SSC 13

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PROGRESS REPORT

on

# METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

by

C. E. SIMS, H. M. BANTA AND A. L. WALTERS
BATTELLE MEMORIAL INSTITUTE
Under Navy Contract NObs-31219

COMMITTEE ON SHIP CONSTRUCTION
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL RESEARCH COUNCIL

Advisory to

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Under Contract NObs-34231

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Copy No. 142

Date: November 17, 1947

NATIONAL RESEARCH COUNCIL
2101 Constitution Avenue
Washington, D. C.

November 17, 1947

Chief, Bureau of Ships
Navy Department
Washington, D. C.

Dear Sir:

Attached is Report Serial No. SSC-13 entitled "Metallurgical Quality of Steels used for Hull Construction". This report has been submitted by the contractor as a progress report of the work done on Research Project SR-87 under Contract NObs-31219 between the Bureau of Ships, Navy Department and Battelle Memorial Institute.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Construction, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

Frederick M. Feiker

Frederick M. Feiker, Chairman
Division of Engineering and
Industrial Research

Enclosure

## Preface

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals that were actively associated with this research program. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels."

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# PROGRESS REPORT

on

# NAVY RESEARCH PROJECT NObs 31219

# METALLURGICAL QUALITY OF STEELS USED FOR HULL CONSTRUCTION

by

C. E. Sims, H. M. Banta, and A. L. Walters

BATTELLE MEMORIAL INSTITUTE

May 31, 1947

# TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

## Figures

TABLE OF CONTENTS (Continued)

## Tables

Page

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on

*NAVY RESEARCH PROJECT NObs 31219*

METALLURGICAL QUALITY OF STEELS
USED FOR
HULL CONSTRUCTION

May 31, 1947

From:
Battelle Memorial Institute

Report Prepared By:
H. M. Banta
A. L. Walters

C. E. Sims, Supervisor

SUMMARY

In order to obtain definite information concerning the relationships among chemical composition, underbead weld cracking, and the mechanical properties, especially the tensile and notched-bar impact characteristics, a series of 30 laboratory heats was made and studied in the hot-rolled state to determine the individual influence of each of the following constituents when varied over a range sufficiently broad to definitely establish the trend of the effect; carbon, manganese, silicon, molybdenum, vanadium, and aluminum.

For a standard chemical composition, a typical HTS analysis was selected, and the elements studied were then varied one at a time in this standard composition.

This investigation revealed that the carbon content should most probably be limited to 0.15-0.20 per cent as above this value the crack sensitivity increases with marked rapidity which is entirely out of line with the increase in tensile and yield strength. Increased carbon content was also accompanied by a reduction in the notched-bar impact strength.

While manganese increases the tensile and yield strengths at a rapid rate, it also increases the weld crack sensitivity at a rapid rate. One advantage of manganese is that it is not appreciably detrimental to the notched-bar impact strength in the temperature range of -70°F. to 210°F.

While silicon contents above that normally used in HTS steel did appear to offer some advantages over plain carbon-manganese steels for obtaining slightly higher yield strengths and low underbead cracking, silicon is not comparable with either molybdenum or vanadium for this purpose.

The use of either molybdenum or vanadium appeared to be the most promising means of increasing the tensile and yield strengths without marked detrimental effects upon the degree of underbead cracking. However, both of these alloys lower the notched-bar impact strength to an appreciable degree, especially at room temperature and lower.

Data from a single series of heats in which the aluminum addition was varied from 0 to 5 pounds per ton indicated that the aluminum content is an important factor in establishing the underbead weld crack sensitivity. The steels made with low and medium amounts of aluminum were quite crack sensitive as compared with the steels containing no aluminum or a very large aluminum content, such as that obtained by an addition of 5 pounds per ton. Since this wide aluminum range has not been previously investigated, it will be necessary to confirm these results with additional data.

An aluminum addition of about 2 pounds per ton, .064 per cent acid-soluble aluminum content in the steel, was found to have the most beneficial influence upon the notched-bar impact strength. This effect was especially noticeable at low temperatures.

No relationship was found between the tensile properties of the plate normal to the surface and the aluminum content. A previous study made on commercial plate revealed a good correlation between aluminum content and the properties normal to the plate surface. This difference in behavior of the laboratory steels and the commercial heats may be caused by the large difference in the amount of reduction between ingot and plate, the directional properties being amplified by the increased reduction of the commercial product.

The notched-bar impact properties normal to the surface were all found to be quite low as compared with the longitudinal properties. As in the case of the longitudinal tests, the steel made with an aluminum addition of 2 pounds per ton displayed the highest notched-bar impact strength when tested normal to the surface.

## INTRODUCTION

The previous work on this project has been confined to an investigation of the mechanical properties, metallurgical characteristics, and the underbead cracking tendencies of HTS steels that have been used in welded naval construction. Briefly, the range of chemistry covered was from 0.14 to 0.23 per cent carbon and 0.81 to 1.53 per cent manganese, together with small additions of titanium or vanadium or both. This range represents about the extreme limits found in commercial steels of this grade.

In the past, the summation of the carbon, manganese, and other alloys has been definitely limited because of underbead cracking. Recent work on this project has revealed that the total alloy content of the steel may be relatively high without being detrimental to the welding characteristics, especially underbead cracking, provided the steel has been homogenized to reduce or eliminate alloy segregation. This provides a means for using a higher alloy steel with resultant higher strength which is not susceptible to underbead cracking under normal welding conditions.

The purpose of this phase of the investigation is to determine the influence of chemical composition covering a much wider range than found in the commercial HTS steels. The ultimate object is to find the composition which will give the highest yield strength and still have a sufficiently low level of crack sensitivity to be satisfactory for welded ship construction.

# EXPERIMENTAL WORK

## A Study of the Influence of Chemical Composition

### Preparation of Laboratory Heats

Previous work on laboratory heats has shown that in the case of small induction furnace heats, it was necessary to increase slightly the carbon and manganese contents in order to obtain the average level of underbead cracking normally found in commercial HTS steels. It was found that laboratory heats containing 0.21 per cent carbon and 1.32 per cent manganese were quite suitable for investigational purposes as these steels cracked well within the limits of the weld crack-sensitivity test conditions used for commercial steels. Using this approximate analysis as a standard for comparison, a series of 30 induction furnace heats were made to study the influence of carbon, manganese, silicon, molybdenum, vanadium, and aluminum contents upon the welding characteristics and mechanical properties. These heats consisted of 450-pound melts deoxidized with an addition of 0.4 pound of aluminum per ton of steel, with the exception of six heats made to study the effect of aluminum additions ranging from 0 to 5 pounds.

The steel was cast into two 6-5/8-inch-square ingots and subsequently processed by forging from a temperature of 2200°F. to 2300°F. to 2 by 5-inch slabs. Following reheating to 2200°F., the slabs were hot rolled to 1-inch plate in six passes. The finishing temperature after rolling was approximately 1750°F. The plates were stood on edge and allowed to air cool as in normalizing. By processing each ingot in this manner, a uniform hot-rolled condition was produced throughout the seven lots of steel.

The heats made with various aluminum contents were cast in 8 by 8-inch ingots and reduced by hot rolling on a commercial mill to 1-inch plate, the reasons for which will be discussed later.

A brief outline of the heats under consideration is shown in Table 1 which lists the group and heat numbers, the elements being investigated, and the range through which the elements were varied.

The complete chemical analysis of all thirty heats is shown in Table 2.

TABLE 1. OUTLINE OF LABORATORY HEATS MADE TO STUDY THE INFLUENCE OF CHEMICAL COMPOSITION

| Group No. | Heat No. in Group | Element Being Investigated | Range Covered in Per Cent |
|---|---|---|---|
| 1 | X-1 to X-5, incl. | Carbon | 0.17 to 0.32 |
| 2 | X-6 to X-9, incl. | Manganese | 0.93 to 1.51 |
| 3 | X-10 to X-13, incl. | Silicon | 0.41 to 0.92 |
| 4 | X-14 to X-18, incl. | Molybdenum | 0.10 to 0.43 |
| 5 | X-19 to X-22, incl. | Vanadium | 0.04 to 0.29 |
| 6 | X-23 to X-28, incl. | Aluminum | 0 to 0.18 |
| 7 | X-45 to X-46, incl. (Standard composition for comparison purposes) | | |

## Tensile Properties

Standard 0.505-inch threaded-end tensile specimens were machined from the center of the plate, duplicate specimens being prepared in both the longitudinal and transverse directions with respect to rolling. The

TABLE 2. CHEMICAL ANALYSIS OF LABORATORY HEATS

| Heat No. | C | Mn | P | S | Si | Ti | Mo | V | Al* |
|---|---|---|---|---|---|---|---|---|---|
| (Group 1) | | | | | | | | | |
| X-1 | 0.17 | 1.36 | .023 | .024 | 0.31 | .014 | - | - | - |
| X-2 | 0.20 | 1.30 | .021 | .023 | 0.25 | .001 | - | - | - |
| X-3 | 0.25 | 1.36 | .022 | .023 | 0.29 | .014 | - | - | - |
| X-4 | 0.28 | 1.42 | .022 | .020 | 0.22 | .014 | - | - | - |
| X-5 | 0.32 | 1.26 | .022 | .020 | 0.22 | .013 | - | - | - |
| (Group 2) | | | | | | | | | |
| X-6 | 0.21 | 0.93 | .021 | .022 | 0.27 | .010 | - | - | - |
| X-7 | 0.19 | 1.22 | .023 | .018 | 0.28 | .011 | - | - | - |
| X-8 | 0.22 | 1.37 | .023 | .018 | 0.29 | .012 | - | - | - |
| X-9 | 0.21 | 1.51 | .023 | .018 | 0.29 | .011 | - | - | - |
| (Group 3) | | | | | | | | | |
| X-10 | 0.21 | 1.30 | .025 | .018 | 0.41 | .012 | - | - | - |
| X-11 | 0.21 | 1.37 | .024 | .019 | 0.55 | .012 | - | - | - |
| X-12 | 0.19 | 1.39 | .023 | .018 | 0.79 | .011 | - | - | - |
| X-13 | 0.20 | 1.31 | .024 | .019 | 0.92 | .010 | - | - | - |
| (Group 4) | | | | | | | | | |
| X-14 | 0.22 | 1.45 | .023 | .019 | 0.30 | .025 | 0.10 | - | - |
| X-15 | 0.21 | 1.49 | .020 | .020 | 0.35 | .012 | 0.12 | - | - |
| X-16 | 0.23 | 1.29 | .023 | .022 | 0.28 | .012 | 0.24 | - | - |
| X-17 | 0.23 | 1.32 | .020 | .020 | 0.30 | .012 | 0.32 | - | - |
| X-18 | 0.24 | 1.37 | .023 | .020 | 0.29 | .014 | 0.43 | - | - |
| (Group 5) | | | | | | | | | |
| X-19 | 0.21 | 1.27 | .020 | .019 | 0.32 | .013 | - | 0.04 | - |
| X-20 | 0.20 | 1.30 | .021 | .020 | 0.30 | .016 | - | 0.08 | - |
| X-21 | 0.20 | 1.29 | .020 | .019 | 0.30 | .014 | - | 0.19 | - |
| X-22 | 0.21 | 1.28 | .020 | .020 | 0.29 | .018 | - | 0.29 | - |
| (Group 6) | | | | | | | | | |
| X-23 | 0.20 | 1.25 | .021 | .022 | 0.27 | .007 | - | - | Nil |
| X-24 | 0.23 | 1.36 | .019 | .021 | 0.29 | .006 | - | - | <.005 |
| X-25 | 0.22 | 1.24 | .020 | .020 | 0.27 | .013 | - | - | <.005 |
| X-26 | 0.22 | 1.31 | .021 | .021 | 0.27 | .016 | - | - | .029 |
| X-27 | 0.20 | 1.29 | .018 | .020 | 0.31 | .015 | - | - | .064 |
| X-28 | 0.22 | 1.26 | .019 | .020 | 0.27 | .015 | - | - | 0.180 |
| (Group 7) | | | | | | | | | |
| X-45 | 0.21 | 1.35 | .021 | .030 | 0.27 | .015 | - | - | .003 |
| X-46 | 0.22 | 1.35 | .023 | .032 | 0.28 | .015 | - | - | .003 |

* Acid-soluble aluminum content
Heats X-1 to X-22, inclusive, made with an addition of 0.4 lbs. aluminum per ton.

yield strength was determined from the stress-strain diagram using the load at 0.2 per cent offset. The data from these tests are summarized in Table 3 which lists the average of the duplicate tests. The complete data are listed in Table 1 of Appendix A.

Effect of Carbon Content. The influence of carbon content in the range of 0.17 to 0.32 per cent upon the tensile and yield strength is shown graphically in Figure 1. This figure reveals that as the carbon is raised from 0.17 to 0.32 per cent, the longitudinal yield and tensile strength increased progressively from approximately 45,000 p.s.i. to 55,000 p.s.i. and the tensile strength from 71,000 p.s.i. to 90,000 p.s.i. This increase in strength was accompanied by the usual decrease in ductility as indicated by the elongation and reduction in area.

A comparison of the transverse and longitudinal properties revealed the expected lower ductility in the transverse direction. There was also a tendency for slightly lower yield and tensile strength in the transverse direction, but in most cases, the difference can not be considered significant. A similar difference in directional properties was noted throughout all thirty heats.

The Effect of Manganese Content. Figure 2 illustrates the influence of manganese in the range of 0.93 to 1.51 per cent upon the tensile and yield strength. As the manganese is increased from 0.93 to 1.51 per cent, the longitudinal yield strength increased progressively from approximately 39,000 p.s.i. to 48,000 p.s.i., and the longitudinal tensile strength from 70,000 p.s.i. to 77,000 p.s.i. A similar trend and strengths were found in the transverse direction.

TABLE 3. TENSILE PROPERTIES OF HOT-ROLLED PLATE FROM LABORATORY HEATS

| Heat No. | Test Direction | Elong. in 2 Inches, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| (Group 1) | | | | | |
| X-1 | Long. | 37.3 | 74.5 | 45,630 | 71,380 |
| " | Trans. | 31.5 | 62.1 | 44,750 | 72,400 |
| X-2 | Long. | 36.0 | 68.9 | 44,250 | 74,600 |
| " | Trans. | 32.8 | 63.0 | 41,630 | 73,880 |
| X-3 | Long. | 31.8 | 67.0 | 47,380 | 81,550 |
| " | Trans. | 29.5 | 61.1 | 46,250 | 80,200 |
| X-4 | Long. | 30.9 | 67.5 | 51,000 | 86,850 |
| " | Trans. | 27.8 | 56.4 | 48,750 | 86,450 |
| X-5 | Long. | 28.5 | 64.6 | 55,000 | 89,800 |
| " | Trans. | 26.5 | 52.4 | 49,380 | 87,280 |
| (Group 2) | | | | | |
| X-6 | Long. | 35.5 | 66.5 | 39,130 | 70,150 |
| " | Trans. | 32.0 | 58.2 | 39,630 | 69,500 |
| X-7 | Long. | 34.8 | 69.6 | 44,630 | 73,450 |
| " | Trans. | 29.9 | 58.3 | 43,130 | 71,900 |
| X-8 | Long. | 35.6 | 70.5 | 46,750 | 77,350 |
| " | Trans. | 30.0 | 59.2 | 44,500 | 75,950 |
| X-9 | Long. | 34.8 | 72.1 | 48,380 | 77,180 |
| " | Trans. | 31.6 | 59.6 | 46,380 | 77,650 |
| (Group 3) | | | | | |
| X-10 | Long. | 34.9 | 69.7 | 47,630 | 78,450 |
| " | Trans. | 32.3 | 60.2 | 44,130 | 76,300 |
| X-11 | Long. | 33.2 | 68.6 | 50,880 | 80,000 |
| " | Trans. | 29.7 | 60.7 | 46,630 | 79,600 |
| X-12 | Long. | 33.0 | 68.5 | 52,500 | 85,450 |
| " | Trans. | 28.8 | 58.9 | 51,000 | 83,830 |
| X-13 | Long. | 33.0 | 66.0 | 49,750 | 83,950 |
| " | Trans. | 30.5 | 59.6 | 49,250 | 83,200 |

TABLE 3. (Continued)

| Heat No. | Test Direction | Elong. in 2 Inches, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| (Group 4) | | | | | |
| X-14 | Long. | 31.8 | 66.9 | 50,630 | 80,000 |
| " | Trans. | 28.8 | 58.6 | 46,000 | 79,050 |
| X-15 | Long. | 31.8 | 64.1 | 51,380 | 81,400 |
| " | Trans. | 28.8 | 58.3 | 48,880 | 80,950 |
| X-16 | Long. | 29.0 | 63.2 | 56,000 | 82,250 |
| " | Trans. | 24.1 | 55.2 | 56,750 | 82,650 |
| X-17 | Long. | 24.0 | 63.0 | 68,630 | 98,630 |
| " | Trans. | 20.9 | 49.7 | 66,250 | 93,810 |
| X-18 | Long. | 22.0 | 62.6 | 78,250 | 99,490 |
| " | Trans. | 20.8 | 53.5 | 75,880 | 97,280 |
| (Group 5) | | | | | |
| X-19 | Long. | 32.4 | 65.8 | 49,130 | 79,600 |
| " | Trans. | 29.5 | 59.0 | 47,750 | 78,100 |
| X-20 | Long. | 32.6 | 67.8 | 56,880 | 84,200 |
| " | Trans. | 27.3 | 59.5 | 54,000 | 82,450 |
| X-21 | Long. | 27.0 | 61.1 | 66,880 | 93,530 |
| " | Trans. | 23.0 | 52.4 | 64,630 | 92,550 |
| X-22 | Long. | 25.3 | 59.4 | 78,500 | 105,130 |
| " | Trans. | 20.3 | 48.8 | 73,880 | 100,400 |
| (Group 6) | | | | | |
| X-23 | Long. | 34.5 | 66.4 | 47,500 | 74,900 |
| " | Trans. | 29.3 | 52.2 | 45,750 | 73,800 |
| X-24 | Long. | 31.3 | 64.5 | 50,880 | 82,230 |
| " | Trans. | 27.8 | 50.7 | 49,380 | 81,850 |
| X-25 | Long. | 33.0 | 68.2 | 47,750 | 77,380 |
| " | Trans. | 27.8 | 54.1 | 46,380 | 76,380 |
| X-26 | Long. | 33.0 | 68.1 | 49,630 | 79,650 |
| " | Trans. | 26.8 | 53.3 | 49,380 | 79,980 |

TABLE 3. (Continued)

| Heat No. | Test Direction | Elong. in 2 Inches, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| X-27 | Long. | 33.5 | 69.6 | 48,250 | 76,600 |
| " | Trans. | 28.3 | 56.9 | 45,750 | 75,980 |
| X-28 | Long. | 33.5 | 68.7 | 48,380 | 77,750 |
| " | Trans. | 28.5 | 55.9 | 46,880 | 75,800 |
| (Group 7) | | | | | |
| X-45 | Long. | 33.8 | 67.2 | 52,100 | 79,100 |
| " | Trans. | 23.8 | 35.7 | 48,880 | 75,950 |
| X-46 | Long. | 35.0 | 70.1 | 50,750 | 80,300 |
| " | Trans. | 28.0 | 51.2 | 52,000 | 79,830 |

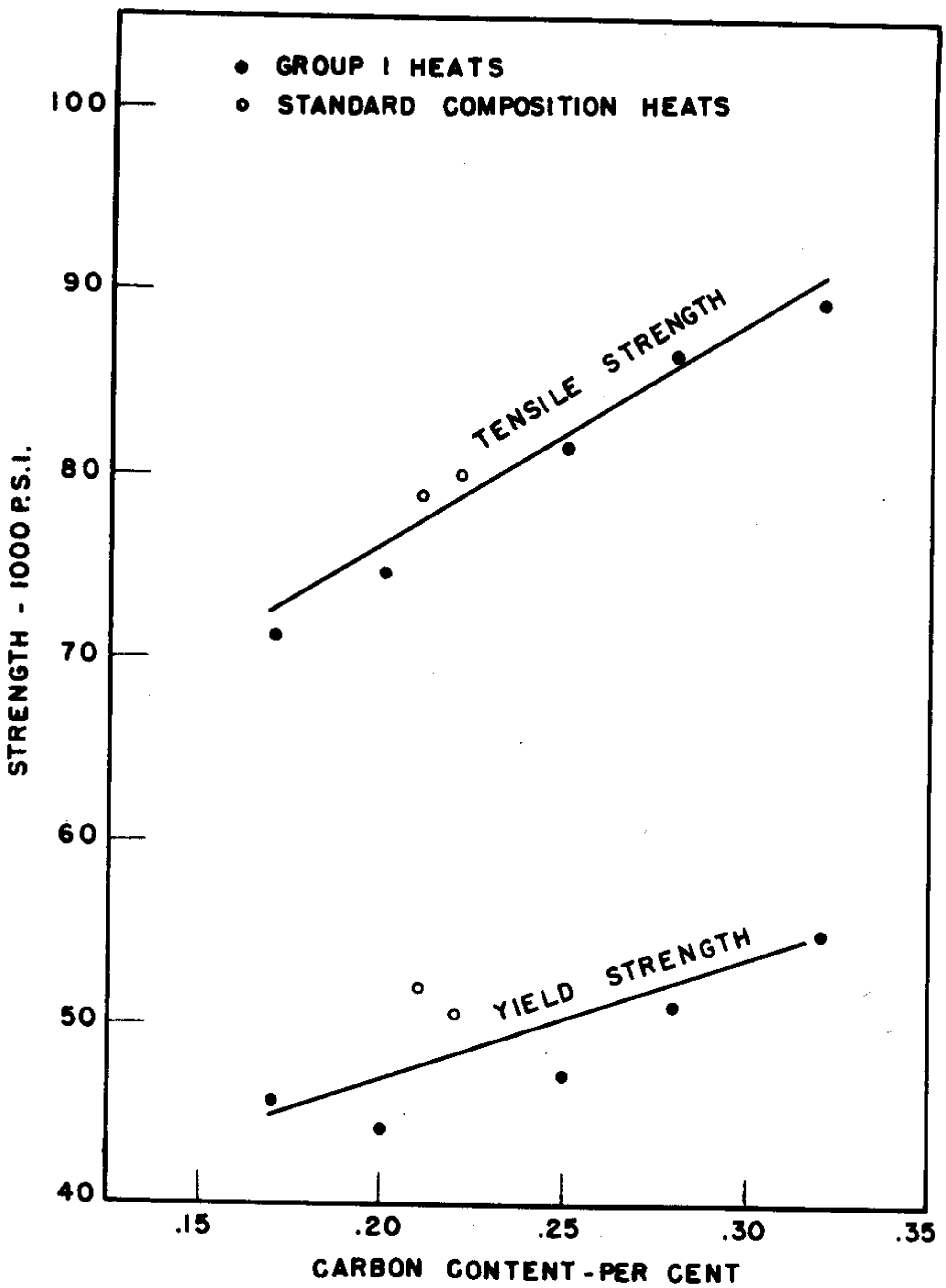


FIGURE I. RELATIONSHIP BETWEEN CARBON CONTENT AND TENSILE AND YIELD STRENGTH

0-5412

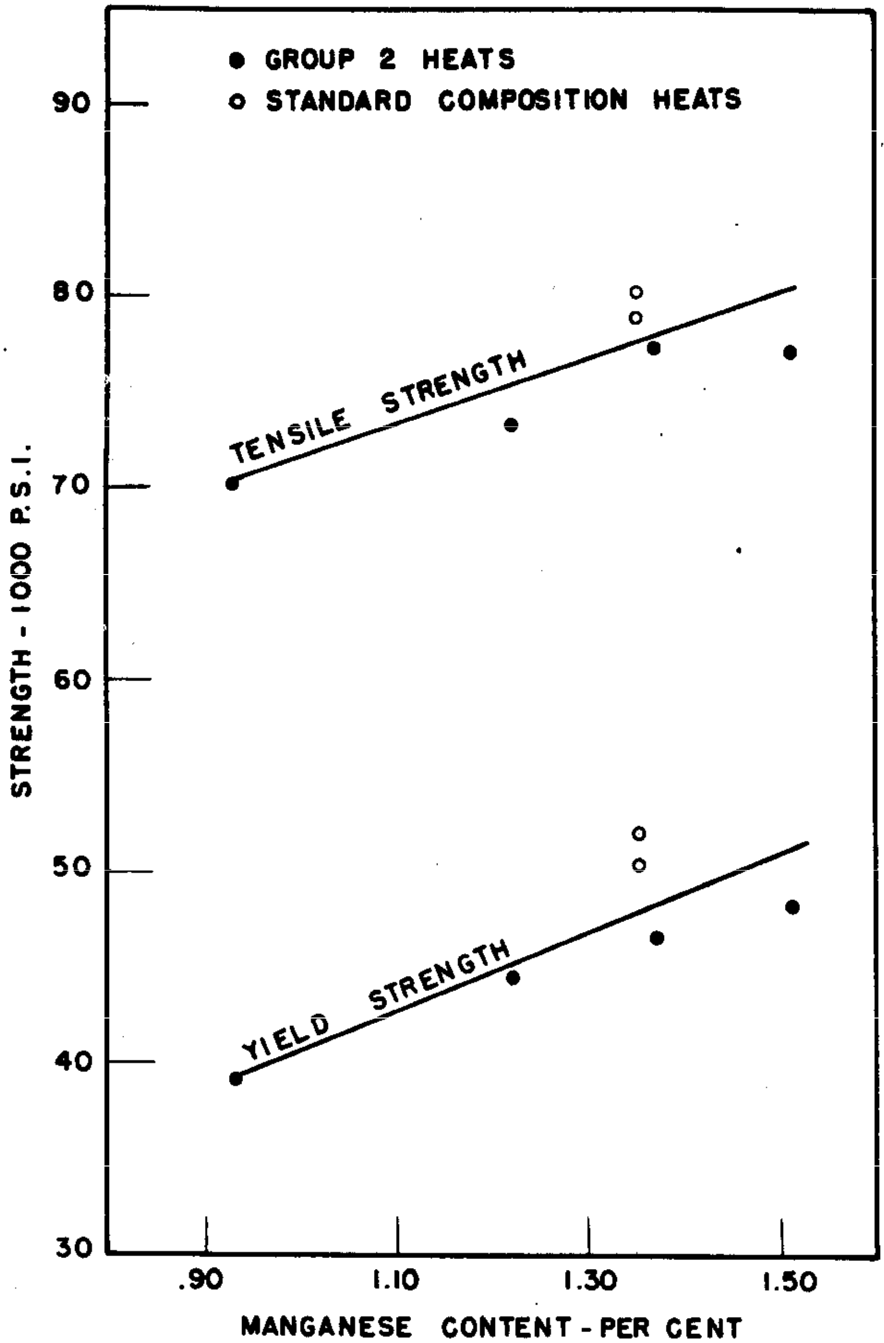


FIGURE 2. RELATIONSHIP BETWEEN MANGANESE CONTENT AND TENSILE AND YIELD STRENGTH

O-5413

The increased manganese content did not decrease the ductility as indicated by the reduction of area and elongation in both the longitudinal and transverse directions. While there was a slight increase in the reduction of area in the longitudinal direction with increased manganese content, this change was not enough to be considered significant.

