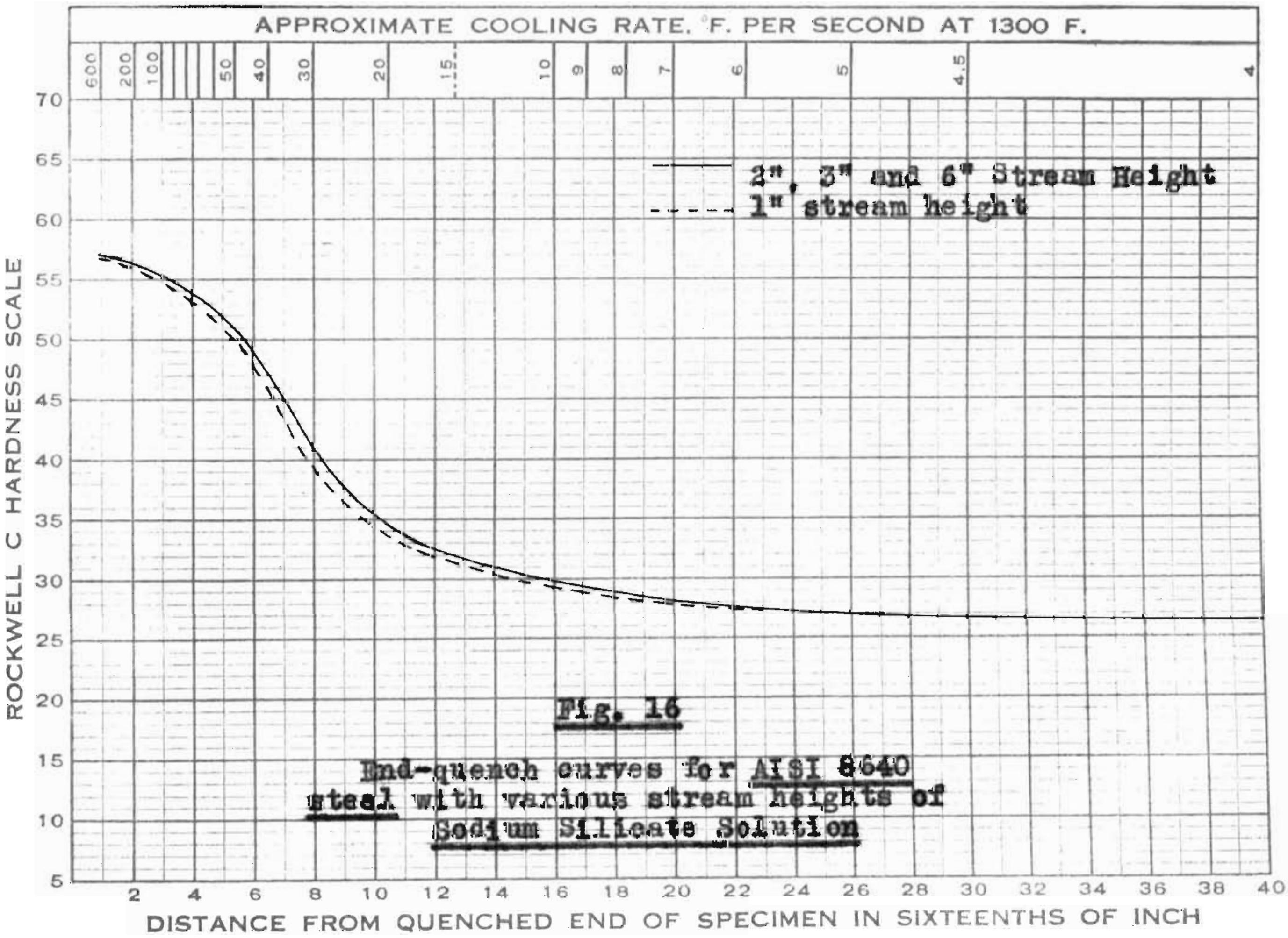

Fig. 16

End-quench curves for AISI 8640 steel with various stream heights of Sodium Silicate Solution

A. S. T. M. END QUENCH TEST FOR HARDENABILITY OF STEEL (A 255 - 46 T)

DATE __________
LABORATORY __________
TYPE SPECIMEN __________
TEST NO. __________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

