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UNITED STATES NAVAL ENGINEERING EXPERIMENT STATION

REPORT

Magnetic Characteristics of
"Non-Magnetic" Metallic Materials
Permeability and Coercive Force in Strong Fields
100-200 Oersteds
- NS-011-083, 013-118 -

ANNAPOLIS, MARYLAND

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Report on
Magnetic Characteristics of "Non-Magnetic" Metallic Materials
Permeability and Coercive Force in Strong Fields
100-200 Oersteds

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ABSTRACT

This is the first report covering the magnetic characteristics of "non-magnetic" metallic materials. The report contains data on a wide variety of materials such as brasses, bronzes, copper-nickel alloys, nickel base alloys, wrought and cast austenitic stainless steels, austenitic stainless steel weld metals, and austenitic manganese steels. Tabulations include chemical composition, mechanical properties, normal permeability, coercive force and resistivity data for the materials tested. The permeability and coercive force measurements were performed in strong magnetic field (100-200 oersteds). The effect of composition and cold deformation on the magnetic properties of the various materials is discussed and considerable attention is focused on the austenitic stainless steels. In addition to general conclusions, the report contains generalizations as to the expected magnetic behavior of the various types of materials.

TABLE OF CONTENTS

INTRODUCTION

1. The Bureau of Ships requires "non-magnetic" mechanical equipment for use in certain shipboard applications. Although many metallic materials appear to be non-magnetic in the sense that they are not readily attracted by a magnet, many exhibit magnetic properties of sufficient magnitude to exclude their use in the intended applications. With this in mind, the Bureau authorized the Station in reference (a) to determine the magnetic characteristics of non-magnetic ferrous and non-ferrous materials considered for use in the construction of such equipment. The Bureau, at the same time, made arrangements for the Station to borrow the Fahy Low-mu permeameter from the U.S. Naval Metals Laboratory, Munhall, Pennsylvania. This instrument is ordinarily used by them to determine the magnetic permeability of materials for submarine periscope tubes.

2. As soon as the instrument was received, permeability and coercive force measurements were begun on a selected list of materials. In the meantime a test agenda for the investigation was prepared and forwarded to the Bureau as reference (b). The agenda proposed that the Station measure both the normal permeability of the materials in a magnetic field of 200 oersteds, and the coercive force after being subjected to an identical field. This field strength is similar to that used in determining the permeability of periscope tube materials.

3. At the time the agenda was submitted uncertainties existed as to the magnetic field strengths to be used in the tests. Station personnel suggested that a meeting of all interested parties be called to clarify this situation. As a result of this meeting, BuOrd requested that measurements be made in a field comparable to the earth's magnetic field, i.e., approximately 0.5 oersted. Arrangements were then made to perform the weak field determinations at the U.S. Naval Ordnance Laboratory, as facilities for making these measurements are not available at the Station. In this arrangement the Station is required to furnish the test materials and to report the results of magnetic tests along with other mechanical and physical properties to the Bureau. This set-up is now in effect.

4. In the meantime, considerable testing in the region of 100 to 200 oersteds has and is being accomplished at the Station because it is believed that such information will be of considerable value in screening, selecting, and understanding the materials. It is the purpose of this report to present the data obtained at the Station up to the present time.

5. Before proceeding with the detailed report of the equipment and data, the magnetic properties determined herein will be briefly discussed. Terms related to magnetic testing are precisely defined in reference (c), and no attempt will be made to restate these terms. Instead, an effort will be made to explain them in the simplest possible manner.

6. Metallic materials can be devided into three classes insofar as their magnetic properties are concerned. These are (1) ferromagnetic, (2) paramagnetic, and (3) diamagnetic. The differences in the classes lies in their behavior in a magnetic field. Elongated samples of a ferromagnetic material assume a position parallel to the magnetic field and become strongly magnetized. On the other hand materials of classes (2) and (3) become weakly magnetized and assume positions either parallel to the field (paramagnetic) or perpendicular to the field (diamagnetic); in the latter case a non-uniform field is a necessary condition. In the last two classes of materials, the effects are relatively feeble and for all practical purposes the paramagnetic and diamagnetic substances are called non-magnetic.

7. Magnetic permeability may be defined in a general way as the ability of a material to be magnetized. In more scientific terms the normal permeability, μ, is defined as the ratio of normal induction to the magnetic force. The magnetizing force is designated by the symbol H; the unit is the oersted. Normal induction is designated by the symbol B; the unit is the gauss. Ordinarily, the permeability of a substance is expressed in terms relative to air or vacuum; air being artibrarily given a normal permeability of 1.000. Both ferromagnetic and paramagnetic substances have permeabilities greater than 1, whereas diamagnetic substances have permeabilities less than 1. Furthermore the permeability is constant in all field intensities for truly paramagnetic and diamagnetic materials whereas the permeabilities of ferromagnetic substances vary.

8. If the normal induction in a feebly magnetic material were determined directly, as a step in the determination of the permeability of such a material, the sensitivity of such a measurement would be too low to be practicable. As mentioned previously, permeability is equal to B/H. B is made up of two factors: the magnetizing force acting, H, and the intrinsic induction designated as B_i. In low permeability testing, H is ordinarily a large quantity, while B_i is quite small. For the sake of both precision and accuracy, the desirable procedure becomes the measurement of H and B_i separately. Then the sought for normal permeability is determined by the relations:

$$\text{Normal permeability } (\mu) = \frac{B}{H} = \frac{H+B_i}{H} = 1 + \frac{B_i}{H}$$

The ratio B_i to H is called the intrinsic permeability and reflects the permeability of the material in excess of that in air.

9. Magnetization is an irreversible process. When the magnetizing field is reduced from an initial high value, the induction in the material does not decrease along the same curve as it did when it was first magnetized. When the magnetization is reduced to zero, a certain residual induction, called remanence, remains. This residual induction can be removed by applying a small field in the opposite direction. This value of the field required to reduce the normal induction, B, to zero is called the coercive force and is denoted by Hc.

DESCRIPTION OF MATERIALS

10. Both ferrous and non-ferrous metals, constituting a wide variety of constructional alloys, have been tested. No attempt will be made to describe the materials here. Instead each class will be described and discussed along with the results of tests.

METHOD OF TEST

11. The Fahy Low-mu permeameter is one of several standard instruments used to measure the permeability of feebly magnetic materials. Detailed descriptions of the apparatus are available in the literature and a schematic wiring diagram and test procedure are given in reference (d). Briefly, the apparatus at the Station consists of (1) a control box containing variable resistances, an ammeter, a reversing switch, and a calibrated inductance; (2) a solenoid for producing a relatively uniform magnetic field; (3) a specimen holder which fits inside the solenoid and contains two coils, one (coil H) having a plastic core and the other (coil B) surrounding the specimen, and (4) a ballistic galvanometer. Prior to inserting the specimen, the galvanometer is calibrated with the known inductance and coils B and H are balanced so that when the field in the solenoid is reversed, the differential EMF between coils B and H is zero. The specimen is inserted in the holder, demagnetized, and then cyclically magnetized. The magnetizing force, H, is measured by reversing the field of the solenoid and noting the galvanometer deflection caused by the EMF produced in coil H by induction. The intrinsic induction, B_i, is then measured by noting the galvanometer deflection caused by the differential EMF produced between coils B and H as a

result of the specimen. The intrinsic permeability and the normal permeability are calculated from the relationship shown previously.

12. The coercive force, Hc, is determined as above except that the magnetizing force, H, is reversed only slightly, and by varying amounts. The normal induction, B, is calculated for each reversal and is plotted against the field strength. This procedure constitutes the development of a portion of the hysterisis loop near the B and H axes. From the plot, the reversed magnetizing force to reduce the remanence to zero is obtained. This is the coercive force, Hc.

13. During the testing of specimens, Bureau of Standards permeability samples are frequently run to check the apparatus. These standards are usually checked within ± 2%. Although no attempts have been made to develop the procedure to insure high accuracy and precision, it is believed that the normal permeability results presented herein are accurate within ± 3%.

14. It is difficult to appraise the accuracy of the coercive force measurements since no standards are available. However, indications are that the values shown are within ± 1 oersted.

RESULTS OF TESTS ON NON-FERROUS MATERIALS

Brasses and Bronzes

15. The brasses and bronzes tested thus far are tabulated in Table I. For convenience, the appropriate specifications, chemical composition, mechanical properties, hardness, and resistivity have been listed in addition to the normal permeability and coercive force. The data definitely indicate that the only element which affects the permeability and coercive force of these alloys is iron. In every instance where the percentage of iron is low the normal permeability and coercive force is 1.00 and 0, respectively. Of even greater importance, however, is the fact that none of the alloys tested exceeded a normal permeability of 1.40.

16. The effect of iron on the alloys is shown in Plate I. There appears to be no definite relationship between the iron content and the permeability principally because permeability in these alloys is structure sensitive, i.e., it varies with casting conditions, heat treatment, rate of solidification, amount of hot work, etc. There is no evidence that the condition in which the materials are furnished, this is, cast or wrought has any direct bearing on the trend of the permeability.

17. None of the alloys showed a decided change in permeability between 100 and 200 H. This is an indication that the permeability of the individual alloys are relatively constant and that they behave like paramagnetic materials.

18. In the "Remarks" column of Table I, magnetic test results are given for several static torsion specimens. These specimens were twisted in a static torsion machine until broken and the magnetic characteristics then measured. The magnetic properties of none of the materials tested in this manner were affected by cold work.

19. The coercive force of some of the aluminum bronzes was found to be 2 oersteds. However, this is after the material has been subjected to a stronger field than may ever be encountered in service. If coercive forces of this magnitude are considered to be an important factor, then the use of these bronzes must be carefully considered.

Cupro-Nickel Alloys

20. The magnetic characteristics of the cupro-nickel alloys tested are shown in Tables II and III. In Table II only the 80:20 Cu-Ni + Fe alloy showed a permeability substantially greater than 1. This particular alloy behaved ferromagnetically as indicated by the changes in permeability with field strength. It is to be noted that all of the alloys had low permeability and coercive force in the annealed condition.