The Effect of Silicon Content. The longitudinal tensile data from the four heats made to study the influence of silicon content are shown in Figure 3. From this figure it will be noted that the silicon content in the range of about 0.30 to 0.90 per cent has little influence upon the yield strength and the effect upon the tensile strength is only slight.

In the range investigated, the silicon content had no perceptible influence upon the elongation or reduction in area.

Effect of Molybdenum Content. The marked influence of molybdenum content upon the longitudinal yield and tensile strengths is shown in Figure 4. By increasing the molybdenum content from 0.10 to 0.43 per cent, the yield strength was raised from approximately 51,000 p.s.i. to 78,000 p.s.i. and the tensile strength from 57,000 psi. to 99,000 p.s.i.

This increase in strength was accompanied with the usual decrease in elongation and reduction in area.

The Effect of Vanadium Content. Figure 5 reveals that the increase in longitudinal yield and tensile strength produced by the addition of vanadium was even more marked than that of molybdenum. By increasing the vanadium content from 0.04 to 0.29 per cent, the yield strength was raised from 49,000 p.s.i. to 78,000 p.s.i., and the tensile strength from 60,000 p.s.i. to 104,000 p.s.i. With this

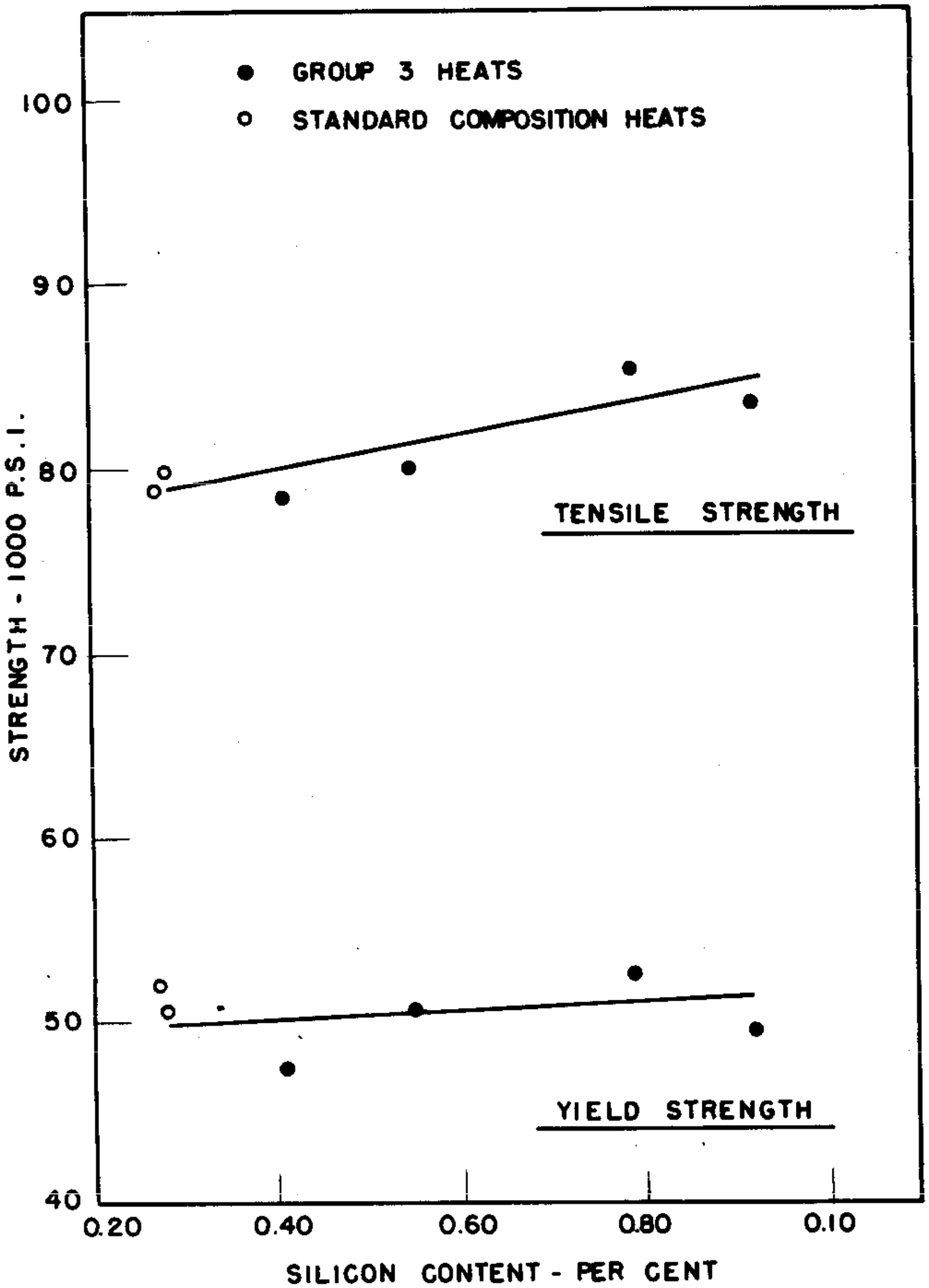


FIGURE 3 . RELATIONSHIP BETWEEN SILICON CONTENT AND TENSILE AND YIELD STRENGTH

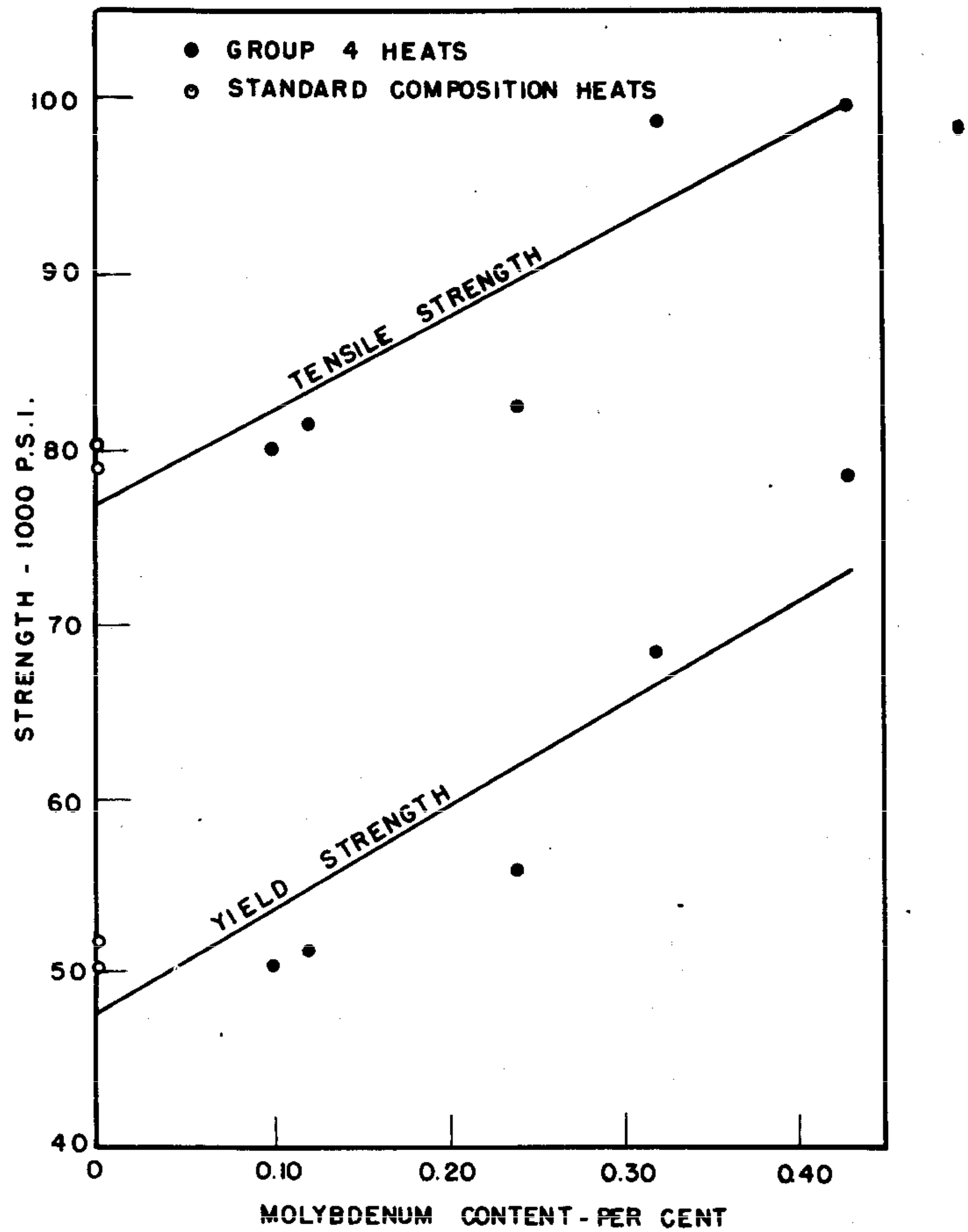


FIGURE 4 . RELATIONSHIP BETWEEN MOLYBDENUM CONTENT AND TENSILE AND YIELD STRENGTH

0-5415

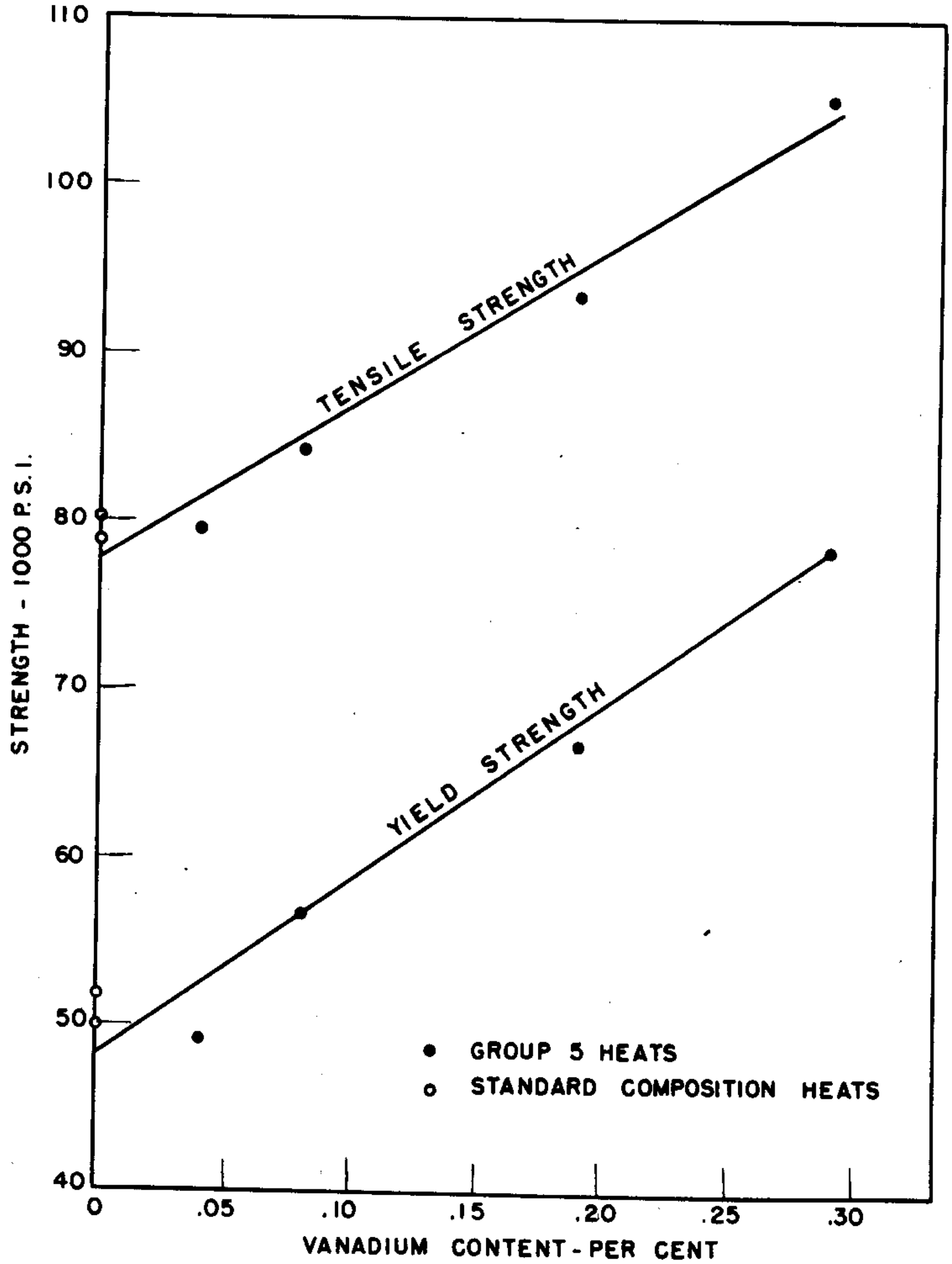


FIGURE 5. RELATIONSHIP BETWEEN VANADIUM CONTENT AND TENSILE AND YIELD STRENGTH

0-5416

increase in strength, the elongation dropped from 32.4 to 25.3 per cent and the reduction of area from 65.8 to 59.4 per cent.

The Effect of Aluminum Content. As would be expected, the aluminum content had no perceptible effect upon the tensile properties of either the longitudinal or transverse tests. The influence of aluminum upon the properties normal to the surface will be discussed later in this report.

## Underbead Weld Crack Sensitivity

The underbead weld crack sensitivity of all thirty heats in the hot-rolled condition was determined by the single-bead weld test as previously described in the reports on this project. Five weld specimens were made on each heat and a summary of the results is listed in Table 4. The complete data are listed in Table 2 of the Appendix.

The Effect of Carbon Content. The pronounced influence of carbon content upon the extent of underbead cracking is illustrated in Figure 6. This figure shows that the crack sensitivity increases quite rapidly as the carbon content is raised. The heats with 0.20 per cent or less carbon had a cracking index of 27 or less as compared with 85 and higher for heats with 0.25 per cent or more carbon.

The Effect of Manganese Content. The effect of manganese content in the range of 0.93 per cent to 1.51 per cent upon the degree of underbead cracking is shown in Figure 7. While the data in this figure do not form a smooth curve because of other factors such as the variation in carbon content, the results do indicate that the underbead cracking

TABLE 4. UNDERBEAD WELD CRACKING INDEXES FOR HEATS X-1 TO X-28, X-45 AND X-46 IN THE HOT-ROLLED CONDITION

| Heat No. | Constituent Varied | | Weld Crack-Sensitivity Index |
|---|---|---|---|
| X-1 | 0.17 ) | | 21 |
| X-2 | 0.20 ) | % | 27 |
| X-3 | 0.25 ) | Carbon | 85 |
| X-4 | 0.28 ) | content | 97 |
| X-5 | 0.32 ) | | 104 |
| X-6 | 0.93 ) | % | 28 |
| X-7 | 1.22 ) | Manganese | 19 |
| X-8 | 1.37 ) | content | 75 |
| X-9 | 1.51 ) | | 59 |
| X-10 | 0.41 ) | % | 50 |
| X-11 | 0.55 ) | Silicon | 84 |
| X-12 | 0.79 ) | content | 84 |
| X-13 | 0.92 ) | | 64 |
| X-14 | 0.10 ) | | 69 |
| X-15 | 0.12 ) | % | 86 |
| X-16 | 0.24 ) | Molybdenum | 66 |
| X-17 | 0.32 ) | content | 71 |
| X-18 | 0.43 ) | | 66 |
| X-19 | 0.04 ) | % | 51 |
| X-20 | 0.08 ) | Vanadium | 64 |
| X-21 | 0.19 ) | content | 78 |
| X-22 | 0.29 ) | | 74 |
| X-23 | nil ) | | 6 |
| X-24 | < .005) | | 95 |
| X-25 | < .005) | % Aluminum | 74 |
| X-26 | .029) | content | 81 |
| X-27 | .064) | (acid soluble) | 57 |
| X-28 | .180) | | 17 |
| X-45 | Standard composition heat | | 57 |
| X-46 | " " " | | 60 |

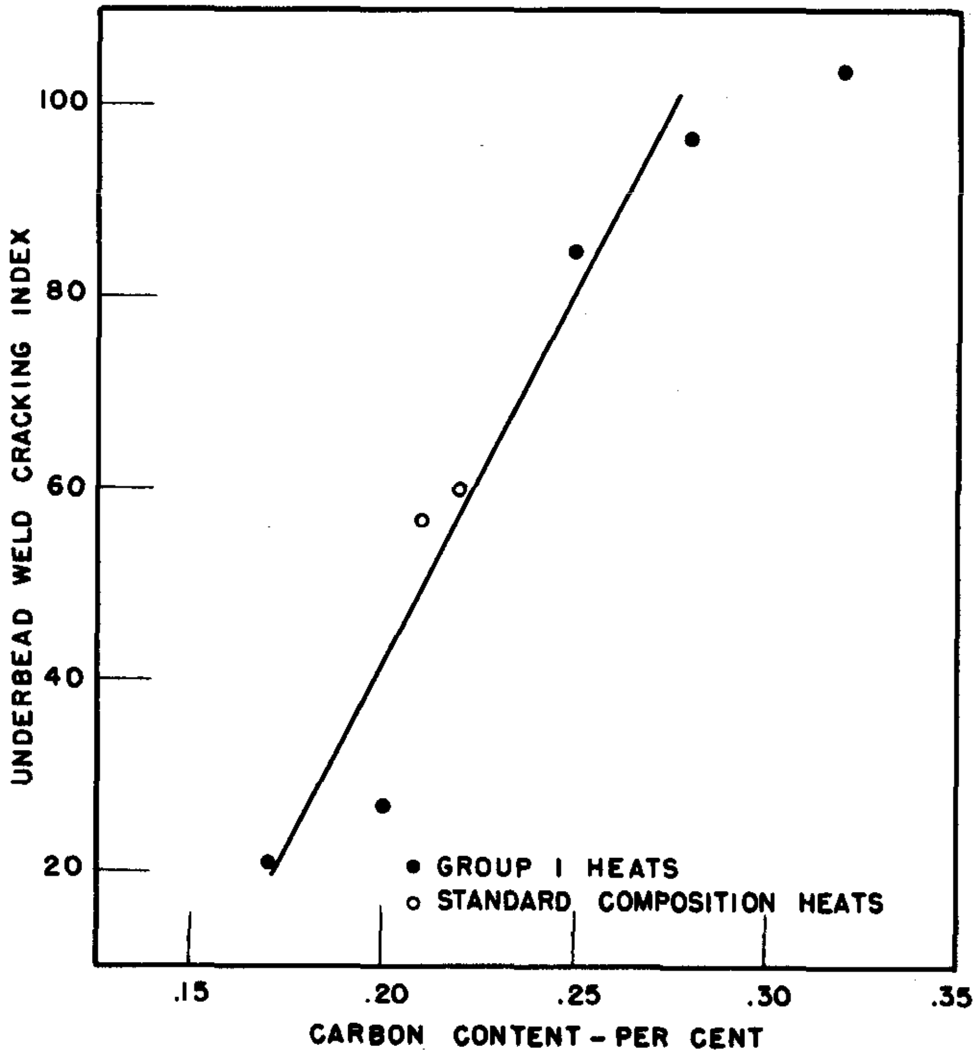


FIGURE 6 . THE EFFECT OF CARBON CONTENT UPON THE UNDERBEAD WELD CRACK SENSITIVITY

0-5417

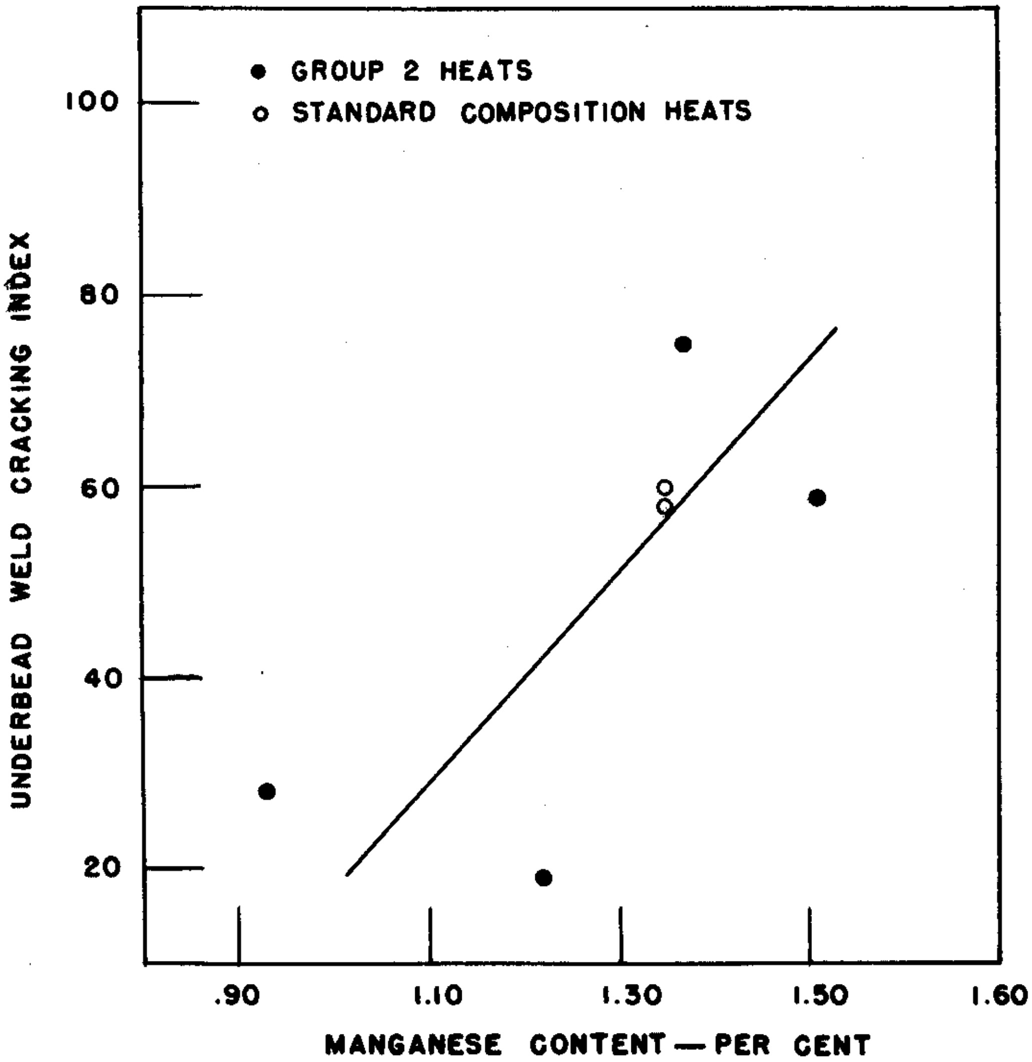


FIGURE 7. THE EFFECT OF MANGANESE CONTENT UPON THE UNDERBEAD WELD CRACK SENSITIVITY

O 5418

increased rapidly as the manganese content increased. More data will be obtained on these steels in order to obtain more points for plotting the manganese content-crack sensitivity curve.

<u>The Effect of Silicon Content.</u> The addition of silicon above that normally used in HTS steel was found to increase the extent of underbead cracking. The data show, however, that an increase from 0.79 per cent to 0.92 per cent silicon resulted in a decrease in the crack sensitivity. (See Figure 8.) While it is well established that large additions of silicon, about 1.00 per cent, decrease the tensile and yield strengths as illustrated in Figure 3, additional data are needed to confirm the effect of silicon content in this range upon the weld crack sensitivity. The high-silicon end of the crack-sensitivity curve in Figure 8, therefore, should be considered as incomplete.

<u>Effect of Molybdenum Content.</u> Molybdenum proved to be unique in that additions ranging from 0.10 to 0.43 per cent did not increase underbead cracking to any appreciable extent, although the yield and tensile strengths were increased to a marked extent. The curve comparing underbead cracking with the molybdenum content is shown in Figure 9.