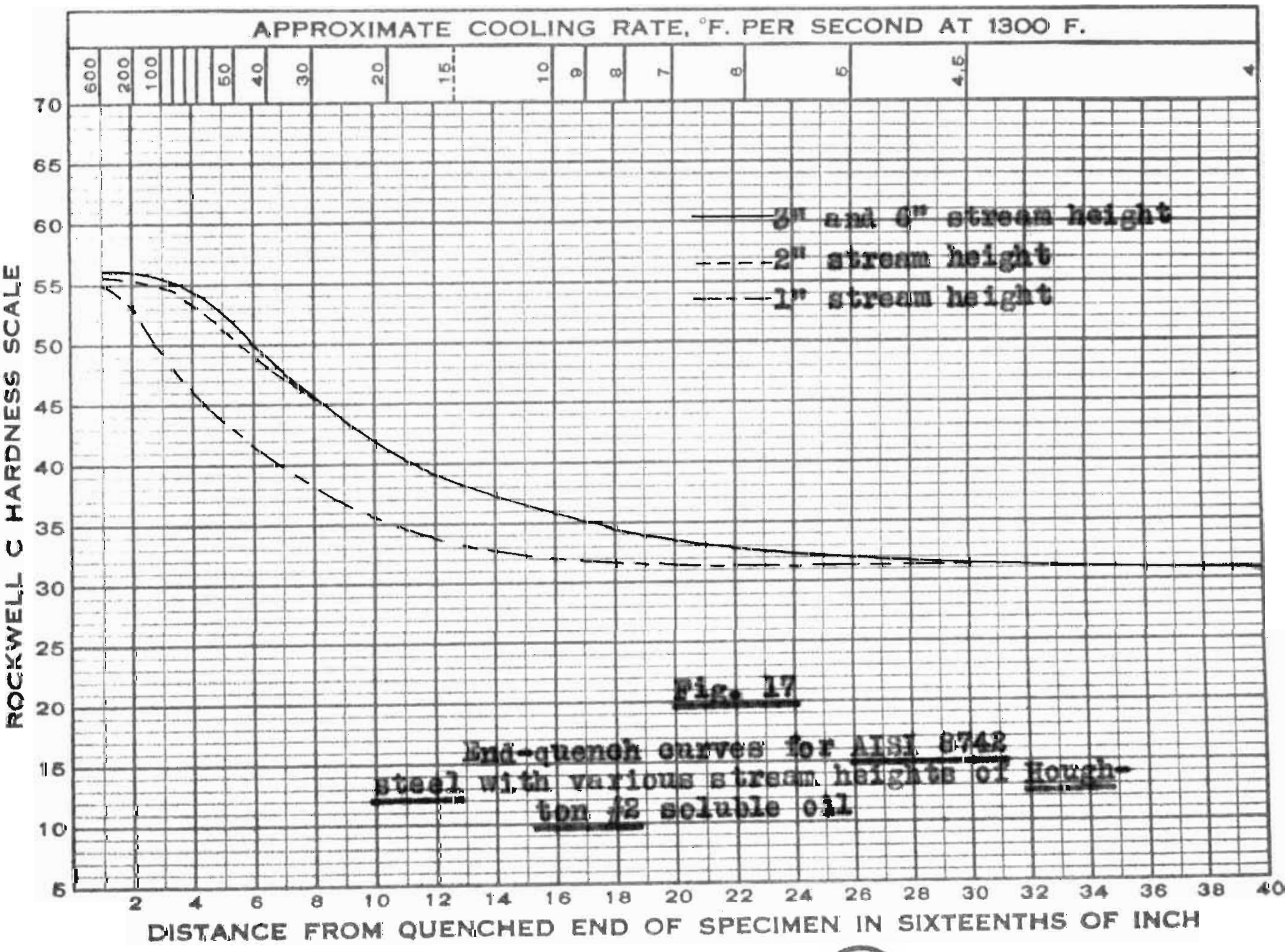

Fig. 17

End-quench curves for AISI 8742 steel with various stream heights of Houghton #2 soluble oil

A. S. T. M. END QUENCH TEST FOR HARDENABILITY OF STEEL (A 255 - 46 T)

DATE__________
LABORATORY__________
TYPE SPECIMEN__________
TEST NO.__________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

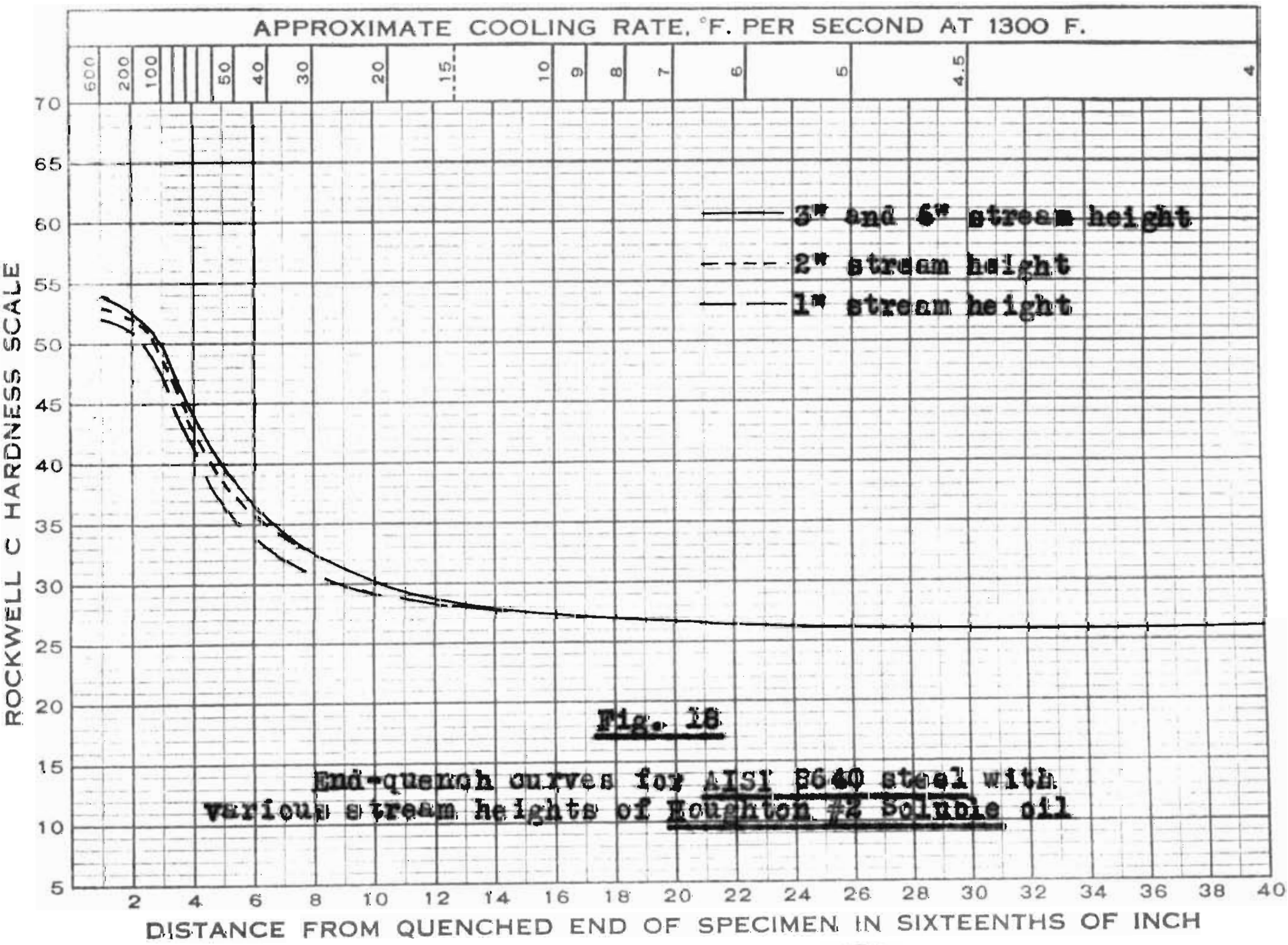

Fig. 18

End-quench curves for AISI 8640 steel with various stream heights of Houghton #2 Soluble oil

A. S. T. M. END QUENCH TEST FOR HARDENABILITY OF STEEL (A 255 - 46 T)

DATE__________
LABORATORY__________
TYPE SPECIMEN__________
TEST NO.__________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

