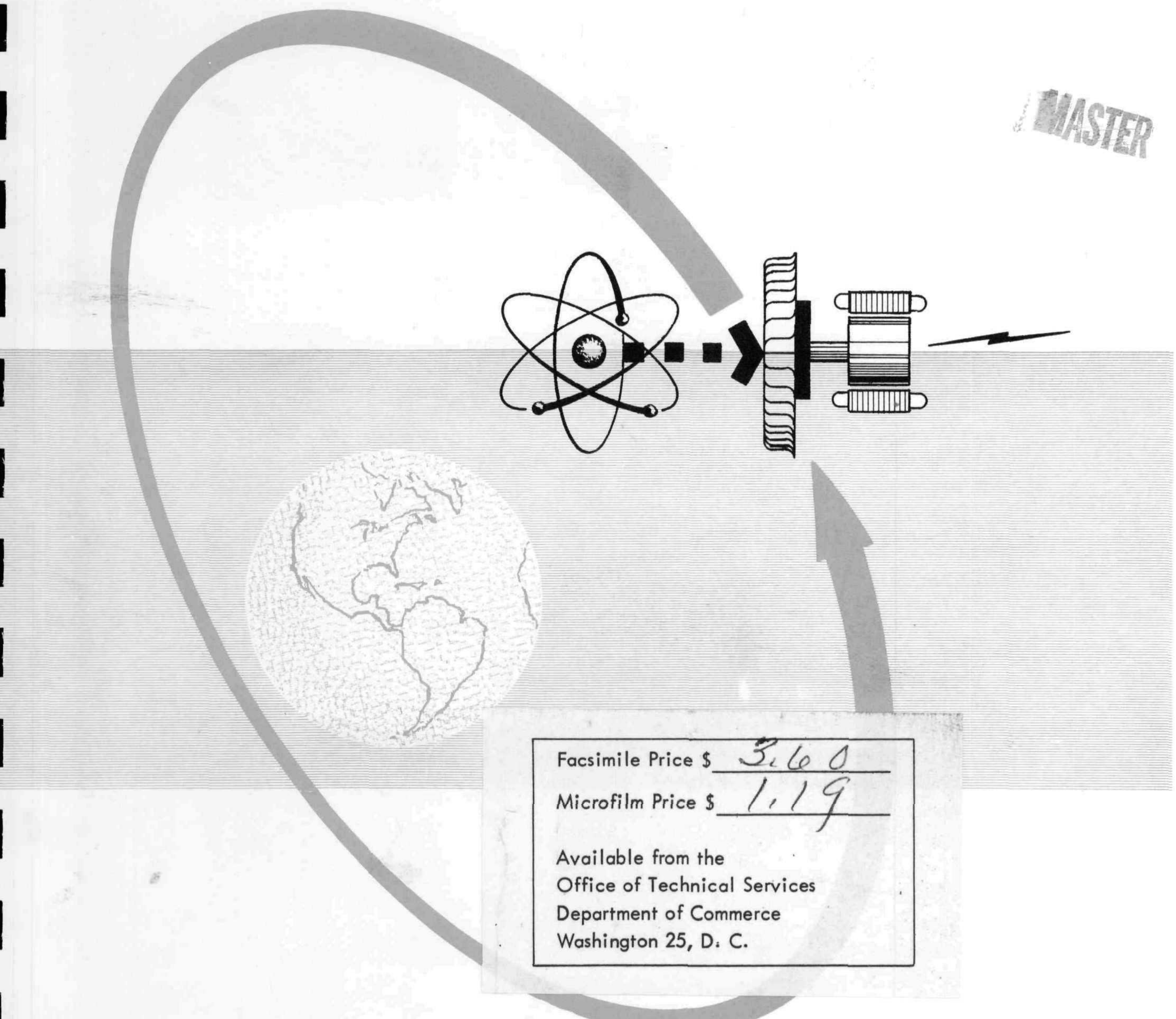
40
2-4-64

NAA-SR-6310
TRW REPORT No. ER-5075
AEC CATEGORY C-92B, M-3679 (31ST EDITION)
SNAP 2 TOPICAL REPORT No. 18
ROTATIONAL SPEED CONTROL

MASTER



Facsimile Price $ 3.60
Microfilm Price $ 1.19

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

AEC RESEARCH AND DEVELOPMENT REPORT

PREPARED UNDER SUBCONTRACT N 843 FS - 101221 FOR ATOMICS INTERNATIONAL, A DIVISION OF NORTH AMERICAN AVIATION, INC.

TRW ELECTROMECHANICAL DIVISION
THOMPSON RAMO WOOLDRIDGE INC.
CLEVELAND, OHIO 44117

DISCLAIMER

Total number of pages 38. Printed in USA. Charge 75¢. Available from the U.S. Atomic Energy Commission, Division of Technical Information Extension, P.O. Box 1001, Oak Ridge, Tenn. Please direct to the same address inquiries covering the procurement of other classified AEC reports.

PROJECT

512-168252-08

NAA-SR-6310
SNAP 2 POWER CONVERSION SYSTEM
TOPICAL REPORT NO. 18
ROTATIONAL SPEED CONTROL
TRW REPORT NO. ER-5075

PREPARED BY:

W. E. Dauterman
Senior Development Engineer

E. J. Viton
Development Engineer

CHECKED BY:

L. J. Gilbert
Project Engineer

G. Y. Ono
Senior Project Engineer

APPROVED BY:

D. L. Deibel
Project Manager

Prepared under Subcontract N843FS-101221 for Atomics International, a Division of North American Aviation, Inc.

DATE

Prepared: November 1962
Published: December 1963

DEPARTMENT

Rankine Power Systems

Thompson Ramo Wooldridge Inc.

CLEVELAND, OHIO, U. S. A.

ABSTRACT

The rotational speed control for the SNAP 2 power conversion system employs the concept of controlling speed by electrically loading the alternator. Speed is controlled in this manner to ± 1% of nominal. This report covers work performed from March 1, 1960 to July 1, 1961.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

Previous analysis and work with systems similar to SNAP 2 had shown that the basic power conversion loop is unstable in the absence of a suitable control system. This instability is caused by pump pressure being developed as a function of speed squared. Thus, turbine output power is also proportional to speed squared. Because the normal system load is proportional to speed, the system will tend to run away at speeds above design level or stall at speeds below design level without some type of compensating control.

This report describes the philosophy used in designing a parasitic loading type of frequency control for the SNAP 2 power conversion system. It discusses the design and development of a two-phase breadboard model, presents test data on this low temperature breadboard model, discusses the availability of high temperature components, and explains the design approach for a similar control suitable for environmental temperatures of 350°C.

Assuming a constant input of heat to the boiler, two basic approaches are applicable for control of SNAP 2 rotational speed:

1. control turbine output power,
2. control alternator loading.

The first approach would employ a type of flow modulating valve either to throttle the input to the turbine or to act as a by-pass control around the turbine. The second approach, which uses a controlled electrical load in parallel with the system load of the alternator, has the following advantages:

1. maintains operation of the entire system at one set design point (full load),
2. has a fast response,
3. has no moving parts,
4. has a high degree of reliability,
5. is relatively easy to develop,
6. has readily adjustable system gain.

These advantages make control of alternator loading using a parasitic load superior to the modulating valve type control for the SNAP 2 system.

A parasitic load frequency control is one that presents a variable controlled load in parallel with the system load. Power to this variable load is increased as the alternator speed and frequency increase and is decreased as the speed decreases so as to stabilize the system for various system loads with a speed droop characteristic. This control has a range that is adequate to overcome any speed changes resulting from system load changes, external perturbations, limited excess power input, or system component performance variations. The parasitic load is electrical in nature and is imposed on the alternator output, thus giving a high degree of accuracy and fast response. This type of control allows thermal and rotating components to operate consistently at design point, regardless of the alternator useful load.

This report covers work performed during the period from March 1, 1960 to July 1, 1961.

