Long-Term Stability of Alnico 5 and 8 Magnets

at 700-1200°F

by

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Components Technology Division

BASE TECHNOLOGY

November 1973

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SUMMARY

The results of this experiment showed that two processes combine to affect magnetic stability of Alnico 5 and 8 magnets at temperatures above 700°F: loss of field strength with time, the rate of loss increasing with temperature, and partial recovery of the loss caused by a high-temperature stabilization. Conclusion is that, for a given temperature, the most stable performance will be obtained by balancing these two processes with an optimum stabilization procedure. This procedure has yet to be established.

For 12,000-hr operation, the recommended maximum temperatures are 1000°F for Alnico 5 ($< \pm 10\%$ drift), and 1100°F for Alnico 8 ($< \pm 15\%$ drift).

I. INTRODUCTION

This report describes the pre-test stabilization treatments and subsequent vacuum furnace tests performed to determine the long-term (12,000 hr) stability of Alnico 5 and 8 magnets suitable for use in permanent-magnet in-core sodium flowmeters at temperatures ranging from 700°F (EBR-II bulk sodium temperature) to 1200°F (maximum sodium temperature for projected LMFBR Demo Plants). These tests were prompted by an EBR-II irradiation of Alnico magnets, which revealed that the magnets were not significantly affected by neutron doses up to 1.3×10^{22} nvt, but that temperature had a marked effect on magnet stability, test X063 in EBR-II.¹ In addition, earlier studies of magnet temperature stability had shown that, when properly stabilized, Alnico 5 and 8 magnets could be cycled from room temperature to 1200°F and back in about four hours, with less than 1% variation from their respective temperature magnetic field plots.

It was also known that the operating point of a magnet on its demagnetization curve had an effect on magnetic stability. Magnets operated with a high B/H ratio were more stable against external demagnetization, especially if the operating point was above the "knee" for square-loop materials. When operated

"open circuit" in air, the operating point of a magnet is determined by its length-to-diameter (L/D) ratio. For sodium flowmeter applications, L/D ratios of 1 to 4 were of interest, the low end for probe-type flowmeters, and the upper end for flow-through types.

II. DESCRIPTION OF MAGNET SAMPLES

Alnico alloys are the only class of magnetic materials generally available that have high Curie temperatures and high specific energy. Of these, Alnico 5 and 8 are the most applicable to sodium flowmeters. Both are oriented during manufacture: Alnico 5 can be cast in relatively complicated shapes, while Alnico 8 is limited to simple blocks and cylinders. However, Alnico 8 has a high coercive force which makes it particularly suitable for the short, simple magnet shapes used in probe-type flowmeters. Alnico 5 is a square loop material and is reported to be most stable when used above the "knee" of the B-H curve or with L/D ratios of 3.5 or greater.

Alnico 6 also was considered as a test alloy, but was rejected because of the wide variation in temperature stability exhibited by magnet samples during test X063 in EBR-II.

The quantity of samples was chosen to give a broad coverage of temperature and L/D ratios, and thus yield sufficient data for significant statistical analysis. Five supposedly identical samples were chosen for each temperature and L/D ratio. Thus, by measuring each pole of each sample, 10 data samplings were available for statistical analysis. Based on the "Students T" distribution of small-sampling theory, the 90 percent confidence limits of the mean would be 0.6 of the standard deviation.

The temperature range of 700 to 1200 F was divided into six 100° increments. Since the oven facility was limited to nine constant-temperature zones, the following test temperatures were selected for each alloy:

<u>Alnico 5</u>	<u>Alnico 8</u>
700°F	900°F
800	1000
900	1100
1000	1200
1100	

These temperatures were selected because Alnico 5 was known to be unsuitable for use at 1200 F, and Alnico 8 was thought to be totally suitable at temperatures below 900°F. Also, there were existing applications for Alnico 5 at 700°F (EBR-II) for which stability data would be useful.

The sizes of the samples also were determined by the oven size. Each constant-temperature zone measured 5 in. ID $\times$ 13 in. long. Adequate spacing was required around each sample to prevent interaction between their external fields. With proper spacing, each zone could accommodate 15 samples, five of each L/D ratio. The sample sizes were: $1/4$ in. dia. $\times$ 1 in. long for L/D = 4; $3/8 \times 3/4$ for L/D = 2; and $1/2 \times 1/2$ for L/D = 1.