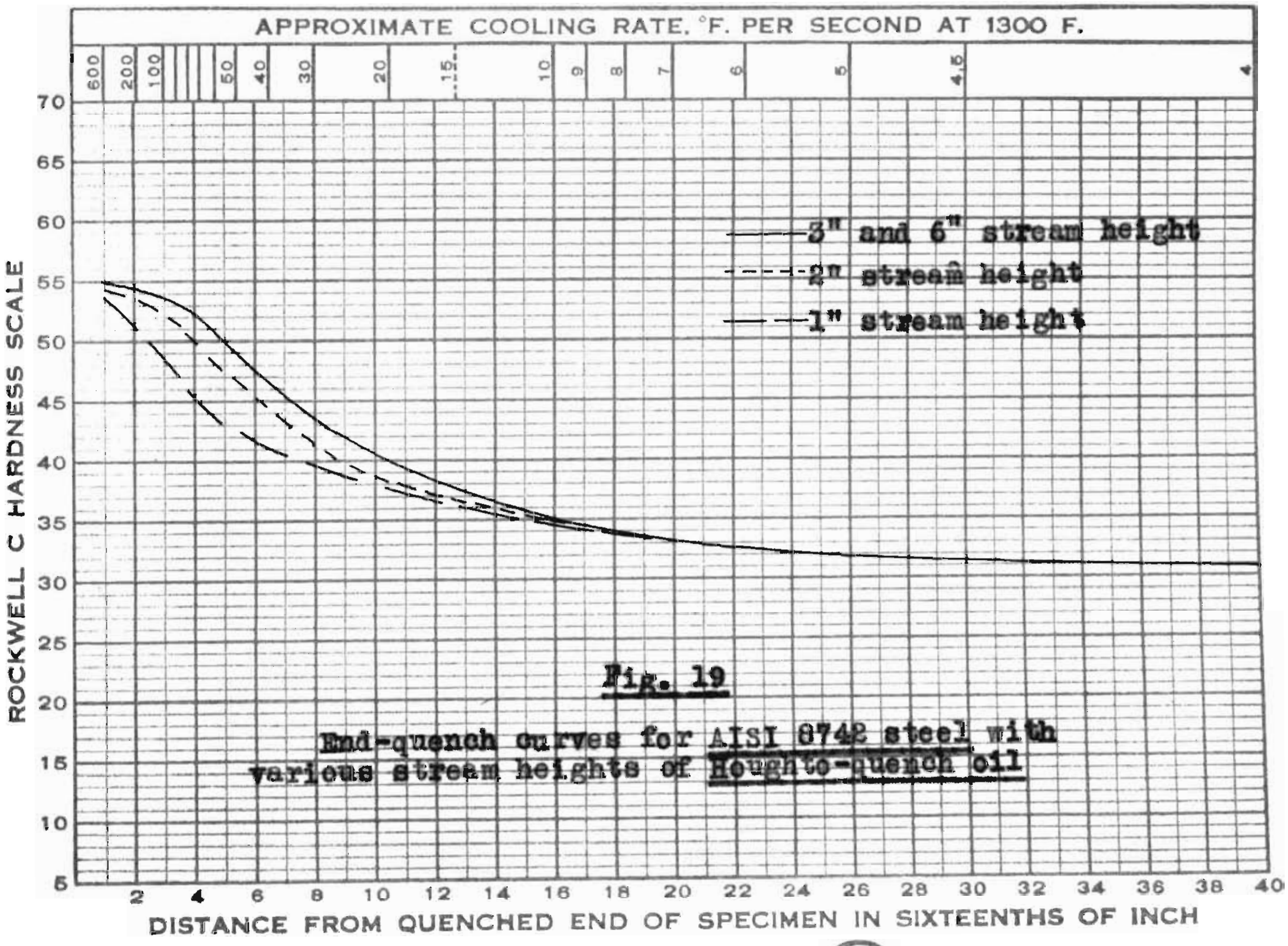

Fig. 19

End-quench curves for AISI 8742 steel with various stream heights of Houghto-quench oil

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE ____________________
LABORATORY ____________________
TYPE SPECIMEN ____________________
TEST NO. ____________________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

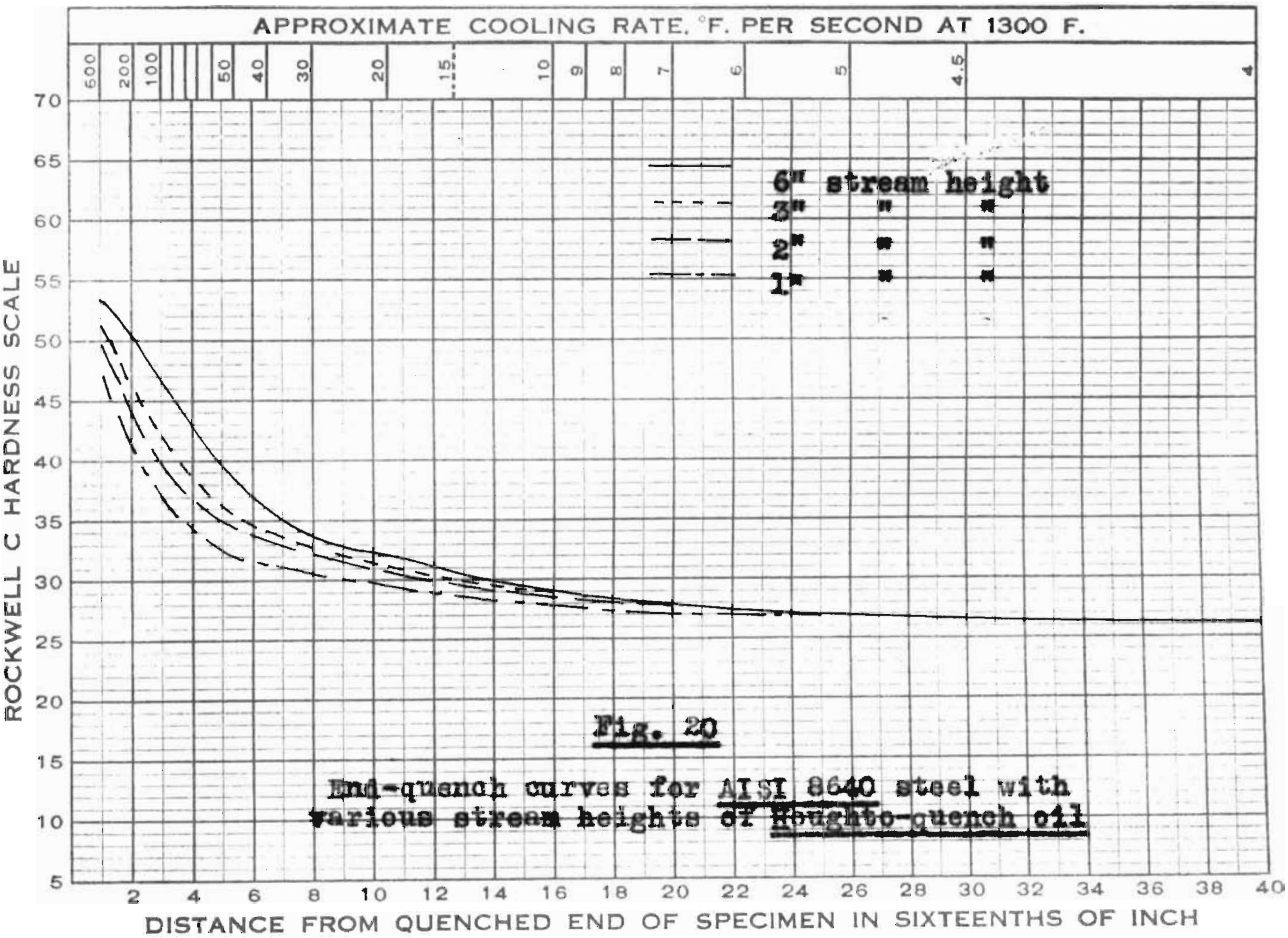

Fig. 20

End-quench curves for AISI 8640 steel with various stream heights of Houghto-quench oil