<u>The Effect of Vanadium Content.</u> The relationship of underbead cracking to the vanadium content is illustrated in Figure 10. This figure indicates that additions of vanadium increases the underbead cracking to a very small extent.

<u>The Effect of Aluminum Content.</u> The study of the effect of aluminum content in the range of 0 to 0.18 per cent (acid soluble) yielded results which were quite unexpected and will require additional data for confirmation.

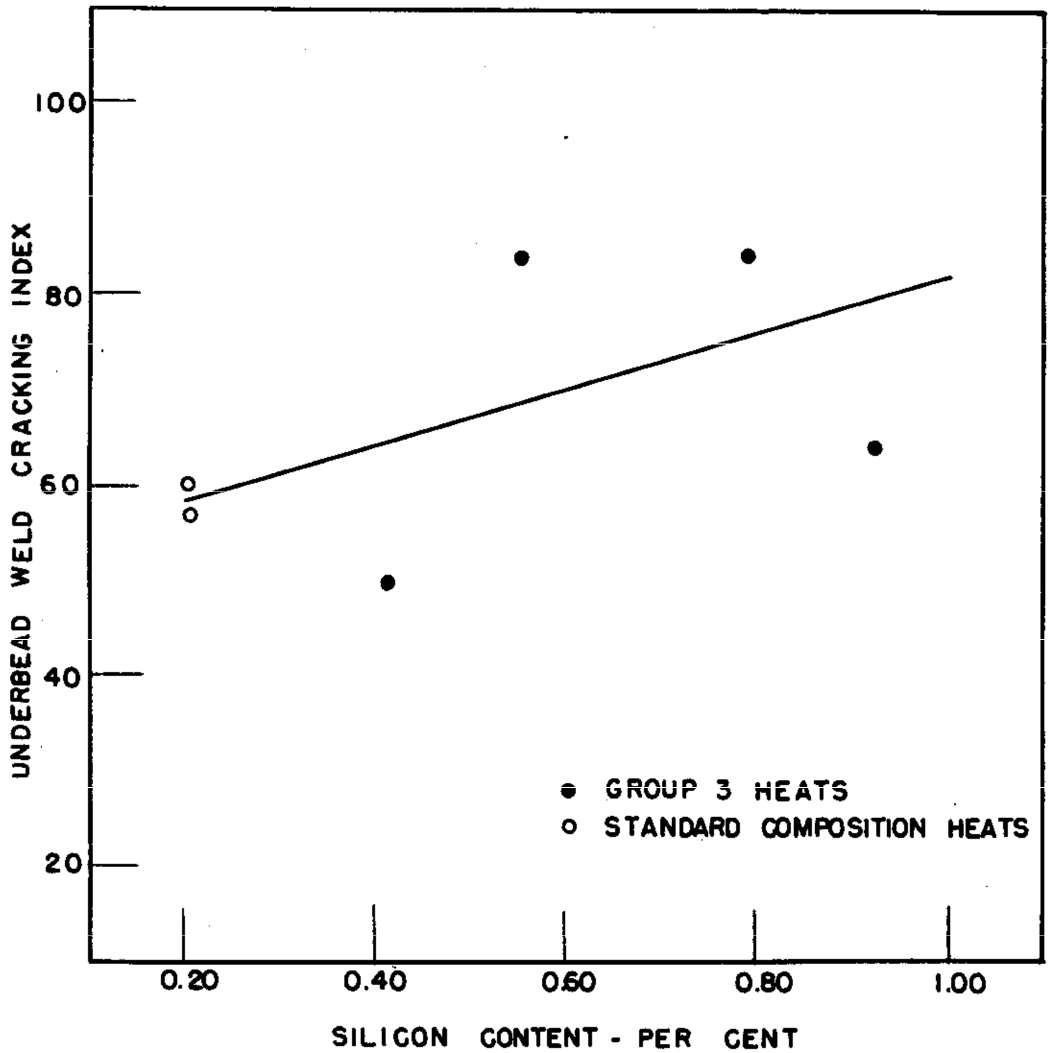


FIGURE 8. THE EFFECT OF SILICON CONTENT UPON THE UNDERBEAD WELD CRACK SENSITIVITY

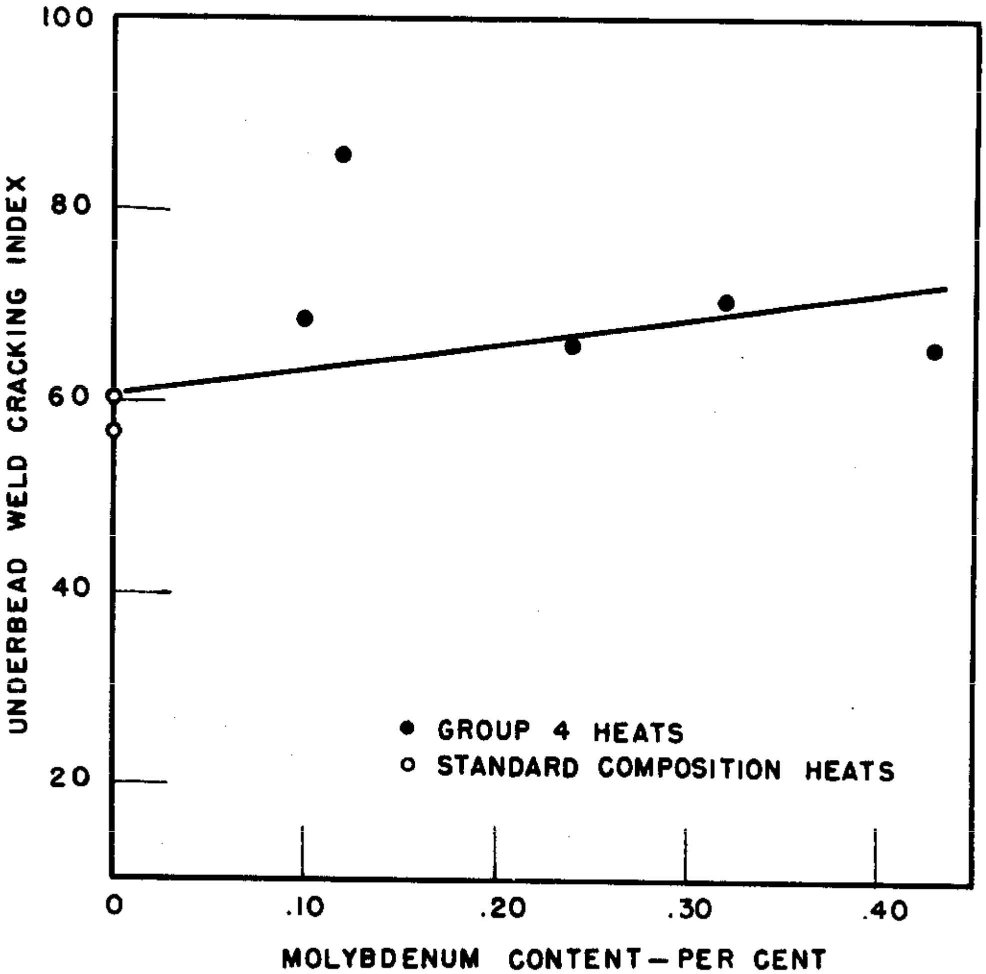


FIGURE 9. THE EFFECT OF MOLYBDENUM CONTENT UPON THE UNDERBEAD WELD CRACK SENSITIVITY

0-5420

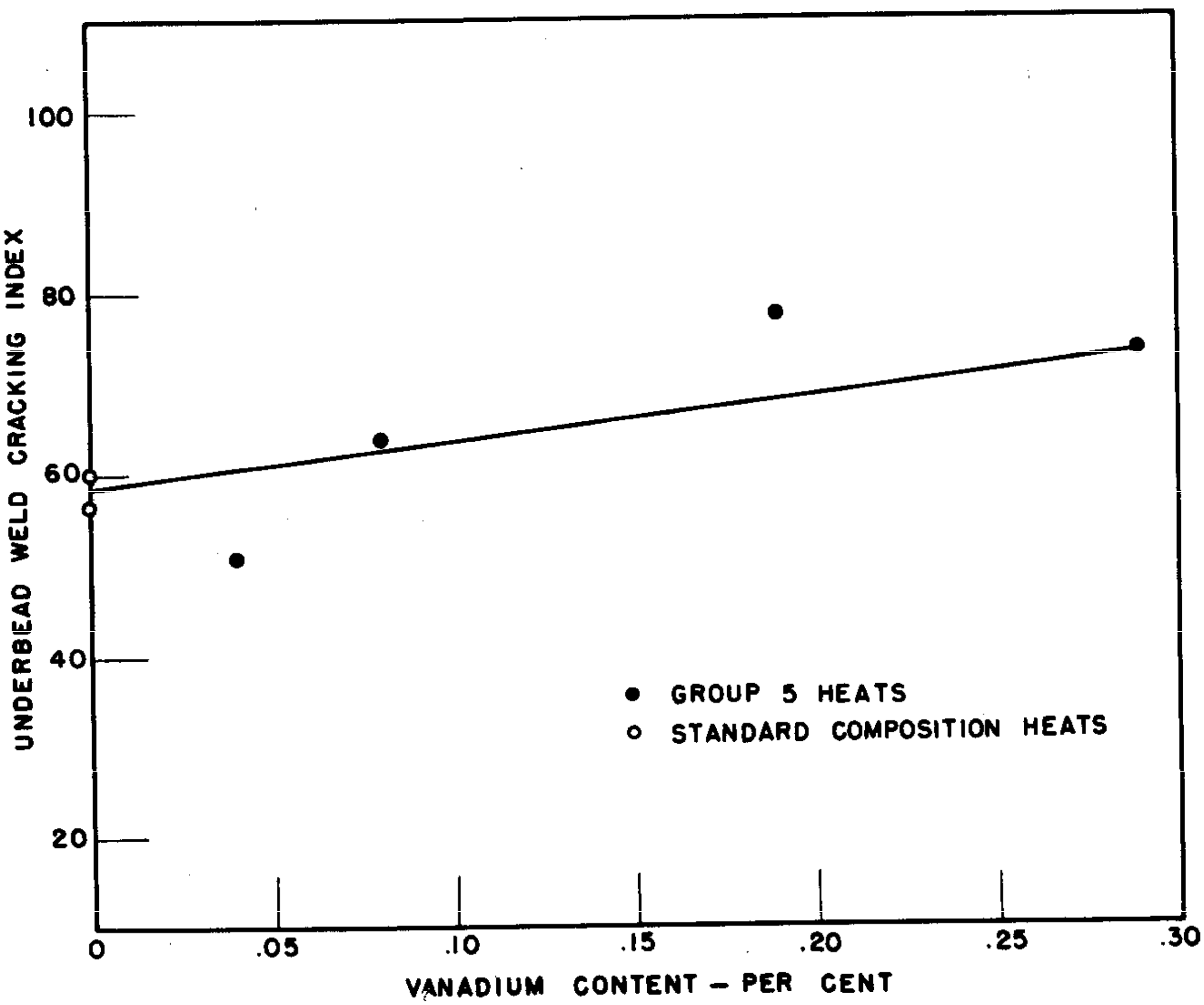


FIGURE 10. THE EFFECT OF VANADIUM CONTENT UPON THE UNDERBEAD WELD CRACK SENSITIVITY

O-5421

The data showing the influence of aluminum content upon the crack sensitivity of the six heats made in this investigation are shown in Figure 11. These data indicate that the extent of underbead cracking is extremely low in the steel made with no aluminum addition and increased very rapidly as the aluminum was added, the maximum cracking occurring in the neighborhood of .01 per cent aluminum and progressively decreasing with additional aluminum.

Since the reasons for the apparent marked influence of aluminum content are not obvious at this time, and as the above results were unexpected and based on relatively few data, it will be necessary to obtain additional data to confirm or refute these results.

Notched-Bar Impact Properties

In order to determine the effect of chemical composition upon the notched-bar impact properties, four duplicate specimens were broken from each of the 30 experimental heats at five different temperatures ranging from -75°F. to 210°F. The standard Charpy test specimen was used with the V-type Izod notch cut parallel with the plate surface. Only longitudinal tests were made, the length of the test specimen being the direction of rolling.

The results of these tests are shown graphically in Figures 12 to 32, inclusive, and the data from which these figures were constructed are listed in Table 3 of Appendix A.

The Effect of Carbon Content. A comparison of Figures 12 to 14, inclusive, reveals that as the carbon content is raised, the notched-bar impact strength drops rapidly. This is well illustrated in Figure 27 which shows the impact strength at +75°F. for a carbon range of 0.17 per cent to 0.32 per cent.

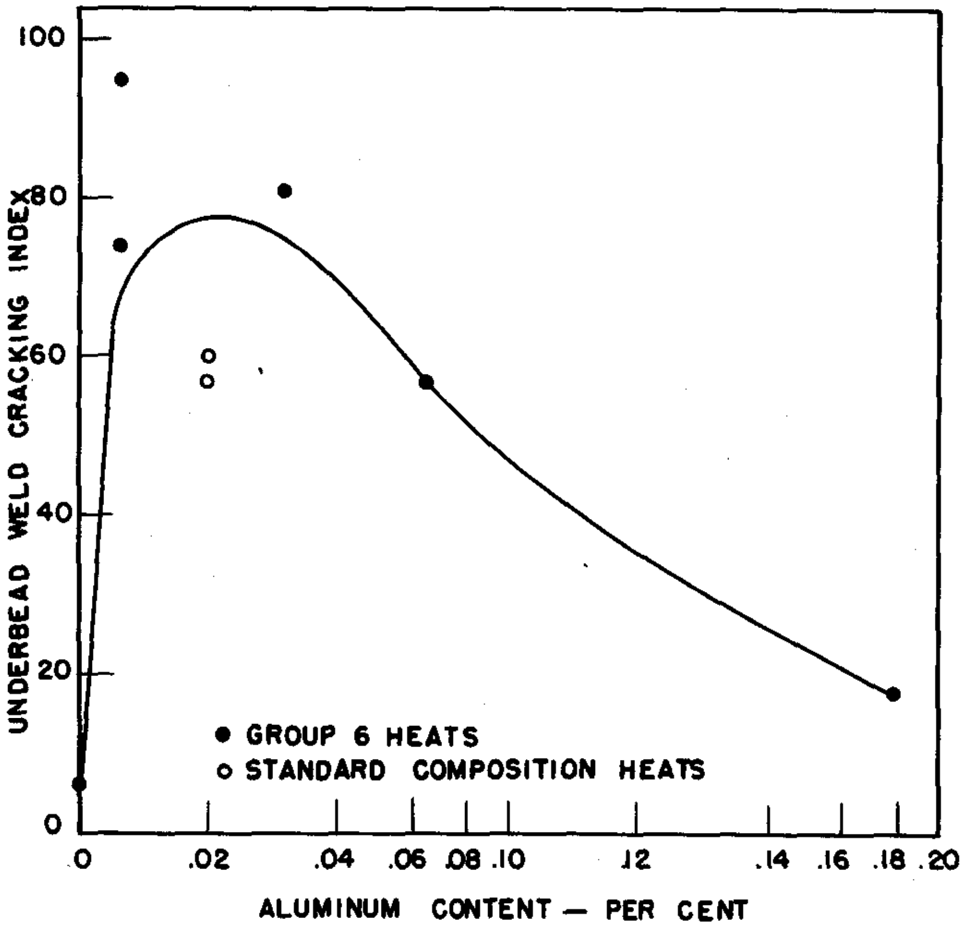


FIGURE 11. THE EFFECT OF ALUMINUM CONTENT UPON THE UNDERBEAD WELD CRACK SENSITIVITY

O-5422

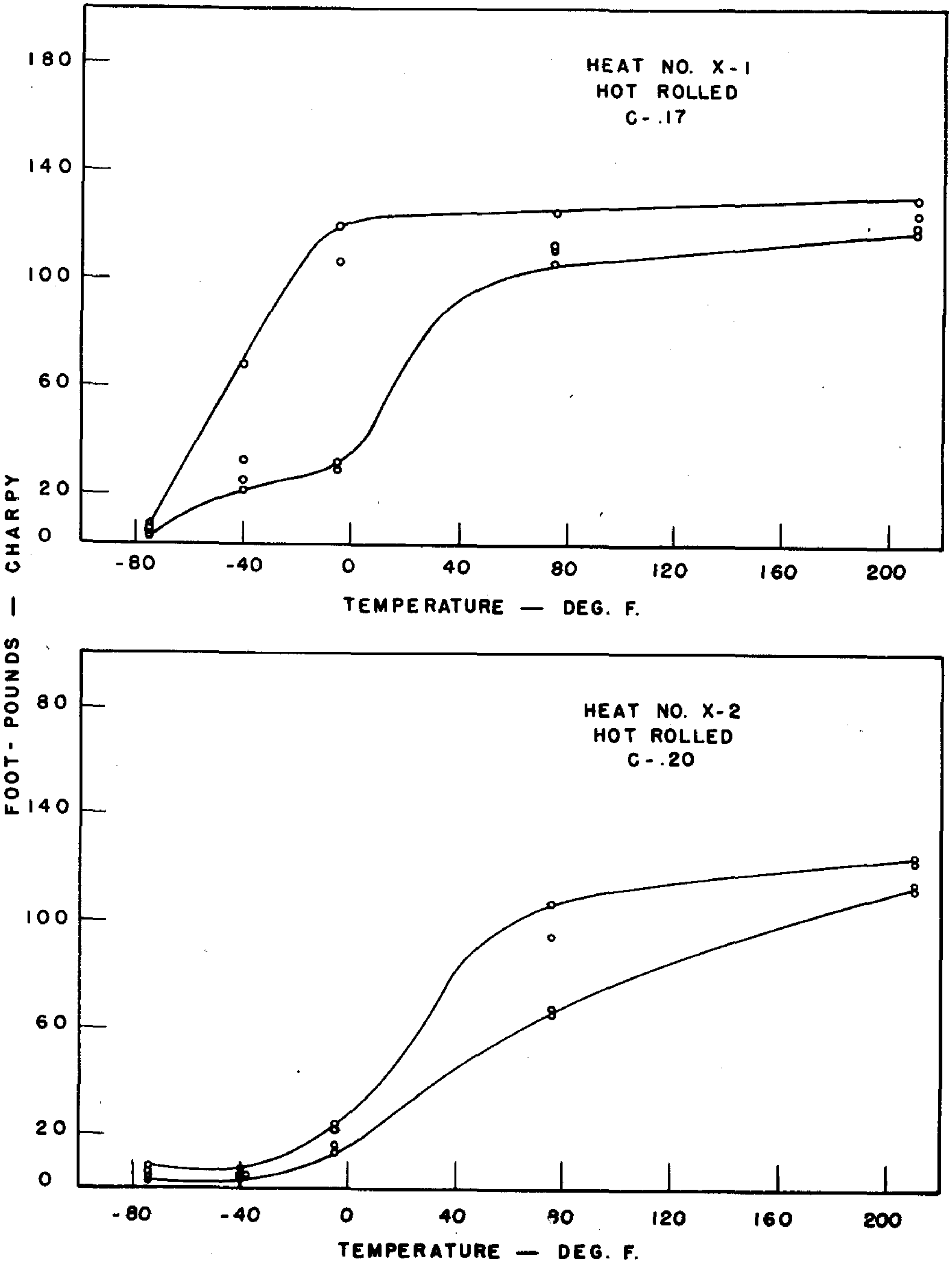


FIGURE 12. NOTCH-BAR IMPACT PROPERTIES

O-5423

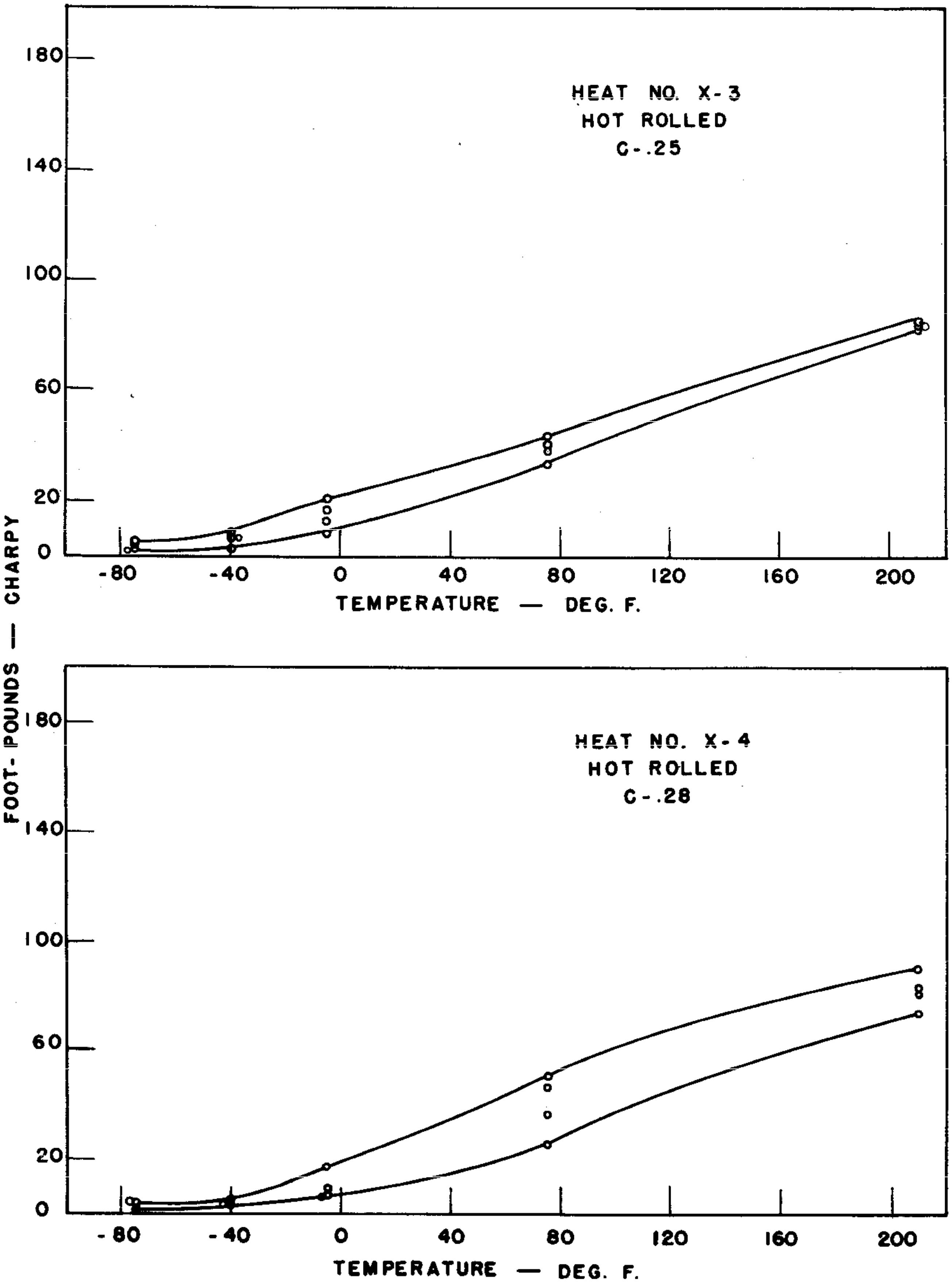


FIGURE 13. NOTCH-BAR IMPACT PROPERTIES

0-5424

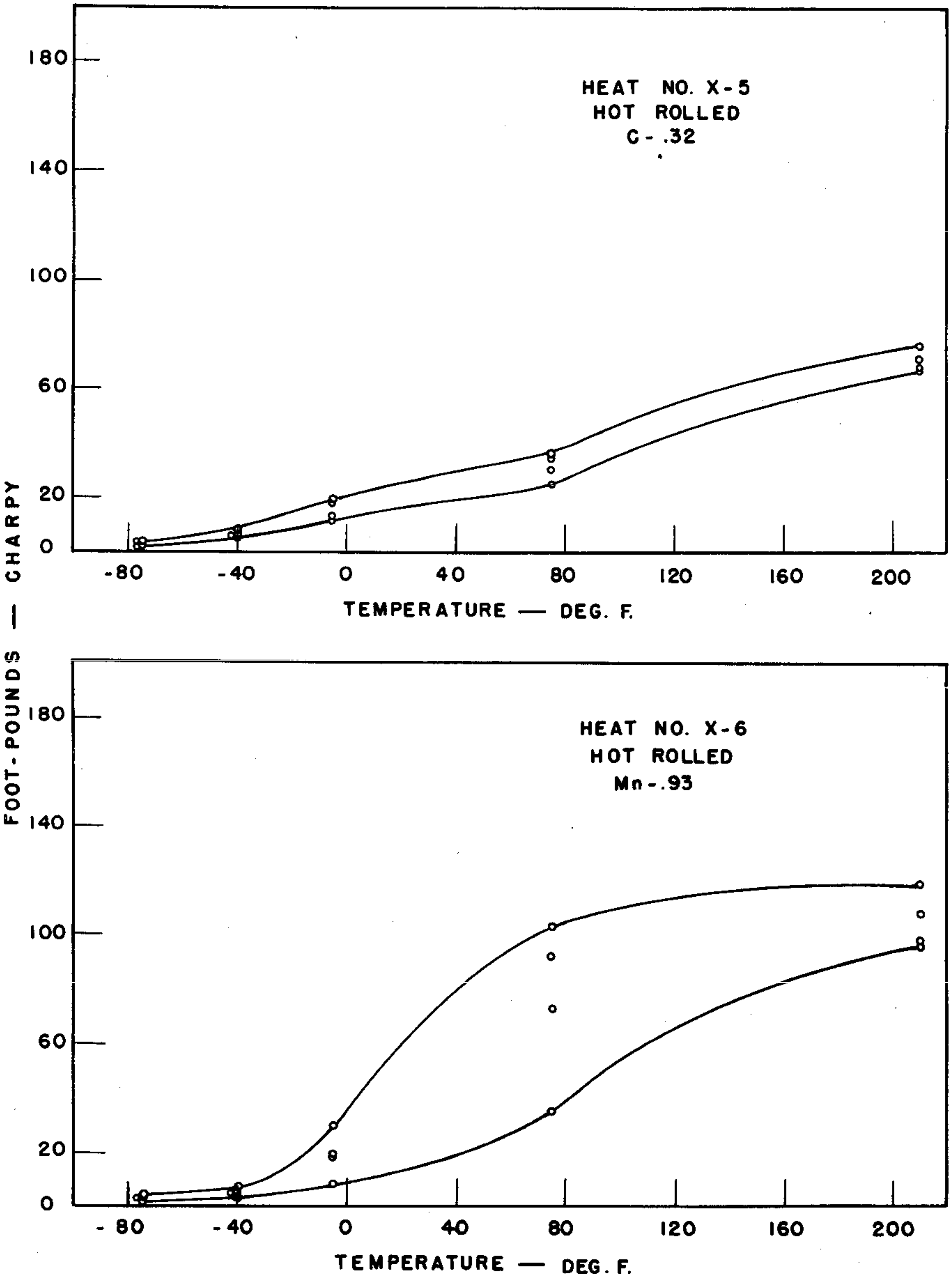


FIGURE 14 . NOTCH - BAR IMPACT PROPERTIES

0-5425

Effect of Manganese Content. In the range investigated, 0.93 to 1.51 per cent, it was found that the manganese content had little if any influence upon the notched-bar impact strength. (See Figures 14 to 16, inclusive.)

