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EFFECT OF LOW TEMPERATURES ON THE PROPERTIES OF AIRCRAFT METALS

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ABSTRACT

The effect of subzero temperatures down to −78° C was determined upon the tensile properties, hardness, and impact resistance of metals commonly used in aircraft construction. The materials were divided into three general groups: (1) Ferritic steels, (2) austenitic stainless steels and nickel alloys, and (3) light metal alloys (Al- and Mg-base).

None of these properties of any of the materials tested was adversely affected by low temperatures with the exception of the impact resistance of the ferritic steels. A decrease in impact resistance as the test temperature was lowered was characteristic of these steels.

CONTENTS

I. INTRODUCTION

The temperature of the atmosphere in which aircraft operate frequently is considerably lower than the temperatures on the earth's surface and may reach a minimum of −60° C at high altitudes. It is known that such subzero temperatures may have marked effects upon certain mechanical properties of metals. Although the general relationship of mechanical properties and low temperatures is familiar to many metallurgists and engineers, test data on specific commercial materials are usually a welcome addition to technical literature.

This paper contains the results of tests to determine the effect of low temperatures upon specific alloys used or considered for use in aircraft. The tests were made at the National Bureau of Standards, under the sponsorship and direction of the Bureau of Aeronautics, U. S. Navy Department.

II. PREVIOUS INVESTIGATIONS

Various investigators are in agreement that yield and tensile strengths, endurance limit, and hardness of metals increase as the temperature of test decreases. Ductility, as evidenced by elongation and reduction of area, usually varies but slightly down to about −80° C. At extremely low temperatures, however (liquid air or liquid hydrogen), elongation and reduction of area are markedly decreased.

The property most deleteriously affected by low temperatures is impact resistance. In most nonaustenitic steels the resistance to impact decreases more or less rapidly as the temperature drops from about +20° to −80° C (with the ordinary type of impact test specimen and velocity of blow). The major decrease, from maximum to minimum values, frequently occurs within narrow temperature limits termed the "transition range" to cold brittleness. Below −80° C the impact values decline at a much slower rate.

The deleterious effect of notches becomes considerably more pronounced at low temperatures. The impact resistance of notched bars drops with decreasing test temperatures. Decreased sharpness of notch causes the transition range to appear at lower temperatures and in unnotched bars the impact resistance may not be materially affected until considerably lower temperatures are reached.

So many factors influence the impact resistance of metals that, in order to secure some idea of the relative value and proper interpretation of impact test data, it is practically imperative that an understanding of the general theoretical facts underlying impact testing be had. McAdam and Clyne [1] [1] review the theory of impact testing and explain the influence of velocity of blow, form, and size of specimen, size of notch, and other variables on cold brittleness. According to these authors, test factors contributing to an increased tendency to cold brittleness are increased velocity of deformation, increased size of specimen, and increased depth and sharpness of notch.

Russell [2], in a paper summarizing the literature, gave a list of the changes in properties caused by low temperatures as follows:

Yield point	Increase.
Tensile strength	Do.
Elongation	Probably small decrease.
Reduction of area	Decrease.
Impact resistance	Do.
Hardness	Increase.
Endurance limit	Do.
Modulus of elasticity	Do.
Compressibility	Decrease.
Thermal expansion	Do.
Specific heat	Do.
Thermal conductivity	Increase.
Electrical conductivity	Do.

[1] Figures in brackets refer to the literature references at the end of this paper.

In discussion of Russell's paper, Strauss maintained that not all of these generalizations were warranted.

The selected references at the end of this paper contain material which is either of general interest to the subject of impact testing at low temperatures or else gives data on the low-temperature properties of metals similar to some included in the present work.

III. APPARATUS AND METHODS OF TEST

Since the minimum temperature to which aircraft may be subjected in service is approximately −60° C (−76° F), the sublimation point of carbon dioxide (−78.5° C) (−109° F) was chosen as the lowest temperature of test. Tensile, hardness, and impact tests were made at the following temperatures:

Tensile tests—room temperature and −78° C
Hardness tests—room temperature, 0°, −40°, and −78° C
Impact tests—+100° C (certain steels only), room temperature, 0°, −20°, −40°, and −78° C.

Tests were also made at room temperature after previous exposure of specimens at −78° C to determine whether any change in mechanical properties occurred after temporary exposure to this temperature. It may be noted here that testing at room temperature after prolonged exposure at −78° C had no effect upon the tensile, hardness, or impact properties of any of the metals tested, with but one or two exceptions, which will be noted in the proper place.

1. METHODS OF SECURING TEST TEMPERATURES

The temperature of +100° C was obtained by the use of boiling water. The temperature of 0° C was readily obtained by the use of melting crushed ice. An excess of solid carbon dioxide in a mixture of equal parts of carbon tetrachloride and chloroform was used for temperature maintenance at −78° C. Since carbon dioxide passes directly to a gas from the solid state, no dilution or other change occurred in the liquid bath and carbon dioxide could be added as needed. Temperatures between 0° and −78° C were easily maintained by regulated additions of carbon dioxide. The mixture utilized for the bath had the added advantage of being nonflammable.

The temperature of the cooling bath at −20° and −40° C was measured with a copper-constantan thermocouple. No measurements, except during calibration, were made at the other temperatures.

2. TENSILE TESTS

In view of the fact that a study of the literature revealed that the tensile properties of metallic materials are not adversely affected at temperatures down to −80° C, and since these tests are very time-consuming, it was decided to make tensile tests at room temperature and −78° C only. The only adverse effect of low temperature on tensile properties which might be expected would be exhibited in the ductility and it was felt that this property could be better evaluated by means of the impact tests.

All tensile tests were made in duplicate in an Amsler hydraulic testing machine of 50,000-lb capacity. The type of specimen used for the tensile tests of all materials except the wrought aluminum alloys is shown in figure 1. Because of the deleterious effect of notches the diameter of the tensile specimen at the gage marks was made appreciably greater than the diameter of the gage length itself. This design was effective in preventing breaks through the gage marks. Strain readings taken on such a specimen, however, were slightly lower than the true strain readings over the full gage length

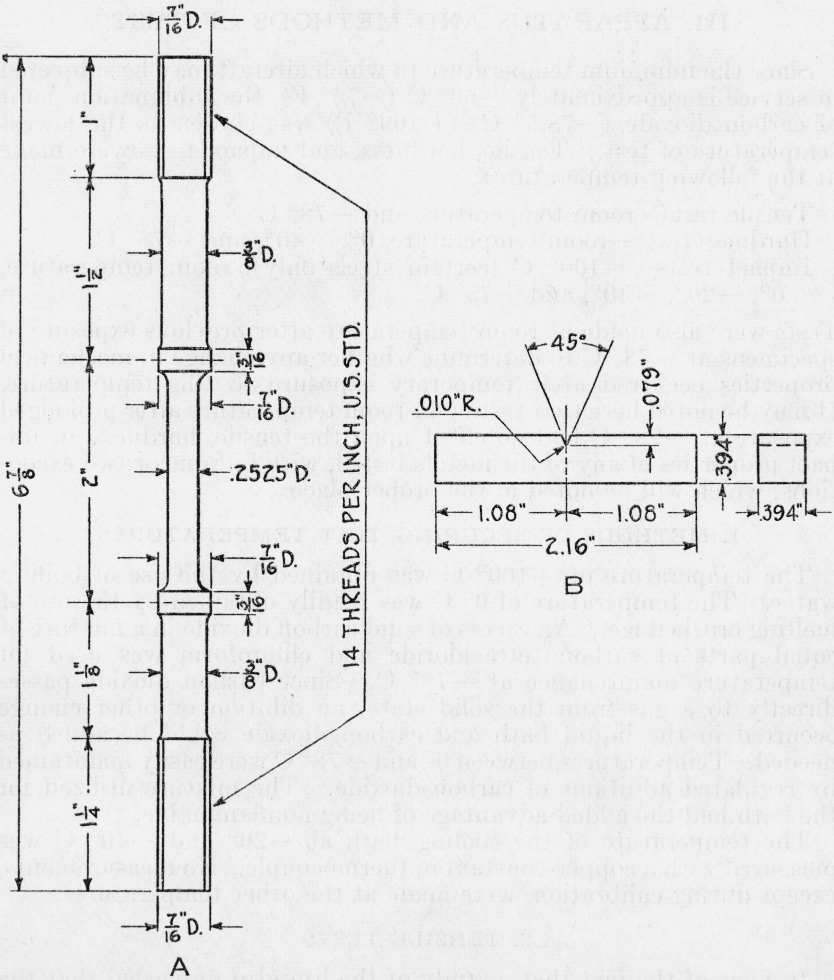

FIGURE 1.—*Specimens used for tensile and impact tests of all materials except the wrought aluminum alloys.*

A, tensile specimen; *B*, impact specimen.

of uniform diameter and the resultant stress-strain curve gave a modulus of elasticity which was higher than the actual value. A correction (−6.5 percent) calculated from the shape of the specimen, was applied to all determinations of modulus of elasticity.

Since the wrought aluminum alloys were supplied in plates ½ in. thick, it was necessary to use a different type of tensile specimen (fig. 2) for these alloys. As before, the cross-sectional area at the gage marks was somewhat greater than the area of the reduced sec-

