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WATERTOWN ARSENAL LABORATORY

EXPERIMENTAL REPORT

NO. WAL. 710/430

HELMETS

DEVELOPMENT OF A TEST FOR HADFIELD MANGANESE STEEL HELMETS

BY

J. H. Hollomon
1st Lt., Ord. Dept.

DATE

WATERTOWN ARSENAL
WATERTOWN, MASS.

ahk
mm

Report No. 710/430
Watertown Arsenal
(Ex. O. 41-A 46)

June 3, 1942

HELMETS

Development of a Test for
Hadfield Manganese Steel Helmets

The objective of this 1942 report was

OBJECT

To investigate the possibility of a nondestructive magnetic test for helmets, and to investigate the relation of other physical properties of helmet stock to the ballistic performance of helmets. It was concluded that it

REFERENCES

O.O. 350.05/65 (c) - W.A. 421/255 - February 11, 1942

The correspondence pertaining to this report is submitted as Appendix A.

CONCLUSIONS

1. It is not possible to devise a magnetic test which will distinguish in all cases between helmets which have different ballistic properties.

2. A sensitive magnet placed a few inches away from the helmets will pick out those which are badly

decarburized. It will not distinguish between helmets of any other variation of heat-treatment.

3. Sheet stock quenched from below 1600° F. will have low ductility and the finished helmets will have poor ballistic properties. The magnetic properties of these helmets are essentially the same as those which have been properly heat-treated.

4. The present difficulty experienced in deep drawing some lots of helmet stock appears to arise from quenching from temperatures below 1600° F.

5. According to the data obtained, helmets made from Hadfield manganese steel sheet having 30% elongation in 2" (Federal Specification QQM-151, Fig. 3) will have ballistic limits between 900 and 1000 f.p.s.

J. H. Hollomon
2nd Lt., Ord. Dept.

APPROVED:

H. H. Zornig
Colonel, Ord. Dept.
Director of Laboratory

INTRODUCTION

The correspondence (Appendix A) evidences some confusion regarding the interpretation of magnetic properties of steel helmets. In the correspondence, it is suggested that a correlation exists between the magnetic and ballistic properties of the helmets. On the basis of such a correlation, the Canadian Government is applying a magnetic test to finished helmets. Since the data concerning this correlation is meager, the use of a magnetic test for helmets had to be investigated.

The steel used for helmets contains approximately 13 per cent manganese and 1.3 per cent carbon. The phase diagram is presented as Figure 1. Cooling a steel of this composition fairly rapidly will cause the retention of the high temperature phases. Quenching this steel from above 1000° C. (1825° F.) will retain non-magnetic austenite at room temperature, whereas quenching from between 700° C. (1290° F.) and 1000° C. (1825° F.) will retain austenite and grain boundary carbide. Quenching from below 700° C. (1290° F.) will cause the retention of austenite, carbide and magnetic ferrite.

If carbide precipitates, it may cause the formation of some magnetic ferrite due to the straining of the material surrounding the precipitate*. Cold-working of the austenite will bring about the formation of ferrite whether or not carbides are precipitated. The effects of the presence of grain boundary material and the decrease in carbon content of the austenite by its formation had to be investigated. Since a lower carbon content could quite possibly affect the ease of the transformation of austenite during cold working, decarburization was a factor which had to be investigated.

In order to obtain more nearly reproducible results, the cold-working was performed by rolling sheets of helmet steel. The magnitude of the deformation was comparable to that occurring in the forming of helmets (Figure 2). The maximum reduction in thickness was approximately 20 per cent. The material used in the tests was obtained from the McCord Radiator Company, and consisted of circles approximately 20 inches in diameter, and .043 inches in thickness. Rectangles 12 inches x 12 inches were cut from the circles, heat-treated and cold-rolled. Ballistic, physical, and magnetic tests were performed upon the cold-rolled sheets.

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*Hollomon, Ruehl & Wulff - Trans. Amer. Inst. of Mining and Met. Engr., Vol. 140, P. 368.

SCHEDULE OF TREATMENT

SHEET NO.	TREATMENT								
1	Quenched	from	1475°	F.	in	water,	no	reduction
2	"	"	1475	F.	"	"	7½	"
3	"	"	1475	"	"	"	10	"
4	"	"	1475	"	"	"	11	"
5	"	"	1475	"	"	"	15	"
6	"	"	1475	"	"	"	20	"
7	"	"	1825	"	"	"	no	"
8	"	"	1825	"	"	"	7½	"
9	"	"	1825	"	"	"	9	"
10	"	"	1825	"	"	"	10	"
11	"	"	1825	"	"	"	15	"
12	"	"	1825	"	"	"	20	"

The initial and final dimensions of the rolled sheets are presented as Inclosure A.

RESULTS AND DISCUSSION

1. Microexamination

Characteristic photomicrographs of the heat-treated and rolled sheets are presented as Figures 3 to 6. Figures 3 and 5 illustrate the difference between the microstructures in two sheets quenched from 1475° F. and 1825° F. respectively. The former shows carbide on the grain boundaries, while the latter is free of such precipitation. Quenching from any temperature below 1800° F. would have caused carbide precipitation in an amount determined by the phase diagrams. In Figures 4 and 6, the microstructures are compared after about 20 per cent reduction by cold-rolling. These photomicrographs illustrate the deformation which has occurred due to the rolling operation.

In Appendix B are included photomicrographs of samples taken from three lots of helmet stock as received by the McCord Radiator Company. The microstructure of the sample from Lot 290 is comparable to that of Figure 3, indicating that at least some of the sheet received by the fabricator has been improperly heat-treated. The presence of these carbides leads to cracking during the deep drawing of the helmets.

2. Physical Tests

Specimens for tensile tests (Federal Specification [illegible]-151, Figure 5) were cut from the rolled sheets. The results of the tests are presented as Figure 7 (the data are included as Inclosure B). The effect of the grain boundary carbide is to decrease the tensile strength and per cent elongation while increasing the hardness as compared to the sheets quenched from 1825° F. The per-cent elongation of the properly heat-treated and undeformed sheet was about 35, while the sheet quenched from 1475° F. had an elongation of 10 per cent. The effect of the carbide precipitation is to make the material extremely brittle.

3. Ballistic Tests

In Figure 8 the ballistic limits are plotted as a function of the per cent reduction by cold-rolling. (Firing data may be found in Inclosure C.) For the samples quenched from 1825° F., two curves are presented; in one, account has been taken of the variation of thickness by assuming the ballistic limit is a linear function of the thickness*. The greatest variation in ballistic properties between the sheets of different heat-treatment occurs after cold rolling, and it is to be noted that the difference in the ductility of the

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*W.A. Report No. 710/418

sheets is most marked after deformation, as shown in Figure 7. The samples quenched from 1475° F. and cold-rolled have a ballistic limit less than 325 f/s, and an elongation less than 2 per cent, while for the samples quenched from 1625° F., the ballistic limit is greater than 780 f/s, and the per-cent elongation is greater than twenty. The difference between the type of penetration is illustrated in Figures 9 and 10. In Figure 9 the "as-quenched" samples are compared, and in Figure 10, the quenched and rolled sheets are compared. The sheets quenched from 1475° F. bulge very little and crack up around the holes. In order to illustrate more clearly the relation between ductility and ballistic properties, Figure 11 is presented in which the ballistic limits are plotted as a function of the per-cent elongation. All of the samples from which this curve was derived were quenched from 1625° F. The data from the one sheet quenched from 1475° F., from which a ballistic limit could be obtained, do not fall upon the straight line; however, both its ductility and ballistic limit were very low.

Thin sheet, such as that studied in these experiments, appears to fail by tension when struck by ball ammunition. The shot strikes the sheet, bends it until it reaches maximum elongation, and then the sheet fails by tension. The ballistic limit would therefore depend primarily upon the thickness of the plate and the ductility.

4. Magnetic Tests

The detailed description of the magnetic tests is presented as Inclosure D, and the data, as Inclosure E. The theory of the magnetic measurement may be found in a text by Stoner*. Samples were quenched from 1825° F. and 1475° F. and electrolytically etched in order to remove about .012 inches of the thickness and all decarburized material. Another set of samples was quenched from 1825° F. and etched to a depth just sufficient to remove all magnetic material, but not the entire decarburized layer. The samples were cold-rolled as indicated in Table IV. The magnetic susceptibility was then obtained by measuring the force on the samples in a magnetic field, and, from the susceptibility, the permeability was determined. The permeability at a given field strength (below saturation) measures the magnetism of the samples and is related to the

*Stoner, "Magnetic Measurements", London, 1934.

amount of magnetic material present. The results are plotted as Figures 12 and 13. The effect of quenching from 1475° F. is to introduce a small amount of magnetism, probably by means of the transformation of the strained material surrounding the precipitated carbides. The permeability of the cold-rolled steels quenched from 1825° F. and 1475° F. is essentially the same, indicating that the slight decrease in carbon content due to the precipitation of the carbides does not appreciably increase the tendency of the austenite to transform during deformation. The effect of carbon is to stabilize* the austenite, but the loss of carbon may be just counteracted by the effect of the carbides on the extent of the plastic deformation.

When the carbon is definitely removed by decarburization, the amount of magnetic material produced by the deformation increases as illustrated in Figure 13. (It is to be noted that the scale of Figure 13 is much greater than that of Figure 12). The loss of carbon from the surface has definitely decreased the stability of the austenite and allowed an appreciable transformation by cold-rolling.

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*Epstein "Alloys of Iron and Carbon", New York - 1936.

The tests indicate that if carbides are present on the grain boundaries and the material is cold-rolled, the magnetism will be only slightly different from a properly heat-treated steel, but the ballistic limit and ductility will be very much lowered. Decarburized sheet transforms easily upon cold-rolling, and its magnetism is very much greater than properly heat-treated sheet.

SUMMARY

The effect of heat-treatment on the ballistic, physical, and magnetic properties of cold-rolled Hadfield manganese steel was determined. The effect of grain boundary carbides precipitated by quenching from temperatures below 1800° F. is to lower the ductility and ballistic limits as compared to samples quenched from above 1800° F. The magnetism induced by cold deformation appears to be unaffected by the precipitation of the carbides. If, however, decarburization occurs during heat-treatment, a relatively large amount of the austenite will revert to ferrite upon cold-rolling, and the magnetism will be increased correspondingly. It is virtually impossible to devise a magnetic test, the results of which can be correlated with the ballistic properties of the helmets since in some cases both good and bad helmets have the same magnetic properties. The ballistic limits may be correlated best with the ductility; the greater the ductility, the higher the ballistic limit.