Figure 28 shows the impact strength at room temperature plotted against the manganese content. While these data might be interpreted as indicating that an intermediate manganese content was advantageous, it appears that this indication is only incidental as similar conditions are not noted at lower or higher temperatures.

Effect of Silicon Content. At room temperature and lower, the notched-bar impact strength falls off rapidly as the silicon content is increased. (See Figures 16 to 18, inclusive.) This effect of silicon content at room temperature is illustrated in Figure 29.

At a temperature of 10°F., the silicon content has no appreciable effect upon the impact strength.

Effect of Molybdenum Content. While the addition of 0.10 per cent molybdenum lowered to some extent the notched-bar impact strength when tested at 75°F., increased contents up to 0.32 per cent had no further effects. The indications were, however, that as the molybdenum content was raised to about 0.40 per cent, the impact strength dropped to a marked extent.

The influence of molybdenum content upon the impact strength at 75°F. is shown in Figure 30. The data for the entire range of temperatures and compositions studied are shown in Figures 18 to 20, inclusive.

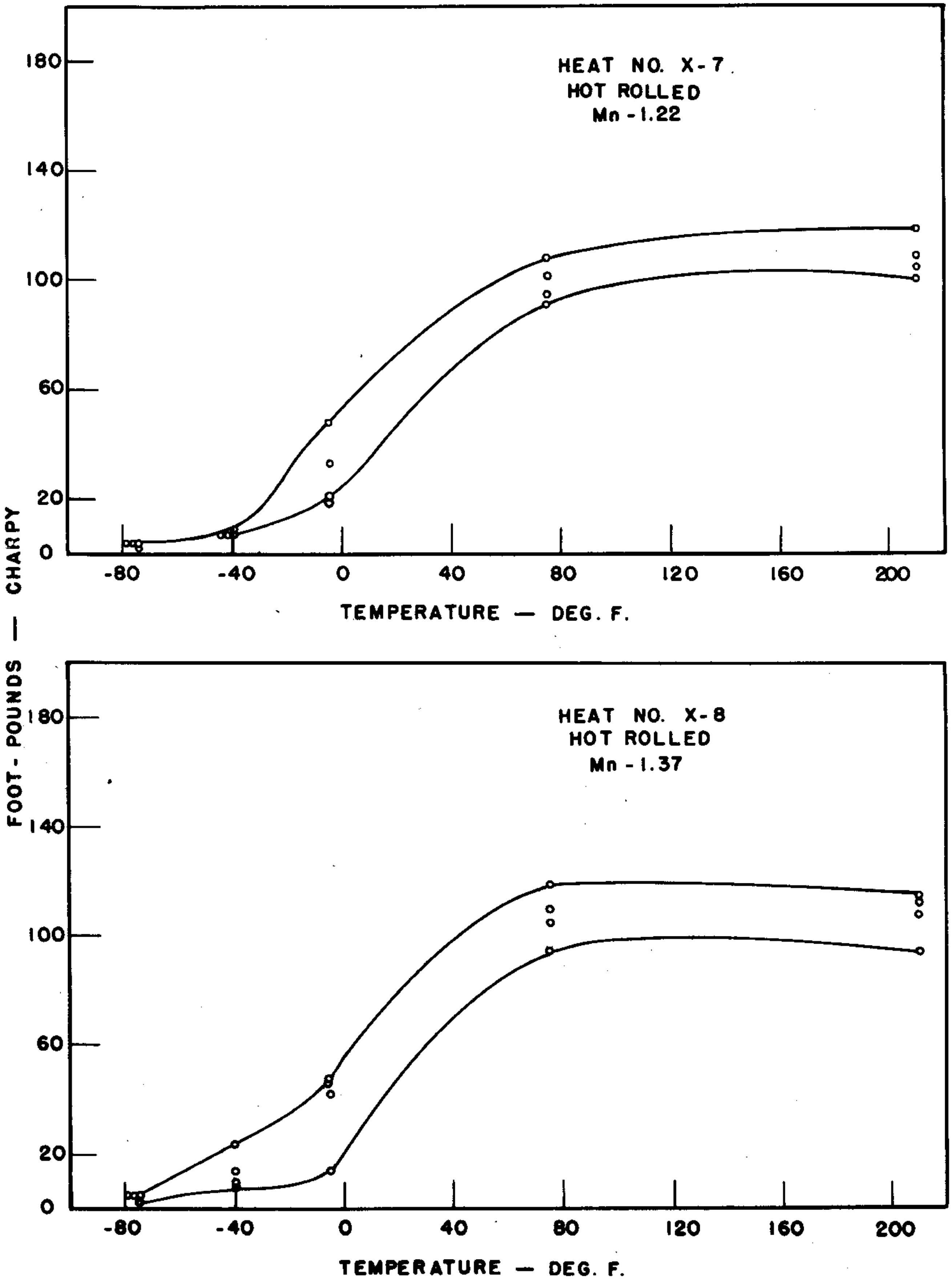


FIGURE 15. NOTCH-BAR IMPACT PROPERTIES

O-5426

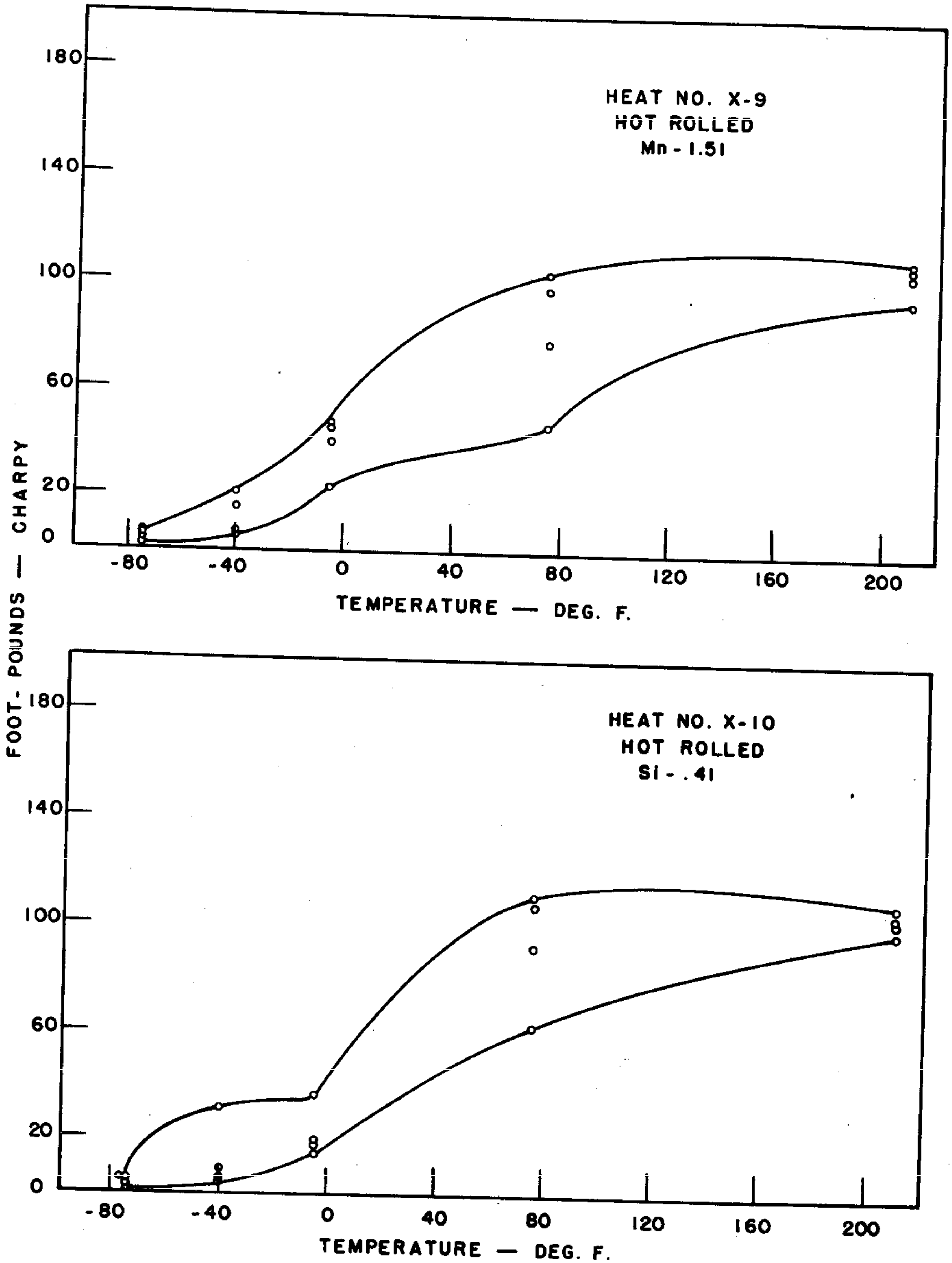


FIGURE 16. NOTCH - BAR IMPACT PROPERTIES

0-5427

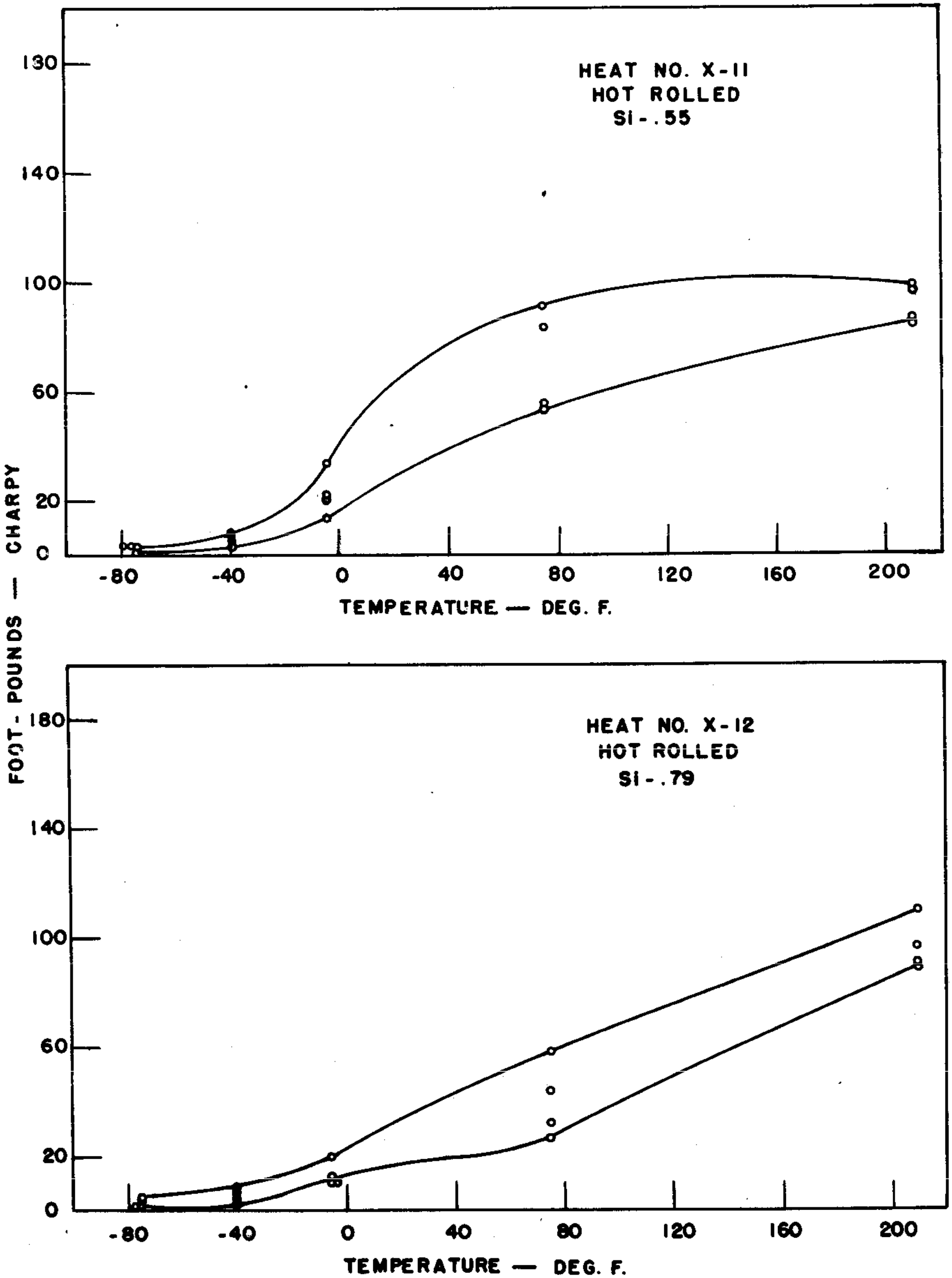


FIGURE 17. NOTCH - BAR IMPACT PROPERTIES

0-5428

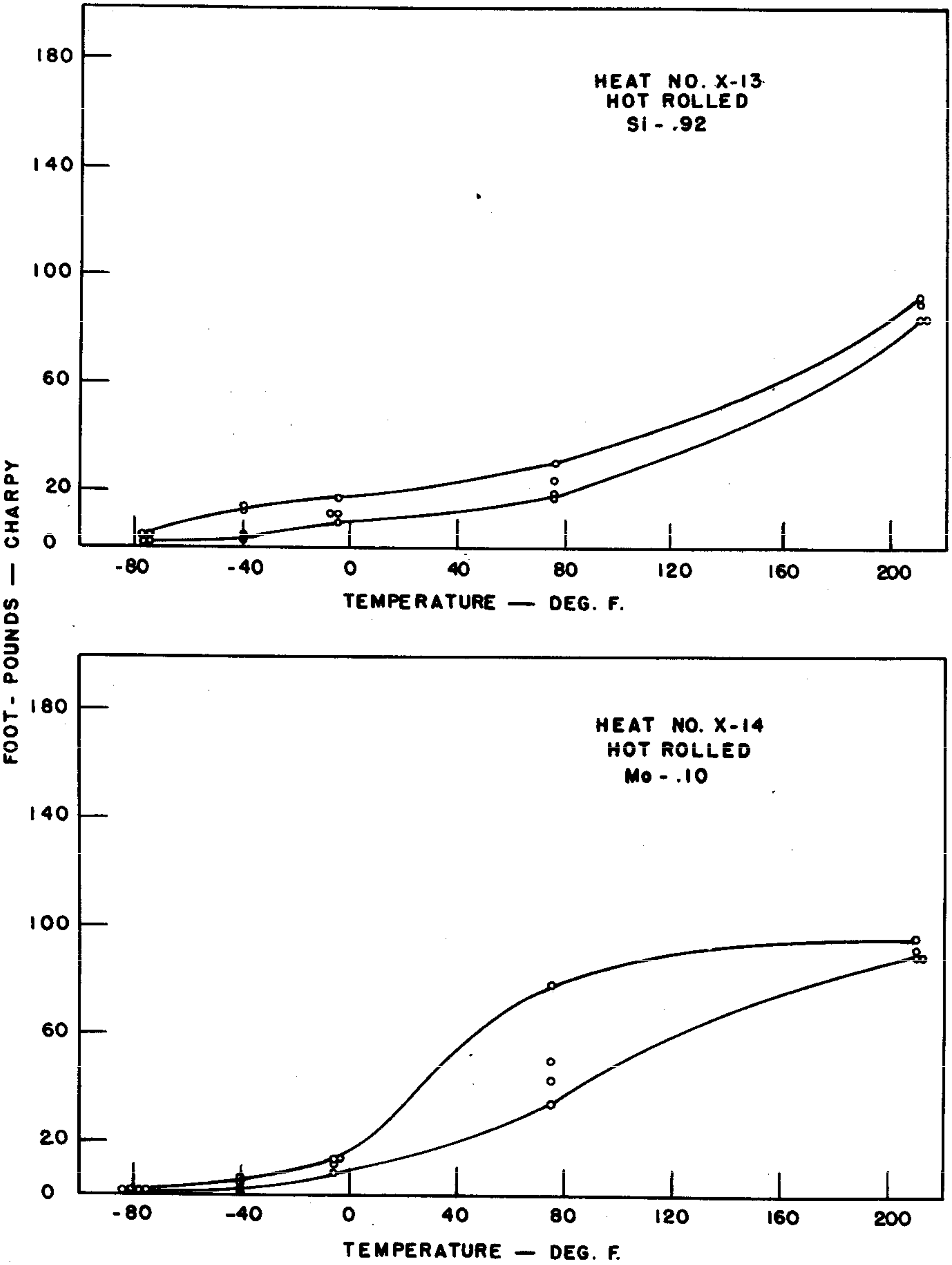


FIGURE 18 NOTCH - BAR IMPACT PROPERTIES

0-5429

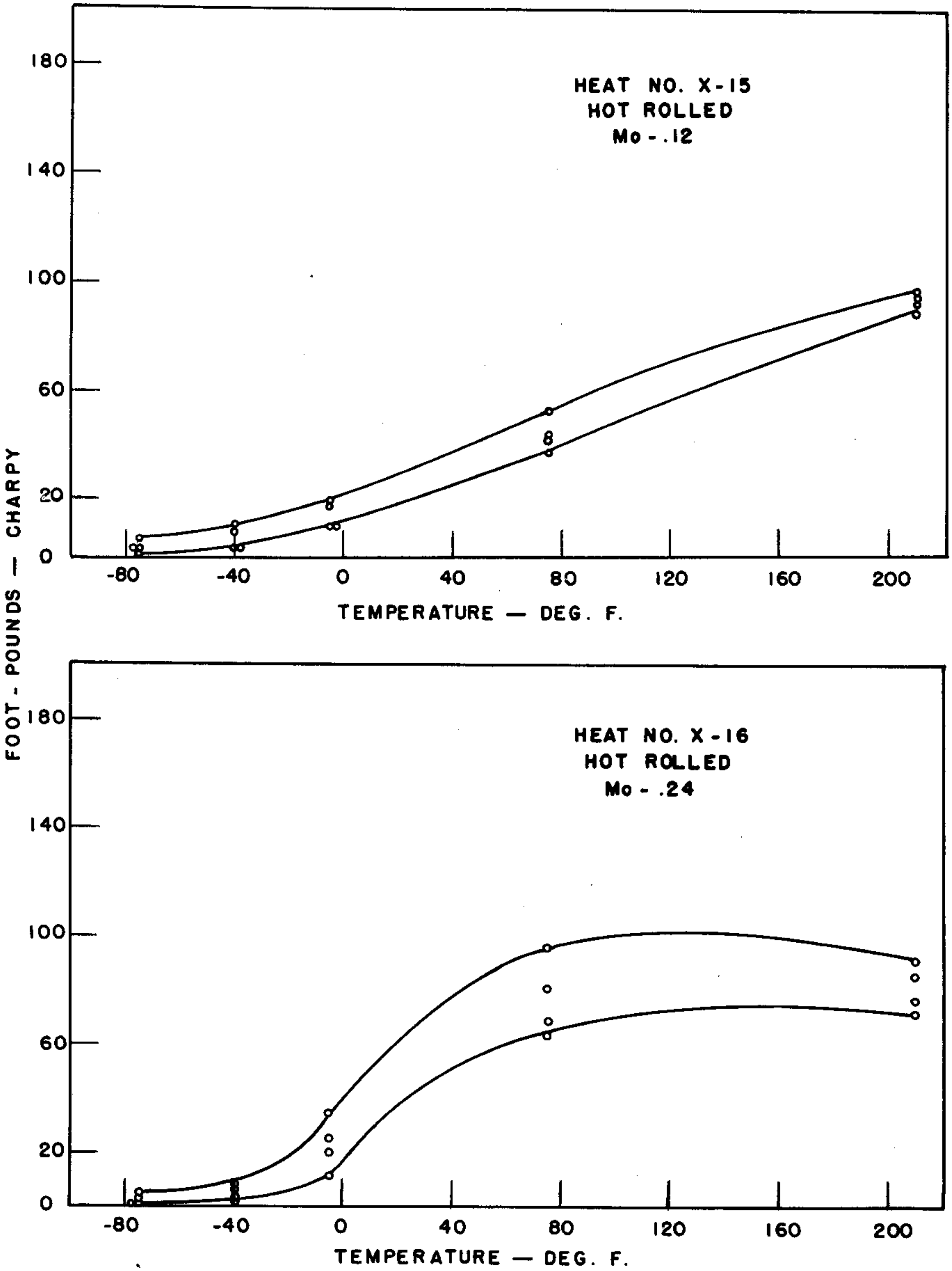


FIGURE 19 . NOTCH - BAR IMPACT PROPERTIES

0-5430

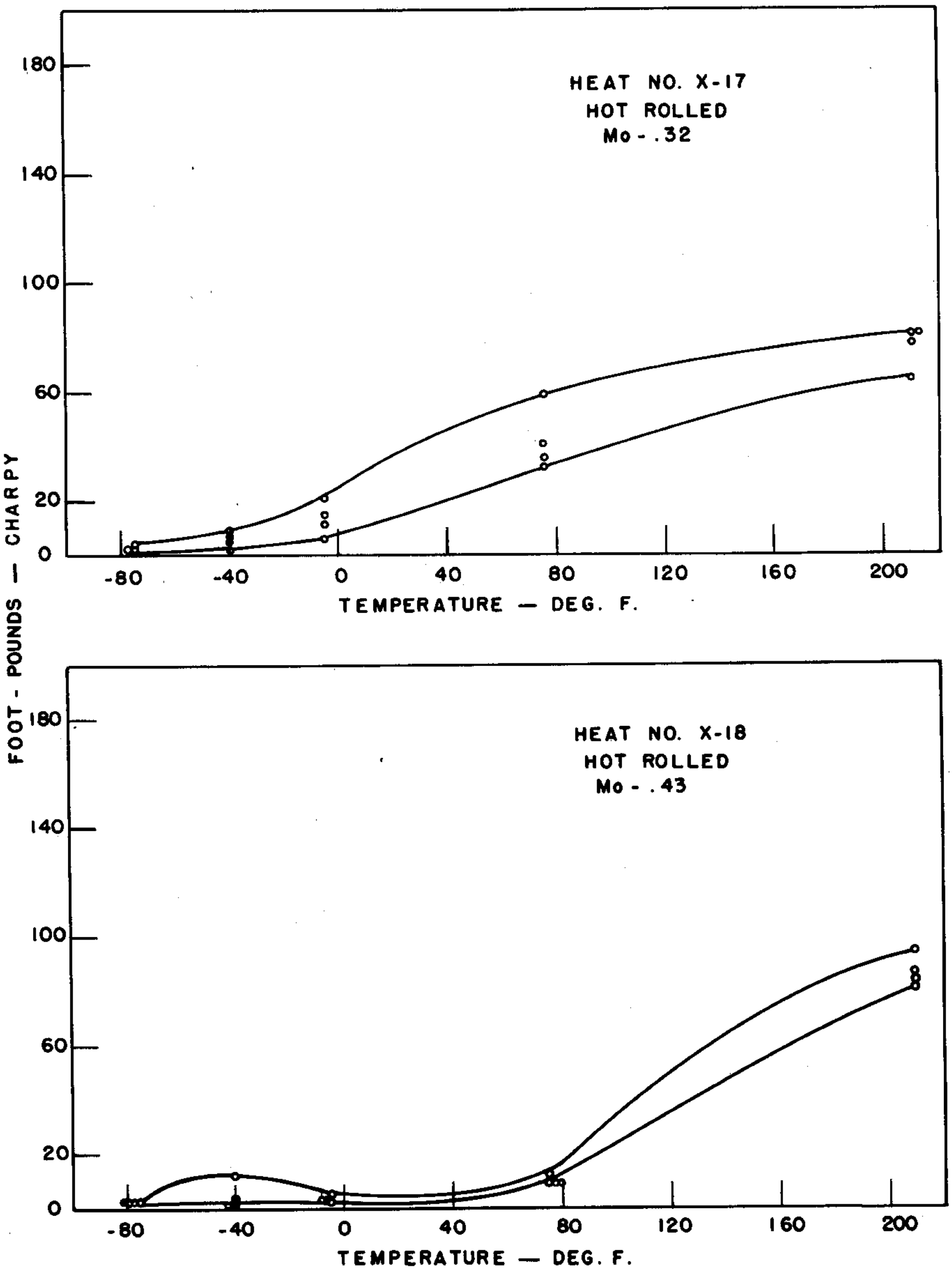


FIGURE 20. NOTCH - BAR IMPACT PROPERTIES

0-5431

Effect of Vanadium Content. The effect of vanadium content upon the notched-bar impact strength at 75°F. is shown in Figure 31. From this figure it will be seen that the impact strength decreases as the vanadium content is increased. This would be expected in view of the marked increase in yield strength.

