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REVIEW OF ALUMINUM-IRON MAGNETIC
ALLOYS AND ASSOCIATED SYSTEMS
(0 to 10% ALUMINUM)

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[0 To 10% Aluminum]

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ABSTRACT: This is the second of a series of reports concerned with the intrinsic physical and magnetic properties of the "soft" magnetic alloys commonly used in such operations as power conversion and amplification, guidance and control instrumentation, magnetic detection, and various other electro-mechanical operations. Specific emphasis is placed on the usefulness and limitation of these alloys in various unusual environmental situations to which they are exposed in present day applications, particularly environments involving nuclear radiation, elevated temperature, and unusual mechanical shocks and vibrations.

The initial report¹ (NAVWEPS Report 7331) was concerned with the iron-silicon magnetic alloy system. The present report presents results of work on the iron-aluminum magnetic alloy system with main emphasis on those alloys containing from 0% to 10% aluminum by weight.

Room-temperature magnetic properties of iron-aluminum alloys subjected to normal anneals and to "magnetic annealing" are reported as well as properties of materials exposed to temperatures up to 500°C and radiation environments of $\sim 10^{17}$ fast neutrons/cm². Oxidation resistance, magnetostriction, and special crystalline orientations are also discussed for these alloys.

The present study has indicated that low-percentage aluminum-iron alloys demonstrate the same excellent behavior when exposed to nuclear radiation, temperature, and mechanical stress as was observed in the low-percentage silicon-iron alloys.

These aluminum-iron materials show no detrimental order-disorder transformations during cooling cycle variations and magnetic data on these alloys are comparable with that obtained on the silicon-iron family. Sixty cps core loss values as low as 0.42 watts per pound were obtained on a magnetic annealed 7.68% aluminum-iron alloy (0.010 thickness) at induction levels of 10 Kilogauss.

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These alloys respond favorably to magnetic annealing processes. Permeability values in excess of 50,000 were obtained on alloys in the range of 7 to 10 w/o aluminum as result of magnetic annealing.

Manganese additions ($\leq 3\%$) were made to the 4% aluminum-iron alloys and noticeable effects were observed in the response of these alloys to magnetic annealing. Permeability changes from 17,800 to 35,600 occurred as result of the manganese additions. These additions also caused considerable reduction in slag formation during melting and improved the metal surface conditions.

The aluminum-iron alloys demonstrated excellent oxidation resistance for periods in excess of 400 hours at temperature of 500°C , particularly after these alloys were subjected to preferential oxidation annealing cycles in wet hydrogen.

These alloys have an inherent ductility advantage over the silicon iron alloys thus making the processing into sheet much easier. They also respond favorably to special crystalline orientation techniques.

Indications are that this family of alloys will offer considerable resistance to nuclear radiation environments and they are not subject to induced radioactivity as is the case of the cobalt bearing magnetic alloys.

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The increasing need for magnetic components that will operate under extreme environmental conditions has necessitated the acquisition of information on the effects of environment on the ferromagnetic core materials used within these components. This report has been prepared to provide the Bureau of Naval Weapons and its contractors with background material for ascertaining the limitations and capabilities of the iron-aluminum soft magnetic alloys for unusual environmental applications. This investigation has been performed as a part of BuWeps Magnetic Materials Task RRMA-02-008.

ROBERT ODENING
Captain, USN
Commander

A handwritten signature in cursive script, reading "L. R. Maxwell".

L. R. MAXWELL
By direction

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REVIEW OF ALUMINUM-IRON MAGNETIC
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[0 to 10% Aluminum]

INTRODUCTION

The rapid technical developments in recent years in the fields of high speed aircraft, missiles, nuclear powered devices, and space travel in general have imposed many unusual demands on electronic and magnetic components. Because of these advancements it has become imperative that investigations be conducted on selected magnetic alloy systems for the purpose of determining their usefulness in these components and particularly for determining their capabilities in the extreme environments encountered in many of today's applications. Consideration must be given to such environmental and operational factors as elevated temperature, radiation from nuclear sources, shock, vibration, pressure and humidity, as well as component weight, component volume, power handling capacity and operation at higher frequencies.

The "soft" magnetic alloy systems that appear particularly promising in satisfying most of these new and extreme environmental conditions are as follows:

- a. Silicon-Iron Alloys (0 to 6.5% Silicon)*
- b. Aluminum-Iron Alloys (0 to 16% Aluminum)*
- c. Aluminum-Silicon-Iron Alloys (0 to 16% Aluminum + 0 to 10% Silicon)*

*These alloys may or may not contain manganese or other minor constituents. Percentages listed are weight concentrations.

These alloys have been selected for investigation because a majority of them have special inherent properties which make them superior to most other "soft" magnetic alloys for applications in these environments. Some of these favorable characteristics are as follows:

- a. Good a-c and d-c properties over a wide range of ambient temperatures
- b. High Curie temperatures
- c. High saturation inductions
- d. Good permeabilities (particularly at high flux levels)
- e. High resistivities
- f. Good oxidation resistance

- g. Stability at elevated temperatures (up to 500°C)
- h. Stability in nuclear radiation environments
- i. Minimum order-disorder transformation
- j. Suitable ductility for thin gauge processing
- k. Minimum core loss values
- l. Reasonable density
- m. Compliancy to special orientation processes
- n. Availability and economy

The first of the magnetic alloy systems listed above, namely, the "silicon-iron alloys" has been reported on by the author.¹ The present report is a continuation of this effort, with emphasis on the aluminum-iron alloy system. It especially describes those properties of the aluminum-iron alloys that make them suitable for applications in unusual and severe environments.

IRON-ALUMINUM MAGNETIC ALLOY SYSTEM

History

As was true of the iron-silicon magnetic alloys, it was Barrett, Brown and Hadfield² who in 1890 first investigated iron-aluminum magnetic alloys containing low percentages of aluminum. However, their open air melting techniques, resulting in the rapid oxidation of aluminum, and the relative expense of aluminum vs silicon at that time shifted the emphasis to iron-silicon alloys. This picture has continued up to the present era; however, the advent of vacuum and controlled atmosphere melting techniques, together with the ready availability of aluminum in recent years has encouraged investigators to reconsider the iron-aluminum system.

In 1917 T. D. Yensen and W. A. Gatward³ reported on both the iron-aluminum and iron-silicon soft magnetic alloys melted in a vacuum of approximately 1 mm Hg and subsequently hot and cold rolled to sheet. They found aluminum to be a more powerful deoxidizer than silicon and they observed improved ductility in the iron-aluminum alloys. Certain alloys in the iron-aluminum series, particularly the low percentage aluminum, looked exceedingly promising when compared with equivalent iron-silicon alloys. However, they found it more difficult to prevent segregation of aluminum in iron-aluminum alloys than to prevent segregation of

silicon in equivalent iron-silicon alloys.

Masumoto⁴ made extensive investigations of the ferrous magnetic alloy systems containing aluminum, silicon, and combinations thereof in the early thirties. His efforts were in fair agreement with those of Yensen, thus indicating considerable promise for certain compositions of these systems. Much of Masumoto's success was due to the use of vacuum melting and annealing techniques; however, because of lack of ductility of many of the high aluminum alloy compositions it was necessary that his test specimens be made in the form of ring castings. This technique proved quite suitable for obtaining DC properties and his investigation eventually led to development of "Sendust," a high permeability, high resistivity, brittle alloy composed of 9.5% silicon-5.6% aluminum and remainder iron. However, from a practical economical standpoint, this method of producing magnetic cores was not particularly desirable, therefore, additional work was required for improving the processing techniques on these alloys.

Sykes and Bampfylde⁵ in 1934 reported extensively on the electrical, thermal, and mechanical properties of the iron-aluminum alloys, however their materials were air-melted which affected the purity thus resulting in a drastic reduction of ductility for alloys containing more than 5% aluminum.

In 1937 Zaymovski and coworkers⁶ reported on work on aluminum-iron alloys with manganese additions. They found that ternary alloys containing as much as 6.5% aluminum and 2.8% manganese proved more ductile than the binary 4% silicon-iron alloy, whereas the magnetic and electrical properties were approximately equivalent. The higher percentage ternary alloys also had a higher electrical resistivity.

Bozorth, Williams, and Morris⁷ in the thirties and early forties looked into the production of low percentage aluminum-iron alloys. These investigators included cold rolling and cold drawing operations in their studies. They found that directional properties could be imparted to these alloys thus providing an increase in their permeabilities, particularly at high inductions.

Additional work has been performed on the aluminum-iron magnetic alloy system since the early forties, particularly in Japan; however, the amount of published work is somewhat limited. Masumoto and Saito⁸, Yamamoto and Tanaguchi⁹, Sato¹⁰, and Sugihara¹¹⁻¹², have been quite active in recent years in studying the ferromagnetic alloys of the aluminum-iron system.

Results of an extensive investigation of the mechanical and physical properties of iron-aluminum alloys containing up to 18.5

weight percent aluminum have been reported recently by Kayser¹³. He discussed the first phase of this study which was concerned mostly with the preparation of materials, testing procedures, and room temperature and elevated temperature results on mechanical properties.

Most recent efforts on this system have been concerned with the less ductile, high percentage aluminum-iron magnetic alloys containing 10% to 17% aluminum. These alloys are referred to as Alfenol in this country and Alperm or Hipermaal in Japan. Nachman and Buehler¹⁴, Pavlovic and Foster¹⁵, Masumoto and Saito¹⁶, Sugihara¹⁶ and others have made extensive studies on these higher percentage aluminum-iron ferromagnetic alloys, therefore, only occasional mention of these alloys will be made in the present report.

Because there is a scarcity of information on the aluminum-iron alloys containing low concentrations of aluminum [$<10\%$ by weight], the remainder of this report will place emphasis on this lower composition range. The relevant work of other investigators will be discussed in those sections where they have made contributions.

Phase Diagram

Although there are several grey areas which require additional investigation, certain portions of the iron-aluminum phase diagram have been fairly well established. By means of thermal, magnetic, resistivity, x-ray, microscopic, and dilatometric analyses such investigators as Isawa and Murakami¹⁷, Wever and Muller¹⁸, Ageew and Vher¹⁹, Gwyer and Phillips²⁰, Bradley and Jay²¹, Bradley and Taylor²², Sykes and Evans²³, Taylor and Jones²⁴, and others have contributed to this diagram. Using composite data from many of these investigators, Hansen²⁵, has published the iron-aluminum phase diagram shown in Fig. 1.

There continues to be many unanswered questions relating to the iron-aluminum diagram, therefore, the transformation curves and dashed structure boundaries in Fig. 1 are to be regarded as tentative. Information relative to the exact location of the gamma loop (see inset of Fig. 1) is somewhat contradictory, however it may be assumed that the vertex of this gamma loop is located at about 1150°C for aluminum contents in a range between 0.6 and 1.0 percent by weight, whereas the $\alpha + \gamma$ zone will extend slightly beyond this composition. Carbon impurities are particularly effective in extending this gamma loop, just as in the case of the iron-silicon alloy system.

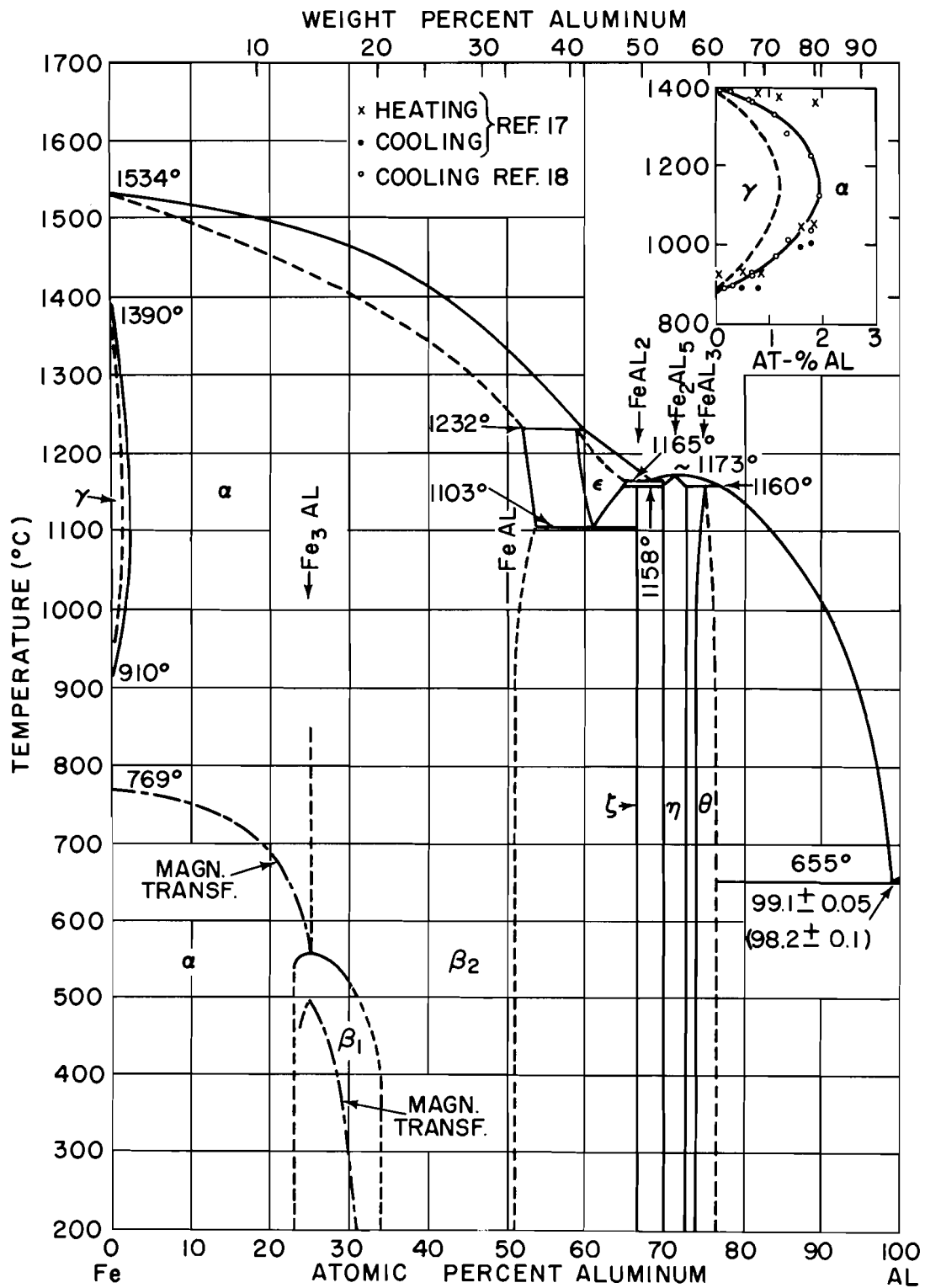


FIG. 1 PHASE DIAGRAM FOR IRON-ALUMINUM ALLOYS
(FROM HANSEN²⁵)

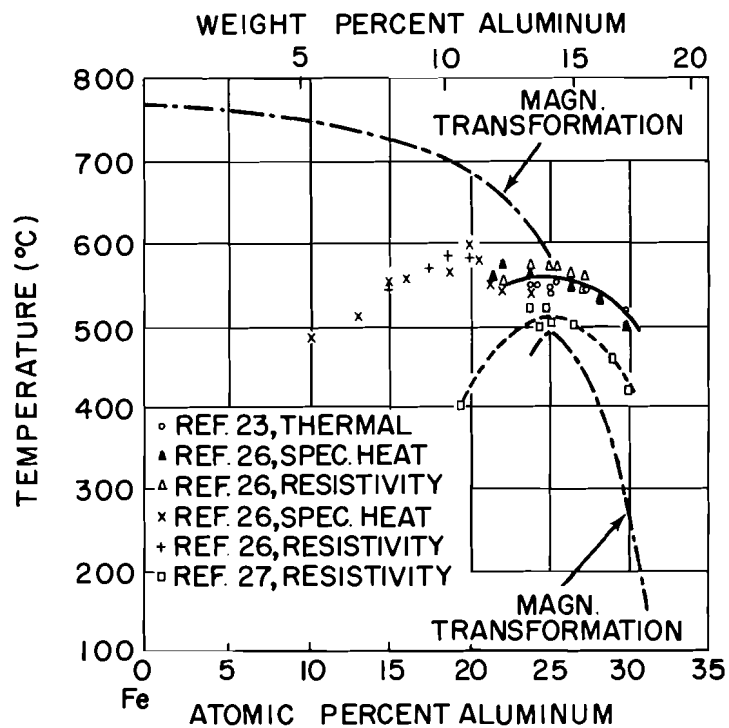


FIG. 2- ORDER-DISORDER AND MAGNETIC TRANSFORMATION TEMPERATURES OF AL-FE ALLOYS IN THE Fe_3Al REGION. (FROM HANSEN²⁵)

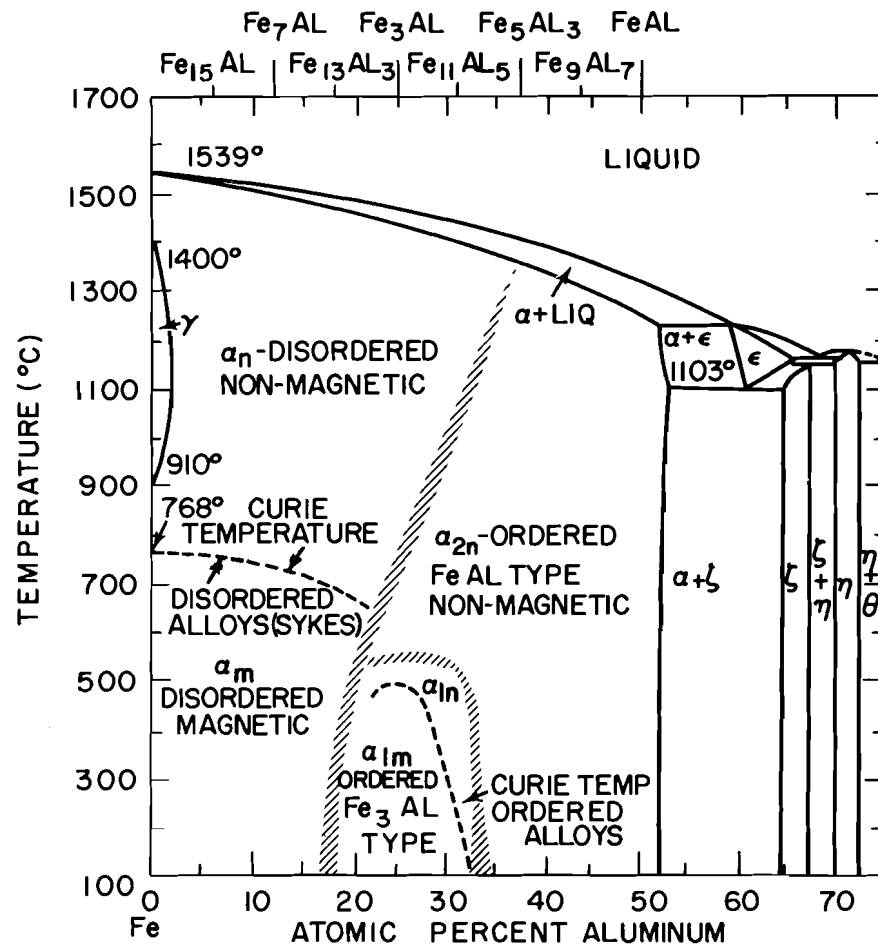


FIG. 3- NEW CONSTITUTION DIAGRAM OF IRON-RICH IRON-ALUMINUM ALLOYS. (FROM TAYLOR AND JONES²⁴)

Another point in question concerns the transition temperatures in the range from about 10 to 35 atomic percent aluminum. Saito²⁶, and others^{23,27}, found transition temperatures in the range of 10-30 atomic percent aluminum as indicated in Fig. 2. Saito claimed that alloys in this range belong to a short range ordered superstructure corresponding to the $\text{Fe}_{13}\text{Al}_3$ type (18.75 at. % Al).

Ageew and Vher¹⁹ found that the body-centered cubic solid solution of aluminum in alpha iron extends, from 0 to 52 atomic percent aluminum, however Bradley and Jay²¹, then later Taylor and Jones²⁴ and McQueen and Kuczynski²⁸ have shown that this α -phase field may be subdivided into three distinct regions based on the type of atomic ordering present. Fig. 3 illustrates the recent findings of Taylor and Jones on these regions. As may be observed, the first region consists of a random substitutional solid solution of aluminum in iron. It terminates in a sloping boundary originating at 18.75 atomic percent aluminum at room temperature and rising to approximately 37 atomic percent aluminum at 1375°C. Alloys ranging from 18.75 to 33.3 atomic percent aluminum lying below 550°C have an ordered structure typified by Fe_3Al while alloys lying outside the Fe_3Al field and to the right of the sloping boundary have a superstructure of the FeAl type.

Fortunately, the alloys of interest in the present report contain less than 10% by weight (18.7 atomic %) aluminum, therefore they are located in the random substitutional solid solution region and are not subject to order-disorder transitions.

Magnetic Properties

D-C Properties (Room Temperature) Aluminum-iron alloys having zero to 10% (by weight) aluminum content were prepared in accordance with the section on "Alloy Preparation" (Appendix I). The purity of elements used in preparation of these melts is given in Table I. The chemical analyses of typical as-cast slabs are shown in Table II.

Toroidal laminated and tape cores were made from these melts following hot and cold rolling operations. Material thicknesses of 0.014 and less were used in preparation of these cores. The cores were then subjected to various annealing cycles in a pure dry hydrogen atmosphere (-90°F Dewpoint) and then boxed, wound, and tested for magnetic characteristics. Types of annealing operations performed and typical static magnetic properties obtained using standard ballistic galvanometer test methods are reported in Tables III - VI. The maximum permeability of these alloys following normal anneal and following magnetic anneal are illustrated in Fig. 4 and 5.

TABLE I

ANALYSIS OF ELEMENTS USED IN PREPARATION OF ALUMINUM-IRON MELTS

	Fe	AL	Mn	C	S	Si	P	Mo
Electrolytic Iron (typical)	99.92	Nil	0.006	0.0124	0.011	0.014	0.005	0.002
99.99% Grade Ingot Aluminum	0.005	99.98	0.003	nil	nil	0.009	nil	nil
Electrolytic Manganese	0.003	0.004	99.95	0.020	0.015	0.005	0.004	0.001

	Ni	Cr	Cu	Co	W	Mg	O ₂	V
Electrolytic Iron (typical)	nil	nil	0.006	nil	nil	---	0.021	Nil
99.99% Grade Ingot Aluminum	nil	nil	0.002	---	nil	0.004	---	nil
Electrolytic Manganese	nil	nil	0.001	nil	nil	0.001	---	nil

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TABLE II

ALUMINUM CONTENT OF ALUMINUM-IRON ALLOYS (HOT ROLLED CONDITION)

<u>Melt No.</u>	<u>Nominal Percentage</u>	<u>Actual Percentage</u>
607	1%	0.95%
608	1.5%	1.44%
609	2%	1.90%
610	3%	2.95%
611	4%	3.88%
612	5%	4.80%
924	6%	5.95%
928	8%	7.68%
929	10%	10.00%

TYPICAL IMPURITY CONTENT OF ABOVE ALLOYS

<u>C</u>	<u>S</u>	<u>O₂</u>	<u>N₂</u>	<u>H₂</u>
0.003	0.0015	0.00007	0.0001	0.00006

TABLE III
MAGNETIC PROPERTIES OF ANNEALED IRON-ALUMINUM ALLOYS
(Nominal Thickness of Material is 0.014)

Specimen Number	Aluminum Content (By wt)	D-C Magnetic Properties (Hm = 30 oersteds)					60 cps Core Loss* (watts/lb)	Type Anneal**
		μ_{20}	μ_{max}	H_C	B_r	B_m		
3396	0.0%	700	12,550	0.486	13,810	16,790	1.08	Standard (1000°C)
1358	0.0%	920	11,440	0.431	11,805	16,250	-	Hi-Temp. (1220°C)
3525	0.3%	960	14,660	0.397	13,470	16,220	0.88	Standard (1000°C)
3570	0.3%	1190	13,200	0.248	8,440	14,940	1.09	Hi-Temp. (1220°C)
3526	0.5%	880	14,560	0.445	14,150	15,990	0.87	Standard (1000°C)
3527	0.5%	990	16,770	0.248	13,160	15,530	-	Hi-Temp. (1220°C)
3354	0.95%	2040	20,210	0.329	14,100	16,350	0.70	Standard (1000°C)
3496	0.95%	1130	16,400	0.291	12,630	15,640	0.90	Hi-Temp. (1220°C) 4 hrs
3355	1.44%	1980	15,960	0.436	14,370	16,370	0.69	Standard (1000°C)
3356	1.90%	1890	14,820	0.470	14,270	16,220	0.72	Standard (1000°C)
3357	2.95%	1920	12,810	0.450	13,740	16,280	0.70	Standard (1000°C)
3497	2.95%	870	14,800	0.233	9,270	14,620	0.72	Hi-Temp. (1220°C) 4 hrs
3358	3.88%	1890	11,740	0.475	13,100	16,060	0.69	Standard (1000°C)
3359	4.80%	2380	12,620	0.329	10,150	15,450	0.64	Standard (1000°C)
3498	4.80%	1020	8,760	0.271	5,820	13,950	0.84	Hi-Temp. (1220°C) 4 hrs
3509	5.95%	780	7,650	0.615	10,300	14,400	0.90	Standard (1000°C)
3579	5.95%	1130	4,540	0.530	4,910	12,670	-	1000°C + Rapid Cool
3489	7.68	510	3,460	0.550	3,240	13,390	1.06	Standard (1000°C)
3508	7.68	1070	6,060	0.298	3,580	12,490	-	1000°C + Rapid Cool
3488	10.0%	330	1,730	0.760	1,810	13,030	0.99	Standard (1000°C)
3580	10.0%	1200	4,850	0.293	2,620	11,750	-	1000°C + Rapid Cool
2975B	11.72%	4840	29,890	0.081	4,240	13,450	-	Standard (1085°C)

* For maximum induction of 10 kilogauss. Calculated from Ferrotracer²⁹ hysteresis loops.

