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**EFFECTS OF HIGH TEMPERATURE ON THE PERFORMANCE OF
ALNICO V AND ALNICO VI PERMANENT MAGNETS**

Submitted to Aircraft Nuclear Propulsion Department by

**W. H. Roberts
D. L. Mitchell**

Instrumentation Department
Measurements and Industrial Products Division

REPRODUCIBLE COPY

GENERAL ELECTRIC

AIRCRAFT NUCLEAR PROPULSION DEPARTMENT
ATOMIC PRODUCTS DIVISION

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GENERAL ELECTRIC

**AIRCRAFT NUCLEAR PROPULSION DEPARTMENT
ATOMIC PRODUCTS DIVISION**

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ABSTRACT

The effect of temperatures up to 600°C and the combined effect of temperature and vibration on the magnetic performance of Alnico V and Alnico VI magnet was investigated.

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INTRODUCTION

The objective of this investigation was to determine the design parameters and limitations of permanent magnets for applications involving high and low temperatures and vibration. A knowledge of the performance of permanent magnets under these new conditions is essential for the effective design of future aircraft instruments. This is necessitated by the high skin temperatures and other operating conditions existing in present and proposed military aircraft.

The temperature range studied in this investigation included -70°C to 600°C with the emphasis placed on long time operation at 500°C . Vibration frequencies ranged from 5 cycles per second to 2000 cycles per second combined with an amplitude great enough to produce an acceleration of at least 20G.

Before any experimental work was done, a search of the literature, principally "Ferromagnetism" by R. M. Bozorth and the Instrument Department files, was made to eliminate materials which would obviously be unsuitable for operation at 500°C . This search eliminated all of the available permanent magnet materials except Alnico V, Alnico VI, and Alnico VII.

Most of the materials could not be used at 500°C because the curie or magnetic transformation temperature was either near or below 500°C . A few materials were also eliminated because of low magnetic energy which limited their application. The curie temperature of Alnico V, Alnico VI, and Alnico VII is about 875°C . The magnetic energy of these alloys is 4.5×10^6 , 3.5×10^6 and 2.5×10^6 gauss-oersteds respectively. The major effort in this investigation was concentrated on Alnico V and Alnico VI because of their higher magnetic energy.

An analysis was made of the possible mechanisms by which high or low temperatures or a combination of these conditions with vibration could change the useful flux of a magnet during operation.

These mechanisms can be divided into two general classifications: Changes in magnetization and changes in the fundamental magnetic properties of the material. Changes in magnetization can be defined as a change in the useful flux which is not associated with a change in the metallurgical structure of the material. Changes in magnetization can be recovered by remagnetizing and/or changing the operating conditions. Changes in magnetic properties are caused by a change in the metallurgical structure of the material. This

results in a permanent change in the hysteresis loop of the material. It is necessary to reheat-treat the material to restore the original magnetic properties after a change of this nature.

As a result of this analysis, it was decided that the following mechanisms would be the most probable causes of any change in useful flux:

- 1) a permanent change in the magnetization of the magnet due to cycling through two extremes of temperature. (Temperature cycling experiment)
- 2) a temporary change in the magnetization of the magnet due to changes in temperature. (Temperature coefficient experiment)
- 3) a permanent change in the magnetic properties of the material due to changes in the structure of the material caused by holding at high temperature for a long period of time. (Heat aging experiment)
- 4) a combination of changes in magnetization and magnetic properties due to continuous exposure to high temperature. (Heat exposure experiment)
- 5) changes in magnetization caused by exposure to a combination of either high or low temperature and vibration. (Combined heat and vibration experiment)

Based on the mechanisms listed above, a series of five experiments was designed to determine the effect of each on the useful flux of Alnico V and Alnico VI magnets. Because magnet design was known to have a pronounced effect on the magnetization of a magnet, three designs of each material were tested. One design was the equivalent of a very long magnet (0.100 in. gap), the second was the equivalent of a medium length magnet (0.300 in. gap), and the third was a very short magnet (cylindrical). These magnets and their operating lines are shown in Figure 1 and Figure 2. Where possible, the effect of varying heat treatment and practical demagnetization by exposure to an a-c field were also studied.

The following section of this report is a discussion of the results of each experiment along with the specific conclusions which can be drawn from the results of that experiment. This is followed by general conclusions and recommendations for the preparation of magnets for operation up to 500°C. The last section of the report is a detailed description of the preparation of the samples, design and construction of the test equipment and test procedures.

MAGNET DESIGNS

1.000"
 $\pm .001$

1.200"
 $\pm .001$

CYLINDER

0.300"
 $\pm .001$

0.500"
 $\pm .001$

1.5"

0.300 INCH GAP

0.100"
 $\pm .001$

0.500"
 $\pm .001$

2.0"

0.100 INCH GAP

Figure 1

Figure 2

SECOND QUADRANT DEMAGNETIZATION CURVE
FOR ALNICO V SHOWING
OPERATING LINES FOR THE
THREE MAGNET DESIGNS

TEMPERATURE CYCLING

If a magnet is saturated at room temperature and the temperature is either raised or lowered when the magnet is brought back to room temperature, it will have lost part of its useful flux. This change in useful flux is caused by a permanent change in the magnetization of the magnet and cannot be recovered without remagnetizing.

The magnitude of this loss is determined by the change in temperature and the number of such temperature cycles the magnet has experienced after saturation. If the highest temperature does not exceed a critical limit, the magnet will become stabilized after a number of cycles between two temperature extremes. When a magnet has been stabilized in this manner, there will be no further change in useful flux due to cycling in that temperature range. For this purpose of this experiment, stability is defined as a change in useful flux of less than 1% between two successive temperature cycles.

The purpose of this series of tests was to establish the number of cycles required to stabilize the various test magnets. The percent loss in useful flux due to stabilization was also determined. The temperature extremes investigated included the following: -70°C to 20°C , -70°C to 100°C , -70°C to 200°C , -70°C to 300°C , -70°C to 400°C , -70°C to 500°C and 25°C to 600°C .

Three magnets of each design of Alnico V and Alnico VI were tested. One magnet was saturated, one magnet was partially demagnetized by exposing it to an ac field of 100 oersteds (KD-100H) and one magnet was partially demagnetized by exposing it to an ac field of 250 oersteds (KD-250H).

The results of the temperature cycling test are given in Figures 3 - 7. Figures 3 and 4 show the number of cycles required to achieve stability, and Figures 5 and 6 show the percent of useful flux lost due to stabilization. Figure 7 shows the effect of temperature cycling in the range 25°C to 600°C .