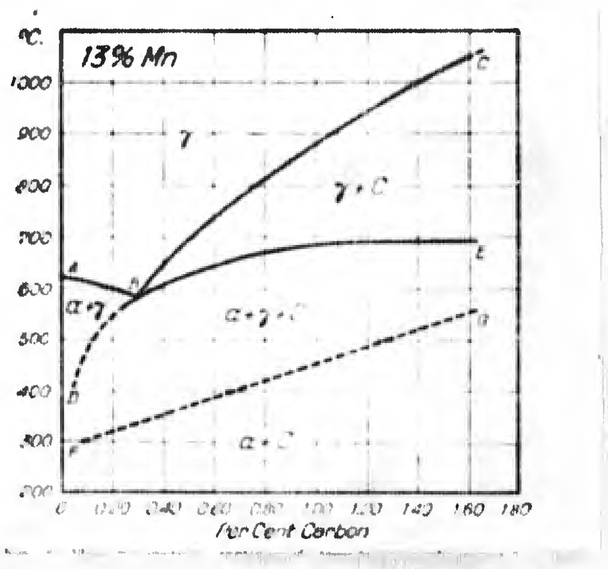


Figure 1. Phase Diagram of 13% Manganese Steel

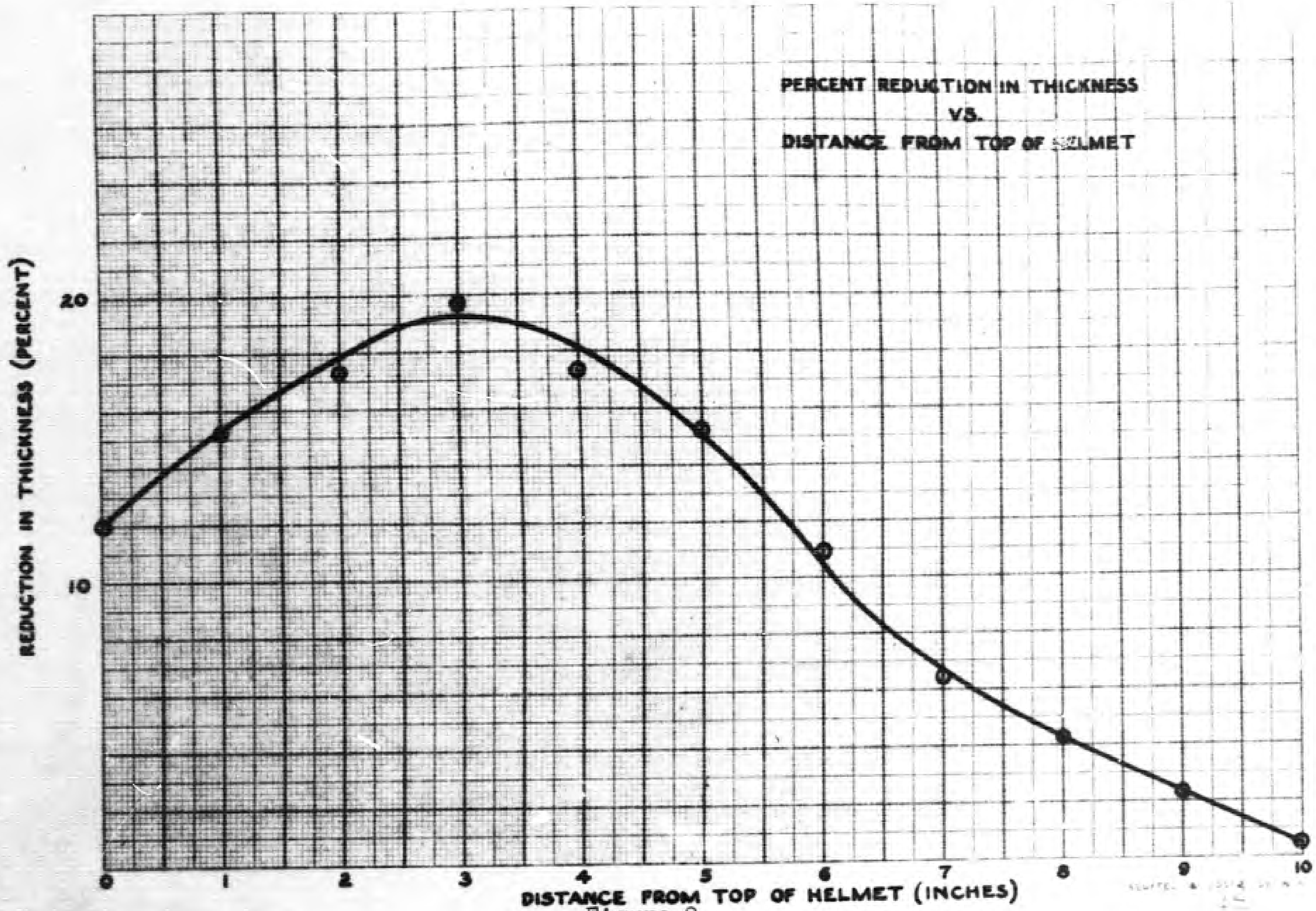

PERCENT REDUCTION IN THICKNESS
VS.
DISTANCE FROM TOP OF HELMET
REDUCTION IN THICKNESS (PERCENT)
20
10
0
1
2
3
4
5
6
7
8
9
10
DISTANCE FROM TOP OF HELMET (INCHES)

Figure 2

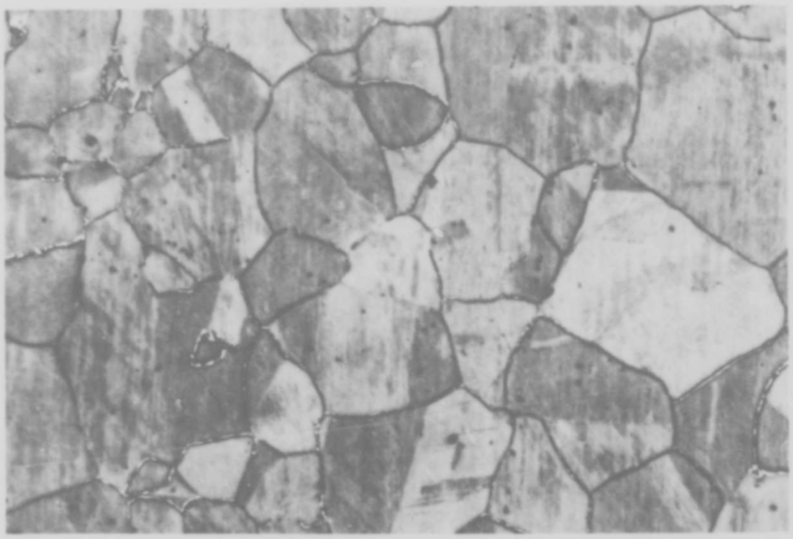


FIGURE 3 HELMET SHEET QUENCHED FROM 1475°F X 250

FIGURE 4 HELMET SHEET QUENCHED FROM 1475°F AND REDUCED 16 % BY COLD ROLLING X 250

W.A.639-4155

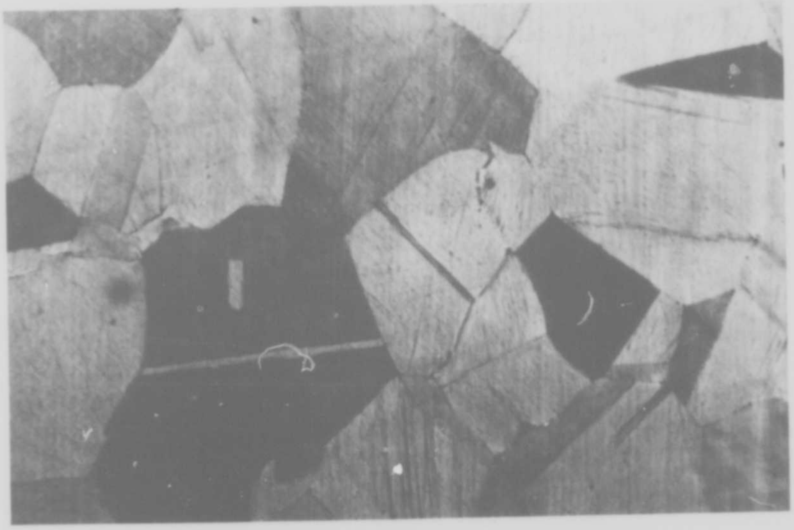
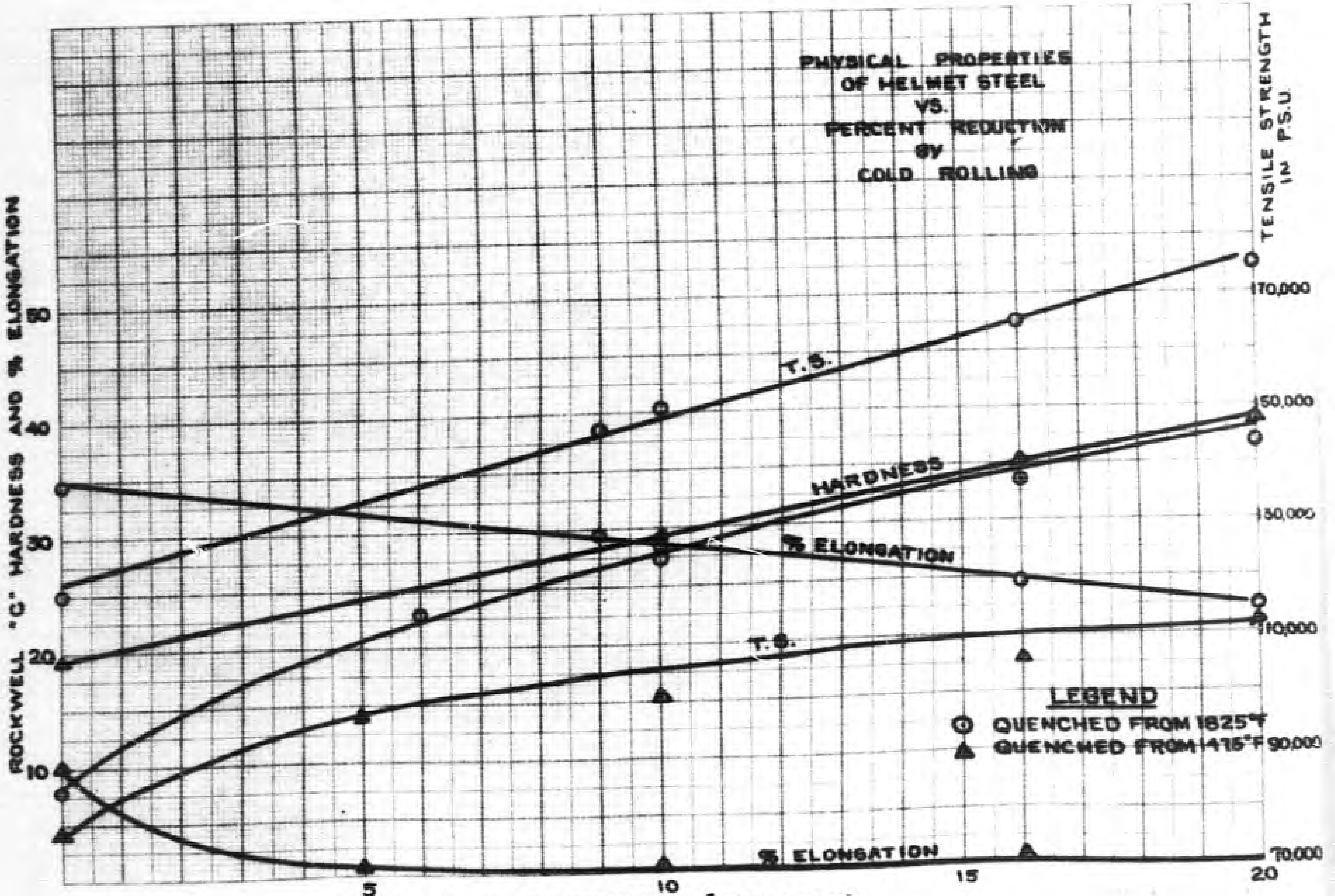


FIGURE 5 HELMET SHEET QUENCHED FROM 1825°F X 250

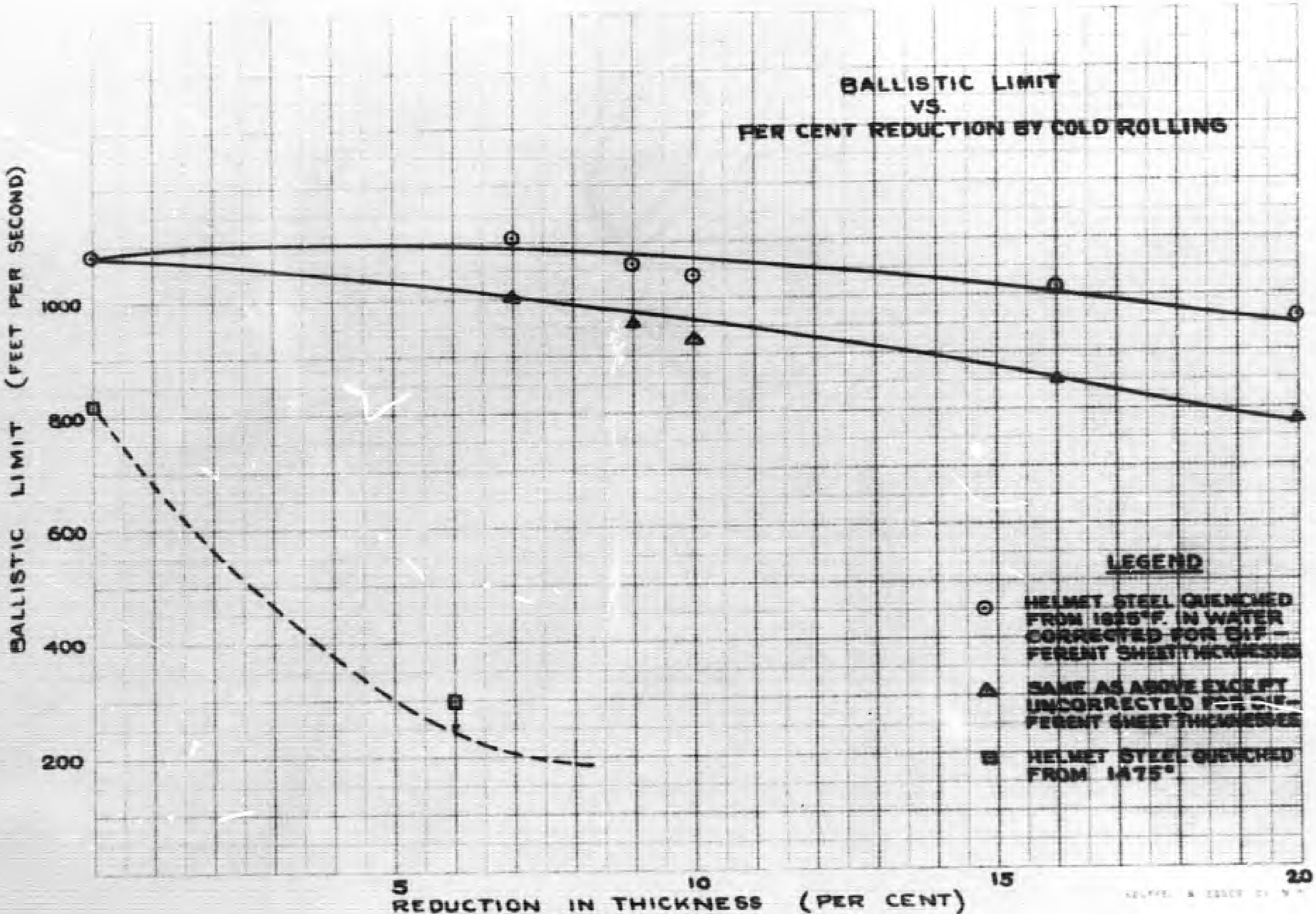
FIGURE 6 HELMET SHEET QUENCHED FROM 1825°F AND REDUCED 20% BY COLD ROLLING X 250