The identity of each sample was maintained throughout the test program as follows: the L/D ratio was determined by measurement. The Alnico type and a serial number were vibroetched on the side or end of each sample. The samples also were identified by position in trays and sample holders. For purposes of recording data, each sample was identified by a sequence of numbers which included the L/D ratio, Alnico type, and serial number. For example, 4-8-21 represents a sample with an L/D ratio of 4, fabricated of Alnico 8, and a serial number 21.

III. TEST EQUIPMENT AND PROCEDURES

Consistent with the test plan, the magnet samples were: (1) cut to the desired L/D ratios; (2) magnetized to vendor specifications; (3) stabilized at the prescribed temperatures; (4) exposed to their respective test temperatures in the vacuum furnace; and (5) periodically (1000-hr intervals) cooled to room temperature, removed from the furnace, and subjected to measurements for changes in magnetic field strength.

It was recognized that changes in magnetic field strength measured at room temperature might not provide a good indication of changes incurred at test temperature. However, the latter mode of measurement would have markedly reduced the number of samples selected to provide broad coverage of temperatures and L/D ratios. Also, references in the open literature indicated that the temperature coefficient was constant with aging, at least for short periods; therefore, the percentages would be the same for changes measured at test temperature and room temperature.

A. Stabilization

An important parameter for the magnet samples is their pre-test temperature stabilization. Studies had been made in previous programs to determine the optimum technique for stabilizing Alnico magnets against permanent change when exposed to high temperatures.

The samples are first fully magnetized, then cycled at least three times from room temperature to 100°F above the proposed test temperature, followed by one more cycle with slow rise and slow cool. Once stabilized, a magnet could be subjected to several short cycles between room and operating temperature with no further decrease in magnetic field strength.²

The actual stabilizing temperatures selected for the Alnico 5 and 8 magnets were as follows:

<u>Alnico</u>	<u>Test Temp., °F</u>	<u>Stab. Temp., °F</u>
5	700; 800; 900	1000
	1000; 1100	1200
8	900; 1000	1300
	1100; 1200	1300

B. Vacuum Furnace Facility

The available test facility was essentially a 5-in-ID stainless steel tube furnace with nine, temperature-controlled zones, each 13 in. long. The interior of the furnace was maintained at a vacuum of $<50 \mu$.

To maintain uniform temperatures in each zone a four inch OD copper tube of 1/4 inch wall x 11-1/2 inch long was used to surround the samples. The samples were held in smaller copper tubes, 3/4 OD x 1/16 wall. Three of these tubes were arranged in the larger tube on a 1-5/16 radius. Five samples were spaced in each small tube using aluminum or copper spacers. The cross sectional arrangement is given in Figure 1. The tubes were supported on each end by the frame of Figure 2. Temperature profiles measured with thermocouples mounted on the surface of the 4-in.-OD tube showed that this arrangement resulted in a temperature differential of $<10^{\circ}\text{F}$ across each zone, while maintaining a 100°F differential between adjacent zones.

The samples were aligned with the same polarity in their respective sample holder tubes; i.e., with all north poles in the same direction. This alignment resulted in the least interaction between magnets. Placing the magnets end to end in each tube yielded a slight increase in magnetic field of each magnet, and placing the magnets in parallel with samples in other tubes yielded a slight decrease in the respective field values.

C. Instrumentation

The main information desired from this test was the relative change in magnetic field of the samples. Available instruments included Hall-effect gaussmeters and integrator-type fluxmeters. The latter was chosen as the more

Fig. 1. Typical cross section of vacuum furnace showing arrangement of magnet samples.

Fig. 2. Sample holder.

stable of the two types. The actual instrument used was an O. S. Walker Co. Model MF-1H transistorized integrator-type fluxmeter with a basic accuracy of 1% full scale. The difference between readings is more dependent on stability and precision of the instrument than on the absolute accuracy. To monitor instrument stability, a set of reference magnets were subjected to field measurements along with the magnets under test.

The search coils used with the fluxmeter were wound with 50 turns of #36 copper magnet wire on bobbins (1/8 in. long) that were close fitting on the test magnets. These bobbins were mounted flat on a phenolic board so that the magnet would extend 1/8 in. into the coil, with the center of the coil 1/16 in. from the end of the magnet. Thus only the flux coming out of the ends of the magnets was measured. This allowed rapid readings without searching for the null point along each sample. It also allowed independent readings for each end of each sample, which improved the statistics of the data.