** Anneals were performed in hydrogen as follows:

Standard (1000°C)---Furnace heat to 1000°C - Hold 2 hours - Furnace cool

Hi-Temp. (1220°C)---Furnace heat to 1220°C - Hold 12 hours - Furnace cool

1000°C + Rapid Cool---Furnace heat to 1000°C - Hold 2 hours - Furnace cool to 600°C - Water quench

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TABLE IV

EFFECT OF THICKNESS AND INSULATION ON MAGNETIC PROPERTIES OF NOMINAL 2% AND 4% ALUMINUM-IRON ALLOYS
(STANDARD HYDROGEN ANNEAL)*

Specimen Number	Aluminum Content (By wt)	Core Form	Material Thickness**	Insulation	D-C Magnetic Properties ⁷					60 cps [□] Core Loss (Watts/lb)
					μ_{20}	$\mu_{\max}$	H_C	B_R	B_m	
3458	1.90%	Tape	0".002	MgO	1300	8570	0.72	13,690	15,580	0.66
3541	1.90%	Tape	0".002	None	1120	11,320	0.66	14,320	16,240	-
3505	1.90%	Tape	0".004	MgO	1860	13,400	0.45	13,100	15,700	0.48
3542	1.90%	Tape	0".004	None	2290	16,760	0.43	14,270	16,270	-
3356	1.90%	Lams.	0".014	MgO	1890	14,820	0.47	14,270	16,220	0.72
3460	3.88%	Tape	0".002	MgO	1520	7,800	0.72	13,000	15,600	0.66
3504	3.88%	Tape	0".004	MgO	1600	10,860	0.48	12,100	15,400	0.53
3543	3.88%	Tape	0".004	None	1350	10,920	0.55	12,600	15,300	-
3358	3.88%	Lams.	0".014	MgO	1890	11,740	0.47	13,100	16,060	0.69

* All cores had identical anneal (Furnace heat to 1000°C - Hold 2 hours-furnace cool).

** All materials were cold rolled from 0".100 thickness to finished gauge.

⁷ Coercive force (H_C), Residual Induction (B_R), and Maximum Induction (B_m) measured from $H_m = 30$ oersteds.

[□] For maximum induction (B_m) of 10 kilogauss. Calculated from ferrotracer²⁹ hysteresis loops.

TABLE V

EFFECT OF MAGNETIC ANNEAL ON MAGNETIC PROPERTIES OF IRON-ALUMINUM RING LAMINATED CORES

Specimen Number	Material Thickness (Nominal)	Aluminum Content (By wt)	D-C Magnetic Properties ($H_m = 30$ oersteds)					60 cps Core Loss* (Watts/lb)	Annealing Cycle** Temp. Time at Temp.	D-C Field Applied During Anneal (Oersteds)
			μ_{so}	μ_{max}	H_c	B_r	B_m			
3396	0".014	0.0%	700	12,550	0.486	13,810	16,790	1.08	1000°C 2 hrs	None
3396 ^x	0".014	0.0%	690	21,580	0.435	14,930	16,840	1.02	800°C 2 hrs ^x	1.7
3526	0".014	0.5%	880	14,560	0.445	14,150	15,990	0.87	1000°C 2 hrs	None
3526 ^x	0".014	0.5%	1020	19,660	0.444	14,260	16,220	0.84	800°C 2 hrs ^x	1.7
3354	0".014	0.95%	2040	20,210	0.329	14,100	16,350	0.70	1000°C 2 hrs	None
3354 ^x	0".014	0.95%	1900	26,480	0.315	14,160	16,070	0.64	800°C 2 hrs ^x	1.7
3357	0".014	2.95%	1920	12,810	0.450	13,740	16,280	0.70	1000°C 2 hrs	None
3357 ^x	0".014	2.95%	1850	17,340	0.491	13,990	15,840	0.62	800°C 2 hrs ^x	1.7
3359	0".014	4.80%	2380	12,620	0.329	10,150	15,450	0.64	1000°C 2 hrs	None
3359 ^x	0".014	4.80%	2320	36,000	0.296	13,160	15,330	0.48	800°C 2 hrs ^x	1.7
3359 ^{x a}	0".014	4.80%	2820	28,570	0.259	12,760	15,110	0.47	800°C 2 hrs ^{x a}	10.0
3512□	0".014	4.80%	340	17,500	0.530	12,600	14,400	0.77	800°C 2 hrs□	1.7
3509	0".014	5.95%	780	7,650	0.615	10,300	14,400	0.90	1000°C 2 hrs	None
3509 ^x	0".014	5.95%	460	19,200	0.484	12,500	14,600	0.70	800°C 2 hrs ^x	1.7
3489	0".014	7.68%	510	3,460	0.550	3,240	13,390	1.06	1000°C 2 hrs	None
3489 ^x	0".014	7.68%	1140	50,900	0.269	10,900	12,800	0.48	800°C 2 hrs ^x	1.7
3490	0".010	7.68%	570	3,340	0.600	3,420	13,410	0.90	1000°C 2 hrs	None
3490 ^x	0".010	7.68%	1650	32,200	0.255	11,500	13,500	0.42	800°C 2 hrs ^x	1.7
3491	0".0065	7.68%	640	2,830	0.690	3,540	13,010	0.93	1000°C 2 hrs	None
3491 ^x	0".0065	7.68%	1660	12,700	0.321	9,940	12,400	0.75	800°C 2 hrs ^x	1.7
3488	0".014	10.0%	330	1,740	0.760	1,810	13,030	0.99	1000°C 2 hrs	None
3488 ^x	0".014	10.0%	950	53,550	0.180	10,430	13,110	0.65	800°C 2 hrs ^x	1.7
2975B	0".014	11.72%	4840	29,890	0.081	4,240	13,450	-	1085°C 1 hrs	None
2975B ^x	0".014	11.72%	5190	33,350	0.100	4,900	13,900	-	800°C 2 hrs ^x	1.7

* Designates magnetic anneal following standard 1000°C anneal on same core.

□ Designates magnetic anneal with no previous anneal.

* For maximum induction of 10 kilogauss. Calculated from ferrotracer^{2a} hysteresis loops.

** Anneals were performed in hydrogen as follows:

1000°C - 2 hrs---Furnace heat to 1000°C - Hold 2 hrs - Furnace cool

800°C - 2 hrs^x---Furnace heat to 800°C - Hold 2 hrs in magnetic field - Furnace cool in field.

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TABLE VI

EFFECT OF MANGANESE ADDITIONS AND MAGNETIC ANNEAL ON MAGNETIC PROPERTIES OF 4% AND 8% ALUMINUM-IRON Alloys
(RING LAMINATED CORES, 0.014 THICK MATERIAL)

Specimen Number	Nominal Aluminum Content (By wt)	Manganese Addition (By wt)	D-C Magnetic Properties ($H_m = 30$ oersteds)					60 cps Core Loss* (Watts/lb)	Annealing Cycle**		D-C Field Applied During Anneal (Oersteds)
			μ_{20}	μ_{max}	H_c	B_r	B_m		Temp.	Time at Temp.	
3358	4.0%	0.0%	1890	11,740	0.475	13,100	16,060	0.69	1000°C	2 hrs	None
3358 ^x	4.0%	0.0%	1850	17,800	0.473	13,870	15,940	0.60	800°C	2 hrs ^x	1.7
3360	4.0%	0.5%	2200	14,170	0.341	10,980	15,510	0.71	1000°C	2 hrs	None
3360 ^x	4.0%	0.5%	1640	26,790	0.410	13,740	15,690	0.44	800°C	2 hrs ^x	1.7
3361	4.0%	1.0%	2200	14,420	0.328	10,970	15,540	0.60	1000°C	2 hrs	None
3361 ^x	4.0%	1.0%	2040	30,320	0.333	13,245	15,530	0.46	800°C	2 hrs ^x	1.7
3561	4.0%	2.0%	1960	13,740	0.323	9,770	14,590	0.63	1000°C	2 hrs	None
3561 ^x	4.0%	2.0%	2080	35,300	0.292	12,400	14,590	0.53	800°C	2 hrs ^x	1.7
3562	4.0%	3.0%	1900	13,550	0.290	9,160	14,430	0.63	1000°C	2 hrs	None
3562 ^x	4.0%	3.0%	2150	35,610	0.268	12,200	14,180	0.47	800°C	2 hrs ^x	1.7
3489	8.0%	0.0%	510	3,460	0.550	3,240	13,390	1.07	1000°C	2 hrs	None
3489 ^x	8.0%	0.0%	1140	50,900	0.269	10,900	12,800	0.45	800°C	2 hrs ^x	1.7
3577	8.0%	1.0%	470	2,890	0.675	2,760	12,700	-	1000°C	2 hrs	None
3577 ^x	8.0%	1.0%	1380	28,360	0.273	10,280	12,950	0.90	800°C	2 hrs ^x	1.7
3578	8.0%	2.0%	500	3,200	0.610	2,860	12,840	-	1000°C	2 hrs	None
3578 ^x	8.0%	2.0%	1360	35,030	0.272	10,620	12,840	0.60	800°C	2 hrs ^x	1.7

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^x Designates magnetic anneal following standard 1000°C anneal on same core.

* For maximum induction of 10 kilogauss. Calculated from ferrotracer²⁹ hysteresis loops.

** Anneals were performed in hydrogen as follows:

(1000°C - 2hrs)-Furnace heat to 1000°C - Hold 2 hours - Furnace cool

(800°C - 2hrs^x)-Furnace heat to 800°C - Hold 2 hours in magnetic field - Furnace cool in field

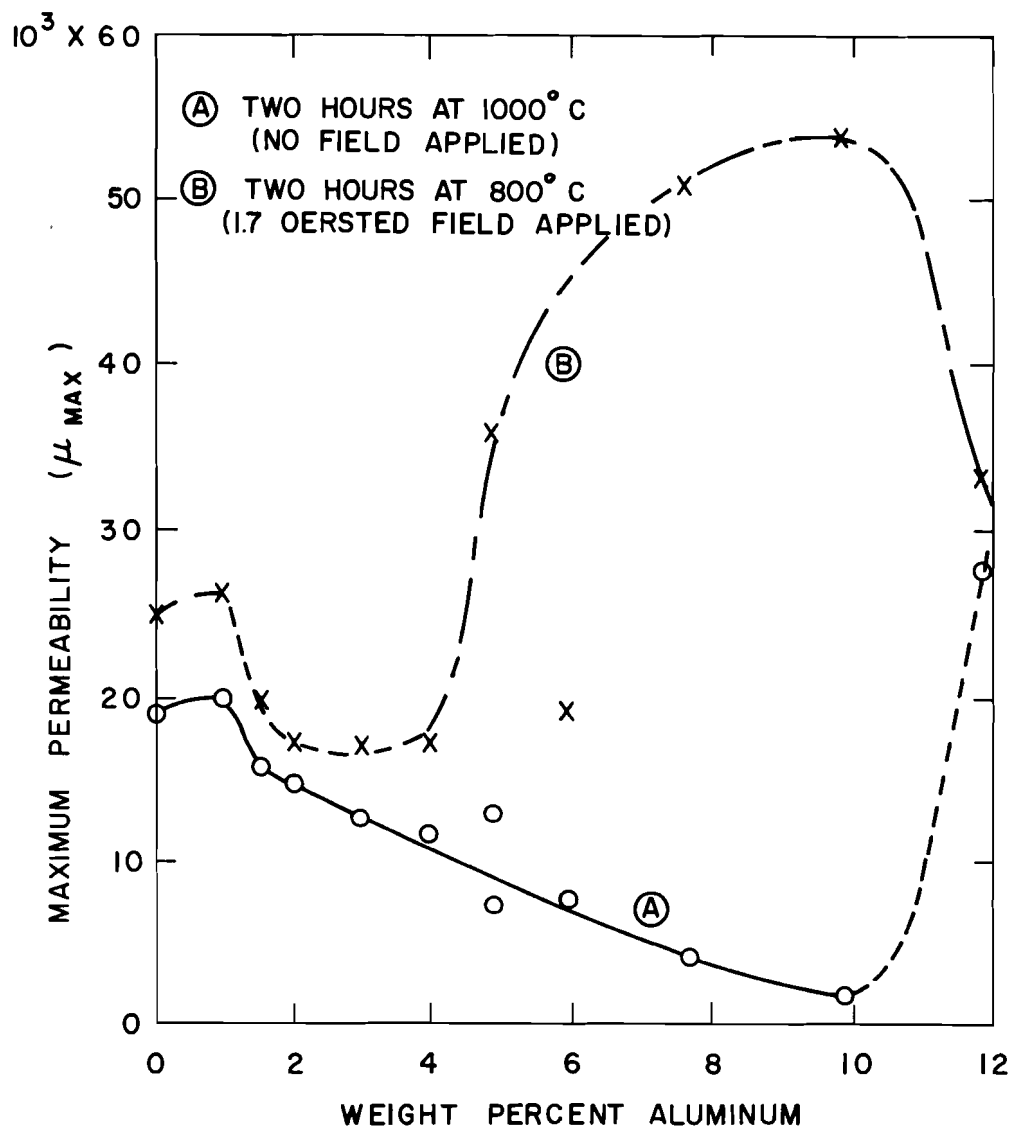


FIG. 4 - EFFECT OF MAGNETIC ANNEAL
VS NORMAL ANNEAL ON D-C
PERMEABILITY OF IRON-ALUMINUM
ALLOYS (0.014 MATERIAL)

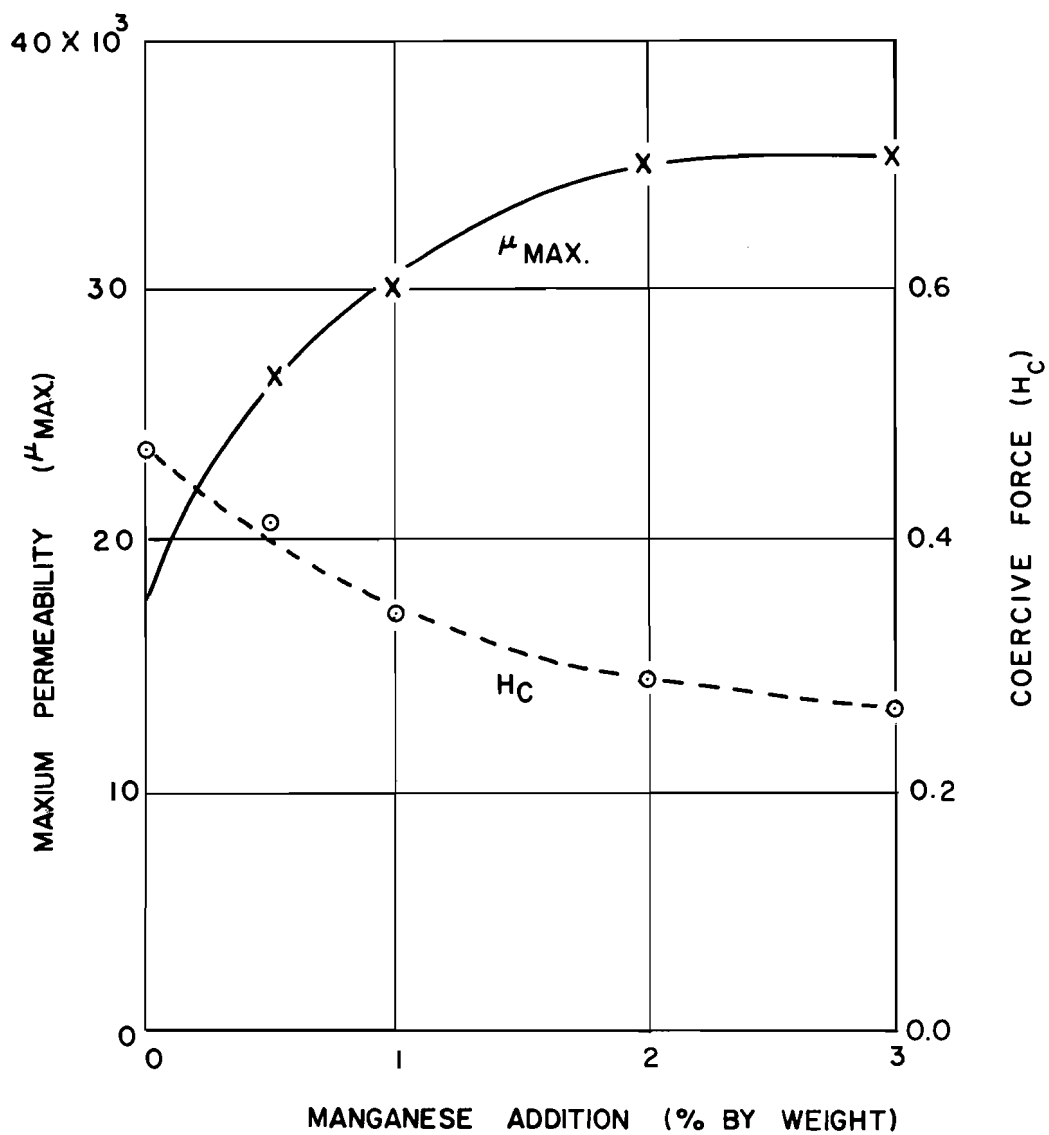


FIG.5 - EFFECT OF MANGANESE ADDITIONS
ON MAGNETIC PROPERTIES OF 4% AL-FE
ALLOY (MAGNETIC ANNEALED)

Conclusions that may be drawn from this d-c data are as follows:

a. In general, the permeability, coercive force and core loss values obtained on 0.014 thick laminated aluminum-iron cores are slightly inferior to the values obtained on equivalent silicon-iron alloy compositions. (See Ref. 1)

b. As is true of the silicon-iron alloys, the aluminum-iron materials acquire their maximum permeability values at high induction levels [not itemized in Tables]. Alloys containing up to 6% aluminum acquire their peak permeabilities in the range of 8 to 11 kilogauss. Above 6% aluminum these induction levels for peak permeabilities start dropping off with increase in aluminum.

c. From Table III it may be observed that high temperature, long time anneals in pure dry hydrogen atmosphere do not promote sufficient improvement in magnetic properties of aluminum-iron alloys to warrant the added time and expense required to obtain these temperatures. The exception to this statement occurs where high temperatures are required for obtaining special orientations or where high purities are desired in the low percentage aluminum alloys, particularly those approaching pure iron in composition. In general, an increase in the annealing temperature of isotropic aluminum-iron alloys produces a slight improvement in permeability, a reduction in coercive force, and a reduction in residual induction, although the magnitude of these changes is usually negligible.

d. The highest d-c permeabilities (~20,000) and lowest coercive forces (~0.33) obtained on the isotropic 0.014 thick laminated samples using the standard 1000°C anneal were found in alloys containing approximately 1% aluminum (see Table III and Fig. 4). In general, these properties deteriorated with increased aluminum content except in instances when cores were subjected to magnetic annealing. [Additional comments on this beneficial effect will be discussed under section "Magnetic Annealing Effects."] Masumoto and Saito⁸ found permeability peaks of about 16,500 on a 1.22% aluminum-iron alloy and 12,100 on an alloy containing 4.05% aluminum. There was considerable difference in melting, processing, core fabrication and annealing techniques used by these investigators compared to those used by the present author. Nevertheless, the results obtained were quite comparable for a 1000°C annealing temperature.

e. Contrary to expectations there were no drastic improvements observed in alloys containing less than 1% aluminum. This may have been due to the degree of purity of the alloys under study. Although the impurity content was quite low in these alloys, it may not have been sufficient to obtain optimum properties for these compositions. The other factor that would have affected the magnetic properties pertains to the grain refinement resulting when these iron-rich aluminum-iron alloys are annealed above 1000°C, thus placing them within the gamma transformation region.

Cioffi³⁰ obtained a maximum permeability of about 250,000 on pure iron (0% aluminum) but only after exposing it for long periods of time to an extremely high temperature (above 1400°C) and by carefully controlling the cooling rate through this critical alpha-gamma transformation zone. Yensen and Gatward³ were able to obtain a maximum permeability of 43,000 on a vacuum annealed 0.4% aluminum-iron alloy.

It is desirable to obtain improved properties in these low aluminum-iron alloys because of their high magnetic saturation values and because of their ease in fabrication, however the procedure for obtaining these properties must be a practical one. The specific deficiencies of these low percentage alloys are: low resistivity values, and phase transformations that occur during elevated temperature annealing. This latter deficiency may also occur in alloys containing more than 1% aluminum when the impurity contents are not carefully controlled since the shape and extension of the gamma loop are quite responsive to changes in purity of the alloy.

f. Particular emphasis should be placed on the observed effects of magnetic annealing on the properties of the aluminum-iron alloys, specifically those alloys containing from 4% to 10% aluminum by weight and also those alloys having manganese additions. (Refer to Tables V and VI and to Figs. 4 and 5) Maximum permeability values in range of 50,000 were obtained on the nominal 8% and 10% aluminum-iron alloys following magnetic anneal. When manganese additions of 2% and 3% were made to the 4% aluminum-iron alloy, permeability values of 35,600 were obtained following magnetic anneal. Because of the drastic effects observed on these alloys as result of magnetic anneal, a more detailed discussion of these effects is reserved for a later section of this report. (See "Magnetic Annealing Effects")

g. As with other magnetic alloys, material thickness affects the magnetic properties of the aluminum-iron alloys. Table IV illustrates such effects on nominal 2% and 4% aluminum-iron compositions. No attempt was made to obtain special orientations

in this study, however, it was found that alloys containing up to 5% aluminum could be cold reduced from 0.100 thickness down to a thickness of 0.0005 without any great difficulty. Using heavy cold reduction procedures of this type and a simple 1000°C hydrogen anneal, optimum properties were obtained at 0.004 thickness and above. Ordinarily a decrease in tape thickness is advantageous from standpoint of eddy current losses, particularly at elevated frequencies. However, this advantage may be offset by the increase in surface-to-volume ratio thus making the material more susceptible to detrimental contamination from insulations thus affecting the total core loss values. The magnesium oxide insulation used during anneal of most of the cores under study here may not be ideal for aluminum-iron alloys. Possibly a cataphoretic application of aluminum oxide or, better yet, an exposure of the strip to an elevated temperature in open air for a short period of time thus forming a thin aluminum oxide coating may prove to be a more compatible insulation. These possibilities were not examined at this time.

h. Another interesting result of these experiments concerned the effect of material thickness on the magnetic properties of the 7.68% aluminum-iron alloy following magnetic anneal. (See Table V) No drastic changes were observed when the materials were exposed to the normal 1000°C anneal except for an increase in coercive force with decrease in thickness. However, when the cores were subjected to a magnetic annealing cycle the effect of thickness was more obvious. The 0.014 material produced a permeability of 50,900 whereas a value of only 12,700 was obtained from the 0.0065 material.

i. It is known that order-disorder transformations, particularly of the long range type, become a major consideration as the aluminum content of iron-aluminum alloys is increased above the 10% range. It may also be observed that certain changes occurred in the present study in some of the alloys containing less than 10% aluminum when these alloys were subjected to variations in cooling rates. For instance, water quenching of the 7.68% and 10% aluminum-iron cores (Table III, cores #3508 and #3580) from above 600°C gave coercive force values that were considerably lower than those obtained using the slow cooling procedure (cores #3489 and #3488). A less noticeable change was observed in the coercive force of the 5.95% aluminum iron alloy when subjected to a variation in cooling rate (core #3509 vs #3579); however, different residual induction (Br) values were obtained on this alloy. Resistivity measurements gave no indication that the different cooling rates drastically affected the atomic arrangement of these alloys. However, changes in magnetic values were observed and they may have resulted from the freezing-in of a particular atomic arrangement or they may have been

caused by the severe surface strains produced when the specimens were quenched in water.