The effect of temperature upon the impact strength of the four vanadium-bearing steels is shown in Figures 21 and 22.

Effect of Aluminum Content. The aluminum content was found to influence the notched-bar impact strength in the expected manner, that is, the impact strength especially at low temperatures increased as the aluminum content (acid soluble) was increased until a maximum was reached, after which the impact strength declined with further addition of aluminum. The aluminum content is known to affect other properties such as grain-coarsening temperature and hardenability in a similar manner.

The influence of aluminum content upon the notched-bar impact strength at -40°F. is illustrated in Figure 32. The complete data covering the entire temperature range studied are shown in Figures 23 to 25, inclusive.

Standard-Composition Heats. The notched-bar impact properties of the two standard chemical composition heats, X-45 and X-46, are shown in Figure 26. The curves for these two heats are in good agreement but do not duplicate the results for heats of similar composition, X-8 for example, as well as might be expected.

## A Discussion of the Significance of the Test Data

A study of the tensile properties, weld crack sensitivity, and the notched-bar impact properties of the thirty experimental heats

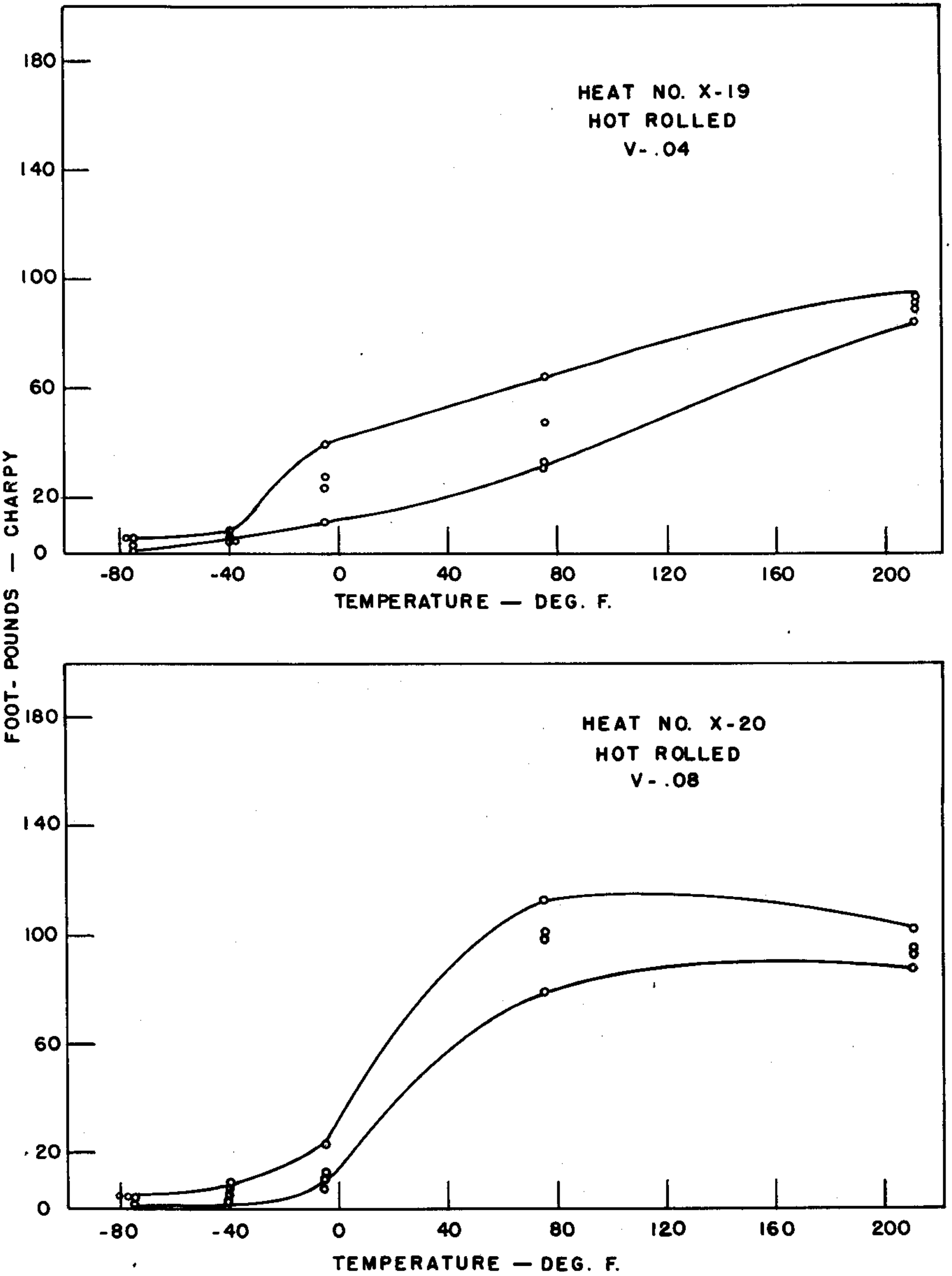


FIGURE 21. NOTCH-BAR IMPACT PROPERTIES

O-5432

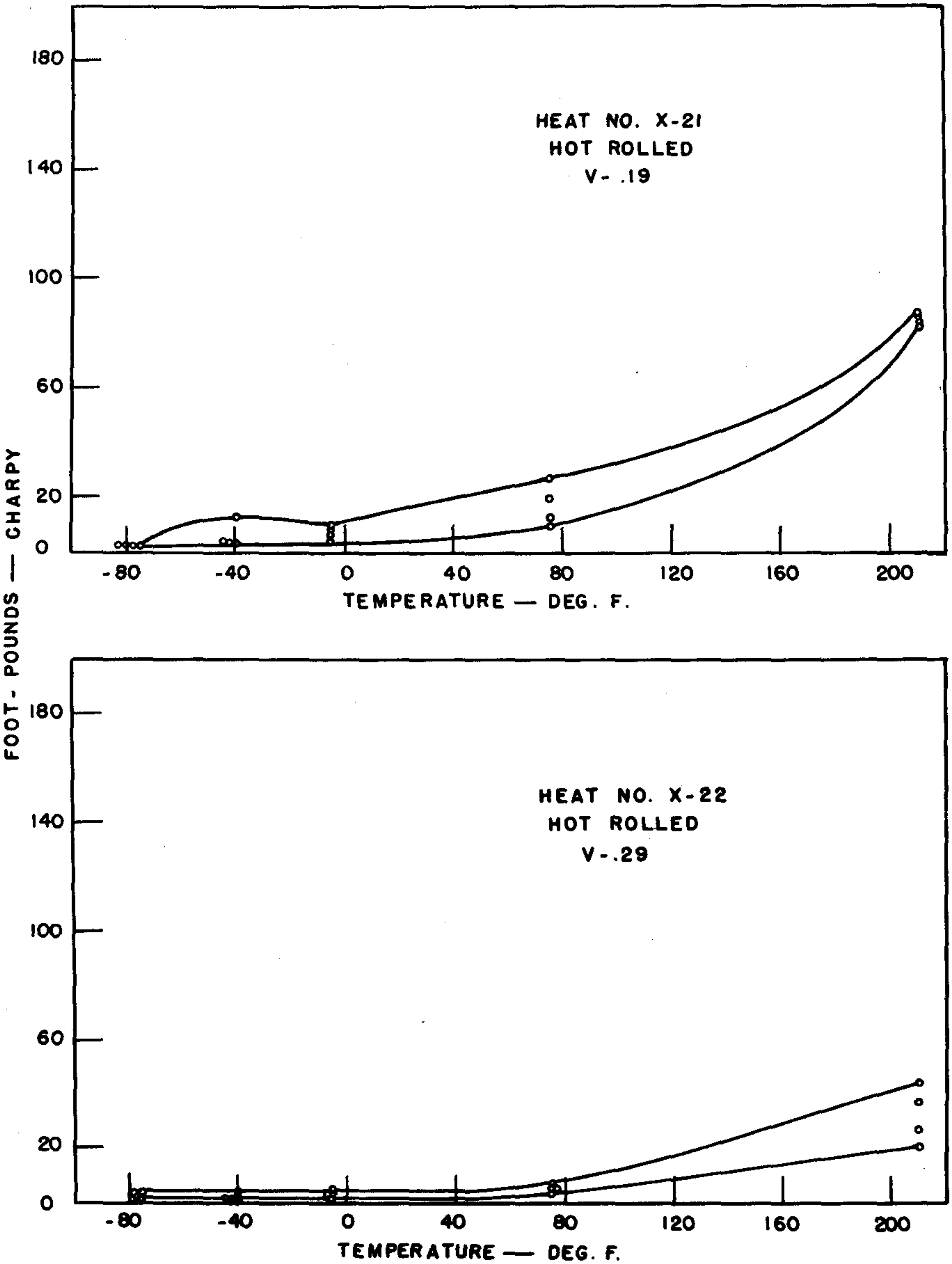


FIGURE 22 . NOTCH - BAR IMPACT PROPERTIES

0-5433

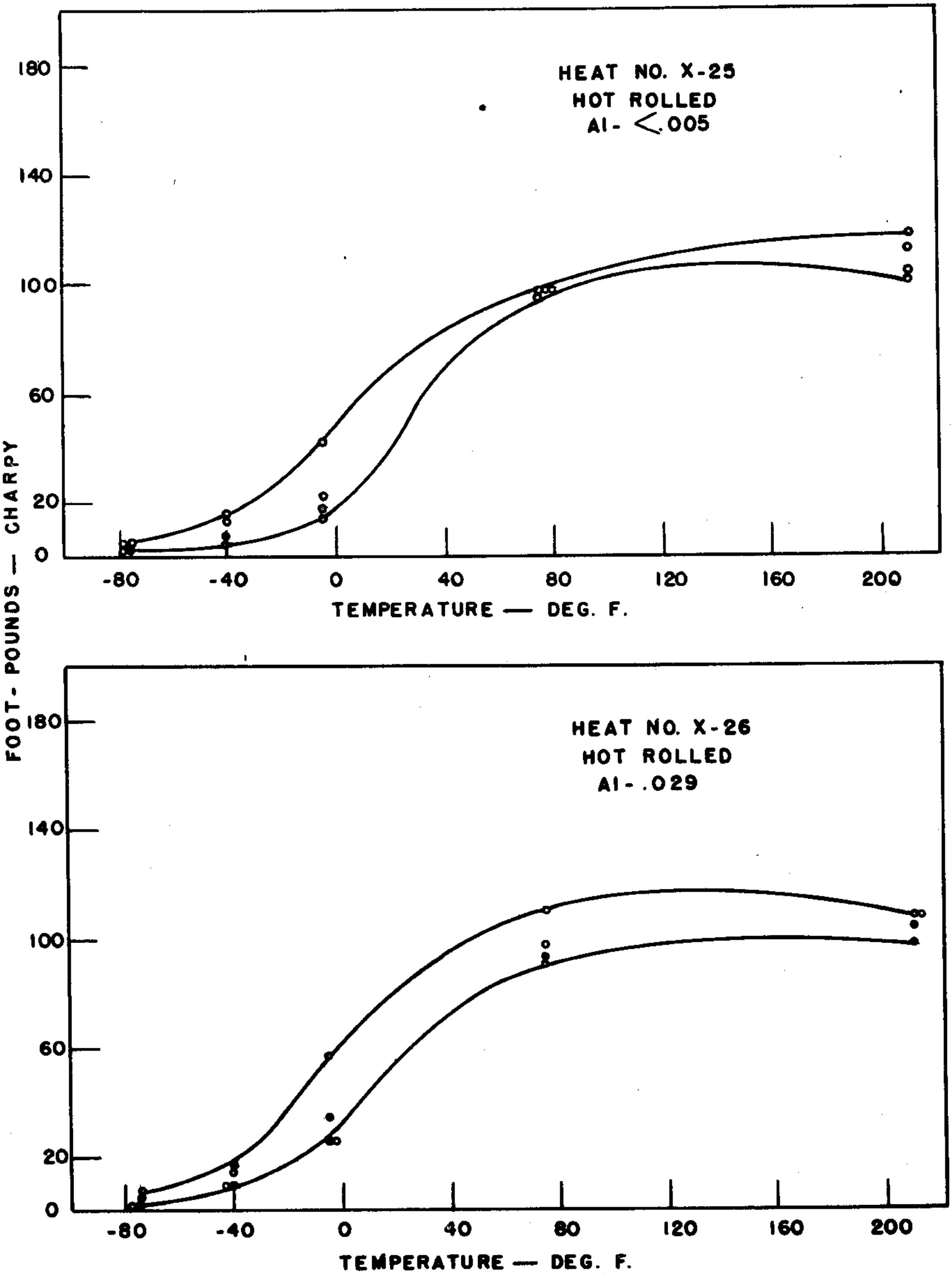


FIGURE 24. NOTCH-BAR IMPACT PROPERTIES

0-5435

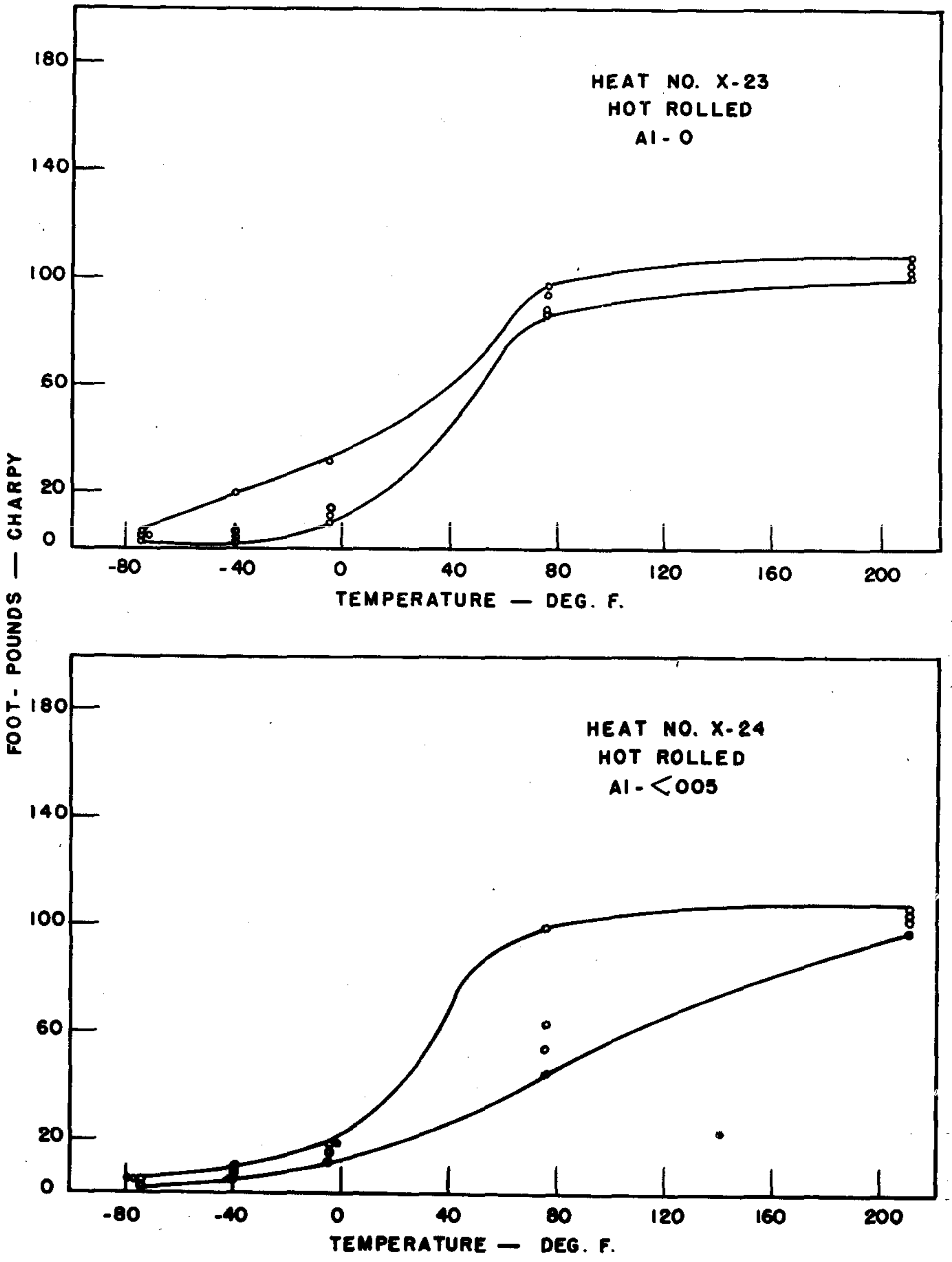


FIGURE 23. NOTCH - BAR IMPACT PROPERTIES

0-5434

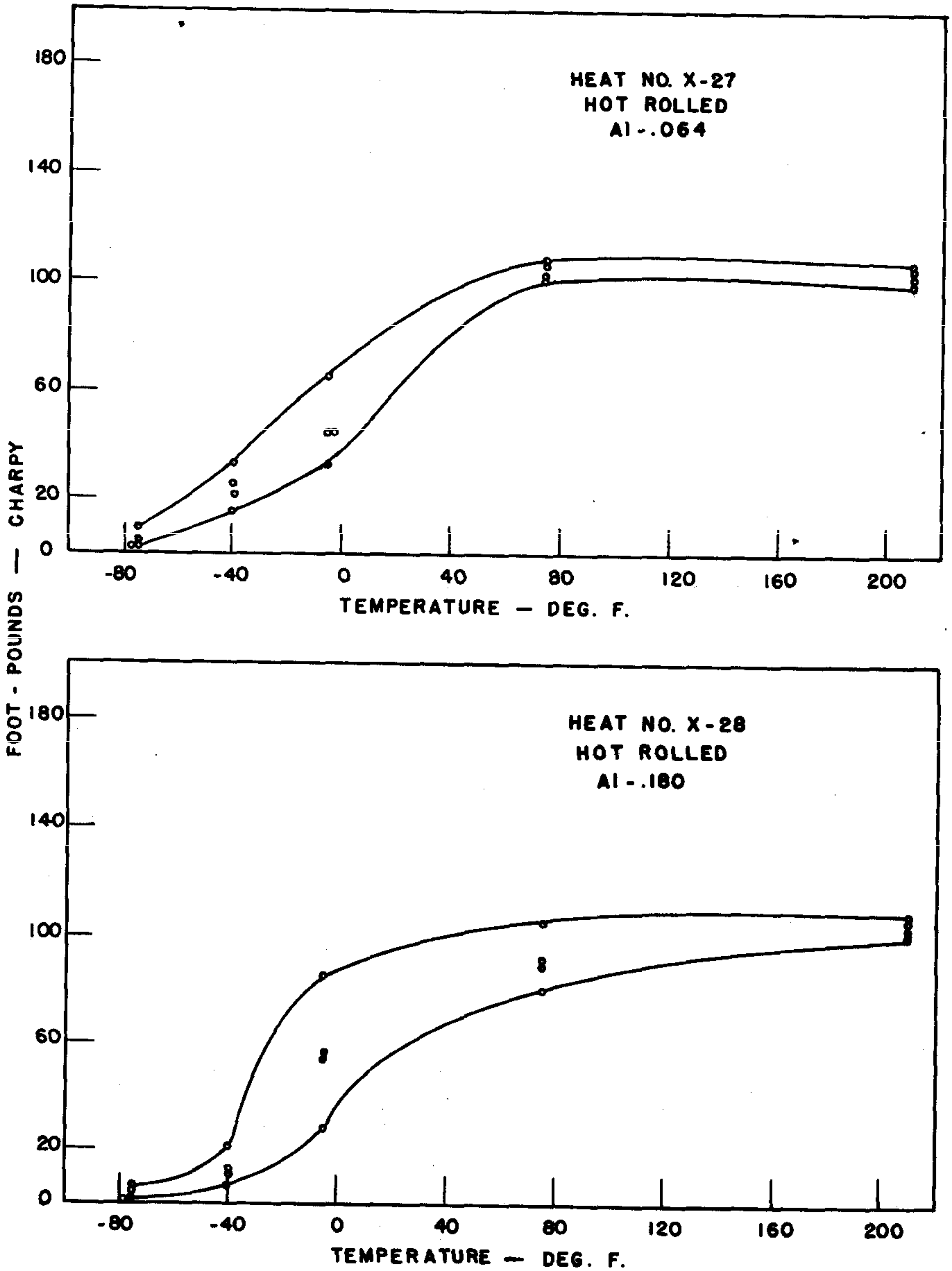


FIGURE 25 . NOTCH - BAR IMPACT PROPERTIES

0-5436

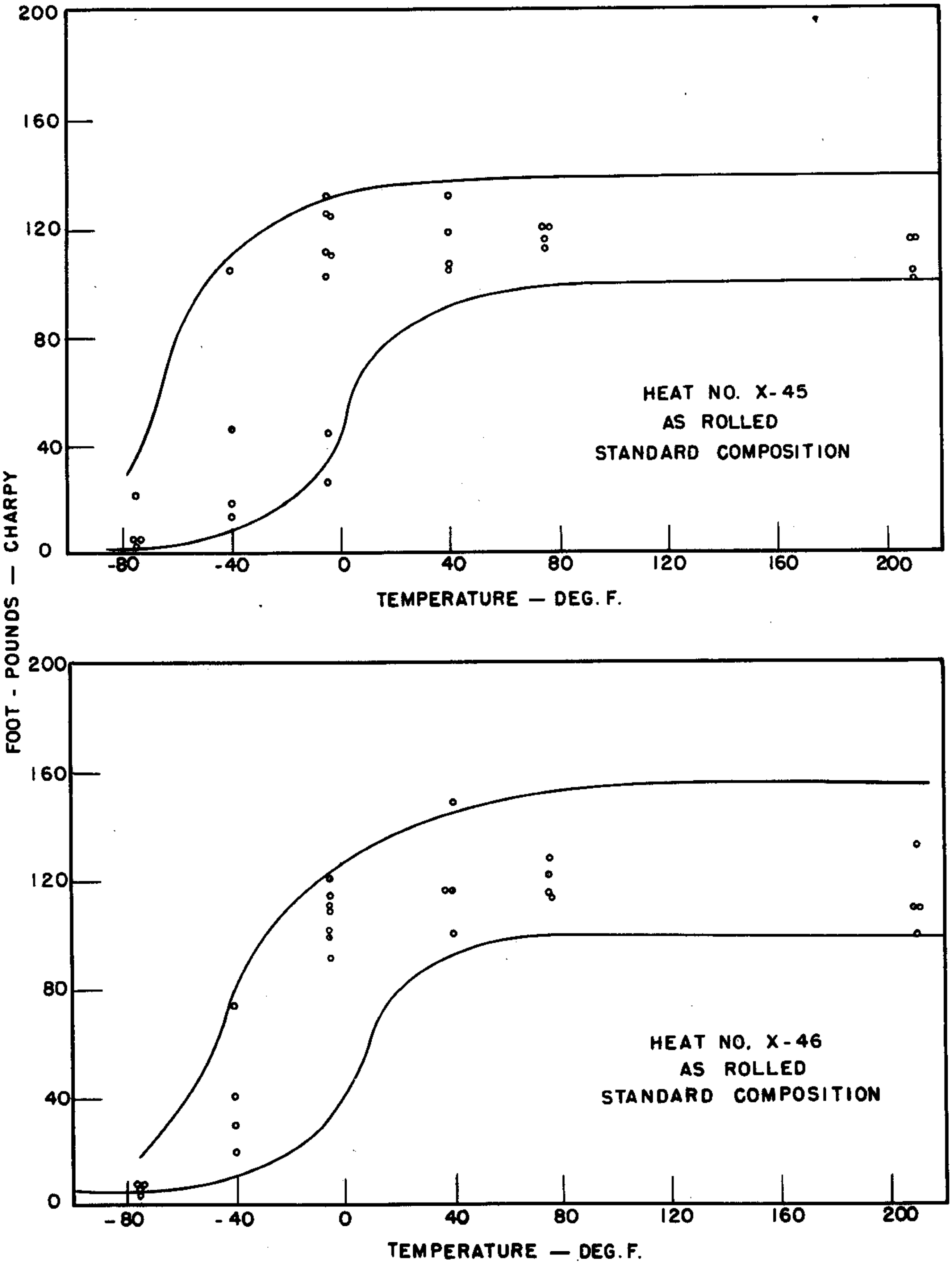


FIGURE 26. NOTCH-BAR IMPACT PROPERTIES

0-5437

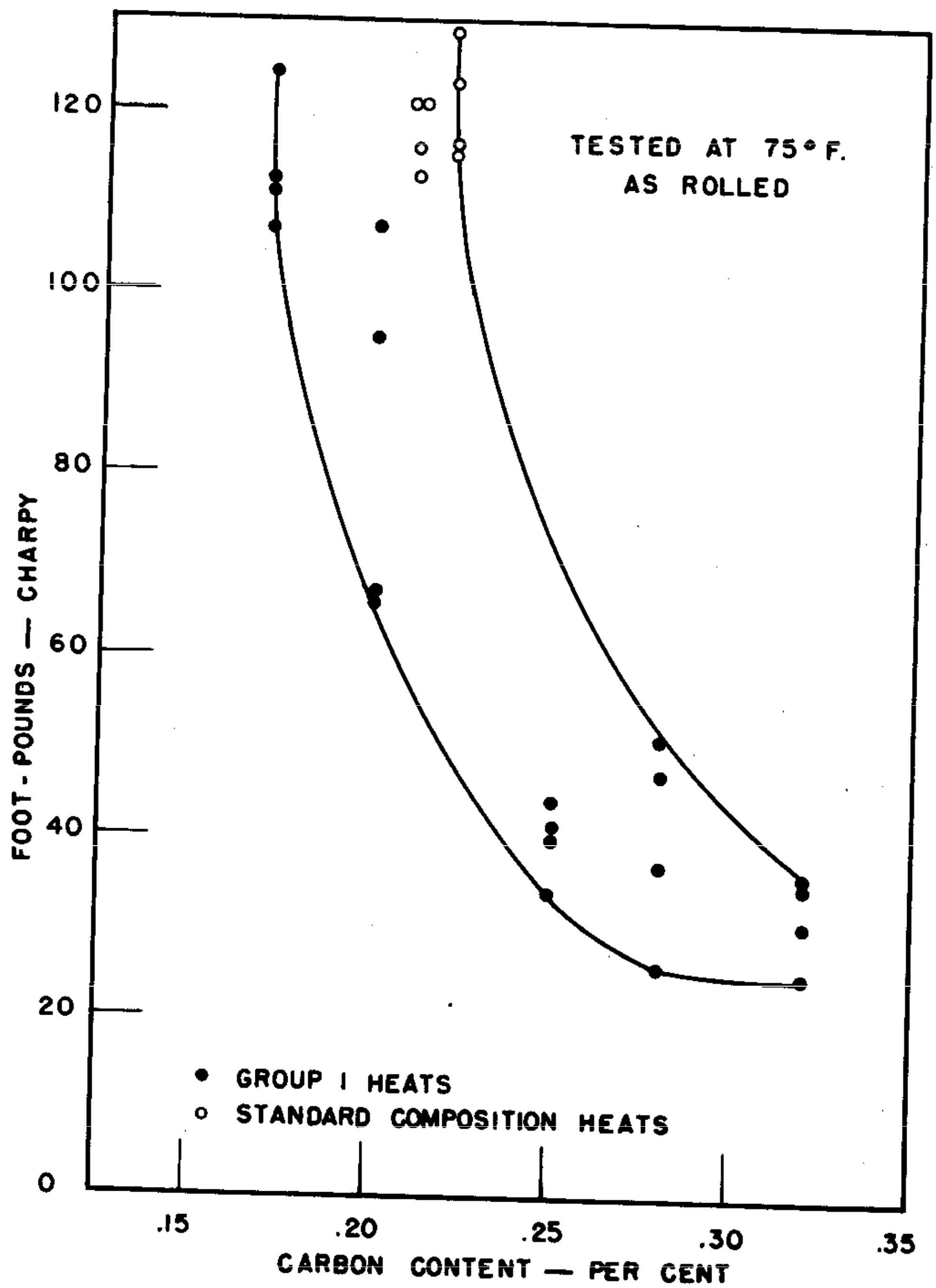


FIGURE 27. THE EFFECT OF CARBON CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5438