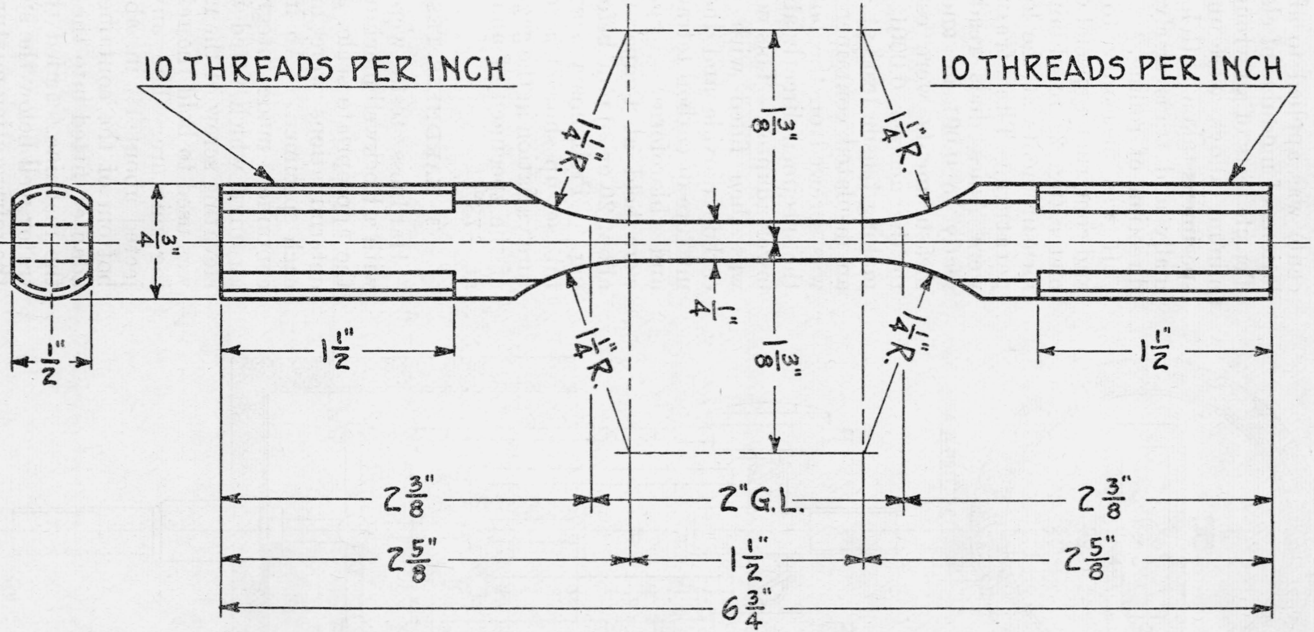

FIGURE 2.—*Specimen used for tensile tests of the wrought aluminum alloys.*

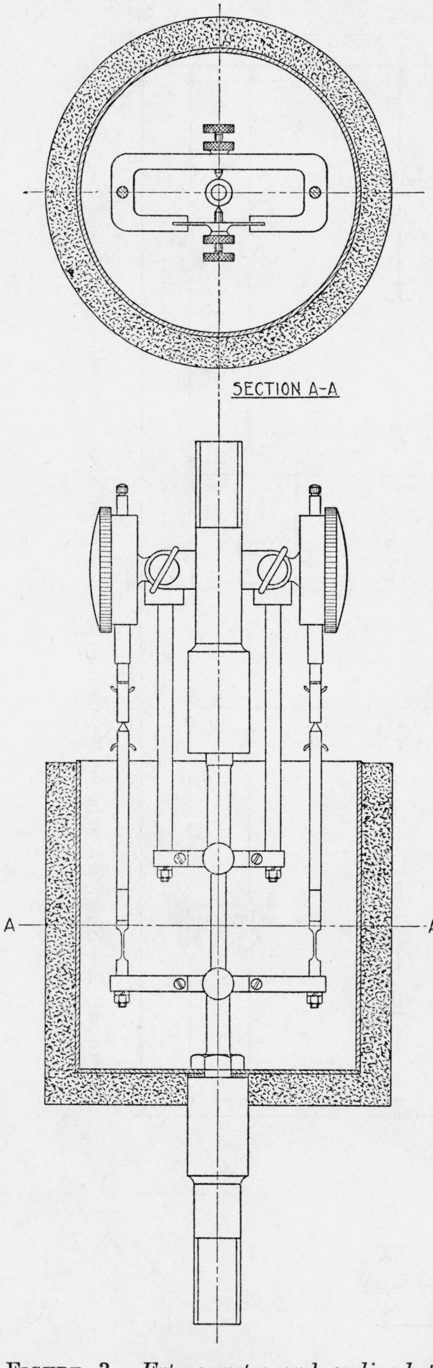

FIGURE 3.—*Extensometer and cooling-bath assembly used in the tensile tests.*

tion and a correction (−2.4 percent) was applied to all calculations of modulus of elasticity. Tensile tests of all wrought aluminum alloys were made on specimens taken both longitudinally and transversely to the direction of rolling.

It was necessary to design and construct a special extensometer (fig. 3) to obtain strain measurements at the low temperature. The strain gages were Ames dials reading directly to 0.001 in. and strain measurements were estimated to the nearest 0.0001 in. In making tensile tests at −78° C an insulated container (fig. 3) was screwed on the bottom of the specimen directly above the lower adapter. This container was then filled with cracked carbon dioxide and the 50–50 mixture of carbon tetrachloride and chloroform. Specimens were held at temperature for about 20 or 30 min before testing. Preliminary surveys of this set-up showed a temperature variation in the gage length of the specimen of about ±1° at −78°C.

3. HARDNESS TESTS

Hardness tests were made with a Rockwell machine, using the appropriate scale, and five determinations were made on each specimen. An insulated container, made integral with an anvil which fitted into the elevating screw of the machine, was used to hold the refrigerating mixture. The anvil projected about 1½ in. above the bottom of the container. An adapter, fitted into the head of the machine, carried the penetrator well below the surface of the refrigerating mixture. Thus the test specimen, anvil, and penetrator were all immersed in the cooling bath during the test. Specimens were held at temperature for about 20 or 30 min before testing.

4. IMPACT TESTS

The type of test specimen used for impact tests of all materials except the wrought aluminum alloys is shown in figure 1. A modified specimen (fig. 4) was used for the latter in order to get some measure of the differences in impact resistance caused by the cold-worked skin. With the wrought aluminum alloys, impact tests were made on specimens taken both longitudinally and transversely with respect to the direction of rolling. Impact tests on the SAE steels were made

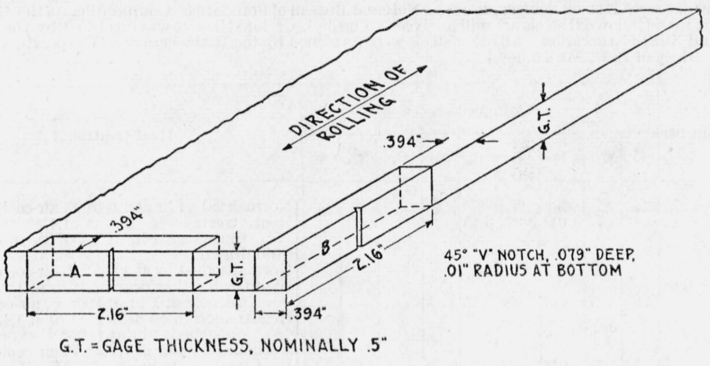

FIGURE 4.—*Location of Charpy impact specimens in wrought aluminum alloy plate.* *A*, transverse specimen; *B*, longitudinal specimen.

in duplicate at all temperatures except +100° C, at which temperature four specimens were tested; impact tests on all other materials were made in quadruplicate. The light metal alloys, with the exception of alloys 3S and 52S, were tested in a Charpy machine of 30 ft-lb capacity; all other materials were tested in a machine of 224 ft-lb capacity. The constants of these two Charpy machines were as follows:

Capacity	224.1 ft-lb	30 ft-lb.
Weight of hammer	50.8 lb	8.436 lb.
Height of drop of hammer	4.411 ft	3.556 ft.
Distance from center of axis of rotation to center of gravity of striking mass	2.277 ft	1.583 ft.
Distance from center of axis of rotation to center of percussion	2.478 ft	1.833 ft.
Velocity of hammer at time of impact	16.85 ft/sec	15.14 ft/sec.
Distance between supports	1.6 in	1.6 in.

The specimens were placed in an insulated container holding the cooling bath, held at temperature for at least 30 min., and then quickly transferred to the impact machine and broken. The average time required to transfer the specimens from the cooling bath to the machine and then to trip the hammer was about 2 sec. Calibration of dummy specimens showed no appreciable changes in temperature during this interval.

IV. MATERIALS TESTED

The materials tested may be divided into three general groups, as follows: (1) Ferritic steels; (2) austenitic stainless steels and nickel alloys; and (3) light metal alloys (Al- and Mg-base).

1. FERRITIC STEELS

The term "ferritic steels" is used in this report to designate all steels which contain alpha iron at room temperature, regardless of the method of cooling. The steels used in this study which fall into this classification are various SAE steels, a Cr-Ni-Mo steel and a hardenable stainless steel of the 16-Cr–2-Ni type.

TABLE 1.—*Chemical compositions and heat treatments of the ferritic steels*

[Analyses of the SAE steels were made at the National Bureau of Standards. Compositions of the Cr-Ni-Mo and the high-Cr–low-Ni steels are mill analyses. The high-Cr–low-Ni steel was furnished by the Rustless Iron and Steel Corporation. All other steels were furnished by the Bethlehem Steel Corporation, through the courtesy of P. E. McKinney.]

SAE Number	Composition									Heat treatment
	C	Mn	P	S	Si	Ni	Cr	Mo	V	
	%	%	%	%	%	%	%	%	%	
1045	0.45	0.77	0.013	0.022	0.21					Normalized—1 hr at 1,600° F, air-cooled. Heat treated—¾ hr at 1,475° F, water quenched; 1 hr at 1,000° F, air-cooled. Cold drawn.
1095	.93	.27	.014	.023	.15					Normalized—1 hr at 1,475 °F, air-cooled. Heat treated (low draw)—½ hr at 1,425° F, oil quenched; 1 hr at 600° F, air-cooled. Heat treated (high draw)[1]—1 hr at 1,425° F, oil quenched; 1 hr at 1,075° F, air-cooled.
2330	.34	.72	.018	.017	.26	3.30				Normalized—1 hr at 1,700° F, air-cooled. Heat treated—½ hr at 1,475 °F, oil quenched; 1 hr at 1,000 °F, air-cooled.
X4130	.29	.50	.015	.013	.16		0.98	0.21		Normalized—1 hr at 1,600 °F, air-cooled. Heat treated (low draw)—¾ hr at 1,575 °F, oil quenched; 1 hr at 600° F, air-cooled. Heat treated (high draw)[1]—½ hr at 1,575° F, oil quenched; 1 hr at 1,075° F, air-cooled.
6130	.29	.69	.017	.022	.01		.96		0.17	Normalized—1 hr at 1,700° F, air-cooled. Heat treated—½ hr at 1,625° F, oil quenched; 1 hr at 1,175° F, air-cooled.
Cr-Ni-Mo	.47	.80	.014	.025	.29	1.80	1.04	.22		Annealed—4 hr at 1,450° F, furnace cooled 1 hr, then cooled to 1,100° F at the rate of approximately 150° F per hr and then cooled to 850° F at the rate of approximately 250° F per hr. Heat treated—annealing treatment as above, then ¾ hr at 1,520° F, oil quenched; 1 hr at 1,100° F, air-cooled.
High-Cr-low-Ni.	.11	.44	.014	.024	.26	1.72	16.27			Heat treated—1,800° F, oil quenched; 850° F, air-cooled.

[1] Impact tests only were made on these materials.

All steels were received in the form of ⅝-in. diameter rods. Heat treatments were carried out on the ⅝-in. rods, the test specimens being subsequently machined therefrom. The SAE steels, with the single exception of one cold-drawn steel, were received in the hot-rolled condition. The Cr-Ni-Mo steel and the high-Cr–low-Ni steel were received as heat treated. Details of composition and heat treatment are given in table 1.

2. AUSTENITIC STAINLESS STEELS AND NICKEL ALLOYS

All these materials were received in the form of ⅝-in. diameter rods. Details of compositions and heat treatments are given in table 2.