A-C Properties (Room Temperature)

It is highly desirable to have high permeability, low coercive force, and other good static values in a magnetic alloy, however, in most practical applications these characteristics are not necessarily the deciding factors in determining the capabilities of a particular alloy.

As is true in the case of most magnetic alloys it is the a-c properties which govern the usefulness of the aluminum-iron alloys in most applications, particularly in power type applications. These properties are expressed in terms of core loss measurements at various induction levels (e.g. 10 or 15 kilogausses) and at various frequency levels (60 cps. 400 cps, etc.). They provide the designer information as to the amount of electrical power that will be expended during magnetization of the core material. Of course, such things as exciting current limitation, squareness of hysteresis loop, permeabilities at different induction levels, resistivity, and saturation values are important to the designer; however, the core loss value is probably the most important factor in a majority of applications.

Typical 60 cycle core loss data measured at magnetic induction levels of 10,000 gauss on nominal 0.014 thick aluminum-iron materials processed at the Naval Ordnance Laboratory (Appendix I) are given in Tables III to VI. For these measurements toroidal laminated cores were tested using an x-y recorder and an automatic hysteresis loop tracer circuit developed in this Laboratory by Geyger²⁹.

The changes in core loss obtained with change in aluminum content may be observed in these tables. A reduction in core loss with increase in aluminum occurs in alloys containing up to 5% aluminum when subjected to the standard 1000°C anneal (Table III). When these alloys are exposed to a magnetic anneal (Table V), this reduction in core loss with aluminum content is continuous up to 8% and 10% aluminum except for the alloy containing 6% aluminum. This latter alloy seems degraded in all properties and did not respond to various treatments used in this investigation. There is no obvious reason for this unless possibly the alloy was contaminated during melting or processing. Of course higher aluminum-iron alloys (12% and 16% aluminum) show improved properties over those listed in the table, however, their ductilities are quite poor and they do not respond favorably to magnetic annealing.

The lowest 60 cps core loss value obtained in this investigation was a value of 0.42 watts/lb obtained on 7.68% Al-Fe, 0.010 thick, at an induction level of 10 kilogauss following magnetic anneal (Core #3490X, Table V). A 4.8% Al-Fe core #3359X) made of 0.014 thick material gave a value of 0.48 watts/lb under similar conditions. These data were obtained on fairly isotropic aluminum-irons. Special orientations such as Goss's³¹ (110)[001] cube-on-edge or Assmus's³² (100)[001] cube orientation would permit higher magnetic flux densities without increase in either core loss or exciting current.

From these data, it may be seen that the aluminum-iron alloys are perfectly satisfactory for use in power type application, particularly the 60 cycle application; however, their core loss values are slightly inferior to those of equivalent silicon-iron alloys. Fig. 6 illustrates typical 60 ~ loops on a laminated core of 4.8% aluminum-iron (0.014 thickness) following standard and magnetic anneals.

Magnetic Annealing Effects

Data of Tables V and VI, and Figs. 4-6 readily demonstrate the effects of subjecting aluminum-iron alloys (0 to 10% aluminum by weight) to a magnetic annealing cycle following exposure to a normal annealing cycle in minute ambient field conditions. These effects are also common to other ferromagnetic alloy systems such as silicon-iron, nickel-iron, and cobalt-iron. Bozorth³³, Becker³⁴ and Graham³⁵ have discussed in some detail the various theorys related to these magnetic annealing effects.

In the present study the alloys demonstrating the greatest changes as result of a magnetic anneal are those containing 7.68% aluminum and 10% aluminum. Permeability improvements from 3,400 to 51,000 and 1,700 to 53,500 occurred following a magnetic anneal on these two alloys (refer to cores 3489 and 3488, Table V).

These results are somewhat different from those reported by Sugihara¹¹. His results gave highest maximum permeability of about 28,000 occurring at 10.20% aluminum whereas the present work gave peak permeability value of 53,500 occurring at ~ 10% aluminum by weight. Details on higher aluminum alloys are not included in the present report although results on a 11.72% aluminum-iron alloy are included in Fig. 4 and Table V to indicate the changes that occur in these higher aluminum alloys. The differences in the present work and that covered by Sugihara are stated here for information purposes. Both sets of data were taken on ring shape specimens; however, Sugihara's data

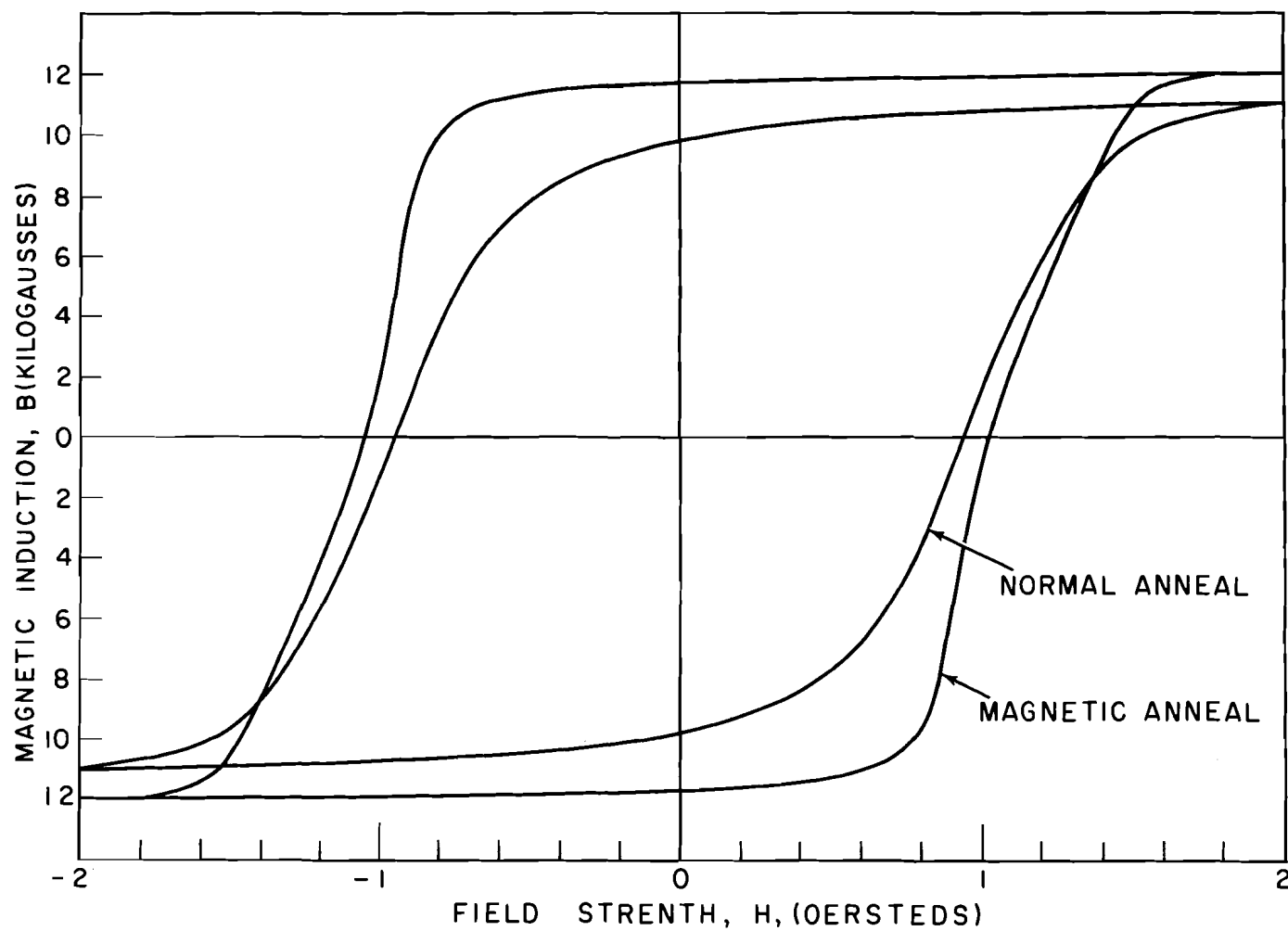


FIG. 6 EFFECT OF MAGNETIC VS NORMAL ANNEAL ON 60 CPS
HYSTERESIS LOOP OF 4.8% ALUMINUM - IRON.
(NOMINAL 0.014 MATERIAL)

were measured on a specimen cut from hot rolled material having 0.8 mm thickness (0.032). This specimen was then vacuum annealed at 1000°C for one hour, furnace cooled, then subjected to a second anneal at various reduced temperatures and cooled in a circular magnetic field of about 12 oersteds.

The samples of the present report were ring core laminations stamped from 0.014 thick material produced by hot rolling operations followed by cold or warm rolling to finish gauge. These specimens were initially hydrogen annealed at 1000°C for two hours and furnace cooled with no field applied. This was followed by the magnetic anneal which consisted of reheating the specimens to 800°C, holding in a circular field for two hours and furnace cooling the specimen while maintaining the field. A magnetic field of only 1.7 to 2.0 oersteds was used in most cases. Just as was the case with the silicon-iron alloys, it has been found that small fields are more effective than the higher fields for obtaining high maximum permeabilities whereas the high fields will, in general, produce a higher initial permeability, a lower coercive force, and slightly lower core loss. (Refer to Table V, Core #3359X vs #3359X²). This applies more so to the higher percent aluminum than to the low percent aluminum-iron alloys.

A maximum annealing temperature of 800°C was used in the present investigation for a standard magnetic anneal because this temperature encompasses the Curie temperatures of all alloys under study. However, it should be emphasized that magnetic annealing is effective only at temperatures below the Curie temperature of the material. In fact, for the aluminum-iron and silicon-iron alloy systems this effective range is from the Curie temperature down to temperatures that are quite low. Sugihara's¹¹ data on aluminum-iron alloys verifies this statement since he was able to obtain some large effects by applying magnetic fields at a temperature of only 250°C. Perhaps even greater improvements would have occurred if he had used periods of time longer than 30 minutes, since there is a known time-temperature relationship for this type of annealing.

Bozorth and Dillinger³⁶ investigated time-temperature effects for magnetic annealing of permivar and 65 permalloy. Their studies indicated that the magnetostrictive strains set up in domains during a magnetic annealing cycle will be relieved if time and temperature allow. Within experimental error, they found the logarithm of the relaxation time, τ , to be proportional to the reciprocal of the absolute temperature, T . This relationship can be expressed as follows:

$$\tau = A e^{\frac{W}{kT}}$$

where τ = minimum time (secs) at temperature

$A = 2.8 \times 10^{-12}$ secs. (Emperical Constant)

$W = 3.4 \times 10^{-12}$ ergs (Activation Energy)

$k = 1.38 \times 10^{-16}$ erg/degree [Boltzmann's Constant]

T = Absolute Temperature ($^{\circ}\text{K}$)

This low-temperature magnetic-annealing process is not only important from standpoint of producing materials with improved properties, but it becomes of particular concern when these materials are used in core components that are subjected to temperatures above room temperature during operation. The energizing current of the cores may in effect create conditions of magnetic anneal, therefore, it is necessary that we understand how these magnetic alloys respond to such treatments. More discussion on this effect can be found in the section "Temperature Cycling" below.

Fig. 6 illustrates changes that transpired in the 60 cycle hysteresis loop of a 4.8% aluminum-iron core that was first subjected to a normal annealing cycle and then to a magnetic anneal. As may be observed, the magnetic anneal tends to produce a more rectangular hysteresis loop, higher residual induction values, and somewhat higher maximum induction values at low energizing field strengths. However, the magnetic anneal does not cause a lowering of the coercive force for the 60 cycle loop as it ordinarily does for the d-c loop.

Fig. 7 illustrates 60 cps dynamic loops of a number of aluminum-iron alloys, containing various aluminum contents, which have been subjected to a magnetic annealing cycle of 800°C for two hours and subsequently cooled in a field of 1.7 oersteds. The loops shown were made on an x-y recorder using Geyger's²⁹ ferrotracer circuit with a maximum energizing field of about four oersteds. The decline of maximum induction, residual induction, and coercive force values with increase in aluminum content can be readily observed.

Of particular interest is the effect of magnetic annealing on aluminum-iron alloys with manganese additions. The data of Table VI and Fig. 5 illustrate these effects very clearly on 4% and 8% aluminum-iron alloys containing various manganese additions. For example, the maximum permeability of a straight binary 4% aluminum-iron alloy was 17,800 following magnetic anneal whereas this value increased to 35,300 when a 2% manganese addition was made to this alloy. Core loss values were considerably improved in the 4% aluminum-iron alloys with addition of manganese and

subsequent magnetic anneal. Values of 0.44 and 0.46 watts/pound were obtained on 4% aluminum-iron alloys containing 0.5% and 1.0% manganese respectively. These values were obtained following magnetic anneal and they were measured using 60 cps at induction levels of 10 kilogauss on 0.014 thick material. It may be noted that manganese additions did not have the same effect on core loss for the 8% aluminum-iron and they caused a degradation in the d-c properties following magnetic anneal.

The improvements observed here on aluminum-iron alloys as a result of magnetic annealing were not indicated by Hall's³⁷ study on single crystals; however, the experimental procedures and the test specimen configurations were noticeably different. Hall observed no significant changes in magnetic properties due to magnetic annealing of single crystal "picture frames" of ferromagnetic aluminum-iron alloys whereas the noticeable changes in properties of aluminum-iron alloys observed in the present report were obtained on ring laminations of relatively isotropic polycrystalline materials. Hall's single crystal samples were probably very high purity specimens and this may have been one reason for poor response to magnetic anneals. According to Heidenreich, Nesbitt, et al³⁸, the nickel-iron and nickel-iron-cobalt alloys respond to magnetic annealing only when impurity faults are present. These faults may result from oxygen impurities in the processed material or from diffusion in a slightly oxidizing atmosphere during anneal, and they may be a requisite for successful magnetic annealing of all magnetic alloys.

The single-crystal "picture frame" samples used by Hall were cut with the [100] direction parallel to the legs, this being the "easy" direction of magnetization for several of his low percentage aluminum-iron alloys. Other investigators (Fahlenbrach³⁹, and Fiedler and Pry⁴⁰) have indicated that the greatest changes occur (for silicon-iron alloys) when the materials are magnetic annealed with the field applied in directions other than parallel to the easy direction of magnetization. Consequently, the studies of these investigators indicate that magnetic annealing will not necessarily provide the same order of improvement on high purity specially oriented aluminum-iron and silicon-iron alloys as may be obtained on the more isotropic polycrystalline materials.

One notable exception to the findings above concerns the work of M. Goertz⁴¹ on low percentage silicon-irons, particularly the 6.5% silicon alloy. On a single crystal hollow rectangle of this alloy, having each side parallel to [100], the "easy" direction of magnetization, Goertz was able to obtain a permeability of 3,800,00 following heat treatment in a magnetic

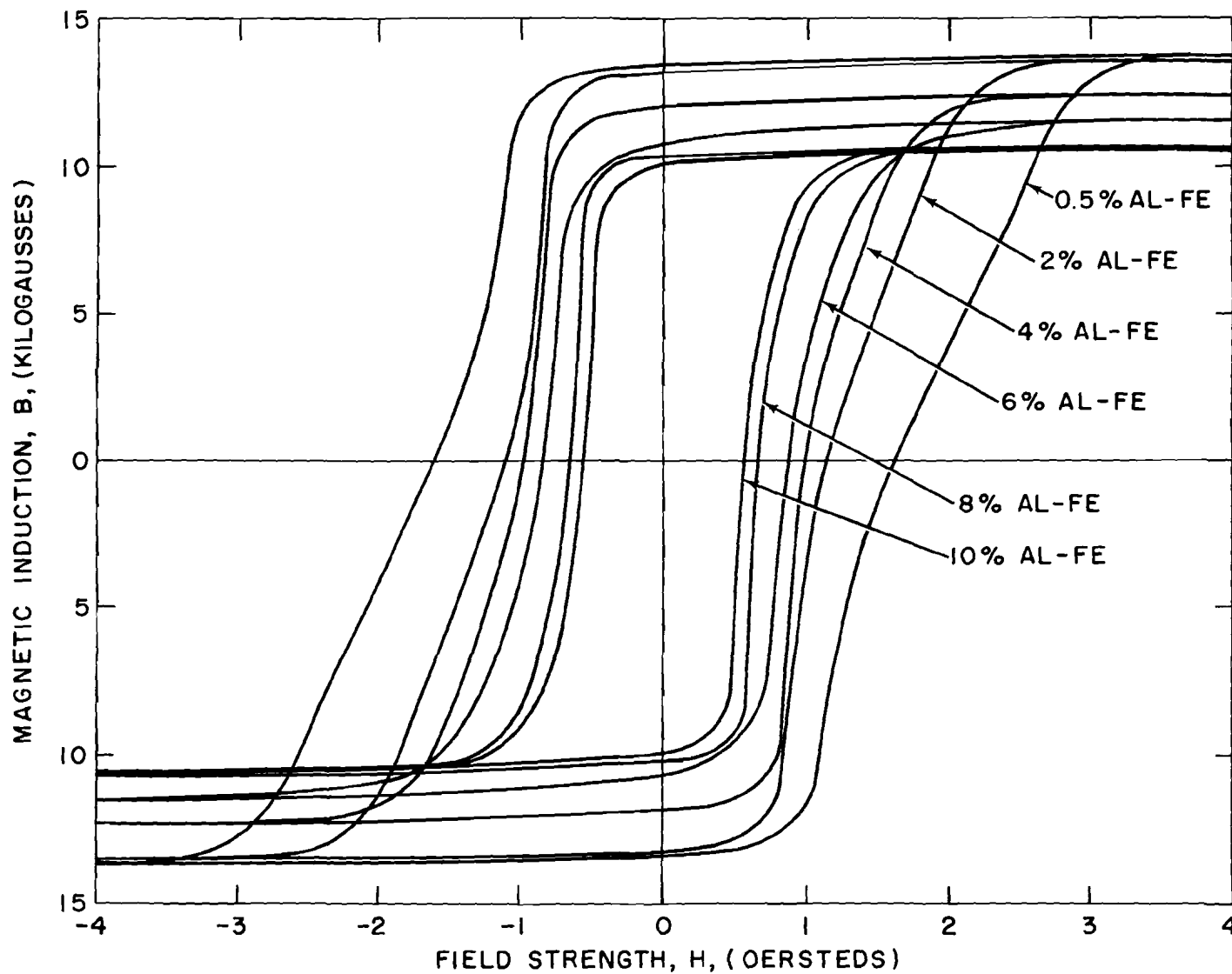


FIG. 7 DYNAMIC LOOPS (60 CPS) FOR IRON ALUMINUM LAMINATED CORES (0.014 MATERIAL) AFTER ANNEAL IN MAGNETIC FIELD (1.7 OERSTEDS)

field. It is of particular interest to note that this magnetic anneal was usually preceded by a very high temperature purification anneal (1300°C) in order to obtain the optimum properties for these alloys.

The work of the present author has indicated that magnetic annealing is an effective method of improving properties of ring-laminated, isotropic, polycrystalline, low percentage aluminum-iron alloys. The direction of field application during these anneals approximately paralleled the operational flux path of the cores under study. A hydrogen purification anneal for two hours at 1000°C prior to the magnetic annealing cycle proved beneficial in the final results. (Compare Core #3359X of Table V with Core #3512 which had only a magnetic anneal.)

Curie Temperature

The magnetic transformation curve for the aluminum-iron alloy system shows a gradual decrease from a maximum of 768°C for 0% aluminum (pure iron) to a low of about 690°C for 10 w/o aluminum-iron (Fig. 3). In fact, the slope of this curve is less than the equivalent silicon-iron curve; therefore based on Curie temperature alone, the aluminum-iron alloys should serve as well if not better than identical silicon-iron alloys for high temperature applications. However, for most elevated temperature environments, the magnitude of the Curie temperature is not necessarily the most important factor, particularly if this value is above the required operational temperature maxima. Of more importance is the stability of properties with variation in ambient temperature. Components that show minimum changes up to 500°C are desirable and those that show reasonable stability up to 600°C are to be considered exceptional⁴². Additional details on the degree of stability of the aluminum-iron alloys in elevated temperature environments will be presented under the section titled "Elevated Temperature Properties."

Of all the commercially available soft magnetic materials, only pure iron (770°C), pure cobalt (1120°C), and some of the cobalt-iron alloys have higher Curie temperatures than the aluminum-iron alloys.

Saturation Induction

The magnetic flux carrying capacity [saturation induction] is one of the more important magnetic properties of a material, particularly in power type application and in applications where a reduction in component size and weight is of concern. The data reported in Tables III-VI (indicated by B_m) are the

induction values obtained on aluminum-iron alloys using a field intensity of 30 oersteds at room temperature. These values should not be considered true saturation induction values since much higher field intensities would be required to obtain peak values. However, the listed values are indicative of the type of variation one obtains as aluminum content is changed. For true room temperature saturation values refer to Fig. 8. The data for this curve were obtained by Fallot⁴³ on annealed specimens and substantiated to some degree by Sucksmith⁴⁴, Bennett⁴⁵, and by Yamamoto and Taniguchi⁹. The latter two investigators observed an irregularity in the curve at about 13.9 w/o aluminum but it was not nearly as distinct as the one indicated by Fallot. Sucksmith and Bennett each observed more regularity in the curve in this area than did the other investigators. Those investigators who studied annealed vs quenched specimens found considerable uniformity up to approximately 10 w/o aluminum at which point the quenched specimen values became slightly higher than the annealed specimen values.

Saturation induction values for a number of these aluminum-irons, together with the values for other soft magnetic alloys are listed in Table VII for comparison purposes.

TABLE VII
MAGNETIC SATURATION INDUCTION VALUES OF
SOFT MAGNETIC ALLOYS

Aluminum-Iron Alloys	Saturation Induction (Gausses)	Other Alloys	Saturation Induction (Gausses)
2% Aluminum-----	20,400	Iron-----	21,580
4% Aluminum-----	19,300	4% Si-Fe-----	19,700
6% Aluminum-----	18,100	6.4% Si-Fe-----	18,100
8% Aluminum-----	17,000	2% V-Permendur----	24,000
12% Aluminum-----	14,800	50-50 NiFe-----	15,800
16% Aluminum-----	8,100	4-79 Mo- -----	8,500
		Permalloy	

As may be observed, aluminum-iron and silicon-iron alloys of equivalent compositions have room temperature saturation induction values that are very similar in magnitude. Pure iron and 2% vanadium permendur have saturation induction values of greater magnitude; however pure iron has a low electrical resistivity ($\sim 10 \mu\Omega\text{-cm}$) and it is subject to drastic aging changes, particularly at elevated temperatures; while the cobalt iron alloys (permendurs) are difficult to manufacture, have low resistivity values, and they are subject to order-disorder transformations which make them relatively unstable in applications wherein temperature cycling is involved.

Like the silicon-iron alloys, the low percentage aluminum-iron alloys also display their highest permeability values at relatively high inductions (7,000 to 10,000 gauss). This is a desirable feature since modern transformers are expected to operate at relatively high induction levels.

Because of their high induction values, high resistivities, ability to be oriented, and stability with temperature, the aluminum-iron alloys like the silicon-iron alloys should prove advantageous for low-loss, high induction, power type applications, particularly when elevated temperature environments may be encountered.

Resistivity

The electrical resistivity of a magnetic alloy is of both practical and theoretical importance. This is particularly true in present day applications where devices operating at higher frequencies are required for improved sensitivity and for miniaturization of components. An improvement in electrical resistivity, production of thinner gauges, and better insulating techniques all contribute toward an increase in operating frequency.