CONCLUSIONS

Both the number of cycles to stabilize and the loss of useful flux due to stabilization can be minimized by the following:

- 1) Using long magnets with short air gaps.
- 2) Increasing the prior ac demagnetization.
- 3) Reducing the maximum temperature.

The effect of temperature cycling was slightly less on Alnico VI magnets than on Alnico V magnets. However, the difference is so small that it would probably not be significant in design.

Stability was achieved in all cases by five cycles or less up to a temperature range of -70°C to 500°C .

Cycling stability was not achieved after eight cycles in the range 25°C to 600°C . In fact, these tests showed a definite departure from the pattern established up to 500°C . This is to be expected since metallurgical changes in the structure of the alloy are known to take place quite rapidly at 600°C . The effects of cycling from 500°C down are principally changes in the magnetization of the magnet.

TEMPERATURE

Temperature Range

CYCLING ON

ALNICO V

MAGNETS

-70°C to
25°C

-70°C to
100°C

-70°C to
200°C

-70°C to
300°C

-70°C to
400°C

-70°C to
500°C

CYLINDER

SATURATED

K.D. 100 H.

K.D. 250 H.

0.300 INCH

GAP

SATURATED

K.D. 100 H.

K.D. 250 H.

0.100 INCH

GAP

SATURATED

K.D. 100 H.

K.D. 250 H.

1 3 5

1 3 5

1 3 5

1 3 5

1 3 5

1 3 5

NUMBER OF CYCLES TO STABILIZE

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7-5-56

Figure 3

TEMPERATURE

TEMPERATURE RANGE

CYCLING ON

 -70°C to
 25°C -70°C to
 100°C -70°C to
 200°C -70°C to
 300°C -70°C to
 400°C -70°C to
 500°C

ALNICO VI

MAGNETS

CYLINDER { SATURATED

K.D. 100 H.

K.D. 250 H.

SATURATED

0.300 INCH { K.D. 100 H.

GAP

K.D. 250 H.

SATURATED

0.100 INCH { K.D. 100 H.

GAP

K.D. 250 H.

1 3 5

1 3 5

1 3 5

1 3 5

1 3 5

1 3 5

NUMBER OF CYCLES TO STABILIZE

D.L. MITCHELL

7-5-56 6

Figure 4

TEMPERATURE

TEMPERATURE RANGE

CYCLING ON

ALNICO V

MAGNETS

-70°C to
25°C

-70°C to
100°C

-70°C to
200°C

-70°C to
300°C

-70°C to
400°C

-70°C to
500°C

CYLINDER { SATURATED

K.D. 100 H.

K.D. 250 H.

0.300 INCH
GAP

SATURATED

K.D. 100 H.

K.D. 250 H.

0.100 INCH
GAP

SATURATED

K.D. 100 H.

K.D. 250 H.

0 2 4 6 8 0 2 4 6 8 0 2 4 6 8 0 2 4 6 8 10 0 2 4 6 8 10 0 2 4 6 8 10 12

% CHANGE BEFORE STABILIZATION

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7-5-56

Figure 5

6

TEMPERATURE

TEMPERATURE RANGE

CYCLING ON

ALNICO VI

MAGNETS

-70°C to
25°C

-70°C to
100°C

-70°C to
200°C

-70°C to
300°C

-70°C to
400°C

-70°C to
500°C

CYLINDER { SATURATED
K.D. 100 H.
K.D. 250 H.

0.300 INCH GAP { SATURATED
K.D. 100 H.
K.D. 250 H.

0.100 INCH GAP { SATURATED
K.D. 100 H.
K.D. 250 H.

0 2 4 6 8 0 2 4 6 8 0 2 4 6 8 0 2 4 6 8 0 2 4 6 8 10

% CHANGE BEFORE STABILIZATION

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Figure 6

Figure 7

TYPICAL RESULTS OF TEMPERATURE CYCLING 25°C to 600°C

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TEMPERATURE COEFFICIENT

When the temperature of a magnet is changed, the amount of useful flux in the gap or surrounding the magnet is changed. In general, low temperatures result in increased flux and high temperatures result in decreased flux. If the magnet has been stabilized by temperature cycling through the temperature range involved, the change in useful flux caused by a given change in temperature is quite repeatable.

The change in useful flux of stabilized magnets due to changes in temperature is a temporary change in magnetization. This is a distinctly different phenomena than the permanent change in magnetization due to temperature cycling or stabilizing. In order to recover the flux lost due to temperature stabilization, it is necessary to remagnetize the magnet, whereas the flux lost by a stable magnet due to changes in temperature can be recovered by simply bringing the magnet back to room temperature.

Since the change in useful flux per unit change in temperature is not linear for a wide range of temperature, it can be expressed most clearly as a flux-temperature curve. The purpose of this series of test was to determine the flux temperature curves for Alnico V and Alnico VI magnets over the temperature range -70°C to 500°C .

In order to minimize the effect of any metallurgical aging which might take place during the temperature coefficient test, all of the magnets used for this series of test were preaged 100 hours at 500°C . The magnets were also given five temperature cycles from -70°C to 500°C before the temperature coefficient tests were made.

The temperature coefficient curves for Alnico V and Alnico VI test magnets are given in Figures 8 - 13. The numerical values for the temperature coefficients in % per $^{\circ}\text{C}$ are given in the following table.

		-70°C	25°C	25°C	25°C	25°C	25°C
		$\pm 25^{\circ}\text{C}$	100°C	200°C	300°C	400°C	500°C
Alnico V	cylinder	$\pm .0104$	$-.0078$	$-.0125$	$-.0156$	$-.0179$	$-.0208$
	0.300" gap	$\pm .0144$	$-.0090$	$-.0120$	$-.0147$	$-.0179$	$-.0206$
	0.100" gap	$\pm .0120$	$-.0082$	$-.0101$	$-.0128$	$-.0158$	$-.0184$
Alnico VI	cylinder	.0000	$-.0038$	$-.0052$	$-.0111$	$-.0153$	$-.0193$
	0.300" gap	$\pm .0092$	$-.0030$	$-.0078$	$-.0131$	$-.0181$	$-.0219$
	0.100" gap	$\pm .0095$	$-.0052$	$-.0078$	$-.0125$	$-.0168$	$-.0200$

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CONCLUSIONS

In addition to the results indicated above, the following conclusions can be drawn from this data:

- 1) The temperature coefficient of these magnets is less than half the value established for Alnico V and Alnico VI magnets heat treated in the normal manner and tested near room temperature.
- 2) The reason for the unusually low temperature coefficient of these magnets is probably the preaging treatment of 100 hours at 500°C which was given the magnets prior to testing.
- 3) From 25°C to 500°C the temperature coefficient increased as the temperature increased.
- 4) Magnet design had very little effect on the temperature coefficient.
- 5) The temperature coefficient of the Alnico VI magnets was lower than that of the Alnico V magnets.
- 6) The temperature coefficient curves for Alnico V are more nearly linear than the curves for Alnico VI.