21. Table III presents the magnetic properties of a group of 90:10 Cu-Ni specimens prepared for sea water corrosion tests. Seven heats of alloys containing various amounts of iron have been subjected to three different heat treatments. Heat Treatment "A", an annealing treatment, showed no changes in permeability or coercive force with varying iron contents. Heat Treatment "B", designed to produce a fairly complete precipitation of the iron content, shows increases in permeability above .70% Fe but in no case does it exceed the maximum acceptable permeability of 2. The coercive force in this series increases rapidly above .95% Fe. Heat Treatment "C", designed to develop substantially maximum precipitation hardness in quenched material, shows increases in permeability above .50% Fe and exceeds 2 at approximately 1.5% Fe. The coercive force of this series remains rather low throughout the entire range of iron contents. As in the case of brasses and bronzes, we find that in the absence of iron the permeability of the 90:10 cupro-nickel alloy is unaffected by treatment. Furthermore, it is apparent from Tables II and III that the iron content does not affect the permeability of annealed cupro-nickel alloys.

Miscellaneous Copper Base Alloys

22. The magnetic characteristics of miscellaneous copper base alloys are shown in Table IV. All of these alloys had a permeability of 1.00 except the cast CuSi alloy which contains iron.

TABLE I

PROPERTIES OF BRASS

Type of Name	Specification	Condition and Treatment	Source	Lab	Chemical Composition in % Cu	Zn	Sn	Pb	Fe	Ni	Al	Mn	Si	Other
Yellow Brass	ASTM-B36 No.8	Half Hard	Am. Brass Co.	EES	65.3	34.5	None	.06	.08					
Cartridge Brass	MIL-B-895(Ships)	Full Hard	"	"	70.7	29.2	None	.02	.02					
Bronze	AMPCO 72	Sand Cast	AMPCO Metal Inc.	AMPCO	88.14	Bal	8.67	.40	.02	.33				
Bronze	AMPCO 79	Sand Cast	"	"	86.84	Bal	10.39	.12	.03	.12				
Bronze	AMPCO 675	Cent. Cast	"	"	59.66	Bal	1.02		1.14			.25		
Al-Bronze	N. D. 46B18 Cl. 1 (AMPCO 12)	Sand Cast	"	"	87.09				3.16	.21	9.50	.02		
Al-Bronze	AMPCO A-3	Sand Cast	"	"	88.6				.98	.07	10.3	.01		
Al-Bronze	AMPCO A-3	Forged	"	"	89.0				1.4	.12	9.4	.03		
Al-Bronze	AMPCO 8	Extruded	"	"	90.63				2.31	.11	6.92	.01		
Al-Bronze	AMPCO 8	Rolled	"	"	90.6				2.2	.16	7.0	.02		
Al-Bronze	AMPCO 16	Sand Cast	"	"	85.83				3.36	.43	10.31	.05		
Al-Bronze	AMPCO 18	Sand Cast	"	"	85.6				3.6	.22	10.5	.03		
Al-Bronze	AMPCO 18	Extruded	"	"	85.31				3.53	.28	10.82	.03		
Al-Bronze	AMPCO 18	Forged	"	"	85.8				3.5	.22	10.3	.03	.13	
Al-Bronze	AMPCO 20	Extruded	"	"	84.18			.10	3.80	.47	11.37	.03	.03	
Al-Bronze	AMPCO 22	Extruded	"	"	81.35				4.53	.39	13.68	.03		
Al-Mn Bronze	N. D. 46B29a-Cla (AMPCO 66)	Sand Cast	"	"	62.76	Bal			3.74		5.52	3.78		
Al-Mn Bronze	N. S. 46B29a-Clb (AMPCO 64)	Sand Cast	"	"	65.00	Bal			2.37		4.14	3.69		
Al-Mn Bronze	AMPCO 435	Cent. Cast	"	"	86.60				.02		9.99	3.05	.26	
Al-Mn Bronze	AMPCO 435 H. T.	Sand Cast Quenched & Drawn	"	"	87.52				.08		10.12	1.88	.38	
Al-Ni Bronze	N. D. 46B17 (AMPCO 45)	Extruded	"	"	81.57				2.63	5.47	9.58		.73	
Al-Ni Bronze	AMPCO 46-22	Sand Cast	"	"	80.6				4.5	4.2	10.6	.05		
Al-Ni Bronze	AMPCO 46-22	Cent. Cast Quenched & Drawn	"	"	80.46				4.73	4.52	10.24	.03		
Hydraulic Bronze	N. D. 46B23e (AMPCO 74)	Sand Cast	"	"	85.47	Bal	4.16	4.69	.03	.50				
Mn-Bronze	46B15e	Wrought	J. H. Jolley & Co.	EES	58.63	39.49	.91	.22	.72		None	.02		
Mn-Bronze	N.D. 46B3f (AMPCO 62)	Cent. Cast	AMPCO Metal Inc.	AMPCO	59.40	Bal			1.13		1.16	.33		
Mn-Bronze	N. D. 46B3f	Prop Casting	Cramp Brass & Iron Fds.	EES	57.93	39.18	.78	Nil	.69		.65	.78		
Mn-Bronze		As Cast Beta Phase	Phila. Naval Shipyard	"	53.2	42.79		Nil	1.75		1.22	1.14		
Phosphor Bronze - 5%	ASTM B139-A	Half Hard	Am. Brass Co.	EES	94.5	Nil	5.4		.07					
Phosphor Bronze - 8%	ASTM B139-C	Full Hard	"	"	91.5	Nil	8.4		.06					P .13
Phosphor Bronze - 10%	ASTM B139-D	Full Hard	"	"	89.4		10.5		.07					P .14
Leaded Tin Bronze(Comp "M")	N. D. [illegible]	Sleeve Casting	Unknown	"	89	3.5	5.7	1.4		.5				P .011
Leaded Tin Bronze(Comp. "M")	N. D. 46B8i (AMPCO 71)	Sand Cast	AMPCO Metal Inc.	AMPCO	88.77	Bal	6.19	1.76	.02	.11				
Tin-Nickel Bronze	N. D. 46B32 Type I	Cast	NRL	EES	84.9	3.1	6.0			5.9				
Tin-Nickel Bronze	N. D. 46B23 Type II	Cast	NRL	"	86.9	2.5	4.8	1.7		4.1				
Tin-Nickel Bronze	AMPCO 50	Sand Cast	AMPCO Metal Inc.	AMPCO	83.81		10.26	2.48	.03	3.45				

NOTES: (1) All resistivity data based on information obtained from the literature
(A) Indicates accurate data
(B) Indicates interpolated data of good accuracy, and
(C) Indicates interpolated data of reasonable accuracy

(2) Johnson's limit
(3) 0.2% set
(4) Proof stress

TABLE I

OPERTIES OF BRASSES AND BRONZES

mical Composition in %							Mechanical Properties				Hard-ness	Normal Permeability - μ		Coercive Force-Hc in oersteds	Resistivity in Microhm-Centimeter (1)	Remarks
Pb	Fe	Ni	Al	Mn	Si	Other	T.S. in psi	Y.S. (.5%)	Elong. % - 2"	R.A. %		100 oersteds	200 oersteds			
.06	.08						54,100	33,600(2)	42	66		1.00	1.00	0	6.4 (A)	
.02	.02						76,200	58,000(2)	18.5	57		1.00	1.00	0	6.2 (A)	
.40	.02	.33					46,000	24,000	26.0	26.0	70 BHN	1.00	1.00	0	13 (B)	
.12	.03	.12					46,000	22,000	24.0	24.0	75 BHN	1.00	1.00	0	16 (B)	
	1.14			.25			70,000	32,000	41.0	47.0	120 BHN	1.09	1.09	0	6 (B)	
	3.16	.21	9.50	.02			80,000	30,000	40.0	40.0	132 BHN	1.17	1.18	1	13.0 (A)	
	.98	.07	10.3	.01			84,000	31,500	24	26	143 BHN	1.05	1.05	0	17 (B)	
	1.4	.12	9.4	.03			85,000	39,000	26	26	143 BHN	1.05	1.05	0	17 (B)	Broken μ=1.06 @ 100 H Static Torsion - μ=1.06 @ 200 H Hc=0
	2.31	.11	6.92	.01			73,000	33,000	42.0	47.0	157 BHN	1.16	1.17	2	14 (B)	
	2.2	.16	7.0	.02			75,000	38,500	49	50	143 BHN	1.10	1.10	0	14 (B)	Broken μ=1.13 @ 100 H Static Torsion - μ=1.14 @ 200 H Hc=1
	3.36	.43	10.31	.05			90,000	32,000	22	22	146 BHN	1.28	1.29	2	20 (B)	
	3.6	.22	10.5	.03			94,000	36,500	19	18	156 BHN	1.26	1.27	0	20 (B)	
	3.53	.28	10.82	.03			95,000	45,000	12	8	175 BHN	1.35	1.36	2	20 (B)	
	3.5	.22	10.[illegible]	.03	.13		93,300	40,000	21	21	149 BHN	1.18	1.18	1	20 (B)	Broken μ=1.19 @ 100 H Static Torsion - μ=1.14 @ 200 H Hc=1
.10	3.80	.47	11.37	.03	.03		95,000	40,000	5.0	4.5	223 BHN	1.22	1.25	0	22 (B)	
	4.53	.39	13.[illegible]8	.03			85,000	70,000	0.5	0.0	331 BHN	1.17	1.19	2	24 (C)	
	3.74		5.52	3.78			115,000	65,000	15.0	15.0	212 BHN	1.09	1.09	0	7 (B)	
	2.37		4.14	3.69			92,000	48,000	22.0	22.0	183 BHN	1.27	1.24	1	7 (B)	
	.02		9.99	3.05	.26		103,500	30,000	21.0	23.0	156 BHN	1.00	1.00	0	17 (B)	
	.08		10.12	1.88	.38		94,500	46,500	13.0	15.2	174 BHN	1.00	1.00	0	17 (B)	
	2.63	5.47	9.58		.73		110,000	50,000	9.0	9.0	220 BHN	1.02	1.02	0	24 (C)	
	4.5	4.2	10.6	.05			112,000	66,500	17	23	207 BHN	1.05	1.07	1	24 (C)	
	4.73	4.52	10.24	.03			120,000	70,000	18.0	18.0	223 BHN	1.21	1.21	0	24 (C)	
4.69	.03	.50					38,000	20,000	26.0	26.0	60 BHN	1.00	1.00	0	18 (C)	
.22	.72		None	.02			74,400	35,100(4)	33.7	45.8	137 BHN	1.09	1.09	1	7 (B)	
	1.13		1.16	.33			75,000	29,000	35.0	35.0	143 BHN	1.10	1.09	0	7 (B)	
Nil	.69		.65	.78			46,000-60,000		8.0-22		103-108 BHN	1.09	1.10	0	7 (B)	
Nil	1.75		1.22	1.14			85,500	15,700(4)	31.5	27.8		1.18	1.19	1	7 (B)	
	.07						63,500	44,500(2)	38.5	73.8		1.00	1.00	0	9.6 (A)	
	.06					P .13	94,800	64,000(2)	22	60		1.00	1.00	0	13 (A)	
	.07					P .14	90,500	55,000(2)	34	66		1.00	1.00	0	16 (A)	
1.4		.5				P nil	40,500	18,500(3)	29.5	29.7		1.00	1.00	0	12.3 (A)	Broken μ=1.00 @ 100 Static Torsion - μ=1.00 @ 200 Hc=0
1.76	.02	.11					40,000	20,000	30.0	30.0	65 BHN	1.00	1.00	0	12.3 (A)	
		5.9					50,500		43			1.00	1.00	0	20 (C)	
1.7		4.[illegible]					39,000		20			1.00	1.00	0	18 (C)	
2.48	.03	5.45					47,000	27,000	20.0	20.0	86 BHN	1.00	1.00	0	22 (C)	