A typical reading involved warming up the instrument and zeroing the drift. Next the sample was inserted into the coil with the zero switch held closed. When the sample was firmly seated in the bottom of the coil opening, the zero switch was released and the sample withdrawn. The meter reading was noted on the 0-100 scale, and the process repeated. When a consistent reading was noted, it was recorded on the data sheet. The scale-factor dials of the instrument set the full-scale kilomaxwell turns. Therefore, the meter reading may be considered a percentage of the scale factor setting.

The first reading in the data for a given sample was always the north pole. The north pole was recognized by the direction of reading on the meter, which was originally checked with a compass.

IV. RESULTS AND ANALYSIS

A. Effect of Pre-test Stabilization

Tables I and II list the calculated percent change in magnetic field strength incurred by each magnet during pre-test stabilization. The voluminous individual data are presented to illustrate the variability from sample to sample that is common to Alnico alloys, even though the samples were from the same batch from the same manufacturer. The average for each group shows, in a general way, the effect of stabilization temperature and L/D ratio on magnetic field strength. When stabilized at 1200°F, Alnico 5 incurs a much greater decrease in field strength than when stabilized at 1000°F. The general rule is that magnets with larger L/D ratios are more stable; this rule apparently holds for Alnico 8, but does not seem to hold for Alnico 5.

B. Long-Term Drift

The raw data on long-term drift of the magnet samples is too voluminous to present. Table III lists the average percent long-term drift categorized by alloy, L/D ratio, and exposure temperature. The changes in magnetic field strength for each exposure temperature are plotted in Figs. 3 to 8. In both the table and figures: (1) All data starts at zero percent for zero hours; (2) each data point is the average of 10 measurements, two from each of five similar samples; and (3) as mentioned earlier, the samples were stabilized by the same method but not at the same temperature.

Apparently, two time- and temperature-related processes occur that produce the total changes observed in the samples: First, a recovery process, as evidenced by the positive changes at all exposure temperatures except 1200°F; the rate of recovery increases with temperature, but decreases with time. The second process is a time-dependent decay, probably caused by disorientation of the magnetic particles within the alloy matrix; the rate of decay also increases with temperature. Both processes combine to give an initial increase, followed by a steady decrease.

Table I. Effect of L/D ratio and Pre-test Stabilization Temperature on Magnetic Field Strength of Alnico 5 Magnets

Stabilization Temp.: 1000°F						Stabilization Temp.: 1200°F					
L/D = 1		L/D = 2		L/D = 4		L/D = 1		L/D = 2		L/D = 4	
Sample No.	Change, %	Sample No.	Change, %	Sample No.	Change, %	Sample No.	Change, %	Sample No.	Change, %	Sample No.	Change, %
1-5- 1	12.7 12.7	2-5- 1	1.8 2.2	4-5- 1	29.3 30.1	1-5-19	58.5 57.7	2-5-19	60.9 60.1	4-5-19	53.4 50.3
- 2	11.1 11.1	- 2	3.3 3.8	- 2	25.2 26.5	-20	53.5 53.0	-20	60.3 60.8	-20	49.3 48.6
- 3	12.0 12.3	- 3	16.5 4.4	- 3	24.3 24.7	-21	56.3 56.3	-21	58.8 59.1	-21	43.1 43.8
- 4	12.5 12.0	- 4	1.7 6.6	- 4	26.8 27.5	-22	58.1 58.1	-22	74.9 75.3	-22	45.3 46.7
- 5	9.7 8.0	- 5	5.4 1.6	- 5	24.7 26.0	-23	56.0 56.0	-23	68.9 68.5	-23	49.6 50.0
- 6	11.9 10.9	- 6	3.7 1.6	- 6	17.1 19.2	-24	53.2 53.2	-24	66.1 64.7	-24	51.8 51.8
- 7	10.6 10.6	- 7	2.7 0.6	- 7	16.7 18.1	-25	51.4 51.4	-25	66.7 66.5	-25	50.0 50.4
- 8	13.0 13.2	- 8	3.1 5.1	- 8	21.4 22.3	-26	54.1 54.4	-26	69.9 70.5	-26	47.9 48.6
- 9	8.1 9.4	- 9	0.0 -1.9	- 9	13.7 12.9	-27	35.0 35.6	-27	42.4 41.8	-27	50.0 50.0
-10	8.6 8.3	-10	8.2 15.9	-10	12.1 10.8	-28	30.5 29.9	-28	38.8 37.2	-28	56.0 56.4
-11	6.3 6.9	-11	0.0 -0.6	-11	13.6 13.7	Average:	50.7		60.7		49.7
-12	10.9 11.5	-12	1.3 1.9	-12	21.4 21.9	High:	58.5 = 2.0		70.5 = 1.9		56.4 = 1.3
-13	5.3 6.5	-13	1.2 5.0	-13	7.7 7.1	Low:	29.9		37.2		43.1
-14	5.3 4.7	-14	-0.6 1.3	-14	3.4 5.3						
-15	4.8 4.8	-15	-0.5 0.0	-15	3.5 7.6						
Average:	9.5		3.2		17.8						
High:	13.2		16.5		30.1						
Low:	4.7 = 2.8		0.0		3.4 = 8.9						