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superimposed separately. The effects of altering the agitation changed the quenching behaviour of the oils in different ways for different oils and steels. One general phenomena, observed in all cases for Sodium Silicate Solution, and Houghton #2 Soluble oil with any of the steels used and for Houghto-quench oil when A.I.S.I. 8742 steel was used, is that after a certain amount of agitation, further increase in the rate of agitation had no effect on the hardness figures of the steels. These particular rates at which increase of hardness was stopped again varied from liquid to liquid and steel to steel for the same liquid. There seems to be an optimum rate of agitation for each oil depending upon the steel used above which further increase of agitation has very little effect on the hardness values of the steel. In this way, for the sodium silicate solution, there was no further effect of increasing agitation after 2" stream height when A.I.S.I. 8742 steel was used. The curves for 2", 3" and 6" all coincided. In case of Houghton #2 Soluble oil, the curves with A.I.S.I. 8640 steel did not alter after 3" height, and curves for 3" and 6" heights were similar. The curves for the A.I.S.I. 8742 steel for the same oil also did not change after 3" stream height. Similarly the curves for A.I.S.I. 8742 steel for the Houghto-quench oil were not affected after increasing the height beyond 3". In the case of curves for Houghto-quench oil with A.I.S.I. 8640 steel, there was appreciable difference between the 3" and 6" heights of stream. Further increase of stream height beyond 6" was not practicable, hence it could not be ascertained if it was possible to increase still further the hardness values.

Again it can be observed from the curves that dropping of the curves due to decrease in agitation is comparatively small in cases of sodium silicate and Houghton #2 soluble oils for the A.I.S.I. 8640 steel. But the curves from Houghto-quench oil with both the steels are quite sensitive to decreasing rate of agitation below the optimum rate. In case of Houghton #2 soluble oil with A.I.S.I. 8742 steel, curves for 2" and 3" are almost similar, excepting a very little distance at the beginning of the curves. But there is very sudden drop in the curve for 1" liquid height. Houghto-quench oil curve for 8640 steel show also a regular and good extent of dropping with decreasing liquid height.

It has been inferred before that a certain rate of agitation of the quenching media, called the optimum rate, gives the highest quenching speed of the particular media and this optimum rate varies from medium to medium and for the same medium from steel to steel. The maximum improvement of the hardening power of the liquid due to agitation should be a property of the liquid only, i.e., the steel should not have any role to play in it. If steel had some part in it, it may be assumed that a dropping off of further increase of the hardness of the steel under consideration is due to the steel attaining the highest possible hardness values. On this assumption improvement of the quenching speed of the oil did not stop after the optimum rate but the steel refused to harden to higher values at the respective distances from quenched end. But this cannot be true as both the steels had higher hardness figures when water or sodium silicate solution was used than the maximum values obtained with the different oils under so-called optimum rate of agitation. It may be inferred that the optimum quenching rate giving the maximum hardening to a steel is neither optimum for the steel nor the liquid, but a temporary optimum value both for the steel and the liquid. The so-called optimum rates of agitation for the A.I.S.I. 8742 and A.I.S.I. 8640 steels at 3" and higher stream height may be due to the fact that under the degree of agitation obtained with 3" liquid height A.I.S.I. 8742 steel attained temporarily a so-called maximum hardening capacity in a particular range of agitation. The A.I.S.I. 8640 steel possibly could not attain that maximum capacity in that rate of agitation.

The sudden increase of the hardness figures of A.I.S.I. 8742 steel quenched in Houghton #2 soluble oil from 1" to 2" stream height may also be attributed to similar phenomena. Possibly at the second inch of stream height improvement of the quenching speed was considerable enough for the A.I.S.I.

8742 steel which responded very sensitively in this region. The same extent of improvement in the case of 8640 steel was not sufficient enough for the steel to show sensitiveness at this range of intensity of agitation. T-T-T diagrams for steels on continuous cooling might indicate in the same way the behaviour of different steels.

In the sets of curves in figures 21 thru 24, the comparative behaviours of two oils with A.I.S.I. 8742 and A.I.S.I. 8640 steels under different rates of agitation obtained with different liquid heights, as 6", 3", 2" and 1" have been shown. An attempt was made to determine the approximate rates of agitation after which the effect of vapour blanket and vapour transport stages of cooling are eliminated to such an extent that considerable alteration of the behaviours of the oils would take place. The curves for the A.I.S.I. 8742 and A.I.S.I. 8640 steels behave in different ways. In case of the A.I.S.I. 8742 steel the curves of the different liquid heights of the Houghto-quench oil are always below the respective curves of Houghton #2 Soluble oil, excepting 1" stream height. At 1" height the hardness values started higher for Houghton #2 Soluble oil but after about 3/16" distance from end the values were appreciably higher for the Houghto-quench oil. Thus it may be said that Houghto-quench oil has almost assumed its original quenching behaviour in comparison with the Houghton #2 Soluble oil. In case of the A.I.S.I. 8640 steel the hard-

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE
LABORATORY
TYPE SPECIMEN
TEST NO.