Although it was not included as a part of this investigation, previous investigations and experience by Instrument Department personnel indicate that it would not be practical to magnetically compensate magnets over such a large range as -70°C to 500°C for two important reasons. The curie temperatures of the nickel-iron alloys generally used as thermo-magnetic shunts are well below 200°C. Even if the curie temperature were higher, these alloys are metallurgically unstable and their properties are affected drastically by the rate of cooling from about 600°C to 100°C.

If it is necessary to compensate for the changes in useful flux of a magnet over a temperature range as great as -70°C to 500°C some method other than magnetic shunting must be devised. One method which seems feasible is to overcompensate the electrical circuit by means of temperature sensitive shunts or resistors. Another method which might work in certain applications is the selection of a spring material with a matching temperature coefficient to work in conjunction with the magnet.

TEMP. in °C

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Figure 13

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HEAT AGING 500°C

Since proposed specifications call for the operation of permanent magnets at 500°C for as long as 1000 hours, it was necessary to determine what effect this would have on the useful flux of magnets. At this temperature, the useful flux of the magnet could be affected by changes in the metallurgical structure of the material and changes in the magnetization of the magnet. Changes in the useful flux of a magnet due to changes in magnetization are temporary and can be recovered by reducing the temperature and/or remagnetizing. Changes in useful flux caused by changes in the metallurgical structure of the material are relatively permanent and can only be recovered by reheat treating the magnet.

The purpose of this series of test was to determine the effect of changes in the metallurgical structure of the material due to aging at high temperatures on useful flux. It was decided that the best measure of this effect could be obtained by holding the magnets at high temperature for a period of time and then measuring the useful flux at room temperature. The effects of changes in magnetization and combined effects are dealt with in other sections of this report.

Alnico V and Alnico VI magnets of each design were aged for 1000 hours at 500°C. In order to determine the margin of safety at 500°C, a few magnets of each material and each design were aged 200 hours at 600°C. In addition, standard test bars of Alnico V, Alnico VI, and Alnico VII were aged at 500°C for 1000 hours and at 600°C for 500 hours to determine the effect on the fundamental magnetic properties.

The effect of aging Alnico V and Alnico VI magnets for 1000 hours at 500°C is shown in Figures 14 - 21.

CONCLUSIONS

From these results it can be concluded that:

- 1) the useful flux of the magnets at room temperature increased in every case except one.
- 2) most of the changes occurred during the first 200 hours of aging.
- 3) from 200 hours to 1000 hours the net change in useful flux at room temperature was less than $\pm 1\%$ in nearly every case.

- 4) the change was greatest on magnets designed to operate near the maximum energy point (0.300 gap).
- 5) partially demagnetizing the magnets prior to aging did not reduce the change in useful flux due to aging.
- 6) rate of cooling from directionalizing had little or no effect on the change in useful flux due to aging except in cylindrical Alnico V magnets.
- 7) the change in useful flux of Alnico V magnets reached a maximum between 200 hours and 1000 hours and then either leveled off or began to decline very slowly.
- 8) in all cases the useful flux of the Alnico VI magnets continued to increase up to 1000 hours.

TEST BARS

The effect on the important magnetic properties of aging Alnico V, Alnico VI, and Alnico VII test bars at 500°C for 1000 hours is shown in Figures 22 - 24.

CONCLUSIONS

From the results of these tests it can be concluded that:

- 1) in all cases the saturation induction (B_s), residual induction (B_r), and maximum energy (BH_{max}) showed a definite increase up to about 200 hours and then leveled off.
- 2) in all cases the coercive force (H_c) increased to a maximum and then began to decline between 800 and 1000 hours.
- 3) the decrease in coercive force was greatest for Alnico VII and least for Alnico VI.
- 4) the effect of aging on the fundamental magnetic properties of the test bars confirms the observed effect on the useful flux of the test magnets.

Both the increase in useful flux of the magnets and the increase in magnetic properties of the test bars due to aging at 500°C indicate that the standard precipitation heat treatment given these materials is not optimum for magnetic properties. The standard treatment which consists of four

hours at 600°C is used by the Instrument Department and most other manufacturers of Alnico V and Alnico VI. This treatment is probably the best compromise between the magnetic properties and the cost of high production magnets. However, the cost of low production magnets for special applications would not be such an important consideration.

The results of this investigation indicate that the best magnetic properties are developed by aging four hours at 600°C followed by an additional 200 hours at 500°C. It is quite possible that the same results could be obtained by a second treatment consisting of a shorter time at some temperature between 500°C and 600°C. Such a treatment would reduce both the cost and the elapsed time in preparing the magnets. This possibility should be investigated more thoroughly.

500°C AGING OF SATURATED ALNICO V MAGNETS -

FAST COOLED FROM DIRECTIONALIZING

500°C AGING OF ALNICO V MAGNETS K.D. 100 H. -

FAST COOLED FROM DIRECTIONALIZING

500°C AGING ON ALNICO V MAGNETS K.D. 100 H. -

SLOW COOLED FROM DIRECTIONALIZING

Figure 17

500°C AGING OF ALNICO VI SATURATED MAGNETS -

FAST COOLED FROM DIRECTIONALIZING

Figure 19

500 °C AGING OF SATURATED ALNICO VI MAGNETS - SLOW COOLED FROM DIRECTIONALIZING

500°C AGING ON ALNICO VI MAGNETS K.D. 100 H.

500°C AGING ON ALNICO VI MAGNETS K.D. 100 H. -

Figure 22

Figure 23

Figure 24A

HEAT AGING 600°C

It was originally planned to run the 600°C heat aging experiment for 500 hours. However, this series of test was discontinued at the end of 200 hours because it was obvious that all of the magnets had become unstable.