2.0 SUMMARY

The parasitic load speed control for the SNAP 2 power conversion system consists of a frequency discriminator low level magnetic amplifier, magnetic amplifier power stages, and a resistive load. Design and development have progressed to the point where experimental results have confirmed the present breadboard design approach. Frequency is controlled within ± 1% and all functional control specifications of the SNAP 2 system have been met. High temperature component testing has shown that basic components are available for operation at elevated temperature (350° C) in most areas. High temperature diodes are still required. Work is progressing on a flight package to meet flight specifications.

3.0 DESIGN OBJECTIVES

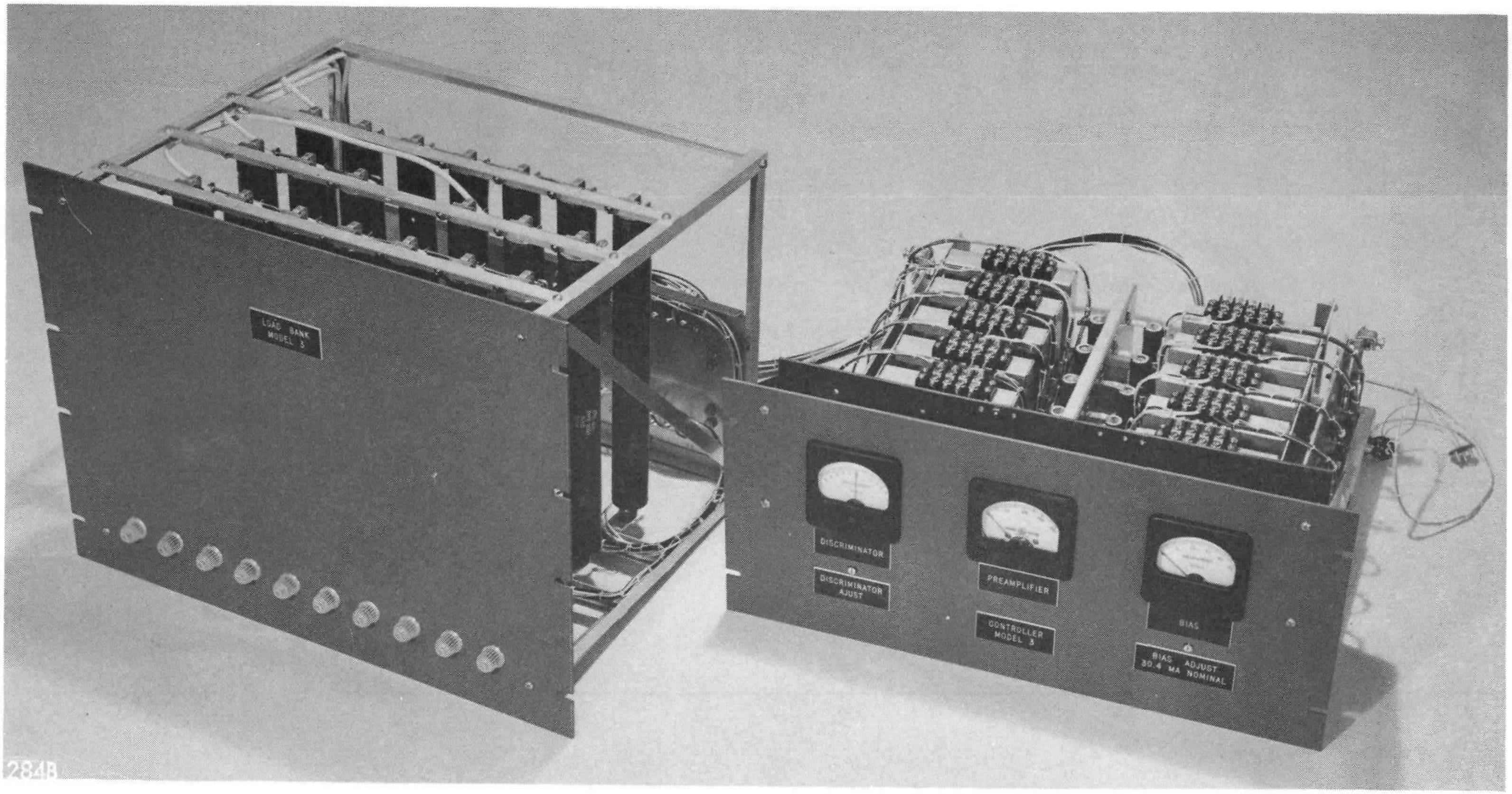
Control development work for SNAP 2 has three main objectives: design of a breadboard control such as shown in Figure 1, design of a flight package, and design of a high temperature (315°C) controller. In addition to meeting system specifications, some other objectives in the design of the SNAP 2 control are as follows:

Frequency range (steady state)	1980 to 2020 cps
Parasitic power at 2020 cps	3450 watts
Alternator voltage (two phase)	110 + 5% volts
Total harmonic content	7%
Effective response time	0.020 sec max

The control must in no way initiate or sustain an unstable condition in the system. The power, weight, and size of the controller must be held to a minimum, and only circuits exhibiting maximum reliability can be incorporated in the design.

The parasitic loading type of frequency control, shown in Figure 2, senses the operating frequency and, by means of amplification, uses signal to control the magnitude of the parasitic load that is applied to the alternator output. The alternator output is a two-phase voltage in quadrature. According to specifications, the parasitic load may be required to consume as much as 3450 watts at an alternator voltage of 110 volts ± 5%. Since we desire a control that will control at least 3450 watts for a 40 cps change, it was necessary to choose the design limits somewhat closer to include the voltage variations (104.5 to 115 volts) as well as component value variations and ambient changes in temperature. A design transfer function of 3450 watts for 20 cps was selected. This should limit transient disturbances of speed to ± 1/2%.

Gains in the first breadboard control were proportioned in the following way. Assuming no power gain within the frequency discriminator, since it is only a sensing device, we obtained 4 milliwatts of output power for a 20 cps change in frequency. The preamplifier stage exhibited a power gain of approximately 2100, while the power gain of the combined power stages was approximately 420. This results in the 3450 watts being controlled over a 20 cps range at 25°C ambient temperature.