The electrical resistivity (see Fig. 8) increases almost linearly with addition of aluminum to iron. Fig. 8 illustrates data obtained by Sykes and Evans²³ and substantiated in most part by the present author and by Masumoto and Saito⁸. These resistivity values are not particularly sensitive to cooling rates until a composition is reached wherein atomic ordering occurs. This definitely takes place for compositions of about 10.7% aluminum and above, but it does not concern the alloys of interest in the present report. It should be mentioned that the resistivity values of low percentage aluminum-iron alloys are practically equivalent with identical silicon-iron compositions,

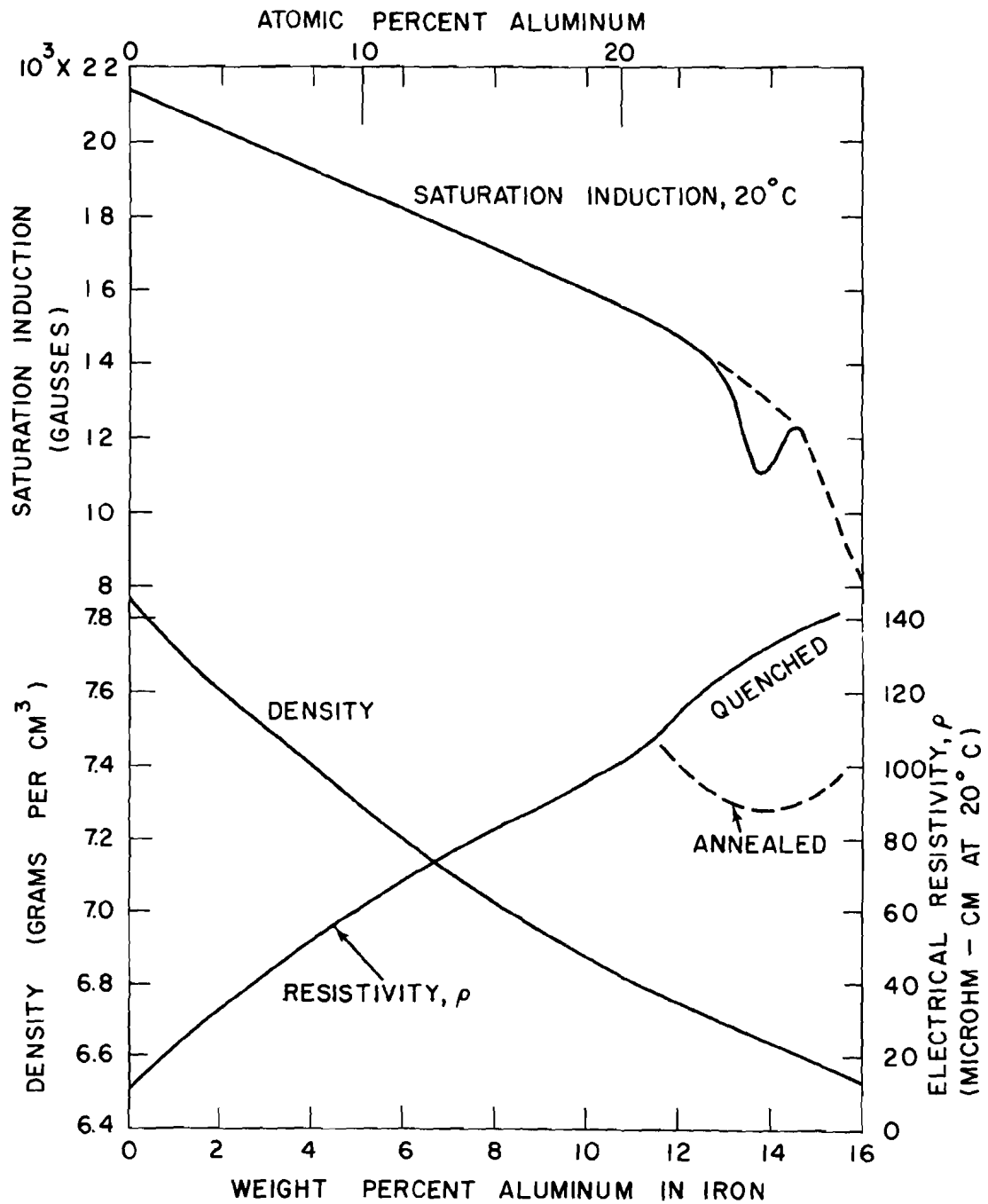


FIG. 8 - SATURATION INDUCTION, ELECTRICAL RESISTIVITY AND DENSITY OF ALUMINUM-IRON ALLOYS AT ROOM TEMPERATURE

and the values for both of these systems are not unusually high until 6% or 8% alloying addition is reached.

Typical values of a number of annealed soft magnetic alloys are as follows:

TABLE VIII

Resistivity Values of Soft Magnetic Alloys

Aluminum-Iron Alloys	Electrical Resistivity ($\mu\Omega$ -cm)	Other Alloys	Electrical Resistivity ($\mu\Omega$ -cm)
2% Aluminum-----	32	2% Silicon-Iron-----	37
4% Aluminum-----	52	4% Silicon-Iron-----	58
6% Aluminum-----	68	6% Silicon-Iron-----	77
8% Aluminum-----	81	4-79 Moly-Permalloy---	55
12% Aluminum-----	100	50-50 Nickel-Iron-----	45
16% Aluminum (disordered)-----	153	2% V-Permendur -----	26
		Iron-----	10

The resistivity values for the low aluminum-iron alloys are adequate for most applications, since modern rolling equipment makes possible the economical reduction of material thickness, thus providing further reduction in eddy current losses for these materials. Unfortunately, when thicknesses of approximately 0.002 and below are reached there is a gradual degradation of permeability and coercive force for these alloys. One reason for this degradation pertains to the high surface-to-volume ratio that exists for these thinner materials. This encourages contamination and straining from insulations during the annealing cycles.

Density

Since weight and space are factors to be considered in the present era, the density and efficiency of magnetic alloys are of considerable importance. Any improvement in core material efficiency with corresponding reduction in core material weight is a desirable advancement, and this is particularly true in power equipment since this type of equipment is usually quite massive in nature.

Actually the density itself is not a sufficient controlling factor since use of low density materials having low magnetic saturation or low resistivity could result in much heavier finished components than would be obtained using a high density material having high saturation and/or high resistivity. Therefore, when weight and space must both be considered in component design it is more meaningful to consider the combination of operating induction or core loss with density rather than to consider the density of the material alone. For these circumstances, the aluminum-iron alloys with their low density values, their high saturation inductions, and their good resistivities would rate comparable with the iron-silicon alloys and the vanadium-permendum alloys.

Room temperature density data are plotted in Fig. 8 and typical density values of a number of soft magnetic alloys are presented in the following table for comparison purposes:

TABLE IX
Density of Soft Magnetic Alloys

Material	Density (g/cm ³)	Material	Density (g/cm ³)
Pure Iron-----	7.86	Pure Nickel-----	8.90
2% Aluminum-Iron-----	7.61	2% Silicon-Iron-----	7.73
4% Aluminum-Iron-----	7.41	4% Silicon-Iron-----	7.60
6% Aluminum-Iron-----	7.22	50-50 Nickel-Iron-----	8.25
12% Aluminum-Iron-----	6.74	4-79 Mo-Permalloy-----	8.76
16% Aluminum-Iron-----	6.53	2% V-Permendur-----	8.20

ELEVATED TEMPERATURE PROPERTIES

Prior to being acceptable for elevated temperature operation, a magnetic alloy must possess certain intrinsic characteristics. Such factors as Curie temperature (discussed in previous section); order-disorder transformation; temperature effects on resistivity, permeability, retentivity, strain sensitivity, and ductility;

recrystallization; and oxidation resistance all become points of consideration for this type of environment. Based on reliable estimates⁴² and for purpose of discussion here, an ambient temperature of 500°C has been selected as a desirable upper limit at which magnetic components should continue to operate.

The aluminum-iron alloys are equivalent to the silicon-iron alloys with respect to resistance to elevated temperature environments. To substantiate this statement certain factors will be considered in the following sections of this report. These factors are:

- a. Oxidation resistance
- b. Magnetic property stability (aging)
- c. Temperature cycling and cooling rate effects
 - (1) Magnetic anneal analogy
 - (2) Order-disorder transformations
- d. Strain sensitivity and magnetostriction

Oxidation Resistance

Unless magnetic components are encapsulated or hermetically sealed they will ordinarily be subjected to an air environment when operating at elevated temperatures. This type of environment may cause serious degradation of magnetic properties whether it be due to oxygen diffusion into the metal, severe flaking, porosity, etc. Since most contemporary soft magnetic materials are ferrous types, then it is necessary to make additions to suppress this rapid oxidation at elevated temperatures.

Chromium, silicon, and aluminum are all effective suppressors of iron oxidation;^{46,47} however, chromium is of little immediate interest from a magnetic standpoint. Silicon and aluminum are somewhat similar in that they both form refractory oxides which stabilize the surface of iron to some extent. Aluminum is the most effective addition after the white Al_2O_3 coating has formed on the surface; however, internal oxidation is said to be severe in these alloys causing impoverishment of the alloy in aluminum after "long" periods of exposure. This would tend to cause severe local attack at damaged areas on the surface. Since the terminology "long periods of exposure" is not very definitive, and since oxidation of metals and alloys is such a difficult and complicated subject, then the most conclusive results can be obtained only by conducting experimental tests on these materials in the environments to which they will be exposed.

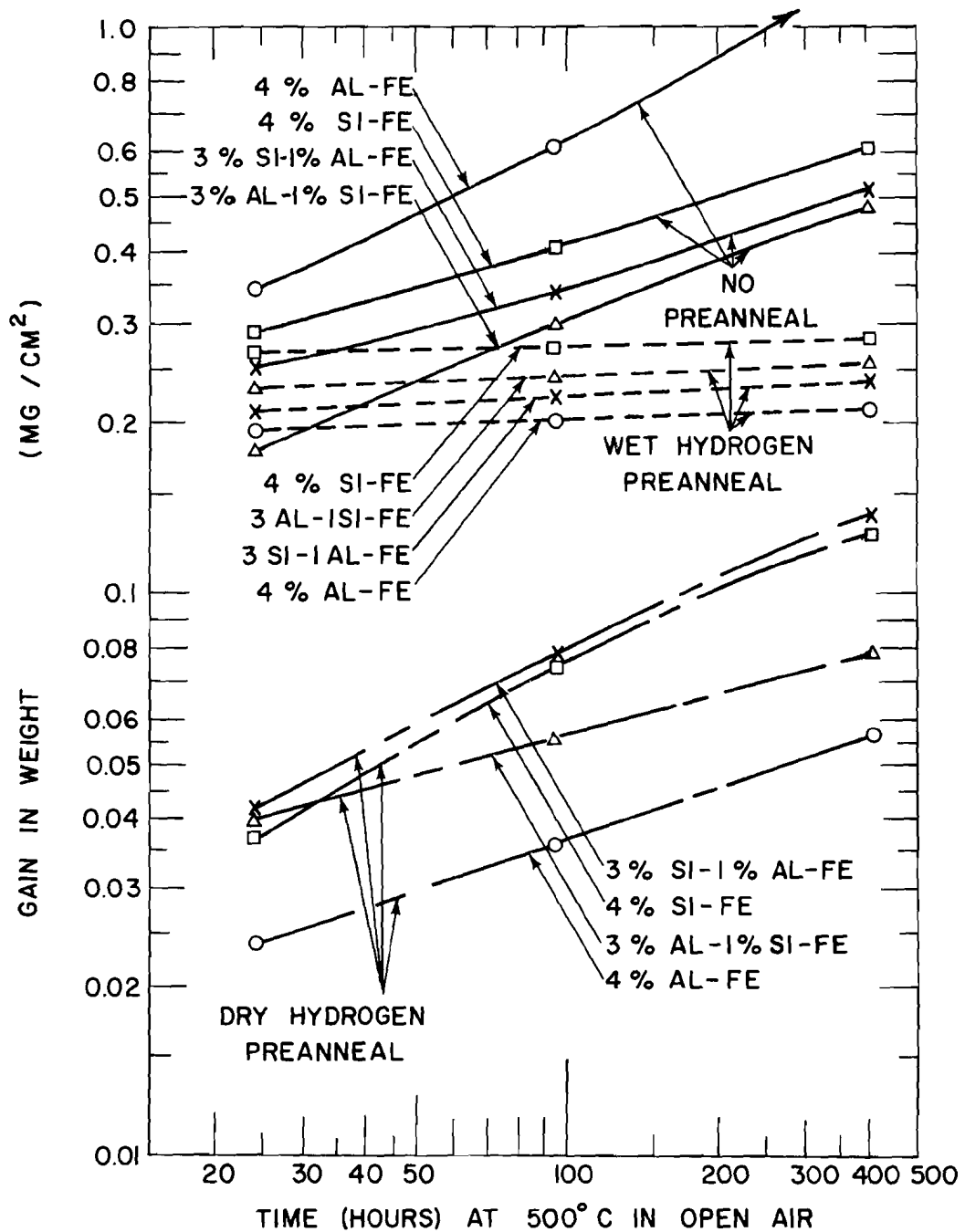


FIG. 9 - EFFECTS OF VARIOUS PREANNEALS ON OXIDATION RESISTANCE OF ALUMINUM - IRON, SILICON - IRON, AND ALUMINUM - SILICON - IRON MAGNETIC ALLOYS.
(MATERIAL THICKNESS ----- 0.014)

Figure 9 illustrates data obtained on binary aluminum-iron, binary silicon-iron, and ternary aluminum-silicon alloys prepared in this Laboratory. Tests were conducted on these magnetic alloys in their normal operational physical condition. That is, the specimens were cut from 0.014 thick material that had been processed by means of a procedure that is standard for materials of this type (See Appendix I). These specimens received no special surface preparation but they were exposed to typical annealing cycles which affected their surface conditions to some extent. In order to observe these effects, which are chiefly due to the moisture content of the annealing atmosphere, one group of specimens was annealed in wet hydrogen (Dew Point + 60° F), a second group was annealed in dry hydrogen (Dew Point < -90° F), and the third group of specimens was not subjected to anneal prior to test. This third group was tested in the as-rolled condition which would be the most likely condition of these materials when used in other than magnetic applications.

Oxidation rates on these test specimens were determined by accurately measuring gain in weight of specimens after exposure to a temperature of 500°C in open air for various periods of time up to 408 hours.

Although a number of alloys were examined in this experiment, only the ones containing approximately 4% total alloy addition are illustrated here (Fig. 9). Conclusions from these test are as follows:

1. Preferential oxidation of specimens in wet hydrogen atmosphere at 1000°C produced samples that showed a fairly high initial gain in weight when exposed to 500°C in open air, however with continued exposure there was practically no additional gain in weight up to 408 hours at which time test was concluded.

2. For the four different alloys that were preferentially oxidized in wet hydrogen the amount of oxide formed on each alloy after 24 hours exposure to 500°C was about the same.

3. Preferential oxidation of iron alloys (having aluminum and/or silicon additions) by pre-annealing in a wet hydrogen atmosphere should be a very useful method of controlling rate of oxidation not only for magnetic alloys but for other alloys or components that are capable of being subjected to this type pre-anneal.

4. A pre-anneal of these specimens in dry hydrogen produces an initial oxidation rate that is considerably less than the rate for samples pre-annealed in wet hydrogen; however, increased time of exposure produces continuous gain in weight for dry hydrogen annealed specimens with very little tendency to stabilize

completely. It should be noted however that specimens that were annealed in dry hydrogen had the thinnest oxide coatings even after 406 hours of exposure.

5. The 4% aluminum-iron binary alloy demonstrated the best oxidation resistance of the group when pre-annealed in dry hydrogen at 1000°C, this being a normal annealing procedure for soft magnetic alloys of this type. This same alloy was the least resistant to oxidation when tested in the as-rolled condition with no pre-anneal. These results of course, are affected by amount and tenacity of oxide accumulated during the hot and cold rolling operations.

6. Although dry hydrogen annealing is the normal method for obtaining optimum magnetic properties (and the best short range oxidation resistance was obtained on alloys subjected to this type pre-anneal) it may be advisable, for purpose of long time oxide stability, to subject alloys of this type to an anneal in moist hydrogen. The moisture content of the annealing atmosphere would of course depend on the alloy under consideration. It should be stressed that any moisture addition to the annealing atmosphere will prove somewhat detrimental to the magnetic properties, but for attainment of oxide stability it may be necessary to resort to this technique.

Magnetic Property Stability (Aging)

Magnetic aging is a function of time and temperature and may be caused by such things as precipitation of iron nitride (Koster)⁴⁸, carbon reabsorption (Spooner)⁴⁹, precipitation of carbides, etc. At any rate, aging is the result of impurities in the system and may be readily observed via magnetic property changes, particularly a gradual increase in coercive force and hysteresis loss.

A temperature increase is known to accelerate the aging process with subsequent variations in magnetic properties, because the solubility rates of carbon, nitrogen and oxygen in iron are all increased with temperature.⁵⁰ Koster⁴⁸ has found that aluminum added to iron decreases the solubility of nitrogen in iron; an addition of only 0.2% aluminum prevented the aging of iron altogether. Therefore, aluminum seems to be even better than silicon as an addition to iron for purpose of controlling aging phenomena.

Although aging of aluminum-iron alloys is practically non-existent at room temperature, there are certain changes that take place in the magnetic properties when these alloys are exposed to elevated temperatures, or to temperature cycling in general, particularly when these excursions occur in open air.

TABLE X

D-C PROPERTIES OF ANNEALED¹ 3% ALUMINUM-1% SILICON-IRON RING
LAMINATED CORE AS AFFECTED BY OPEN AIR TEMPERATURE

(Material Thickness - 0.014)

Test Temperature ²	D-C Properties ³					
	μ_{20}	μ_{max}	H_c	B_r	B_m	$\frac{B_r}{B_m}$
24°C	1740	16,300	0.287	10,700	15,420	0.69
300°C	2530	17,500	0.283	10,060	15,100	0.67
400°C	3080	20,600	0.194	9,320	15,020	0.62
500°C	1090	26,100	0.128	8,680	14,760	0.58
24°C	1850	29,600	0.281	11,370	15,340	0.74
500°C	-	36,700	0.095	8,000	14,530	0.55
24°C	1690	29,600	0.275	11,290	15,420	0.73
500°C	-	36,700	0.105	8,120	14,660	0.55
24°C	1660	29,600	0.271	11,180	15,440	0.72
600°C	-	43,600	0.083	6,650	13,990	0.48
700°C	-	56,000	0.038	3,590	10,760	0.33
750°C	ABOVE CURIE TEMPERATURE					
24°C	-	15,300	0.285	8,630	15,170	0.57

1. Core was subjected to standard 1000°C anneal in hydrogen before above tests were conducted.
2. Core was held at temperature indicated in open air for 1 hour before measurements were made.
3. Coercive force (H_c), Residual Induction (B_r) and Maximum Induction (B_m) measured for $H_m = 30$ oersteds

TABLE XI

D-C PROPERTIES OF ANNEALED¹ 4% ALUMINUM - 1% SILICON-IRON
RING LAMINATED CORE AS AFFECTED BY OPEN AIR TEMPERATURE

(Material Thickness - 0.014)

Test Temperature ²	D-C Properties ³					
	μ_{20}	μ_{max}	H_c	B_r	B_m	$\frac{B_r}{B_m}$
24°C	1740	12,400	0.358	10,130	14,800	0.69
300°C	2670	15,500	0.245	8,600	14,300	0.60
400°C	-	20,800	0.156	7,820	14,000	0.56
500°C	-	31,700	0.111	7,660	13,700	0.56
24°C	1250	24,400	0.357	10,450	14,690	0.71
500°C	-	31,700	0.107	7,590	13,630	0.56
24°C	1250	24,400	0.360	10,420	14,680	0.71
500°C	-	31,700	0.108	7,670	13,750	0.56
24°C	1270	24,200	0.333	9,930	14,580	0.68
600°C	-	36,200	0.096	6,190	13,110	0.47
700°C	-	40,000	0.040	3,310	9,840	0.34
750°C	ABOVE CURIE TEMPERATURE					
24°C	-	11,450	0.345	8,600	14,580	0.59

1. Core was subjected to standard 1000°C hydrogen anneal before above tests were conducted.
2. Core was held at indicated temperature in open air for 1 hour before measurements were made.
3. Coercive force (H_c), Residual Induction (B_r), and Maximum Induction (B_m) measured for $H_m = 30$ oersteds.

TABLE XII

D-C PROPERTIES OF ANNEALED¹ 5% ALUMINUM-IRON RING LAMINATED
CORE AFTER EXPOSURE TO VARIOUS TEMPERATURES IN OPEN AIR
(Material Thickness - 0.014)

Test Temperature ²	Open Air Exposure Prior to Test		D-C Properties ³				
	Temp.	Time	μ_{20}	μ_{max}	H_c	B_r	B_m
Room (24°C)	Annealed	Condition	1320	9550	0.540	11,270	15,080
Room (24°C)	300°C	4 hrs.	1320	9630	0.550	11,320	14,930
Room (24°C)	400°C	4 hrs.	1230	10,620	0.540	11,000	15,180
Room (24°C)	500°C	24 hrs.	1080	11,920	0.550	10,710	15,170

1. Core was subjected to standard 1000°C anneal in hydrogen prior to above tests.
2. Core was shielded from stray magnetic fields and testing was performed only at room temperature.
3. Coercive Force (H_c), Residual Induction (B_r), and Maximum Induction (B_m) measured for $H_m = 30$ oersteds.

Unfortunately, the high percentage (12% and 16%) aluminum-iron alloys were the only binary aluminum-iron materials available when temperature cycling tests on soft magnetic alloys were being conducted in this Laboratory and results on these particular alloys are well covered in Navord Report 6132.⁶¹ However, several ternary aluminum-silicon-iron alloys were investigated during these tests and results from certain of these alloys which have not previously been reported will be discussed here.

The ternary alloys 3% aluminum-1% silicon-iron and 4% aluminum-1% silicon-iron will be discussed because they contain aluminum additions in the range in which we are interested and their silicon contents are relatively negligible. Tables X and XI show effect of temperature on DC properties of ring laminated (0"014 material) cores made from these materials. The cores were tested at temperatures in the order as given; for example, they were tested at room temperature, heated to 300°C, held for 1 hour for stability, tested, heated to 400°C, held for 1 hour, tested, etc. No protective atmosphere was used during the tests. Details of testing procedure are discussed in Navord 6132.⁶¹ Sixty cycle AC measurements were also made on these cores. Figs. 10, 11, and 12 illustrate effect of temperature on the DC and AC magnetic properties of these materials. The cores used in these tests were initially subjected to a standard dry hydrogen anneal of 1000°C for 2 hours, resulting in a fairly isotropic material.

In general, the effect of temperature on these cores follows the same trend observed in the binary silicon-iron materials (see Navwep Reports 7331¹ and 6132⁵¹). Increased temperature results in increased permeability and slight decrease in such properties as coercive force, maximum and residual induction, and hysteresis loss. On return to room temperature (24°C), after the initial excursion to 500°C, these materials show a maximum permeability (μ_{Max}) that is much higher and a coercive force (H_C) that is much lower than the original values.

These improved properties remain until a temperature excursion is made to 750°C, this being just above the Curie temperature for these alloys. On return to room temperature from 750°C the core materials no longer retain their improved properties but retrogress to a condition quite similar to that of their original state. This latter change is not a degradation due to oxidation impurities but it results from the core material passing above the magnetic transformation temperature. This brings about complete erasure of effects resulting from magnetic fields set up by the core control windings at lower temperatures. A more detailed discussion of this effect will be presented in the following section of the present report.