W.A.639-4154



PHYSICAL PROPERTIES OF HELMET STEEL VS. PERCENT REDUCTION BY COLD ROLLING
TENSILE STRENGTH IN P.S.U
ROCKWELL "C" HARDNESS AND % ELONGATION
T.S.
HARDNESS
% ELONGATION
T.S.
% ELONGATION
LEGEND
QUENCHED FROM 1825°F
QUENCHED FROM 1475°F
170,000
150,000
130,000
110,000
90,000
70,000
50
40
30
20
10
5
10
15
20
REDUCTION IN THICKNESS (PER CENT)

Figure 7



BALLISTIC LIMIT
VS.
PER CENT REDUCTION BY COLD ROLLING
BALLISTIC LIMIT (FEET PER SECOND)
1000
800
600
400
200
5
10
15
20
REDUCTION IN THICKNESS (PER CENT)
LEGEND
HELMET STEEL QUENCHED FROM 1625°F. IN WATER CORRECTED FOR DIF-FERENT SHEET THICKNESSES
SAME AS ABOVE EXCEPT UNCORRECTED FOR DIF-FERENT SHEET THICKNESSES
HELMET STEEL QUENCHED FROM 1475°.

Figure 8

HELMET STEEL QUENCHED IN WATER FROM 1475°F
BALLISTIC LIMIT 825 F.S. WITH .45 CAL.BALL
AMMUNITION W.A.710-1808-2

HELMET STEEL QUENCHED IN WATER FROM 1825°F
BALLISTIC LIMIT 1090 FS WITH .45 CAL. BALL
AMMUNITION

ORDNANCE DEPT U.S.A.
WATERTOWN ARSENAL

Figure 9

HELMET STEEL QUENCHED IN WATER FROM 1475°F
REDUCED 10% BY COLD ROLLING BALLISTIC
LIMIT LESS THAN 325 F.S. W.A.710-1807-2

HELMET STEEL QUENCHED IN WATER FROM 1825°F
REDUCED 10% BY COLD ROLLING BALLISTIC
LIMIT 1040 F.S.

Figure 10

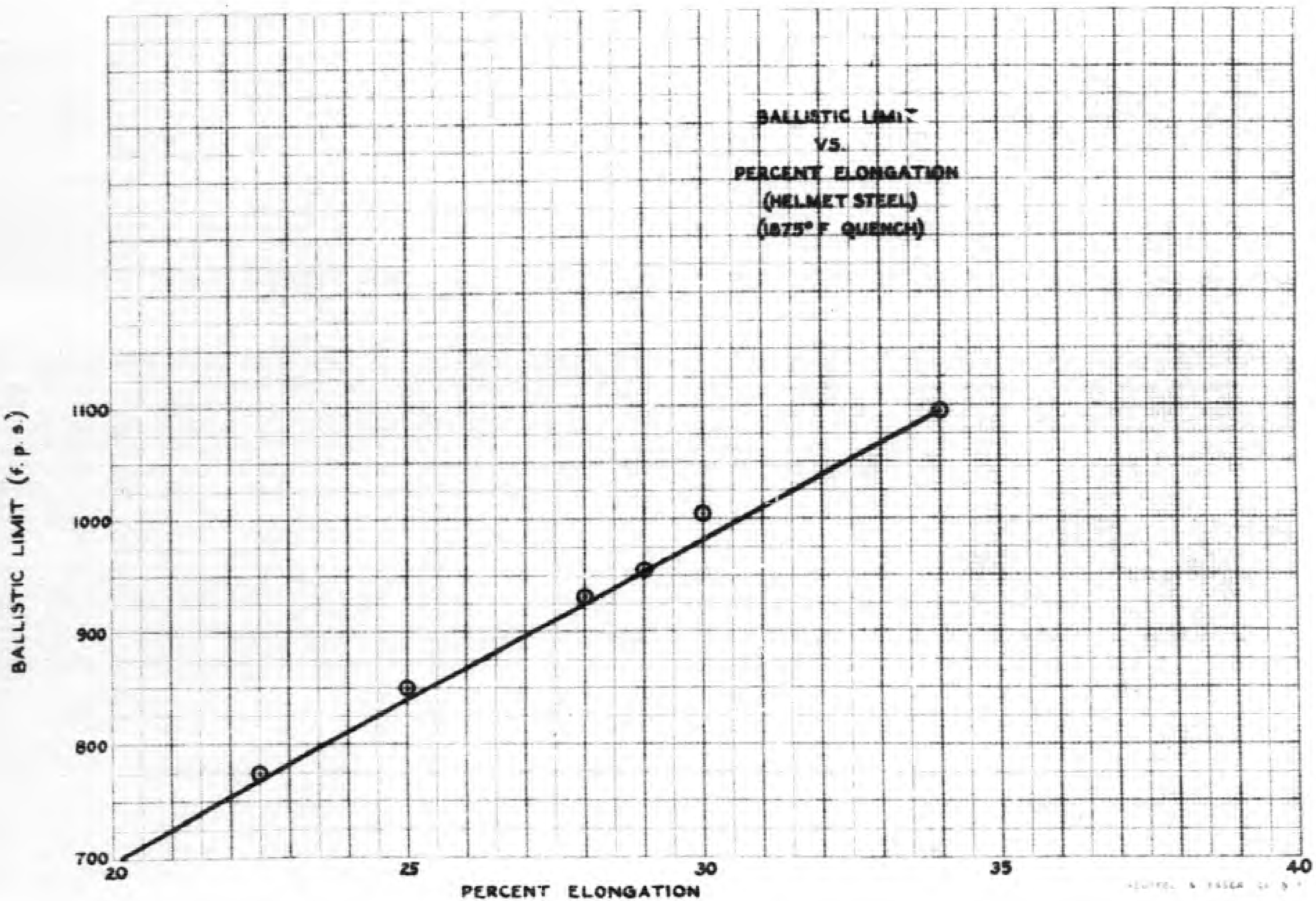
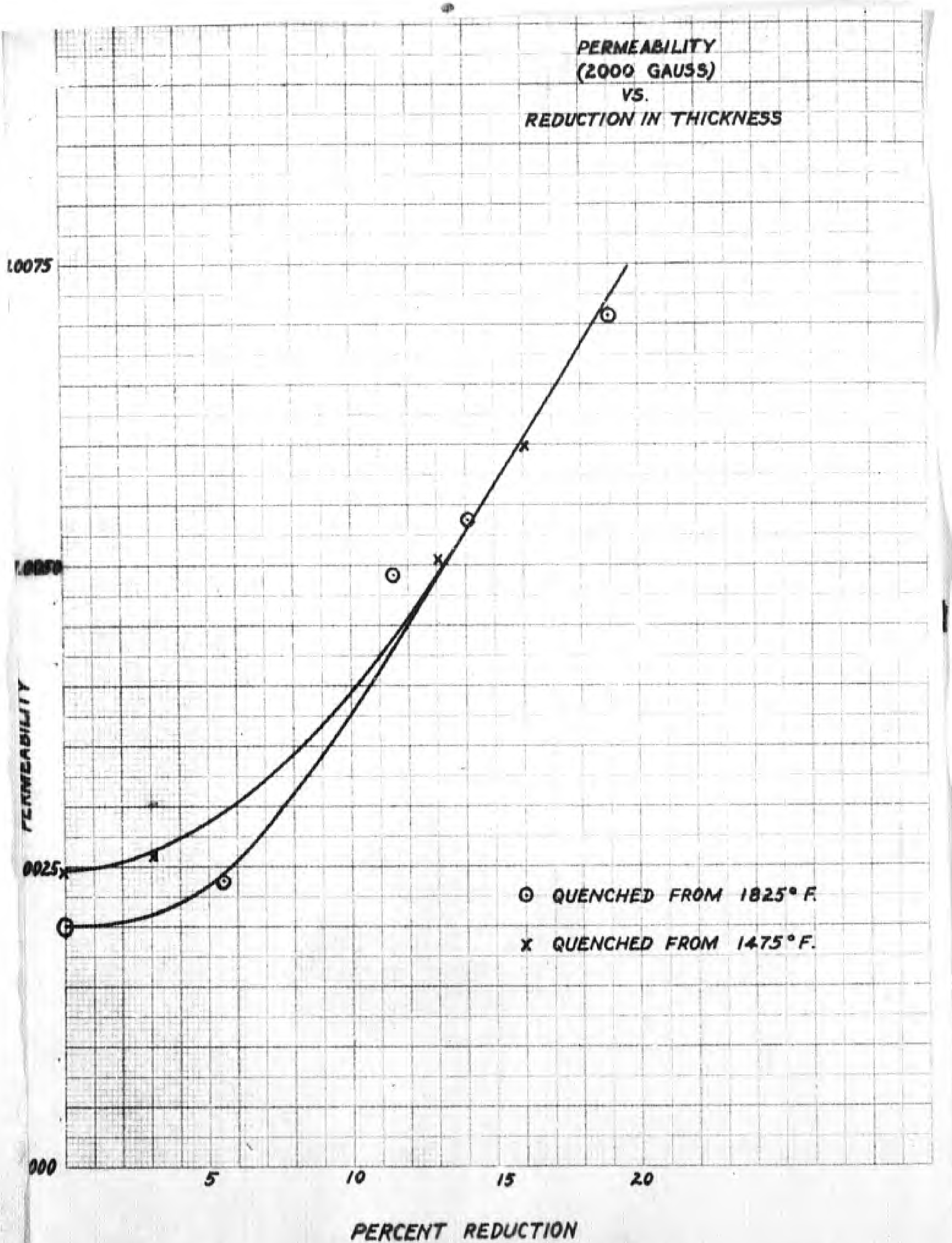

BALLISTIC LIMIT
VS.
PERCENT ELONGATION
(HELMET STEEL)
(1875° F QUENCH)
BALLISTIC LIMIT (f. p. s.)
700
800
900
1000
1100
20
25
30
35
40
PERCENT ELONGATION

Figure 11


PERMEABILITY
(2000 GAUSS)
VS.
REDUCTION IN THICKNESS
PERMEABILITY
1.0075
1.0050
.0025
000
5
10
15
20
⊙ QUENCHED FROM 1825° F.
x QUENCHED FROM 1475° F.
PERCENT REDUCTION
Figure 12