SNAP 2 SPEED CONTROL BREADBOARD

FIGURE 1

CONTROL BLOCK DIAGRAM

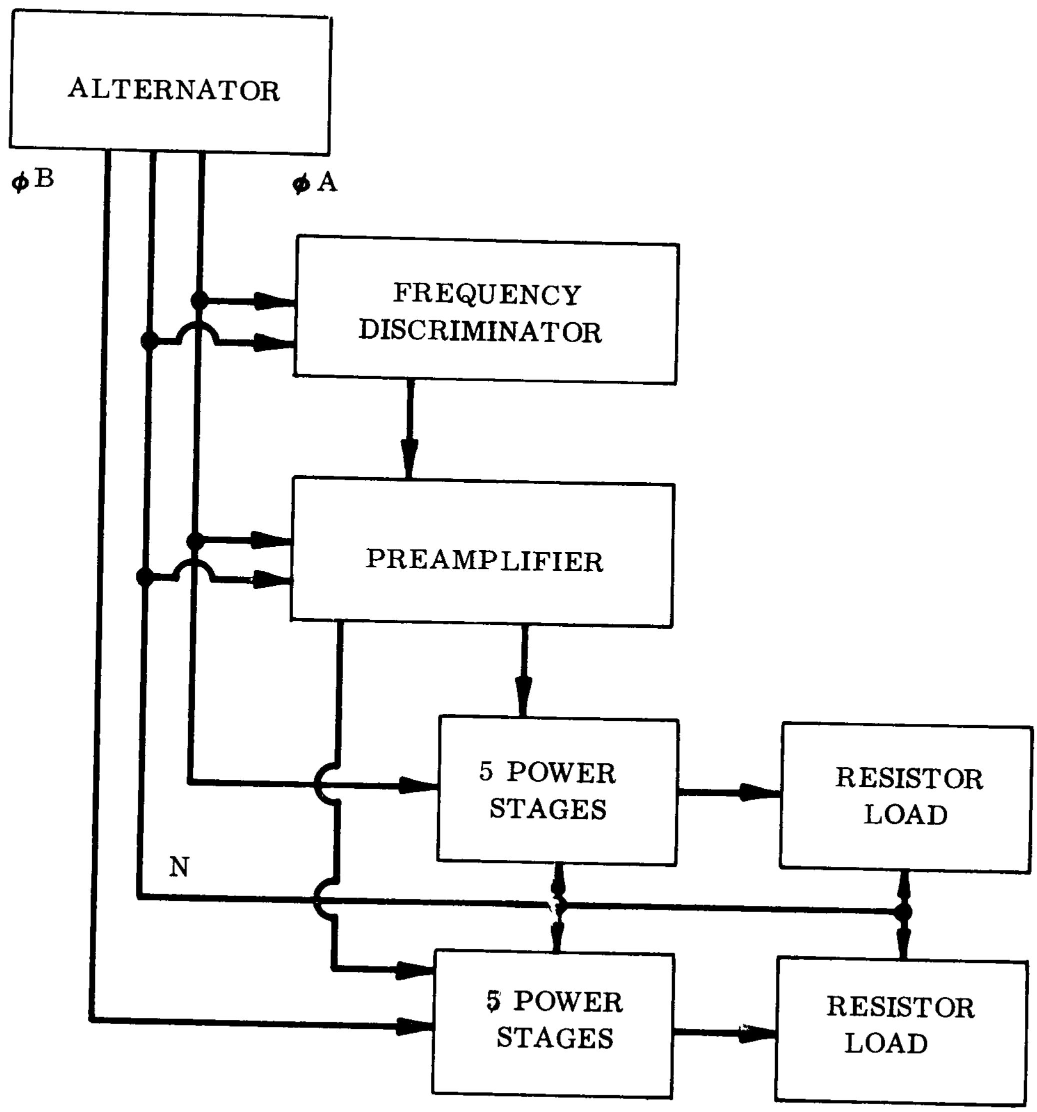


FIGURE 2

The time constant of the rotating member is related to the energy stored in the member and to the energy lost from the member per unit time. The SNAP 2 shaft has a time constant of approximately 3 seconds. If the system load is dropped to zero, the frequency will increase by 20 cps (+1%) in about 90 milliseconds at design conditions without a control. A computer study, utilizing a control gain of 3450 watts per 17 cps and two lags each with a time constant of 20 milliseconds, indicated satisfactory operation with about a 50% overshoot in frequency for any given load change. Where the power changes are 1500 watts, 50% overshoot represents 3.25 cps. The control design gain of 3450 watts per 20 cps with three lags of about 5 milliseconds each should yield a satisfactory overshoot and stable operation should be achieved.

4.0 COMPONENT DESIGN

4.1 Discriminator

The discriminator provides a passive frequency reference and frequency comparator whose output is a function of the input frequency. It is composed of two L-C tank circuits that sense frequency and generate a signal proportional to frequency error in the frequency range of interest. The basic type of discriminator circuit used is shown in Figure 3. Design of the discriminator to provide a maximum gain was based upon the chosen circuit configuration, published and experimental core characteristics, and an analysis of the circuits. The operating Q resulting from this approach influences the width of the operating frequency band and the response time. Computed gain is 4.2 milliwatts per 20 cps change. Experimental data indicate 4.0 milliwatts per 20 cps.

The discriminator was designed to be linear within 5% over a 20 cps deviation from the center frequency. Figure 4 is a plot of experimental data. The transient response of the discriminator output for a step change in frequency to provide a 2 milliamperes change in output current is shown in Figure 5. Also, the frequency of the discriminator input was varied sinusoidally at a constant amplitude and the output was measured and compared over a wide range of modulating frequencies. The resulting gain and phase versus frequency curves are shown in Figure 6.

4.2 Preamplifier Stage

The preamplifier stage is used to match the discriminator to the power stages. Its power gain is based upon the discriminator power output and the power input requirements of the power stages.

The preamplifier is controlled by the differential magnetomotive force of the discriminator output currents in the two equal control windings. As the frequency increases from 1% below nominal to 1% above nominal, the preamplifier output current varies from about 5% to 80% of maximum, and is used as the control current for the five power stages. To avoid some interaction, a short time constant filter is placed in this lead. Figure 7 shows the basic preamplifier circuit.