Table XII illustrates effects of open air exposure to temperatures up to 500°C on a 5% aluminum-iron ring laminated

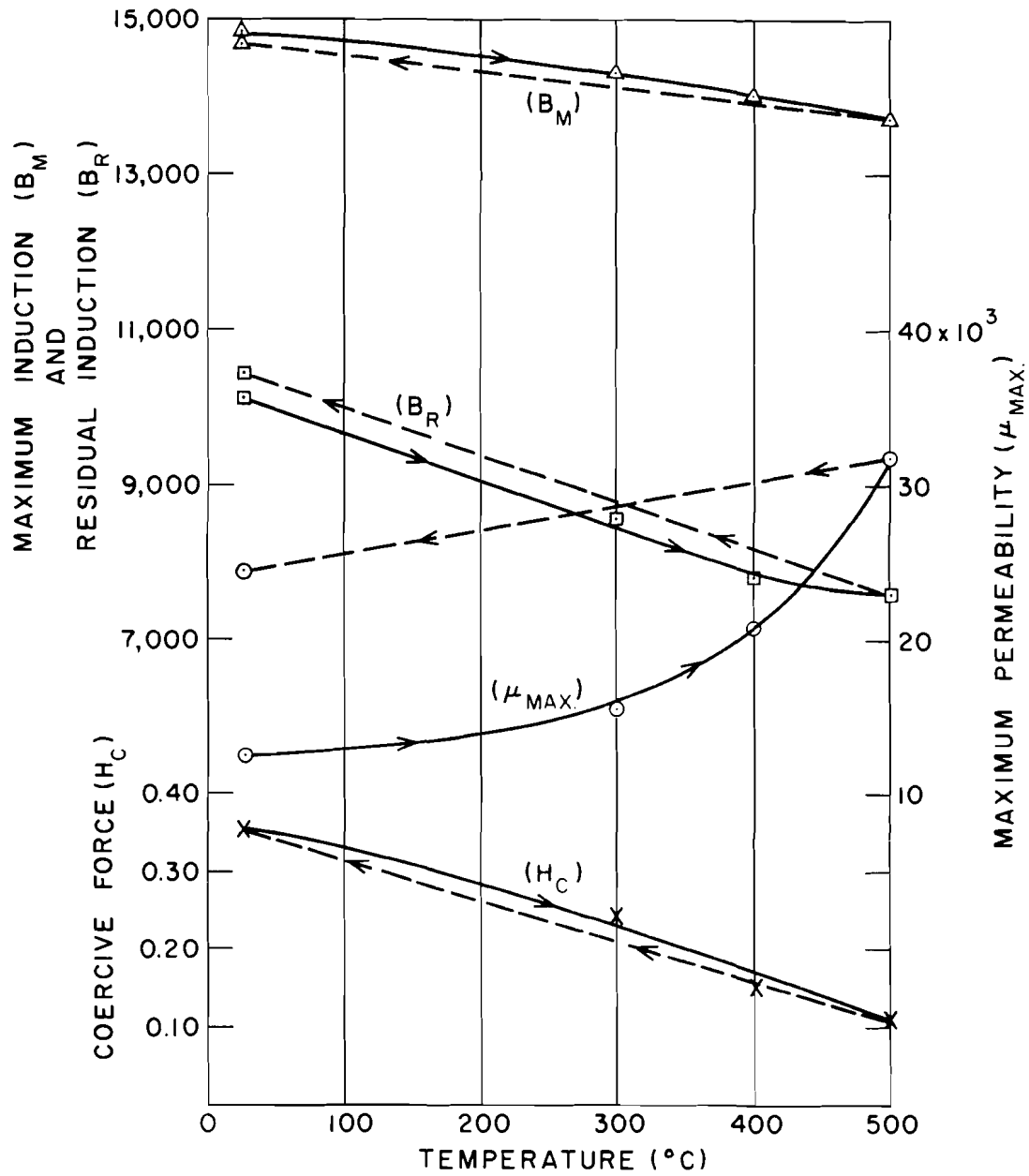


FIG. 10 VARIATION OF D-C MAGNETIC PROPERTIES OF 4% ALUMINUM - 1% SILICON - IRON LAMINATED CORE WITH TEMPERATURE.

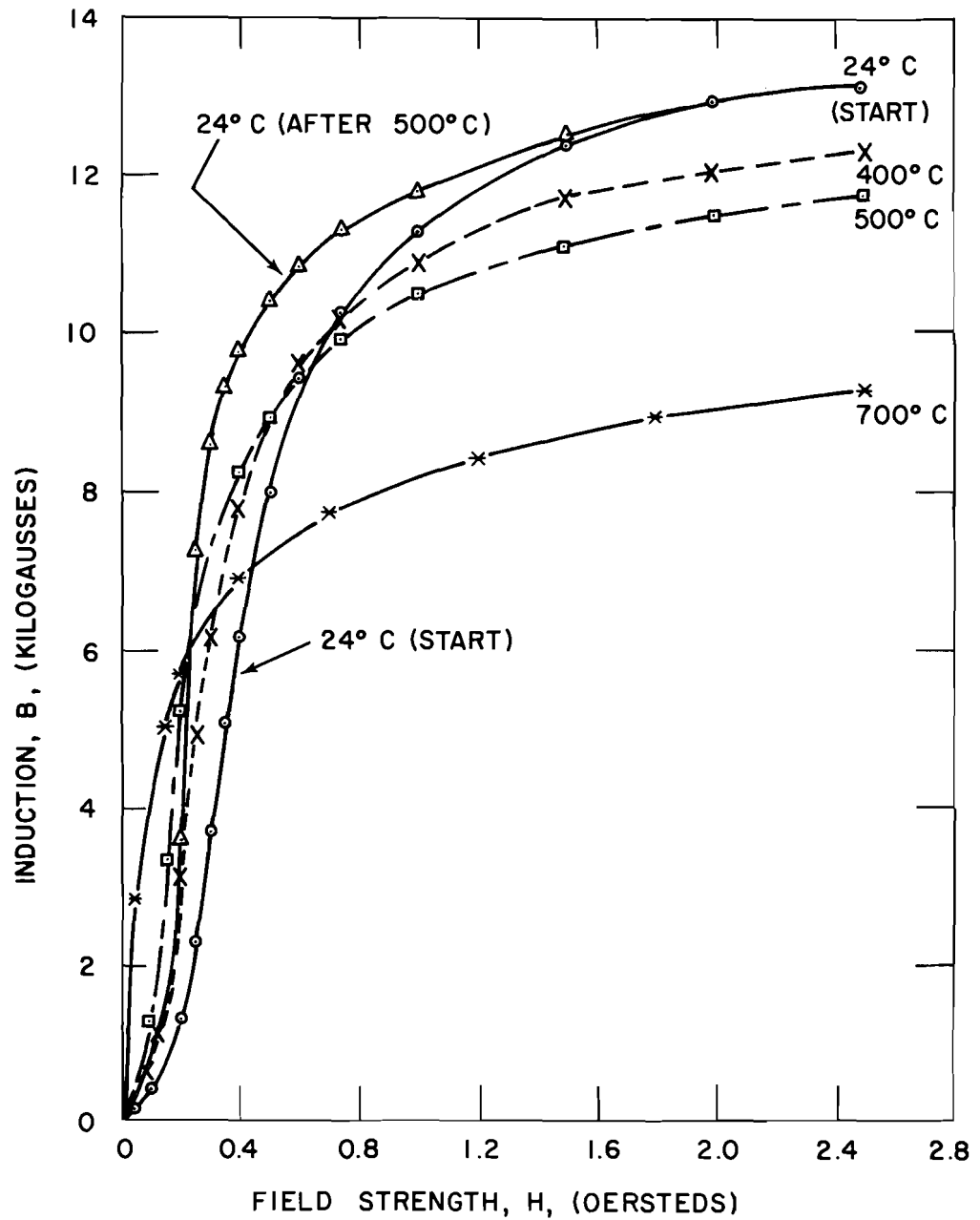


FIG. II - D-C MAGNETIZATION CURVES OF 3% ALUMINUM
-1% SILICON-IRON LAMINATED CORE MEASURED
AT TEMPERATURES UP TO 700° C.

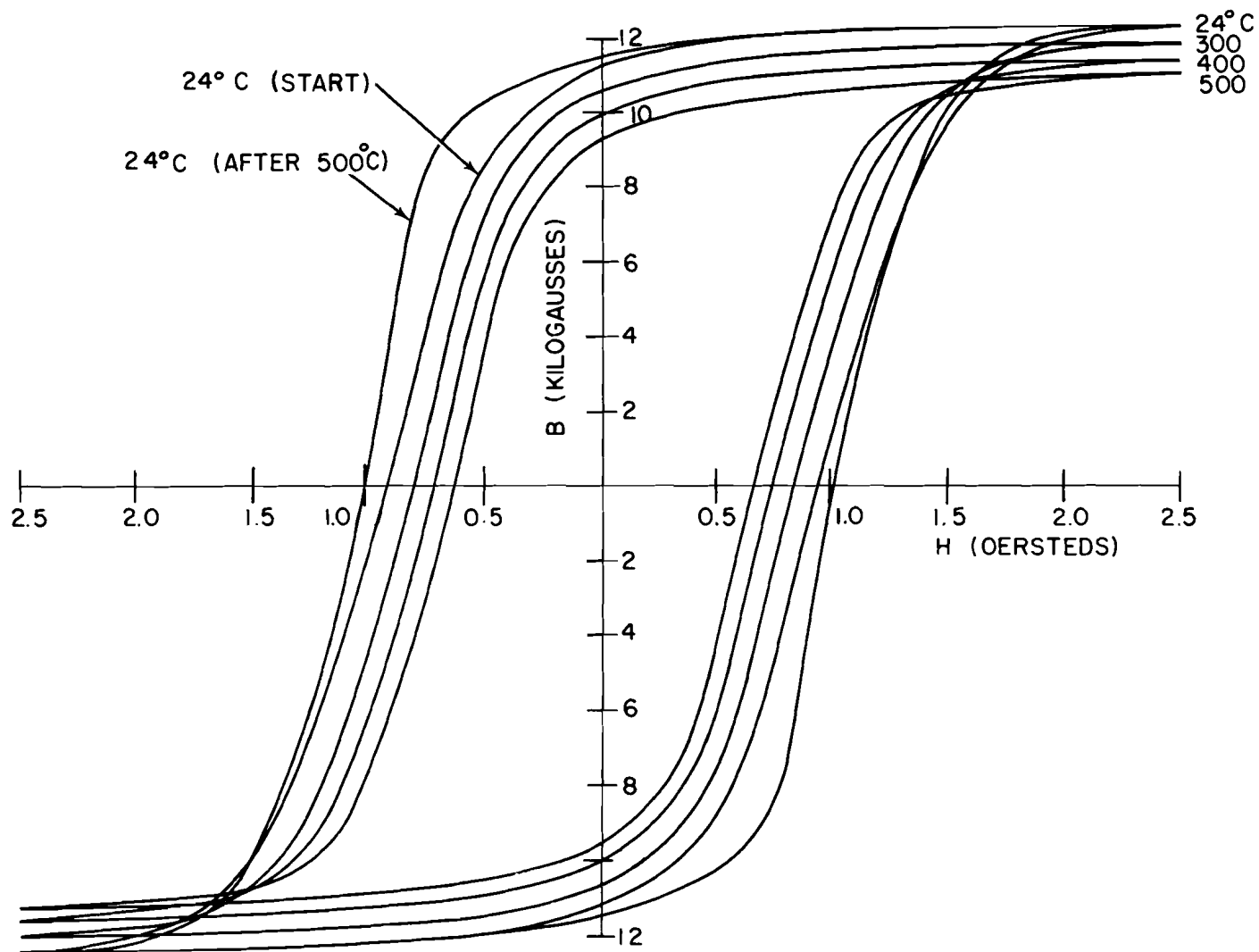


FIG. 12 - 60 CPS DYNAMIC LOOPS OF 3% ALUMINUM-
1% SILICON-IRON LAMINATED CORE IN
TEMPERATURE RANGE OF 24°C-500°C

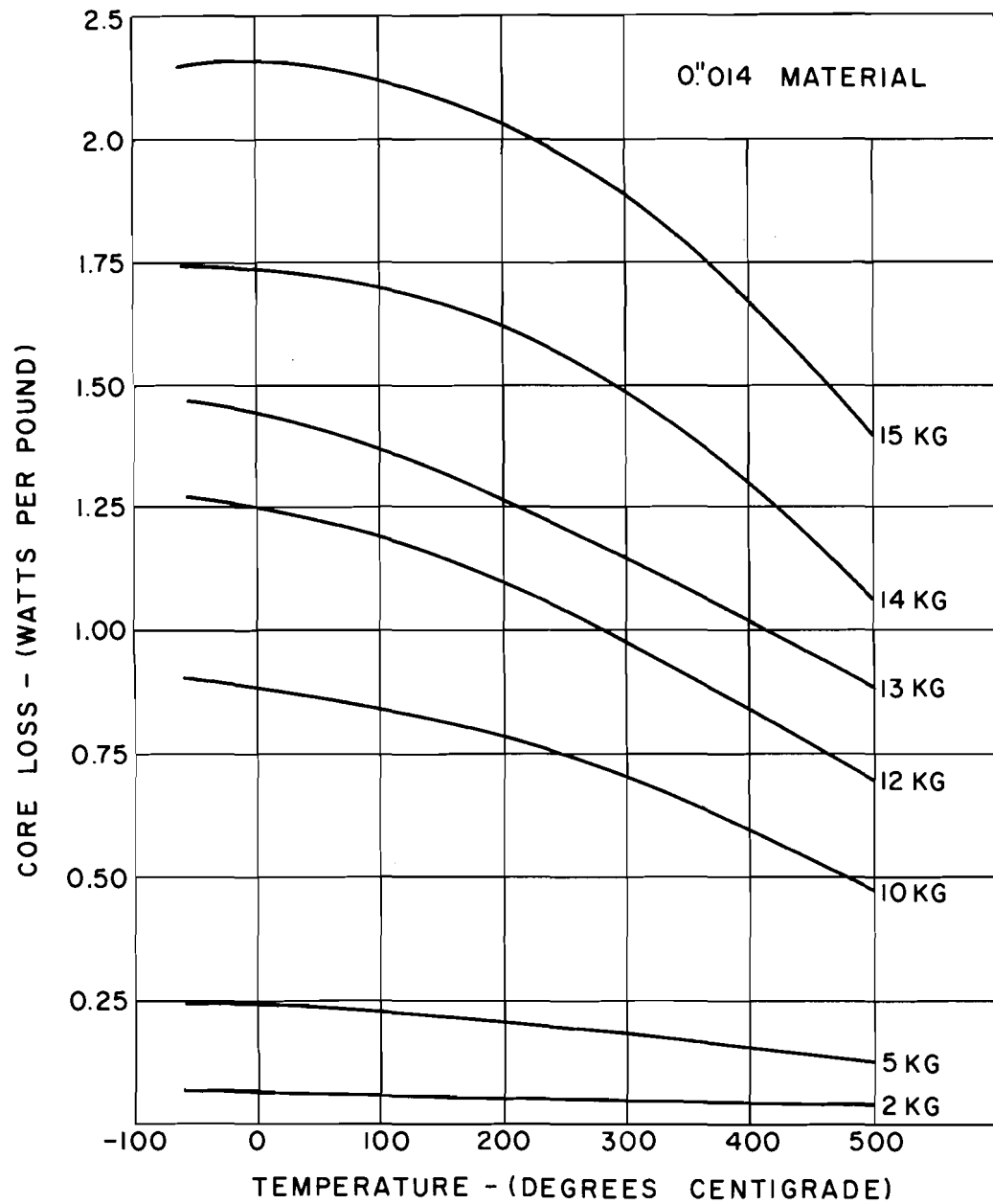


FIG.13 60 CPS CORE LOSS OF 2.6% ALUMINUM-IRON LAMINATED CORE AT VARIOUS INDUCTIONS AND TEMPERATURES. (FROM CLARK AND FRITZ⁽⁵²⁾)

(0%014 material) core. There were two major differences in procedure used on this core that were not followed on the cores of Tables X and XI. First, this core was shielded in a permendur shield so as to eliminate effects of stray magnetic fields such as the earth's field, fields set up by furnace windings, or other extemporaneous fields. The cores of Tables X and XI had no such shielding. Second, the present core was not subjected to testing at elevated temperature. Following the 1000°C anneal in dry hydrogen, the core was tested at room temperature, exposed to elevated temperature for a period of time, then returned to room temperature for testing. This procedure was followed for the various temperatures. This eliminated the magnetic annealing effect that results from fields set up by the core control windings during operation or during testing at elevated temperature. Conversely, the cores of Tables X and XI were subjected to tests at elevated temperatures and thus were exposed to these fields. It is apparent from this data that stray fields, whether they originate from an extemporaneous source or from the core control windings, are capable of producing magnetic property changes in materials that are exposed to temperatures above room temperature.

There is little additional data available relating to temperature effects on aluminum-iron magnetic alloys. Clark and Fritz⁵² conducted tests on a 2.6% aluminum-iron alloy along with several silicon-iron alloys and two cobalt-iron alloys. Although these investigators did not discuss the aluminum-iron alloy to any great extent, it is apparent from their data that the behavior of this alloy when exposed to elevated temperatures was comparable to that of the non-oriented silicon-iron alloys containing 3.25% and 3.65% silicon. One interesting feature observed on these alloys by Clark and Fritz was the substantial reduction in core loss values obtained with increase in temperature, particularly at high induction levels. (Fig. 13)

Temperature Cycling

(a) Magnetic Anneal Analogy:³³⁻³⁶ As is true of the silicon-iron magnetic alloys¹, the aluminum-iron alloys are highly responsive to "magnetic annealing" (see Table V). Therefore, this factor must certainly be considered by equipment designers when using these alloys at elevated temperatures.

It is quite probable that certain electronic and magnetic components may be subjected to elevated temperatures for extended periods of time or they may be cycled through various temperature ranges during normal operational procedures. This temperature cycling during exposure to a magnetic field is a particularly effective method of magnetic annealing a core material.

Since careful design can usually afford shielding of the core material from any extemporaneous external magnetic fields

one might ask why the concern about this effect. The real problem relates to the field set-up by the control windings on the magnetic core itself. If a magnetic core is operational during exposure to temperature cycling, the fields as set up from the core windings, whether a-c or d-c will in effect cause magnetic annealing of the core material. Now a magnetic anneal in itself cannot be considered detrimental to a magnetic core since there usually is considerable improvement of properties resulting from this type anneal. (See Table V) However, the material properties do change during a magnetic anneal and the designer must be aware of these changes in order to provide stability in his component designs.

This effect was responsible for some of the changes in magnetic properties that resulted when the aluminum-silicon-iron magnetic cores were exposed and tested at elevated temperatures (See previous section, Tables X and XI). The fields set up by the furnace windings and by the test windings undoubtedly affected the properties of these cores. Table XII proves the stability of a 5% aluminum-iron core when proper shielding and testing procedures are followed. However, it is not always possible to shield cores in this manner and in certain applications it may be necessary to energize the core while at some elevated temperature. In these circumstances it is necessary that the designer be fully aware of changes that take place in properties of materials with which he is concerned.

Based on experiments discussed previously by the author under section "Magnetic Annealing Effects," certain factors must be considered when there is a possibility of exposure of magnetic components to a magnetic field during a temperature excursion. These factors are as follows:

1. An a-c field is as effective as a d-c field for magnetic annealing a core material.
2. Magnetic annealing may take place at temperatures well below the Curie temperature of the material. Lower temperatures usually require longer times of exposure to the magnetic field, while temperature excursions above the Curie require the field to be applied at **some** temperature below this transformation point during the cooling cycle.
3. Fields as low as 2.0 oersteds are as effective for magnetic annealing aluminum-iron and silicon-iron core materials as are much higher fields.
4. Even though a core may be shielded from external fields it cannot be shielded from the fields set up by its control windings.

Since these effects exist, then certain precautions must be taken when magnetic core materials are to be operated at elevated temperatures, and particularly when they are cycled through various temperature ranges while being energized. These precautions are as follows:

1. Designer must be aware of maximum changes that can result from a full magnetic anneal and design his equipment to operate within this range.
2. The magnetic core may be stabilized by subjecting it to a magnetic anneal prior to installation into an operational component. This will reduce but not entirely eliminate the problems brought about by elevated temperature operation. This stabilizing anneal should be based on operational conditions to be encountered by the component.
3. If a magnetically annealed core is held at elevated temperature for a long period of time without being energized it is best to energize the core prior to cooling and preferably during the cooling cycle to provide maximum stability.
4. When possible, the core material should be shielded from all external fields at elevated temperatures.

(b) Order-Disorder Transformations: Using such techniques as encapsulation, hermetic sealing, magnetic shielding, etc., it may be possible to nullify or at least to control certain changes that take place at elevated temperatures due to oxidation, energizing fields, etc. However, these protective devices do not apply to alloys having low Curie temperatures or those that are subject to order-disorder transformations. When alloys have these inherent properties, then their operational capabilities in elevated temperature environments should be examined. Unless the components containing these alloys are maintained in a temperature-controlled environment, their stability and possible permanent degradation due to metallurgical and magnetic changes make them extremely unreliable. This degradation of properties is particularly noticeable when the materials are subjected to temperature cycling with associated variable cooling rates.

Fortunately for the low aluminum-iron alloys, ordering is not detected until one reaches a concentration of approximately 10% (by weight) aluminum.^{21,24} This provides a wide range of aluminum-iron alloys that are free from this condition and are not susceptible to property changes when subjected to various cooling rates. The low percentage silicon-iron alloys (containing up to approximately 6.7% silicon) are likewise relatively free from this condition.

Such materials as the nickel-iron alloys, cobalt-iron alloys, iron-nickel-molybdenum alloys, and 12 to 16% aluminum-iron alloys are susceptible to changes in magnetic properties with variation in cooling rates because of order-disorder transformations. Such alloys that are subject to these changes should be used only where the local environment can be controlled.

Strain Sensitivity and Magnetostriction

Recent environmental demands on ferromagnetic core materials place much emphasis on resistance to stress resulting from vibration, shock, acceleration, and temperature variations. Stress ranks with temperature, radiation, and external field strength as a factor determining the state of magnetization of the material. Therefore, it is desirable to develop and use materials with minimum strain sensitivity, particularly in applications requiring use of spirally wound tape cores that may be subjected to temperature changes or to mechanical shock.

Bozorth⁵³ and others have covered quite thoroughly the relation between the direction of stress application, the direction of applied magnetic fields and the sign of the magnetostriction value as to effect on a particular alloy in question. For instance, a tension stress applied in the same direction as the magnetic field causes an increase in permeability for a positive magnetostriction material and a decrease in permeability for a negative magnetostriction material. Conversely a compressional stress applied in the same direction as the magnetic field causes a decrease in permeability in a positive magnetostriction material and an increase in permeability for a negative magnetostriction material.

When a compression stress is applied perpendicular to the magnetic flux lines and perpendicular to the surface of the core material, then, according to Fischell,⁵⁴ both negative and positive magnetostriction materials exhibit a decrease in permeability with increased pressure, the degree of sensitivity to these stresses being dependent on the magnitude of the magnetostriction. Therefore, this effect is a governing factor in the packaging of laminated cores as well as in their shock resistance.

It should be stated that magnetostriction of a material is not only important from standpoint of changes in magnetization due to applied stresses, referred to as the "Villari Effect," but it also applies to the change of dimensions of a ferromagnetic material when exposed to magnetic fields, this latter effect being known as the "Joule Magnetostriction Effect."