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TABLE II

PROPERTIES OF COPPER-NICKEL ALLOYS

Type or Name	Specification	Condition and Treatment	Source	Lab	Chemical Composition in %								
					Cu	Ni	Fe	Zn	Sn	Mn	Si	Pb	C
70:30 Cu-Ni	-	Wrought-Annealed	INCO	INCO	70.37	29.50	.006	<.01	<.01	.05		.003	.02
70:30 Cu-Ni	-	Above-Cold Red. 20%	INCO	INCO	70.37	29.50	.006	<.01	<.01	.05		.003	.02
70:30 Cu-Ni+Fe	N.D. 46C6b	Wrought-Annealed		EES	68.09	30.86	.31	<.01	<.01	.74		<.01	
70:30 Cu-Ni+Fe	N.D. 46C6b	Wrought-Annealed	INCO	INCO	69.55	29.51	.50	<.01	<.01	.37		.003	.01
70:30 Cu-Ni+Fe	-	Above-Cold Red. 20%		INCO	69.55	29.51	.50	<.01	<.01	.37		.003	.01
70:30 Cu-Ni+Fe	-	Wrought-Annealed	INCO	INCO	67.53	30.49	.91	<.01	<.01	1.11		.005	.02
70:30 Cu-Ni+Fe	-	Above-Cold Red. 20%		INCO	67.53	30.49	.91	<.01	<.01	1.11		.005	.02
80:20 Cu-Ni+Fe	-	Cent. Cast	Sandusky	EES	77.8	20.1	.82	.01	.01	.89	.48		
80:20 Cu-Ni+Fe	-	Cent. Cast Annealed at EES	Sandusky	EES	77.8	20.1	.82	.01	.01	.89	.48		
55:45 Cu-Ni+Fe	-	Wrought Hot Rolled		EES	53.77	44.68	.52	None	None	1.14			

Type or Name	Mechanical Properties				Hardness BHN	Normal Permeability - μ		Coercive Force - Hc in oersteds	Resistivity in Microhm - Cent. (1)	Remarks
	TS in PSI	YS .2% Set	Elong. % 2"	R.A. %		100 oersteds	200 oersteds			
70:30 Cu-Ni					115	1.00	1.00	0	36.6 (A)	
70:30 Cu-Ni						1.00	1.00	0	36.6 (A)	
70:30 Cu-Ni+Fe						1.00	1.00	0	36.6 (A)	
70:30 Cu-Ni+Fe					133	1.00	1.00	0	36.6 (A)	
70:30 Cu-Ni+Fe						1.00	1.00	0	36.6 (A)	
70:30 Cu-Ni+Fe					122	1.00	1.00	0	36.6 (A)	
70:30 Cu-Ni+Fe						1.00	1.00	0	36.6 (A)	
80:20 Cu-Ni+Fe	74,500	56,700	11	19	166	1.50(3)	1.29(3)	0	26.5 (A)	Broken Static Torsion - μ = 1.23 @ 200H
80:20 Cu-Ni+Fe						1.00	1.00	0	26.5 (A)	
55:45 Cu-Ni+Fe	71,500	30,000(2)	47.5	78.5		1.00	1.01	0	49 (A)	

NOTES (1) All resistivity data based on information obtained from the literature. (A) indicates accurate data.
(2) Proof Stress
(3) Additional Permeability Data

	Bu Stds	EES
μ @ 25H	1.88	1.83
50H	1.72	-
75H	1.60	-
100H	1.50	1.48

TABLE III

MAGNETIC PROPERTIES OF 90:10 COPPER-NICKEL ALLOYS CONTAINING IRON

Samples Furnished by American Brass Company

Heat	Chemical Composition %				Heat Treatment "A" (1)			Heat Treatment "B" (2)			Heat Treatment "C" (3)		
No.	Cu	Ni	Fe	Mn	μ @ 100 H	μ @ 200 H	Hc	μ @ 100 H	μ @ 200 H	Hc	μ @ 100 H	μ @ 200 H	Hc
6758	89.67	9.98	.01	.32	1.00	1.00	0	1.00	1.00	0	1.00	1.00	0
6759	89.20	9.99	.48	.32	1.00	1.00	0	1.00	1.00	0	1.00	1.00	0
6760	89.00	9.95	.71	.32	1.00	1.00	0	1.00	1.00	0	1.18	1.18	0
6761	88.75	9.97	.95	.32	1.00	1.00	0	1.04	1.04	1	1.14	1.14	0
6762	88.48	10.00	1.19	.32	1.00	1.00	0	1.23	1.27	4	1.55	1.55	1
6763	88.18	10.05	1.44	.32	1.00	1.00	0	1.23	1.28	8	1.82	1.83	2
6764	87.56	10.14	1.96	.33	1.00	1.00	0	1.34	1.44	12	2.39	2.40	0

NOTES: (1) Heat Treatment "A" - Annealed 1 hour @ 900°C and quenched.
(2) Heat Treatment "B" - Rolled 6 B&S Nos. Hard. Then annealed 1 hour @ 900°C and quenched plus 8 hours @650°C air cooled.
(3) Heat Treatment "C" - Heats 6758 to 6761 incl. - Annealed 1 hour @900°C and quenched plus 2 hours @ 550°C.
Heats 6762 to 6764 incl. - Annealed 1 hour @900°C and quenched plus 2 hours @ 600°C.

TABLE IV

PROPERTIES OF MISCELLANEOUS COPPER-BASE ALLOYS

Type or Name	Specification	Condition and Treatment	Source	Lab	Chemical Composition in %								
					Cu	Zn	Sn	Fe	Ni	Mn	Si	Be	Other
Cu-Be-Co Alloy	AMPCO 91-20	Extruded Soln. Quench and Aged	AMPCO Metal Inc.	AMPCO	96.68			.02			.04	.44	Co 2.81
Cu-Be-Co Alloy	AMPCO 95N-20	Cent. Cast Soln. Quench and Aged	AMPCO Metal Inc.	AMPCO	98.84			.02	.43		.05	.23	Co .43
Cu-Be-Co Alloy	AMPCO 95N-20	Extruded Soln. Quench and Aged	AMPCO Metal Inc.	AMPCO	97.66			.05	.63	.01	.03	.21	Co 1.41
Cu-CR Alloy	AMPCO 97-20	Extruded Soln. Quench and Aged	AMPCO Metal Inc	AMPCO	99.26	None		.04			.02		CR .63
Cu-Be Alloy	N.D.46C10(INT) (AMPCO 83-20)	Extruded Soln. Quench and Aged	AMPCO Metal Inc.	AMPCO	97.74			.03	.02	.01	.06	1.87	Co .29
Cu-Be Alloy	AMPCO 86-20	Sand Cast Soln. Quench and Aged	AMPCO Metal Inc	AMPCO	96.12			.02	1.17			2.65	
Cu-Si Alloy	N.D.46B28a	Cast	NRL	EES	90.9	3.0	1.0	1.25		.56	3.2		
Cu-Si Alloy "Duronze"		Wrought Hard Drawn	Bridgeport Brass	EES	97.2	1.96	None	.01	None	None	.83		
Cu-Si-Mn Alloy		Wrought Hard Drawn	Am. Brass	EES	96.25			.17		.95	2.72		

Type or Name	Mechanical Properties					Normal Permeability - μ		Coercive Force-Hc in oersteds	Resistivity in Microhm-cent. (1)
	T.S. in psi	Y.S. (.5% Set)	Elong. % in 2"	R.A. %	Hardness	100 oersteds	200 oersteds		
Cu-Be-Co Alloy	99,000	72,000	10.0	12.0	244 BHN	1.00	1.00	0	8 (C)
Cu-Be-Co Alloy	90,000	65,000	8.0	8.0	228 BHN	1.00	1.00	0	6 (C)
Cu-Be-Co Alloy	110,000	75,000	15.0	24.0	228 BHN	1.00	1.00	0	6 (C)
Cu-CR Alloy	78,000	55,000	15.0	15.0	80 RB	1.00	1.00	0	4 (B)
Cu-Be Alloy	176,000	121,000	8.0	17.6	321 BHN	1.00	1.00	0	6.8-9.8 (A)
Cu-Be Alloy	160,000	100,000	2.5	2.5	375 BHN	1.00	1.00	0	6.8-9.8 (A)
Cu-Si Alloy	49,600		9.3			1.10	1.10	0	14 (C)
Cu-Si Alloy "Duronze"	111,300	45,600(2)	12.4	57.9		1.00	1.00	0	6 (C)
Cu-Si-Mn Alloy						1.00	1.00	0	6 (C)

NOTES: (1) All resistivity data based on information obtained from the literature.
(A) indicates accurate data.
(B) indicates interpolated data of good accuracy, and
(C) indicates interpolated data of reasonable accuracy.