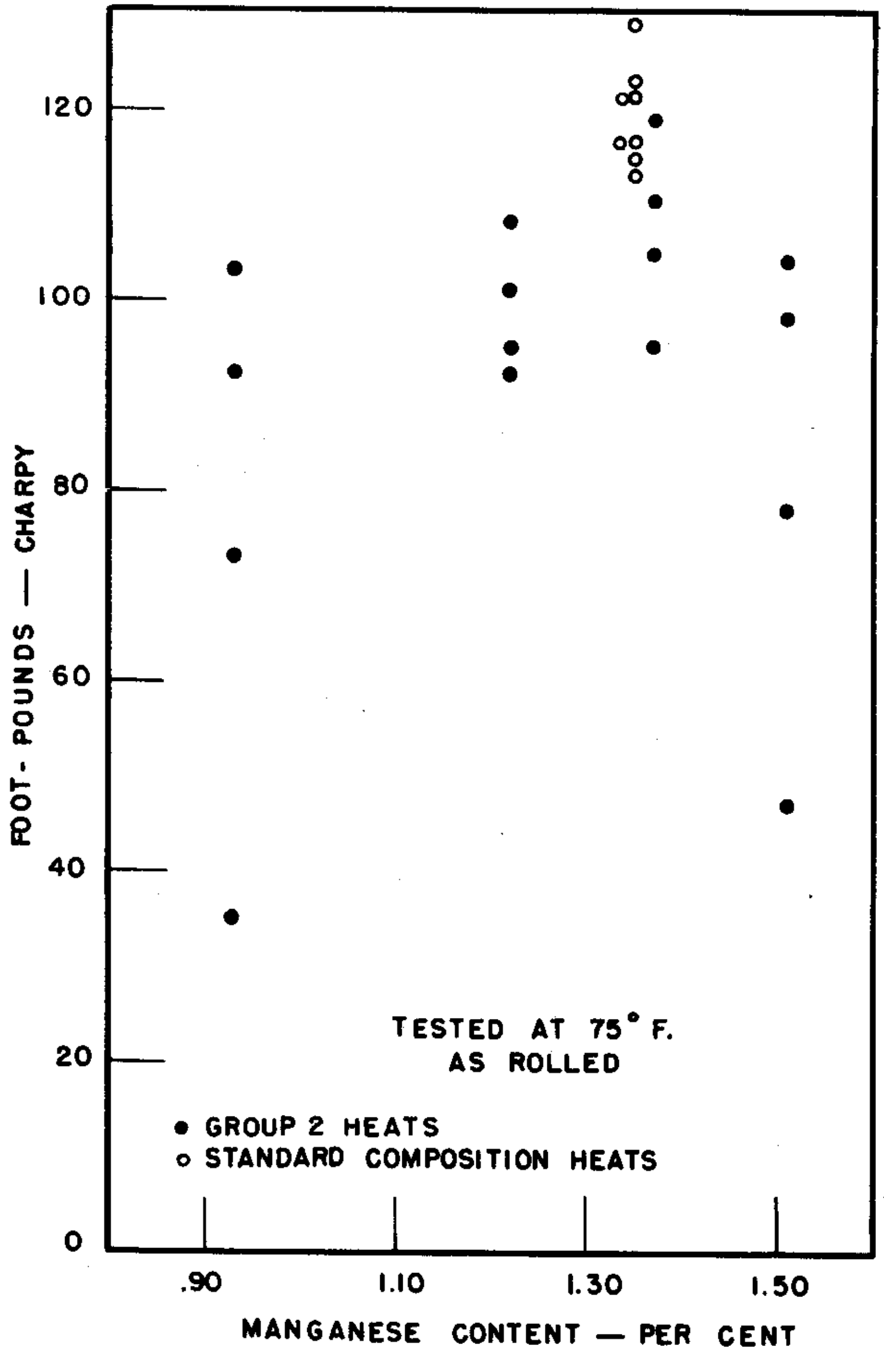


FIGURE 28. THE EFFECT OF MANGANESE CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5439

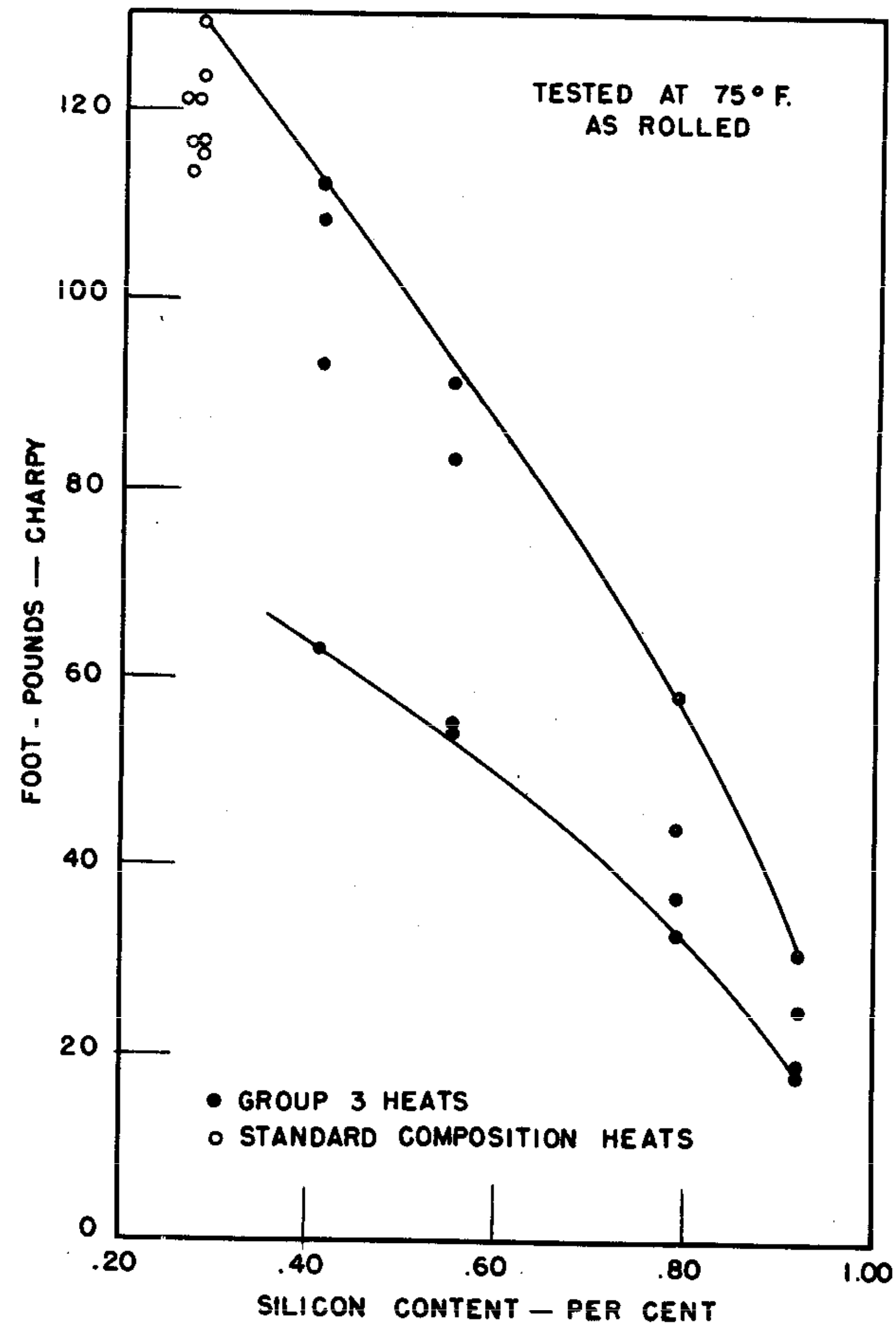


FIGURE 29. THE EFFECT OF SILICON CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

0-5440

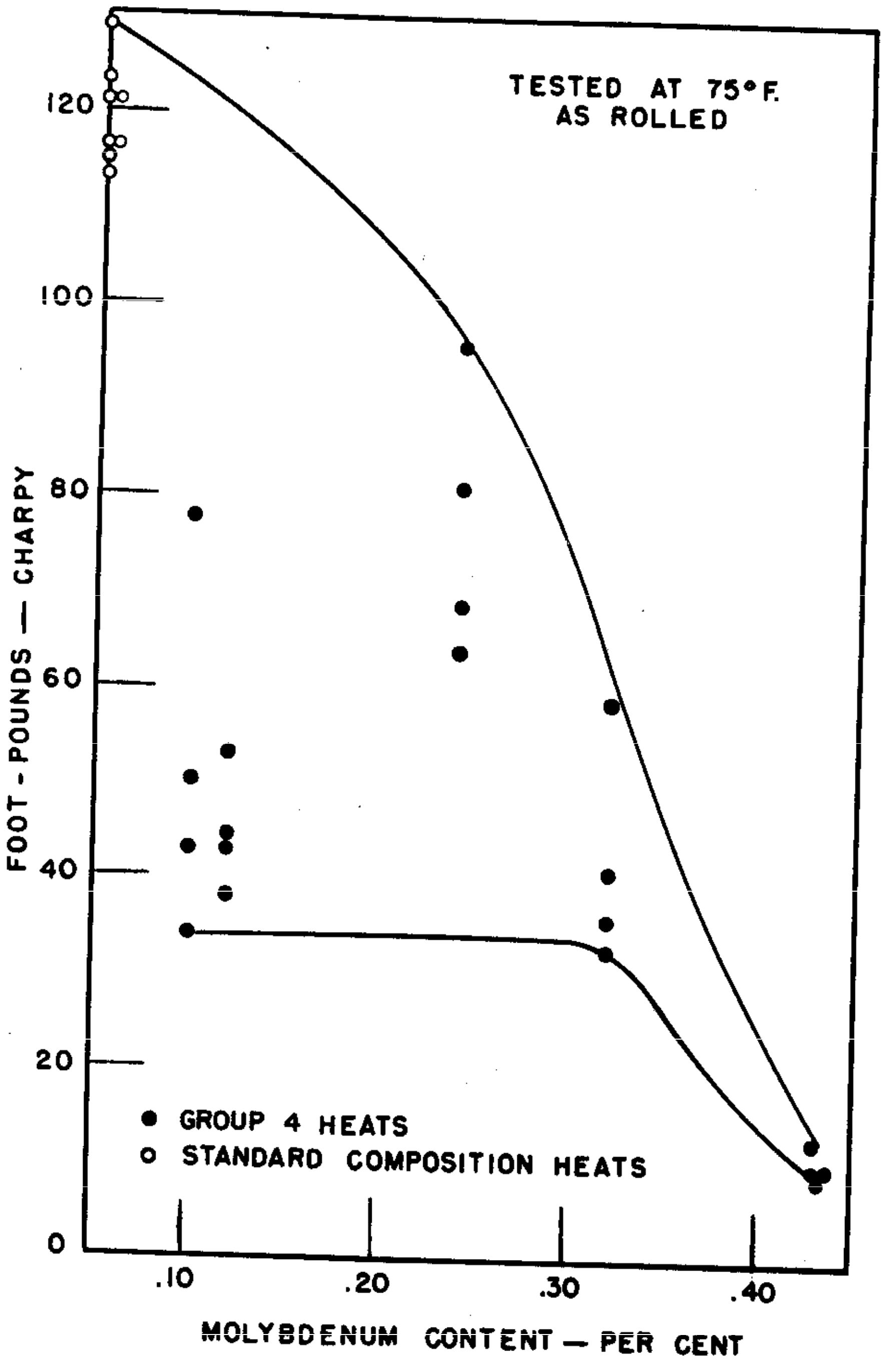


FIGURE 30. THE EFFECT OF MOLYBDENUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75°F.

O-5441

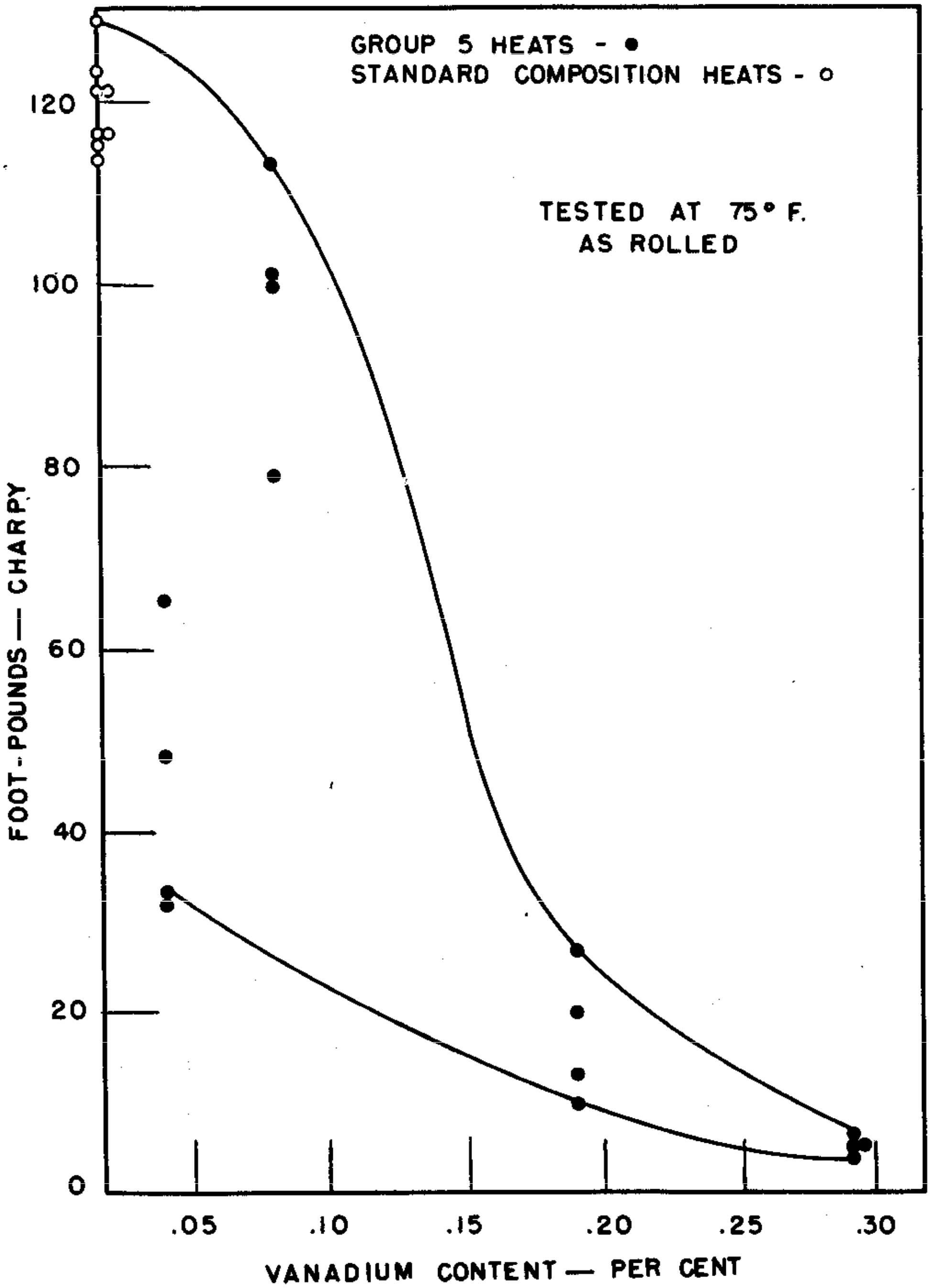


FIGURE 31. THE EFFECT OF VANADIUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT 75° F.

O-5442

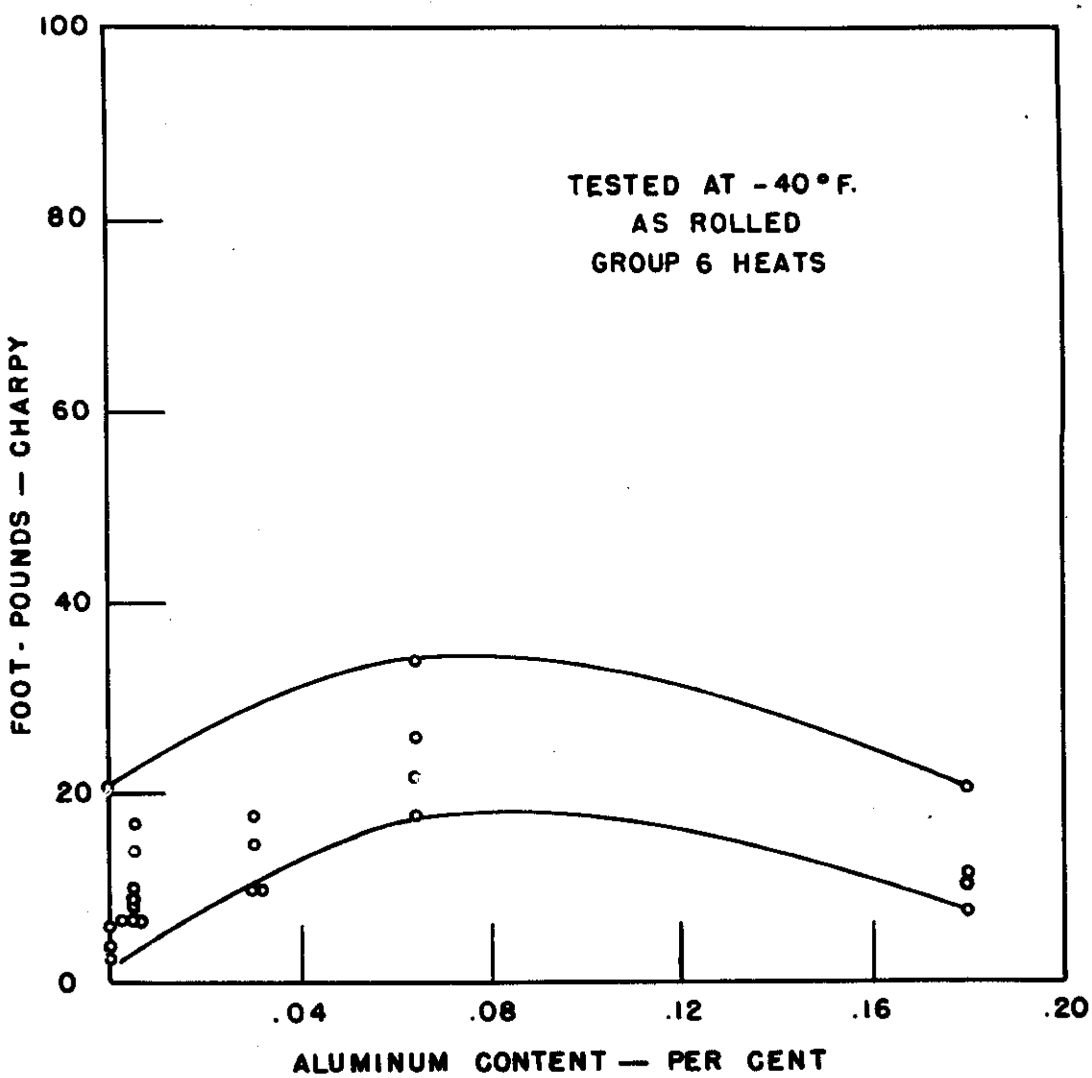


FIGURE 32. THE EFFECT OF ALUMINUM CONTENT UPON THE NOTCHED-BAR IMPACT STRENGTH AT -40°F.

0-5443

tested in the hot-rolled state reveals the limitations and possible advantages that might be obtained by varying the carbon, manganese, silicon, molybdenum, vanadium, and aluminum contents.

From this investigation, it is quite obvious that the carbon content is very definitely limited. Above this limiting value of about 0.15 to 0.20 per cent carbon, the crack sensitivity increases with marked rapidity which is entirely out of line with the increase in yield strength. The increase in carbon is also accompanied with a reduction in the notched-bar impact strength.

While manganese increases the yield strength to a marked extent, it also raises the crack sensitivity quite rapidly and is, therefore, limited in the case of hot-rolled steel to some place between about 1.10 to 1.30 per cent, depending upon other factors. One apparent advantage of manganese is that it is not detrimental to the notched-bar impact strength in the range investigated.

While the use of silicon as an alloy in this grade of steel appears to offer an advantage over plain carbon-manganese steels for obtaining yield strengths up to about 52,000 p.s.i., silicon is not comparable with either molybdenum or vanadium for producing higher yield strength steels that exhibit a low degree of underbead cracking.

It appears quite possible that the use of molybdenum and vanadium as alloying agents may prove to be advantageous. Additions of either of these alloys produces a substantial increase in the yield and tensile strength, which in the case of molybdenum is accompanied by little or no increase in weld crack sensitivity, and only a moderate increase in the case of vanadium. The addition of these allcys does, however, lower the notched-bar impact strength especially at room temperature and below.

The data from the six heats made to study the influence of aluminum content indicate that aluminum is an extremely important factor in establishing the weld crack sensitivity, the low-and-medium aluminum steels being quite crack sensitive as compared with steels containing no aluminum or very large additions of aluminum.

Since this pronounced effect of aluminum had not been noted in the previous work, which may be because the proper range was not investigated, it will be necessary to obtain more data to confirm or refute these results.

The study of aluminum content again confirmed the beneficial effects of relatively large aluminum additions, two pounds per ton, upon the notched-bar impact strength. This effect is especially noticeable at low temperatures.

## The Influence of Aluminum Content Upon the Mechanical Properties Normal to the Plate Surface

In order to obtain more information about the influence of aluminum and especially its effect upon the physical properties normal to the plate surface, Heats X-23 to X-28, inclusive, were made with aluminum additions ranging from 0 to 5 pounds per ton. (See Tables 1 and 2.)

These heats were made from 350-pound induction furnace melts which were poured into a single 8 by 8-inch ingot, the maximum size that can be conviently handled in the laboratory. This large size was selected in order to obtain the maximum reduction during hot-rolling to a 1-inch plate. To prevent the structure from being broken up by forging, these ingots were rolled directly to 1-inch plate on a small commercial mill.

The analysis of these six heats, including the acid-soluble aluminum content and the amount of aluminum added, are shown in Table 5.