Unfortunately all of the magnets in this experiment were not aged at exactly the same temperature because of a temperature gradient in the furnace. The actual temperature at which each magnet was aged is indicated on the performance curves. This reduces the precision of the experiment slightly, but it also makes available useful data which otherwise would not have been obtained. The two c-shaped designs were divided equally between a zone above 600°C and a zone below 600°C. All of the cylindrical magnets were located in a zone that was exactly 600°C.

The effect on the useful flux at room temperature of aging the test magnets at about 600°C is shown in Figures 24 - 31.

CONCLUSIONS

The useful flux of all of the magnets aged at about 600°C changed drastically in the first 200 hours of aging. For the purposes of this experiment, stability is defined as a change in useful flux of less than 5% in 500 hours. The useful flux of some of the magnets aged at about 600°C decreased as much as 45% in the first 200 hours of aging. In addition, there seemed to be no tendency to level off as indicated in the 500°C aging test.

TEST BARS

The effect on the important magnetic properties of Alnico V, Alnico VI, and Alnico VII test bars aged 500 hours at 600°C is shown in Figures 32 - 34.

CONCLUSIONS

Although the effect on test bars is not as pronounced as the effect on magnets, the changes in the magnetic properties of the test bars clearly indicate that Alnico V and Alnico VI are not stable at 600°C. The effect of aging at 600°C is somewhat less pronounced on the magnetic properties of Alnico VII test bars. The lack of stability and erratic behavior of magnetic properties of the Alnico V and Alnico VI test bars aged at 600°C undoubtedly explain the marked instability of the magnets.

Figure 24 B

600°C HEAT AGING ON SATURATED
ALNICO V MAGNETS - FAST
COOLED FROM DIRECTIONALIZING

Figure 25

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600°C AGING ON ALNICO V MAGNETS K.D. 100 H. -

FAST COOLED FROM DIRECTIONALIZING

600°C AGING ON ALNICO V MAGNETS K.D. 100 H. -

SLOW COOLED FROM DIRECTIONALIZING

Figure 2

600°C AGING ON SATURATED ALNICO VI MAGNETS -

FAST COOLED FROM DIRECTIONALIZING

600°C AGING ON SATURATED ALNICO VI MAGNETS -

600°C AGING ON ALNICO VI MAGNETS K.D. 100 H -

Figure 30

FAST COOLED FROM DIRECTIONALIZING

600°C AGING ON ALNICO VI MAGNETS K.D. 100 H. -

SLOW COOLED FROM DIRECTIONALIZING

Figure 31

+10.0

0.0

-10.0

-20.0

-30.0

% CHANGE FROM
0-HOUR VALUE
AT RT (25°C)

MAGNET DESIGNS {
□ = CYLINDER
○ = 0.300 INCH GAP
△ = 0.100 INCH GAP

~ 550°C

~ 600°C

~ 650°C

0

40

80

120

160

200

HOURS AT 600°C

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Figure 32

200°C AGING

Alnico 6
Bar 15

DS Jones
JUNE 1956

Figure 33

600° C AGEING

Alnico 5
Bar 5

OS Jones
June 1956

Figure 34

HEAT EXPOSURE 500°C

Heat exposure is distinguished from heat aging in that the test magnets were held at 500°C continuously and the useful magnetic flux was measured at 500°C. The heat aging test discussed in a previous section deals with changes in useful flux due to relatively permanent metallurgical changes in the structure of the alloy. In addition to this effect it was anticipated that continuous exposure to high temperature might produce an effect due to changes in the magnetization of the test magnets.

The purpose of the heat exposure test was to measure the combined effects of metallurgical changes in the structure and changes in magnetization on the useful flux of the test magnets at high temperatures. Since it was desirable to use permanent magnets in measurement applications for as long as 1000 hours at 500°C it was decided that the initial test would be run under these conditions. If the test magnets proved unstable at 500°C, the temperature would be lowered until the highest stable operating temperature was established. The time would then be extended to 1000 hours at that temperature. For purposes of this test magnetic stability is defined as a change in useful flux of not more than 5% in 500 hours.

Although test procedures and equipment will not be discussed in this section of the report, some of the experience accumulated in building the equipment for the heat exposure test may be of value to designers of high temperature instruments. The test fixture used to measure the useful flux of the magnets at 500°C was in essence a fairly sensitive electric instrument which operated continuously at 500°C for 1000 hours. Those who are interested in this phase of the experiment should refer to that part of the section on Experimental Procedure and test equipment which deals with the heat exposure test.

The effect of 500°C heat exposure on the useful flux of the test magnets is shown in Figures 35 - 44. The results of the heat exposure test indicate the following:

- 1) the useful flux of the cylindrical magnets which operated near the coercive force of the material decreased in all cases.
- 2) the useful flux of the c-shaped magnets which operated near the maximum energy point or residual induction of the material increased in all cases.
- 3) most of the change in useful flux occurred during the first 200 hours of heat exposure.

4) between 200 and 1000 hours stability within - 2% can be realized for all designs at 500°C.

5) prior ac demagnetization had little or no effect on magnetic stability at 500°C.

The principle difference between the results of the 500°C heat aging test and the 500°C heat exposure test was the effect on the cylindrical magnets. The useful flux of the cylindrical magnets subjected to heat aging at 500°C increased in all cases except one where as the useful flux of the cylindrical magnets subjected to 500°C heat exposure decreased in all cases. This would suggest that there is some loss of coercive force at 500°C since the cylindrical magnets operate very near the coercive force of the material.

The effect of 500°C heat aging and 500°C heat exposure was approximately the same for the c-shaped magnets. The useful flux of the c-shaped magnets subjected to both tests increased about 4%, above the useful flux at the beginning of the test. It should be pointed out, however, that the 4% increase in useful flux of the c-shaped magnets subjected to the heat exposure test does not represent a net gain over the useful flux of this magnet at room temperature. The temperature coefficient would reduce the useful flux of these magnets about 10% when the temperature of the magnets was increased to 500°C. This means that the magnets would lose 10% due to the increase in temperature and regain about 4% due to aging for a net loss of about 6% of the useful flux.

Figure 35

HEAT EXPOSURE ON SATURATED ALNICO V CYLINDRICAL MAGNET

HEAT EXPOSURE ON SATURATED ALNICO V

HEAT EXPOSURE ON ALNICO V MAGNETS K.D. 250 H.

HEAT EXPOSURE ON ALNICO V MAGNETS K.D. 250 H.