(2) Proof stress.

TABLE V

PROPERTIES OF NICKEL

Type or Name	Specification	Condition and Treatment	Source	Lab	Chemical Composition in %							
					Ni	Cu	Fe	Al	Mn	Si	C	C
Monel	N.D.46M7gClb	Hot Rolled	INCO	EES	Bal	29.54	2.13		1.44	.02	.18	
"K" Monel	N.D.46N5	Shaft Age Hardened	N.Y. Naval Shpyd	EES	63.79	29.63	1.04	4.89	.56	.23	.26	
"K" Monel (2)	N.D. 46N5	Annealed Quenched			66.	29	.9	2.75	.75	.50	.15	
"K" Monel (2)	N.D. 46N5	Annealed Age Hardened			66	29	.9	2.75	.75	.50	.15	
"K" Monel (2)	N.D. 46N5	Cold Drawn 20%			66	29	.9	2.75	.75	.50	.15	
"K" Monel (2)	N.D. 46N5	Cold Drawn 20% Age Hardened			66	29	.9	2.75	.75	.50	.15	
"K" Monel (2)	N.D. 46N5	Cold Drawn 50%			66	29	.9	2.75	.75	.50	.15	
"K" Monel (2)	N.D. 46N5	Cold Drawn 50% Age Hardened			66	29	.9	2.75	.75	.50	.15	
"S" Monel	N.D.46N7C1A	As Cast	Norfolk Naval Shpyd	EES	66.14	28.10	1.49		.62	3.65		
"S" Monel	N.D.46N7C1B	Cast Age Hardened	"	EES	66.19	28.49	.25		.85	4.01	.05	
Inconel (3)		Annealed			77.0	.2	7.0		.25	.25	.08	15
Inconel (3)		Cold Drawn 20%			77.0	.2	7.0		.25	.25	.08	1
Inconel (3)		Cold Drawn 50%			77.0	.2	7.0		.25	.25	.08	1
Inconel (3)		Cold Drawn 50% Stress Equalized			77.0	.2	7.0		.25	.25	.08	1
Inconel (3)		Cold Drawn 50% Carbide Precip.			77.0	.2	7.0		.25	.25	.08	1
Modified Inconel		Hot Rolled Annealed	INCO	INCO	76.03		6.0	1.30	.19	.42	.03	13

NOTES:
(1) All resistivity data based on information obtained from the literature. (A) indicates accurate data.
(2) Data obtained from INCO Technical Bulletin T-9 dated Dec. 1949.
(3) Data obtained from INCO Technical Bulletin T-7 dated Mar. 1950.
(4) Johnson's Limit.
(5) Yield strength (.1% set)

TABLE V

NICKEL-BASE ALLOYS

...position in %						Mechanical Properties				Hardness	Normal Permeability - μ		Coercive Force Hc in oersteds	Resistivity in Microhm CM. (1)
Si	C	Cr	Co	Ti	S	T.S. in psi	Proof Stress psi	Elong. %-2"	R.A. %		100 H	200 H		
.02	.18					89,800	55,300(4)	36.5	69.5		>3	>3	N.D.	48.2 (A)
.23	.26					162,800	121,000	21.5	39.4		1.01	1.01	0	58.3 (A)
.50	.15					92,500						1.00		58.3 (A)
.50	.15					151,000						1.00		58.3 (A)
.50	.15					137,000						1.00		58.3 (A)
.50	.15					186,500						1.00		58.3 (A)
.50	.15					151,250						1.00		58.3 (A)
.50	.15					198,000						1.00		58.3 (A)
3.65						136,500	102,200	9.7	15.3	316 BHN	1.01	1.01	0	63.3 (A)
4.01	.05									33 Rc	1.01	1.01	0	63.3 (A)
.25	.08	15.0			.007	98,000						1.01		98.1 (A)
.25	.08	15.0			.007	129,000						1.01		98.1 (A)
.25	.08	15.0			.007	150,500						1.01		98.1 (A)
.25	.08	15.0			.007	154,000						1.01		98.1 (A)
.25	.08	15.0			.007	100,000						1.01		98.1 (A)
.42	.03	13.05	.33	.70		106,400	45,600(5)	52.0	64.0		1.00	1.00	0	98.1 (A)

Nickel Base Alloys

23. Properties of nickel base alloys are tabulated in Table V. As noted in the Table, considerable data has been obtained from the published literature. It is well known that monel is attracted by a magnet and as such has a high permeability. It is of interest to note that modified monels containing aluminum or silicon, and inconel having approximately 7% Fe, have low permeabilities.

RESULTS OF TESTS ON FERROUS MATERIALS

Austenitic Stainless Steels - General

24. The metallurgy of the austenitic stainless steels is a complex subject which is covered in great detail in the literature. Consequently only those facts having a direct bearing on the magnetic properties of these steels will be pointed out here. First, let us consider two of the structural phases likely to be encountered in austenitic stainless steels. The one phase, austenite, is a solid solution of iron and other alloying elements. This phase is characterized by a face-centered cubic crystal structure which is non-magnetic and thus has a normal permeability of 1.00. The other phase, ferrite, is also a solid solution of iron and other alloying elements, but unlike austenite it has a body-centered cubic crystal structure and is strongly ferromagnetic. In ordinary plain carbon steels the magnetic constituent, ferrite, is stable at room temperature and the non-magnetic constituent, austenite, is stable at high temperatures. In the case of austenitic stainless steels, sufficient amounts of alloying elements have been added to cause the austenite to be "meta-stable" at room temperature. This is a state of pseudo-equilibrium in which the austenite appears as a stable phase but has a tendency to transform into magnetic ferrite. (The term ferrite is used here for simplicity. Actually this transformation is probably to a pseudo-martensite.)

25. Whether the alloy is entirely austenitic and whether the tendency to transform is strong or weak is greatly influenced by the chemical composition of the alloy. Some of the alloying elements tend to promote the formation of austenite while others tend to promote the formation of ferrite. The amount of each element present in the composition, therefore, determines the ultimate structure and magnetic properties of the alloys. Among the austenite promoters are carbon, nickel, manganese, and nitrogen; while ferrite formers are chromium, silicon, molybdenum, and columbium. These alloys do not all behave with the same potency, however, so that a change in one may be far more effective than another. The relative effect of these alloys will be referred to later in the report.

26. The application of cold plastic deformation promotes the transformation from austenite to ferrite. The more unstable the austenite, the greater the susceptibility of the alloy to cold work. Since the stability of the austenite is directly related to composition, susceptibility to cold work also becomes a function of composition. The effect of this phenomenon on some of these alloys will be dealt with later.

27. In developing an inspection test for determining the normal permeability of austenitic stainless steel periscope tubes, it was found that maximum permeability of these steels occurs in the region of 100 to 300 oersteds. It is expected therefore, that the weak field tests being conducted at room temperature by NOL will give somewhat lower permeabilities than reported herein for the same steels.

Austenitic Stainless Steels - Cast

28. Reference (e) is an excellent paper on the magnetic properties of cast stainless steels and only a brief summary will be presented herein. It was mentioned previously that all alloying elements do not behave with the same potency in determining the stability of the austenite. For example, in the normal ranges of cast and wrought stainless alloys, the effect of each element on the microstructure can be translated into chromium or nickel equivalents in accordance with the following equations:

$$\text{Chromium equivalent} = \text{Cr\%} + 2.5\text{Si\%} + 1.8\text{Mo\%} + 2\text{Cb\%}$$
$$\text{Nickel equivalent} = \text{Ni\%} + 0.5\text{Mn\%} + 30.0\text{C\%}$$

29. Each element is weighted with a factor which indicates its potency as a ferrite or an austenite former. As can be seen from the equations, carbon is 30 times more potent than nickel in forming austenite and molybdenum is 1.8 times more potent than chromium in forming ferrite.

30. Plate 2 is a portion of the tentative constitution diagram taken from reference (e). This provides a means of determining, through the use of equivalent values, the approximate amount of ferrite that may be expected in an alloy.

31. The results of magnetic measurements made on cast austenitic steels are tabulated in Table VI. Some of the data are plotted on Plate 2 in order to show where these steels lie on the tentative constitution diagram. It should be noted that cast Type 316 steels are prone to have percentages of ferrite in excess of 20% and permeabilities in excess of 2.

TABLE VI

PROPERTIES OF CAST AUSTENIT

CR-NI STEEL

Type or Name	Specification	Condition and Treatment	Source	Lab	Chemical Compositio					
					C	S	P	Mn	Si	Cr
Cast-Type 304	MIL-S-867(Ships) Class I	Cast + 2050°F-W Q	Lebanon Steel Fdy	Lebanon	.06	016	.013	80	.97	18 16
"	"	"	"	"	.07	.023	.013	70	1.06	18 50
"	"	"	"	"	.06	.020	.015	.72	.99	19.72
"	"	"	"	"	.07	.014	011	.67	1 22	19.50
Cast-Type 347	MIL-S-867(Ships) Class II	Cast + 2050°F-A.Q.	"	"	.08	.020	015	.79	.75	18.94
"	"	"	"	"	.06	022	.019	.70	.75	18 92
" "	"	"	"	"	.08	.020	.013	71	.81	18 44
"	"	"	"	"	.06	.018	.015	.67	82	18 88
Cast-Type 316	MIL-S-867(Ships) Class III	Cast + 2050°F-W.Q.	"	"	.07	.018	.014	.70	.90	19.46
"	"	"	"	"	.07	029	.017	76	1.01	19.67
"	"	"	"	"	06	.019	.012	.72	1.08	19.67
"	"	"	"	"	.06	.021	.015	.74	94	19.17
Cast 18-8+Cb	MIL-S-867(Ships) Class I(4)	Cast Pipe Stabilized	Crane Co	EES	.06	.015	.017	.65	.83	18.82
Cast-25-20		As-Cast	Mich.Steel CastingsCo.	Mich.	08			.88	.51	24.55
CAST IRONS										
Ductile Ni-Resist		As-Rec'd	St. Line Fdy&Mach.	St. Line Fdy&Mach.	total 2.98	.012	.065	1.15	2.2	2.36
"		Above-annealed @1150°F-1hr	"	"	2.98	.012	065	1.15	2.2	2.36
"		As-Rec'd annealed@1700°F 1 hr	"	"	2.98	.012	.065	1.15	2.2	2.36
"		As-Rec'd Cold Red. in Ten.-6%	"	"	2.98	.012	065	1.15	2.2	2.36
WELD METAL										
19-9 Ti Weld Metal		All Weld	D.K. Mfg.Co.							
19-9 Cb Weld Metal		All Weld-Long. Stabilized	M. W. Kellogg	EES	.06	.013	< 01	1.75	.38	20.23
19-9 Cb Weld Metal		Trans. Weld from pipe. Stabilized	"	"	.09	.015	.02	1.55	.49	19.03
25-20 Weld Metal		All Weld-Long. Stabilized	"	"	.14	.013	.013	1.78	.43	[illegible]5.88
25-12 Ti Weld Metal		All Weld	D.K. Mfg. Co.							