TABLE 2.—*Chemical compositions and treatments of the austenitic stainless steels and nickel alloys*

Material	Composition													Treatment
	C	Mn	P	S	Si	Ni	Cr	Ti	Cb	Mo	Al	Fe	Cu	
	%	%	%	%	%	%	%	%	%	%	%	%	%	
18-8	0.07	0.44	0.012	0.018	0.50	8.63	18.22	----	----	----	----	----	----	Annealed—1 hr at 1,900° F, water quenched. Hot-rolled. Cold drawn.
18-8, stabilized with Ti.	.05	.39	.010	.015	.62	9.15	19.04	0.29	----	----	----	----	----	Annealed—1 hr. at 1,900° F, water quenched. Hot-rolled. Cold drawn.
18-8, stabilized with Cb.	.07	.42	.027	.028	.32	10.29	18.97	----	0.95	----	----	----	----	Annealed—1 hr. at 1,900° F, water quenched. Hot-rolled. Cold drawn.
18-8, stabilized with Mo.	.07	.93	.026	.012	.42	8.93	18.58	----	----	3.36	----	----	----	Annealed (exact treatment unknown).
	.07	.73	.017	.019	.48	7.88	18.41	----	----	2.80	----	----	----	Cold drawn.
K Monel	.23	.25	----	----	.27	diff.	----	----	----	----	3.1	1.7	29.9	Cold drawn and then tempered to grade C (300 BHN).
Monel metal	.18	1.0	----	----	.06	diff.	----	----	----	----	0.10	1.7	29.2	Cold drawn.
Nickel	.14	0.24	----	----	.03	diff.	----	----	----	----	nd [1]	0.10	0.03	Do.
Inconel	.06	.53	----	----	----	diff.	13.4	----	----	----	----	7.4	----	Hot-rolled, then annealed 2 hr at 1,750° F and quenched in alcohol. Cold drawn, then normalized at 525° F and air-cooled.

[1] nd=not detected.

3. LIGHT METAL ALLOYS

The light metal alloys were furnished in the following forms: (1) Cast aluminum alloys, bars 12 in. long, ¾ in. diameter; (2) cast magnesium alloys, bars 8 in. long, ⅝ in. diameter; (3) wrought aluminum alloys, plates 30 in. (in the direction of rolling), 12 in. wide, ½ in. thick; and (4) extruded magnesium alloys, bars about 15 ft long, ½ in. square. Details of composition and treatments are given in table 3.

TABLE 3.—*Chemical compositions and treatments of the light metal alloys*

[All analyses were made at the National Bureau of Standards except those of alloys 195-T4, 220-T4, 355-T4, 356-T4, which were furnished by the Aluminum Company of America. Referring to the wrought aluminum alloys, items finishing in the as-rolled or heat-treated condition were hotrolled directly to the finished gage. Items finishing in the RT temper were hot rolled to 5½ percent above the finished thickness, heat treated, and cold rolled to the final gage. All treatments applied to both the aluminum- and magnesium-base alloys were performed by the manufacturer]

Material	Composition									Treatment
	Si	Fe	Cu	Mn	Zn	Mg	Al	Sn	Cr	
	%	%	%	%	%	%	%	%	%	
3S	0.14	0.45	0.12	1.04	---	----	diff.	----	----	As rolled.
17ST	.46	.43	3.72	0.59	---	0.62	diff.	----	----	1 hr at 935° to 945° F, water quenched.
17SRT	.46	.29	3.90	.63	---	.63	diff.	----	----	
24ST, 24SRT	.14	.16	4.32	.48	---	1.44	diff.	----	----	1 hr at 916° to 924° F, water quenched.
25ST	.70	.50	4.26	.82	---	0.03	diff.	----	----	2 hr at 960° to 970° F, water quenched; aged 18 hr at 290° F.
25SRT	.73	.48	4.41	.80	---	.02	diff.	----	----	
27ST	.81	.36	3.99	.79	---	.01	diff.	0.04	----	1½ hr at 960° to 970° F, water quenched; aged 18 hr at 320° F.
52S	.12	.14	0.05	----	---	2.35	diff.	----	0.27	As rolled.
195-T4	.84	.53	4.35	----	---	----	diff.	----	----	As cast, 16 hr at 960° F, quenched in water at 200° to 212° F.
220-T4	.07	.13	0.03	----	---	10.49	diff.	----	----	As cast, 16 hr at 810° F, quenched in oil at 250° F.
355-T4	4.76	.26	1.25	----	---	0.49	diff.	----	----	As cast, 16 hr at 980° F, quenched in water at 200° to 212° F.

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TABLE 3.—*Chemical compositions and treatments of the light metal alloys*—Con.

Material	Composition									Treatment
	Si	Fe	Cu	Mn	Zn	Mg	Al	Sn	Cr	
	%	%	%	%	%	%	%	%	%	
356-T4	6.71	.26	0.08	----	---	.25	diff.	----	----	As cast, 16 hr at 1,000° F, quenched in water at 200° to 212° F.
Dowmetal M	----	.01	----	1.6	[1]nd	diff.	0.02	----	----	16 hr at 750° F, followed at once, without quenching, by extrusion at 750° F and then air-cooled.
Dowmetal J	----	.06	----	0.22	1.0	diff.	5.8	----	----	Do.
Experimental Dowmetal.	----	.01	----	1.5	4.0	diff.	0.02	----	----	16 hr at 700° F, followed at once, without quenching, by extrusion at 750° F and then air-cooled.
Dowmetal G	----	.02	----	0.24	[1]nd	diff.	10.5	----	----	As sand cast. As sand cast, then 16 hr at 770° F and air-cooled. As sand cast, then 16 hr at 770° F, air-cooled, and aged 16 hr at 350° F.
Dowmetal H	----	.02	----	.28	2.7	diff.	6.3	----	----	As sand cast. As sand cast, then 4 hr at 630° F plus 16 hr at 720° F and air-cooled. As sand cast, then 4 hr at 630° F plus 16 hr at 715° F, quenched in hot water, and aged 16 hr at 350° F.

[1] nd=not detected.

Since the cold work given to heat-treated aluminum alloys is essentially a skin effect, it would not be expected that material ½-in. thick would be representative of fully worked aluminum alloys. It was felt, however, that the trend in mechanical properties caused by cold working would be indicated by the tests.

V. RESULTS OF TESTS

1. FERRITIC STEELS

(a) TENSILE TESTS

The tensile tests (figs. 5 and 6) on the ferritic steels showed the following changes in properties at −78° C as compared to room temperature: (1) The tensile strengths increased between 10,000 and 20,000 lb/in ^{2}; (2) the yield strengths increased between 7,000 and 22,000 lb/in ^{2}, with the greater increases occurring in the heat-treated steels; (3) the modulus of elasticity was unaffected, except for the normalized SAE 2330 steel, where loss resulted; and (4) the elongation values usually exhibited a slight increase, while reductions of area were sometimes lower, thus indicating no significant changes in ductility. The modulus of elasticity of the normalized SAE 2330 steel was also decreased at room temperature after previous exposure at −78° C. With this one exception, the results of these tests indicated quite definitely that the temperature of −78° C had no deleterious effect upon the tensile properties of any of the ferritic steels studied.

(b) HARDNESS TESTS

As a general rule, the hardness of the ferritic steels tended to increase slightly as the test temperature decreased to −78° C (fig. 7).

(c) IMPACT TESTS

The results of the impact tests on the ferritic steels are given in figure 8. An examination of this figure reveals that all steels which had an appreciable resistance to impact at room temperature lost a great portion of this impact resistance at −78° C.

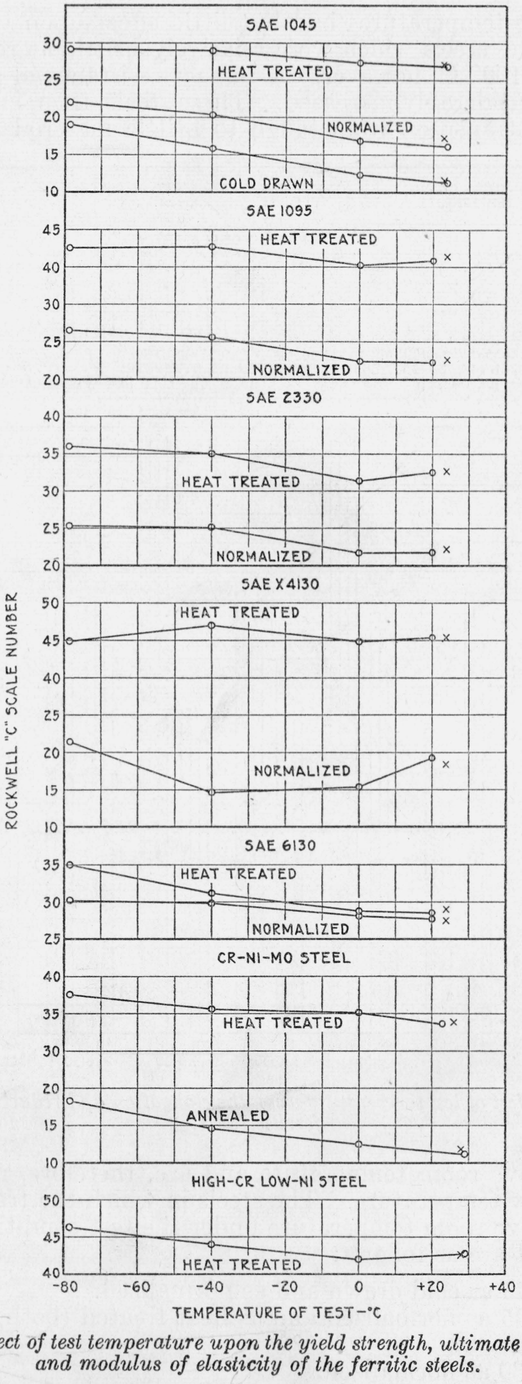

FIGURE 5.—*Effect of test temperature upon the yield strength, ultimate tensile strength, and modulus of elasticity of the ferritic steels.*

Decreasing temperatures had but little effect upon the impact resistance of the steels which were relatively brittle at room temperature. At +100° C, however, the impact resistance of some of these steels was considerably increased. These steels, then, are those which undergo the transition from tough to brittle material at some tem-

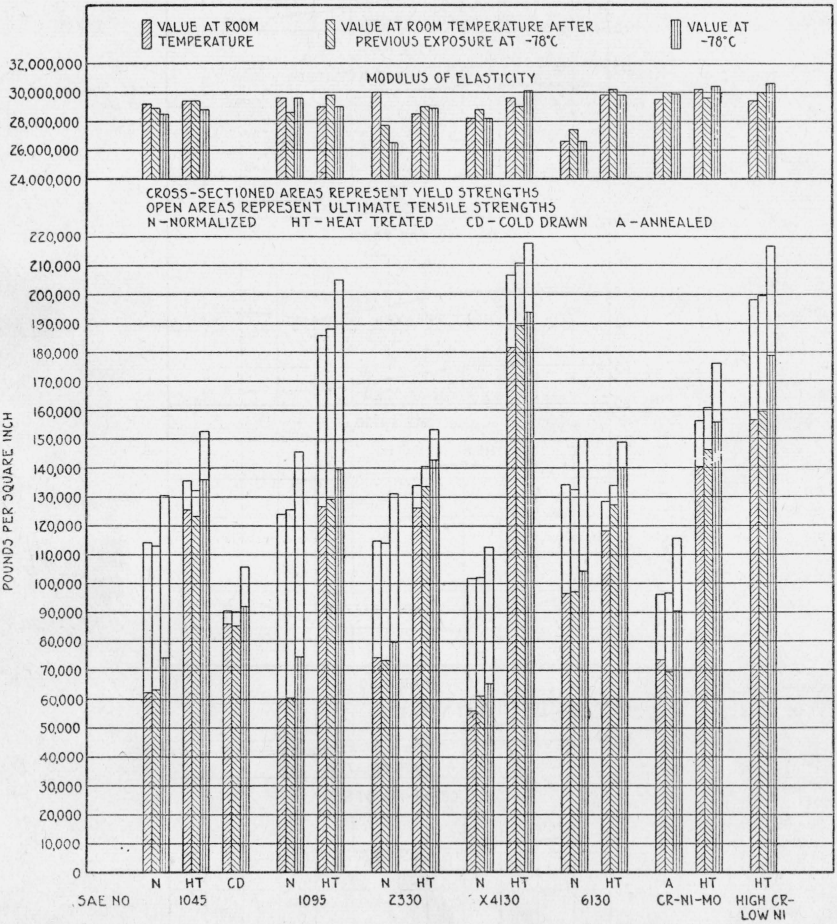

FIGURE 6.—*Effect of test temperature upon the elongation and reduction of area of the ferritic steels.*

perature above room temperature and are, therefore, most unsuited for use at low temperature. The steels in which the transition range occurred above room temperature under the test conditions described in this report are as follows:

SAE 1045 as cold drawn and as normalized.
SAE 1095 as normalized and as heat treated (both high and low draw).
SAE 2330 as normalized.
SAE X4130 as normalized and as heat treated (low draw).
SAE 6130 as normalized.
High-Cr-low-Ni steel as heat treated.