HEAT EXPOSURE ON SATURATED ALNICO VI CYLINDRICAL MAGNET

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COMBINED HEAT & VIBRATION

Vibration and shock are known to have a detrimental effect on the magnetization of the very low coercive permanent magnet materials such as chrome steel. Several investigators have reported that these conditions have little or no effect on the magnetization of the higher coercive materials such as the Alnico's at or near room temperature. However, there was no information available on the effect of vibration at temperatures appreciably above or below room temperature.

The mechanism of magnetic hardening or development of coercive force is not the same for chrome steel and the Alnico's. Because of this there is no reason to expect them to act the same under conditions of vibration. However, the coercive force of Alnico V decreases slightly as the temperature is reduced and very rapidly at some high temperature near the curie point. The addition of vibrational energy to the effect of thermal energy might have been sufficient to change the magnetization of the magnet there by reducing the useful flux. For this reason it was necessary to determine the effect of combined high or low temperatures and vibration on the useful flux of Alnico V and Alnico VI magnets.

Combined heat and vibration tests were made at -70°C , 25°C , and 250°C . The frequency was varied from 5 cps to 2000 cps, but most of the exposure was to the five or six most resonant or damaging frequencies. The amplitude of the vibration depended on the frequency, but was sufficient to produce an acceleration of at least 20 Gs in all cases and as high as 30 Gs in some cases. The vibration time at each temperature is shown below.

The results of the combined heat and vibration test are given in the following table.

Temperature		-70°C	25°C	250°C
Time		33 hr.	37 hr.	38 hr.
Alnico V	Cylinder	-0.25%	-0.25%	-0.75%
	0.300 gap	-0.25%	0.00%	- - -
	0.100 gap	+0.50%	-0.50%	-0.50%
Alnico VI	Cylinder	+0.50%	-0.75%	0.00%
	0.300 gap	+0.75%	-0.25%	-0.25%
	0.100 gap	+0.75%	-0.25%	-0.75%

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CONCLUSIONS

Since none of the above changes are large enough to be significant because of experimental error, the effect of combined heat and vibration appears to be insignificant over the temperature range explored.

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GENERAL CONCLUSIONS

The results of this investigation show that it is definitely practical to use Alnico V and Alnico VI magnets at temperatures up to 500°C for long periods of time. Earlier Instrument Department investigations have shown that these alloys can be used at temperatures as low as -196°C. Vibration at temperatures either above or below room temperature does not effect the useful flux of magnets made from these alloys.

The performance of Alnico V and Alnico VI magnets at temperatures up to 500°C is so nearly the same that one alloy cannot be preferred over the other for that reason. The selection of the alloy should be based on magnet design and other operating conditions.

The use of standard Alnico V or Alnico VI at temperatures above 500°C for more than a few hours does not appear practical. The deterioration of the magnetic properties of these alloys above 550°C is caused by over aging or excessive growth of the precipitate. If it is necessary to operate magnets between 500°C and 600°C the effective life might be extended some by using the silicon-zirconium or columbium modifications of Alnico V. The addition elements in these alloys tend to reduce the rate of precipitation or aging. This could be confirmed by a simple aging experiment.

The effect of magnet design on performance at temperatures up to 500°C is secondary for magnets operating at or above the maximum energy point. Both temperature cycling and temperature exposure have a detrimental effect on the useful flux of very short magnets with long air gaps. However, this type of design does not efficiently utilize the magnetic properties of Alnico V and Alnico VI and therefore is seldom used.

Partial demagnetization in an ac field reduces the number of temperature cycles required to achieve stability and the useful flux lost in stabilization. Unless it is necessary to partially demagnetize for calibration or to protect against extraneous fields, there is little point in doing so. The loss of useful flux due to demagnetization will probably be greater than the loss due to temperature cycling.

The precipitation or aging heat treatment has a significant effect on the magnetic properties. Aging magnets 200 hours at 500°C after the standard treatment increases the useful flux at least four percent. In addition, this treatment probably reduces the temperature coefficient to less than half the normal value. Within the limits of this investigation, rate of cooling from

the directionalizing temperature did not have a significant effect on the performance of magnets at high temperatures. The use of Alnico V magnets in applications such as tachometer generators, torque motors and permanent magnet motors should present no particular problem. In this type of application, the accuracy of the device is not a direct function of the flux output of the magnet. However, it is generally necessary to maintain some minimum level of flux. This can be accomplished by over designing the magnet for room temperature operation.

The amount of over design required is determined by the temperature and the loss of useful flux due to temperature cycling and temperature coefficient associated with that temperature. For instance, in a tachometer generator with an Alnico VI rotor to be operated at 500°C, the loss in useful flux will be 2% due to temperature cycling and 9% due to temperature coefficient. Therefore, the generator should be designed so that the voltage output at room temperature is at least 11% greater than the minimum voltage required when the generator is operating at 500°C.

From the experience gained in this investigation, it would appear that at least two other major components will present much greater problems in the devices described above. The most important of these is an insulation system which will withstand both the temperature and the vibration associated with such devices. Another important problem will be bearings which will operate over a wide temperature range without galling or seizing.

In certain applications the accuracy of the device is a direct function of the flux output of the magnet. The design and preparation of permanent magnets for use in this type of device will present a greater problem than it does in devices where magnet output does not effect accuracy. Examples of this type of device are D.C. ammeters and volt.meters, the magnetic standard, and the second harmonic selsyn.. >

If it is necessary to use permanent magnets that have a direct effect on the accuracy of a device in the temperature range 200°C to 500°C, the magnets should be made from Alnico V, Alnico VI, or Alnico VII. In addition, the magnet should be designed to operate as high on the demagnetization curve as is practical. This can be accomplished by using long magnets with very small air gaps, less than .100 inches for most small magnets.

The following procedure should be used to prepare magnets for applications up to 500°C in this type of device:

- 1) Cast, heat treat, grind and/or otherwise fabricate the magnet to the finished shape.
- 2) Preage the magnets for 200 hours at 500°C even if the maximum operating temperature is below 500°C.
- 3) Saturate the magnets.
- 4) Expose the magnets to an ac field 50 to 100 oersteds higher than the maximum extraneous ac or dc field they are likely to be exposed to in the device.
- 5a) Calibrate the magnets to the strength required for the device by exposing them to an ac or reverse dc field.
- 5b) If the magnet design and operating temperature are such that some loss of strength should be expected due to temperature cycling, the magnets should be calibrated one or two percent stronger than required by the device.
- 6) Temperature cycle the magnets through the maximum and minimum temperature expected in service for at least five cycles.
- 7) Determine the exact temperature coefficient for the magnet and other components which work in conjunction with the magnet.
- 8) Compensate for the temperature coefficient of the system by the use of temperature sensitive resistors or some other electrical method.