NOTES: (1) All resistivity data based on information obtained from the literature.
(A) indicates accurate data.
(B) indicates interpolated data of good accuracy.
(2) Yield strength (.2% set).

TABLE VI

ST AUSTENITIC STAINLESS STEELS

emical Composition in %							Mechanical Properties				• Hardness	Normal Permea-bility - μ		Coercive Force Hc in oersteds	Resistivity in Microhm-CM (1)	Remarks
Mn	Si	Cr	Ni	Mo	Cu	Other	T.S. in psi	Y.P. in psi	Elong %-2"	R.A. %		100 H	200 H			
CR-NI STEELS																
.80	.97	18.16	9.35				69,000	34,000	68.0			1.00	1.00	0	76.9(A)	
.70	1.06	18.50	9.43				69,000	30,500	72.5			1.02	1.02	0	"	
.72	.99	19.72	9.43				71,500	35,000	54.0			1.08	1.08	0	"	
.67	1.22	19.50	9.43				77,000	41,500	44.0			1.34	1.36	2	"	
.79	.75	18.94	10.20			Cb 1.03	77,000	42,500	37.0			1.04	1.04	0	71.0(A)	
.70	.75	18.92	11.00			Cb .70	78,000	38,000	39.0			1.04	1.04	0	"	
.71	.81	18.44	10.68			Cb .97	76,000	38,000	35.0			1.03	1.02	0	"	
.67	.82	18.88	10.38			Cb .84	77,500	40,000	37.0			1.03	1.03	0	"	
.70	.90	19.46	11.00	2.70			79,500	44,000	47.0			2.13	2.20	5	82.0(A)	
.76	1.01	19.67	10.21	2.95			80,500	45,500	52.5			1.79	1.84	4	"	
.72	1.08	19.67	10.37	2.55			82,500	46,000	50.5			2.25	2.32	5	"	
.74	.94	19.17	10.02	2.55			81,000	45,000	52.0			1.44	1.45	2	"	
.65	.83	18.82	9.03			Cb .24	71,000	28,500(2)	29.5	60.1	134 BHN	2.66	2.48	N.D.	76 (B)	
.88	.51	24.55	20.09	.17	.08		70,000 Min.	35,000 Min.	30.0 Min.			1.01	1.01	0	76.4(A)	
CAST IRONS																
1.15	2.2	2.36	20.48			Mg .085	64,500		12.5		91 RB	1.02	1.03	1	140-170 (B)	
1.15	2.2	2.36	20.48			Mg .085						1.02	1.03	1	"	
.15	2.2	2.36	20.48			Mg .085						1.03	1.04	3	"	
.15	2.2	2.36	20.48			Mg .085					92 RB	1.03	1.04	1	"	
WELD METAL																
												1.33	1.38	2	71 (B)	3/32" dia. electrode deposit.
.75	.38	20.23	10.15			Cb .62	94,600	70,600(2)	36.0	50.1		1.74	1.92	20	"	5/32" dia. electrode deposit.
.55	.49	19.03	10.75			Cb .87						1.04	1.04	1		
.78	.43	[illegible]5.88	21.80	.02			91,000	57,500(2)	36.7	43.7	202 BHN	1.00	1.00	0	76 (B)	5/32" dia. electrode deposit.
												1.07	1.09	2	"	1/16" dia. electrode deposit.

32. In examining specification Mil-S-867 (Ships), used in procuring corrosion-resisting austenitic castings, one finds that under the existing chemical composition ranges one can expect a wide range of magnetic properties. If the ferrite forming elements are on the low side and the austenite forming elements are on the high side, then Class I material will be wholly austenitic while Class II and Class III materials will contain approximately 0-5% ferrite and 5-10% ferrite, respectively. On the other hand, if conditions are reversed, i.e., ferrite formers on the high side and austenite formers on the low side, Class I and II will contain approximately 40-60% ferrite and Class III approximately 60-80% ferrite. Judging from Plate 2 it would appear that ferrite in excess of 20% would be undesirable. Consequently, unless the NOL tests indicate otherwise, extreme caution should be exercised in procuring massive castings under this specification. Most desirable would be the specification of 25Cr-20Ni alloy for large castings. This is a standard alloy in which low permeability is insured.

33. The results of tests made on all-weld metal deposits are included in Table VI. In general, the metallurgy of austenitic weld deposits is identical to that of castings and the aforementioned principles apply. Reference (f) is an excellent paper on the subject. It is not unreasonable to expect the normal permeability of some 19-9 welds to be greater than 2. Therefore, the safest approach would appear to be the specification of 25-20 welds.

34. However, one must bear in mind that in general the mass of weld metal will be relatively small and as such should not affect to any great extent the over all permeability of a structure constructed from low permeability materials.

35. Included also in Table VI are the properties of Ductile Ni-Resist. This is a cast iron containing 20% Ni and having a low permeability.

Austenitic Stainless Steels - Wrought

36. As was the case in the cast materials, the magnetic behavior of the austenitic wrought alloys is governed by their composition. However, the wrought and cast alloys differ in several respects. A stainless steel that is to be produced in the wrought form must be one that has satisfactory rolling or forging properties. Similarly a stainless steel which is to be cast must have satisfactory "castability." If one compares the composition ranges of wrought and comparable cast alloys, it is immediately apparent that the ferrite-promoting elements are held down and the austenite-promoting elements increased in the wrought alloys with respect to the cast alloys. As a result, if the nickel and chromium equivalents

are calculated as before, it will be found that in general the wrought alloys will be on the border line of the wholly austenitic area of Plate 2, whereas the cast alloys will lie within the austenite plus ferrite area. One would expect, therefore, that in the as-cast or annealed condition the wrought alloys would have low permeabilities. Reference (h) gives a maximum normal permeability of 1.02 for annealed AISI Types 301, 302, 303, 304, 305, 308, 309, 310, 316, 317, 321, and 347 wrought alloys.

37. As mentioned previously, the stability of the austenite determines the susceptibility of austenitic stainless steels to cold work. Reference (g) is a scholarly discussion of the subject and presents permeability results for a variety of stainless steels. Plate 3 is a plot of some of the data from this paper and serves to show the effect of cold work on three different analyses. Attention is called to the wide difference in response of the two Type 304 steels. It is to be noted that the ordinate in Plate 3 is the intrinsic permeability and 1.00 must be added to the figures shown to obtain the normal permeability.

38. The results of tests made on the wrought stainless steels at the Station are tabulated in Table VII. The high permeabilities of the Type 322, 17-7PH, and 17-4PH steels eliminate their use except possibly for small part applications. In general, it is believed that commercial annealed, straightened, and centerless ground bars of Types 302, 303, 304, 305, 310, 316, 321, and 347 will have an as-received permeability of less than 2. If considerable cold drawing, cold rolling, spinning, or some other type of cold reduction process is applied and the finished part is not to be subsequently annealed, then Types 305 and 310 appear to be the most satisfactory steels from a permeability standpoint. It must be recognized that these are not the only austenitic stainless steels which will exhibit low permeability after considerable cold reduction. Reference (g) lists 9 analyses which can be expected to have completely stable austenites, or at least would require cold reductions greater than 80% to initiate a marked change in permeability. For ready reference these are as follows:

Alloy			Composition %				
No.	C	Mn	Si	Cr	Ni	Mo	Cb
1	0.05	0.50	0.30	18.00	16.00	-	-
2	0.10	0.50	0.30	18.00	13.50	-	-
3	0.15	0.50	0.30	18.00	11.00	-	-
4	0,05	0.50	0.30	18.00	16.00	2.50	-
5	0.10	0.50	0.30	18.00	13.50	2.50	-
6	0.05	2.00	0.30	18.00	13.50	2.50	-
7	0.10	2.00	0.30	18.00	12.00	-	-
8	0.10	2.00	0.30	18.00	14.50	-	1.00
9	0.15	4.00	0.30	20.50	9.75	-	-