Decreasing temperatures had a marked deleterious effect, however, upon those steels which had a relatively high resistance to impact at room temperature. It is worthy of note that at +100° C the impact resistance of these steels was no better than at room temperature; in fact in the case of the heat-treated SAE 6130 steel it was decidedly less. In these steels the temperature at which considerable resistance to impact is developed is room temperature or even lower; the transition range is thus moved to lower temperatures and therefore these

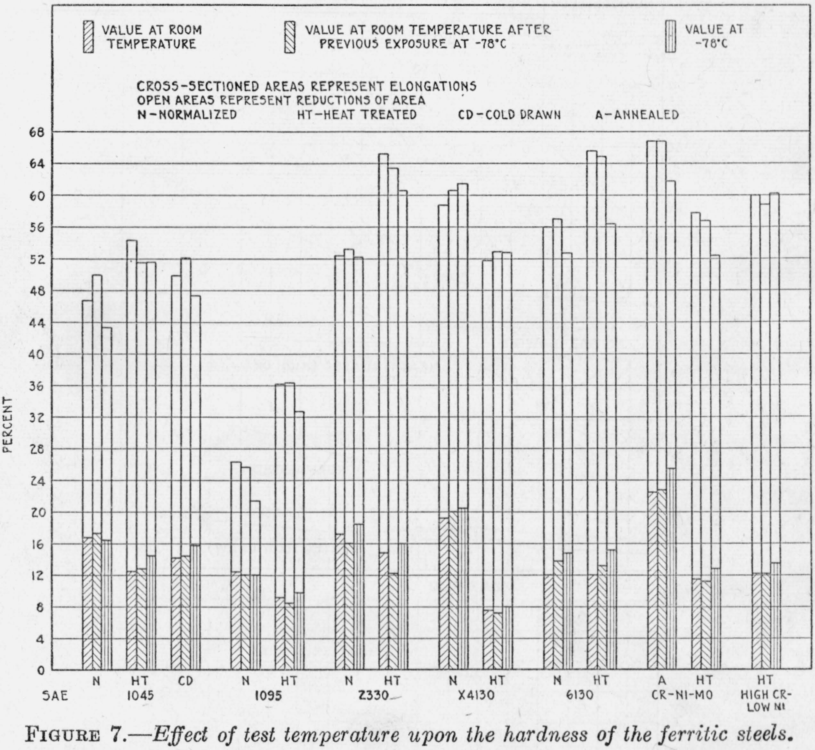

FIGURE 7.—*Effect of test temperature upon the hardness of the ferritic steels.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

steels are more suitable for use at sub-zero temperatures. These steels were as follows:

SAE 1045 as heat treated.
SAE 2330 as heat treated.
SAE X4130 as heat treated (high draw).
SAE 6130 as heat treated.
Cr-Ni-Mo steel as annealed and as heat treated.

It may be noted that the normalized SAE steels tested did not have a very great measure of resistance to impact at room temperature and even less at −78°C. When they were properly heat treated, however, the impact resistance was considerably improved. It is well known that maximum impact resistance is developed in steels which have been completely sorbitized. The effect of a high and low tempering treatment upon the impact resistance may be observed in the case of

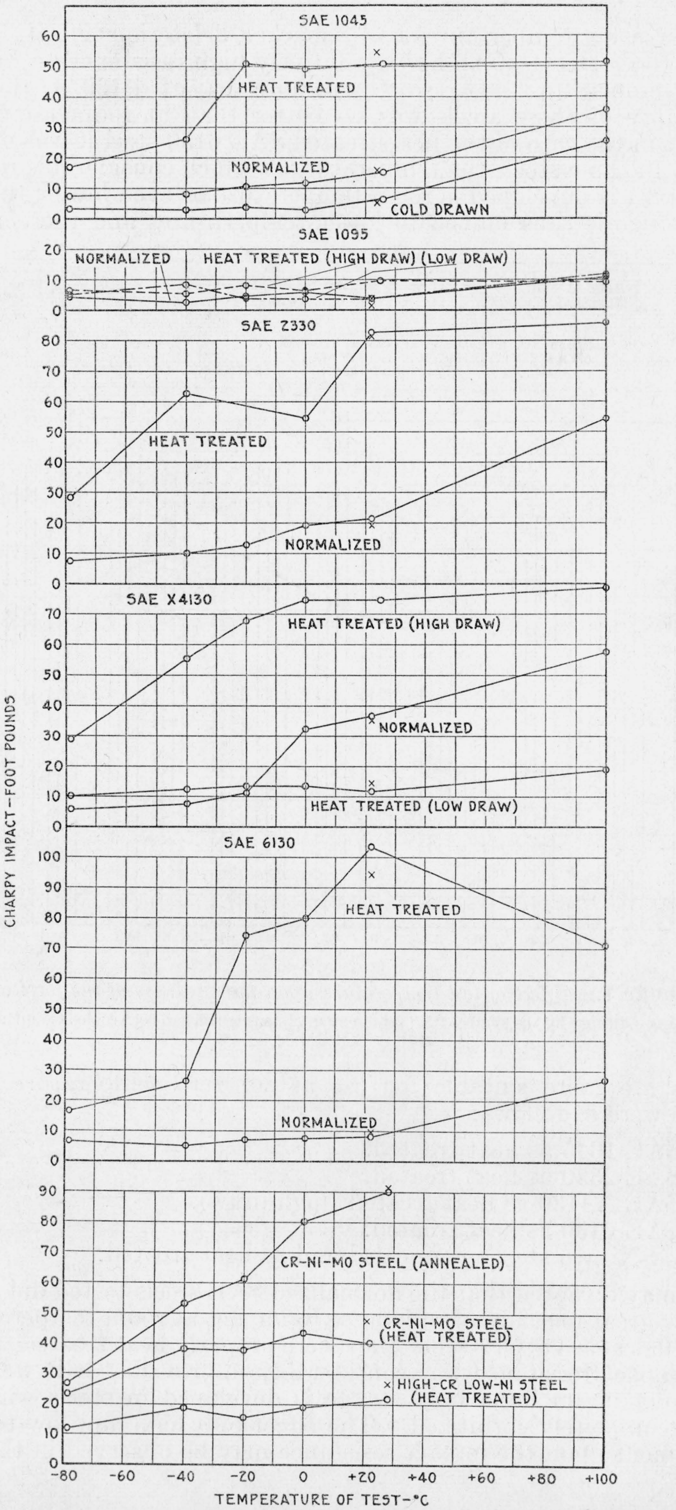

Figure 8.—*Effect of test temperature upon the impact resistance of the ferritic steels.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

the SAE X4130 steel. When tempered at 600° F subsequent to hardening this steel had an impact resistance of only 12 ft-lb at room temperature and 10 ft-lb at −78°C. When tempered at 1,075° F, however, the values were 75 and 29 ft-lb, respectively. The effect of this higher tempering treatment was to move the transition range in this steel from above +100° C to below −40° C. The SAE 1095 steel was normally coarse-grained and brittle and tempering at 1,075° F failed to cause any significant improvement in impact resistance as compared with the steel tempered at 600° F.

The test data showed that the 16-Cr–2-Ni steel did not have very good impact resistance when tempered at 850° F. Some data, not yet available for publication, indicated that high impact resistance in this steel may be obtained with lower tempering temperatures. This is an extremely unusual trend and a detailed study of this particular type of steel is in progress.

It is incorrect to assume that a steel having the highest resistance to impact at room temperature would always maintain this superi-

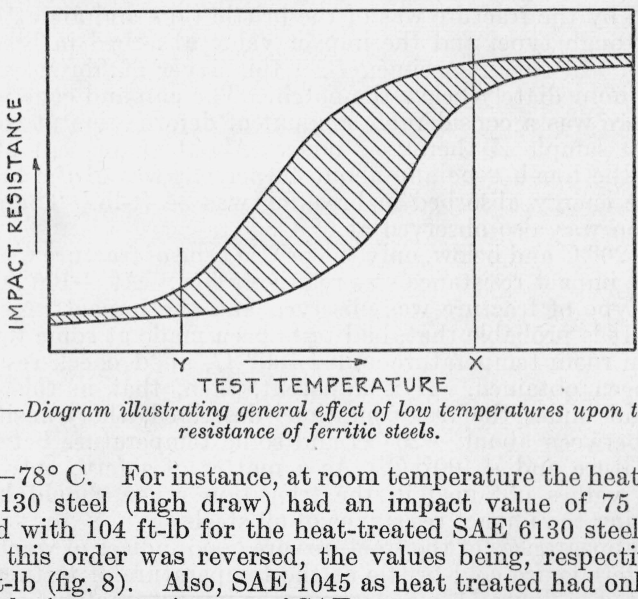

FIGURE 9.—*Diagram illustrating general effect of low temperatures upon the impact resistance of ferritic steels.*

ority at −78° C. For instance, at room temperature the heat-treated SAE X4130 steel (high draw) had an impact value of 75 ft-lb as compared with 104 ft-lb for the heat-treated SAE 6130 steel; but at −78° C this order was reversed, the values being, respectively, 29 and 17 ft-lb (fig. 8). Also, SAE 1045 as heat treated had only about one-half the impact resistance of SAE 6130, at room temperature but both steels had the same values at −40° and at −78° C.

The rate at which the impact resistance drops with decreasing temperature is also important, being rapid in some steels and gradual in others. As a general rule, the steels showing a gradual drop in impact resistance with decreasing temperature should be more suitable for sub-zero service than those showing a more abrupt drop.