It is generally known that ferromagnetic alloys differ in magnitude and sign of magnetostriction. The values are affected by composition,⁵⁵ crystal orientation,⁵⁶⁻⁵⁹ ordering,⁵⁹⁻⁶⁰

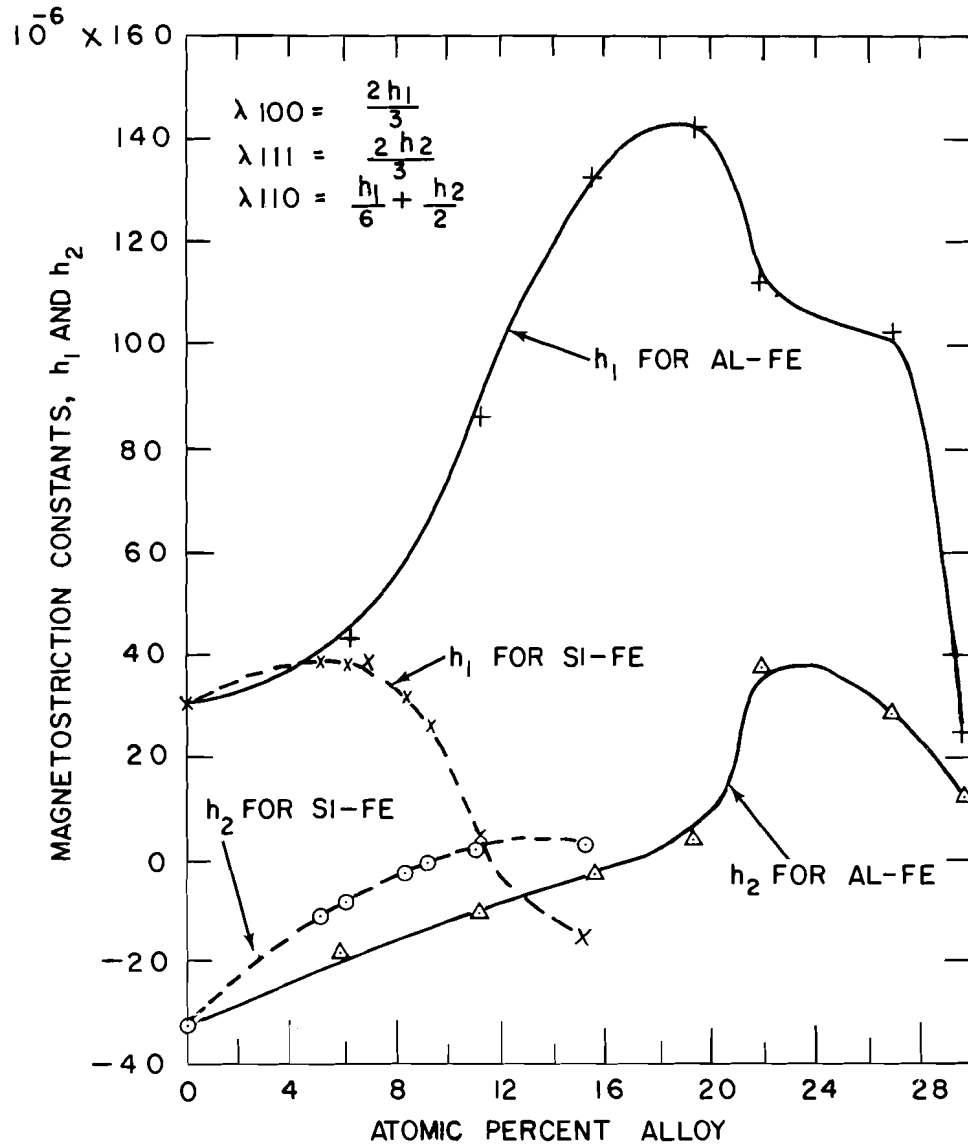


FIG. 14- MAGNETOSTRICTION CONSTANTS, h_1 AND h_2 ,
 FOR ALUMINUM-IRON AND SILICON-IRON ALLOYS.
 (SI-FE DATA FROM CARR AND SMOLUCHOWSKI⁽⁵⁸⁾)
 (AL-FE DATA FROM HALL⁽⁵⁷⁾)

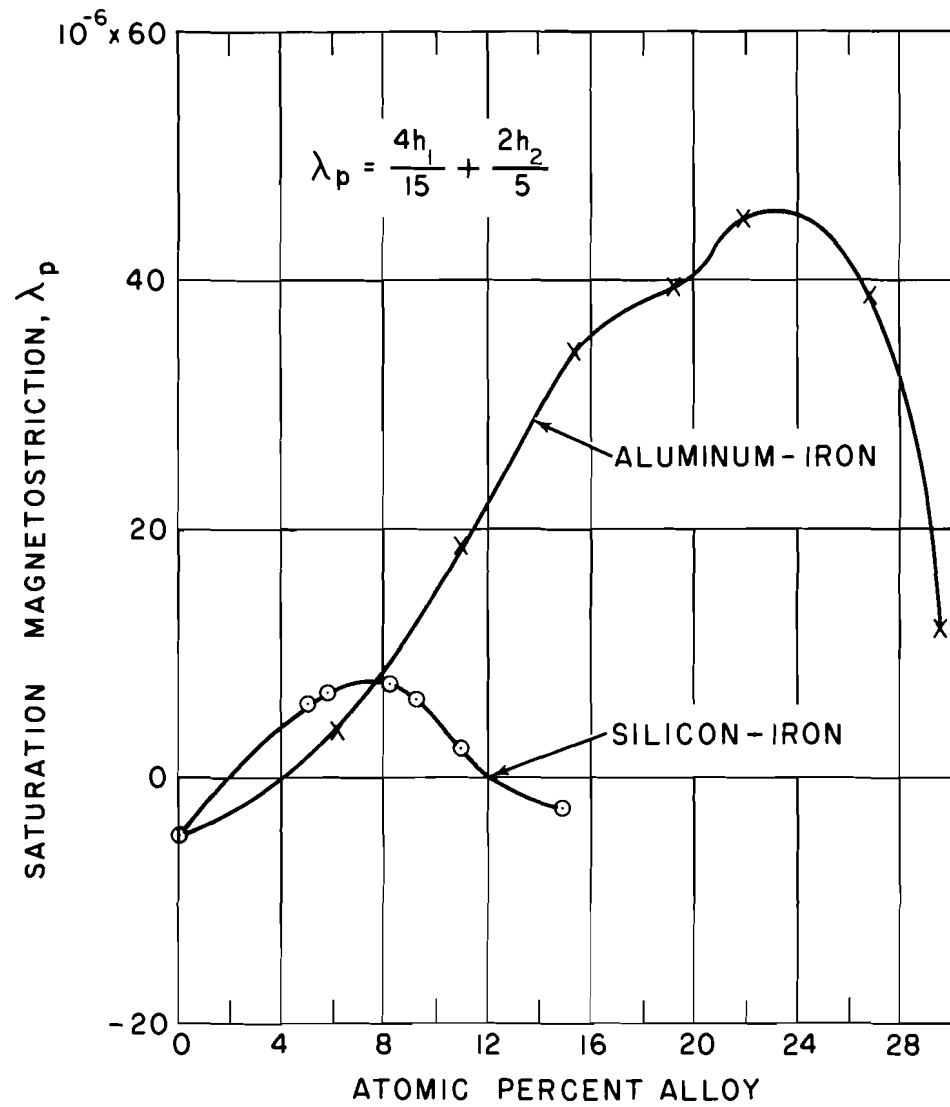


FIG. 15 POLYCRYSTALLINE SATURATION MAGNETOSTRICTION VALUES OF ALUMINUM-IRON AND SILICON-IRON ALLOYS (CALCULATED FROM DATA OF FIG.14)

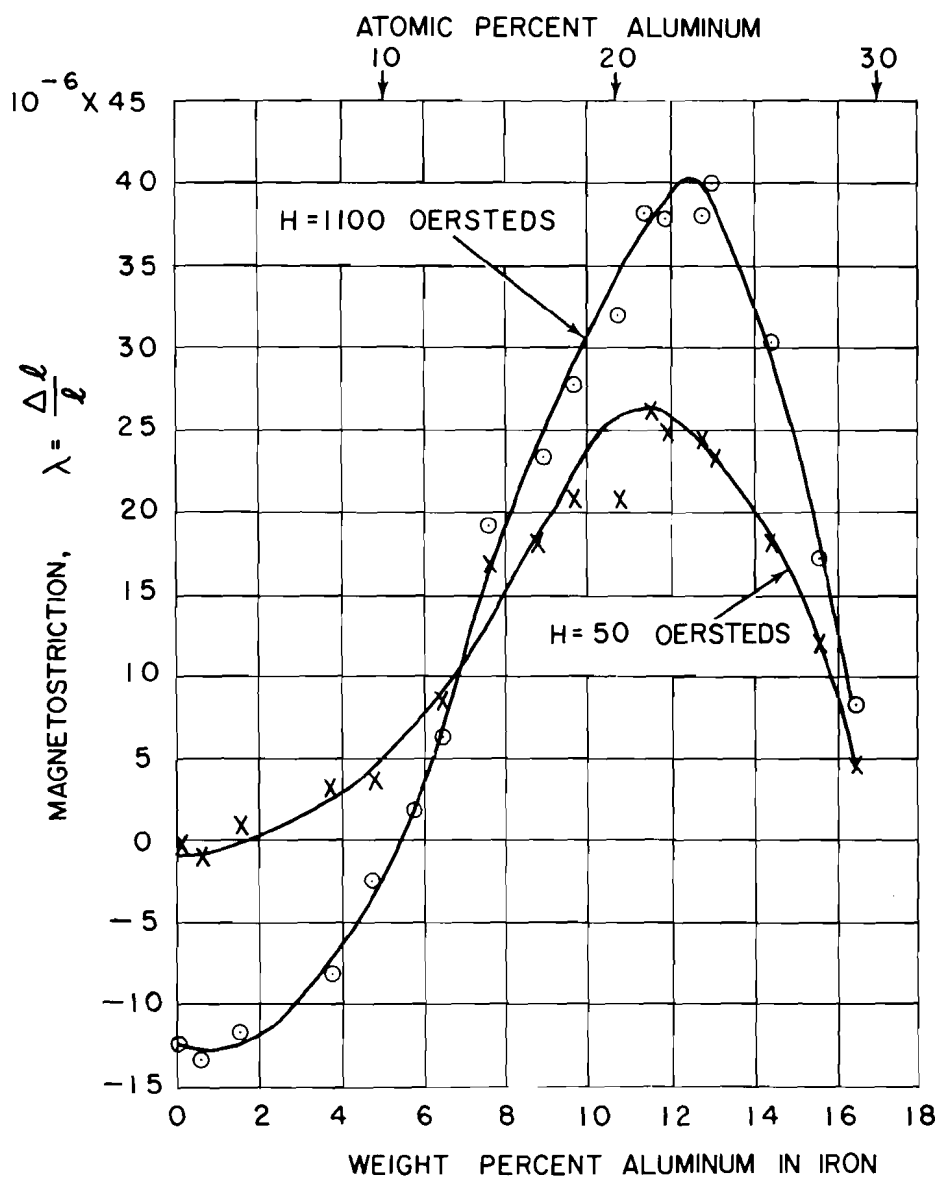


FIG. 16- EFFECT OF FIELD STRENGTH ON
MAGNETOSTRICTION VALUES OF ANNEALED
ALUMINUM-IRON ALLOYS.
(REFER TO BOZORTH⁽⁶⁸⁾)

temperature,⁶¹ field intensity,⁶¹ and stress.⁶¹

Schulze⁶² in 1928 investigated the magnetostriction properties of aluminum-iron alloys containing 0.5 to 10.5% aluminum by weight. He found a maximum saturation magnetostriction value of nearly 35×10^{-6} for the highest aluminum content that he tested, namely, 10.5%.

Honda⁶³ et al did more work on this system in the 1940's and they discovered that approximately 13% aluminum in iron (by weight) gave an optimum static magnetostrictive property of $\sim 40 \times 10^{-6}$. Masumoto and Otomo⁶⁴ investigated dynamic magnetostrictive properties for hot-rolled aluminum-iron alloys containing from 6 to 14% aluminum by weight. They found that compositions between 12 and 13.7% aluminum gave maximum electromechanical coupling coefficients of about 0.24. Davis and Ferebee⁶⁵ obtained maximum electromechanical coupling coefficients of about 0.31 for iron alloys containing close to 12% aluminum.

Masumoto and Saito⁶⁶ conducted magnetostriction measurements on polycrystalline aluminum-iron alloys containing 0 to 16% aluminum (by weight). They obtained maximum values of about 40×10^{-6} for aluminum concentrations of 11.6 to 13%. Their results were somewhat similar to those reported by R. C. Hall^{67, 69} whose work is more recent and more inclusive. Hall's work demonstrated quite readily how saturation magnetostriction values are dependent on crystallographic direction as well as aluminum content of the alloy. A plot of his data on magnetostriction constants of aluminum-iron and on Carr and Smoluchowski's⁶⁸ data on silicon-iron is shown in Fig. 14. Fig. 15 illustrates the saturation magnetostriction values for polycrystalline samples of aluminum-iron and silicon-iron alloys assuming a random crystal distribution. The values shown are calculated using Becker and Doring's⁶⁷ two constant equation, $\lambda = \frac{4}{15}h_1 + \frac{2}{5}h_2$.

Most of the previous effort on the aluminum-iron alloys system has been directed toward the higher aluminum compositions since these alloys have high saturation magnetostriction values and high electromechanical coupling coefficients; these properties being advantageous in transducer type applications. However, in applications where magnetic property stability are of concern and where stress concentrations due to packaging, shock, vibration, temperature, etc. must also be considered, then the lower percentage aluminum-iron alloys with their associated lower magnetostriction values become of considerable value. Fig. 15 illustrates that polycrystalline alloys containing up to 8 atomic percent aluminum (4.03% by weight) have very low saturation magnetostriction values with the 4 a/o aluminum-iron alloy (1.97 w/o) having a value close to zero. These alloys should be good performers in terms of property stability when exposed to

unusual stress concentrations.

It should be emphasized that field intensity and temperature also have definite effects on the magnetostriction values of magnetic alloys. Fig. 16 illustrates effect of field variation on the magnetostriction of annealed aluminum-iron alloys as reported by Bozorth⁶⁸ in referencing the work of Honda⁶³ et al. In general, the magnetostriction becomes positive when aluminum content reaches about 6% and it increases with field when the content is 9% or greater. The values as illustrated for $H=1100$ would be approaching the saturation magnetostriction values for these alloys.

Although no actual measurements were made on effect of temperature on magnetostriction of the aluminum-iron alloys, it has been observed that in general, the magnetostriction of most magnetic alloys decrease in magnitude with increase in temperature. Since such changes do occur with temperature variation, it may be advantageous to make use of this phenomena by artificially controlling the environment to obtain the desired magnetostriction value of a particular material under consideration.

MAGNETIC COMPONENT EVALUATION AT ELEVATED TEMPERATURE

As stated previously, the development of magnetic components using aluminum-iron materials has been practically negligible in this country. However, the similarity between the inherent properties of these alloys and silicon-iron alloys leads us to believe that the elevated temperature behavior of magnetic components using either of these systems would be comparable, particularly in regards to sensitivity and stability. This reasoning applies only to the aluminum-iron alloys containing less than ~ 10% aluminum (by weight) and silicon-iron alloys containing less than ~ 6.5% silicon since the ferrous alloys containing higher percentages of these elements are subject to order-disorder transformations. These latter alloys are particularly sensitive to cooling rates, therefore, they would not be suitable in applications where temperature cycling is a possibility.

Since there is such limited information on aluminum-iron magnetic component evaluation, the reader may want to refer to the work of Harms and Frazer⁶⁹ who studied the effects of radiation, shock, and vibration at elevated temperature (500°C) on power transformers and inductors using oriented 3 1/4% silicon-iron as the magnetic core material. Their work discloses problems encountered and limitations to be expected using oriented silicon-iron components in environments of this type.

Greene, Lee and Lietzan⁷⁰ also conducted elevated temperature tests on EI laminated cores made of cobalt-iron, silicon-iron, and low carbon steels, but they did not include aluminum-iron in their studies. Their work covered temperature cycling and 600 hour aging tests over the temperature range of -65°C to 600°C . The work of Pasnak and Lundsten⁵¹ and Clark and Fritz⁵² on soft magnetic material properties, not components, has been discussed in a previous section.

Trapp, Robenold, and Facaros⁷¹ have recently reported on temperature tests on cobalt-iron alloys versus a silicon-iron alloy (1.25% silicon). Their report was highly favorable toward the cobalt-iron alloys (27%, 35% and 50% cobalt with chromium or vanadium additions). The reasons for this optimism are result of the high magnetic saturation values of these alloys, their high Curie temperatures, and their relative stability as temperature is increased. However, one must not neglect certain deficiencies that occur in these cobalt-iron alloys. First, they are relatively expensive and are considerably more difficult to process than are the silicon-iron alloys or the aluminum-iron alloys. Second, their permeabilities are low and their coercive forces are high unless, of course, the magnetically annealed Supermendur is being considered, in which case the properties at elevated temperatures and during various cooling cycles are drastically degraded. Third, the cobalt-iron alloys have higher core loss values in general than do the silicon-iron or aluminum-iron alloys. Fourth, cobalt-iron alloys can become very hazardous in nuclear radiation environments because of the extremely long half-life of cobalt. Fifth, the cobalt-iron alloys have very high saturation magnetostriction values which is a very desirable characteristic in some applications but is undesirable in most electric power applications. Therefore, the cobalt-iron alloys of the present era are suitable and economical only for very specialized applications, specifically those applications where advantage may be taken of their unusually high saturation induction values, their high Curie temperatures, or their high magnetostriction values. The aluminum-iron and silicon-iron alloys have attributes that make them more suitable for most general applications.

Various publications dealing with elevated temperature evaluation of magnetic core materials and components are given in the reference section at the end of the initial report of this series.¹ Most of these publications refer to silicon-iron applications and there is considerable evidence that devices using silicon-iron alloys are capable of operating in unusual environments even though they may not give optimum performance. Based on data presented in a previous section (Elevated Temperature Properties) of the present report, it can be stated that

components using low percentage aluminum-iron alloys as the core material would behave in a manner comparable to components containing equivalent compositions of silicon-iron.

MISCELLANEOUS CONSIDERATIONS

Stability in Nuclear Radiation Environments

One of the more recent and more difficult environmental conditions encountered by man is that imposed by nuclear radiation. High levels of radiation have drastic effects on many solid materials, therefore, it is desirable to determine safe levels of operation for materials used in magnetic components and to understand the effects of various radiation levels on magnetic properties.

In certain instances, critical components may be shielded from heavy dosages of nuclear radiation but this is usually found to be an expensive and unwieldy solution. It is more desirable to use materials that are resistant to this type of environment, thus reducing the need for bulky shielding.

Sery, Fischell, and Gordon^{72,73} of this Laboratory have conducted a number of tests on various ferromagnetic core materials in order to determine their nuclear radiation stability. These investigators exposed several representative soft magnetic cores to an irradiation level of 1.8×10^{12} total neutrons per square centimeter per second for a period of 16 days and 9 hours. This gave an integrated neutron flux of $\sim 2.7 \times 10^{18}$ neutrons per square centimeter and $\sim 10^{17}$ fast ($E > 1$ ev) neutrons per square centimeter. Magnetic data were taken before, during, and after exposure.

Unfortunately, when these radiation tests were conducted there were no low percentage aluminum-iron alloys available. However, two alloys that were included in the test were a 16% aluminum-iron alloy (sample each in the ordered and disordered state) and a new 3% silicon-1% aluminum-iron ternary alloy which was developed at this Laboratory. From all indications this latter alloy is demonstrative of the behavior of most low percentage aluminum-iron and silicon-iron isotropic materials in this type of environment. In general, these alloys all have relatively high coercive forces when compared with other soft magnetic materials such as 4-79 molybdenum-permalloy, 50-50 nickel-iron, etc.

Results from this radiation test show that the 3% silicon-1% aluminum-iron alloy (which had been magnetic annealed prior to test) was the most stable of all the alloys tested. (Compare Fig. 17 for effects of radiation on D-C hysteresis loop of this

alloy vs Fig. 18 for effects on a 50-50 nickel-iron oriented alloy). Actual changes in permeability, coercive force, and rectangularity of hysteresis loop for the 3% silicon-1% aluminum-iron alloy were only about 1% whereas a 4-79 molybdenum-permalloy alloy showed a -79% change in maximum permeability and a +403% change in coercive force due to radiation.

The high percentage aluminum-iron alloy (16% aluminum) in the ordered condition, which is the poorest magnetic state for this alloy, showed small but significant improvements of about 10-15% due to radiation whereas this same alloy in the disordered condition showed only minor degradation of about 4% in magnetic properties.

Very small changes occurred in the low percentage silicon-iron alloys due to radiation. From results on these alloys and on the 3% silicon-1% aluminum-iron alloy it is reasonable to assume that all low percentage aluminum-iron and/or silicon-iron magnetic alloys are not influenced by levels of nuclear irradiation equivalent to the level used in this test and therefore should be useful magnetic alloys in this type environment. This assumption applies to oriented as well as non-oriented materials except where there are other factors such as temperature and stress which may adversely affect the properties of the oriented materials. Materials of the higher percentage aluminum-iron (>10% aluminum) and silicon-iron (>6.7% silicon) would be expected to portray some changes in magnetic properties when exposed to environments of this type since these alloys are known to display order-disorder type transformations when exposed to thermal variation. Neutron irradiation likewise affects the degree of order in a material although this effect is not as drastic as is that of thermal agitation.

Magnetic Anisotropy

Another factor to be considered in the utilization of ferromagnetic materials is the magnetic anisotropy of the materials. This property determines the ease with which a material can be magnetized and it exists because single crystals of the material themselves are magnetically anisotropic, even though the crystals may have cubic symmetry.

For applications where ease in magnetization is desired and where it is required that the sheet material will magnetize as readily in one direction as in another, a material having very low anisotropy constants is suggested. If the anisotropy constants are close to zero, it will not matter whether some preferred orientation has been produced in the polycrystalline material because the behavior will continue to be magnetically isotropic as long as the applied stresses are kept at a minimum

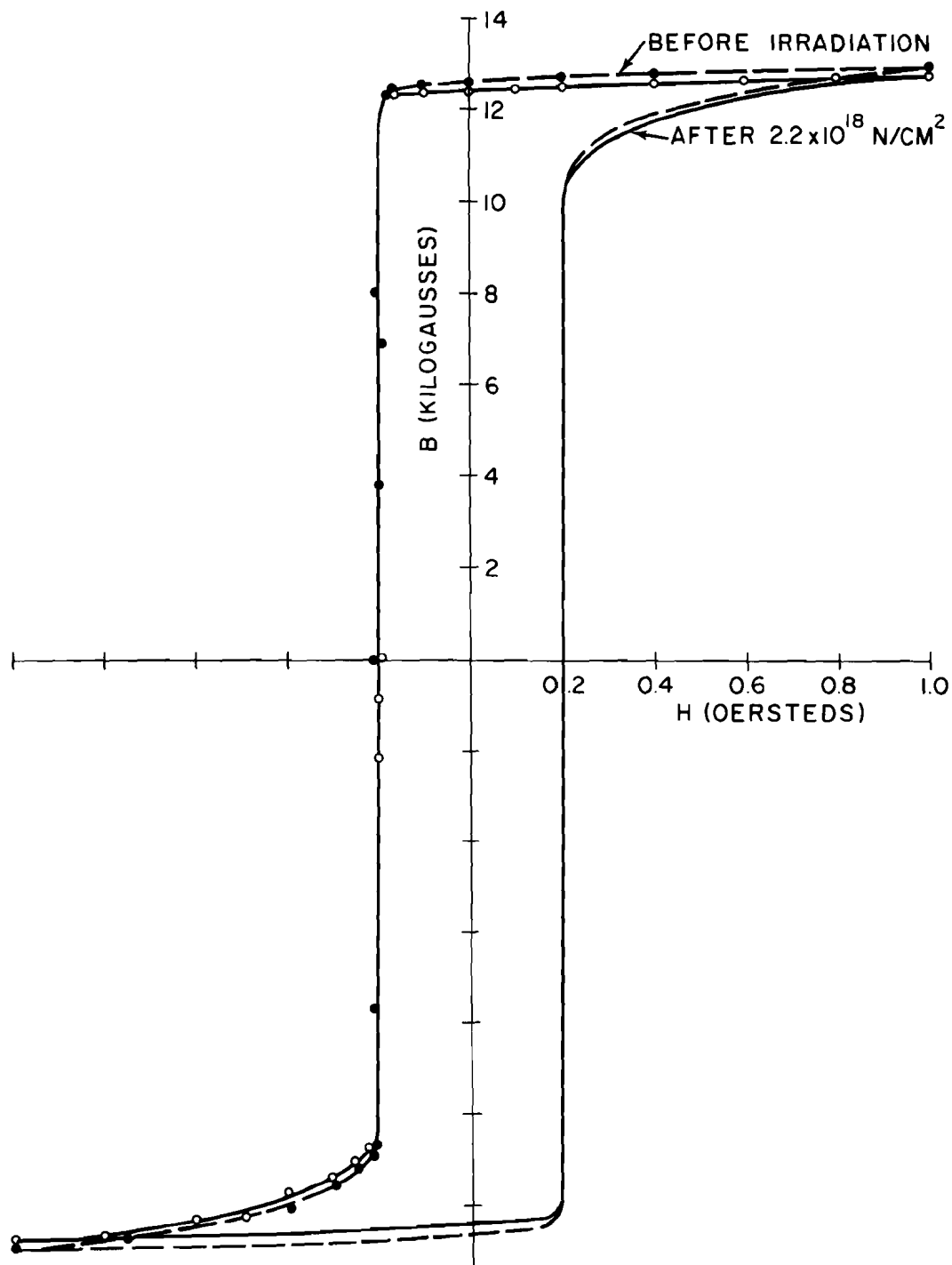


FIG. 17 EFFECT OF IRRADIATION ON D-C HYSTERESIS LOOP
OF A 3% SILICON - 1% ALUMINUM - IRON CORE
(MAGNETIC ANNEALED)

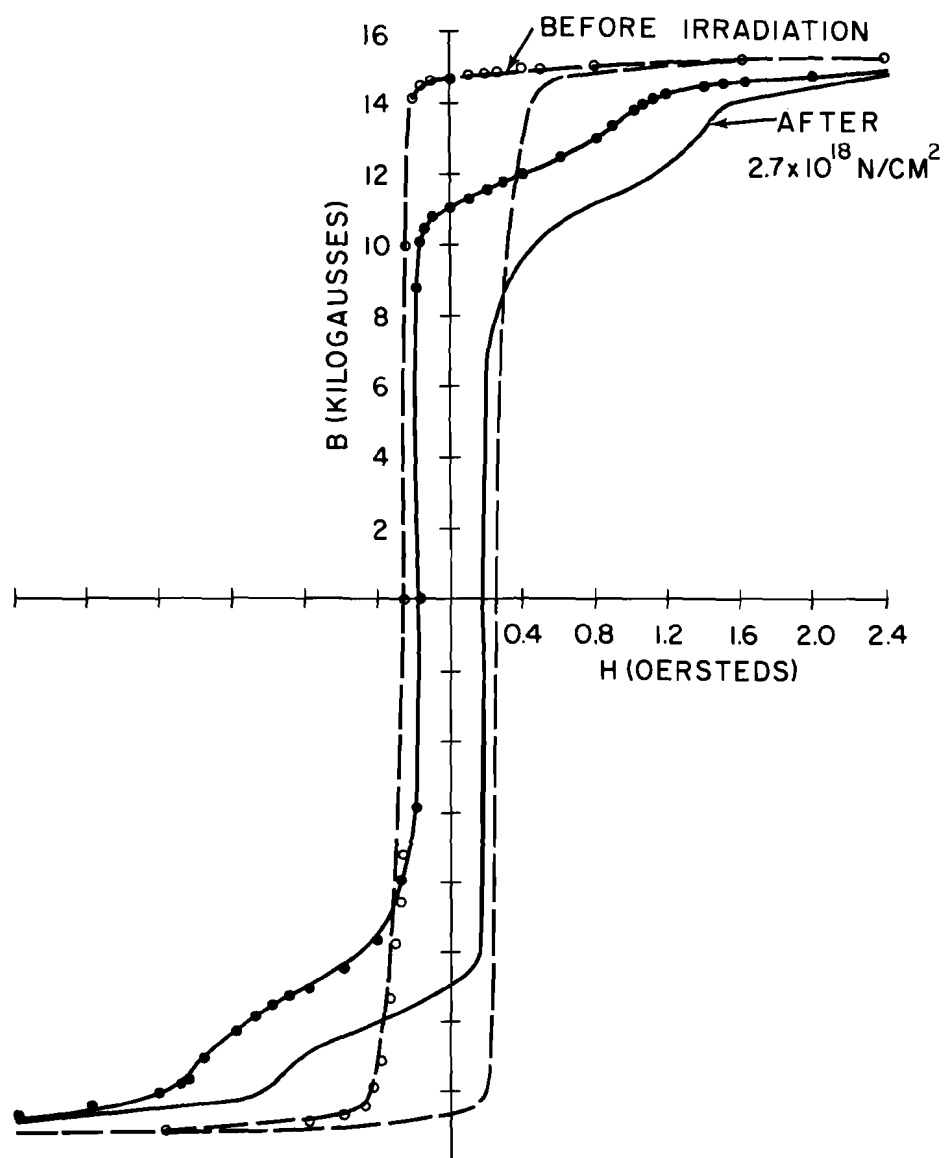


FIG. 18 EFFECT OF IRRADIATION ON D-C HYSTERESIS LOOP OF A 50 NICKEL - 50 IRON (ORIENTED) CORE.