Table II. Effect of L/D Ratio and Pre-test Stabilization Temperature of 1300°F on Magnetic Field Strength of Alnico 8 Magnets

L/D = 1		L/D = 2		L/D = 4	
Sample No.	Change, %	Sample No.	Change, %	Sample No.	Change, %
1-8- 1	55.7 56.0	2-8- 1	57.9 58.3	4-8- 1	20.8 20.8
- 2	56.3 56.5	- 2	58.5 58.5	- 2	19.4 19.9
- 3	57.7 57.8	- 3	60.7 60.4	- 3	20.8 20.5
- 4	64.7 65.2	- 4	64.4 64.5	- 4	21.4 20.9
- 5	63.9 64.2	- 5	62.5 58.1	- 5	25.3 25.2
- 6	60.4 60.5	- 6	58.1 58.5	- 6	19.5 21.2
- 7	62.7 62.1	- 7	60.2 59.5	- 7	20.1 21.7
- 8	67.4 67.0	- 8	66.2 65.6	- 8	21.9 22.4
- 9	62.9 62.3	- 9	54.5 53.3	- 9	23.0 22.9
-10	60.0 59.7	-10	51.5 51.6	-10	20.5 22.7
-11	52.0 51.6	-11	50.4 48.6	-11	23.5 24.5
-12	65.5 65.2	-12	61.6 61.0	-12	26.6 26.9
-13	56.0 55.7	-13	49.8 49.5	-13	24.7 25.5
-14	53.1 52.6	-14	40.9 40.6	-14	20.3 22.4
-15	51.8 51.1	-15 39.1	40.0 39.1	-15	22.3 24.8
-16	55.2 54.7	-16	47.6 47.7	-16	24.4 25.5
-17	41.1 41.4	-17	34.1 33.1	-17	19.5 20.1
-18	44.9 43.1	-18	25.4 24.9	-18	15.0 16.7
-19	39.6 38.9	-19	22.4 21.8	-19	14.7 16.0
-20	48.0 47.4	-20	29.0 25.0	-20	18.3 18.7
Average:	55.8		49.4		21.6
High:	67.4		66.2		26.9
Low:	38.9 = 1.73		21.8 = 3.0		14.7 = .1.