The general effect of low temperatures upon the impact resistance of ferritic steels is diagrammatically illustrated in figure 9. The shaded area represents the scatter of energy absorbed. In the transition range, in which the impact resistance decreases more or less rapidly, there frequently occurs a marked scattering of test values. The results of tests at temperatures above "X" and below "Y" are usually in fair agreement.

An examination of the fractured surfaces of impact test specimens reveals a certain correlation between their appearances and the shape of the impact-temperature curve. At temperatures above "X" the fractures have a dull, fibrous appearance; there is a considerable amount of deformation and they are typical of what are usually referred to as tough fractures. Below temperature "Y" the fractures have a bright, crystalline appearance; there is very little deformation and they are typical of what are usually referred to as brittle fractures. Between these two temperatures (the transition range), fractures having a partly tough and partly brittle appearance are not uncommon.

This is exemplified in figure 10 which shows duplicate impact specimens from a steel tested at room temperature (SAE X4130 as normalized). Sample *A* broke with almost an entirely brittle fracture. A small part of the fracture, representing the area occupied by a slight cup and cone at the sides and a small area at the bottom, had the characteristics of the tough type. About 85 percent of the area covered by the fracture was of the brittle type and about 15 percent of the tough type, and the impact value absorbed in breaking was 19 ft-lb. In check specimen *B*, a thin layer of fibrous appearance existed immediately below the notch. The cup and cone was deeper and there was a considerable amount of deformation at the bottom, while in sample *A* there was none. About 60 percent of the area was of the tough type and about 40 percent was of the brittle type, and the energy absorbed in breaking was 54 ft-lb. The same phenomenon was also observed at 0° C.

At −20° C and below, only the brittle type of fracture was observed and the impact resistance was relatively low. At +100° C only the tough type of fracture was observed and the impact resistance was high. It is probable that, had tests been made at some temperature between room temperature and +100° C, good check results would have been obtained. It is apparent, then, that in this particular steel and under the test conditions described, the transition range exists between about −20° C and some temperature between room temperature and +100° C. As a matter of safety, only the lower impact values obtained in the transition range should be used in evaluating the impact resistance of all steels.

The appearances of the fractures are good indices of whether or not the materials are cold brittle at the temperature of testing. This is illustrated in figure 11, which shows the impact fractures of SAE 1045 steel as normalized, as heat treated, and as cold drawn. Both the normalized and cold-drawn steels exhibited brittle fractures at room and lower temperatures; reference to figure 8 corroborates the fact that the transition range of the steel thus treated exists above room temperature. At +100° C the normalized steel exhibited a fracture which was almost entirely of the tough type (fig. 12). The heat-treated steel, however, exhibited a fibrous fracture at test temperatures down to −20° C, while evidence of a brittle fracture was first found at −40° C. The impact-temperature curve (fig. 8) locates the transition range of the heat-treated steel below −20° C.

The fact that temperature is only one of the variables which affect the brittleness of materials should be emphasized. Other important variables are shape and size of specimen and the velocity of deformation. In the impact tests described in this report all these variables,

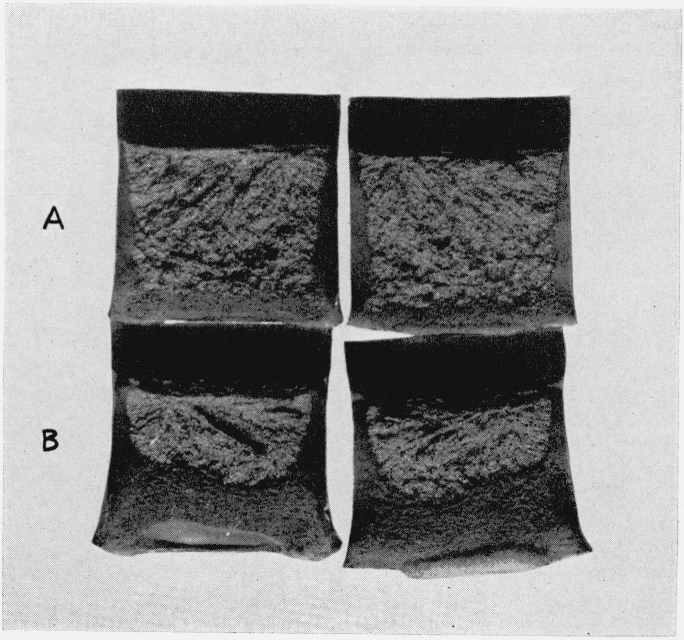

FIGURE 10.—*Appearance of the impact fracture of normalized SAE X4130 steel broken at room temperature.* ×3.

A, Brittle fracture, 19 foot-pounds.
B, Tough fracture, 54 foot-pounds.

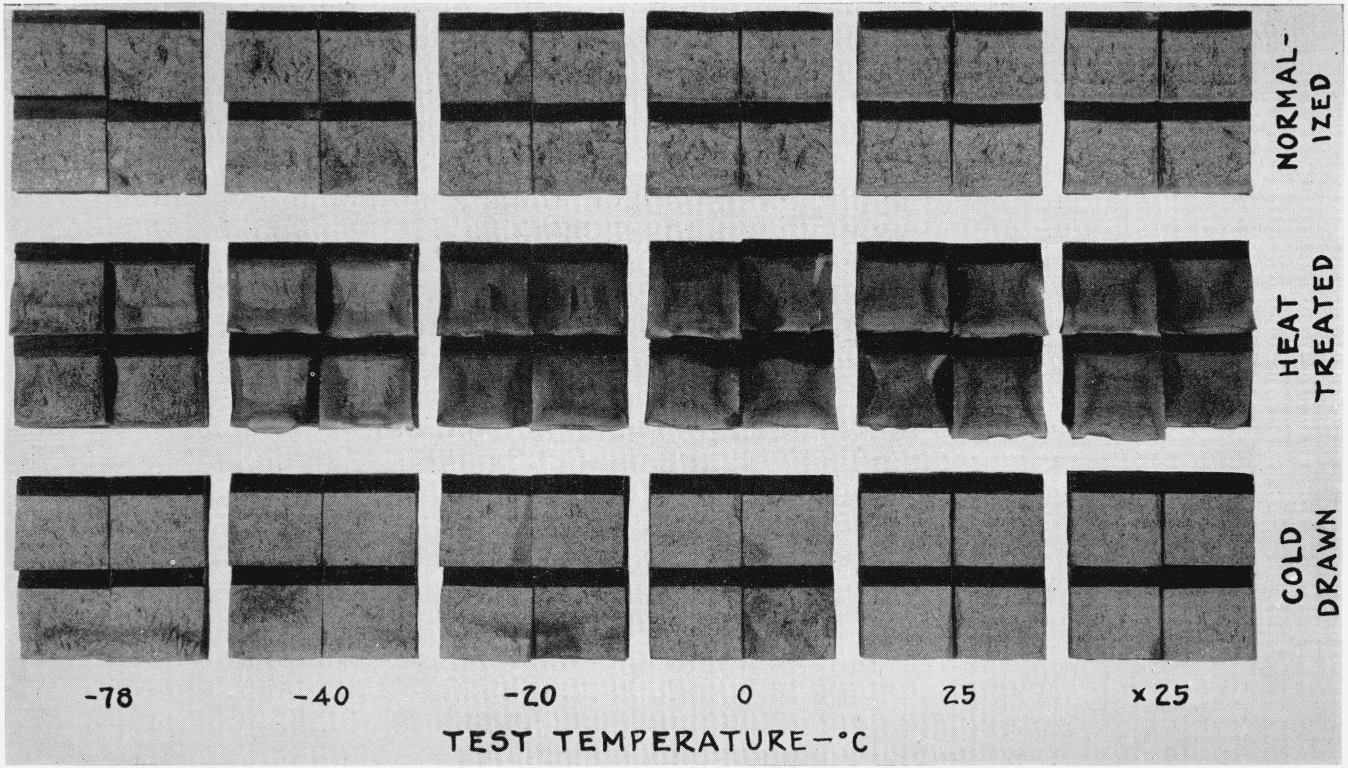

FIGURE 11.—*Impact fractures of SAE 1045 steel.* ×1.

Symbol "X" at the test temperature of 25° C indicates that these specimens had been cooled to and held at −78° C prior to breaking at room temperature.

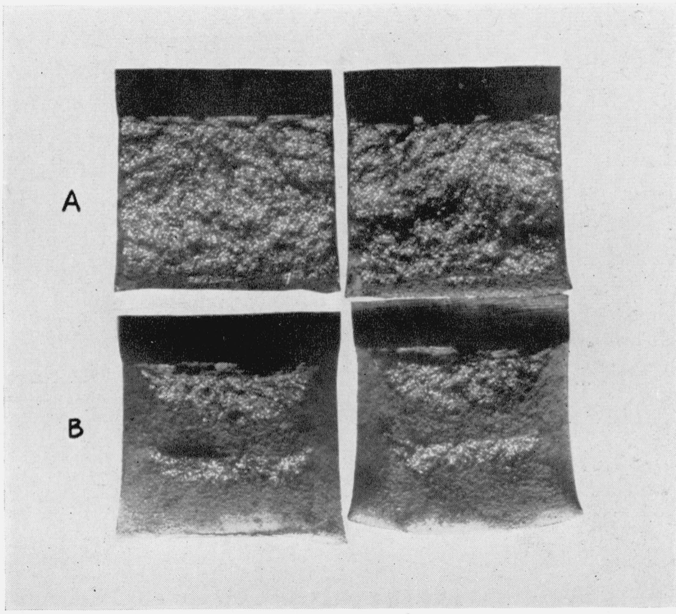

FIGURE 12.—*Appearance of the impact fracture of normalized SAE 1045 steel.* × 3.

A, Broken at room temperature, 15 foot-pounds.
B, Broken at +100° C, 35 foot-pounds.

except temperature, were arbitrarily fixed and the data thus secured gave information about the relative value of these steels at low temperatures. If any one of the other variables had been changed,

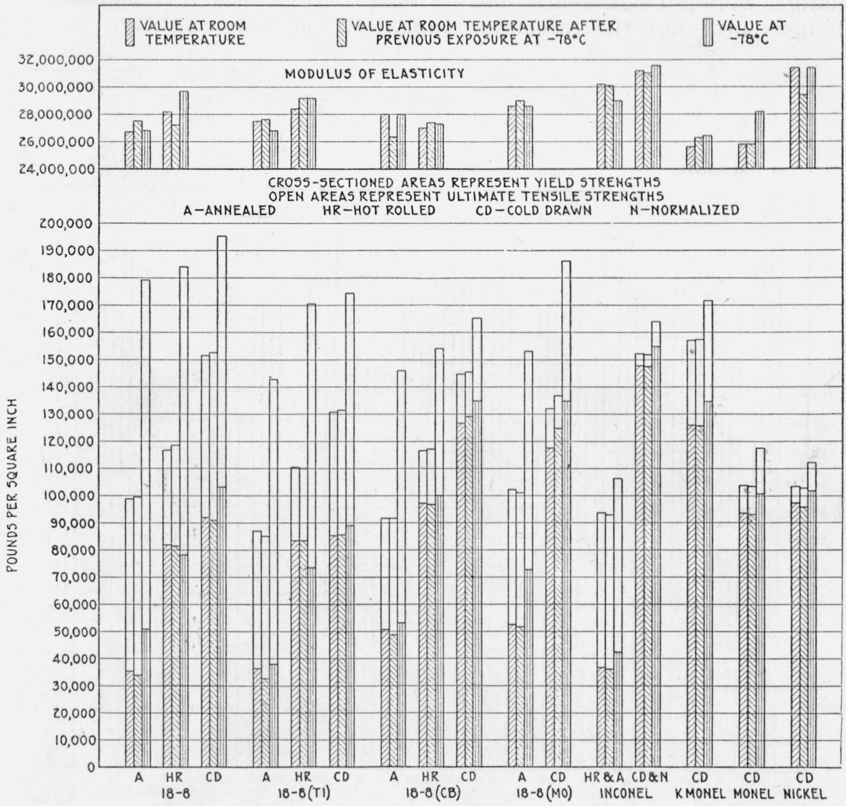

FIGURE 13.—*Effect of test temperature upon the yield strength, ultimate tensile strength, and modulus of elasticity of the austenitic stainless steels and the nickel alloys.*

the temperatures at which cold brittleness appeared might have been different.