TABLE V

PROPERTIES OF WROUGHT AUSTEN

Type or Name	Speci-fication	Condition and Treatment	Source	Lab.	Che			
					C	S	P	Mn
Stainless Steel Type 302[4]	AISI-302	Cold Rolled Streamline Wire	Carpenter Steel Co	EES	.12	.013	.008	.41
"	"	Wrought 1/2 ø bar - as rec'd	DK Mfg. Co	EES DK Mfg.Co	.06 .061	.01	.04	.98 .99
"	"	Above (5) Heat Treatment #1	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #2	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #3	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #4	"	"	"	"	"	"
"	"	Wrought 1" ø bar - as rec'd	"	EES DK Mfg.Co.	.08 .075	.020	.040	.98 .99
"	"	Above Cold Red. in Tension -30%	"	"	"	"	"	"
"	"	Wrought 1-5/8" ø bar - as rec'd	"	EES DK Mfg.Co	.08 .045	.015	.020	1.19 1.25
"	"	Above Cold Red. in Tension -28%	"	"	"	"	"	"
"	"	Wrought 1" ø Condition A (6)	Rustless Iron & Steel	Rustless	.074	.021	.023	1.12
"	"	Wrought 1" ø Condition B (6)	"	"	.085	.009	.024	1.27
"	"	Wrought 5/8" ø Condition C (6)	"	"	.080	.013	.027	1.22
Stainless Steel Type 303	AISI-303	Wrought 1" ø Condition A (6)	"	"	.050	.259	.031	.67
Stainless Steel Type 304	AISI-304	Wrought 1/2" ø - as rec'd	DK Mfg. Co.	EES DK Mfg.Co.	.10 .073	.030	.037	.97 1.03
"	"	Wrought 1" ø bar - as rec'd	"	EES DK Mfg.Co.	.08 .075	.020	.040	.98 .99
"	"	Above Cold Red. in Tension -29%	"	"	"	"	"	"
"	"	Wrought 1-5/8" ø bar - as rec'd	"	EES DK Mfg.Co	.05 .030	.015	.017	1.64 1.32
"	"	Above - Cold Red. in Tension -28%	"	"	"	"	"	"
"	"	Hot Rolled Annealed	Rustless Iron & Steel	EES	.11	.012	.020	.62
"	"	Wrought 1" ø - as rec'd	Naval Stores	EES	.07			.57
"	"	Above - 1/2" ø shot peened	"	"	"			"
"	"	Wrought 1" ø Cold Red. Tension-23%	"	"	"			"
"	"	Wrought 1" ø Cold Red. Tension 37%	"	"	"			"
"	"	Wrought - Broken Tor. Spec.	"	"	"	.		"
Stainless Steel Type 305	AISI-305	Wrought-21/32" ø Condition D (6)	Rustless Iron & Steel	Rustless	.060	.014	.028	.58
Stainless Steel Type 309	AISI-309	Wrought-1-1/4" ø Condition A (6)	"	"	.068	.006	.027	2.17
Stainless Steel Type 310	AISI-310	Wrought-1-1/8" ø Condition A (6)	"	"	.056	.009	.023	1.42
Stainless Steel Type 316	AISI-316	Hot Rolled Annealed	"	EES	.11	trace	.015	1.88
Stainless Steel Type 321	AISI-321	Wrought Annealed	Allegheny-Ludlum	"	.06	.016	.030	.51
"	"	Above (5) Heat Treatment #1	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #2	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #3	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #4	"	"	"	"	"	"
Stainless Steel Type 322		Wrought & Precip. Hardened	Carnegie-Ill. Steel	"	.07	.017	.018	.54
17-7 PH		Wrought & Precip. Hardened	Rustless Iron & Steel	"	.07	.009	.021	.65
17-4 PH		Wrought & Precip. Hardened	"	"	.05	.010	.023	.58
Stainless Steel Type 347	AISI-347	Wrought Pipe Stabilized	M. W. Kellogg	"	.08	.010	.02	1.69
"	"	Above (5) Heat Treatment #1	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #2	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #3	"	"	"	"	"	"
"	"	Above (5) Heat Treatment #4	"	"	"	"	"	"
Discaloy		Wrought Heat Treated	Westinghouse Elec.	Typical Comp.	.05			.70
Discaloy		Above - Cold Red in Tension 12%	"	"	"			"

NOTES (1) All resistivity data based on information obtained from the literature
(A) indicates accurate data.
(2) Yield strength (1% set)
(3) Average properties
(4) Because of their low C content some of the materials classed as Type 302 can be classed as Type 304.
(5) Special Heat Treatments Heat Treatment #1 - as rec'd and 1950°F for 15 minutes. Water Quench.
Heat Treatment #2 - as rec'd and heat treatment #1 and 1700°F for 1 hour Aircool
Heat Treatment #3 - as rec'd and 1950°F for 15 minutes Furnace coo[illegible]
Heat Treatment #4 - as rec'd and heat treatment # and 1700°F for 1 hour - Air cool

TABLE VII

UGHT AUSTENITIC STAINLESS STEELS

Chemical Composition in %											Mechanical Properties				Hard-ness	Normal Permea-bility - μ		Coercive Force HC in oersteds	Resistivity in Microhm CM (1)
C	S	P	Mn	Si	Cr	Ni	Mo	Cu	Al	Other	T. S. in psi	Y.S. (.2%) in psi	Elong. % in 2"	R. A. %		100 H	200 H		
.12	.013	.008	.41	.58	18.55	9.98		.09							26-31Rc	1.56	2.00	37	70.1(A)
.06 .061	.01	.04	.98 .99	.40	17.65 17.60	7.94 8.00	.18	.18			85,000(3)	30,000(3)	60(3)	70(3)	96 Rb	1.08	1.13	0	"
"	"	"	"	"	"	"	"	"								1.01	1.01	0	"
"	"	"	"	"	"	"	"	"								1.01	1.01	0	"
"	"	"	"	"	"	"	"	"								1.01	1.01	0	"
"	"	"	"	"	"	"	"	"								1.01	1.01	0	"
.08 .075	.020	.040	.98 .99	.41	18.76 18.73	8.14 8.03	.29	.12			"	"	"	"	97 Rb	1.28	1.33	5	"
"	"	"	"	"	"	"	"	"							33 Rc	>3	>3	Note(7)	"
.08 .045	.015	.020	1.19 1.25	.48	19.65 18.3	9.00 10.7	.06	.12			85,000(3)	30,000(3)	60(3)	70(3)	86 Rb	1.33	1.36	2	"
"	"	"	"	"	"	"	"	"							26 Rc	1.34	1.43	10	"
.074	.021	.023	1.12	.59	17.81	8.85									159 BHN	1.00	1.00	0	"
.085	.009	.024	1.27	.66	18.38	9.35									321 BHN	1.09	1.18	16	"
.080	.013	.027	1.22	.41	17.73	8.79									321 BHN	1.19	1.44	34	"
.050	.259	.031	.67	.49	18.42	8.55									248 BHN	1.03	1.04	2	"
.10 .073	.030	.037	.97 1.03	.47	18.71 18.87	8.85 8.47	.30	.24			85,000(3)	30,000(3)	60(3)	70(3)	85 Rb	1.00	1.00	0	76.3(A)
.08 .075	.020	.040	.98 .99	.41	18.74 18.73	7.99 8.03	.29	.12			"	"	"	"	93 Rb	1.23	1.26	6	"
"	"	"	"	"	"	"	"	"							35 Rc	>3	>3	Note(7)	"
.05 .030	.015	.017	1.64 1.32	.49	18.49 18.29	10.67 10.72	.04	.11			85,000(3)	30,000(3)	60(3)	70(3)	79 Rb	1.00	1.00	0	"
"	"	"	"	"	"	"	"	"							25 Rc	1.01	1.01	0	"
.11	.012	.020	.62	.41	18.58	9.28	.16				85,000(3)	30,000(3)	60(3)	70(3)	150 BHN	1.02	1.02	0	"
.07			.57		18.87	9.43					"	"	"	"	77 Rb	1.01	1.01	0	"
"			"		"	"										1.01	1.01	0	"
"			"		"	"									100 Rb	1.02	1.04	3	"
"			"		"	"									30 Rc	1.06	1.15	16	"
"	.		"		"	"										1.08	1.12	9	"
.060	.014	.028	.58	.52	18.27	11.24									128 BHN	1.00	1.00	0	77.0(A)
.068	.006	.027	2.17	.18	24.40	13.65									159 BHN	2.47	2.56	5	78.0(A)
.056	.009	.023	1.42	.41	24.90	20.24									163 BHN	1.00	1.00	0	79.0(A)
.11	trace	.015	1.88	.42	17.20	12.75	2.25				85,000(3)	30,000(3)	60(3)	70(3)	150 BHN	1.00	1.00	0	72.4(A)
.06	.016	.030	.51	.93	18.42	9.63	.01			Ti.56	85,000(3)	30,000(3)	55(3)	70(3)	150 BHN	1.18	1.20	2	71.2(A)
"	"	"	"	"	"	"	"			"						1.15	1.15	1	"
"	"	"	"	"	"	"	"			"						1.10	1.10	1	"
"	"	"	"	"	"	"	"			"						1.09	1.09	1	"
"	"	"	"	"	"	"	"			"						1.10	1.11	1	"
.07	.017	.018	.54	.54	16.58	6.78		.11	.19	Ti.48	191,000	179,600(2)	15.0	55.0	393 BHN	> 3	> 3	Note(7)	
.07	.00?	.021	.65	.47	16.93	7.04			1.09		190,800	162,200(2)	18.0	41.0	420 BHN	> 3	> 3	Note(7)	
.05	.010	.023	.58	.36	16.62	4.40		3.85		Cb.43	179,200	166,000(2)	16.0	54.0	363 BHN	> 3	> 3	Note(7)	
.08	.010	.02	1.69	.39	18.13	12.34				Cb.80	90,600	58,900	40.5	65.5	174 BHN	1.00	1.00	0	71.2(A)
"	"	"	"	"	"	"				"						1.00	1.00	0	"
"	"	"	"	"	"	"				"						1.00	1.00	0	"
"	"	"	"	"	"	"				"						1.00	1.00	0	"
"	"	"	"	"	"	"				"						1.00	1.00	0	"
.05			.70	.70	13.0	25.0	3.00		.2	Ti1.80	145,000	106,000	19.0		30 Rc	1.00	1.00	0	
"			"	"	"	"	"		"	"					37 Rc	1.01	1.01	0	

304
ench,
l hour Aircool
l hour Air cool

(6) As received Conditions:
Condition A - Annealed, machine straightened and centerless ground.
Condition B - Annealed, cold drawn approx. 18%, machine straightened and stress relieved. Spec. AN-S-771, Cond. B.
Condition C - Annealed, cold drawn approx. 25%, machined, straightened and stress relieved. Spec AN-S-771, Cond B.
Condition D - Annealed, bumper straightened.
(7) Not determined

Another alloy which has been developed commercially for cold heading applications is the 16Cr - 14Ni steel.

39. The literature indicates that the permeability of wrought austenitic stainless steels should not be adversely affected by hot working operations provided the steels are not heated above nor worked below their recommended temperature ranges. The effect of various heat treatments on the normal permeability of Type 302, 321, and 347 steels is included in Table VII. It should be noted that neither slow cooling from 1950°F, nor stabilizing at 1700°F caused an increase in permeability. Indications are, therefore, that unannealed hot worked and/or stabilized wrought austenitic stainless steels will be acceptable from a permeability standpoint.