Table III. Average Percent Drift of Alnico 5 and 8 Magnets at 700-1200°F

Temp., °F	L/D Ratio	Exposure, hr.													
		800 hrs	1500	1900	2600	3200	4000	5000	6000	7000	8000	9000	10000	11000	12000
Alnico 5															
700	1	-3.2	-3.8	-5.0	-5.2	-5.0	-5.5	-5.6	-5.3	-5.2	-5.3	-5.4	-5.7	-5.8	-5.9
	2	-1.1	-1.1	-1.1	-1.1	-0.5	-0.7	-0.8	-0.6	-0.3	-0.1	00	-0.4	-0.5	-1.4
	4	+0.5	+0.5	+0.3	+0.2	+1.7	+1.8	+1.6	+2.7	+3.4	+3.2	+3.1	+2.7	+2.1	+3.3
800	1	-1.3	-1.0	-1.3	-1.9	-0.7	-0.7	-0.4	+0.3	+0.8	+1.0	+1.2	+0.9	+1.3	+1.5
	2	-0.1	+0.6	-0.1	+0.3	+1.0	+1.0	+1.1	+1.3	+2.0	+2.0	+2.3	+1.7	+1.8	+1.8
	4	00	+0.3	-0.3	-0.9	+1.8	+1.7	+2.1	+2.8	+3.9	+3.8	+3.9	+3.4	+3.6	+4.9
900	1	+2.8	+3.7	+2.9	+4.2	+4.1	+4.0	+4.1	+3.8	+4.6	+4.5	+4.9	+4.4	+4.6	+4.5
	2	+1.8	+2.2	+2.1	+2.9	+3.1	+3.3	+2.2	+2.4	+3.6	+3.7	+3.2	+3.2	+3.2	+3.3
	4	+3.2	+3.7	+3.5	+4.4	+4.2	+4.4	+5.1	+5.2	+6.7	+5.8	+6.0	+5.6	+5.5	+6.8
1000	1	+13.6	+14.0	+13.2	+13.9	+14.0	+13.7	+14.0	+13.3	+13.9	+13.7	+13.8	+12.8	+12.7	+11.9
	2	+6.1	+7.2	+6.1	+6.9	+7.4	+7.4	+6.9	+7.3	+8.0	+8.2	+8.3	+7.5	+7.8	+7.7
	4	+7.5	+7.6	+7.6	+5.9	+7.1	+7.9	+7.9	+8.5	+10.0	+8.7	+9.3	+8.3	+8.6	+9.1
1100	1	+3.2	-4.9	-13.6	-16.2	-21.8	-26.7	-32.7	-38.3						
	2	+0.5	-2.1	-4.9	-7.6	-11.7	-16.2	-21.0	-24.3						
	4	+3.5	+1.8	-6.2	-4.8	-5.4	-11.5	-14.6	-16.8						
Alnico 8															
900	1	+6.1	+7.1	+6.5	+7.6	+8.2	+8.3	+8.6	+9.0	+10.0	+9.8	+10.3	+10.1	+10.4	+10.8
	2	+5.1	+5.9	+5.2	+6.7	+7.5	+7.4	+7.8	+8.3	+9.7	+9.3	+10.2	+9.5	+9.9	+10.0
	4	+4.4	+4.6	+4.1	+4.2	+5.2	+6.7	+7.3	+7.6	+9.1	+9.1	+9.8	+9.0	+9.7	+10.9
1000	1	+14.6	+16.5	+16.9	+20.2	+21.9	+23.5	+24.8	+26.3	+28.2	+28.6	+29.4	+29.4	+29.7	+30.1
	2	+8.5	+10.9	+10.2	+12.8	+14.5	+15.1	+15.5	+16.7	+18.3	+18.2	+19.0	+18.3	+18.4	+18.7
	4	+7.7	+9.1	+8.2	+10.2	+11.8	+13.1	+13.5	+15.4	+16.5	+15.6	+16.0	+15.3	+15.5	+16.4
1100	1	+17.0	+16.8	+15.1	+14.3	+13.5	+11.7	+8.2	+4.2	+1.0	-2.5	-5.9	-9.6	-13.3	-14.2
	2	+11.7	+12.2	+7.9	+9.5	+8.7	+7.5	+4.5	+2.2	+0.4	-2.3	-5.7	-7.7	-8.1	-10.5
	4	+7.8	+7.2	+3.9	+4.7	+4.2	+2.7	+1.1	-1.4	-3.2	-6.7	-8.7	-11.3	-13.0	-13.6
1200	1	-7.0	-24.5	-33.6	-44.5	-53.3	-59.3	-64.7	-72.4						
	2	-10.8	-28.8	-33.0	-43.0	-48.3	-54.0	-59.8	-66.1						
	4	-6.4	-16.4	-25.4	-31.3	-36.3	-41.3	-46.2	-52.8

Fig. 3. Change in field strength of Alnico 5 magnets as a function of exposure at 700°F.

Fig. 4. Change in field strength of Alnico 5 magnets as a function of exposure at 800°F.

Fig. 5. Change in field strength of Alnico 5 and 8 magnets as a function of exposure at 900°F.