2. AUSTENITIC STAINLESS STEELS AND NICKEL ALLOYS

(a) TENSILE TESTS

The tensile tests (fig. 13 and 14) on the austenitic stainless steels and nickel alloys showed the following changes in properties at −78° C as compared with room temperature:

Stainless Steels.—(1) The tensile strengths increased between 20,000 and 80,000 lb/in^2; (2) the yield strengths generally increased between 3,000 and 20,000 lb/in^2, although in some cases there was no change or even a small decrease; (3) the modulus of elasticity was unaffected; and (4) the ductility showed no significant changes, although the elongation values usually exhibited a slight increase, while reductions of area were usually lower.

Nickel Alloys.—(1) The tensile strengths increased between 8,000 and 15,000 lb/in²; (2) the yield strengths increased approximately 5,000 lb/in²; (3) the modulus of elasticity varied somewhat but the changes were not significant; and (4) the ductility showed no significant changes, although the values for elongation increased slightly.

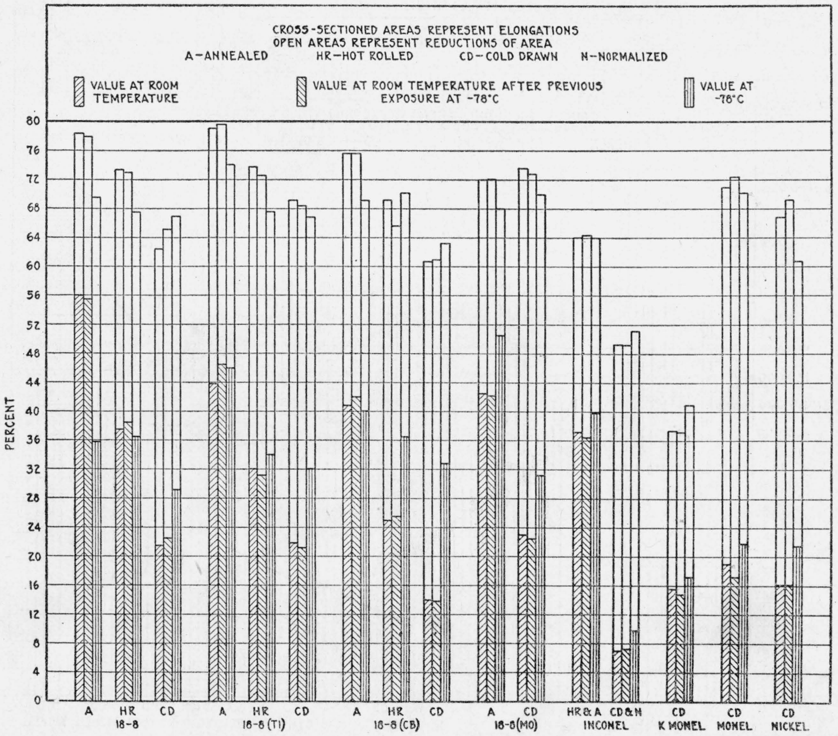

FIGURE 14.—*Effect of test temperature upon the elongation and reduction of area of the austenitic stainless steels and the nickel alloys.*

(b) HARDNESS TESTS

The hardness of these materials, in general, tended to increase slightly as the test temperature decreased (fig. 15).

(c) IMPACT TESTS

The results of the impact tests on the austenitic stainless steels and the nickel alloys are given in figure 16. Neither the nickel alloys nor the austenitic stainless steels were much affected at the lower temperatures.

In view of the remarkable toughness of these materials at room temperature and the negligible effect of temperatures as low as −78° C upon this property, it was apparent that these materials are well-suited for low temperature service. Under the test conditions used, this class of materials exhibited no evidence of cold brittleness down to temperatures as low as −78° C.

3. LIGHT METAL ALLOYS

(a) TENSILE TESTS

The results of the tensile tests on the aluminum-base alloys are summarized in figures 17 and 18. The tensile and yield strengths of these materials were but very slightly increased, while the elongation and reduction of area showed no consistent change at −78° C. The results justified the conclusion that there was no significant change in

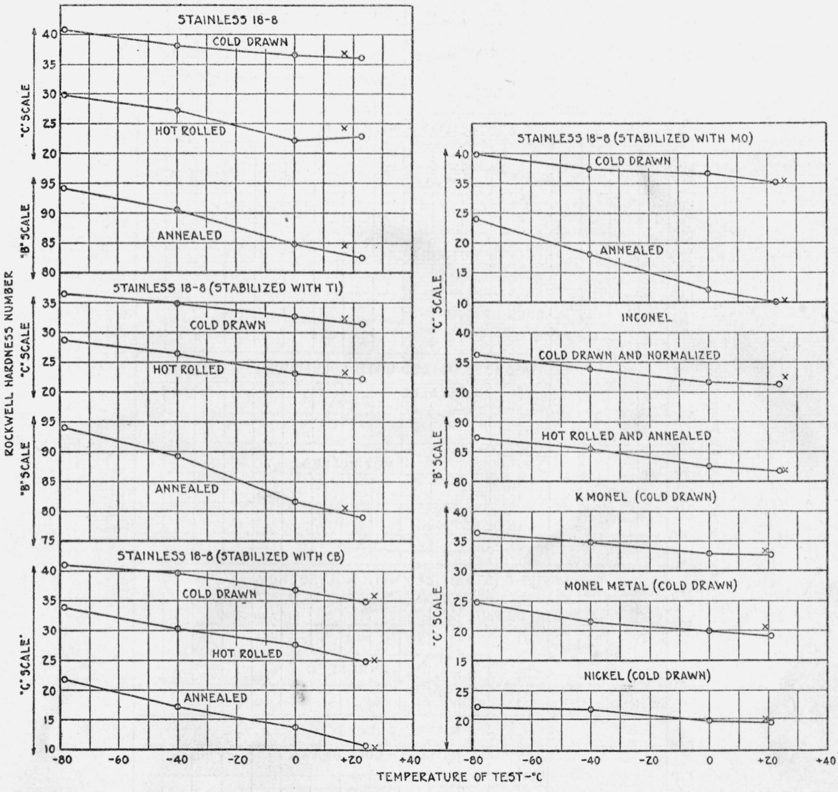

FIGURE 15.—*Effect of test temperature upon the hardness of the austenitic stainless steels and the nickel alloys.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

these properties at the low temperature. The modulus of elasticity tended to increase somewhat at −78° C.

Although not a full measure of the benefits derived from cold working subsequent to heat treatment, the data (figs. 17 and 18) show conclusively the trend in tensile properties caused by cold work. The tensile properties of specimens taken transversely to the direction of rolling were generally somewhat inferior to those of specimens taken longitudinally with the direction of rolling.

The results of the tensile tests on the magnesium-base alloys are summarized in figures 19 and 20. The yield strengths of all these alloys were higher at −78° C than at room temperature. The tensile

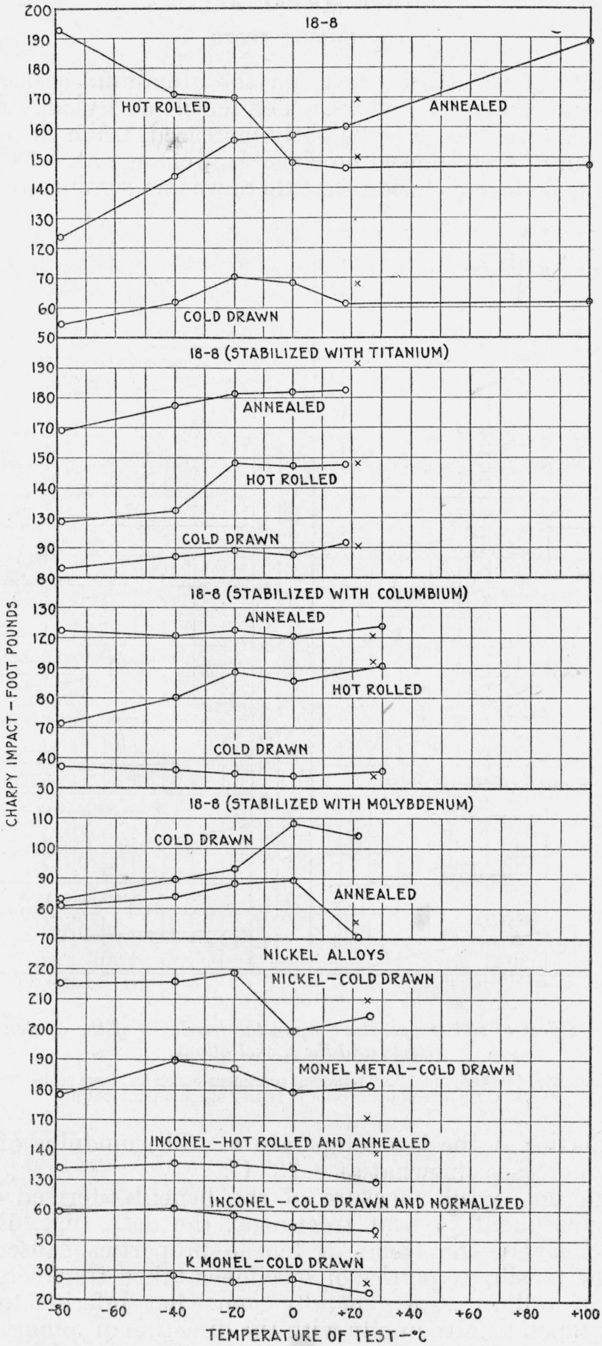

FIGURE 16.—*Effect of test temperature upon the impact resistance of the austenitic stainless steels and the nickel alloys*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