40. Early in the investigation some preliminary work was done to determine the effect of fabrication processes such as shearing and bending on the permeability of Type 304 sheet stock. The results of these few tests are tabulated in Table VIII. It is interesting to note that neither shearing nor 90° bending caused any marked increase in permeability. The over all effect here is a mass effect dependent upon the proportion of worked to unworked metal.

41. In addition to the foregoing, permeability measurements were made on the type 304 sheet after annealing but before pickling. A considerable portion of the scale on these samples remained intact. The permeability of these samples was approximately 1.2 and indicates the necessity of removing the scale from austenitic stainless steel surfaces and welds when practicable.

TABLE VIII

EFFECT OF VARIOUS COLD WORKING TREATMENTS ON THE PERMEABILITY OF AISI TYPE 304 STAINLESS STEEL

Thickness of Sheet	Composition %			Normal Permeability - μ @ 200H					
				Cond. 1	Cond. 2	Cond. 3	Cond. 4	Cond. 5	Cond. 6
	C	Cr	Ni	Annealed @ 1950 F W.Q. and Pickle	As rec'd and two sheared edges	Cond. 1 and 90 Longitudinal bend	Cond. 1 and 11 % cold Reduction	Cond. 1 and 20 % cold Reduction	Cond. 1 and 37 % cold Reduction
.030"	.06	17.50	9.46	1.004	1.007	1.011			
.050"	.08	18.07	8.53	1.002	1.013	1.026	1.020	1.127	2.353
.060"	.07	19.02	9.11	1.005	1.015	1.033			

Austenitic Manganese Steels

42. From the physical metallurgy standpoint the behavior of the austenitic manganese or so-called Hadfield manganese steels is similiar to that of the austenitic stainless steels. As before, the austenite of the manganese steels is stabilized at room temperature by the addition of alloying elements. The original Hadfield steels contained C and Mn as the principal alloying elements. Many modifications of the original alloy have been developed and include the addition of Cr, Ni, Mo, and V. The essential difference between the austenitic manganese and the austenitic stainless steels lies in their resistance to corrosion. In general, the corrosion resistance of the manganese steels are only slightly better than that of plain carbon steel.

43. As in the case of the stainless steels, the susceptibility of the manganese steels to cold work is dependent upon the stability of the austenite. As before the stability is determined by the composition. The properties of the manganese steels tested thus far are tabulated in Table IX. The differences in susceptibility between the various alloys is readily apparent. The important feature of Table IX is that all of the alloys have low permeability in the annealed or as-received condition.

CONCLUSIONS

44. Conclusions are based on the data and information contained herein and consequently apply to strong magnetic fields (100-200 oersteds).

45. In general, the normal permeability and coercive force of all brasses, bronzes, cupro-nickel, and other copper base alloys will be low in the absence of iron. Iron contents up to 5% in the brasses and bronzes do not result in permeabilities in excess of 2 regardless of condition or treatment. The normal permeability of annealed cupro-nickel alloys is not affected by iron contents up to 2%. On the other hand, the permeability of as-cast or hardened cupro-nickel alloys approaches 2 when the iron content exceeds 1.00%. There are indications that some of these alloys are ferromagnetic and as such may have higher permeabilities at lower field strengths. This is the case with the 80Cu - 20Ni + Fe alloy.

46. The permeabilities of the nickel base alloy, "K" monel, "S" monel, and inconel are low under all circumstances.

TABLE IX

PROPERTIES OF AUSTENITIC MANGANESE STEELS

Type or Name	Condition and Treatment	Source	Lab.	Chemical Composition in %								
				C	S	P	Mn	Si	Cr	Ni	Mo	Other
Hadfield Mn Steel	Wrought Dead Soft	E. O. Budd Mfg. Co.	EES	.91	.03	.05	13.52	.33	.05	.05	.01	
Hadfield Mn Steel	Wrought Cold Rolled	E. O. Budd Mfg. Co.	EES	.98	.03	.05	13.48	.33	.08	.05	.02	
Jessop #9	As Rec'd 1/4" Plate	Phila. Naval Shipyard	EES	.41	.020	.010	13.7	.50	4.24	3.06		V .51
Jessop #9	Wrought 1" ϕ bar	Jessop Steel Co.	Jessop	.34	.014	.020	12.15	.30	4.00	3.54	.42	
Jessop #9	Above-Cold Red. in Tension - 31%	Jessop Steel Co.	Jessop	.34	.014	.020	12.15	.30	4.00	3.54	.42	
Jessop #200	Wrought 5/8" ϕ bar	Jessop Steel Co.	Jessop	.29	.080	.065	11.00	.38	.66	7.39		
Jessop #200	Above-Cold Red. in Tension - 11%	Jessop Steel Co.	Jessop	.29	.080	.065	11.00	.38	.66	7.39		
Mn-Ni Steel	Wrought - 1" ϕ As Rec'd	Taylor Wharton		.60-.80			13.0-15.0	1.25-1.75		2.75-3.25		
Mn-Ni Steel	Wrought - 1" ϕ As Rec'd	Am. Brake Shoe	Am. Brake Shoe	.77	.008	.050	14.62	1.17	.31	4.01	None	

Type or Name	Mechanical Properties				Hard-ness	Normal Permea-bility - μ		Coercive Force Hc in oersteds	Resistivity in Microhm CM (1)
	T. S. in psi	Y. P. in psi	Elong. % - 2"	R. A. %		100 H	200 H		
Hadfield Mn Steel	141,400	50,700 (2)	53.1			1.02	1.05	4	68 (B)
Hadfield Mn Steel	171,600	130,000 (2)	14.2			1.58	1.99	31	68 (B)
Jessop #9						1.00	1.00	0	68.0 (A)
Jessop #9	123,000 (3)	87,500 (3)	40 (3)	45 (3)	16-35 Rc	1.00	1.00	0	67.8 (A)
Jessop #9					40-42 Rc	1.13	1.32	28	67.8 (A)
Jessop #200	90,000 (3)	45,000 (3)	65 (3)	50 (3)	92 Rb	1.00	1.00	0	70 (A)
Jessop #200					102 Rb	1.00	1.01	0	70 (A)
Mn-Ni Steel						1.00	1.00	0	68 (B)
Mn-Ni Steel						1.00	1.00	0	68 (B)

NOTES: (1) All resistivity data based on information obtained from the literature.
(A) indicates accurate data
(B) indicates data of good accuracy.
(2) Yield Strength (.1%)
(3) Average properties.

47. The normal permeability and coercive force of austenitic stainless steel weld metal and castings are dependent upon the stability of the austenite which is controlled by the composition. In general, 25Cr - 20 Ni is the only standard casting and welding austenitic stainless steel that has sufficient stability to give consistently low permeability values.

48. The wrought austenitic stainless steels have low permeabilities in the annealed condition. These alloys are, however, susceptible to cold work. The degree of susceptibility is dependent upon the stability of the austenite, which, as in the case of cast alloys, is controlled by the composition. Types 305 and 310 have relatively stable austenites and exhibit low permeabilities after considerable cold work.

49. The austenitic manganese steels are similar to the wrought austenitic stainless steels in their magnetic behavior. Plain Hadfield steels have relatively unstable austenites and are affected by cold work. The addition of nickel as an alloying element reduces this effect.

DISCUSSION

50. For the most part, the discussion has been incorporated in the text of the report and little remains to be added here. Test samples have been and are being prepared and sent to NOL for magnetic tests at low field strengths. An informal concept of the immediate test program at NOL involves the following when applicable:

(a) Maximum ideal permeability in the range of 0-1 oersteds at room temperature.

(b) Maximum ideal permeability for any reasonable field (below 50 oersteds).

(c) Normal residual induction and coercive force from saturation (approximately 1000 oersteds).

(d) Determine the Curie point if within operating range minus 40° to 120° F.

(e) Repeat a, b, c, just below the Curie point to obtain the maximum.

51. Little has been said in regard to the use of coercive force as a criterion for selection of materials. This is because the relative importance of this property on the magnetic signature of the completed component has never been clearly defined.

RECOMMENDATIONS

52. No unqualified recommendations can be made until the work at NOL is completed. Up to this time the normal permeability of some 45 samples which were originally tested at this Station has been determined at -40, +24, and +49°C in a 0.5 oersted field by NOL. The weak field measurements confirm the strong field measurements with but few exceptions. Knowing that a certain element of risk exists, one can therefore make certain generalizations about the magnetic properties of the types of materials covered by this report. The materials logically fall into four classes. These are as follows:

Class I - Those materials which undoubtedly will have satisfactory permeability and coercive force, especially at room temperature or higher.

(a) All as-cast, annealed; or cold worked brasses, bronzes, cupro-nickel and other copper base alloys containing less than 0.20% iron.

(b) All fully annealed brasses, bronzes, cupro-nickel and other copper base alloys containing iron in excess of 0.20% but less than 5%.

(c) Nickel base alloys of the following types: "K" monel, "S" monel, and inconel.

(d) Unannealed 25Cr - 20Ni austenitic stainless steel in the form of castings, weld metal or wrought material.

(e) Fully annealed wrought austenitic stainless steels of the following types: 301, 302, 303, 304, 305, 308, 309, 310, 316, 321 and 347.

(f) Fully annealed austenitic manganese-nickel steels such as Jessop #9 and Jessop #200.

Class II - Those materials whose permeability is less than 2 but which may exhibit coercive forces of varying manitude.

(a) All brasses and bronzes containing 5% or less of iron whether as-cast, hot rolled, cold rolled, or annealed.

(b) All cupro-nickel alloys containing 0.60% or less iron in the as-cast, hot rolled, cold rolled, or hardened condition.

(c) Austenitic cast irons such as Ni-resist Type 2.

(d) Commercial annealed, pickled, and straightened; and unannealed but scale free hot worked, wrought austenitic stainless steels of the following types: 302, 303, 304, 305, 310, 316, 321 and 347.

(e) Cold formed types 305 and 310 wrought austenitic stainless steels.

(f) Fully annealed plain Hadfield austenitic manganese steel.

Class III - Those materials whose permeability, because of composition range or treatment, may be greater or less than 2 and may also exhibit coercive forces of varying magnitude.

(a) Unannealed cupro-nickel alloys containing more than 0.60% iron.