BASIC DISCRIMINATOR CIRCUIT

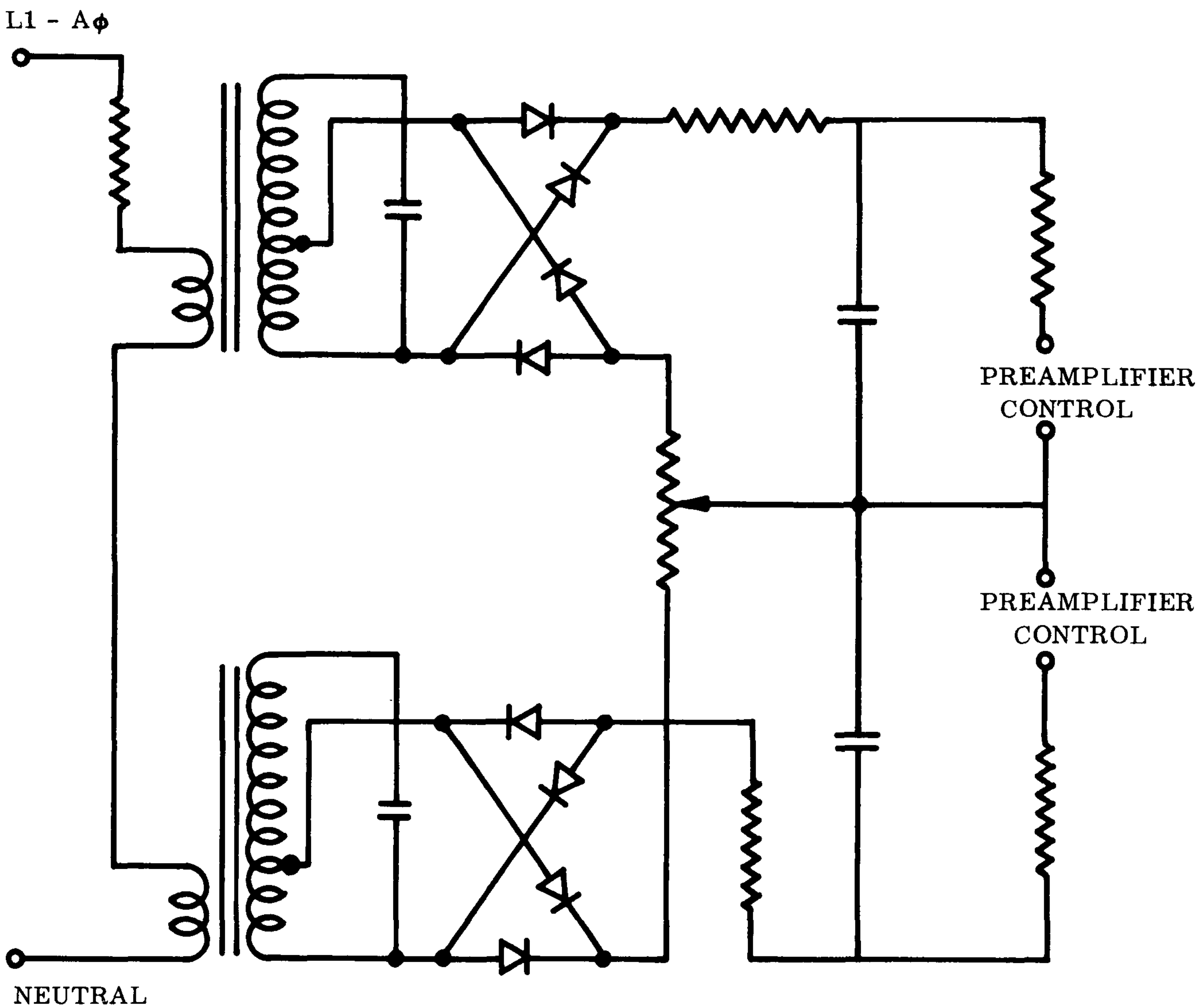


FIGURE 3

DISCRIMINATOR DIFFERENTIAL CURRENT VS. FREQUENCY

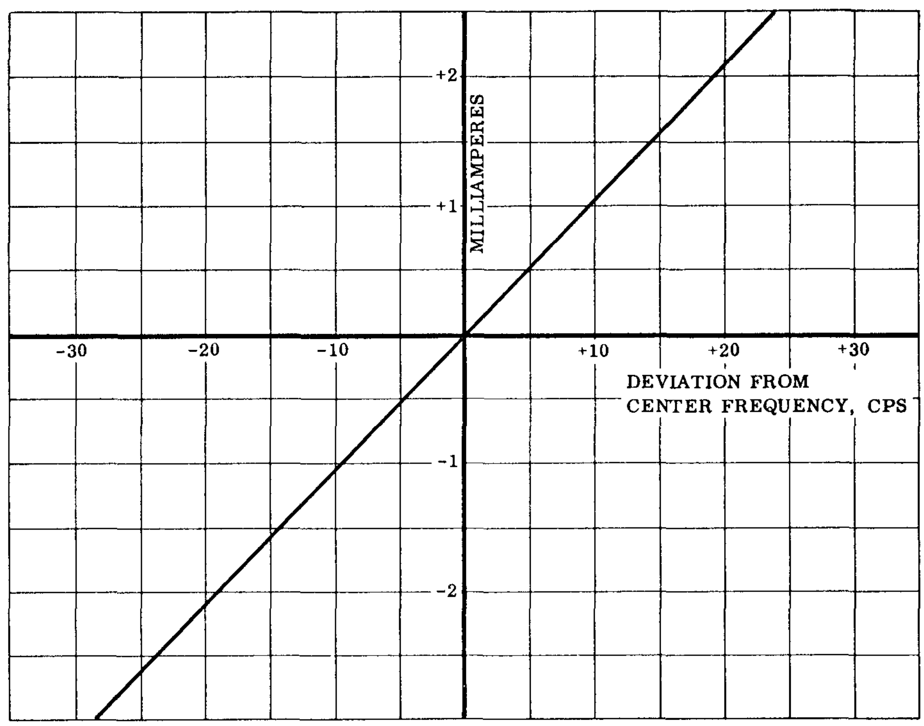


FIGURE 4

DISCRIMINATOR RESPONSE

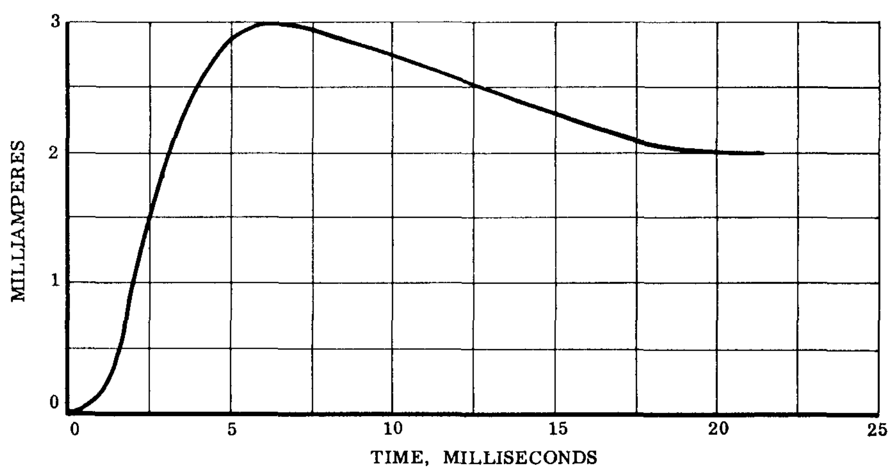


FIGURE 5

DISCRIMINATOR FREQUENCY RESPONSE CURVES

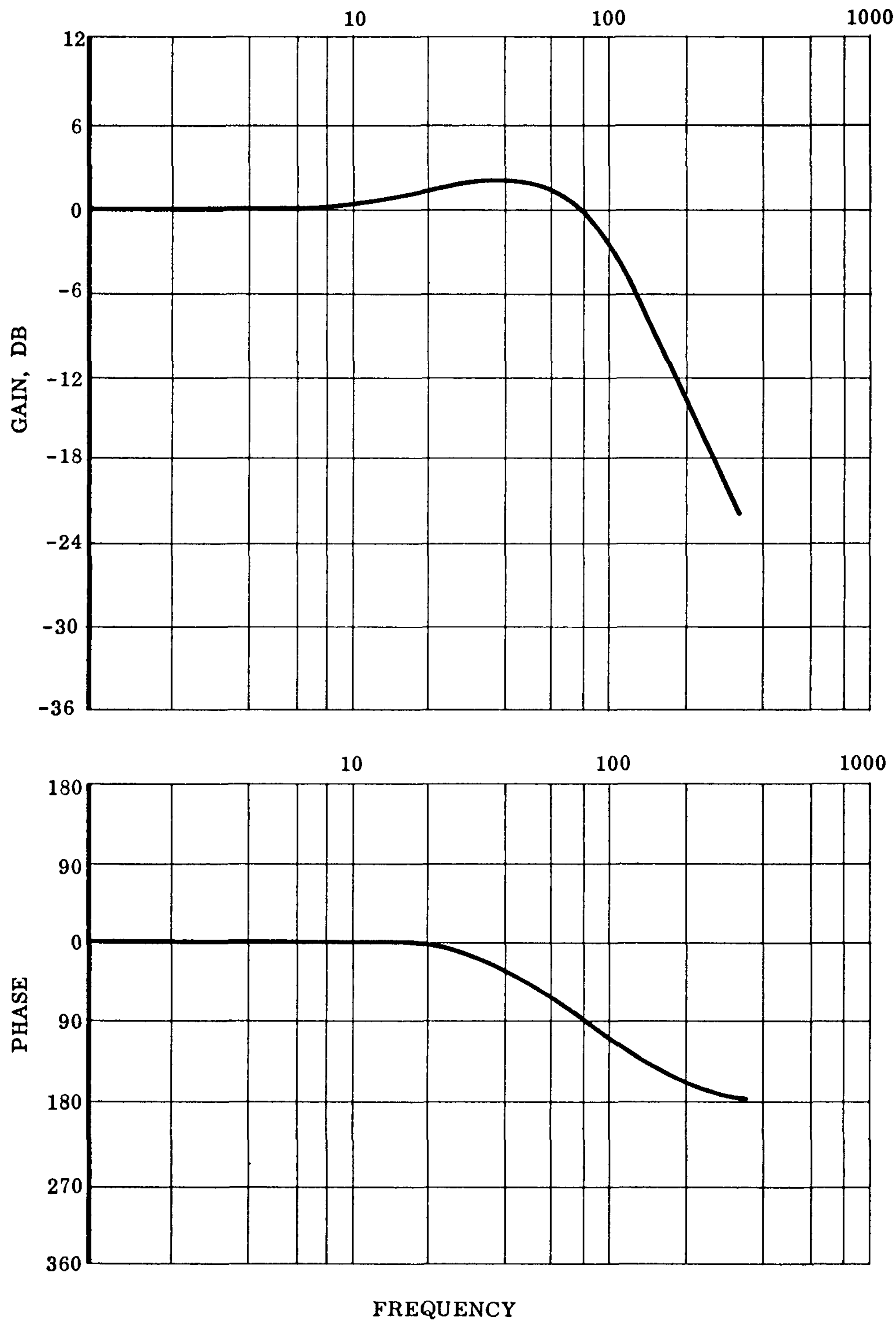


FIGURE 6

BASIC PREAMPLIFIER CIRCUIT

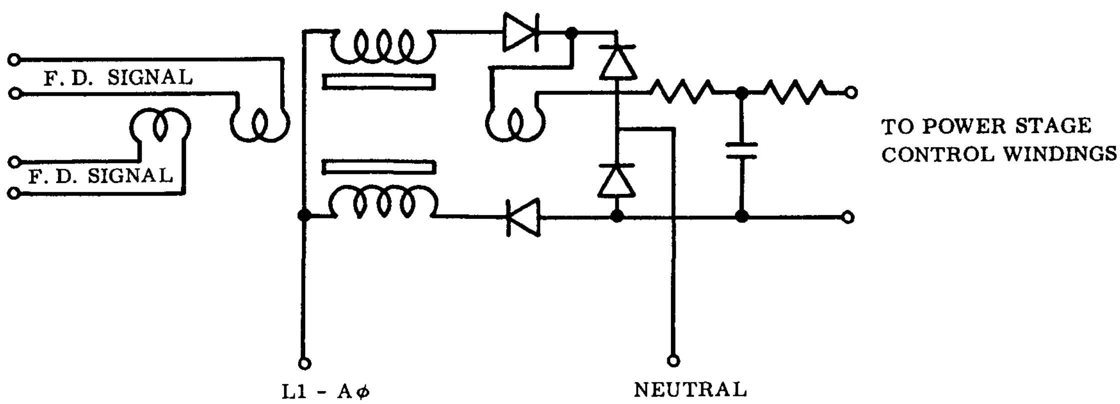


FIGURE 7

PREAMPLIFIER CURRENT TRANSFER CHARACTERISTIC

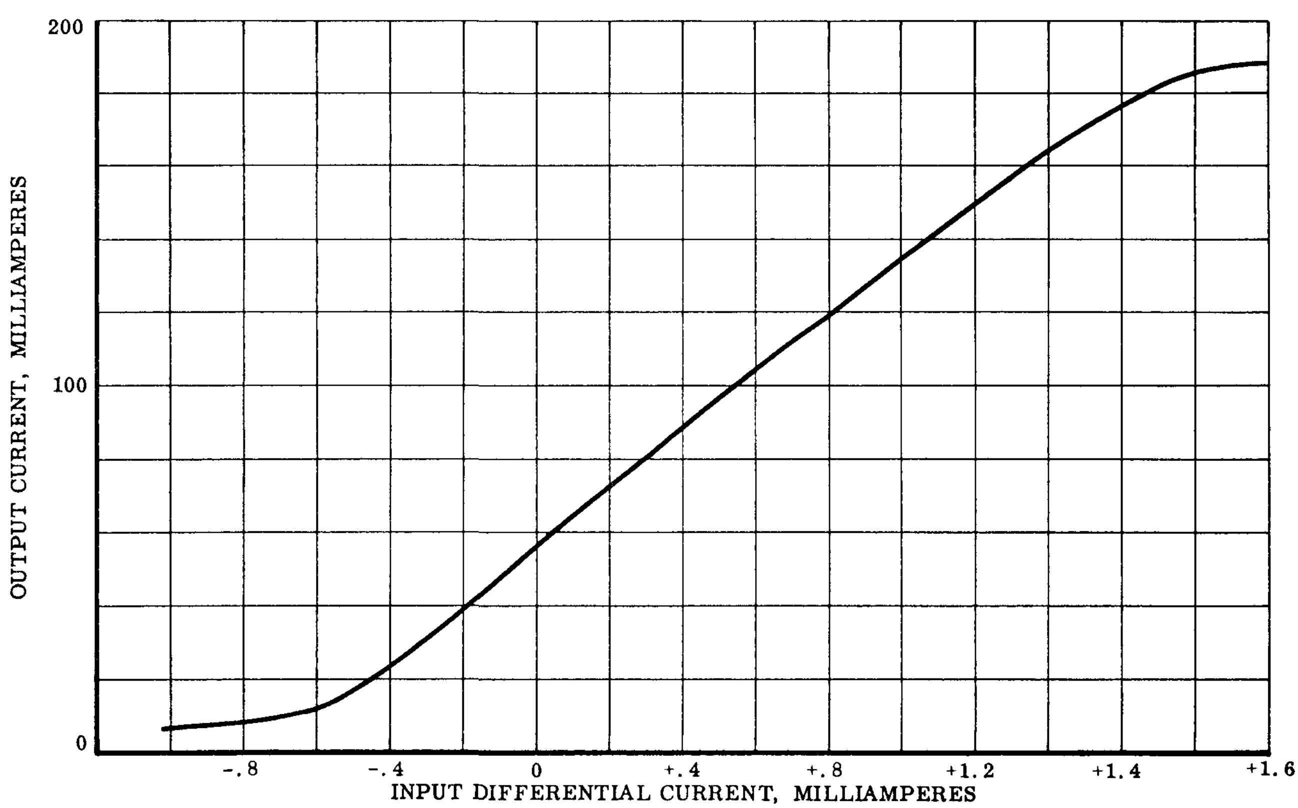


FIGURE 8

The required current gain and output current range are obtained with one pair of cores and a minimum number of components. It is important to note that no bias is used in the preamplifier stage. Although the discriminator primarily determines the center frequency, a shift in the current transfer characteristics of the preamplifier, as shown in Figure 8, will effectively shift the center frequency about which control takes place. By using the negative current available from the discriminator, full advantage is taken of components already available.

The feedback winding in the preamplifier stage stabilizes the stage, linearizes the transfer characteristic, improves the response time, and adjusts the control range to be compatible with the discriminator output. The effective time constant of the preamplifier is approximately 4.5 milliseconds.

4.3 Power Stages

If a device which conducts during a portion of every half cycle, such as a magnetic amplifier or saturable reactor, is used to control the real power consumed in a single resistor parasitic load, it adversely affects the system in at least two ways. First, the alternator would be subjected to large currents during certain portions of each half cycle. Secondly, the harmonic content of the alternator voltage would be increased by the magnetic amplifier type of step loading.