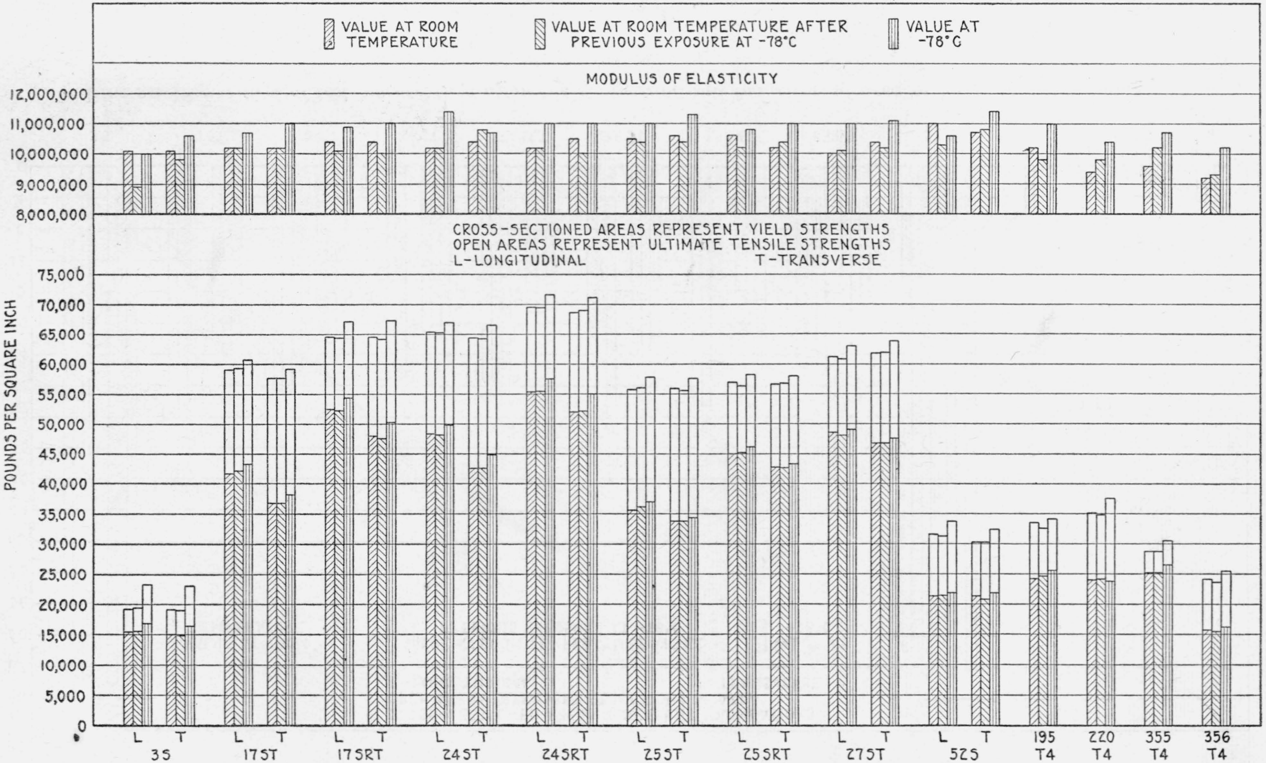

FIGURE 17.—*Effect of test temperature upon the yield strength, ultimate tensile strength, and modulus of elasticity of the aluminum alloys.*

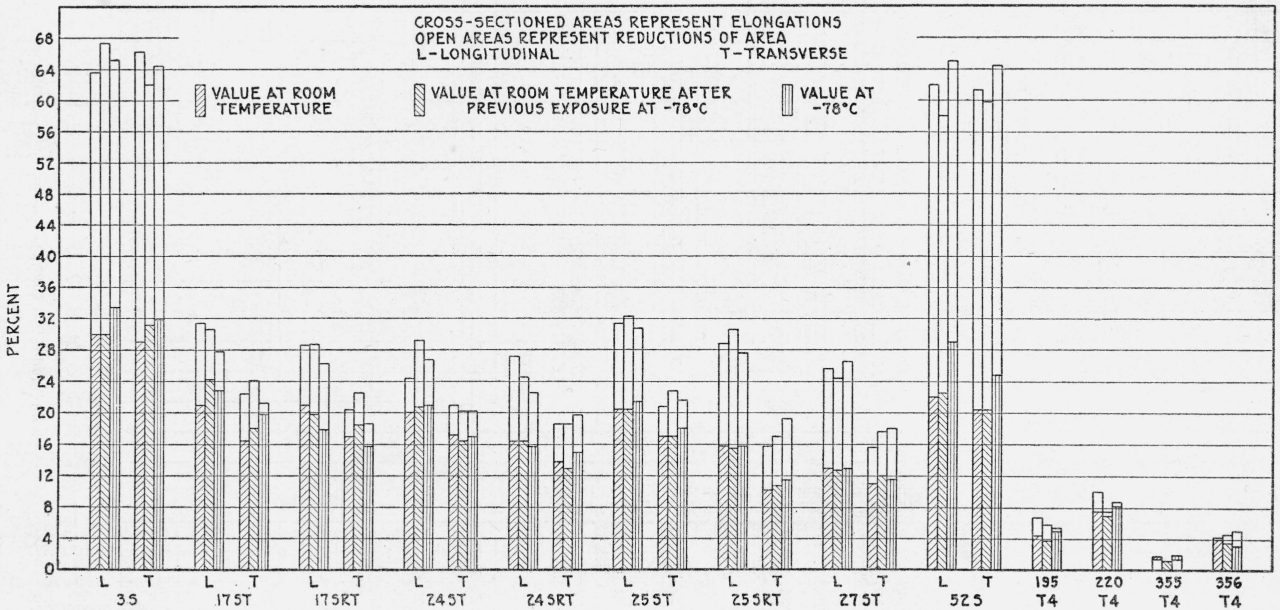

FIGURE 18.—*Effect of test temperature upon the elongation and reduction of area of the aluminum alloys.*

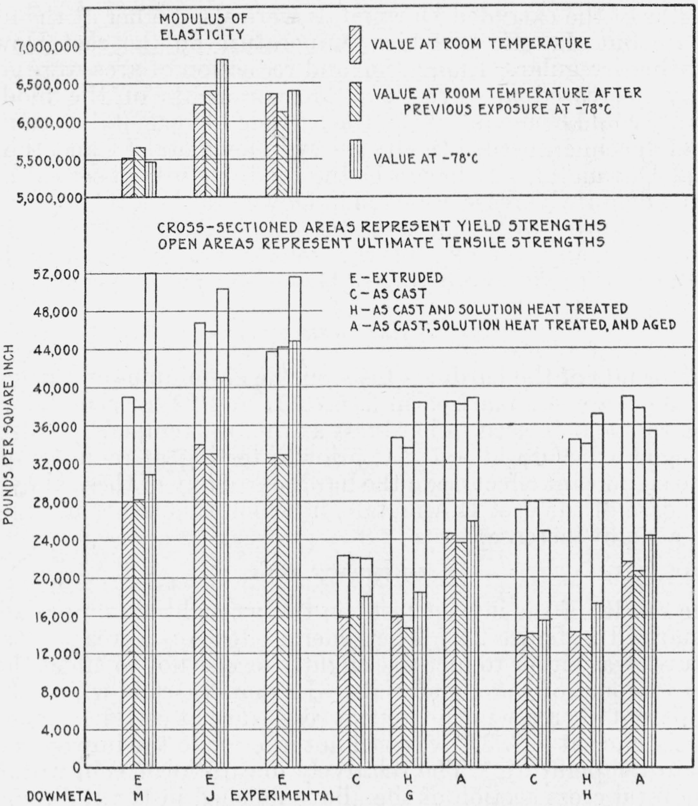

FIGURE 19.—*Effect of test temperature upon the yield strength, ultimate tensile strength, and modulus of elasticity of the magnesium alloys.*

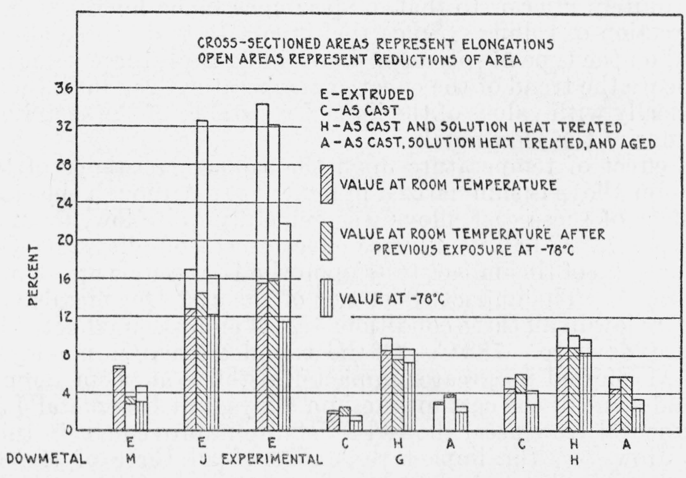

FIGURE 20.—*Effect of test temperature upon the elongation and reduction of area of the magnesium alloys.*

strengths of the extruded Dowmetals were also higher at the low temperature but the effect of low temperature on the cast Dowmetals was rather irregular. Elongation and reduction of area were generally slightly decreased at −78° C. Measurements of the modulus of elasticity could be made only on the extruded Dowmetal, because of the type of specimen used. In the case of Dowmetal M and the experimental Dowmetal, no change in the modulus was observed at −78° C, but a definite increase occurred in Dowmetal J. Prolonged exposure at −78° C prior to testing at room temperature generally caused no significant change in any of the tensile properties, with but one exception—the reduction of area of Dowmetal J was markedly increased after this treatment.

(b) HARDNESS TESTS

The results of the hardness tests on the aluminum- and magnesium-base alloys are summarized in figures 21 and 22, respectively. All of the materials increased in hardness as the test temperature decreased. Prolonged exposure at −78° C prior to testing at room temperature had no significant effect upon the hardness of any of these alloys except in the case of the cast Dowmetals, in which this treatment seemed to cause a slight increase.

(c) IMPACT TESTS

The results of the impact tests on the wrought aluminum alloys are summarized in figure 23. The general effect of decreasing test temperatures was either to increase slightly or else not to affect the resistance to impact of these materials. In some cases in which there was an apparent decrease in the impact resistance at certain temperatures, the resistance at −78° C was still not inferior to the impact resistance at room temperature. The relatively low ratio of cold-worked area to the total cross section of the alloys finished in the RT temper was sufficient to cause some decrease in the impact resistance; low temperatures, however, were not injurious to this property. The impact resistance of specimens taken transversely to the direction of rolling was definitely inferior to that of specimens taken longitudinally with the direction of rolling. Since the impact tests on these alloys were secured on the type of specimen shown in figure 4, these values, except to indicate the trend of the effect of temperature, cannot be compared numerically with values of the impact resistance of the cast aluminum alloys nor of the Dowmetals.

The effect of temperature upon the impact resistance of the cast aluminum alloys is summarized in figure 24. Although the resistance to impact of these cast alloys was generally quite low, temperatures down to −78° C had no adverse effect except on alloy 220–T4.