Fig. 6. Change in field strength of Alnico 5 and 8 magnets as a function of exposure at 1000°F.

Fig. 7. Change in field strength of Alnico 5 and 8 magnets as a function of exposure at 1100°F.

Fig. 8. Change in field strength of Alnico 8 magnets as a function of exposure at 1200°F.

At high temperatures, the initial increase is rapid as shown on Fig. 7 at 1100°F, where the maximum increase apparently occurred before the first reading at 0800 hr. At 900 F (see Fig. 5), the maximum increase had not yet occurred at the last reading, 12,000 hr, particularly for the Alnico 8 magnets.

From Fig. 3, it is obvious that the recovery and decay processes also are operative at the lowest test temperature, 700°F; however the respective rates of change are much lower than for higher temperatures.

The effect of L/D ratio is also apparent from the figures. In general, the short magnets (L/D = 1) incur higher rates of change for both the recovery and decay processes. This generalization works well for Alnico 8, which has a relatively smooth demagnetization curve. For Alnico 5 with a "square" curve, the performance depends on whether the magnets operate above or below the "knee"; magnets with L/D = 4 operate above the "knee", at least at room temperature.

From these results, the maximum long-term operating temperature would appear to be 1000°F for Alnico 5 and 1100°F for Alnico 8. This observation must be tempered by how much drift is allowable, and whether a time-dependent correction factor can be applied. Application of a correction factor is limited by the fact that the performance of individual samples may vary several percent from the average. For example, data taken at 700°F from five samples of Alnico 5 with L/D = 4 were analyzed for statistical spread. The one-sigma limits and maximum/minimum readings are plotted in Fig. 9. Figure 10 shows the results of similar analysis made for Alnico 8 (L/D = 2) samples exposed at 1000 F. In both instances, the maximum deviation of an individual sample from the mean was 4.5%. Therefore, these results would be of no value in predicting the time rate of change of an individual sample to better than about five percent.

Several plots were made in an effort to determine whether the performance of a magnet during stabilization might render a clue to its performance during long-term exposure at high temperature. Figure 11 is a typical plot of stabilization

Fig. 9. Variation in performance of five Alnico 5 magnets (L/D = 4) at 700°F.

Fig. 10. Variation in performance of five Alnico 8 magnets ($L/D = 2$) at 1000°F .

Magnet Alloy: Alnico 5
 Stabilization Temp.: 1200°F
 Test Temperature: 1000°F

Data	L/D Ratio
○	1
□	2
△	4

Fig. 11. Typical correlation between long term stability and stabilization losses.

changes versus changes incurred after exposure for 12,000 hr; there is no apparent correlation.

C. Performance of Reference Magnets

As stated in the experiment description, reference magnets were used to monitor the stability of instrumentation used to measure the changes in field strength of magnets under test. The reference magnets were measured at the same time as the test magnets. The averaged data in Table IV shows that a gradual increase of $\sim 1.6\%$ occurred in the readings. Also, the data spread at 12,000 hr shows a slight scattering compared to the 800-hour spread.

The disparity between drifts exhibited by the Alnico 5 and 8 magnets indicates that the total drift cannot be attributed solely to instrument drift. However, the total drift in reference magnet readings is insufficient to significantly alter the general trends observed in the test magnets. A slight improvement in validity could be achieved by subtracting 1.6% from the average test values at 12,000 hr, and proportionately less for shorter periods.

D. Effects of Pre-test Stabilization Method

As stated in the Introduction, the pre-test stabilization method used on the Alnico 5 and 8 magnets was known to provide good short-term stability against magnetic field changes during repeated short-term temperature cycling. However, the recovery process as displayed on some of the curves in this report was not recognized at that time. The extent of recovery is obviously a function of the amount of decrease caused by the stabilization process. Therefore, the best stabilization process will be one that will balance the recovery against the decay for the required length of time.