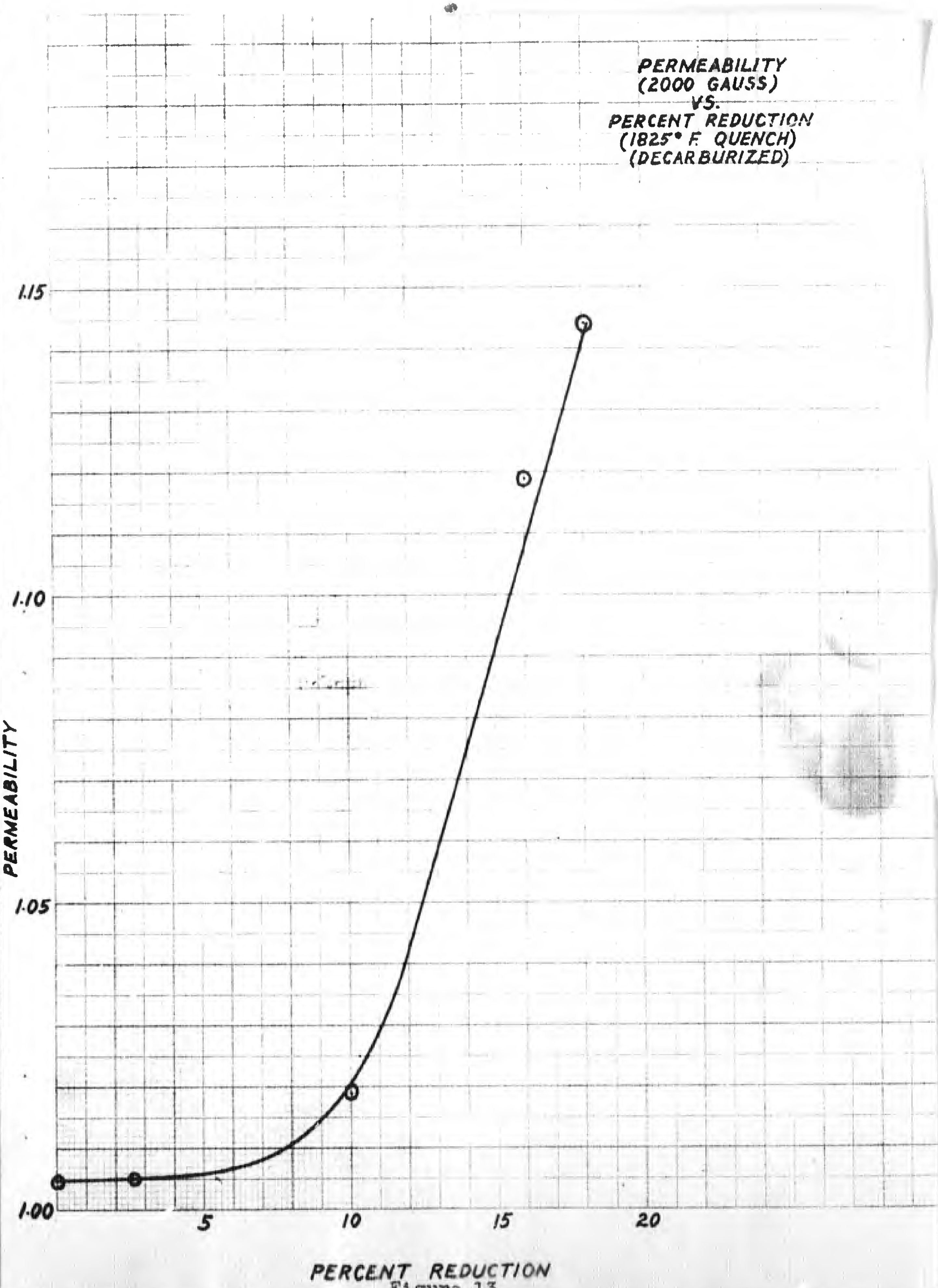

PERMEABILITY
(2000 GAUSS)
VS.
PERCENT REDUCTION
(1825° F. QUENCH)
(DECARBURIZED)
1.15
1.10
1.05
1.00
PERMEABILITY
5
10
15
20
PERCENT REDUCTION

Figure 13

APPENDIX A

CORRESPONDENCE

COPY-8/31/42--ahk CONFIDENTIAL

White/mms

February 11, 1942.

O.O. 350.08/65 (c)

Small Arms Division
Industrial Service

W.A. 421/285

Subject: Magnetic Test of Steel Helmets

To: Commanding General
Watertown Arsenal
Watertown, Massachusetts

1. It is desired to develop a non-destructive test for steel helmets that will give an indication of their ballistic properties. Some type of magnetic test seems to offer the most promising possibilities along this line.

2. In this connection, a copy of file O.O. 350.08/1141, on the subject of magnetic tests for steel helmets, is inclosed. Particular attention is drawn to the inclosure and the seventh and ninth indorsements of this file, wherein the practical application and theoretical justification of a magnetic test for ballistic performance are discussed.

3. It is requested that some form of magnetic test be developed to give a reliable indication of the physical properties of helmet steel after it has been formed into helmets. The method of a suspended Alnico magnet, used by the National Research Laboratory of Canada, should be investigated. Consideration should also be given to some means of passing the helmets through a coil or between the poles of an electro-magnet and registering the resultant change in magnetic field on a galvanometer. It is also possible that positive results may be obtained from the compass test now used by the Detroit Ordnance District Office in the inspection of helmets. Development of a magnetic helmet test need not be limited to the methods outlined however. These are offered merely as suggestions.

4. In conducting this investigation it should be borne in mind that the primary purpose of a magnetic

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White/mma

Commanding General
Watertown Arsenal, Watertown, Mass.

test is not to detect the presence of a slight degree of magnetism, as all helmets are magnetic to a certain extent, but is to determine that amount of magnetism indicative of poor physical characteristics. It is felt that such a test will greatly accelerate the inspection of steel helmets and at the same time give a more exact control of their quality.

By order of the Chief of Ordnance:

G. M. WELLS
Colonel, Ord. Dept.,
Assistant.

1 Incl.
File O.O. 380.05/1141
w/its incl.

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COPY-5/22/42-shk CONFIDENTIAL

O.O. 350.05/65 (c)
W.A. 421/255 1st Ind. HAM/JHM/eam

Watertown Arsenal, Watertown, Massachusetts, May 5, 1942
To: Chief of Ordnance, U.S.A., Washington, D.C.
Attn: SPOIS

1. Reference is made to paragraph 3, 7th Indorsement, and paragraph 5, 9th Indorsement, of this file in which it is suggested that a magnetic test of finished helmets would give a satisfactory indication of their ballistic properties.

2. Experiments performed at Watertown Arsenal indicate that it is difficult to devise a satisfactory magnetic test to be applied easily to helmets. Preliminary tests indicate that the correlation of ballistic and magnetic properties may not be valid under all conditions. The number of variables may be too numerous to permit a satisfactory test.

3. Ballistic properties have been correlated with heat-treatment and physical properties, after the helmet steel sheet has been cold deformed to a comparable extent as that encountered in the deep drawing operation. It is found that improperly heat-treated sheets have very low ballistic limits. It is essential that sheets be quenched from 1000° C. after heat-treatment in a neutral atmosphere furnace if optimum ballistic properties are to be obtained. The ballistic limit of properly fabricated helmets is about 1000 f.p.s. with Cal. .45 ball ammunition. Improper heat-treatment manifests itself in low ductility of the sheet stock. The sheets should have 30 per-cent transverse elongation in a two-inch gauge length by 1/2 inch wide specimen. Helmets manufactured from sheets having low ductility will have low-ballistic limits.

4. Reference is made to paragraph 2, 8th Indorsement, in which information is requested concerning the drawing properties of this material. Samples of helmets from heat-treatment lots which showed excessive breaking

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Chief of Ordnance, U. S. A.
Washington, D. C.

in drawing, but which 70 per cent of the original sheets were accepted as helmets, showed microstructures similar to the sheets which had been incorrectly heat-treated. A sheet which has been properly heat-treated will not only be satisfactory ballistically, but will also exhibit good drawing characteristics.

B. Since the ballistic properties of the helmets are related to the heat-treatment, it is at least essential that a sufficient number of helmets from each heat-treatment lot be tested in order to prevent acceptance of helmets which exhibit poor ballistic performance.

For the Commanding General:

H. H. ZORNIG
Colonel, Ord. Dept.
Director of Laboratory

1 Incl. n/c

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BRITISH SECRET - EQUALS U. S. CONFIDENTIAL
FILE O.O. 350.05/1141

COPY

NATIONAL RESEARCH LAB.

CANADA

11 November, 1941

Lt. Col. B. B. McMahon,
Military Intelligence, Division G-2,
War Department,
Washington, D. C.

Dear Col. McMahon:

I am sending you one copy of report PEE-357, Magnetic Test of Steel Helmets - A. J. Grant.

Yours very sincerely,

A. G. Shenstone (signed)
A. G. Shenstone

AGS/MS

Inc.

Would you please sign and return the attached copy which will serve as a receipt.

BRITISH SECRET - EQUALS U. S. CONFIDENTIAL

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COPY - May 22, 1942 - ahk

SECRET

COPY NO. 7

Report No. PEE-357

21 October, 1941

For: The Director

Ref. Lab. Order 2061, August 1941

SUBJECT: MAGNETIC TESTING OF STEEL HELMETS

AUTHOR: A. J. GRANT

APPROVED

Steel helmets were needed urgently to equip troops, scheduled to sail at an early date.

The specification for steel helmets provides for a destructive test on a few helmets in each lot of a hundred, but since the imported steel used for the helmets was found to give a mixture of good and bad, a non-destructive test had to be found if the requirement for helmets was to be met (tests had to be made on the finished helmets as the processing affected the material).

It was found that the defective helmets were somewhat magnetic. Therefore, the helmets were divided into good and bad lots by passing each one near a suspended Alnico magnet. A deflection of the magnet indicated a magnetic, i.e. a defective helmet. Exhaustive destruction tests indicated that this method of sorting was satisfactory, and the troops sailed equipped with good steel helmets.

We understand the Inspection Board is continuing the magnetic test of steel helmets in addition to the destructive test called for by the specifications.

AJG.IW

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CO 350.05/1141
OCD 400.163/581-030 1st Ind.
G-2, W. D., November 15, 1941 To: The Quartermaster General, Attention of Lieut. Col. L. C. Grice, Standardization Branch, and the Chief of Ordnance, IN TURN.

Report forwarded for your information. Receipt has been accomplished by this office.

For the Acting A. C. of S., G-2:

S. B. McMahon
Lieut. Col., General Staff Corps
Coordinating Section

Incl: 1

OCD 400.163/581-030
CO 350.05/1141
QM 421 S-Std. (Helmets, Steel) 2nd Ind.
War Dept., OQMG, Washington, D. C. November 19, 1941.
TO: Chief of Ordnance.

1. Noted.

For the Quartermaster General:

Lyle A. Clough, (Signed)
LYLE A. CLOUGH
Major, Q.M.C.,
Assistant.

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O. O. 350.05/1141
Attn: Ind. Serv., Small Arms
QM 421 S-Std. (Helmets, Steel)
DOD 400.163/821-939 3rd Ind. Moore/ea

War Department, Ordnance Office, Washington, D. C.
November 24, 1941
To: Detroit Ordnance District Office, Detroit, Michigan.

1. It is requested that the district outline what tests are made by the inspector in determining whether or not helmets manufactured by the McCord Radiator Company are non-magnetic.

By order of the Chief of Ordnance:

W. T. Moore, (Signed)
W. T. MOORE
Major, Ord. Dept.,
Assistant

1 Incl. n/c

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COPY - 5/22/42 - ahk

OO 350.05/1141
Attn: Ind. Serv., Small Arms
QM 421 S-Std. (Helmets, Steel)
DOD 400.163/531-939 4th Ind. Scarbrough/es

Detroit Ordnance District, 1832 National Bank Building, Detroit, Michigan, November 28, 1941
To: Chief of Ordnance, Washington, D. C., Industrial Service Small Arms Division, Attention: Major W. T. MOORE.

1. In compliance with paragraph 1 of 3rd indorsement there is herewith inclosed a tentative specification which this office has been using in the inspection of Helmet Bodies. Your attention is invited to paragraph F-9d.

2. Since receipt of basic letter, this office has carefully checked the magnetic qualities of the Helmet Bodies by various means, such as a compass or magnet which has been suspended by a string. It was found that practically all of the Helmets would slightly attract a powerful magnet held on a long string. It was further found that the edging, which is made of 18-8 stainless steel, was absolutely non-magnetic, whereas the loops, which are made of the same material, are slightly magnetic. The most magnetic part of the Helmet, which has been found, are the stainless steel loops. This office has a certified copy of the analysis of these loops which checks the material specifications. A sample is being sent to a local laboratory to check this analysis.

3. It is the understanding of this office that non-magnetic qualities are desired so that the Helmets will not affect a compass held in the wearer's hand. Based on the foregoing, this office has adopted the following method of inspecting for non-magnetic qualities:

"At least two per cent of the finished helmet bodies shall be tested for non-magnetic qualities by moving the helmet body around a sensitive compass in a circle with a radius of 2-1/2 inches. The compass shall not deflect."

A device has been built in the form of a non-magnetic wheel, with a 5" diameter, mounted on a non-magnetic upright with a sensitive compass mounted at

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OO 350.05/1141
Attn: Ind. Serv., Small Arms
QM 421 S-Std. (Helmets, Steel)
DOD 400.163/531-939 (Cont.) 4th Ind. Scarbrough/es

the center. The compass is stationary and the helmet is tested by moving the helmet around the upright at a distance of 2-1/2" from the center of the compass. Considerable variation was found in the sensitiveness of various compasses. This office is using the most sensitive one that it has been able to obtain.

4. It is the opinion of this office that if the helmet will not affect a compass 2-1/2" away from the helmet, that the helmet will be satisfactory. It is requested that your office either concur with the method of testing shown in paragraph 3 or suggest another method. It should be borne in mind that all of the helmets are magnetic to some degree. It is felt that the test in the inclosed specification is not sensitive enough and that a magnet on a string is too sensitive.

For the District Chief:

J. D. Scarbrough (Signed)
J. D. Scarbrough,
2nd Lt., Ord. Dept.
Assistant

Incl: 1 Copy of Spec.

COPY - 5/22/42 - ahk

O.O. 350.05/1141
Attn: S. A. Div., Ind.
DOD 400.163/531-939
QM 421 S-Std. (Helmets, Steel) 5th Ind. BOOTH; fms

War Department, Ordnance Office, Washington, D. C., December 15, 1941.
To: Detroit Ordnance District Office, Detroit, Michigan, and Commanding General, Rock Island Arsenal, Rock Island, Illinois

IN TURN

1. The method of testing M1 helmets for magnetic properties, by the use of a sensitive compass, as outlined in 4th Indorsement to this file, appears to be satisfactory to this office, and its use is hereby confirmed.