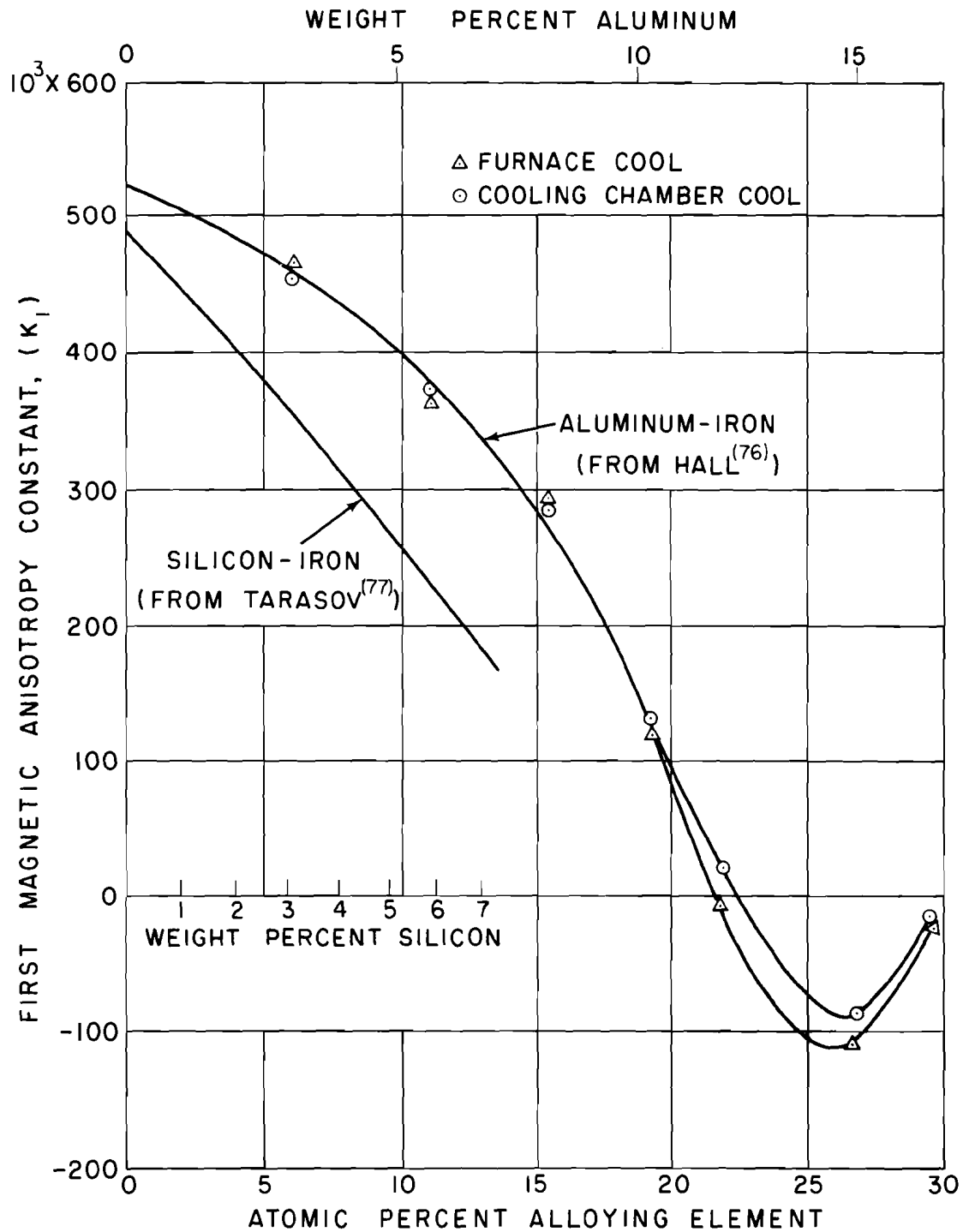


FIG. 19 FIRST MAGNETIC ANISOTROPY CONSTANTS OF ALUMINUM-IRON AND SILICON-IRON ALLOYS.

However, in many applications it may be advantageous to make use of the magnetic anisotropy that exists in the crystal lattice. By orienting the crystals of a polycrystalline material in such manner that the easy directions of magnetization are aligned parallel with the operational flux path of the material, there may occur a drastic increase in magnetic flux density without a corresponding increase in exciting current or in core loss. Examples of this type application are the "cube-on-edge" silicon-iron alloys having $(110)[001]$ texture or the "cube texture" silicon-irons having $(100)[001]$ type orientation. Here again the low percentage aluminum-iron alloys are similar to the silicon-iron alloys in that they are easily magnetized in the $[100]$ direction, while their most difficult magnetization is in the $[111]$ direction.

One method^{74,75} of determining the anisotropy constants of these materials is to make torque measurements in various directions on a disc cut from a single crystal of the composition in question. Subject disc should be exposed to a uniform magnetic infinite field during measurements. For instance, in a cubic crystal the first anisotropy constant (K_1) can be determined by measuring the maximum torque value on a disc cut parallel to the (100) plane. The anisotropy constant K_1 is equal to twice this maximum torque value.

The first anisotropy constants (K_1) at room temperature for the binary aluminum-iron alloys decrease from approximately 480×10^3 ergs/cm³ for pure iron to a value of about 400×10^3 ergs/cm³ for 4% aluminum-iron (weight percentage) and approximately 280×10^3 ergs/cm³ for 8% aluminum-iron.

Fig. 19 is a plot of the room temperature anisotropy constants (K_1) obtained by Hall⁷⁶ on the aluminum-iron alloys and by Tarasov⁷⁷ on the silicon-iron alloys. Hall's method of extrapolating torque readings as a function of the reciprocal of the square root of the field strength (L vs $\frac{1}{\sqrt{H}}$) provide infinite field readings that are approximately 5% higher than those normally obtained using the extrapolation method (L vs $\frac{1}{H}$). However, Hall's experimental techniques and equipment make his data fairly reliable. As may be observed in Fig. 19, zero anisotropy for the aluminum-iron alloys occurs at a composition of about 12% by weight aluminum.

It must be emphasized that these anisotropy constant show considerable change with variation in temperature^{76,78}. For example, K_1 for iron, decreases from a value of about 480×10^3 ergs/cm³ at room temperature to approximately 70×10^3 ergs/cm³ at 500°C. Similar changes occur in the silicon-iron alloys and

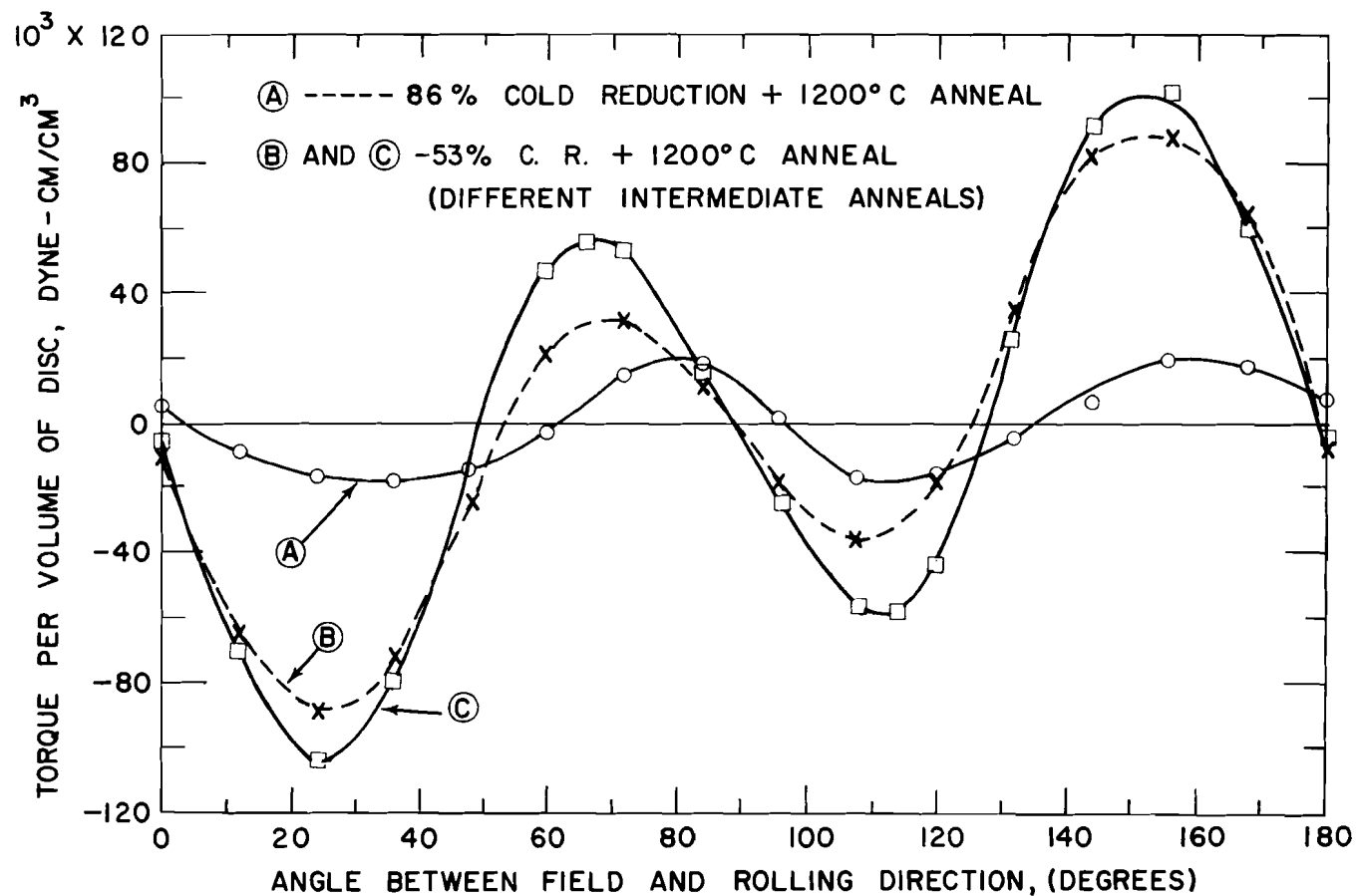


FIG. 20 ROOM TEMPERATURE TORQUE CURVES OF POLYCRYSTALLINE 4% ALUMINUM - IRON DISCS AS AFFECTED BY PROCESSING. (MATERIAL THICKNESS = 0.014)

may likewise be expected to occur in the aluminum-iron alloys. Advantage may be taken of this situation by artificially controlling the environment to obtain some desired anisotropy value. This may be particularly desirable when using aluminum-iron alloys since many of their compositions contain anisotropy constants that are quite high.

Special Crystalline Orientations

As was stated in the previous section, the "easy direction of magnetization" for the body centered aluminum-iron alloys of interest in the present paper is that one along the cube edge or the one normally referred to as the $[100]$ direction. For this reason, the most desirable orientations would be those corresponding to the silicon-iron equivalents, namely, the $(110) [001]$ texture or the $(100) [001]$ type orientation.

Since there has been such neglect of the low percentage aluminum-iron alloys prior to the present era, the development of special orientations in these materials has also been retarded. However, the limited study and experimentation conducted on these alloys have proved their capabilities as regards acquisition of special textures. Bozorth and Williams⁸⁰ demonstrated by special processing and annealing procedures that a 4% aluminum-iron alloy is quite responsive to orientation type processing techniques. One procedure used by these investigators produced optimum magnetic properties in two different directions which were perpendicular to each other, one direction being somewhat more responsive than the other. The torque curve on this alloy indicated an orientation approaching that of the $(110)[001]$ texture.

The author of the present report has produced various textures in a number of low percentage aluminum-iron alloys by exercising control over their compositions and their processing and annealing procedures. Figure 20 demonstrates results of a portion of this effort on a nominal 4% aluminum-iron alloy. All three samples in this figure were the same thickness (0.014) and were exposed to the same 1200°C final annealing cycle. Curve "A" illustrates a material that is fairly isotropic in texture while curves "B" and "C" exemplify materials that show increased preferential orientation. The easiest directions of magnetization of these polycrystalline samples are close to the rolling direction and at 90° to the rolling direction as indicated by the fact that the curves have their greatest negative slopes close to the 0° and 90° points of the abscissa. Slight misalignment of the rolling direction with the direction of field application may be one reason for these curves not passing directly through these points. The other reason of course, is the probability of the polycrystalline texture being directed at some slight angle away from the ideal directions.

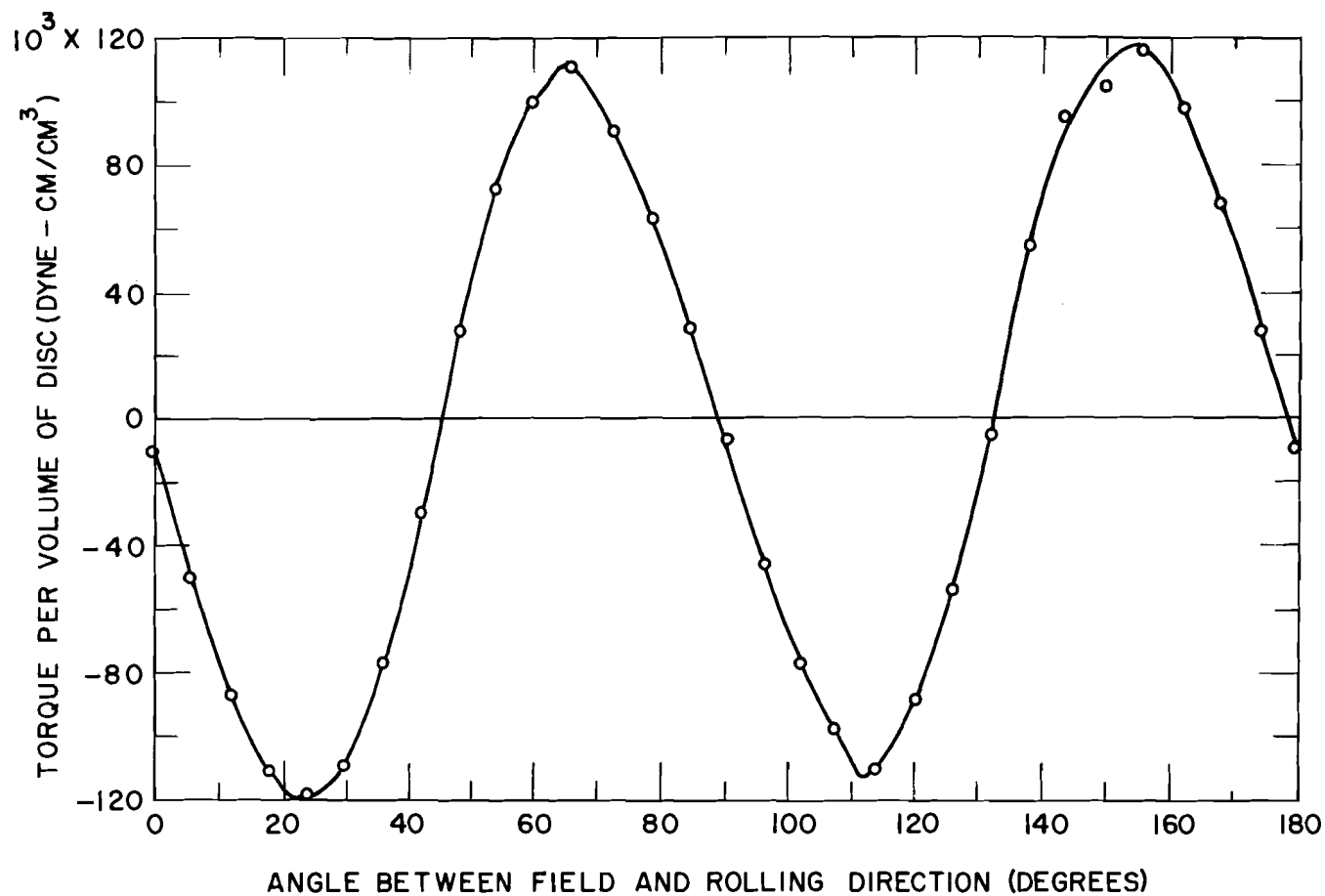


FIG. 21- ROOM TEMPERATURE TORQUE CURVE OF POLYCRYSTALLINE 3% ALUMINUM - 1% SILICON - IRON DISC FOLLOWING SPECIAL PROCESSING
(MATERIAL THICKNESS = 0.008)

As may be observed in Figure 20, the texture of these samples does not correspond to an ideal orientation of the (100) [001] type since the torque curve peaks following the 0° and 90° points are not equal and are not of sufficient magnitude.

Figure 21 illustrates work that was performed on a slightly different alloy system and it indicates a more obvious similarity to the (100) [001] texture although the curve peaks continue to show a deficit. This data was taken on an alloy, developed in this Laboratory, composed of 3% aluminum - 1% silicon and remainder iron. The specimen as illustrated here was made from 0.008 thick material which had been cold reduced approximately 73% and was subjected to a final anneal in a hydrogen atmosphere at 1200°C . Similar results were obtained on a number of these aluminum-silicon-iron ternary alloys of various compositions and in general it was found that these ternary alloys responded to various rolling and annealing procedures in a manner quite similar to that of the binary aluminum-iron and silicon-iron alloys. As may be observed in Figure 21, it appears that a majority of the crystals of this specimen have aligned themselves such that the easy cube direction is close to the rolling direction (greatest negative slopes are close to 0° and 90°), however the cubes are possibly tilted such that the cube plane is not well aligned with the rolling plane. This results in lower maximas and minimas than the theoretical ideals.

Another investigator, Albert,⁸¹ has reported on effects of processing variations on the properties of aluminum-iron alloys containing from 3 to 7 weight percent aluminum. He specifically stresses effects of processing on magnetic remanence of the alloys and discusses a method for obtaining a recrystallized "doubly oriented" iron-aluminum tape material. The properties he lists for this material, particularly the remanence values, are not as favorable as one would expect from a truly "cube texture" type of orientation.

For those readers who have further interest in developing special textures with the aluminum-iron alloys, it is recommended that they first review the literature on oriented silicon-iron alloys. There are several excellent summaries on this subject, among which are publications by Burke and Turnbull,⁸² R. H. Pry,⁸³ and J. R. Brown.⁸⁴

There are certain advantages arising from the use of specially oriented aluminum-iron and silicon-iron materials in magnetic applications. They are as follows:

- a. Improved hysteresis loop rectangularity which permits a reduction in excitation current with associated reduction of

copper windings.

b. Improved efficiency of core material which permits substantial reduction in component weight and size.

c. Three mutually perpendicular easy directions of magnetization which permit construction of special core configurations. E and U shaped laminations are particularly adaptable to the "cube texture" type of orientation.

For a completely comprehensive analysis one must also consider the detrimental aspects concerned with the use of specially textured materials. These are as follows:

a. Possible increase in strain sensitivity, depending of course, on relative directions of stress applications and crystal orientation. This dependence is related to the anisotropy of magnetostriction constants and would be a factor to be considered concerning resistance to shock, vibration, and acceleration.

b. Possible degradation due to temperature variations. This effect is related to magnetic core construction and configuration which in turn are determined by type of available material. For example, material having the cube-on-edge type of orientation is more efficient and subsequently more logical when used in the form of tape wound cores. However, alternate expansion and contraction caused by temperature variations produce stress concentrations in this type of core construction that are especially detrimental to magnetic properties. This in turn creates a problem of instability in this type of environment. Laminated cores made of isotropic material or cube textured material would not be effected in this manner by temperature excursions or by other stress producers, therefore, they should show much greater stability when exposed to these environments.

c. Additional cost and difficulty in production of special textured materials. Alloy purity and close control of processing and annealing procedures are factors that cause increased cost on these materials.

Mechanical Properties of Aluminum-iron Alloys

In most magnetic applications the mechanical properties of the associated alloys are not of prime consideration; however, instances do arise where these properties must be taken into account. For instance, the influence of stress on the magnetization of a material, depending upon the magnetostriction of the alloy, makes possible the devising of special apparatus wherein this inherent property becomes useful. Also, when one is concerned with rolling these materials to thin gauges the ductility

of the alloy becomes quite important. Likewise, the hardness and brittleness become important when one is concerned with stamping or polishing operations on these materials. For these reasons it is desirable to know the mechanical limitations of these materials.

Many investigators ⁸⁵⁻⁸⁷ have studied effects of various elements on the solid solution hardening in iron. Lacy and Gensamer^{88,89} made a comprehensive study of effects of alloying elements in solid solution on the strength and strain hardening of iron. In general, a majority of these investigators found an increase in strength and hardening power corresponding with an increased difference in size of solvent and solute atoms, with decreased solid solubility, and with increased lattice distortion effected by the solute, all of these factors being somewhat related. Silicon, manganese, and aluminum all rate relatively high as regards their strengthening and hardening effects on iron. Sykes and Bampfylde⁹ reported extensively on the electrical, thermal, and mechanical properties of air-melted iron-aluminum alloys as early as 1934 and found that alloys containing more than 5% aluminum were extremely brittle, this probably being due to their air melting technique.

Zaymovski⁶ and co-workers in 1937 reported on the magnetic and physical properties of aluminum-iron alloys to which additions of manganese had been made. These investigators found much improved ductility in these alloys over that obtained in equivalent silicon-iron alloys.

Recent improvements in melting techniques, alloying elements, and processing techniques have made it possible to improve considerably on the magnetic and physical properties of the aluminum iron alloys. Early difficulties with these alloys were due to high oxygen content in the melt, this condition causing formation of massive inclusions of alumina which clustered in the grain boundaries, thus causing severe embrittlement. At the Naval Ordnance Laboratory we have made use of pure alloying elements, controlled atmospheres (hydrogen, helium, and partial vacuum), and improved melting and processing techniques to considerably reduce these deleterious effects. Buehler and Dalrymple^{90,91} of this Laboratory have reported extensively on effects of these techniques on metallurgical and mechanical properties of various aluminum-iron alloys; however, their studies were concerned with the higher percentage aluminum-iron alloys (10-18% aluminum by weight) and with various additions to these alloys whereas the present report is concerned only with alloys containing less than 10% aluminum.