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

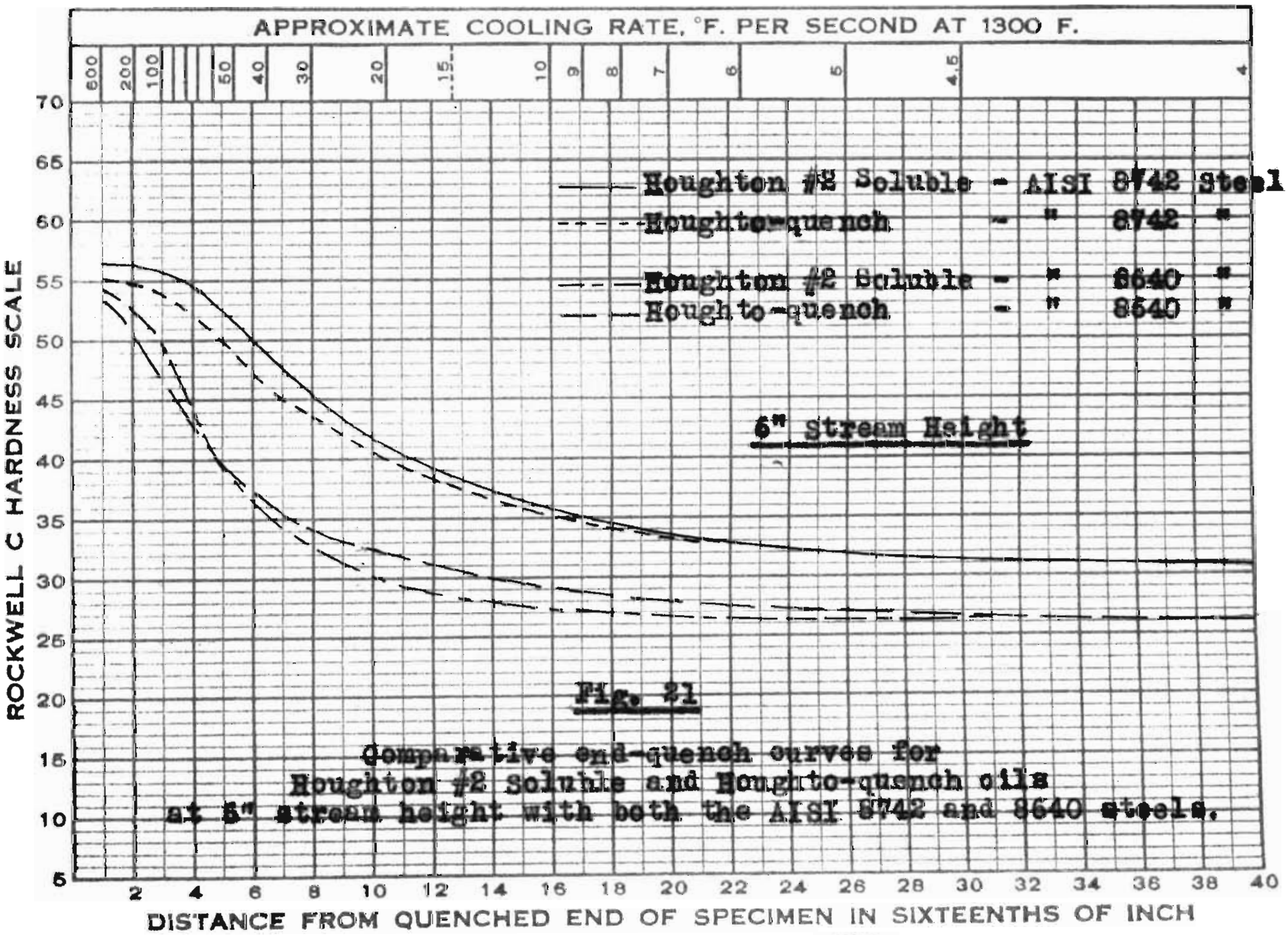

Fig. 21

Comparative end-quench curves for
Houghton #2 Soluble and Houghto-quench oils
at 6" stream height with both the AISI 8742 and 8640 steels.

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DATE ____________
LABORATORY ____________
TYPE SPECIMEN ____________
TEST NO. ____________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

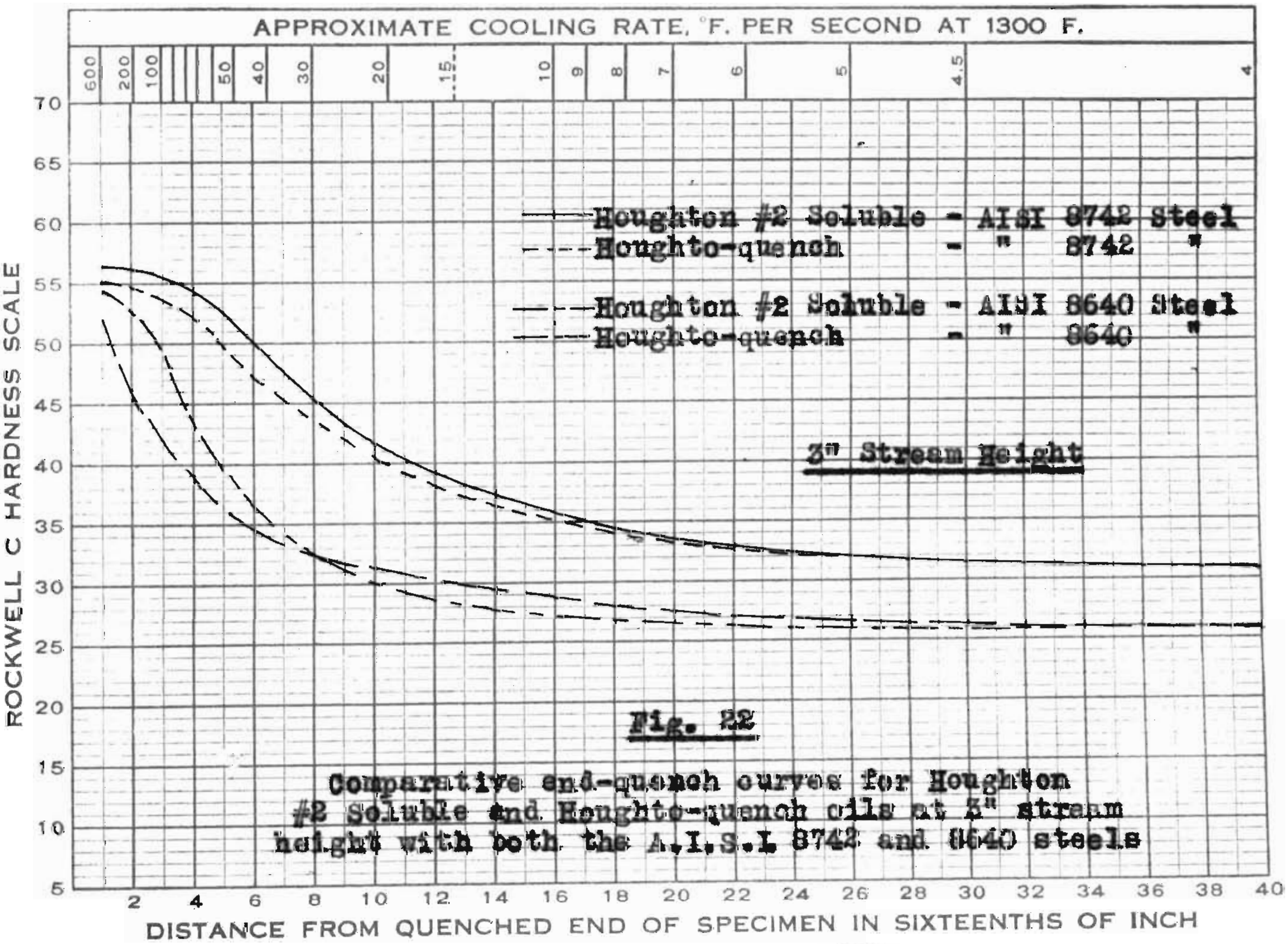

Fig. 22

Comparative end-quench curves for Houghton #2 Soluble and Houghto-quench oils at 3" stream height with both the A.I.S.I 8742 and 8640 steels

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE ______
LABORATORY ______
TYPE SPECIMEN ______
TEST NO. ______