TABLE 5. CHEMICAL ANALYSIS OF LABORATORY HEATS MADE TO STUDY THE INFLUENCE OF ALUMINUM CONTENT

| Heat No. | C | Mn | P | S | Si | Ti | Al | Aluminum Added in Lbs. Per Ton |
|---|---|---|---|---|---|---|---|---|
| X-23 | 0.20 | 1.25 | .021 | .022 | 0.27 | .007 | Nil | 0 |
| X-24 | 0.23 | 1.36 | .019 | .021 | 0.29 | .006 | $<$ .005 | 1/4 |
| X-25 | 0.22 | 1.24 | .020 | .020 | 0.27 | .013 | $<$ .005 | 1/2 |
| X-26 | 0.22 | 1.31 | .021 | .021 | 0.27 | .016 | .029 | 1 |
| X-27 | 0.20 | 1.29 | .018 | .020 | 0.31 | .015 | .064 | 2 |
| X-28 | 0.22 | 1.26 | .019 | .020 | 0.27 | .015 | .180 | 5 |

Tensile Properties Normal to Plate Surface. In order to determine the tensile strength of these steels in the direction normal to the plate surface, tensile specimens were prepared from the hot-rolled plate by welding and machining as indicated in Figure 33. Three by six-inch specimens were cut from each of the six heats, Heats X-23 to X-28, inclusive. Beveled plates were then welded to these specimens as shown in the above figure. The welds were made with four passes using Lincoln Shield-Arc 100(AWS-E10010) electrodes. The first pass was made with a 3/32-inch electrode and reverse polarity direct current using 130 to 140 amperes and an arc voltage of 27 to 30.

Following rough turning of the tensile specimens, they were etched lightly in order to establish definitely the location of the test plate. After determining the position of the test plate, a 3/4-inch

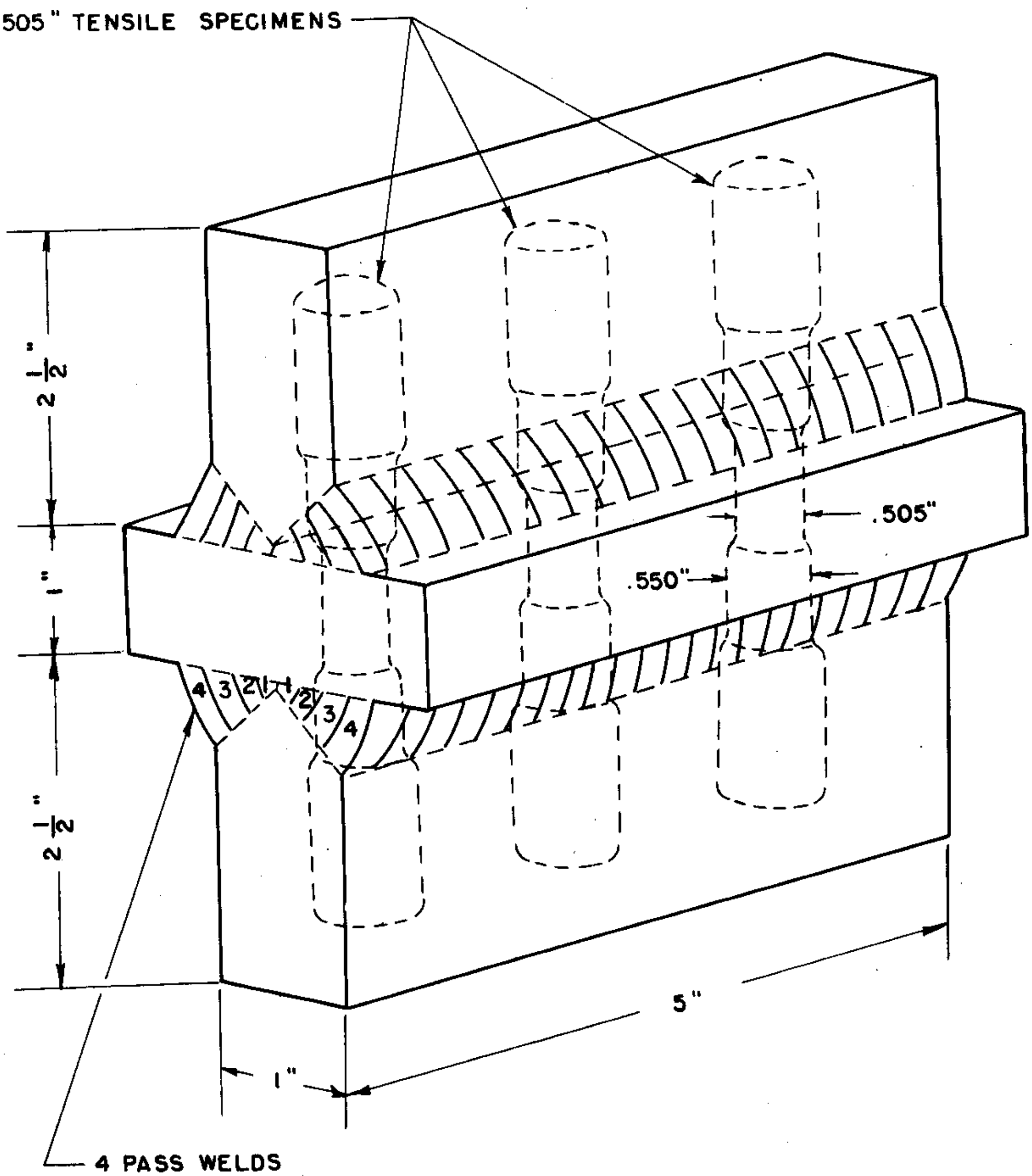


FIGURE 33. AN ILLUSTRATION OF THE PROCEDURE USED FOR MAKING THE SPECIMENS TO DETERMINE THE TENSILE PROPERTIES NORMAL TO THE PLATE SURFACE

section midway between the extremes of the test plate was ground to 0.505-inch diameter, leaving the remainder of the bar 0.550 inch. This precaution was taken to insure that the fracture would occur in the desired section.

The results of the tensile tests are shown in Table 6. A study of these data do not show a marked relationship between the aluminum content and the tensile properties. It will be noted, however, that both the yield and tensile strength of the heat made with no aluminum addition, Heat X-23, are low compared with the other heats in the series. The low strength, however, is not caused entirely by the absence of aluminum since both the carbon and manganese contents are low. While the data may be interpreted in such a manner as to indicate a slight increase in ductility with increased aluminum, this increase is so small that it cannot be considered significant.

A previous study made on commercial HTS steels and reported on pages 87 to 89 of the August 24, 1945, report showed a distinct relationship between the aluminum content and the reduction in area, the steels with little or no acid-soluble aluminum content displaying a much higher reduction in area that those containing an appreciable amount of aluminum. A similar but less marked relationship was noted between the aluminum content and the per cent elongation. The tensile strength in the higher aluminum commercial steels was found to be erratic and sometimes quite low.

This difference between the behavior of the laboratory steels and the commercial heats can probably be attributed to the difference in the amount of reduction between ingot and plate, the directional properties obviously being amplified by increased reduction.

TABLE 6. TENSILE PROPERTIES NORMAL TO THE PLATE SURFACE

| Heat No. | Aluminum Content, % | Elong. in 3/4 Inch, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| X-23 | Nil | 14.7 | 18.4 | 54,000 | 74,600 |
| " | | 9.3 | 14.5 | 53,000 | 73,250 |
| " | | 14.7 | 18.1 | 58,750 | 73,750 |
| X-24 | <.005 | 10.7 | 12.6 | 63,750 | 82,880 |
| " | | 6.7 | 11.5 | 62,500 | 80,630 |
| " | | 9.3 | 14.1 | 62,500 | 84,500 |
| X-25 | <.005 | 17.3 | 22.7 | 61,500 | 80,750 |
| " | | 16.0 | 20.6 | 60,750 | 79,000 |
| " | | 13.3 | 18.1 | 62,000 | 79,380 |
| X-26 | .029 | 13.3 | 18.8 | 61,000 | 78,380 |
| " | | 13.3 | 18.8 | 60,000 | 77,880 |
| " | | 13.3 | 21.3 | 61,500 | 77,750 |
| X-27 | .064 | 14.7 | 23.7 | 63,000 | 78,000 |
| " | | 17.3 | 27.8 | 61,500 | 78,250 |
| " | | 17.3 | 27.8 | 61,500 | 78,630 |
| X-28 | .180 | 16.0 | 24.1 | 62,000 | 79,000 |
| " | | - * | - * | 63,000 | 74,500 |
| " | | 16.0 | 18.4 | 63,000 | 77,880 |

* Specimen broke in gauge mark.

See Figure 19 for details concerning the preparation of the tensile specimens.

Notched-Bar Impact Strength Normal to the Plate Surface. Notched-bar impact specimens, Charpy specimens with V-Izod notches, were prepared from sections similar to those used for the tensile specimens. (See Figure 33.)

Four duplicate specimens were broken at five different temperatures between the limits of -40°F. and +210°F. The data from these tests are shown in Figures 34 to 36, inclusive. The test values are recorded in Table 4 of Appendix A. The above figures reveal that the notched-bar impact strength normal to the plate surface is quite low regardless of the aluminum content, the values at +75°F. falling between 7 and 20-foot-pounds.

A comparison of the six different steels reveals that Heat X-27 made with an addition of two pounds of aluminum per ton had definitely better impact strength as compared with the other heats. Similar results were noted when the steels were tested in the longitudinal direction, that is, the direction of rolling. (See Figures 23 to 25, inclusive.)

## FUTURE WORK

In order to check the effect of aluminum content upon underbead cracking, a second series of heats will be made with aluminum additions ranging from 0 to 5 pounds per ton.

Since increased additions of molybdenum apparently did not increase the crack sensitivity but did raise the tensile and yield strength to a marked extent, it appears desirable to make a second series of heats but at a slightly lower carbon level in order to confirm the previous results.

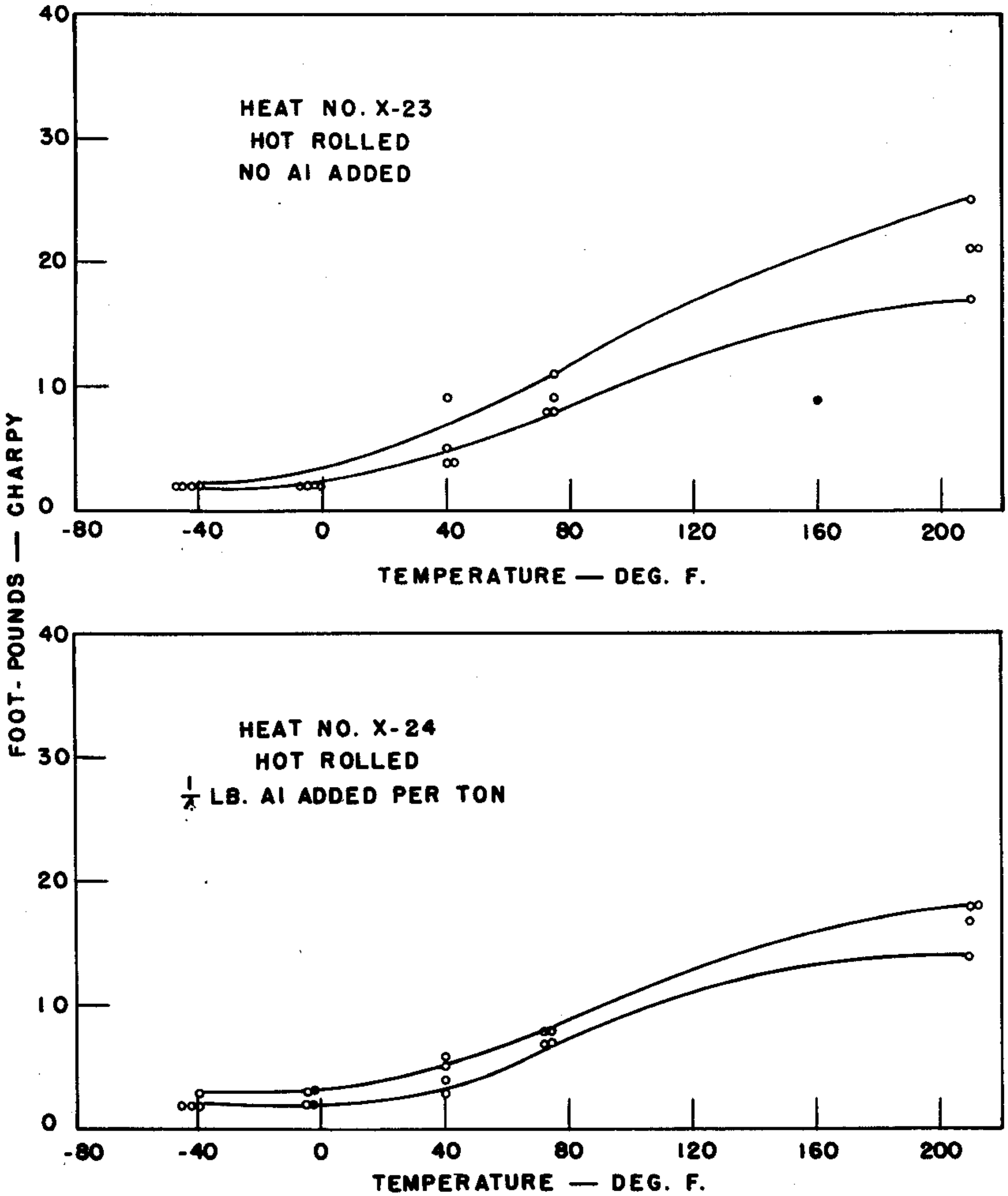


FIGURE 34. NOTCHED-BAR IMPACT STRENGTH NORMAL TO THE PLATE SURFACE

0-5444

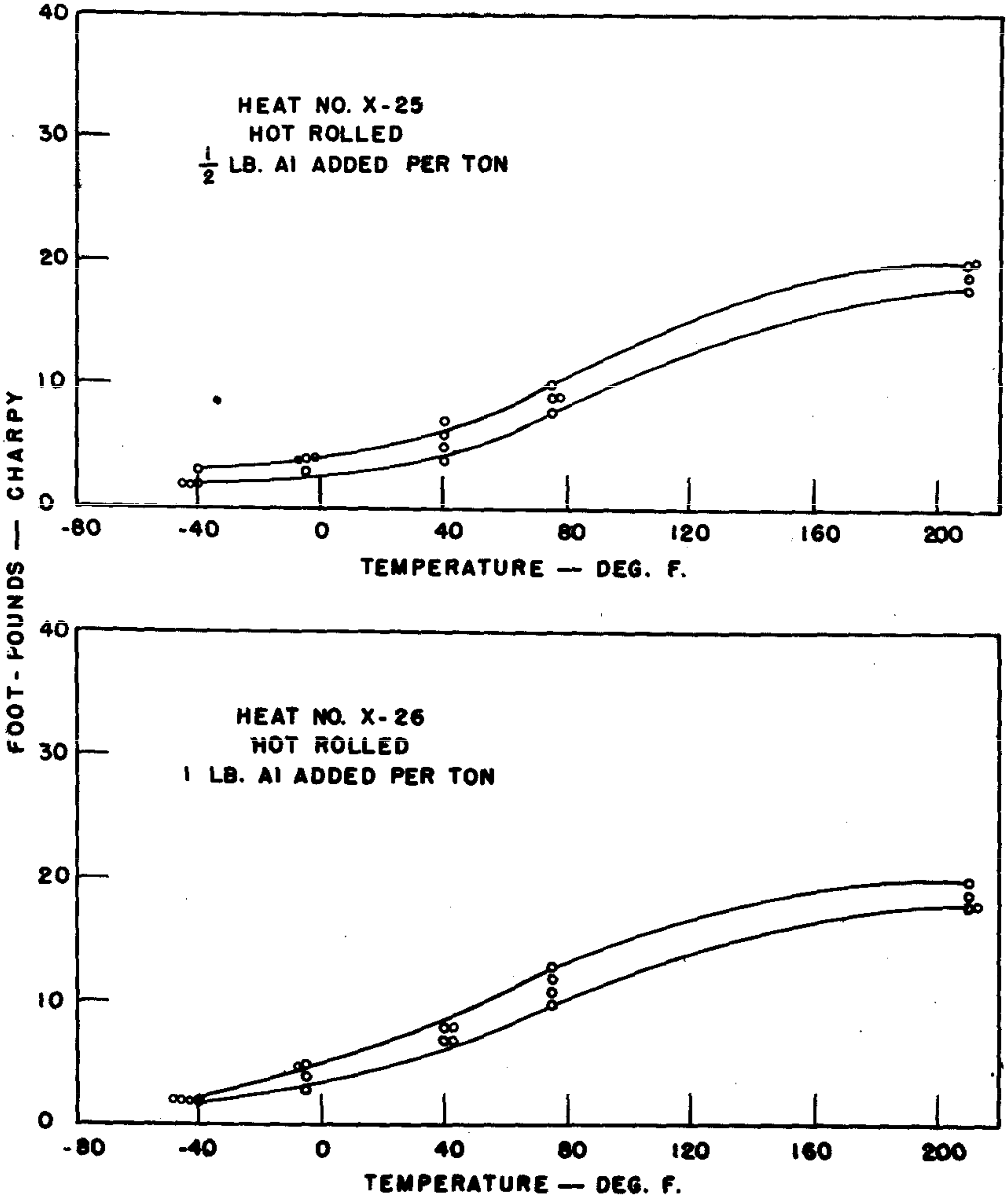


FIGURE 35. NOTCHED-BAR IMPACT STRENGTH NORMAL TO THE PLATE SURFACE

0-5445

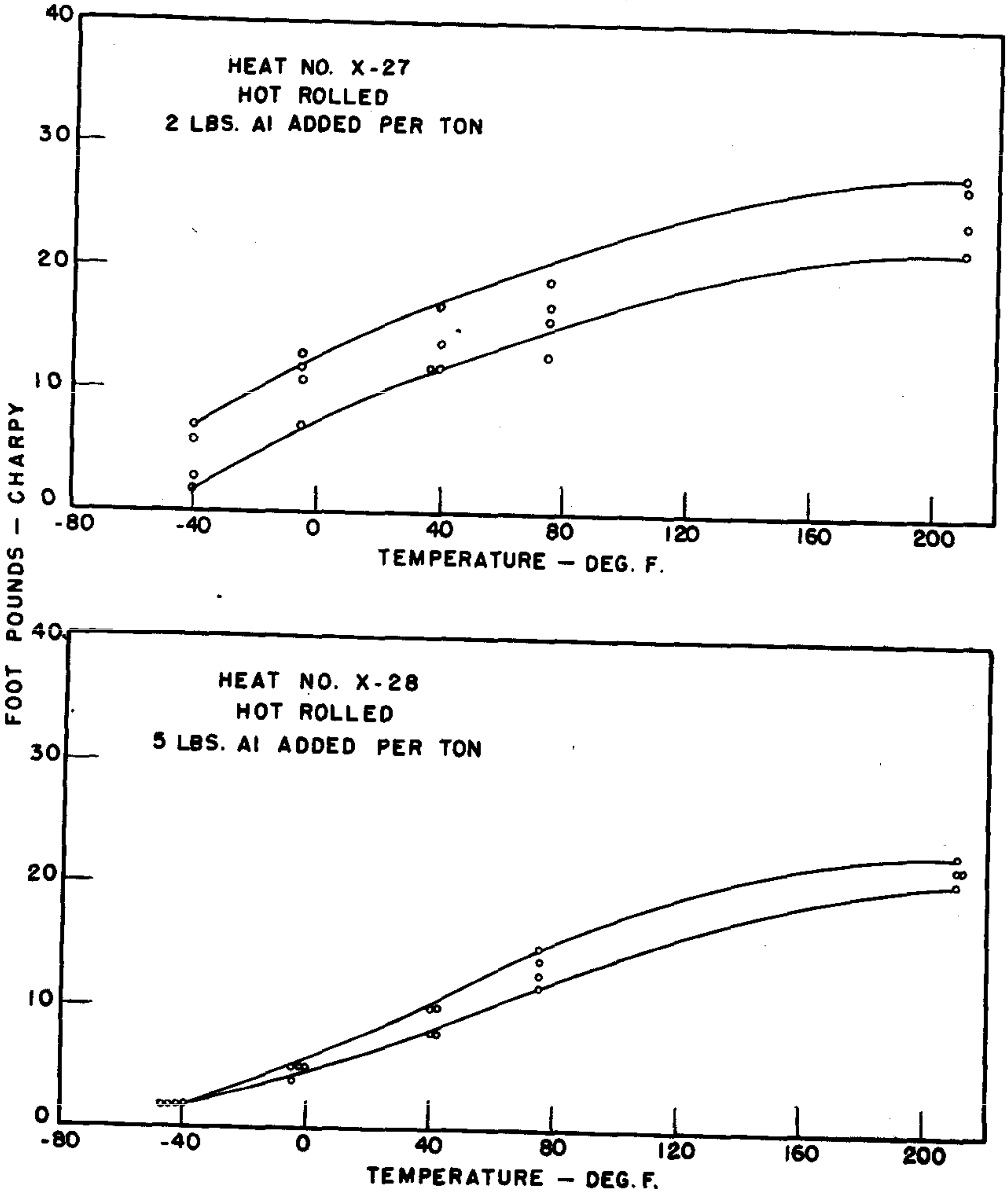


FIGURE 36. NOTCHED-BAR IMPACT STRENGTH NORMAL TO THE PLATE SURFACE

0-5446

The influence of homogenization upon the crack sensitivity and physical properties of the 30 heats discussed in this report will be studied. This phase of the work should aid in establishing the maximum chemical composition that may be used without excessive underbead cracking.

Since it appears that the most practical place to carry out a homogenization treatment in commercial production is while the slab is being heated for rolling to plate, it will be necessary to determine the time and temperature required for this treatment. Sections of commercial slabs of HTS steel have been obtained and a study is being made to determine the time-temperature cycle necessary to homogenize the slab and also the effect of this temperature upon the crack sensitivity of the plate rolled from the treated slab.

Data used in this report can be found in Laboratory Notebook No. 2581, pages 6 to 51, inclusive.