The stabilization methods used in this program were fortuitously ideal for several specific exposure temperatures and L/D ratios. For example, Alnico 5 (L/D = 1 or 2) changed less than two percent in 12,000 hr at 900°F if the

Table IV. Summary of Average Changes in Reference Magnets

<u>Date</u>	<u>Time, hr.</u>	<u>Alnico 5</u>	<u>Alnico 8</u>
7-31-70	0	0%	0%
10-26-70	800	+ .16	- .13
12-18-70	1900	- .63	- .46
1-28-71	2600	- .45	-1.41
3-3-71	3200	- .67	+ .54
7-19-71	6000	+ .78	+ .35
12-8-71	8000	+1.2	+ .87
1-21-72	9000	+1.43	+1.16
3-6-72	10000	+1.46	+1.32
4-19-72	11000	+1.52	+1.23
6-16-72	12000	+1.95	+1.32

	<u>Data Spread, %</u>			
	<u>800 hr</u>		<u>12000 hr</u>	
	<u>Alnico 5</u>	<u>Alnico 8</u>	<u>Alnico 5</u>	<u>Alnico 8</u>
Maximum	+1.4	+0.9	+4.0	+2.7
Minimum	-0.6	-2.0	+0.6	-0.7
Std. Deviation	0.60	0.71	1.01	0.94

initial change before 1000 hr is subtracted. The same holds for Alnico 5 ($L/D = 1, 2$ or 4) at 1000°F . In these cases, the initial 1000-hr exposure could be made a part of the stabilization procedure.

To achieve maximum stability a stabilization process must be keyed to a particular exposure temperature and not to a particular maximum. For example, all Alnico 5 samples exposed at 700, 800, and 900 F were stabilized as a group, by the same method. However, there was a marked difference in their performance under test. In magnets with $L/D = 1$ and 2 tested at 700°F , the decay process predominated and all changes were negative, whereas at 800 and 900°F , the recovery process predominated and the changes were positive.

All Alnico 8 samples were stabilized at the same temperature, 1300°F . This procedure was overly severe for operation at 900 or 1000°F , as indicated by the high recovery changes, as much as 29% for $L/D = 1$ at 1000°F . At 1100°F , the stabilization was near optimum since the changes started at +15% and ended at -15%.

In most of the foregoing analysis there has been the implied assumption that magnetic measurements made on samples at room temperature reflect changes that occurred at the exposure temperature. This problem was recognized at the start of the experiment. Since then, another experiment was undertaken with Alnico 8 magnets designed specifically for a probe-type sodium flowmeter.³ In this experiment, magnetic field readings were taken at the test temperature with a search coil inside the furnace. However, the results are not directly comparable because of differences in stabilization procedure. For example, Alnico 8 magnets ($L/D \approx 1$) exposed to 1200°F decreased an average of 52% in 1200 hr. These samples were pre-test stabilized at 1225°F ; thus there was no recovery phenomenon at the start of exposure. For comparable samples in this experiment (see Fig. 8), the rate of change was 27%/1200 hr.

V. CONCLUSIONS

The objective of this experiment was to determine the long-term stability of Alnico 5 and 8 magnets at temperatures of interest to applications in permanent-magnet sodium flowmeters. The results have posed questions and have rendered some conclusions as follows:

(1) After a stabilization process at a high temperature that severely reduces the field strength of an Alnico magnet, operation at a lower temperature will result in partial recovery of the lost field strength. This recovery process proceeds slowly or not at all at 700°F; at 800°F and above, it proceeds at increasing rates.

(2) The field strength of Alnico magnets is also reduced by a decay process. This process is slow at 700°F, increases with temperature, and combines with the recovery process to cause the total changes in field strength with time.

(3) The maximum exposure temperature for Alnico 5 or 8 magnets depends on the total change acceptable. If a variation of $\pm 10\%$ is acceptable, Alnico 5 is suitable for use up to 1000°F for 12,000 hr. If a variation of $\pm 15\%$ is acceptable, Alnico 8 is usable up to 1100 F.

(4) The curves of averages may be used to predict the performance of an individual sample if $\pm 5\%$ is added for individual variation from averages.

(5) The stabilization method used in this experiment was probably not optimum especially for the Alnico 8 samples exposed at 1000°F and below. It is recommended that magnets be stabilized at not more than 100°F above their use temperature, followed by a 500- to 1000-hour soak at the operating temperature.

The questions posed by this experiment are:

(1) What would be the long-term drift of similar magnets if they were not cycled to room temperature for measurement?

(2) Are there other permanent-magnet alloys (e.g., the rare earths) that might remain stable at 1200°F?

(3) What is the best stabilization procedure for a given magnet operating temperature?

(4) Is there any method of predicting the long-term drift of an individual magnet?

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