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

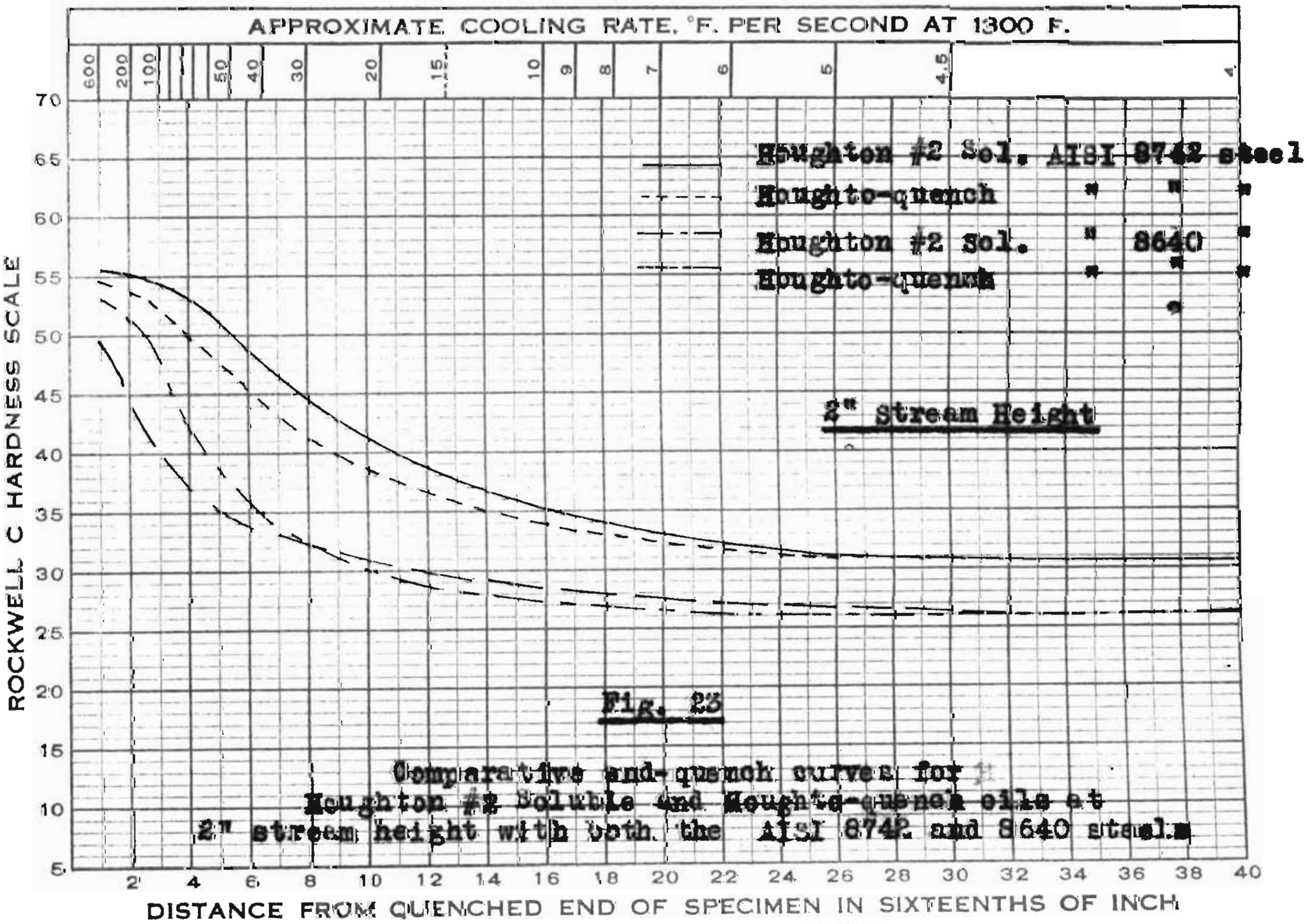

Fig. 23

Comparative end-quench curves for Houghton #2 Soluble and Houghto-quench oils at 2" stream height with both the AISI 8742 and 8640 steels.

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 46 T)

DATE __________
LABORATORY __________
TYPE SPECIMEN __________
TEST NO. __________

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		NORM. TEMP. °F.	QUENCH TEMP. °F.

REMARKS:

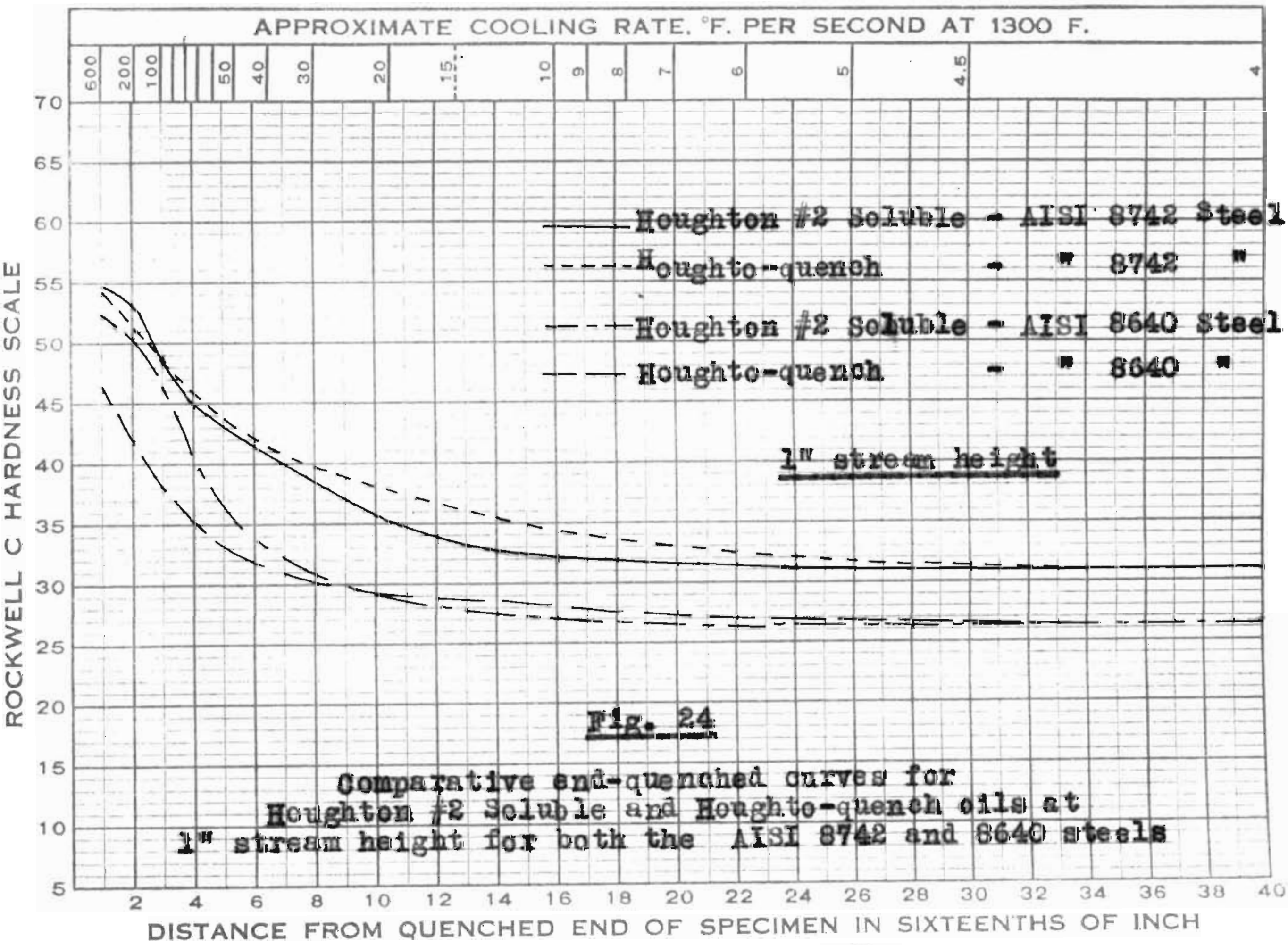

Fig. 24

Comparative end-quenched curves for
Houghton #2 Soluble and Houghto-quench oils at
1" stream height for both the AISI 8742 and 8640 steels