2. The copy of tentative helmet specification prepared by the Detroit Office has been withdrawn.

3. This file is returned to the Detroit Office to confirm the use of the subject test method. It should then be forwarded to Rock Island Arsenal for their information and recording.

By order of the Chief of Ordnance:

T. T. MOORE,
Major, Ord. Dept.
Assistant

1 Incl.
1 Spec. w/d

OO 350.05/1141
Attn.: Ind. Serv., Small Arms
QM 421 S-Std. (Helmets, Steel)
DOD 400.163/531-939 6 Ind RAPHAEL/bol

Detroit Ordnance District, 1832 National Bank Building, Detroit, Michigan, December 20, 1941. To: Commanding General, Rock Island Arsenal, Rock Island, Illinois.

1. Forwarded to your Arsenal for information and recording, as per request of the Office of the Chief of Ordnance.

For the District Chief

J. D. SCARBROUGH (Signed)
J. D. Scarbrough
2nd Lt., Ord. Dept.
Assistant

COPY - 5/22/42 - shk

CO 351.05/1141
QM 421 S-Std. (Helmets, Steel)
OOD 400.163/931-939
NIA 421/757 7th Ind. DWK/mjg

Rock Island Arsenal, Rock Island, Illinois. January 7, 1942.
To: Chief of Ordnance, War Department, Washington, D.C.
ATTN: Industrial Service - Small Arms.

1. The contents of the attached report have been noted.

2. The original test mentioned in paragraph two of this report must have been for the determination of physical properties, by virtue of having been a destructive test. These physical requirements of the specification are not disclosed in the report but are assumed to be ballistic.

3. Inasmuch as any test for magnetism would be non-destructive, it seems evident that the Royal Research Laboratories were not originally concerned with the magnetic properties because of the effect on compasses. Rather they had determined that excessive magnetism and low physical properties in a helmet are coincident. It is known in this country that austenitic helmet stock will have low ballistics if the manganese is below a certain point and this condition will also make the steel magnetic.

4. With reference to paragraph two of the fourth indorsement, it would seem that the higher magnetic properties of the helmet loops would not be significant so long as the helmet proper is satisfactory.

5. From the standpoint of possible effect of the helmet on direction finding equipment, the test outlined in the fourth indorsement is not considered pertinent so long as the soldier carries considerable equipment which is more magnetic than the helmet.

6. If it is desired to inspect our own helmets

OO 351.05/1143
[illegible] 421 1-Std. (Helmets, Steel)
DOD 400.163/531-939
RIA 421/787 7th Ind. (Continued)

by this means, it will be necessary to get detailed data from the Royal Research Laboratories or conduct exhaustive tests to determine just how magnetic this stock can be while still possessing good ballistic properties. If carried on in conjunction with destructive tests, this method would give closer control over the material.

For the Commanding General:

ROBERT T. MYERS
1st Lt., Ord. Dept.,
Assistant

1 Incl. n/c
Report PES-357

COPY - 5/28/42 - ahk

O.O. 300.05/1141
Attn.: Ind. Serv., Small Arms
OM 421 S-Std. (Helmets, Steel)
DOD 400.163/631-039
PIA 421/797
WA 421/244 8th Ind. Moore/en

War Department, Ordnance Office, Washington, D. C., January 13, 1942
To: Commanding Officer, Watertown Arsenal, Watertown, Mass.

1. Forwarded for such information as the Watertown Arsenal Laboratory may have in connection with non-magnetic characteristics of steels. If the arsenal has any information that would be beneficial in determining the ballistic characteristics of helmets through the use of magnetic instruments, it would be helpful in determining whether or not helmets which are accepted without test will be satisfactory. At the present time, samples from a lot of helmets are fired for ballistic characteristics, the selected sample being assumed to be representative of the lot. This might not be the case however.

2. The arsenal may have information regarding the high manganese type of material such as is used in helmets which could be inspected prior to fabricating into helmets for drawing characteristics as well as the ballistic characteristics of the material after its fabrication.

By order of the Chief of Ordnance:

W. T. MOORE (Signed)
W. T. Moore
Lt. Col., Ord. Dept.,
Assistant

1 Incl. n/c

COPY - 5/22/42 - ahk

O.O. 380.05/1141
Attn.: Ind. Serv., Small Arms
QM 401 S-516, (Helmets, Steel)
DOD 400.163/531-020
RIA 481/757
WA 481/244 8th Ind. WTL.gmf

Watertown Arsenal, Watertown, Massachusetts, January 24, 1942.
To: Chief of Ordnance, U.S.A., Washington, D. C.
Attn: Industrial Service, Small Arms Division.

1. Helmets are made largely from "Hadfield" steel which contains 13 per cent or more of manganese. Such steels and also the chrome-nickel austenitic steels are not entirely stable, some of the austenite tending to revert to ferrite on plastic deformation.

2. The reversion to ferrite might occur due to shearing, punching, cold forming, accidental bending, hammering or a variety of other causes.

3. The steel seems to have its best ballistic properties when fully austenitic.

4. Austenite is nonmagnetic; ferrite is magnetic. The degree of reversion of the austenite to ferrite should be determinable by magnetic tests along the lines of those described as having been used in Canada.

5. It is considered that a properly devised magnetic test is probably the best one that could be found for testing for the relative amounts of ferrite in the austenite of the helmet steel, and hence, should be an excellent inspection test.

For the Commanding General:

H. H. Zornig (Signed)
H. H. ZORNIG
Col., Ord. Dept.,
Director of Laboratory

1 Incl. n/c

COPY - 5/23/42 - abk

O. O. 780.05/1141
Attn: Small Arms. Div., Ind. Service
DOD 400.163/531-920 10th Ind. Whim/ams

War Department, Ordnance Office, Washington, D. C.
February 6, 1942
To: Detroit Ordnance District Office, Detroit, Michigan

1. Reference is made to paragraph 3, 7th indorsement and paragraph 5, 9th indorsement, of this file, in which it is indicated that a magnetic test of helmets would give satisfactory indication of their ballistic properties.

2. To secure further information regarding the suitability of a magnetic test for the determination of impact strength of helmets, it is suggested that ballistic tests be conducted on a representative sample of those helmets failing to pass the magnetic test outlined in paragraph 3 of the 4th indorsement. In addition, the magnetic test should be performed prior to firing on all helmets selected for the ballistic test.

By order of the Chief of Ordnance:

W. T. MOORE,
Lt. Col., Ord. Dept.,
Assistant

1 Incl. n/c

APPENDIX B

MICROGRAPHS OF REPRESENTATIVE HEAT-TREATMENT LOTS

5/25/42 - rhm

MLR/HAR/amw

Laboratory

November 18, 1941

Mr. F. L. Barter
Vice Chairman, Subcommittee for
Helmet Steels and Body Armor
McCord Radiator and Mfg. Co.
Detroit, Michigan

Dear Mr. Barter:

We are submitting on the attached data sheet the results of the metallographic examination on the samples of Hadfield Manganese steel Nos. 26B, 26C, and 20A which were submitted with your letter dated October 14, 1941.

The results of this investigation indicate that failure was probably due to the presence of carbide stringers and grain boundary carbide in the material. It is believed that this condition can be corrected by a suitable quench, either an air blast or water spray, from 1800°F. or by finishing on the mill at a higher temperature followed by rapid cooling. Carbide stringers are considered objectionable since they are potential planes of weakness during the forming operation.

Sample No. 26B which was considered a good lot of steel was relatively free from carbide segregations, see Figure I.

Sample No. 20A, representing the average lot, showed the presence of some carbide stringers, see Figure II.

Sample No. 26C, which represented a lot of poor forming steel contained numerous carbide stringers and some grain boundary carbides, see Figure III.

Sample No. 26B had an average Rockwell C hardness of 41, while samples Nos. 20A and 26C had an average Rockwell C hardness of 46.

5/25/42 - rbm

Mr. F. L. Barter, 11/18/41 Page 2

We are sending copies of these results to Major Moore, Mr. Grodrian, Carnegie-Illinois Steel Corp., and to the Detroit Ordnance Office.

For the President of the Board:

Very truly yours,

G. L. Cox,
Major, Ord. Dept.,
Acting Chairman, Subcommittee
for Helmet Steels and
Body Armor.

2 Incls.
Data Sheet
Fig. I, II, III

cc. - Major W. T. Moore
Mr. J. A. Grodrian
Detroit Ordnance Office

DATA SHEET

FIGURE I

Microstructure representative of three helmets from Lot 26B of steel with good forming properties having a great deal of strain lines caused by the cold-working operation. Large stringers of inclusions were found in the specimen cut in the longitudinal direction. Small circular inclusions were found near the surface of the steel plate.

MA-3766

X1000

FIGURE II

Microstructure representative of two helmets from Lot 29A of steel with average forming properties containing banded precipitated carbides. There were no strain lines found in the austenite grains. Small circular inclusions were found near surface of plate.

MA-3767

X1000

FIGURE III

Microstructure representative of four helmets from Lot 26C of steel with poor forming properties containing banded precipitated carbides. No strain lines were found in the austenite grains. There were small circular inclusions near the surface of the plate.

MA-3768

X1000

All specimens etched in Vilella's Reagent.

MICROSTRUCTURE OF HADFIELD STEEL

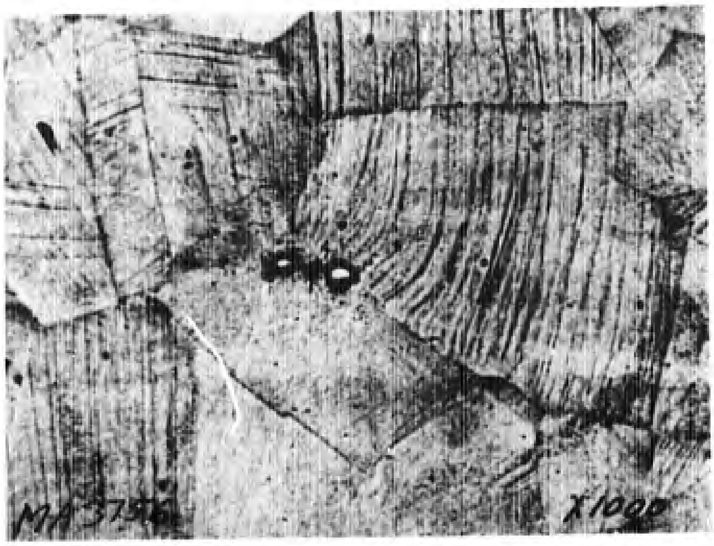


FIGURE 1

TYPICAL STRUCTURE OF GOOD FORMING STEEL

LOT # C.I. 225299
Mc C. 26B

VILELLA'S ETCH

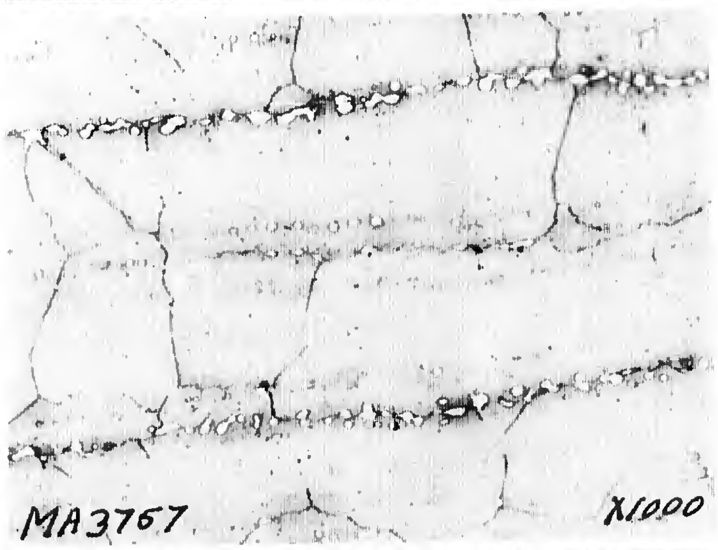


FIGURE 2

TYPICAL STRUCTURE OF AVERAGE FORMING STEEL

LOT # C.I. 175764
Mc C. 29A

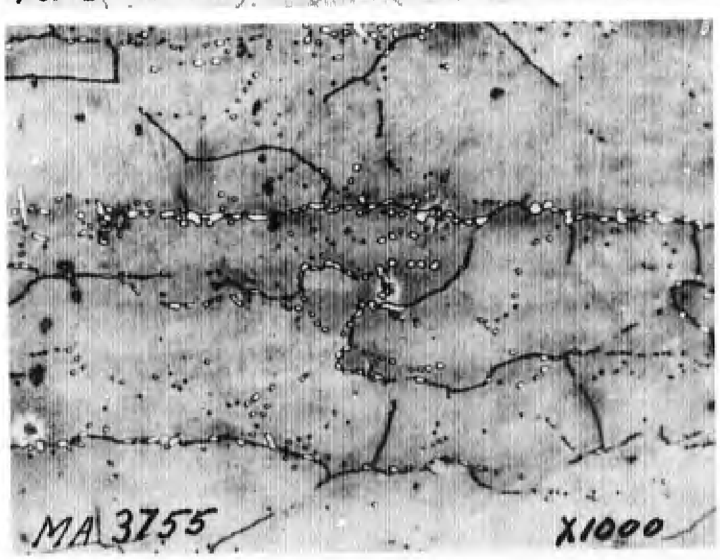


FIGURE 3

TYPICAL STRUCTURE OF POOR FORMING STEEL

LOT # C.I. 254463
Mc C. 28C

W.A.639-4153

INCLOSURE A

COLD ROLLING DATA

TABLE I

COLD ROLLING DATA

Sheet No.	Original Thickness (inches)	Final Thickness (inches)
1	.045	.045
2	.044	.041
3	.045	.0405
4	.047	.042
5	.043	.036
6	.045	.036
7	.045	.045
8	.044	.041
9	.0445	.0405
10	.045	.0405
11	.044	.037
12	.045	.036

INCLOSURE B

PHYSICAL TEST DATA

TABLE II

Sample No.	Area	Rockwell C	Tensile Strength	% Elong. in 2"
1	.0224	19	79,900	10.
2	.0216	23	103,800	0.
3	.0217	29	101,300	0.
4	.0228	31	78,800	1.
5	.0192	34	103,000	1.0
6	.0183	40	113,700	1.0
7	.0205	6	130,400	34.5
7 "a"	.0205	5	137,500	35.5
7 "b"	.0208	6	131,900	36.0
8	.0208	29	131,300	27.
11	.0196	34.5	----	----
12	.0189	36.5	173,100	22.5

"These samples were cut from different sheets.