For these reasons a multiple-stage parasitic load was chosen. Such an arrangement created a logic or switching problem which is discussed later. To equalize the load in two-phase or multiphase systems, the power stages are arranged so that all phases have the same number of stages conducting.

Two multiphase breadboard systems were designed. The first system had five stages per phase and the second system consisted of two stages per phase. In both systems each stage for a given phase was controlled over its full range, and the succeeding stage did not begin to conduct until the preceding stage was full on and conducting all the time. In this way the alternator load changes during a half cycle were much reduced compared to the single stage case; thus the alternator loading and the harmonic content of the voltage wave were held within acceptable limits.

The power stages were designed conventionally to provide adequate gain and short time constant, while maintaining compatability with the load resistance and preamplifier. Attention was given to maintaining a minimum power dissipation in these stages to aid in maximizing overall system efficiency. Minimum power dissipation tends to reduce the temperature rise of the toroid assemblies for a given physical environment. When a stage is not saturating during any portion of the cycle, the power consumed in a pair of toroids is that lost in the core as heat as the BH loop of the core is traversed. When the stage is saturated, power is lost in the gate windings because of load current I^2R losses. The hysteresis power loss of the twenty power stage toroid cores (two cores per stage, five stages per phase, two phases) is 51.6 watts and represents part of the minimum power consumed by the controller. The effective time constant of a single power stage for the two-phase system was measured to be 7 milliseconds and 4 milliseconds, turn-on and turn-off time respectively.