ness values for the Houghton #2 Soluble oil were always higher, up to 7/16 to 9/16" distance from the quenched end, than the Houghto-quench and, after that distance, the figures for Houghto-quench were higher. It can also be observed that differences in hardness values up to the distance mentioned were minimum at 6" stream height and that the difference increased gradually with a lowering of the agitation and was highest at 1" stream height. It seems that the rate of agitation at 1" height is in a sensitive zone or range for the A.I.S.I. 8640 steel with respect to hardening. Though it appears that the unusual alteration of the quenching speed due to partial or complete elimination of vapour phases of cooling is still predominant with this steel, it may possibly alter abruptly after further lowering of agitation, if such were attainable. The amount of the elimination of the vapour phases of cooling may be different at a particular height for different liquids, depending upon the physical properties of the media, but it should be the same for a particular liquid, irrespective of the steel used. Thus the change in the behaviour of the liquids should be independent of the steel used in the test. But the same amount of alteration of the behaviour of the media may affect to different extent and manner, the hardening characteristics of dissimilar steels. That is, what has happened possibly in the cases of A.I.S.I. 8742 and A.I.S.I. 8640 steels with respect to their behaviour with Houghto-quench and Houghton #2 Soluble oils.

V

CONCLUSIONS

1. Under very high states of agitation, as obtained in the end-quench test the usual quenching speed of a quenching medium can be changed abruptly.

2. Under the above conditions, the behaviour of different quenching media are quite different, mainly depending upon the first two stages of quenching. The usual order of the quenching speeds of two liquids, especially oils, may even be reversed.

3. Such an effect on the behaviour of aqueous solutions, as sodium silicate solution, appears to be less abrupt.

4. Change in the quenching speed obtained with different media affects steels of different hardenabilities in different manner.

5. Different quenching media have dissimilar effects on the hardening of steels of similar hardenabilities but different chemical composition.

6. Increase of hardening due to increase in austenitic grain size does not follow the quenching speed of the media proportionately.

7. There is an apparent optimum rate of agitation for each quenching media above which no further appreciable increase in its quenching speed takes place. This so-called optimum is slightly dependent on the harden-

ability of the steel.

8. There is also a critical rate of agitation below which the unusual abrupt change of quenching speed of media (particularly oils) due to agitation cease to be appreciable. This rate again is dependent slightly on the hardenability of the steel.

VI

SUMMARY

An evaluation of various quenching media was carried out by means of the A.S.T.M. end-quench test. The standard A.S.T.M. end-quench test with modifications was used. Water, sodium silicate solution, Gulf #372, Gulf super-quench, Houghton #2 soluble and Houghto-quench oils were used as quenching media. Steels of different hardenabilities as A.I.S.I. 8742 and 8640 were employed as test pieces. Initial temperature of the quenching media was maintained between 84 - 95° F all the time. Hardness results were plotted in the standard manner. Abrupt changes of the behaviour of oils such as a reversal of the comparative quenching speeds of Gulf #372 and Gulf super-quench and Houghton #2 soluble and Houghto-quench oils were observed. Different effects were found with steels of different hardenabilities. Attempts were made to explain these observations. A partial or complete elimination of the vapour phase during quenching was suggested as the main reason for the unusual behaviour.

The effect of using different quenching media on steel of similar hardenabilities but different chemical composition were studied with A.I.S.I. 8742 and 3140 steels. Dissimilar results found may be explained on the assumption that different proportions of transformation products results in similar hardness values.

The effect of using different austenitic grain sizes, produced in the same steel by heating to different temperatures, on the quenching speeds of different media was studied.

Finally, variable rates of agitation were applied to some of the quenching media, using steels of different hardenabilities. The resulting alteration of the properties at the different stages of quenching were observed in a comparative way. An attempt was made to confirm the previous assumptions explaining the unusual changes of quenching behaviour of liquids on the basis of the partial or complete elimination of the vapour phases.

VII

BIBLIOGRAPHY

Periodicals

1. Asimow, M., W. F. Craig and M. A. Grossmann, Correlation between Jominy End-quench Test and Quenched round bars - SAE Journal (Trans) Vol. 49, No. 1, pp. 263 - 293.

2. Austin, C.R., W.G. Van Note and T.A. Prater, Third element effects on hardenability of apure hypereutectoid iron-carbon alloy. Trans. A.S.M. p. 517, June, 1943.

3. Bain, E.C. A study of characteristics common to carbon and alloy steels. Iron Age, Vol. 133, p. 29

4. Bain, E.C. Factors affecting the inherent hardenability of steel. Metal Progress, Nov. 1932, p. 17.

5. Bain, E.C. Functions of alloying elements in steel. Trans. A.S.M. p. 312, 1939.

6. Bain, E.C. Grain size and hardenability of steels to be heat-treated. Br. Iron and Steel Institute, Advance Copy, - 2, October, 1938.

7. Boegehold, A.L. Use of hardenability tests for selection and specification of automotive steels. SAE Journal (Trans), Vol. 49, No. 1, pp. 266-293.

8. Burns, J.L., T.L. Moore and R.S. Archer. Quantitative hardenability. Trans. A.S.M., Vol. 26, p. 1, 1938.

9. Davenport, E.S. and E.C. Bain. General relations between grain size and hardenability and normality of steels. Trans. A.S.M., Vol 22, p. 879, Dec. 1934.

10. Dean, E. W. and G.H.B. Davis. Viscosity variations of oils with temperatures. Chem. Met. Eng., Vol. 36, p. 618, 1929.

11. Ekholm, L.E. "H" steels and their specification. Metal Progress, Vol. 48, p. 673, Oct. 1945.

12. Erb, J. Extending the jominy scale. Iron Age, Vol. 157, pp. 48-51, June 13, 1946.

13. French, H.J. Some aspects of the hardenability of steels. Metal Progress, Vol. 55, p. 505, April, 1949.

14. Flinn, R.A., E. Cook and J.A. Fellows. A quantitative study of austenite transformation. Trans. A.S.M., Vol. 31, pp. 41 - 46, March, 1943.

15. Grossmann, M.A. Hardenability as it affects heat-treated parts. Metal Progress, Vol. 33, p. 373, April, 1938.

16. Grossmann, M.A., M. Asimow and S.F. Urban. Hardenability, its relation to quenching and some quantitative data. Symposium on Hardenability of Alloy Steels, A.S.M., October, 1939.

17. Grossmann, M.A. and M. Asimow. Hardenability and quenching. Iron Age, p. 25, April 25; p. 39, May 2, 1940.

18. Grossmann, M.A. Grain size in metals with reference to grain growth in austenite. A.S.M. Symposium, October, 1934.

19. Grossmann, M.A., R.L. Stephenson. Effect of grain size on hardenability. Trans. A.S.M., Vol. 29, p. 20, 1941.

20. Greene, O.V. and C.B. Post. Determination of specific hardenability of shallow-hardening steels. SAE Journal (Trans), Vol. 49, No. 1, p. 266-293.