Morgan and Zackay⁹² in 1955 obtained improved ductility on aluminum-iron alloys, containing 8% to 14% aluminum, by making

EFFECT OF MANGANESE ADDITIONS ON HARDNESS AND GRAIN
SIZE OF 4% ALUMINUM-IRON ALLOYS

(As Rolled* and Annealed** Conditions)

Manganese Addition to 4% Al-Fe	Material Condition	Hardness Reading		Grain Size (gr/mm ²)
		DPH	Rockwell Equivalent	
0.0%	As-rolled	207	B-93	-
0.5%	As-rolled	231	B-97	-
1.0%	As-rolled	278	C-27	-
2.0%	As-rolled	285	C-28	-
3.0%	As-rolled	293	C-29	-
0.0%	Annealed	168	B-84	20
0.5%	Annealed	180	B-87	56
1.0%	Annealed	197	B-91	67
2.0%	Annealed	172	B-85	53
3.0%	Annealed	186	B-88	28

* All alloys were cold rolled from 0.100 to 0.014 thickness.

** Used normal hydrogen anneal for magnetic alloys: 2 hours at 1000°C -
furnace cool.

use of pure elements, stabilized zirconia melting crucibles, vacuum melting techniques and by making small carbon additions to the melt for the reduction of oxygen content.

Yamamoto and Taniguchi⁹ in 1956 reported on an extensive study of density, magnetic properties, Young's Modulus, and the ΔE -effect of iron-aluminum alloys containing from 0% to 17% aluminum by weight. They used induction melting techniques with pure elements such that they held their impurity contents down to very low levels. Their specimens were hot forged and machined to size and their annealing operations were performed in vacuum. The plot of Young's Modulus in Fig. 22 is taken from the published data of these investigators.

Justusson, Zackay and Morgan⁹³ in 1957 reported fairly extensively on the mechanical properties of iron-aluminum alloys. This was a continuation of their earlier work⁹² whereby induction vacuum melting in stabilized zirconia crucibles was performed and the carbon deoxidation technique was used to reduce oxygen. All of their binary alloys contained a residual of 0.03 to 0.05% carbon and they observed progressive increases in tensile and yield strengths, with increase in aluminum content, up to maximum values of $\sim 112,000$ psi tensile and $\sim 90,000$ psi yield strength. These maximum values occurred close to the stoichiometric composition of the Fe_3Al superlattice.

Because of the interesting results obtained in the present study when low percentage aluminum-iron alloys having manganese additions were magnetic annealed, Table VI, several measurements were made to observe effects of manganese on the hardness and grain size of these alloys in the rolled and annealed conditions. As indicated in Table XIII, manganese additions of 0.5% and 1.0% to the 4% aluminum-iron alloy resulted in increased hardness and grain refinement, whereas the 2% and 3% manganese additions tended to reverse this effect, particularly as regards grain size. Magnetic results on these alloys, following magnetic anneal, indicated gradual improvement in properties with manganese addition up to about 2% with little additional improvement being observed for the 3% addition.

Zaymovski and coworkers⁶ also studied this iron-manganese-aluminum system using alloys with aluminum content approximately twice the manganese content. They observed the same excellent working characteristics for these alloys that were observed by the present author. The magnetic characteristics of their alloys were approximately equivalent to those of a 4% silicon-iron alloy.

A recent summary on mechanical and physical properties of binary iron-aluminum alloys containing up to 18.5 weight percent

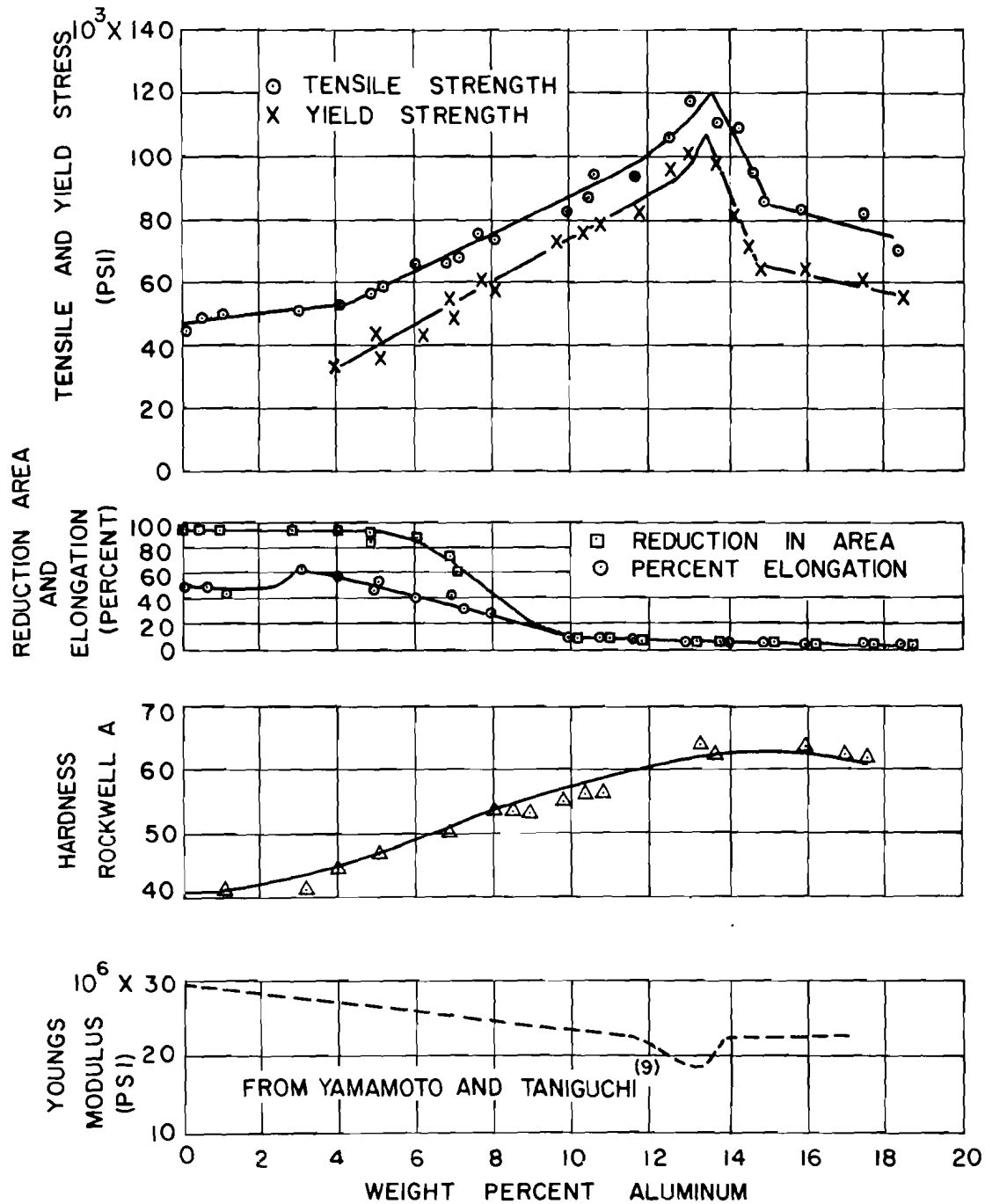


FIG. 22 ROOM TEMPERATURE MECHANICAL PROPERTIES OF IRON-ALUMINUM ALLOYS QUENCHED FROM 1400°F (FROM KAYSER⁽⁹⁴⁾)

aluminum was published in May, 1957 by Kayser⁹⁴. His alloys were induction melted under vacuum, cast under argon, and he made carbon additions to the melt for deoxidation purposes. The resultant castings had from 0.01 to 0.05% residual carbon present. It should be emphasized that although carbon is not generally recommended as an addition to soft magnetic alloys, small percentages may be added for removal of oxygen when using vacuum melting techniques since the carbon monoxide thus formed is removed under vacuum and the residual carbon content is quite low.

Fig. 22 summarizes results of Kayser's study on effect of aluminum addition to iron on tensile strength, yield strength, elongation, reduction in area, hardness, and modulus. These alloys were quenched in oil from 1400°F; however, their properties are quite similar to those on alloys that were furnace cooled, with the possible exception of alloys on the aluminum rich side of Fe₃Al. Kayser also reported on the elevated temperature properties of these alloys; his conclusions being that from the standpoint of hot strength, adequate oxidation resistance, and room temperature ductility, the optimum concentration is 7% by weight.

The studies of these various investigators indicate that for those ferrous alloys with which we are concerned in this report, (namely, 0-10% aluminum by weight) the mechanical properties are quite adequate for the particular conditions to which they may be exposed. Hardness, tensile strength, and yield strength rise continuously with addition of aluminum to a maximum value in the range of 14% aluminum. Room temperature elongation values of 50 to 60% as well as high reduction-in-area values remain constant up to about 5% aluminum at which point there is a gradual decline. Room temperature fracture appearance of alloys containing above 8% aluminum is on the brittle side.

Improved ductility of the aluminum-iron alloys (0 to 10% wt aluminum) over equivalent silicon-iron alloys is the chief advantage derived from replacement of silicon by aluminum in these ferromagnetic alloys. For example, silicon-iron alloys show a rapid drop in elongation and reduction-in-area at about 2.5 to 3% silicon such that cold reduction of 5% silicon-iron is extremely difficult and alloys containing more than 5% silicon are so brittle that standard processing procedures require working temperatures considerably above room temperature. On the other hand, alloys containing up to 6% aluminum may be cold rolled with little difficulty while those containing from 6% to 10% aluminum can be reduced at some temperature slightly above room temperature with little additional effort. This improved ductility permits rolling of higher percentage aluminum-iron alloys to very thin gauges, these factors being important from a resistivity and core loss standpoint.

Availability and Economy

A scarcity in alloy constituents together with difficulties in processing and fabrication of specific alloys will naturally impede the development and acceptance of components requiring these particular alloys. Fortunately, the aluminum-iron alloy system, like the silicon-iron alloys, is not limited by availability of component elements. The percentage composition of the earth's crust proves to be high in both aluminum and in iron and since production difficulties have been solved for making high purity aluminum, this alloy system should vie competitively with the silicon-iron system as regards availability and economical use in magnetic components. As mentioned previously, the aluminum-iron alloys also have the additional advantage of improved ductility even to the extent that alloys containing up to 8% aluminum can be worked without too much difficulty, thus making the system economically feasible.

Powdered and Flake Magnetic Cores

It has been shown that increases in operational frequencies of a magnetic component demand thinner materials with higher resistivities in order to substantially reduce eddy current losses. Unfortunately, a point is reached where the practicality of these types of improvements is limited; thus for further reduction or control of core losses it becomes necessary to subdivide the material into small particles or flakes and then to compact these particles, with suitable electrical insulation, into desired core configurations. Typical examples of this procedure are the powdered iron cores, 2-81 molybdenum permalloy dust cores, and the various types of ferrite cores used in high frequency applications.

As in the case with laminated and tape cores, the use of the aluminum-iron system for producing powdered cores has been practically nil. Actually, the alloys which show poor room temperature ductility are the ones with most promise for pressed powdered core configurations since these alloys are most responsive to the **crushing** and pulverizing operations which are required in producing **powdered** materials. Of course, the normally ductile materials can be used by making special additions to the melt, thus enhancing formation of brittle boundary material which would easily fracture when exposed to pulverizing operations. However, these additions in most cases, are detrimental to the magnetic properties of the materials under consideration.

The most representative sample of brittle material for this type application is "Sendust" which was introduced in 1936 by Masumoto⁴ in Japan. This is a ternary alloy containing approximately 9.5% silicon - 5.6% aluminum and remainder iron. It is

extremely brittle in the cast state. Thurlby⁹⁵ in Australia published work on powdered Sendust while Adams⁹⁶ contributed information on processing techniques and magnetic properties of Sendust powdered cores.

Adams, Haben, and Hubbard⁹⁷ successfully warm-rolled Sendust powder into flake and this flake was subsequently compacted into cores, designated as Flakenol I. High-permeability, low-loss cores were obtained using this method and these cores are a suitable non-strategic substitute for high-nickel powdered cores which are normally used in high frequency applications. This type core was later found⁹⁸ to have a comparatively stable quality factor (μQ) up to a temperature of about 400°C.

The first published data on straight binary aluminum-iron powdered cores is that of Adams and Hubbard⁹⁹ of this Laboratory and their work concerned the brittle high-aluminum (16%) material known as Alfenol. Although this alloy has poor room temperature ductility, it is not as brittle as Sendust, and therefore, is more difficult to pulverize. Results showed that these 16-Alfenol powdered cores had higher permeability, better temperature stability, and better green and annealed tensile strengths than Sendust. They had higher residual losses than did 2-81 molybdenum-permalloy but certain advantageous factors were found in 16-Alfenol powdered cores such as utilization of non-strategic materials, better temperature stability, formation of its own insulation (Al_2O_3) thus permitting air annealing in place of hydrogen, and finally the economics of material cost and production.

As regards the lower percentage aluminum iron alloys (0 to 10% aluminum) there has been very little effort toward incorporation of these alloys into composite powdered or flake core configurations. The only apparent reason for this appears to be that the silicon-iron materials were more readily available. One obvious advantage of aluminum-iron over the silicon-iron alloys would be the extremely thin adherent insulating coating that forms on aluminum-iron alloys. This would serve as a natural insulation between particles of pressed powdered cores. However, this type of coating might be a deterrent in such processing techniques as the production of aluminum-iron strip by rolling of powders, or in the manufacture of powdered cores that require sintering operations.

For the production of Flakenol type compacted cores wherein metal powder is rolled into flakes, the low percentage aluminum-iron alloys would be advantageous from a ductility standpoint, thus making it possible to perform the rolling operations at room temperature which would curtail oxide formation. Of course, this inherent ductility increases the difficulty in the

production of powder by the "pulverization-of-casting" technique. This latter technique would require melt additions that would enhance grain embrittlement such that mechanical disintegration would become feasible.

SUMMARY AND CONCLUSIONS

When such environmental and qualitative factors as temperature, radiation, humidity, shock, vibration, power handling capacity, weight, economy, and availability are being considered, the aluminum-iron magnetic alloys must be rated on the same high level with the silicon-iron alloys. The reasons for this competency of the aluminum-iron system, particularly those alloys containing less than 10 w/o aluminum, may be summarized as follows:

The Curie temperatures are relatively high for the low percentage aluminum-iron alloys, ranging from a maximum of 768°C for 0% aluminum (pure iron) to a low of about 690°C for 10% aluminum-iron. This magnetic transformation curve is slightly higher than the equivalent curve for the silicon-iron alloys.

The magnetic saturation induction values of the low percentage aluminum-iron alloys are practically identical in magnitude with equivalent silicon-iron percentages. They range from 21,580 gauss for 0% aluminum (pure iron) to about 16,000 for 10% aluminum-iron. These values are such as to provide components of minimum weight and size.

Major long range order-disorder transformations are detected in the aluminum-iron alloys only when aluminum concentrations above 10% (by weight) are reached. This provides a wide range of low percentage aluminum-iron alloys that are free from this transformation and therefore provide good property stability when subjected to various cooling rates during temperature cycling. This phenomena is a definite handicap to such alloys as 4-79 molybdenum-permalloy, supermalloy, supermendur, 16-alfenol, etc., for applications where temperature cycling is probable.

For nuclear radiation environments the limited tests conducted to date indicate that low percentage aluminum-iron magnetic alloys, like the silicon-iron alloys, show very little appreciable change in properties when exposed to radiation levels up to 10^{17} fast neutrons/cm²(nvt). This is true for all relatively high coercive force soft magnetic materials. Low coercive force materials display drastic degradation when subjected to radiation levels of this magnitude.

Nuclear radiation environments also create the problem of induced radioactivity. The aluminum-iron alloys are not affected by these environments whereas cobalt bearing magnetic alloys are particularly bad in this respect. [Half-life of cobalt₆₀ = 5.3 years].

The magnetostriction values and their subsequent strain sensitivity effects show more variation with increasing aluminum content than may be found with increasing silicon additions to iron. A polycrystalline sample of about 4 a/o aluminum-iron (1.97 w/o) has a saturation magnetostriction value close to zero but an increase in aluminum content causes a rise in the curve such that peak values in excess of 40×10^{-6} are obtained for alloys in the range of 11.6 to 13% aluminum. These higher magnetostriction values are desirable for transducer type applications, however, low magnetostriction values are more desirable where factors of stress and strain are to be considered.

The aluminum-iron magnetic alloys like the silicon-iron alloys do not compare favorably with nickel-iron alloys when one considers permeability and coercive force alone. However, for permeability at high induction levels and for low-loss power type equipment, the alloys with aluminum and silicon are superior. A 60 cps core loss value as low as 0.42 watts per pound was obtained on a magnetic annealed 7.68% aluminum-iron alloy (0.010 thick) at an induction level of 10 kilogauss.

The aluminum-iron alloys are particularly responsive to magnetic annealing. Permeability improvements from 3,400 to 51,000 and from 1,700 to 53,500 were obtained by magnetic annealing respectively a 7.68% aluminum-iron and a 10% aluminum-iron core. Low applied fields [about 1.7 oersteds] were particularly affective during magnetic annealing of these materials.

Certain aluminum-iron alloys with manganese additions were improved considerably when magnetic annealed. A 4% aluminum-iron binary alloy had a permeability of 17,800 following magnetic anneal whereas this same alloy with a 2% manganese addition gave a permeability value of 35,300. Core loss values dropped from 0.60 to 0.44 watts per pound as result of small manganese additions to the 4% aluminum-iron alloy. Manganese additions also reduced slag formation during melting.

Alloys that are responsive to magnetic annealing may exhibit permanent changes resulting from operation at elevated temperatures. The current in the core control windings can produce magnetic fields sufficient to place the core material in a magnetic annealed state. This additional induced anisotropy usually produces an improvement rather than a degradation in the

core material properties. However, it does result in an instability that must be expected during temperature excursions.

The oxidation resistance of the aluminum-iron magnetic alloys makes them particularly acceptable for elevated temperature applications. Wet hydrogen and dry hydrogen preanneals are effective in stabilizing this resistance over long periods of exposure time. Preferential oxidation of aluminum-iron and silicon-iron samples in wet hydrogen provide oxide stability at temperatures of 500°C for periods in excess of 400 hours.

The aluminum-iron alloys respond to crystalline orientation techniques in a manner similar to that of the low percentage silicon-iron magnetic alloys. The most successful efforts in the present study have been on alloys containing small percentages of both aluminum and silicon, e.g. 3% aluminum-1% silicon-iron. However, for elevated temperature environments it may be advisable to use these alloys in their isotropic condition. This recommendation is based on the particular core configuration normally associated with the various crystalline orientations.

One of the major advantages derived from use of aluminum-iron magnetic alloys in place of silicon-iron alloys concerns the improved ductility of the former. Aluminum-iron alloys containing up to 6 w/o aluminum can be cold reduced more than 98% without too much difficulty while alloys containing from 6% to 10% aluminum can be rolled at temperatures slightly above room temperature with little additional effort.

Above all else, the aluminum-iron alloys like the silicon-iron alloys utilize elements that are economical and readily available. Processing procedures have been perfected to a high degree for producing silicon-iron alloys that are suitable for use in a large and varied assortment of magnetic devices and components. The same equipment and processing techniques can be applied for producing aluminum-iron magnetic alloys with their own special properties and capabilities.

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APPENDIX 1

ALLOY PREPARATION

The various iron base alloys used in this investigation were prepared at the Naval Ordnance Laboratory, Silver Spring, Maryland, using techniques as outlined below.

Melting: Melting was performed in a controlled atmosphere induction furnace having a 30 pound (iron) capacity. High purity magnesium oxide crucibles were used for the preparation of all alloys. To insure low moisture content in the crucibles, a drying out melt of iron was made in each new crucible prior to melting the alloys of interest for this investigation.

The impurity content of elements used in this study are given in Table I of the report and typical analysis of hot-rolled slabs are given in Table II.

The actual melting cycle was initiated by loading the iron in the magnesium oxide crucible while the aluminum (and manganese when required) were placed in a loading device which made it possible to add these elements to the melt at the desired time. The furnace chamber was then evacuated down to a pressure of about 200 microns. The furnace power was then gradually increased until melting occurred at which time the furnace chamber pressure went up to between 500 and 1000 microns.

The molten iron was then given a decarburizing treatment with wet hydrogen, followed by treatment with dry hydrogen [dewpoint approximately -90°F] for about 1/2 hour to effect deoxidation. The hydrogen was then purged from the chamber with pure dry helium, followed by pump down to a pressure of about 3.5 mm (3500 microns). This removes hydrogen dissolved in the melt. The system was then refilled with pure dry helium and the aluminum and manganese additions were made to the melt. The melting chamber was then evacuated to a pressure of about 3.5 mm helium at which time the temperature was adjusted and the alloy was poured into a slab mold coated with a ceramic mold wash. In most cases the slabs were allowed to cool in the melting chamber, however, those alloys containing 8% and above aluminum were removed from the melting chamber while still hot and homogenized in an oven for one hour at 1000°C and furnace cooled.

Hot Rolling: The only operations performed for purpose of preparing the cast slab for hot rolling involved cutting off the shrinkage cavity at top of slab and sand blasting the surface to remove mold wash contamination. No special orientations were being investigated during most of this study, therefore,

a majority of the materials were rolled and processed using procedures that are fairly standard for isotropic silicon-iron alloys.

The slabs were heated for one hour at 1000°C and then hot-rolled on a laboratory 2-high rolling mill using screw down of 0.050 to 0.010 per pass until the surface temperature dropped to a dull red color. The slab was reheated at 1000°C as required and further reductions were made until a plate thickness of about 0.100 was obtained. Finishing temperatures close to 900°C were used on some of the low percentage aluminum-iron alloys when oxidation seemed to be a problem.

After cooling to room temperature the rolled plates were sand blasted to remove mill scale and bad edges were sheared off; however, edge cracking was much less severe with the aluminum-iron alloys than is found in the silicon-iron alloys. The plates were then ready for cold rolling.

Cold Rolling: The cold rolling operations were performed on a 2-high and/or a 4-high rolling mill. A majority of the magnetic aluminum-iron alloys can be rolled without difficulty at room temperature. This includes the aluminum-iron alloys with manganese additions and with low silicon additions that were included in this study. However, those alloys containing 8% or more aluminum can be reduced with much less power by raising their temperatures above room temperature. Heating them to 200°C - 300°C improves their workability considerably. However, in the present investigation a working temperature of 575°C was used on the 8% and 10% aluminum-iron alloys since this is the warm rolling temperature normally used on the higher 12% to 16% aluminum-iron alloys.

All materials were rolled directly to 0.014 or below except when intermediate annealing cycles were introduced in the processing of materials with special orientations.

Annealing Procedures: On completion of the rolling processes, test laminations, anisotropy discs, metallographic specimens, and resistivity strips were stamped or cut from the rolled strip. These specimens were then subjected to various annealing cycles and properties were obtained on the finished samples.

Unless otherwise stated in the report, all annealing operations were performed in closed stainless steel containers using a continuous flow of pure, dry, electrolytic hydrogen [dewpoint less than -90°F] as the protective atmosphere.

Typical annealing cycles were as follows:

- a. Furnace heat to maximum temperature (e.g. 1000°C).
- b. Hold at designated temperature for a period of time (e.g. 2 hours).
- c. Furnace cool to room temperature.

Cooling rates were not considered important for alloys under study for this report since order-disorder transformations were not present in most of these alloys and a majority of the anneals were selected to avoid phase transformations. Some slight effects of cooling rate variation may be observed on alloys containing 6% aluminum and above (Table III), however, the rapid cool was so drastic on these alloys that the changes may have resulted from surface stress concentrations rather than order-disorder transformations.

As regards those materials subjected to a magnetic anneal, it may be observed that very definite improvements occurred in most of these alloys. This magnetic annealing cycle was performed using a pure dry hydrogen atmosphere and only cores that had previously been subjected to a normal high temperature anneal were given this magnetic anneal.

The procedure followed in most cases for magnetic annealing a core was as follows:

- a. Furnace heat to desired temperature (usually 800°C).
- b. Apply d-c magnetic field to core.
- c. Hold at temperature for 2 hours with field applied.
- d. Furnace cool to 250°C or less with magnetic field applied continuously. [cooling rate = 25°C/hour]

Magnetic fields varying from 1.0 to 87.0 oersteds were used in this investigation and these fields were applied to the core material in same direction as the flux path during normal core operation. The lower fields [about 1.7 oersteds] seemed more effective for improving the d-c properties of the aluminum-iron alloys while the higher fields (10.0 oersteds) usually provided a reduction in a-c core losses.

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