ENCLOSURE C

FIRING DATA

TABLE III

All Firing with F. A. Primer and .45 cal. Ball Ammunition

Sheet No.	Gun Round No.	Charge	Striking Velocity	Result on Plate
1.	76	3.0	Lost	P.P. - LB
	77	3.5	Lost	P.P. - LB
	78	4.5	Lost	P.P. - LB
	79	5.0	699	P.P. - LB
	80	5.5	785	P.P. - LB
	81	6.0	809	P.P. - LB
	82	6.5	899	C.P. - P.T.P.
	83	6.2	866	C.P. - P.T.P.
	84	6.1	844	C.P. - P.T.P.
	Ballistic Limit = 825 f/s			
2.	122	service	788	C.P. - P.T.P.
	123	4.0	549	C.P. - P.T.P.
	124	3.5	458	C.P. - P.T.P.
	125	3.0	Lost	C.P. - P.T.P.
	126	2.5	309	C.P. - P.T.P.
	Lowest Complete = 309 f/s			
4.	69	service	726	C.P. - P.T.P.
	70	4.9	649	C.P. - P.T.P.
	71	4.7	Lost	C.P. - P.T.P.
	72	4.4	Lost	C.P. - P.T.P.
	73	4.0	Lost	C.P. - P.T.P.
	74	3.5	428	C.P. - P.T.P.
	75	3.0	346	C.P. - P.T.P.
	Lowest Complete = 346 f/s			

TABLE XIX (continued)

Sheet No.	Gun Round No.	Charge	Striking Velocity	Result on Plate
7.	114	7.0	922	P.P. - L.B.
	115	7.3	944	P.P. - L.B.
	116	7.4	956	P.P. - L.B.
	117	7.5	969	P.P. - L.B.
	118	7.7	997	P.P. - L.B.
	119	8.0	1028	P.P. - L.B.
	120	8.5	1090	C.P. - P.T.P.
	121	8.3	1016	P.P. - L.B.
	Ballistic Limit = 1083 f/s			
8.	102	Service #	789	P.P. - L.B.
	103	6.0	814	P.P. - L.B.
	104	6.8	932	P.P. - L.B.
	105	7.0	944	P.P. - L.B.
	106	7.3	986	P.P. - L.B.
	107	7.4	973	P.P. - L.B.
	108	7.5	Lost	C.P. - P.T.P.
	109	7.5	1007	P.P. - L.B.
	Highest Partial = 1007 f/s			
9.	85	6.5	Lost	P.P. - L.B.
	86	6.8	944	P.P. - L.B.
	87	7.0	937	P.P. - L.B.
	88	7.2	Lost	P.P. - L.B.
	89	7.3	966	C.P. - P.T.P.
	Ballistic Limit = 955 f/s			

TABLE III (continued)

Sheet No.	Gun Round No.	Charge	Striking Velocity	Result on Plate
10.	90	7.0	Lost	P.P. - L.B.
	91	7.2	Lost	P.P. - L.B.
	92	7.4	969	G.P. - P.T.P.
	93	7.2	947	G.P. - P.T.P.
	94	7.0	944	G.P. - P.T.P.
	95	6.9	950	P.P. - L.B.
	96	6.7	925	P.P. - L.B.
	Ballistic Limit = 935 f/s			
11.	110	Service W	780	P.P. - L.B.
	111	7.0	850	G.P. - P.T.P.
	112	6.5	871	G.P. - P.T.P.
	113	5.4	840	P.P. - L.B.
	Ballistic Limit = 856 f/s			
12.	97	7.0	900	G.P. - P.T.P.
	98	6.0	862	G.P. - P.T.P.
	99	Service W	789	G.P. - P.T.P.
	100	Service F A	740	P.P. - L.B.
	101	5.5	765	P.P. - L.B.
	Ballistic Limit = 777 f/s			

ENCLOSURE D

MAGNETIC TESTING

Details of Magnetic Testing

Samples were cut from cold-rolled strip and were placed in a homogeneous magnetic field (gradient of the field was constant over the sample). The gradient was maintained constant, but the field strength was varied from 300 gauss to 1900 gauss. The force on the sample was determined by weighing the sample with the field on and the field off. The difference in the weights determines the force on the sample at any given field strength. The details of the testing may be found in Stoner.

The force on the sample is:

$$F = m\sigma \frac{dH}{dx}$$

where F is the force; m, the mass; $\frac{dH}{dx}$ the gradient of the field strength; and σ the intensity of magnetization. From the constant of the magnet employed:

$$\frac{dH}{dx} = 23.4 \text{ gauss/cm.}$$

Thus, if F is in grams (difference in weight),

$$\sigma = \frac{980\ F}{23.4\ m}$$

$$\therefore \quad \sigma = 41.9 \frac{F}{m}$$

From σ the permeability may be obtained:

$$\mu = 1 + 4\pi \frac{\sigma}{H} \rho.$$

Where μ is the permeability and ρ the density.

List of Symbols

m = mass of sample in grams

F = force on the sample in grams

$\frac{dH}{dx}$ = gradient of magnetic field in gauss/cm

σ = magnetic intensity per unit mass

H = field strength in gauss

μ = permeability

ρ = density, 7.81 gms./cc.

INCLOSURE 2

MAGNETIC DATA

TABLE IV

Treatment of Samples for Magnetic Tests

Number	Original	Final	Per Cent Reduction
		Quenched from 1400° F.	
1	.036	.036	0
2	.036	.032	11.5
3	.035	.033	5.8
4	.035	.032	10.
5	.0355	.0305	14.
		Quenched from 1475° F.	
6	.045	.045	0
7	.045	(.043 - .044)	(2.2 - 4.5) = 3
8	.045	.039	13.3
9	.045	.041	8.9
10	.044	(.036 - .0365)	(15.7 - 17.) = 8
		Quenched from 1400° F. Decarburized	
1A	.036	.036	0
2A	(.038 - .040)	(.0345 - .0355)	(9.2 - 11.2) = 10
3A	.037	.035	5.7
4A	.038	.032	16.
5A	.043	.035	18.

TABLE V

Magnetic Data

Sample No.	Mass.	$\frac{dH}{dx}$	Balance Reading	χ	σ	H
1	2.6440	23.4	39.7361	.0027	.040	1932
		23.4	39.7353	.0019	.030	1549
		23.4	39.7345	.0011	.017	966
		23.4	39.7339	.0005	.005	483
		23.4	39.7334			0
2	2.7914	23.4	39.7813	.0066	.099	1932
		23.4	39.7804	.0057	.0855	1549
		23.4	39.7795	.0048	.072	966
		23.4	39.7783	.0036	.054	483
		23.4	39.7707			0
3	2.4526	23.4	27.87[illegible]	.0026	.0415	1932
		23.4	27.8715	.0021	.033	1549
		23.4	27.8707	.0013	.021	966
		23.4	27.8702	.0008	.013	483
		23.4	27.8694			0
4	2.6121	23.4	39.6081	.0091	.146	1932
		23.4	39.6070	.0081	.125	1549
		23.4	39.6057	.0067	.107	966
		23.4	39.6046	.0056	.090	483
		23.4	39.5990			0

TABLE V (Cont.)

Sample No.	Mass	dH/dx	Balance Reading	F	σ	H
5	3.6166	23.4	39.6192	.0065	.104	1932
		23.4	39.6184	.0057	.091	1349
		23.4	39.6173	.0046	.073	966
		23.4	39.6162	.0035	.056	483
		23.4	39.6127			0
6	3.3473	23.4	28.5914	.0039	.0466	1932
		23.4	28.5903	.0028	.0330	1349
		23.4	28.5894	.0019	.0226	966
		23.4	28.5880	.0005	.0063	483
		23.4	28.5875			0
7	4.1092	23.4	29.3448	.0066	.069	1932
		23.4	29.3426	.0053	.054	1349
		23.4	29.3409	.0036	.0366	966
		23.4	29.3391	.0020	.0204	483
		23.4	29.3373			0
8	3.5136	23.4	28.7606	.0069	.0776	1932
		23.4	28.7594	.0056	.0785	1349
		23.4	28.7577	.0049	.0585	966
		23.4	28.7557	.0029	.0246	483
		23.4	28.7538			0
9	2.5753	23.4	26.6137	.0046	.054	1932
		23.4	26.6131	.0040	.047	1349
		23.4	26.6115	.0024	.0281	966
		23.4	26.6102	.0011	.013	483
		23.4	26.6091			0

TABLE V (Cont.)

Sample No.	Mass	$\frac{dH}{dx}$	Balance Reading	F	σ	H
10	3.2283	23.4	28.4788	.0104	.135	1932
		23.4	28.4766	.0090	.117	1549
		23.4	28.4751	.0013	.0945	966
		23.4	28.4731	.0053	.0686	483
		23.4	28.4676			0

1825° F. Quench Decarburized

Sample No.	Mass	$\frac{dH}{dx}$	Balance Reading	F	σ	H
1A	3.7076	23.4	28.9527	.0048	.0541	1932
		23.4	28.9520	.0041	.0463	1549
		23.4	28.9502	.0023	.0260	966
		23.4	28.9485	.0006	.0068	483
		23.4	28.9479			0
2A	3.3328	23.4	28.5806	.0280	.352	1932
		23.4	28.5769	.0243	.306	1549
		23.4	28.5735	.0209	.262	966
		23.4	28.5682	.0156	.196	483
		23.4	28.5526			0
3A	3.6567	23.4	28.8665	.0049	.0561	1549
		23.4	28.8650	.0034	.039	966
		23.4	28.8634	.0018	.0206	483
		23.4	28.8669	.0058	.0665	1932
		23.4	28.8616			0

TABLE V (Cont.)