CES:HMB:ALW/ab
June 18, 1947
Revised October 9, 1947

# APPENDIX A

## TABLES OF COMPLETE TEST DATA

by

H. M. Banta and A. L. Walters

TABLE A1. TENSILE PROPERTIES OF HOT-ROLLED PLATE FROM LABORATORY HEATS X-1 TO X-28, INCLUSIVE, X-45 AND X-46

| Heat No. | Test Direction | Elong. in 2 Inches, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| X-1 | Long. | 37.0 | 73.9 | 44,250 | 70,750 |
| " | " | 37.5 | 74.9 | 47,000 | 72,000 |
| " | Trans. | 31.5 | 62.1 | 45,500 | 72,300 |
| " | " | 31.5 | 62.1 | 44,000 | 72,500 |
| X-2 | Long. | 37.0 | 67.9 | 45,500 | 75,100 |
| " | " | 35.0 | 69.9 | 43,000 | 74,100 |
| " | Trans. | 33.5 | 63.3 | 41,000 | 73,900 |
| " | " | 32.0 | 62.8 | 42,250 | 73,850 |
| X-3 | Long. | 31.0 | 65.4 | 46,750 | 81,000 |
| " | " | 32.5 | 68.6 | 48,000 | 82,100 |
| " | Trans. | 29.5 | 61.1 | 48,250 | 80,000 |
| " | " | 29.5 | 61.1 | 44,250 | 80,400 |
| X-4 | Long. | 31.7 | 68.2 | 52,750 | 87,800 |
| " | " | 30.0 | 66.8 | 49,250 | 85,900 |
| " | Trans. | 28.0 | 56.0 | 49,000 | 86,700 |
| " | " | 27.5 | 56.8 | 48,500 | 86,200 |
| X-5 | Long. | 29.5 | 65.9 | 55,500 | 89,900 |
| " | " | 27.5 | 63.3 | 54,500 | 89,700 |
| " | Trans. | 26.0 | 53.3 | 49,000 | 87,400 |
| " | " | 27.0 | 51.4 | 49,750 | 87,150 |
| X-6 | Long. | 36.0 | 67.0 | 39,750 | 70,200 |
| " | " | 35.0 | 65.9 | 38,500 | 70,100 |
| " | Trans. | 33.0 | 58.6 | 38,500 | 69,500 |
| " | " | 31.0 | 57.8 | 40,750 | 69,500 |
| X-7 | Long. | 34.5 | 69.9 | 45,250 | 74,100 |
| " | " | 35.0 | 69.3 | 44,000 | 72,800 |
| " | Trans. | 30.0 | 58.1 | 43,500 | 71,900 |
| " | " | 29.7 | 61.8 | 42,750 | 71,900 |
| X-8 | Long. | 35.5 | 71.4 | 46,500 | 77,600 |
| " | " | 35.7 | 69.7 | 47,000 | 77,100 |
| " | Trans. | 30.0 | 60.8 | 44,500 | 75,800 |
| " | " | 30.0 | 57.5 | 44,500 | 76,100 |

TABLE A1. (Continued)

| Heat No. | Test Direction | Elong. in 2 Inches, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| X-9 | Long. | 35.0 | 73.5 | 49,250 | 77,600 |
| " | " | 34.5 | 70.6 | 47,500 | 76,750 |
| " | Trans. | 31.5 | 59.1 | 46,750 | 77,700 |
| " | " | 31.6 | 60.3 | 46,000 | 77,600 |
| X-10 | Long. | 35.5 | 70.4 | 47,750 | 78,300 |
| " | " | 34.2 | 69.0 | 47,500 | 78,600 |
| " | Trans. | 33.5 | 61.8 | 44,000 | 76,500 |
| " | " | 31.0 | 58.6 | 44,250 | 76,100 |
| X-11 | Long. | 32.0 | 67.9 | 52,500 | 79,400 |
| " | " | 34.3 | 69.3 | 49,250 | 80,600 |
| " | Trans. | 30.2 | 57.5 | 47,000 | 79,800 |
| " | " | 29.2 | 59.6 | 46,250 | 79,400 |
| X-12 | Long. | 33.0 | 68.8 | 53,000 | 85,400 |
| " | " | 33.0 | 68.2 | 52,000 | 85,500 |
| " | Trans. | 29.0 | 59.4 | 52,000 | 83,750 |
| " | " | 28.5 | 58.3 | 50,000 | 83,900 |
| X-13 | Long. | 33.0 | 66.1 | 49,750 | 83,800 |
| " | " | 33.0 | 65.9 | 49,750 | 84,100 |
| " | Trans. | 30.5 | 59.6 | 49,500 | 83,300 |
| " | " | 30.5 | 59.6 | 49,000 | 83,100 |
| X-14 | Long. | 31.0 | 65.9 | 50,000 | 80,000 |
| " | " | 32.5 | 67.9 | 51,250 | 80,800 |
| " | Trans. | 28.0 | 58.6 | 46,500 | 79,000 |
| " | " | 29.5 | 58.6 | 45,500 | 79,100 |
| X-15 | Long. | 31.5 | 62.8 | 51,000 | 81,000 |
| " | " | 32.0 | 65.4 | 51,750 | 81,700 |
| " | Trans. | 29.0 | 57.5 | 49,000 | 80,800 |
| " | " | 28.5 | 59.1 | 48,750 | 81,000 |
| X-16 | Long. | 29.0 | 62.8 | 55,000 | 81,000 |
| " | " | 29.0 | 63.5 | 57,000 | 83,500 |
| " | Trans. | 24.5 | 55.5 | 57,000 | 82,700 |
| " | " | 23.7 | 54.9 | 56,500 | 82,600 |
| X-17 | Long. | 23.0 | 61.3 | 66,750 | 97,750 |
| " | " | 25.0 | 64.7 | 70,500 | 99,500 |
| " | Trans. | 21.3 | 49.8 | 65,250 | 93,500 |
| " | " | 20.5 | 49.5 | 67,250 | 94,125 |

TABLE A1. (Continued)

| Heat No. | Test Direction | Elong. in 2 Inches, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| X-18 | Long. | 21.5 | 62.8 | 77,000 | 98,100 |
| " | " | 22.5 | 62.3 | 79,500 | 100,875 |
| " | Trans. | 20.5 | 53.3 | 76,500 | 97,750 |
| " | " | 21.0 | 53.6 | 75,250 | 96,800 |
| X-19 | Long. | 32.0 | 65.6 | 48,750 | 79,200 |
| " | " | 32.7 | 65.9 | 49,500 | 80,000 |
| " | Trans. | 29.0 | 60.6 | 47,500 | 78,000 |
| " | " | 30.0 | 57.3 | 48,000 | 78,200 |
| X-20 | Long. | 32.7 | 67.7 | 57,250 | 84,400 |
| " | " | 32.5 | 67.9 | 56,500 | 84,000 |
| " | Trans. | 27.0 | 58.3 | 53,750 | 82,500 |
| " | " | 27.5 | 60.6 | 54,250 | 82,400 |
| X-21 | Long. | 27.0 | 60.6 | 67,750 | 92,700 |
| " | " | 27.0 | 61.6 | 66,000 | 94,350 |
| " | Trans. | 24.0 | 52.5 | 63,250 | 92,600 |
| " | " | 22.0 | 52.2 | 66,000 | 92,500 |
| X-22 | Long. | 25.5 | 59.4 | 77,500 | 104,500 |
| " | " | 25.0 | 59.4 | 79,500 | 105,750 |
| " | Trans. | 20.0 | 49.2 | 74,000 | 100,400 |
| " | " | 20.6 | 48.4 | 73,750 | 100,400 |
| X-23 | Long. | 35.0 | 67.3 | 47,000 | 74,400 |
| " | " | 34.0 | 65.4 | 48,000 | 75,400 |
| " | Trans. | 29.0 | 52.5 | 46,000 | 73,800 |
| " | " | 29.5 | 51.9 | 45,500 | 73,800 |
| X-24 | Long. | 32.0 | 68.6 | 50,500 | 81,700 |
| " | " | 30.5 | 60.3 | 51,250 | 82,750 |
| " | Trans. | 28.0 | 53.6 | 49,000 | 81,800 |
| " | " | 27.5 | 47.8 | 49,750 | 81,900 |
| X-25 | Long. | 33.0 | 68.2 | 47,500 | 76,750 |
| " | " | 33.0 | 68.2 | 48,000 | 78,000 |
| " | Trans. | 28.0 | 55.2 | 46,750 | 76,350 |
| " | " | 27.5 | 53.0 | 46,000 | 76,400 |
| X-26 | Long. | 33.0 | 68.4 | 49,000 | 78,900 |
| " | " | 33.0 | 67.7 | 50,250 | 80,400 |
| " | Trans. | 27.0 | 53.8 | 49,250 | 80,150 |
| " | " | 26.5 | 52.8 | 49,500 | 79,800 |

TABLE A1. (Continued)

| Heat No. | Test Direction | Elong. in 2 Inches, % | Red. in Area, % | Yield Strength, p.s.i. | Tensile Strength, p.s.i. |
|---|---|---|---|---|---|
| X-27 | Long. | 33.0 | 69.0 | 49,000 | 77,200 |
| " | " | 34.0 | 70.1 | 47,500 | 76,000 |
| " | Trans. | 29.0 | 57.8 | 46,750 | 75,850 |
| " | " | 27.5 | 56.0 | 44,750 | 76,100 |
| X-28 | Long. | 33.5 | 68.8 | 48,500 | 78,000 |
| " | " | 33.5 | 68.6 | 48,250 | 77,500 |
| " | Trans. | 29.5 | 57.3 | 47,250 | 75,800 |
| " | " | 27.5 | 54.5 | 46,500 | 75,800 |
| X-45 | Long. | 34.5 | 69.0 | 51,750 | 78,900 |
| " | " | 33.0 | 65.4 | 52,500 | 79,250 |
| " | Trans. | 24.5 | 37.9 | 48,250 | 77,500 |
| " | " | 23.0 | 33.4 | 49,500 | 77,400 |
| X-46 | Long. | 35.0 | 70.1 | 49,750 | 79,900 |
| " | " | 35.0 | 70.1 | 51,750 | 80,750 |
| " | Trans. | 28.0 | 52.8 | 52,500 | 79,900 |
| " | " | 28.0 | 49.5 | 51,500 | 79,750 |

TABLE A2. UNDERBEAD CRACKING VALUES OF INDIVIDUAL SPECIMENS FROM LABORATORY HEATS X-1 TO X-28, INCLUSIVE, X-45 AND X-46 IN THE HOT-ROLLED STATE

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-1 | 1 | 11 | |
| | 2 | 34 | |
| | 3 | 16 | |
| | 4 | 29 | |
| | 5 | 19 | |
| | 6 | 33 | |
| | 7 | 3 | |
| | 8 | 25 | |
| | 9 | 13 | |
| | 10 | 24 | Avg. 21% |
| X-2 | 1 | 35 | |
| | 2 | 21 | |
| | 3 | 18 | |
| | 4 | 30 | |
| | 5 | 16 | |
| | 6 | 26 | |
| | 7 | 21 | |
| | 8 | 33 | |
| | 9 | 48 | |
| | 10 | 21 | Avg. 27% |
| X-3 | 1 | 94 | |
| | 2 | 80 | |
| | 3 | 70 | |
| | 4 | 91 | |
| | 5 | 89 | |
| | 6 | 88 | |
| | 7 | 95 | |
| | 8 | 78 | |
| | 9 | 84 | |
| | 10 | 80 | Avg. 85% |
| X-4 | 1 | 104 | |
| | 2 | 105 | |
| | 3 | 89 | |
| | 4 | 81 | |
| | 5 | 93 | |
| | 6 | 108 | |
| | 7 | 106 | |
| | 8 | 68 | |
| | 9 | 113 | |
| | 10 | 105 | Avg. 97% |

TABLE A2. (Continued)

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-5 | 1 | 120 | |
| | 2 | 115 | |
| | 3 | 104 | |
| | 4 | 88 | |
| | 5 | 96 | |
| | 6 | 103 | |
| | 7 | 101 | |
| | 8 | 104 | |
| | 9 | 109 | |
| | 10 | 99 | Avg. 104% |
| X-6 | 1 | 48 | |
| | 2 | 36 | |
| | 3 | 23 | |
| | 4 | 18 | |
| | 5 | 24 | |
| | 6 | 25 | |
| | 7 | 19 | |
| | 8 | 30 | |
| | 9 | 25 | |
| | 10 | 31 | Avg. 28% |
| X-7 | 1 | 8 | |
| | 2 | 18 | |
| | 3 | 8 | |
| | 4 | 39 | |
| | 5 | 11 | |
| | 6 | 35 | |
| | 7 | 4 | |
| | 8 | 40 | |
| | 9 | 5 | |
| | 10 | 9 | Avg. 19% |
| X-8 | 1 | 74 | |
| | 2 | 76 | |
| | 3 | 86 | |
| | 4 | 71 | |
| | 5 | 88 | |
| | 6 | 70 | |
| | 7 | 69 | |
| | 8 | 79 | |
| | 9 | 50 | |
| | 10 | 89 | Avg. 75% |

TABLE A2. (Continued)

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-9 | 1 | 71 | |
| | 2 | 74 | |
| | 3 | 76 | |
| | 4 | 68 | |
| | 5 | 60 | |
| | 6 | 34 | |
| | 7 | 58 | |
| | 8 | 70 | |
| | 9 | 6 | |
| | 10 | 71 | Avg. 59% |
| X-10 | 1 | 53 | |
| | 2 | 60 | |
| | 3 | 65 | |
| | 4 | 73 | |
| | 5 | 46 | |
| | 6 | 23 | |
| | 7 | 44 | |
| | 8 | 70 | |
| | 9 | 45 | |
| | 10 | 20 | Avg. 50% |
| X-11 | 1 | 84 | |
| | 2 | 79 | |
| | 3 | 76 | |
| | 4 | 93 | |
| | 5 | 81 | |
| | 6 | 89 | |
| | 7 | 78 | |
| | 8 | 89 | |
| | 9 | 95 | |
| | 10 | 80 | Avg. 84% |
| X-12 | 1 | 91 | |
| | 2 | 75 | |
| | 3 | 88 | |
| | 4 | 75 | |
| | 5 | 78 | |
| | 6 | 78 | |
| | 7 | 91 | |
| | 8 | 88 | |
| | 9 | 90 | |
| | 10 | 85 | Avg. 84% |

TABLE A2. (Continued)

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-13 | 1 | 64 | |
| | 2 | 60 | |
| | 3 | 56 | |
| | 4 | 80 | |
| | 5 | 83 | |
| | 6 | 63 | |
| | 7 | 68 | |
| | 8 | 59 | |
| | 9 | 66 | |
| | 10 | 43 | Avg. 64% |
| X-14 | 1 | 59 | |
| | 2 | 80 | |
| | 3 | 86 | |
| | 4 | 58 | |
| | 5 | 75 | |
| | 6 | 66 | |
| | 7 | 76 | |
| | 8 | 50 | |
| | 9 | 89 | |
| | 10 | 53 | Avg. 69% |
| X-15 | 1 | 95 | |
| | 2 | 78 | |
| | 3 | 84 | |
| | 4 | 86 | |
| | 5 | 81 | |
| | 6 | 93 | |
| | 7 | 86 | |
| | 8 | 89 | |
| | 9 | 80 | |
| | 10 | 93 | Avg. 86% |
| X-16 | 1 | 73 | |
| | 2 | 68 | |
| | 3 | 69 | |
| | 4 | 58 | |
| | 5 | 80 | |
| | 6 | 70 | |
| | 7 | 56 | |
| | 8 | 69 | |
| | 9 | 48 | |
| | 10 | 74 | Avg. 66% |

TABLE A2. (Continued)

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-17 | 1 | 71 | |
| | 2 | 74 | |
| | 3 | 54 | |
| | 4 | 74 | |
| | 5 | 71 | |
| | 6 | 71 | |
| | 7 | 63 | |
| | 8 | 81 | |
| | 9 | 84 | |
| | 10 | 64 | Avg. 71% |
| X-18 | 1 | 64 | |
| | 2 | 70 | |
| | 3 | 63 | |
| | 4 | 68 | |
| | 5 | 60 | |
| | 6 | 70 | |
| | 7 | 73 | |
| | 8 | 69 | |
| | 9 | 66 | |
| | 10 | 60 | Avg. 66% |
| X-19 | 1 | 58 | |
| | 2 | 34 | |
| | 3 | 56 | |
| | 4 | 50 | |
| | 5 | 55 | |
| | 6 | 48 | |
| | 7 | 60 | |
| | 8 | 61 | |
| | 9 | 50 | |
| | 10 | 43 | Avg. 51% |
| X-20 | 1 | 73 | |
| | 2 | 49 | |
| | 3 | 79 | |
| | 4 | 55 | |
| | 5 | 61 | |
| | 6 | 61 | |
| | 7 | 68 | |
| | 8 | 63 | |
| | 9 | 83 | |
| | 10 | 48 | Avg. 64% |

TABLE A2. (Continued)

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-21 | 1 | 80 | |
| | 2 | 90 | |
| | 3 | 80 | |
| | 4 | 74 | |
| | 5 | 75 | |
| | 6 | 64 | |
| | 7 | 81 | |
| | 8 | 81 | |
| | 9 | 79 | |
| | 10 | 75 | Avg. 78% |
| X-22 | 1 | 74 | |
| | 2 | 80 | |
| | 3 | 78 | |
| | 4 | 70 | |
| | 5 | 71 | |
| | 6 | 65 | |
| | 7 | 95 | |
| | 8 | 79 | |
| | 9 | 70 | |
| | 10 | 54 | Avg. 74% |
| X-23 | 1 | 0 | |
| | 2 | 5 | |
| | 3 | 5 | |
| | 4 | 13 | |
| | 5 | 0 | |
| | 6 | 18 | |
| | 7 | 3 | |
| | 8 | 14 | |
| | 9 | 4 | |
| | 10 | 0 | Avg. 6% |
| X-24 | 1 | 95 | |
| | 2 | 98 | |
| | 3 | 89 | |
| | 4 | 90 | |
| | 5 | 99 | |
| | 6 | 86 | |
| | 7 | 94 | |
| | 8 | 95 | |
| | 9 | 104 | |
| | 10 | 101 | Avg. 95% |

TABLE A2. (Continued)

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-25 | 1 | 83 | |
| | 2 | 70 | |
| | 3 | 83 | |
| | 4 | 68 | |
| | 5 | 80 | |
| | 6 | 66 | |
| | 7 | 70 | |
| | 8 | 85 | |
| | 9 | 65 | |
| | 10 | 69 | Avg. 74% |
| X-26 | 1 | 86 | |
| | 2 | 85 | |
| | 3 | 83 | |
| | 4 | 85 | |
| | 5 | 86 | |
| | 6 | 85 | |
| | 7 | 68 | |
| | 8 | 79 | |
| | 9 | 78 | |
| | 10 | 78 | Avg. 81% |
| X-27 | 1 | 46 | |
| | 2 | 74 | |
| | 3 | 46 | |
| | 4 | 40 | |
| | 5 | 71 | |
| | 6 | 35 | |
| | 7 | 58 | |
| | 8 | 64 | |
| | 9 | 65 | |
| | 10 | 68 | Avg. 57% |
| X-28 | 1 | 30 | |
| | 2 | 15 | |
| | 3 | 19 | |
| | 4 | 4 | |
| | 5 | 16 | |
| | 6 | 23 | |
| | 7 | 18 | |
| | 8 | 11 | |
| | 9 | 23 | |
| | 10 | 15 | Avg. 17% |

TABLE A2. (Continued)

| Heat No. | Specimen No. | Underbead Cracking, Per Cent | |
|---|---|---|---|
| X-45 | 1 | 14 | |
| | 2 | 40 | |
| | 3 | 99 | |
| | 4 | 70 | |
| | 5 | 64 | |
| | 6 | 25 | |
| | 7 | 91 | |
| | 8 | 46 | |
| | 9 | 36 | |
| | 10 | 83 | Avg. 57% |
| X-46 | 1 | 64 | |
| | 2 | 75 | |
| | 3 | 90 | |
| | 4 | 86 | |
| | 5 | 29 | |
| | 6 | 53 | |
| | 7 | 68 | |
| | 8 | 75 | |
| | 9 | 9 | |
| | 10 | 53 | Avg. 60% |
| Steel 37 (Control) | 1 | 10 | |
| | 2 | 9 | |
| | 3 | 24 | |
| | 4 | 8 | |
| | 5 | 6 | |
| | 6 | 19 | |
| | 7 | 5 | |
| | 8 | 30 | |
| | 9 | 5 | |
| | 10 | 5 | Avg. 11% |

TABLE A3. LONGITUDINAL NOTCHED-BAR IMPACT PROPERTIES OF LABORATORY HEATS X-1 TO X-28, INCLUSIVE, X-45 AND X-46 IN THE HOT-ROLLED STATE. ALL SPECIMENS NOTCHED PARALLEL TO THE PLATE SURFACE

| Heat No. | Testing Temperature, Degrees F. | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -75° | | | | -40° | | | | -5° | | | | +75° | | | | +210° | | | |
| X-1 | 3 | 6 | 5 | 2 | 68 | 25 | 21 | 32 | 106 | 119 | 31 | 30 | 107 | 124 | 111 | 112 | 120 | 124 | 119 | 129 |
| X-2 | 8 | 2 | 4 | 3 | 4 | 7 | 4 | 3 | 24 | 22 | 16 | 14 | 107 | 95 | 66 | 67 | 123 | 115 | 125 | 112 |
| X-3 | 4 | 3 | 2 | 2 | 7 | 3 | 8 | 7 | 13 | 21 | 17 | 8 | 34 | 40 | 41 | 44 | 86 | 85 | 84 | 85 |
| X-4 | 2 | 3 | 4 | 4 | 5 | 3 | 4 | 4 | 8 | 18 | 10 | 8 | 26 | 47 | 51 | 37 | 74 | 90 | 83 | 81 |
| X-5 | 4 | 2 | 4 | 2 | 7 | 8 | 7 | 6 | 13 | 18 | 12 | 19 | 36 | 31 | 25 | 35 | 67 | 68 | 76 | 71 |
| X-6 | 3 | 4 | 2 | 3 | 6 | 6 | 7 | 4 | 9 | 19 | 18 | 30 | 35 | 73 | 103 | 92 | 96 | 119 | 98 | 108 |
| X-7 | 4 | 3 | 4 | 4 | 8 | 8 | 8 | 9 | 48 | 20 | 33 | 21 | 101 | 95 | 92 | 108 | 108 | 100 | 104 | 118 |
| X-8 | 5 | 5 | 5 | 3 | 8 | 10 | 24 | 14 | 42 | 46 | 48 | 14 | 105 | 95 | 119 | 110 | 95 | 112 | 108 | 115 |
| X-9 | 4 | 6 | 3 | 2 | 22 | 5 | 16 | 6 | 48 | 46 | 41 | 24 | 98 | 47 | 104 | 78 | 108 | 97 | 109 | 105 |
| X-10 | 5 | 4 | 5 | 3 | 5 | 7 | 6 | 32 | 20 | 19 | 37 | 16 | 63 | 108 | 93 | 112 | 100 | 110 | 106 | 105 |
| X-11 | 5 | 3 | 2 | 3 | 7 | 5 | 6 | 7 | 22 | 21 | 14 | 34 | 83 | 54 | 55 | 91 | 86 | 85 | 98 | 96 |
| X-12 | 3 | 3 | 5 | 4 | 9 | 6 | 8 | 4 | 20 | 12 | 12 | 14 | 37 | 58 | 33 | 44 | 89 | 90 | 97 | 110 |
| X-13 | 4 | 4 | 2 | 2 | 13 | 14 | 3 | 4 | 12 | 18 | 9 | 12 | 25 | 18 | 19 | 31 | 85 | 85 | 93 | 91 |
| X-14 | 2 | 2 | 2 | 2 | 3 | 4 | 5 | 6 | 13 | 12 | 9 | 13 | 78 | 50 | 34 | 43 | 96 | 90 | 90 | 92 |
| X-15 | 6 | 3 | 2 | 3 | 3 | 9 | 3 | 11 | 20 | 11 | 11 | 19 | 53 | 43 | 38 | 44 | 95 | 90 | 93 | 97 |

TABLE A3. (Continued)

| Heat No. | Testing Temperature, Degrees F. | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -75° | | | | -40° | | | | -5° | | | | +75° | | | | +210° | | | |
| X-16 | 6 | 2 | 2 | 3 | 5 | 4 | 8 | 7 | 35 | 21 | 12 | 26 | 69 | 64 | 96 | 81 | 77 | 73 | 92 | 86 |
| X-17 | 3 | 3 | 4 | 2 | 7 | 9 | 8 | 3 | 9 | 21 | 15 | 12 | 33 | 59 | 41 | 36 | 78 | 65 | 81 | 81 |
| X-18 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 13 | 5 | 4 | 4 | 4 | 13 | 10 | 10 | 10 | 84 | 82 | 87 | 95 |
| X-19 | 5 | 2 | 3 | 2 | 6 | 7 | 5 | 5 | 12 | 40 | 25 | 28 | 48 | 32 | 33 | 65 | 89 | 91 | 94 | 85 |
| X-20 | 3 | 2 | 3 | 3 | 3 | 7 | 8 | 5 | 8 | 11 | 13 | 23 | 113 | 101 | 79 | 100 | 94 | 89 | 95 | 103 |
| X-21 | 2 | 2 | 2 | 2 | 3 | 13 | 3 | 3 | 8 | 6 | 9 | 4 | 27 | 10 | 13 | 20 | 87 | 86 | 85 | 84 |
| X-22 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 4 | 2 | 4 | 5 | 6 | 5 | 37 | 44 | 27 | 21 |
| X-23 | 4 | 5 | 4 | 2 | 4 | 6 | 3 | 21 | 13 | 33 | 14 | 11 | 94 | 89 | 90 | 98 | 108 | 107 | 104 | 105 |
| X-24 | 3 | 3 | 2 | 3 | 7 | 7 | 10 | 8 | 18 | 17 | 18 | 13 | 55 | 99 | 45 | 63 | 106 | 105 | 98 | 103 |
| X-25 | 4 | 4 | 2 | 2 | 9 | 14 | 17 | 7 | 17 | 22 | 19 | 44 | 96 | 98 | 98 | 98 | 105 | 103 | 113 | 118 |
| X-26 | 4 | 3 | 5 | 3 | 15 | 10 | 18 | 10 | 26 | 35 | 26 | 58 | 99 | 111 | 93 | 95 | 99 | 109 | 109 | 106 |
| X-27 | 10 | 5 | 4 | 4 | 34 | 26 | 18 | 22 | 45 | 45 | 66 | 34 | 104 | 108 | 109 | 105 | 106 | 105 | 104 | 108 |
| X-28 | 6 | 5 | 4 | 4 | 11 | 21 | 8 | 12 | 29 | 85 | 57 | 55 | 80 | 89 | 105 | 90 | 105 | 104 | 108 | 106 |
| X-45 | 4 | 6 | 6 | 22 | 14 | 19 | 46 | 105 | 27 | 102 | 111 | 125 | 113 | 116 | 121 | 121 | 104 | 111 | 116 | 116 |
| X-46 | 6 | 8 | 9 | 9 | 20 | 30 | 41 | 75 | 30 | 100 | 115 | 121 | 115 | 116 | 123 | 129 | 100 | 110 | 110 | 133 |

Note: The above impact values are given in foot-pounds. The specimens used were the standard V-notch Charpy bars which were broken on a Riehle impact machine having an initial energy of 220 foot-pounds.

TABLE A4. NOTCHED-BAR IMPACT PROPERTIES NORMAL TO THE PLATE SURFACE OF HEATS X-23 TO X-28 IN THE HOT-ROLLED STATE

| Heat No. | Testing Temperature, Degrees F. | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -40° | | | | -5° | | | | +40° | | | | +75° | | | | +210° | | | |
| X-23 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 9 | 4 | 5 | 4 | 8 | 9 | 11 | 8 | 21 | 21 | 25 | 17 |
| X-24 | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 5 | 6 | 4 | 3 | 8 | 7 | 7 | 8 | 17 | 18 | 18 | 14 |
| X-25 | 2 | 3 | 2 | 2 | 4 | 4 | 3 | 4 | 7 | 6 | 4 | 5 | 10 | 8 | 9 | 9 | 18 | 19 | 18 | 19 |
| X-26 | 2 | 2 | 2 | 2 | 5 | 5 | 4 | 3 | 7 | 8 | 8 | 7 | 10 | 11 | 13 | 12 | 18 | 18 | 20 | 19 |
| X-27 | 6 | 2 | 7 | 3 | 13 | 12 | 11 | 7 | 12 | 14 | 12 | 17 | 16 | 19 | 17 | 13 | 27 | 28 | 24 | 22 |
| X-28 | 2 | 2 | 2 | 2 | 4 | 5 | 5 | 5 | 8 | 10 | 10 | 8 | 15 | 14 | 12 | 13 | 23 | 22 | 22 | 21 |

Note: The above impact values are given in foot-pounds. The specimens used were the standard V-notch Charpy bars which were broken on a Riehle impact machine having an initial energy of 220 foot-pounds.