If the above procedure is carefully followed, it should be possible to limit the magnet error in this type of device to about 1% for operation at 500°C for 1000 hours. The error contributed by the magnet will be reduced if the operating temperature is lowered or the time of operation shortened. However, the results of this investigation indicate that an error much less than 1% cannot be realized at 500°C for a period of 1000 hours if the accuracy of the device is a direct function of the flux output of the magnet.

It does not seem feasible to use permanent magnets in devices where the magnet error is seen as a squared error in the device at temperatures more than a few degrees above 100°C. An example of such a device is a tachometer indicator. Fortunately, such devices are usually panel mounted and therefore would not be required to operate at very high temperatures.

The general conclusions which can be drawn from the results of this investigation are quite favorable. The use of Alnico V and Alnico VI permanent magnets in most aircraft applications under conditions of vibration and temperatures up to 500°C appears to be quite feasible. Because of the temperature coefficient and variation in the temperature coefficient, it will probably be necessary to use a design not involving permanent magnets for a very few devices if the ambient temperature exceeds 100°C by more than a few degrees.

EXPERIMENTAL PROCEDURE AND TEST EQUIPMENT

In this section of the report, the test equipment and experimental procedure used for the various tests will be discussed. The various tests will be described individually except where there is a duplication of equipment or procedure used in a previous test. Each experiment will be described in sufficient detail to permit duplication of the experiment.

MATERIALS

The materials tested were selected because of a combination of high magnetic energy and high curie temperature. The curie temperature was an important consideration because that is the temperature at which a magnetic material is transformed to a non magnetic material by thermal energy. The emphasis was placed on Alnico V and Alnico VI because they have a desirable combination of the important properties described above, and they are readily available. Alnico VII was also studied under certain conditions. The table below shows the nominal composition of these alloys.

	<u>Alnico V</u>	<u>Alnico VI</u>	<u>Alnico VII</u>
Aluminum	8.25%	8.25%	8.50%
Nickel	14.00	15.00	18.00
Cobalt	24.00	24.00	24.00
Copper	3.20	3.00	3.25
Titanium	-	1.25	5.00
Iron	Bal.	Bal.	Bal.

The curie temperatures of these alloys are approximately the same; about 875°C. The significant Magnetic properties are listed in the following table:

	<u>Alnico V</u>	<u>Alnico VI</u>	<u>Alnico VII</u>
Residual Induction (BR)			
gauss	12 000	11 000	6 500
Coercive Force (Hc)			
oersteds	650	750	1 000
Energy Product (B Hmax)			
gauss-oersteds x 10 ⁰	4.5	3.5	2.5

MAGNET DESIGN

Because magnet design was known to effect both resistance to demagnetization and magnetic temperature coefficient, three different magnet designs of each material were tested. (See Figure 1). The principal difference between these designs is the ratio of the length of the magnetic flux path inside the magnetic material to the length of the flux path in the air gap. Roughly speaking, the self-demagnetization of a magnet increases as the air gap increases and decreases as the magnet length increases. This is generally expressed as the slope of an operating or load line. (See Figure 2). By design these magnets were selected to operate near the following points on the demagnetization curve:

- 1) Near the residual induction, B_r , (0.100 in. gap).
- 2) Near the maximum energy point, BH_{max} , (0.300 in. gap).
- 3) Near the coercive force, H_c , (cylindrical).

HEAT TREATMENT

The magnets were cast in baked sand molds and broken out hot approximately 60 seconds after casting. After casting the magnets were heated to about 950°C ; a temperature slightly above the curie temperature, and cooled in a magnetic field of at least 1000 oersteds. This treatment produces a preferred direction of magnetization and results in a considerable increase in the magnetic properties parallel to that direction. Because the rate of cooling during the directionalizing treatment was known to effect the results of subsequent heat treatments, cooling rates both faster and slower than the standard rate for magnets of this size were also investigated. The following table shows the approximate time to cool from 950°C to 600°C .

<u>Cooling Rate</u>	<u>Time in Min.</u>
Fast	2.5
Standard	8.0
Slow	15.0

After directionalizing, all of the magnets were given the standard precipitation or aging heat treatment (four hours at 600°C) to fully develop the magnetic properties.

PREPARATION OF THE SAMPLES

The air gaps and the two large flat surfaces of the two C-shaped magnets were ground. The cylindrical magnets were ground on all external surfaces and were ground concentric about the center locating hole. After grinding all magnets were permanently marked with identification numbers using an electric engraving pencil.

In order to be sure that all magnetic tests would be comparable, a set of standard magnets was prepared for calibrating test coils. These standards consisted on one Alnico V magnet of each design which had been saturated and then calibrated by demagnetizing slightly in an a c field of 100 oersteds. To further stabilize these standards they were temperature cycled five times between -20°C and 75°C . After stabilizing the standards, magnets were placed in a box made of wood and brass to isolate them from extraneous demagnetizing forces.

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TEMPERATURE CYCLING

The purpose of this series of tests was to determine the number of cycles between a minimum temperature and a maximum temperature required to stabilize a magnet over that temperature range. This fixture was constructed of 12 in. dia. by 1/4 in. thick transite shelves separated by stainless steel posts. The total height of the fixture was about 15 in. The various test magnets were rigidly attached to the fixture by means of brass posts.

Temperatures above room temperature were obtained by dropping the fixture into a small Lindberg forced air furnace. Temperature regulation was accomplished by means of a thermocouple and a recorder-controller. Temperatures below room temperature were obtained by submerging the fixture in a container of dry ice and alcohol.

Six magnets of each design and each material (2 saturated, 2 KD-100 and 2 KD-250H)* placed on the fixture in such a way that the demagnetizing effect of one magnet on the magnets adjacent to it was minimized.

After preparation, the magnetic strength of each magnet was determined at room temperature. Temperature cycling consisted of cooling the fixture and magnets to -70°C , heating to the highest temperature for that cycle and then cooling to room temperature. All magnetic measurements in this series of test were made at room temperature. Temperature cycling was continued between each set of temperature extremes until there was an insignificant change in the useful flux of the magnets at room temperature between two consecutive cycles. This condition was defined as stability.

The temperature extremes investigated in this series of test are shown in the following table:

1. -70°C to 25°C
2. -70°C to 100°C
3. -70°C to 200°C
4. -70°C to 300°C
5. -70°C to 400°C
6. -70°C to 500°C
7. $+25^{\circ}\text{C}$ to 600°C

*KD-100H means the magnets were saturated and then exposed to an a c field of 100 oersteds.