Sample No.	Mass	dH/dx	Balance Reading	F	σ	H
4A	3.3058	23.4	28.6701	.1400	1.775	1340
		23.4	28.6620	.1319	1.67	964
		23.4	28.6581	.1280	1.55	723
		23.4	28.6356	.1055	1.335	483
		23.4	28.6125	.0824	1.043	242
		23.4	28.5301			0
5A	3.6119	23.4	40.7313	.2162	2.505	1340
		23.4	40.7055	.1904	2.21	966
		23.4	40.6870	.1719	1.99	723
		23.4	40.6619	.1468	1.70	483
		23.4	40.6277	.1126	1.305	242
		23.4	40.5151			0

TABLE VI

Calculation of Magnetic Permeability

$$\mu = 1 + 4\pi \frac{\sigma}{H} \rho$$

Field Strength	Per Cent Reduction				
	(1625° F. Quench)				
H	0	5.5	11	14	19
400	1.00175	1.00320	1.0112	1.0133	1.0206
800	1.00197	1.00240	1.0085	1.0089	1.0130
1200	1.00204	1.00258	1.00673	1.00705	1.0402
1600	1.00204	1.00256	1.00575	1.00608	1.0084
2000	1.00208	1.00250	1.00495	1.00531	1.0074
	(1475° F. Quench)				
	0	1	2	11	16
400	1.00246	1.00296	1.00443	1.00736	1.00150
800	1.00246	1.00283	1.00356	1.00648	1.00108
1200	1.00246	1.00278	1.00306	1.00673	1.00672
1600	1.00246	1.00278	1.00305	1.00550	1.00785
2000	1.00246	1.00256	1.00348	1.00501	1.00605
	(1625° F. Quench Decarburized)				
	0	2.5	10	15	18
400	1.00246	1.00384	1.0449	1.305	1.380
800	1.00246	1.00366	1.0396	1.194	1.260
1200	1.00246	1.00346	1.0348	1.148	1.196
1600	1.00246	1.00344	1.0300	1.111	1.164
2000	1.00246	1.00344	1.0177	1.092	1.144

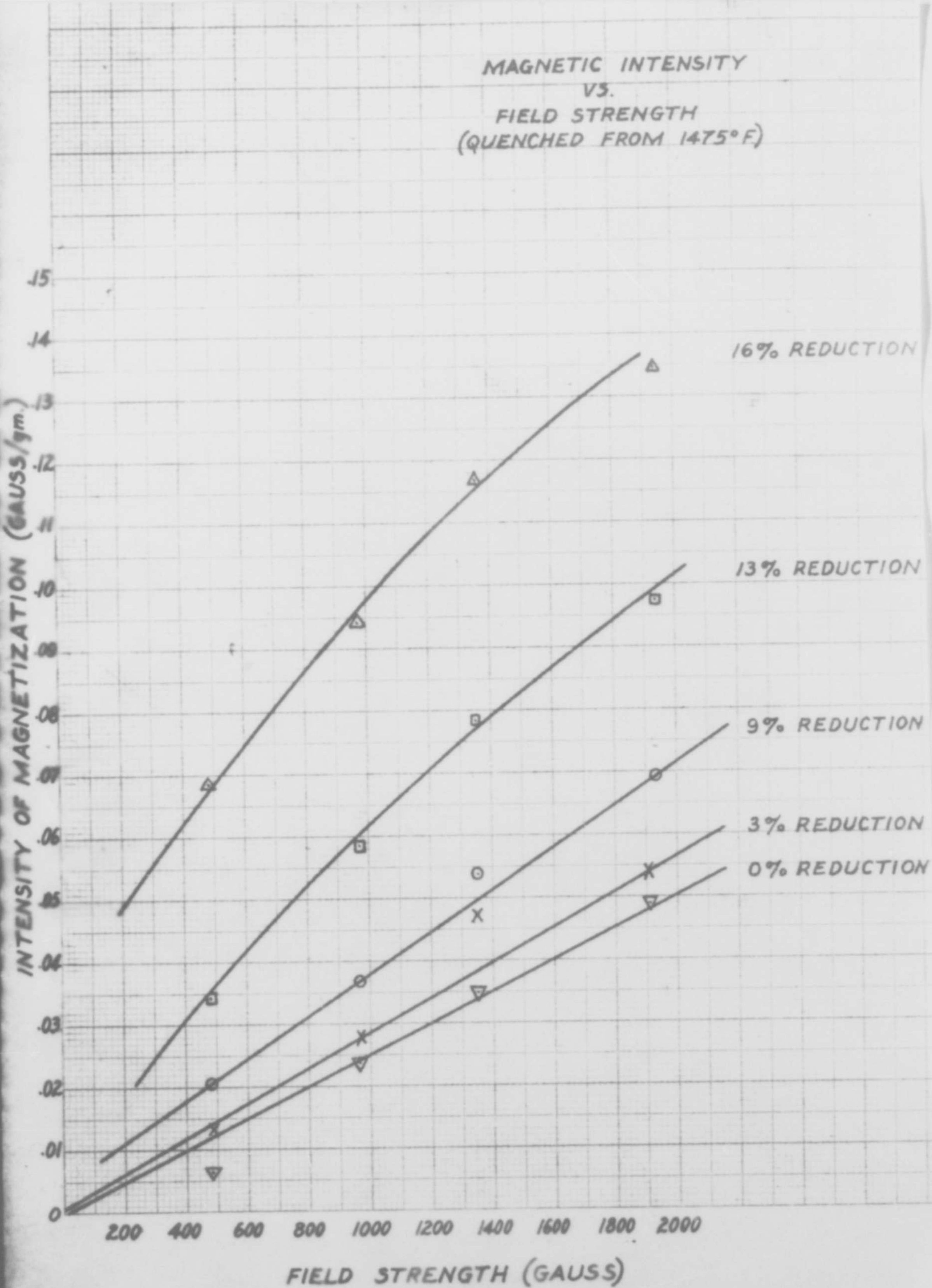
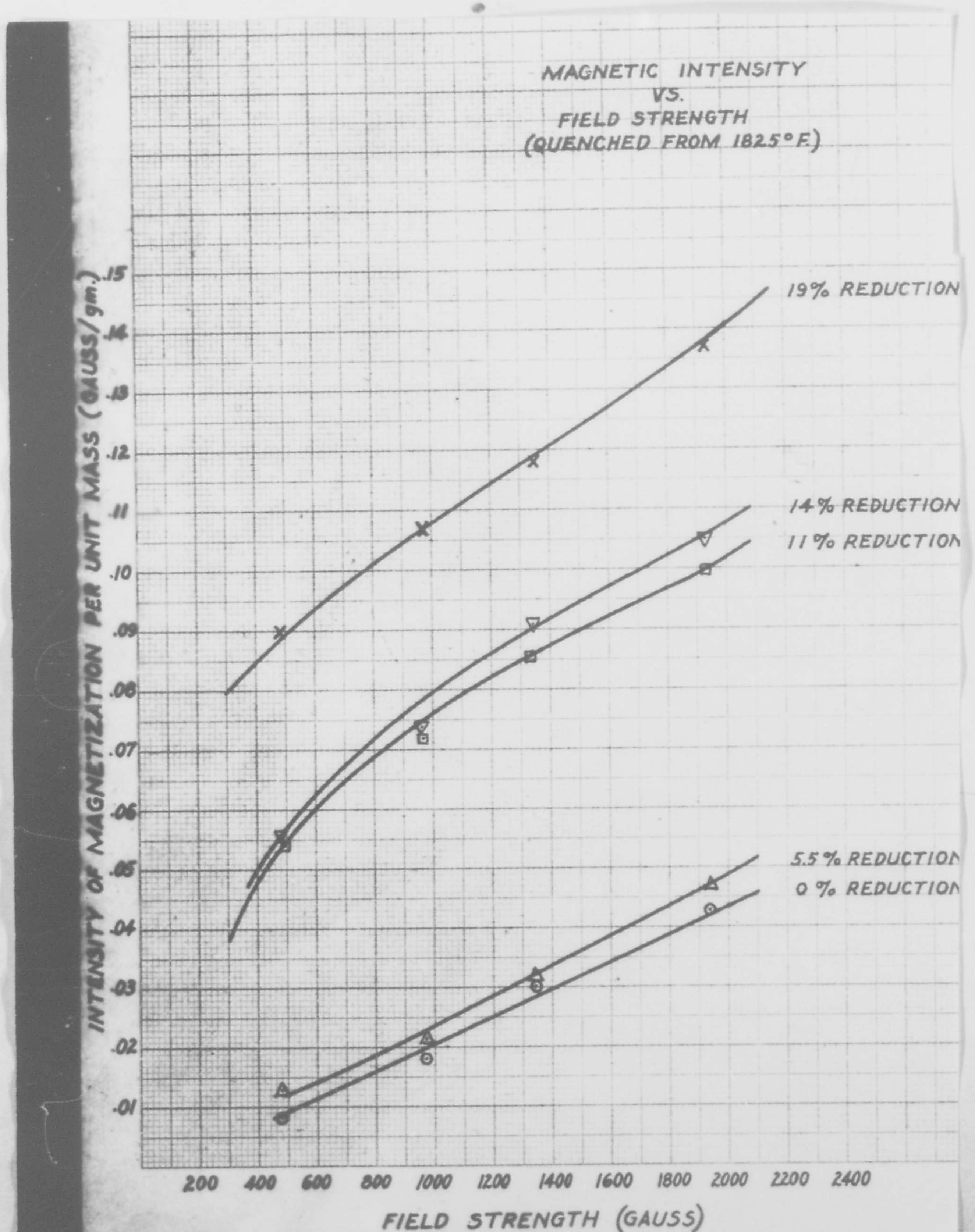

MAGNETIC INTENSITY
VS.
FIELD STRENGTH
(QUENCHED FROM 1475° F)
16% REDUCTION
13% REDUCTION
9% REDUCTION
3% REDUCTION
0% REDUCTION
INTENSITY OF MAGNETIZATION (GAUSS/gm.)
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
200
400
600
800
1000
1200
1400
1600
1800
2000
FIELD STRENGTH (GAUSS)

Figure 14


MAGNETIC INTENSITY
VS.
FIELD STRENGTH
(QUENCHED FROM 1825° F.)
19% REDUCTION
14% REDUCTION
11% REDUCTION
5.5% REDUCTION
0% REDUCTION
INTENSITY OF MAGNETIZATION PER UNIT MASS (GAUSS/gm.)
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
.14
.15
200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400
FIELD STRENGTH (GAUSS)
Figure 15

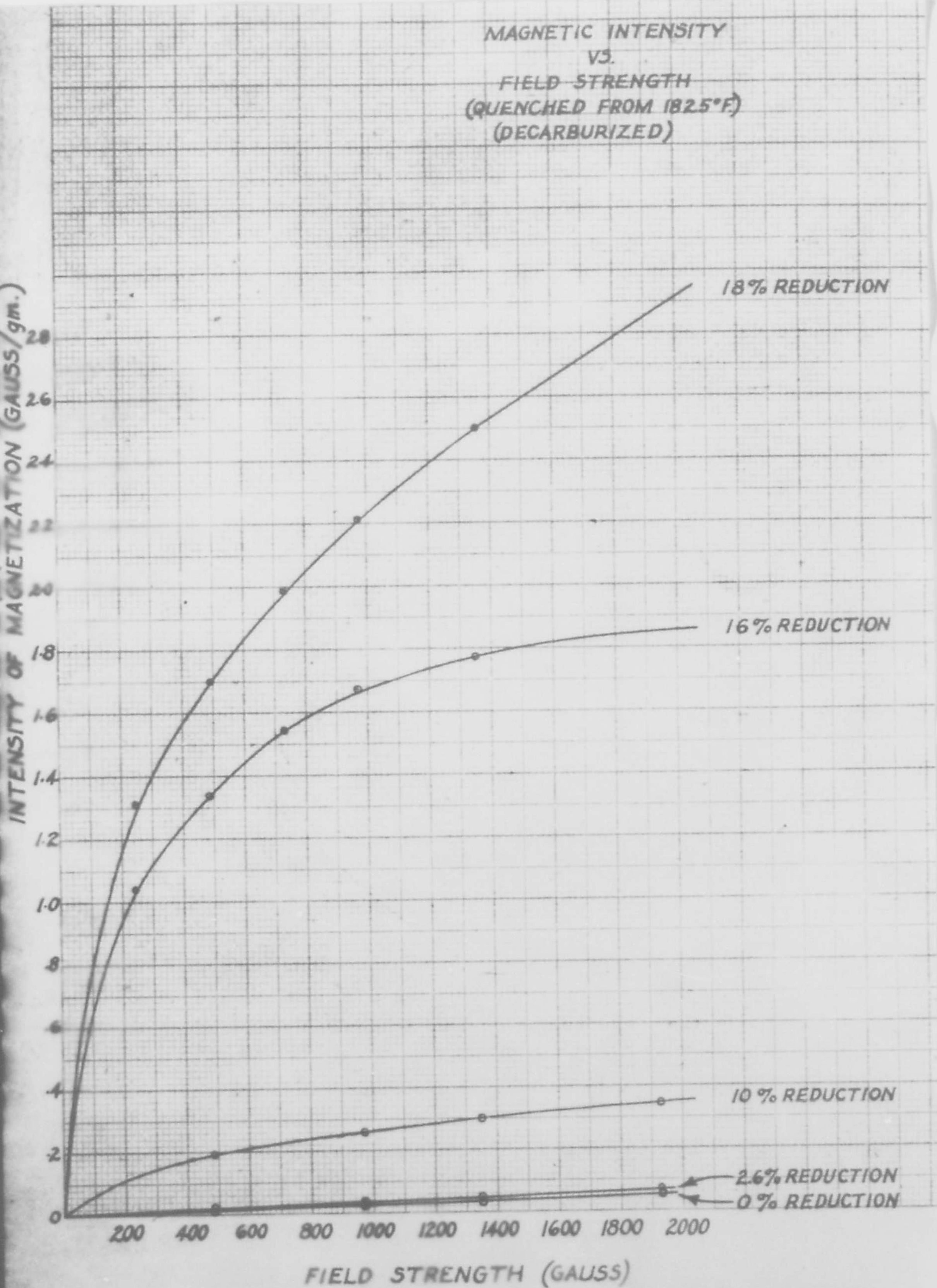

MAGNETIC INTENSITY
VS.
FIELD STRENGTH
(QUENCHED FROM 1825°F)
(DECARBURIZED)
18% REDUCTION
16% REDUCTION
10% REDUCTION
2.6% REDUCTION
0% REDUCTION
INTENSITY OF MAGNETIZATION (GAUSS/gm.)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
200
400
600
800
1000
1200
1400
1600
1800
2000
FIELD STRENGTH (GAUSS)