When five stages are connected, using the logic circuits discussed later, the response time is approximately the same as a single stage. If the control current rises from zero to that value required to just turn on all stages, all stages are initially over-driven in the absence of logic currents and tend to turn on rapidly and simultaneously. As the logic currents begin to flow, the turn-on of some stages is only slightly retarded. Turn-off conditions can be regarded in the same manner where all the logic currents tend to turn off the last stage very rapidly. The net effect should be response times approximating those of a single stage. Experiments indicate the turn-on and turn-off times of the five stages of one phase of the two-phase controller are 8 milliseconds and 5 milliseconds, respectively.

The power diodes and their heat dissipating mountings are rated and calculated to operate satisfactorily in free air at 170° C ambient temperature. The bias supply is not unusual, and serves to bias the power toroids to the proper operating point. The series bias resistor has been chosen to consume as little power as possible consistent with maintaining adequate response time in the power toroids. Alternator power to the bias circuit is approximately 3.5 watts.

Having decided upon a multiple stage controller, attention was turned to the problem of applying the parasitic load in some predetermined logical manner. A study of various schemes of logic switching was made with the favored circuit being one that could be incorporated in the power stages, taking advantage of the diodes already present in the power stages to provide the direct current logic information required.

Consider the first stage reactor, SC 1A of phase A, shown in the schematic Figure 9. As the control current increases from zero, the power stages tend to be turned on (saturation angle decreased) by the magnetomotive force (MMF) of the control current through the control windings connected in series. Some of the output current from the first stage is rectified and passed through R11 and through the logic windings of the subsequent SC's (saturable cores). The MMF of this logic current tends to cancel the MMF of the control current and thus the subsequent stages do not turn on. As the control current increases, the saturation angle of the first stage continues to decrease until it reaches zero and the parasitic load current and the logic current of the first stage are a maximum.

A further increase in control current tends to turn on the subsequent stages. However, the logic current from the second stage cancels the effect of the control current in stages beyond the second and only the second stage actually turns on. To maintain power balance in a two-phase controller, a stage in each phase turns on simultaneously. In the event a malfunction occurs within a stage, control action is not lost; only the effect due to the loss of the stage that is inoperative is apparent.

Although the logic current was described as cancelling the effect of the control current, complete cancellation does not occur because of the nonlinear relationship between effective control current and effective logic current. Theoretically, complete cancellations occur only at saturation angles of 180 degrees and 0 degree. Because of unavoidable practical variations in stages, the cancellation varies from the theoretical. In the two-phase system having five stages per phase, the minimum value for the saturation angle of a subsequent stage is approximately 155 degrees.

4.4 Parasitic Load

Use of a resistance element load appears to be the simplest means for consuming the parasitic load power. The power is then dissipated in the form of heat by radiation, conduction, or convection. In the load bank used with the breadboard control in early system tests, the heat was carried away primarily by

SCHEMATIC OF POWER STAGES FOR TWO PHASE CONTROLLER

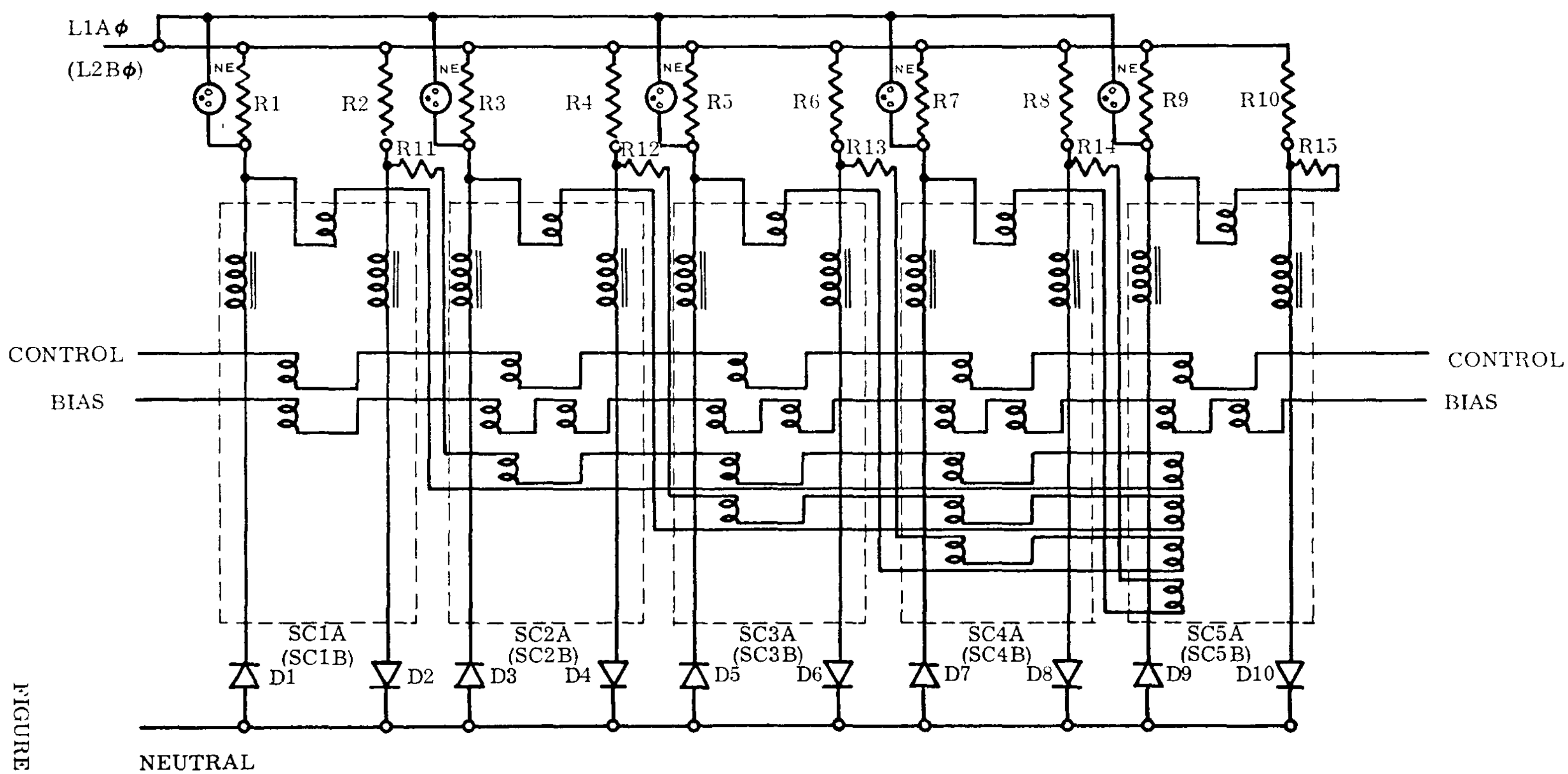


FIGURE 9

forced convection. In the case of an orbital vehicle, radiation directly to space is possible. Conduction may be through electrical insulating coatings to a frame, shell, skin, or some device which requires heating, or through return to the system where desirable. Convection cannot be considered when operating in space.

The maximum power to be consumed by the parasitic load is the maximum power available from the alternator minus the minimum external load power. Should the parasitic load be found wanting because of any combination of influences, the system would overspeed.

The resistor load bank for use in the test cell consists of twenty 200-watt, tubular, ceramic form resistors mounted vertically in an open cage to permit forced convection cooling. They are connected to provide ten 400-watt resistive loads of 31.5 ohms resistance ± 1% at 25° C for use with the five stages per phase models. Later models of two stages per phase require four 1000-watt loads of 12.6 ohms ± 1% at 25° C. The temperature coefficient for later models is +20 ppm/° C to 100° C with a slightly higher coefficient from 100° C to 300° C, their full load hot spot temperature. A blower having a capacity of 300 cubic feet per minute is required to carry away the heat.