The same set of magnets were used throughout the test, but the magnets were resaturated or resaturated and demagnetized by the appropriate a c. field before starting the next range of temperature cycles. The time required for the magnets and fixture to come to temperature was a function of the particular temperature cycle, however, all magnets were held at temperature for at least 15 minutes before testing.

The useful flux of the C-shaped magnets was determined by accurately locating a search coil of known $n a$, in the air gap of the magnets, removing the search coil, and reading the resultant deflection on a G. E. fluxmeter. The useful flux of the cylindrical magnets was determined by locating a search coil in the neutral or magnetically central section of the magnets, removing it, and reading the resultant deflection in the manner described above.

Only deflection or percent change in deflection were recorded in this investigation because change from the original value or stability were the prime consideration. However, flux density can be calculated from the formula, $\frac{\text{deflection in mm} \times K}{n a} = B$. In this formula K is a constant for the particular fluxmeter which was used and $n a$ is the number of amper turns per unit area expressed in square centimeters.

TEMPERATURE COEFFICIENT

The purpose of this series of test was to determine the percentage of the useful flux which was either lost or gained due to changes in the temperature of a stabilized magnet. The test equipment used for these tests was the same equipment used for the heat exposure test. This will be described in detail in a later section of the report. The same furnace used for the heat exposure test was used to obtain temperatures above room temperature and dry ice and alcohol were used to obtain temperatures below room temperature.

Three magnets of each design of Alnico V and Alnico VI were used to obtain the data in this experiment. These magnets were saturated and then preaged 100 hours at 500°C to minimize the effect of any aging that might occur during the temperature coefficient test. The magnets were then given five temperature cycles from -70°C to 500°C and mounted in the test equipment.

The temperature coefficient curves were obtained by starting at the lowest temperature and increasing the temperature in steps of about 100°C. After coming to temperature, the magnets were held at temperature for an additional 15 minutes before measuring the useful flux.

Measurements were made at -70°C, -40°C, 25°C, 100°C, 200°C, 300°C, 400°C, and 500°C. After completing the test, the room temperature (25°C) measurement was repeated to be sure there had been no permanent change in the useful flux of the magnets as a result of the test.

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HEAT AGING

The purpose of this series of tests was to determine the permanent change in the useful flux of the test magnets and magnetic properties of the materials caused by aging or metallurgical changes in the structure of the materials. The fixture used for the 500°C aging test was the same as the fixture used for the temperature coefficient test. The fixture used for the 600°C aging was of similar design but adapted to fit another furnace. The magnets aged at 500°C and all of the test bars were aged in a Linberg forced air furnace. The magnets aged at 600°C were aged in a muffle-type electric furnace.

Four magnets of each design and each material were used for the heat aging test. Two of these magnets were cooled rapidly from directionalizing temperature and two were cooled slowly from the directionalizing temperature. This was done because the rate of cooling from directionalizing was known to effect the results of the precipitation heat treatment and therefore might effect the results of additional aging at 500°C or 600°C.

One magnet of each design and each heat treatment was partially demagnetized by exposing it to an a c field of 100 oersteds. This was done because there was some indication that this might reduce the effect of aging at high temperature.

In addition to the magnets, two test bars of Alnico V, Alnico VI, and Alnico VII were aged at 500°C and 600°C. This test was performed to determine the effect of aging at 500°C and 600°C on the fundamental magnetic properties of the materials. The test bars were prepared by casting in a magnetic field to obtain a more uniform heat treatment and make them more comparable to standard test bars. After cooling to room temperature, they were given the standard aging or precipitation heat treatment, 4 hours at 600°C.

Since the time at temperature was so long in this series of tests, heating and cooling rates are insignificantly small. The magnets aged at 500°C were held at temperature for 1000 hours. Although it was originally planned to age magnets for 500 hours at 600°C, the test was discontinued after 200 hours because nearly all of the magnets had failed by that time. Test bars were aged 1000 hours at 500°C and 500 hours at 600°C.

The temperature in the furnace used to age the magnets at 500°C, and the test bars at both 500°C and 600°C was quite uniform throughout the furnace. Shortly after the magnets to be aged at 600°C were placed on test,

a temperature gradient of about 100°C was observed from the top to the bottom of the furnace. The control thermocouple was located near the center of the furnace so that this area was maintained at 600°C . The area near the top of the furnace was about 650°C and the area near the bottom of the furnace was about 550°C . All of the cylindrical magnets were located in the center of the furnace so they were aged at 600°C . The two c-shaped magnets were distributed between the top and bottom of the furnace so that some were aged at 550°C and some at 650°C . The actual aging temperature for each of the c-shaped magnets is indicated on the performance data.

All of the measurements in this series of tests were made at room temperature. The fixture and magnets or test bars being removed from the furnace and allowed to cool to room temperature before any measurements were made. The useful flux in the magnets and the magnetic properties of the test bars were measured at shorter intervals of time at the beginning of the test and longer intervals as the test progressed.

The useful magnetic flux of the magnets was measured in the same manner described in the temperature cycling test. The magnetic properties of the test bars were measured with a saturation permeater. Only the important points on the demagnetization curve were reported. These included saturation induction (B_s), residual induction (B_r), maximum energy ($B H \text{ max.}$), and coercive force (H_c).

HEAT EXPOSURE

The purpose of this series of tests was to determine the effect of changes in magnetization and metallurgical changes caused by continuous exposure to temperatures as high as 500°C. It is distinguished from the heat aging test in that the magnets subjected to this test were held at temperature throughout the test and the useful flux of the magnets was measured at temperature.

Prior to starting this investigation it was decided that the initial experiment would be made at 500°C and that the time of exposure would be 1000 hours. If the magnets proved to be unstable at 500°C, the temperature would be lowered in steps of 50°C until the maximum stable operating temperature was established. For purposes of this experiment magnetic stability is defined as a change in useful flux of less than 5% in 500 hours.

Building the test equipment for this experiment presented a particularly difficult task since the test equipment was in essence a fairly sensitive electric instrument to be operated at temperatures up to 500°C. This test equipment was also used for the temperature coefficient experiment and was intended for use in the confined temperature and vibration experiment.