The results of the impact tests upon the Dowmetals are summarized in figure 25. The impact resistance of the cast Dowmetals G and H was quite low in all three conditions tested and was unaffected by temperatures down to −78° C. Of the extruded magnesium alloys, Dowmetal M showed no greater impact resistance at room temperature than did some of the cast magnesium alloys, but Dowmetal J and the experimental Dowmetal showed a definite improvement in this property. However, the impact resistance of all three of these alloys decreased steadily as the test temperature decreased.

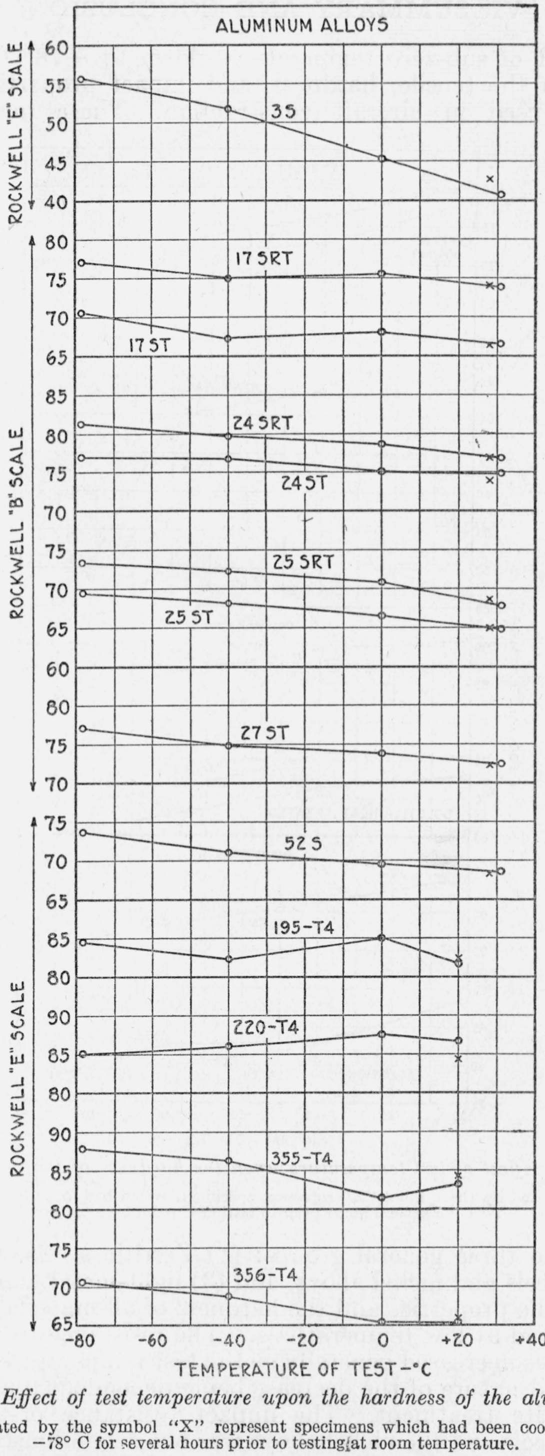

FIGURE 21.—*Effect of test temperature upon the hardness of the aluminum alloys.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

VI. SUMMARY AND CONCLUSIONS

The effect of sub-zero temperatures down to −78° C was determined upon the tensile, hardness, and impact properties of metals commonly used in aircraft construction. These materials were

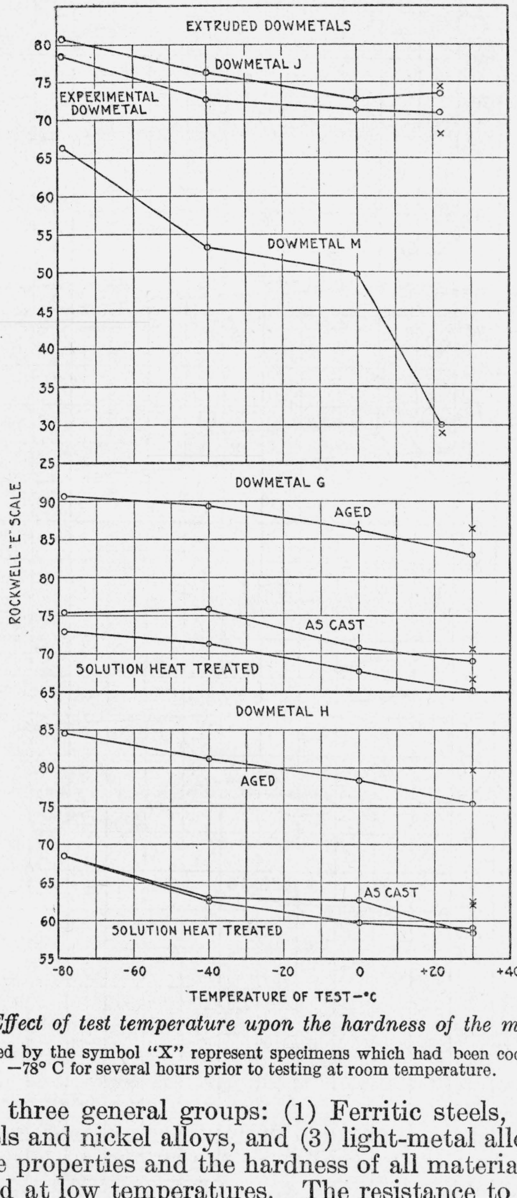

FIGURE 22.—*Effect of test temperature upon the hardness of the magnesium alloys.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

divided into three general groups: (1) Ferritic steels, (2) austenitic stainless steels and nickel alloys, and (3) light-metal alloys.

The tensile properties and the hardness of all materials were generally improved at low temperatures. The resistance to impact of the ferritic steels decreased generally as the test temperature was lowered, the rate and nature of the decrease being dependent upon the type of steel and its treatment. The impact resistance of the austenitic stainless steels and the nickel alloys was not deleteriously affected and they were considered best adapted for service at low temperatures. The impact resistance of the aluminum-base alloys was not decreased; the impact resistance of the wrought magnesium-base alloys was adversely affected by the low temperatures, while that of the cast magnesium-base alloys was not. These last-named materials were, however, extremely brittle even at room temperature.

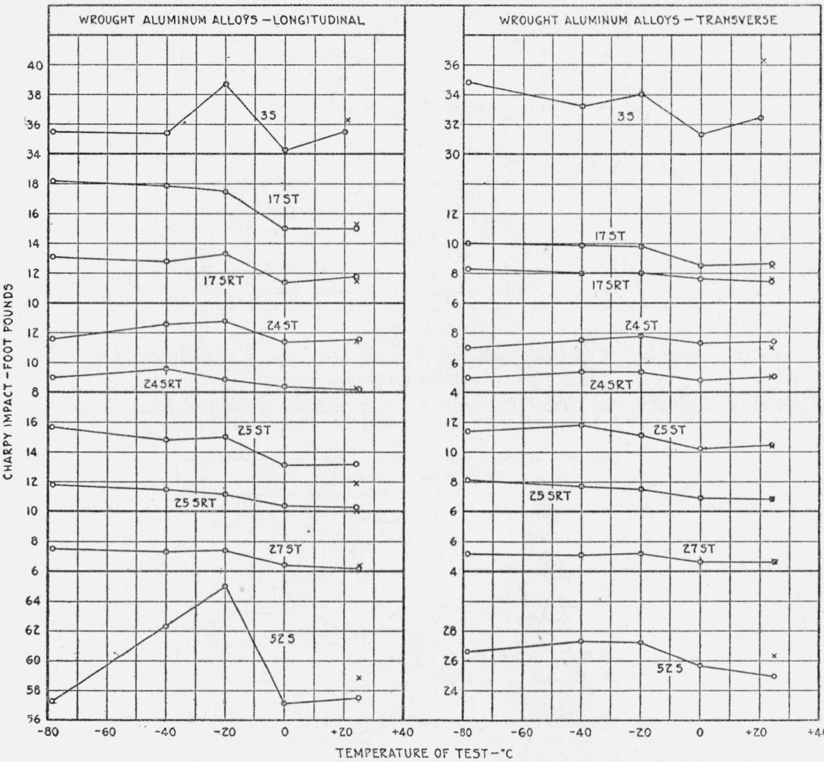

FIGURE 23.—*Effect of test temperature upon the impact resistance of the wrought aluminum alloys.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

The author is indebted to P. Devaney, National Bureau of Standards, for the construction of the special test apparatus and the machining of the hundreds of test specimens required, and to H. E. Francis, also of the National Bureau of Standards, for his help in the construction of some of the apparatus and his assistance in many of the tests.

This work was made possible through the interest and assistance of J. E. Sullivan and H. J. Huester, of the Bureau of Aeronautics, U. S. Navy Department.

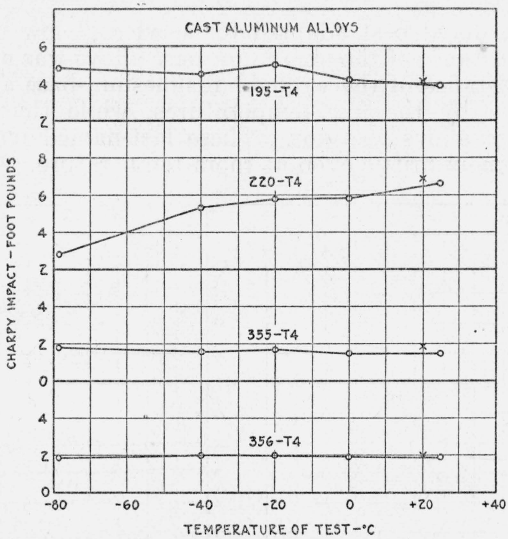

FIGURE 24.—*Effect of test temperature upon the impact resistance of the cast aluminum alloys.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

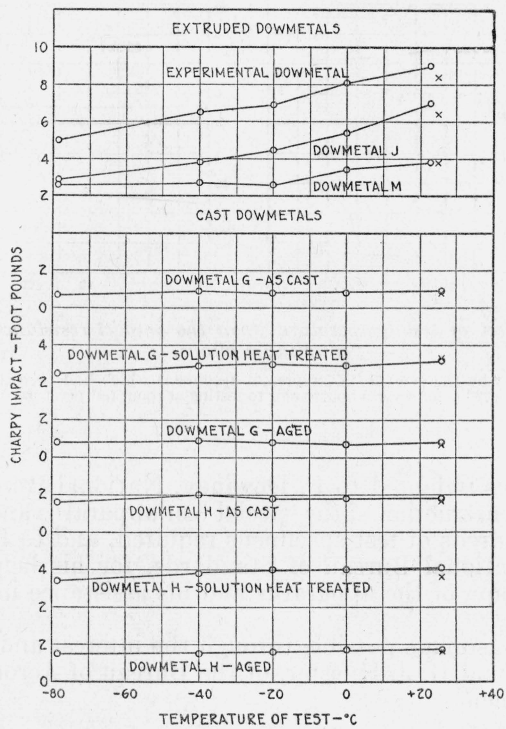

FIGURE 25.—*Effect of test temperature upon the impact resistance of the magnesium alloys.*

The points indicated by the symbol "X" represent specimens which had been cooled to and held at −78° C for several hours prior to testing at room temperature.

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