At present two schemes are under consideration for the flight load. One is a load bank made up on resistive elements that would be required to dissipate all of its heat by radiation directly or indirectly to external space. The other scheme involves putting the heat of the parasitic load back into the system at a desirable and useful point. The heat of the parasitic load will be small compared to the total heat of the system and for this reason should in no way impair the overall system operation. This second scheme has one particular advantage, that of maintaining the load at a nearly constant temperature and thus reducing load variations due to thermal cycling of the resistive elements.

4.5 Breadboard Test Data

The response time of a complete five-stage breadboard unit was obtained by observing the voltage drop across a line current shunt on an oscilloscope for a step change in frequency. The rms line current as a function of time is plotted in Figures 10 and 11. Figure 10 is for frequency limits from load full off to load off on. Figure 11 is for frequency limits to provide power limits between

LINE CURRENT VERSUS STEP CHANGE IN FREQUENCY
(0 TO 100% CURRENT CHANGE)

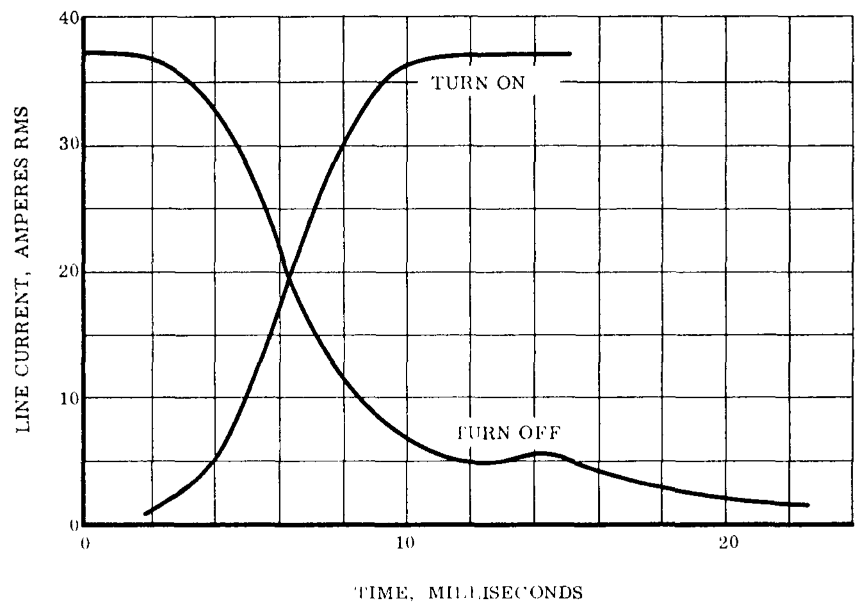


FIGURE 10

LINE CURRENT VERSUS STEP CHANGE IN FREQUENCY
(25 to 75% CURRENT CHANGE)

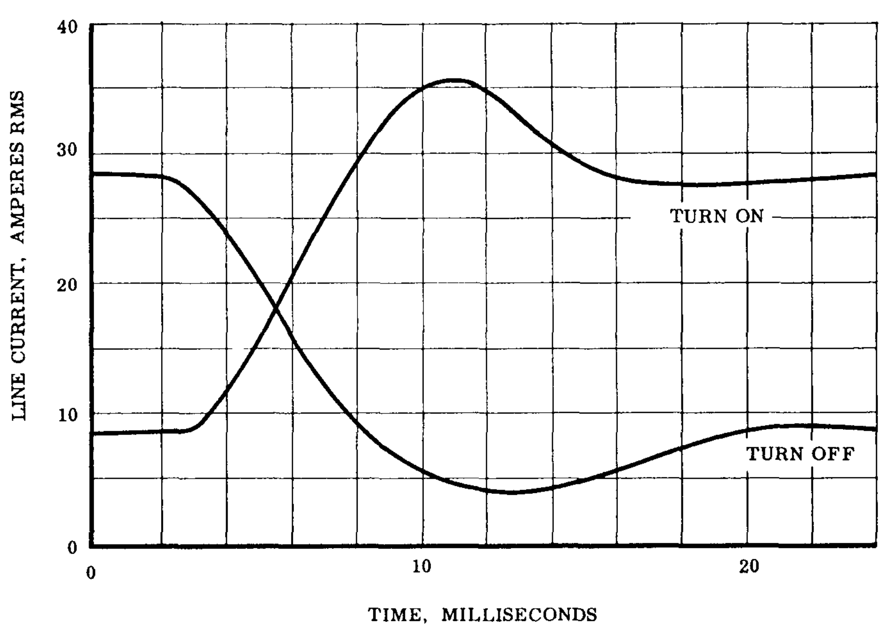


FIGURE 11

25% and 75% current change. The overshoot in Figure 11 is caused by the overshoot in the discriminator characteristic. In Figure 10 the power stages are in effect saturated and cannot reflect the discriminator overshoot.

Harmonics tests were also run on the five-stage, two-phase breadboard controller prior to operating with the system. These tests were run using a variable alternating current drive motor to drive the SNAP 2 alternator at rated speed. Harmonic content of the alternator output voltage wave was measured while supplying current to a resistive load, and then measured again at various levels of parasitic load. The total harmonic content was found to be well within the required specifications. Therefore, a two-stage, two-phase controller was constructed and similar test data were taken. The magnitude of total harmonic content was still found to be satisfactory and within specifications.

5.0 HIGH TEMPERATURE CONTROL APPROACH

The two main deterrents to the design of a high temperature control are the sensitivity of the magnetic material to high temperature and the lack of power rectifiers. These facts have dictated a thorough evaluation of existing materials and components along with a study of fabrication techniques. The approach to the problem was to attempt to find all materials and components required to build a control that would withstand 315°C. If in any area this could not be achieved, an attempt was made to use a component of lower temperature rating until the state of the art is advanced.

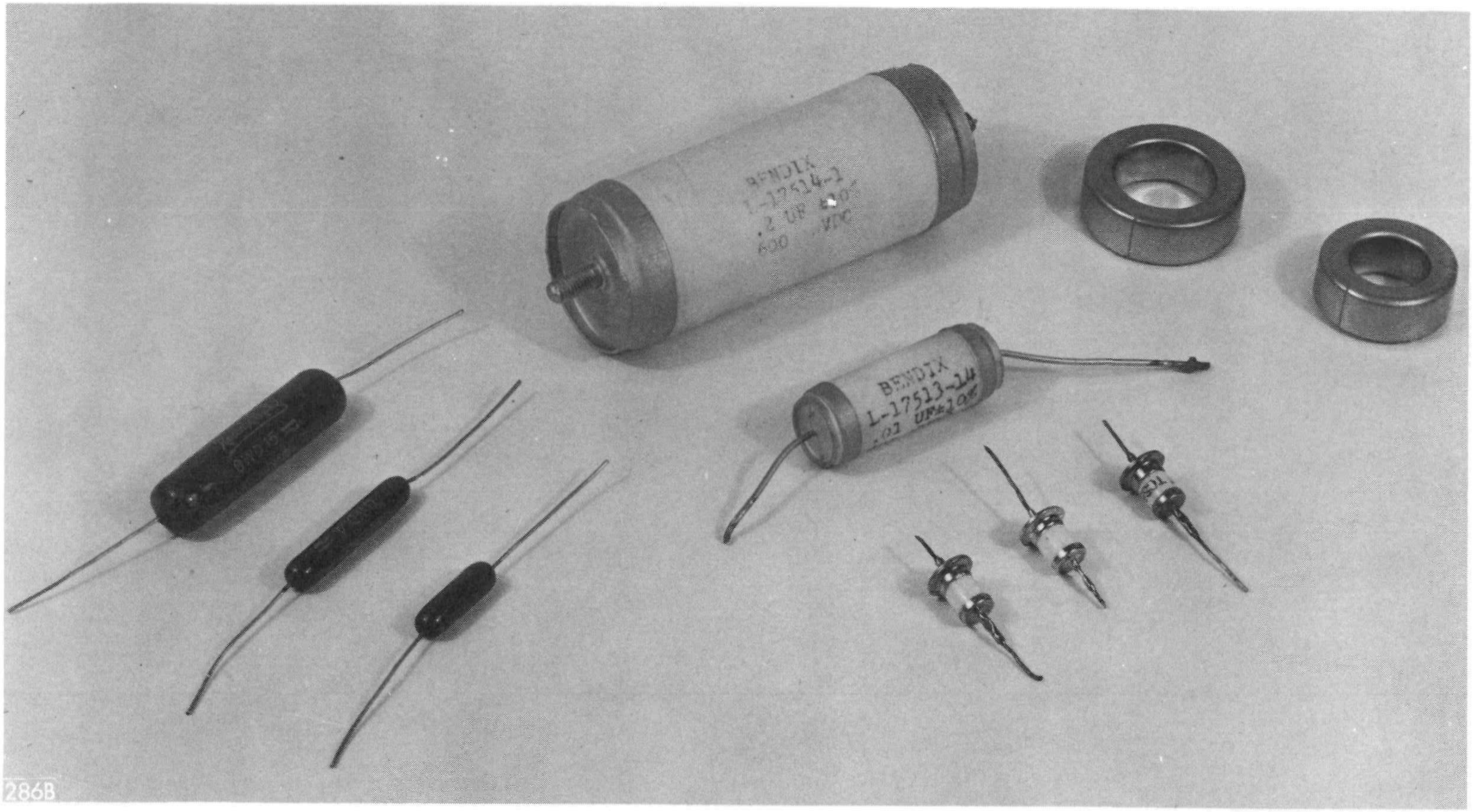
An investigation of high temperature components and materials has been underway for the past year. Figure 12 shows a group of various high temperature components investigated. The results to date are discussed below.