This equipment consisted on a non-magnetic stainless steel box with the two c-shaped magnets attached to the bottom by means of stainless steel plates and the cylindrical magnet bolted to one end. The search coils used to measure the useful flux of the two c-shaped magnets were attached to a stainless steel tube. Magnetic measurements were made by rotating the search coils from an accurately located position in the gaps of the magnets to a position remote from the gaps and reading the resultant deflection on a fluxmeter. The search coil used to measure the useful flux of the cylindrical magnet was located in the center of a cup which fitted over the magnet. This cup was attached to a second stainless steel tube. Magnetic measurements were made by pulling the search coil from the neutral or magnetically central section of the magnet to a point remote from the magnet and reading the resultant deflection on a fluxmeter.

The search coils used to measure the useful flux of the c-shaped magnets were wound on stainless steel coil forms. The leads to the search coils were taken through the base of the coils forms into a sintered ceramic insulator. This insulator ran through the stainless steel tube to a point remote from the hot zone of the test equipment. At this point the leads were

attached to a terminal block which was rigidly attached to the tube. After pulling the leads from the search coils through the insulator, the coil form was bolted and then welded to the tube to insure dimensional stability.

The search coil used to measure the useful flux of the cylindrical magnet was wound on the outside of the cup. Leads from this search coil were brought back along the outside of the cup and into a ceramic insulator located inside the tube, to a terminal board rigidly attached to the other end of the tube. The other two holes in the ceramic insulator were used to bring back leads from a Chromel-Alumel thermocouple used to control the temperature in the hot zone of the test equipment. The cup was welded to the end of the stainless steel tube to insure dimensional stability.

Insulation of the wire used for the search coils and lead wires proved to be one of the most difficult problems in constructing the test equipment for the heat exposure test. Although the voltages involved were low, millivolts, turn to ground and turn to turn insulation was essential. In the first case, shorts made measurement impossible and in the second case shorts caused inaccuracies in the measurement.

Coils made from 0.009 in. dia. anodized aluminum wire were easy to construct and performed very well in service. In order to obtain better physical and electrical separation of the anodized aluminum wire a suspension of aluminum in amyle acetate was applied while the coils were being wound. The lower resistance of this wire made it possible to make the connection to the fluxmeter leads external to the hot zone of the test equipment. After winding, a mixture of high temperature metal oxides and solium silicate was used with much success to support and protect both the coil windings and the external terminals.

The stainless steel tube, which was pulled back and forth through a set of bearings gave much more bearing trouble than the tube which was rotated in a set of bearings. Bearing failures were generally due to galling and seizing in the bearing nearest to the hot zone of the test equipment. This problem was eventually solved by using graphite bushings for the bearing surface and increasing the clearance between the stainless steel tube and the graphite bushing to about 0.015 in. on the diameter.

Two special electric furnaces with rectangular muffels designed to fit over the test equipment were constructed for the heat exposure test. These furnaces maintained an essentially constant temperature of 500°C over the 6 1/2 in. length in which the magnets and test coils were located. These furnaces were reverse wound so that the magnetic fields resulting from the current flowing in the winding was canceled out. This was done to minimize a c demagnetizing due to the heating current.

One magnet of each design of Alnico V was saturated, placed in the test equipment, and the useful flux was measured at room temperature. The test equipment was then placed in the furnace, brought to 500°C, held at temperature for one hour, and the useful flux was measured at 500°C. The initial useful flux at 500°C was used as a reference and future changes were calculated as a percentage of that quantity. Measurements were made at increasingly larger intervals of time up to 1000 hours. The above procedure was repeated using one magnet of each design of Alnico VI.

An additional set of magnets of each design of Alnico V and Alnico VI were saturated and partially demagnetized by an a c field of 250 oersteds. These magnets were exposed to 500°C for 250 hours because the major effect of heat exposure on the saturated magnets had occurred during that period.

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COMBINED HEAT AND VIBRATION

The purpose of the combined heat and vibration was to determine whether exposure to vibration at temperatures either appreciably above or below room temperature would have a significant effect on the useful flux of the test magnets. Originally, it was planned to make the high temperature vibration test at 500°C using the test equipment designed for the heat exposure test. However, this proved to be impossible because of electrical failures in the search coils and lead wire.

The search coils and lead wire in the heat exposure test equipment were replaced several times, but none could withstand more than one or two hours of vibration at 500°C. The only fine wire available with a satisfactory insulation at 500°C was anodized aluminum. When the strength of the anodized aluminum wire at 500°C proved to be too low to withstand vibration, this approach was abandoned. However, no change in useful flux which could be attributed to vibration was observed in the relatively short period these tests were run at 500°C.

When it became apparent that the heat exposure test equipment could not be used for the high temperature vibration test, another test fixture was built. This fixture was constructed so that the search coils and leads could be removed during vibration and then inserted in the gaps of the magnets only during the measurement of useful flux when the vibration was shut off.

The vibration fixture consisted of a non magnetic insulated container with heating coils wound on the outside of the container. Six magnets, one of each design of Alnico V and Alnico VI were bolted to the bottom of the fixture. The fixture was attached rigidly to the table of the Caladyne unit.

A mixture of dry ice and alcohol was used to obtain a temperature of -70°C. A Lavite salt bath to obtain a temperature of 250°C. Operating the test equipment at temperatures above 250°C proved to be impractical because the thermal mass of the Caladyne table caused considerable variation in temperature. Measuring the useful flux of the magnets by this method at temperatures above 250°C also presented a considerable problem because the precision required precluded the use of asbestos gloves. Measurements were made by locating a search coil at the end of a long handle accurately in the gap of the magnet, withdrawing it, and reading the resultant deflection on a flux meter.

The effect of combined vibration and temperature was determined for one magnet of each design and each material at -70°C , room temperature (25°C) and 250°C . The magnets were saturated, placed in the fixture, brought to temperature held at temperature for fifteen minutes, and the useful flux was measured. This initial value of useful flux was used as a reference and all changes are reported as a percentage of this quantity.

The initial vibration tests were made according to the following schedule:

<u>Frequency</u>	<u>Double Amplitude</u>
5 - 10 cps.	0.050 in.
10 - 75 cps.	0.036 in.
75 - 2000 cps.	± 10 G

These tests were made for the purpose of determining the resonant frequencies of the test fixture and magnets. Later the useful flux of the magnets was measured after about five hours of vibration at each of the six most resonant frequencies at each temperature. The total time of vibration at each temperature was about 35 hours. The frequency of vibration varied from 5 to 2000 cycles per second and the amplitude was the equivalent of at least 20 G and in some cases as high as 30 G.