21. Hill, M. End-quench test reproducibility. Trans. A.S.M., Vol. 31, p. 923, 1943.

22. Hill, M. The end-quench test hardenability of aircraft steels and its representation. Trans. A.S.M., Vol. 31, p. 902, Dec. 1943.

23. Hodge, J.M. and M.A. Orehoski. Relationship between hardenability and percentage of martensite in some low alloy steels. A.I.M.E. Tech. Pub. 1800. Metals Technology, Vol. 12, p. 12, Sept. 1945.

24. Hodge, J.M. and M.A. Orehoski. Hardenability effects in relation to the percentages of martensite. A.I.M.E. Tech. Pub. 1994. Metals Technology, Vol. 13, p. 10, 1946.

25. Jackson, C.E. and A.L. Christiansen. The effect of quenching temperature on the results of the end-quench hardenability test. A.I.M.E. Tech. Pub. 1647. Metals Technology. Vol. 10, p. 11, Dec. 1943.

26. Johnson, W.A. A new method of evaluating grain size. Steel. Vol. 117, p. 128, Aug. 20, 1945.

27. Jominy, W.E. Commercial aspects of hardenability tests. Metal Progress. Vol. 38, p. 585, Nov. 1940.

28. Jominy, W.E. Hardenability tests. Metal Progress. Vol. 39, p. 447, April, 1941.

29. Jominy, W.E. Standardisation of hardenability tests. Metal Progress. Vol. 40, p. 911, Dec. 1941.

30. Jominy, W.E. and A.L. Boegehold. A hardenability test for carburising steels. Trans. A.S.M., Vol. 26, p. 574, June, 1938.

31. Jominy, W.E. Hardenability tests. Smyposium on Hardenability of Alloy Steels, October, 1939.

32. Kramer, L.R., S. Siegel and J.G. Brooks. Factors for the calculation of hardenability. A.I.M.E. Tech. Pub. 2029, Metals Technology, Vol. 13, p. 28, June, 1946.

33. Liedholm, C.A. Continuous cooling transformation diagram from modified end-quench method. Metal Progress, Vol. 45, p. 94, January, 1944.

34. McCleary, F.E. and R. Wuerfel. Determining hardenability of small sizes. SAE Journal (Trans), Vol. 49, No. 1, pp. 266-293, July, 1941.

35. Manning, G.K. End-quench hardenability versus hardness of quenched rounds. Metal Progress, Vol. 50, p. 647, October 1946.

36. Manning, G.K. and CH. Lorig. The relationship between transformation at constant temperatures and transformation during cooling. A.I.M.E. Tech. Pub. 2014, Metals Technology, Vol. 13, p. 22, June, 1946.

37. Morral, F.R. Heat treating diagrams, S or T.T.T. curves. Metal Progress, Vol. 48, p. 399, October, 1945.

38. Parker, C.M. Selecting steels by hardenability bands. Materials and Methods. Vol. 25, p. 68, March, 1947.

39. Pilling, N.B. and T.D. Lynch. Cooling properties of Technical quenching liquids. Trans. A.I.M.E., Vol. 62, p. 665, 1920.

40. Queneau, B.R. and W.H. Mayo. Hardenability and designation the hardenability line. Symposium on Hardenability of Alloy Steels. October, 1939.

41. Ricket, R.L. Planning heat treatment by S curves, Metal Progress. Vol. 43, p. 79, January, 1943.

42. Ricket, R.L., J.G. Gutton, C.B. Bernhart, Jr. and J.R. Milliken. Isothermal transformation and end-quench hardenability of some NE steels. Trans. A.S.M., Vol. 35, p. 22, 1945.

43. Scott, H. Quenching properties of Glycerin and its water solution. Trans. A.S.S.T. Vol. 6, p. 13, 1924.

44. Spieth, K.G. and H. Lange. On the quenching power of liquid hardening mediums. Mitt Kaiser - Wilhelm Inst. Eisenforsch, Vol. 17, p. 175, 1935.

45. Trembour, F.W. and H. Scott. A test method for the evaluation of aqueous quenching media for steel hardening. Trans. A.S.M., Vol. 28, p. 513, 1940.

46. Van Dyke, G. How to use the jominy end-quench test. Steel. Vol. 112, p. 106, May 17, 1943.

47. Vilella, J.R. and E.C. Bain. Revealing the austenitic grain size of steel. Metal Progress. Vol. 30, p. 39, September 8, 1936.

48. Williams, G.T. Hardenability variations in alloy steels, some investigations with end-quench test. Trans. A.S.M. Vol. 28, p. 157, 1940.

49. Welchner, J., E.S. Rowland and J.E. Ublen. Effect of time, temperature and prior structure on the hardenability of several alloy steels. Trans. A.S.M., Vol. 32, p. 521, 1944.

50. Wilks, C.R., E. Cook and H.S. Avery. Further developments of the end-quench hardenability test. Trans. A.S.M. Vol. 35, p. 1, January, 1945.

MISCELLANEOUS

1. Grain Size Symposium. A.S.M. Convention. Oct. 1-5, 1934.

2. Hardenability of alloy steels, A.S.M. Convention, Oct. 17-21, 1938.

3. Bullens, D.K. Steel and its heat-treatment. Published by John Wiley and Sons, Inc., New York. 5th Edition. 1948.

4. U.S.S. Carilloy steels. Published by Carnegie-Illinois Steel Corp., Pittsburgh and Chicago. 1948.

5. A report of the steel users subcommittee, hardenability division of the SAE Iron and Steel Tech. Committee, H-band hardenability specifications - favourably received by users of the automotive alloy steels. SAE Journal, Vol. 56, No. 10, Oct. 1948.

6. Symposium on the hardenability of steel. British Iron and Steel Institute, special report 26. p. 430, 1946.

7. Tentative hardenability bands, contributions to the metallurgy of steel. No. 11, American Iron and Steel Institute, p. 50, July, 1944.

8. Gulf Super Quench. A bulletin published by the Gulf Oil Corporation - Gulf Refining Company, Pittsburgh, Pa.

9. Houghton on quenching. A bulletin published by the E.F. Houghton and Co., Philadelphia, Pa.

VIII

VITA

The author was born in Barisal, East Bengal, East Pakistan (formerly in India), on August 1, 1922. He received a Bachelor of Science Degree with Honours in Chemistry in 1942 and then a Bachelor of Metallurgy Degree with Honours in 1944, respectively from Scottish Church College and Bengal Engineering College, University of Calcutta, Calcutta, India. After graduation he worked under the Metallurgical Inspectorate, Government of India at Tatanagar for about four years, in connection with the Tata Iron and Steel Co., India. He came to the United States in September, 1948 and enrolled at the Missouri School of Mines and Metallurgy, Rolla, Missouri to continue post-graduate studies in Metallurgical Engineering.