Figure 16

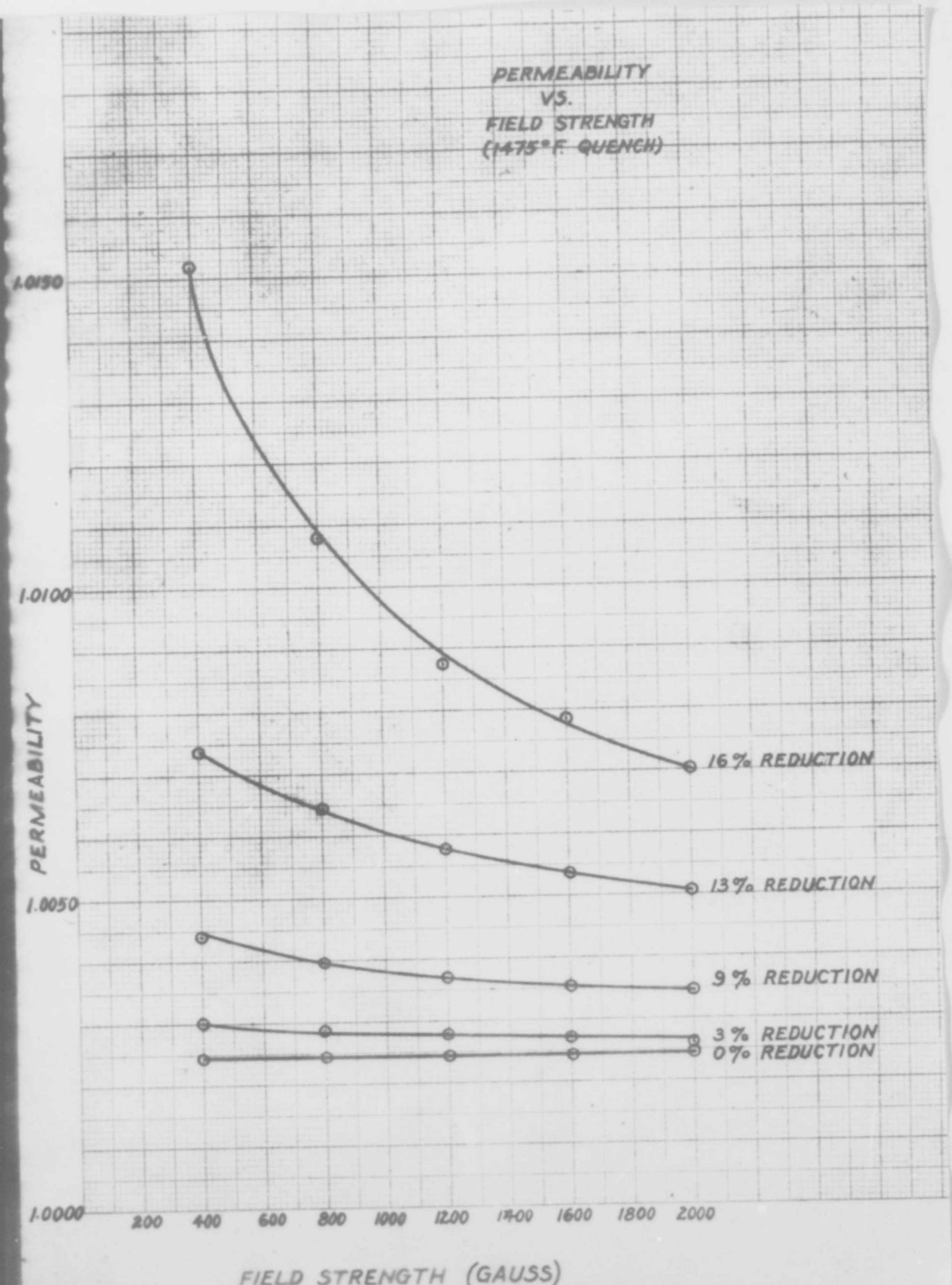

PERMEABILITY
VS.
FIELD STRENGTH
(1475° F. QUENCH)
1.0150
1.0100
1.0050
1.0000
PERMEABILITY
16% REDUCTION
13% REDUCTION
9% REDUCTION
3% REDUCTION
0% REDUCTION
200
400
600
800
1000
1200
1400
1600
1800
2000
FIELD STRENGTH (GAUSS)

Figure 17

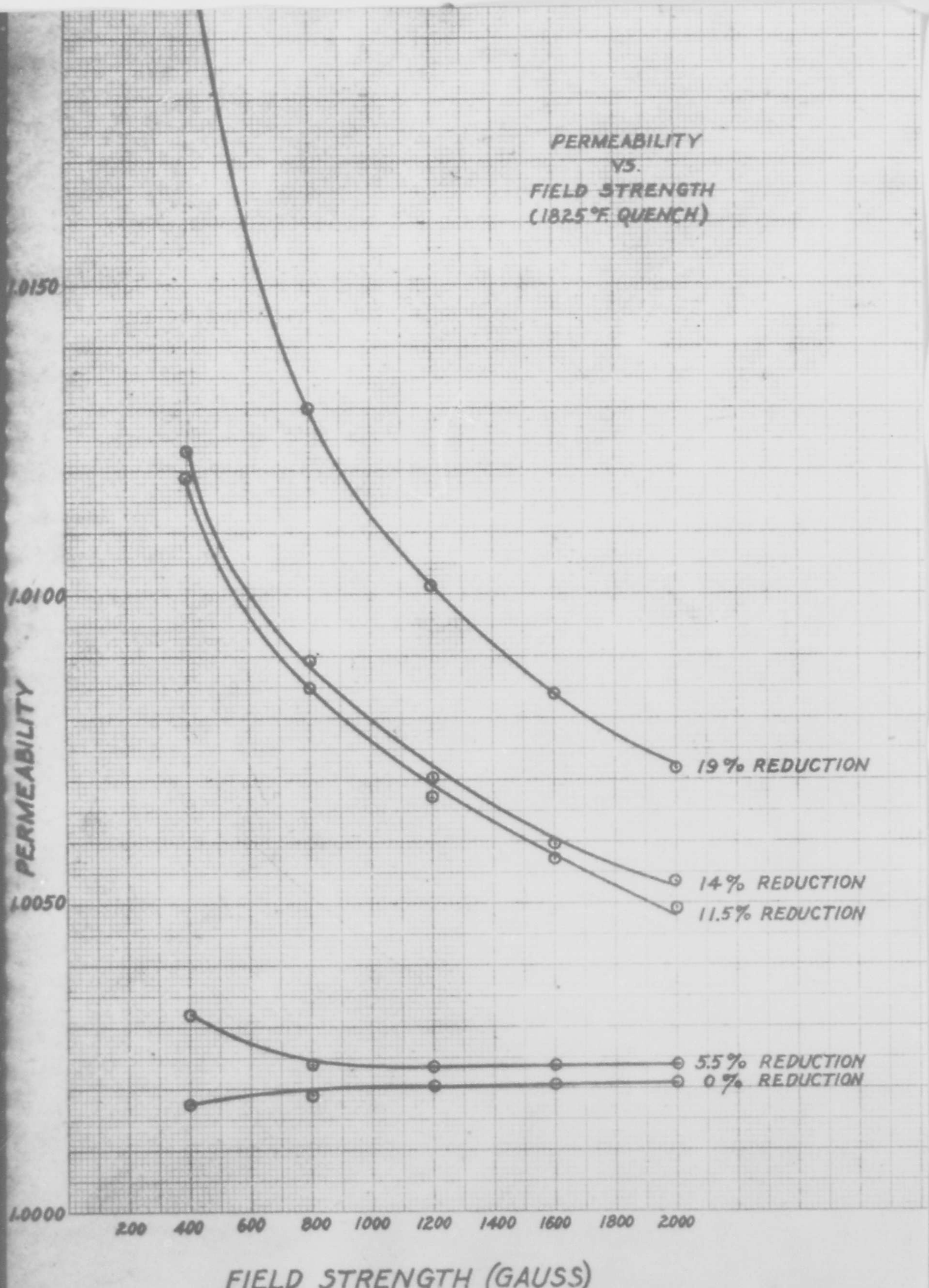

PERMEABILITY
VS.
FIELD STRENGTH
(1825°F. QUENCH)
1.0150
1.0100
1.0050
1.0000
PERMEABILITY
19% REDUCTION
14% REDUCTION
11.5% REDUCTION
5.5% REDUCTION
0% REDUCTION
200
400
600
800
1000
1200
1400
1600
1800
2000
FIELD STRENGTH (GAUSS)

Figure 18

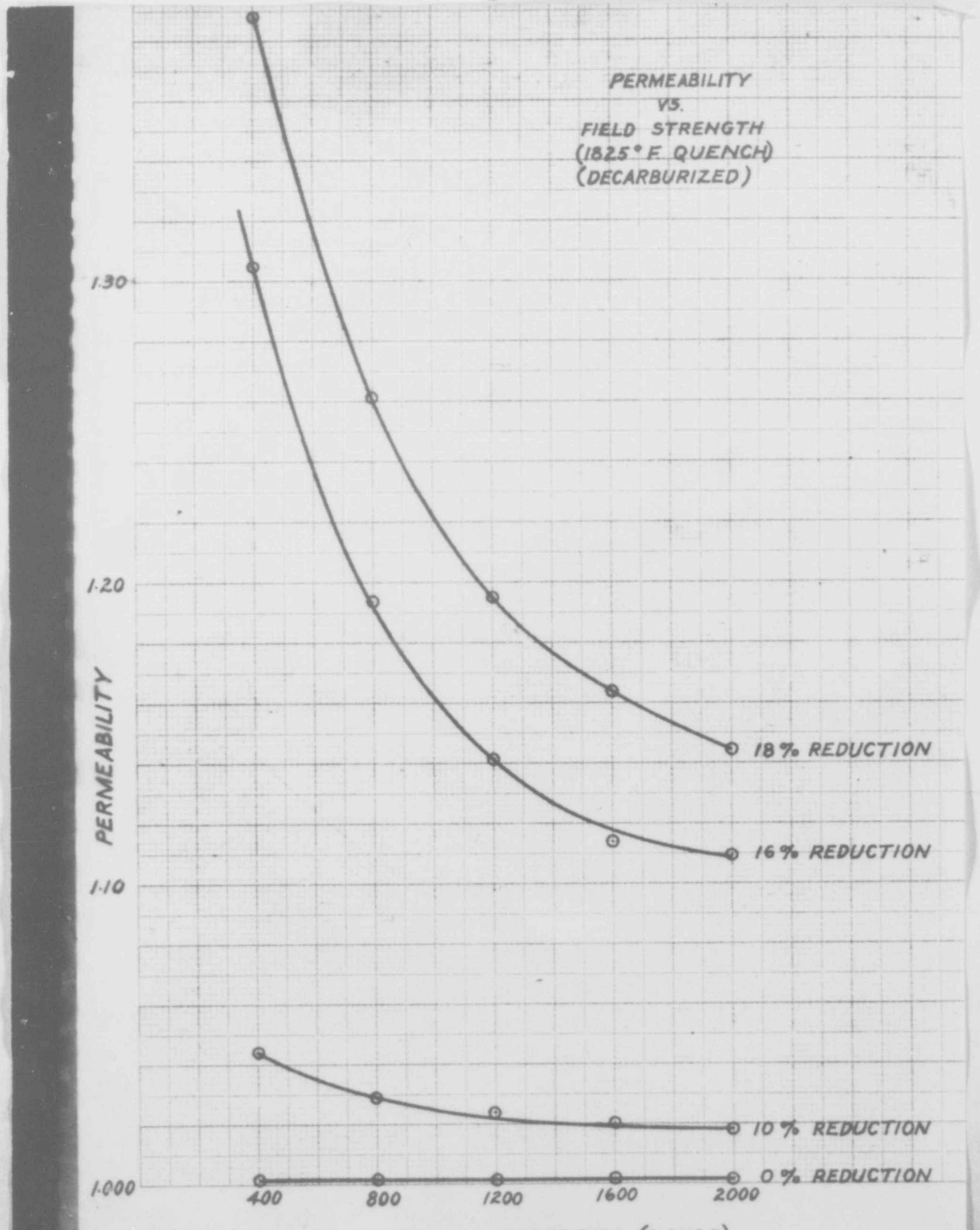

PERMEABILITY
VS.
FIELD STRENGTH
(1825° F. QUENCH)
(DECARBURIZED)
PERMEABILITY
1.30
1.20
1.10
1.000
400
800
1200
1600
2000
FIELD STRENGTH (GAUSS)
18% REDUCTION
16% REDUCTION
10% REDUCTION
0% REDUCTION

Figure 19