(b) Austenitic stainless steel castings conforming to Classes I, II, and III of specification Mil-S-867 (Ships).

(c) Austenitic stainless steel weld metal of the 19-9 and 25-12 type.

(d) Cold worked wrought austenitic stainless steels of the following types: 301, 302, 303, 304, 308, 309, 316, 321 and 347.

(e) Cold worked plain Hadfield steel and Jessop #9 manganese nickel steel.

Class IV-Those materials which show unacceptable permeabilities in the condition in which they must be used.

(a) Straight monel metal.

(b) Precipitation hardening stainless steels of the type 322, 17-7PH, and 17-4PH.

REFERENCES

(a) BuShips ltr JJ46-1-(19)(343) Serial 343-505 dtd 10 Oct. 1950.
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(c) "Standard Definitions of Terms, with Symbols, Relating to Magnetic Testing" ASTM Standard Designation A340-49.
(d) "Standard Methods of Test for Permeability of Feebly Magnetic Materials" ASTM Standard Designation A342-49.
(e) Schoefer, E. A. "Magnetic Properties of Cast Stainless Steel", Alloy Casting Bulletin, No. 13, Aug. 1949.
(f) Schaeffler, A. L. "Selection of Austenitic Electrodes for Welding Dissimilar Metals," Welding Journal, Volume 26, No.10, Research Supl. 601S-620S, Oct. 1947.
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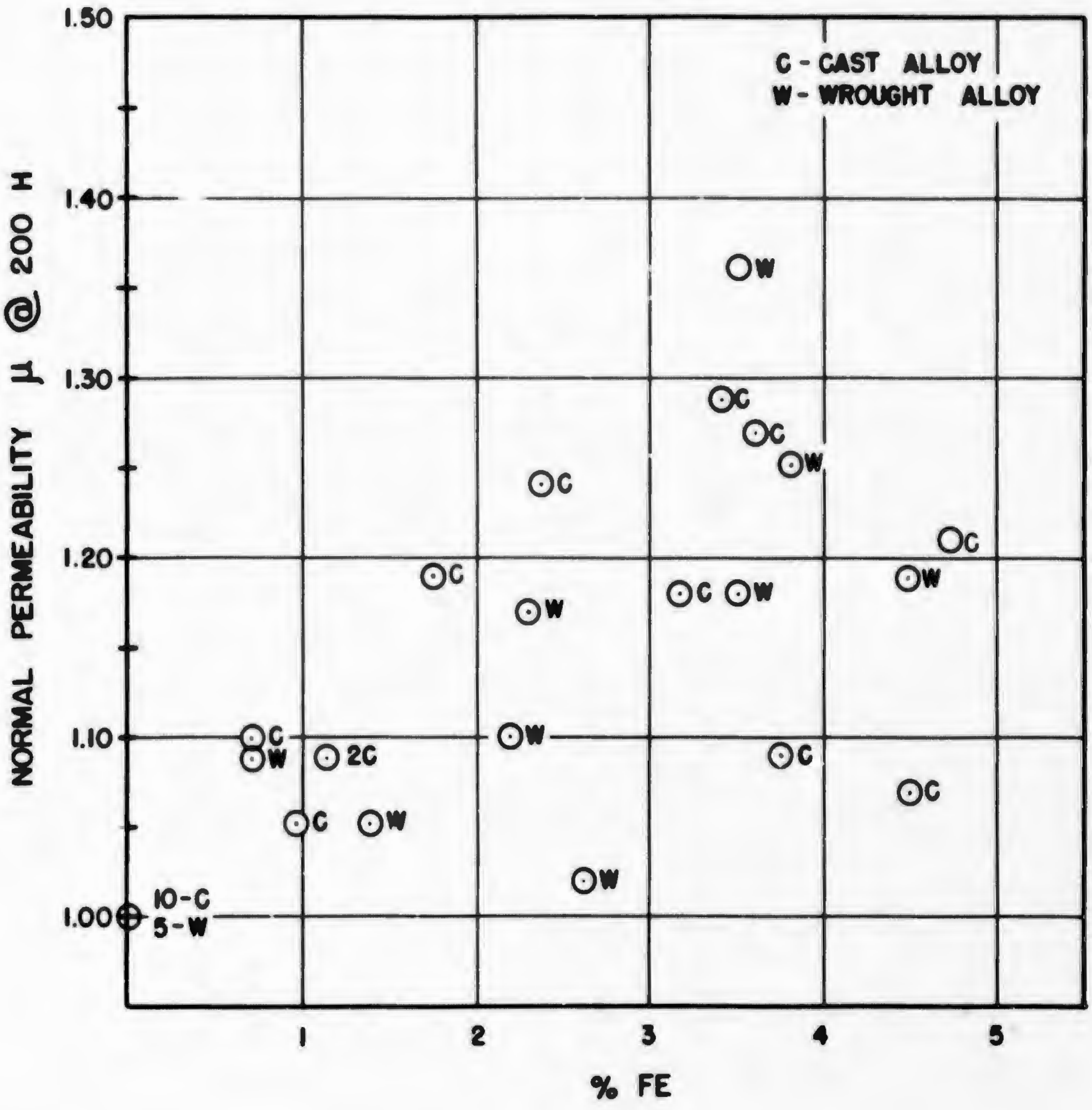
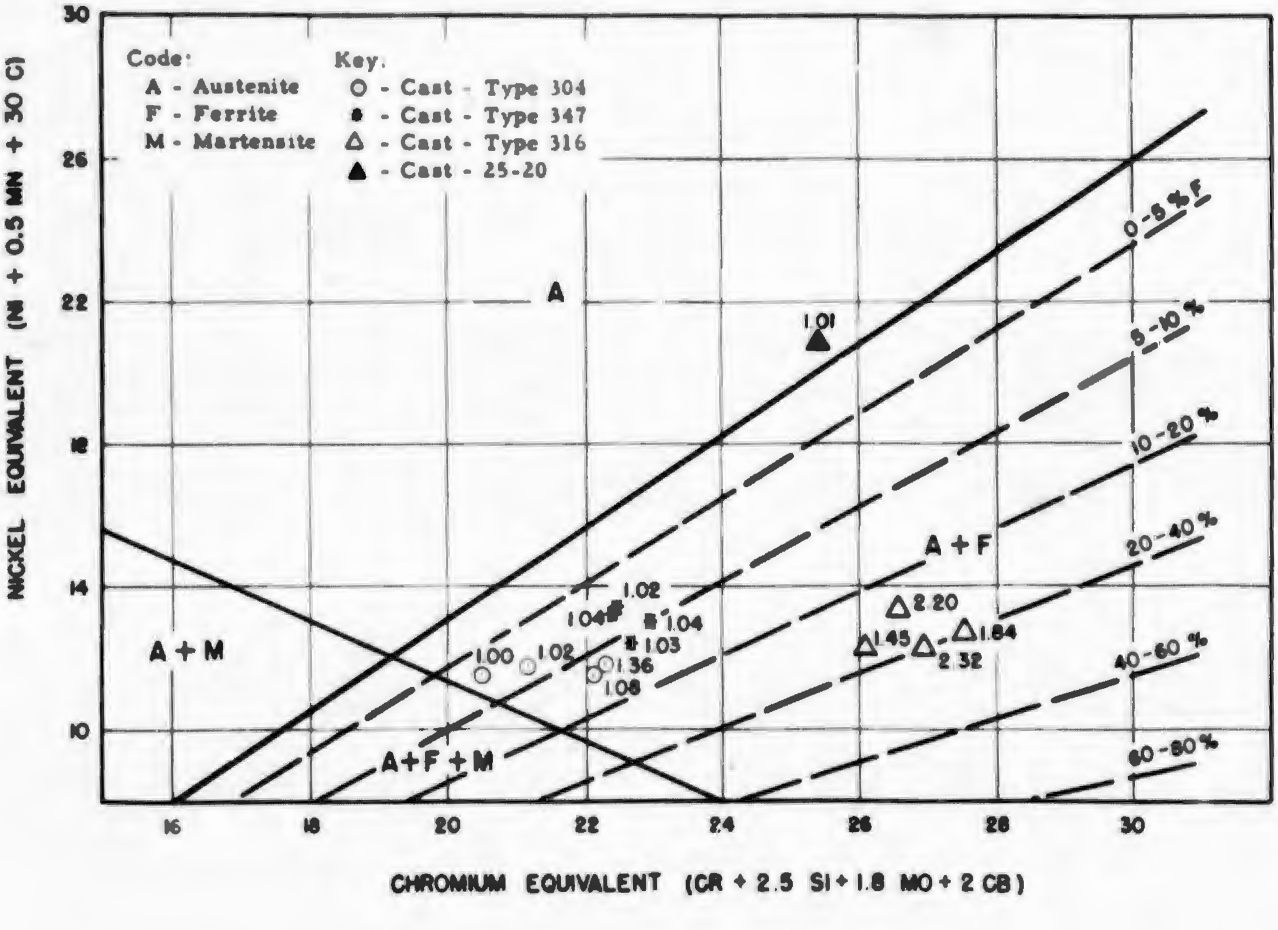
(h) Zapffe, C. A. "Stainless Steels," ASM Publication, 1949.
(i) Helmut Thielach, "Physical Metallurgy of Austenitic Steels," Welding Research Supplement, Vol. XV, No. 12, Dec. 1950, pp 577-6215

RELATIONSHIP BETWEEN NORMAL PERMEABILITY AND % IRON FOR BRASSES AND BRONZES



TENTATIVE CONSTITUTION DIAGRAM FOR CHROMIUM-NICKEL STEELS



EFFECT OF COLD WORK ON THE INTRINSIC PERMEABILITY OF TYPICAL TYPE 302 and 304 STAINLESS STEELS

Type 302	Type 304	Type 304
C - .126% Mn - .63%	C - .046% Mn - .38%	C - .030% Mn - .79%
Si - .40% Cr - 18.40%	Si - .23% Cr - 19.16%	Si - .63% Cr - 18.95%
Ni - 8.99%	Ni - 8.43%	Ni - 10.72%
Cr Equiv. = 19.20	Cr. Equiv. = 19.62	Cr Equiv. = 20.21
Ni Equiv. = 13.11	Ni Equiv. = 10.00	Ni Equiv. = 12.02