5.1 Capacitors

At the present time only two sources for 400°C capacitors have been found. Bendix Aviation Corporation has 315°C capacitors in production. Their values range from 0.05 to 4.0 mfd at 600 volts DC. Under development, they have capacitors rated for 400°C operation with values ranging from 0.001 to 6.0 mfd, at both 150 volts DC and 600 volts DC. Several of these capacitors have been tested and appear to be quite satisfactory. They are being used in the design of the SNAP 2 high temperature speed control. Airborne Accessories also has high temperature capacitors available. General Electric states they have 500°C capacitors in the micro-microfarad range.

5.2 Magnetic Core Materials

Although many alloys have been developed to obtain desirable ferromagnetic properties for magnetic cores, not all are suitable for use in extreme environments. The selection of satisfactory core materials to be used in magnetic type components design was accomplished through a literature search of available data plus experimental tests covering the areas that were found to be lacking in published data. In general, only a small amount of data was available above 250°C. Data from testing of various alloys at temperatures up to 370°C indicated that powdered iron cores of 81% nickel, 2% molybdenum and the balance iron are quite satisfactory as inductors in tuned circuits. The choice for saturating core devices reduced to cores having from 1.5 to 5%



HIGH TEMPERATURE COMPONENTS

FIGURE 12

silicon and the balance iron, or a material having 49% cobalt, 2% vanadium, and the balance iron.

5.3 Magnet Wire

It was recognized very early that one of the major problems to be overcome before the design of high temperature components could be completed is the procurement of a suitable magnet wire. At least two important factors must be considered in the selection of this wire. One is the insulation over the wire and the other is the conductor itself.

Some of the types of insulation available that will withstand 315 to 370° C consist of a ceramic fired in place, glass fired in place, Ceramicite*, anodized aluminum and a double glass serving impregnated with silicone varnish. The fired-in-place ceramic or glass did not appear to be practical in the winding of toroidal coils, since this type of insulation must not be moved after being fired. Anodized aluminum has outstanding dielectric qualities as insulation but there is no satisfactory method for easily joining the basic aluminum wire. Early in our investigation of wire, Ceramicite seemed to be a satisfactory insulation, but after several toroids wound with this type of insulation developed shorts between turns, it was abandoned in favor of a double glass serving impregnated with silicone varnish. At present, the type being used is "Silotex" served by Anaconda. This has proven satisfactory not only from the standpoint of operation under high temperature environments but also because certain sizes can be wound with a reasonable degree of success on a toroidal coil winder.

Various types of conductors are available today. Some of these are made from only one material while others are a composite, which takes the form of a plated or clad conductor. Aluminum, copper, silver, silver-plated copper, silver-plated copperweld, nickel-plated copper, nickel-clad copper, Inconel-clad copper and stainless steel-clad copper are a few of the types available.

Tests of conductors in the SNAP 2 program have been confined to copper, nickel-clad copper and silver. Silver wire has a lower resistance than copper, but at present this does not appear essential to our program. A copper conductor in a high temperature environment with oxygen present will oxidize readily. This

* Developed by Consolidated Electrodynamics, Glendale, California

is the reason for using a nickel-clad copper conductor. The one drawback with nickel-clad copper is the permanent change in resistivity associated with a long aging period at high temperatures. Present information indicates this change starts to manifest itself around 426° C. Data from tests run at 370° C ambient temperature indicate nickel-clad copper to be quite stable with regard to aging.

5.4 Semiconductor Diodes and Rectifiers

Some of the work going on in the semiconductor field indicates that high temperature semiconductor components will be available in the near future.

At present we have successfully tested a small number of silicon carbide diodes for some 750 hours at 370° C, but we are unable to obtain any more. The manufacturer has stated their output yield of this unit is very bad. This combined with a very small market potential has forced them to temporarily revert to the research and development stage.

To date the testing of gallium arsenide diodes has not proven satisfactory. These were tested to the Manufacturer's specifications of 400° C. The percentage of failures and departure from specifications was quite high after only one week of test time.

Due to some initial test results of a certain type silicon diode at 315° C and the availability of these units, it was decided that these units be put on a life test at 204° C in an effort to determine their reliability at this temperature. To date these units are showing satisfactory results.

Resistors appear to be no problem. At least two types have been tested to 537° C while operating at 100% rated power.

5.5 Miscellaneous High Temperature Materials

A survey was made of miscellaneous materials, hardware, and components applicable at high temperatures. While these items are not in general considered to be control components, application could arise in a specific system for one or more items of this nature. Also, it is quite evident that a need exists for high temperature insulations in the form of varnish, resin or potting compounds.

To date, a resin, a cement, and a high temperature paint have been under test for over 500 hours at 370° C. These items are all being tested on toroidal transformers as a means of both anchoring the windings and insulating between turns.

5.6 High Temperature Circuit Design and Testing

Based on the above information for available materials and components it was decided that a control using one frequency discriminator, two preamplifiers and four saturable reactors, as shown in the block diagram of Figure 13, be the circuit configuration for the high temperature control. The high temperature control would be constructed to operate with as high an ambient temperature as the present state of the art permits.

A digital computer program was initiated to evaluate the effects of various parameters of the frequency discriminator on its gain. This was done because it was realized that the gain of the overall system would be reduced by the high temperature requirement and every effort must be made to increase the gain of all of the component parts.

Figure 14 shows a discriminator that has been operated some 700 hours at 370° C. Its characteristics show very little change due to aging. This unit has all high temperature components, including silicon carbide diodes.

Experimental test results showed that an increase in gain could be made by using larger cores and making appropriate design changes. These changes would be included in the design of the high temperature discriminator.

Present plans are to investigate two types of circuits for use as a magnetic preamplifier. The first is that of a standard full wave magnetic amplifier, and the second is a Ramey type circuit.

The full wave preamplifiers have been made and tested to 370° C except for diodes that were kept outside the oven at room temperature. The toroidal cores were constructed and tested primarily to test two types of core material, Mo-Permalloy* and Silectron*. As expected, the hysteresis loop became more narrow and the

*Arnold Engineering Company, Marengo, Illinois.

BLOCK DIAGRAM OF HIGH TEMPERATURE FLIGHT CONTROL

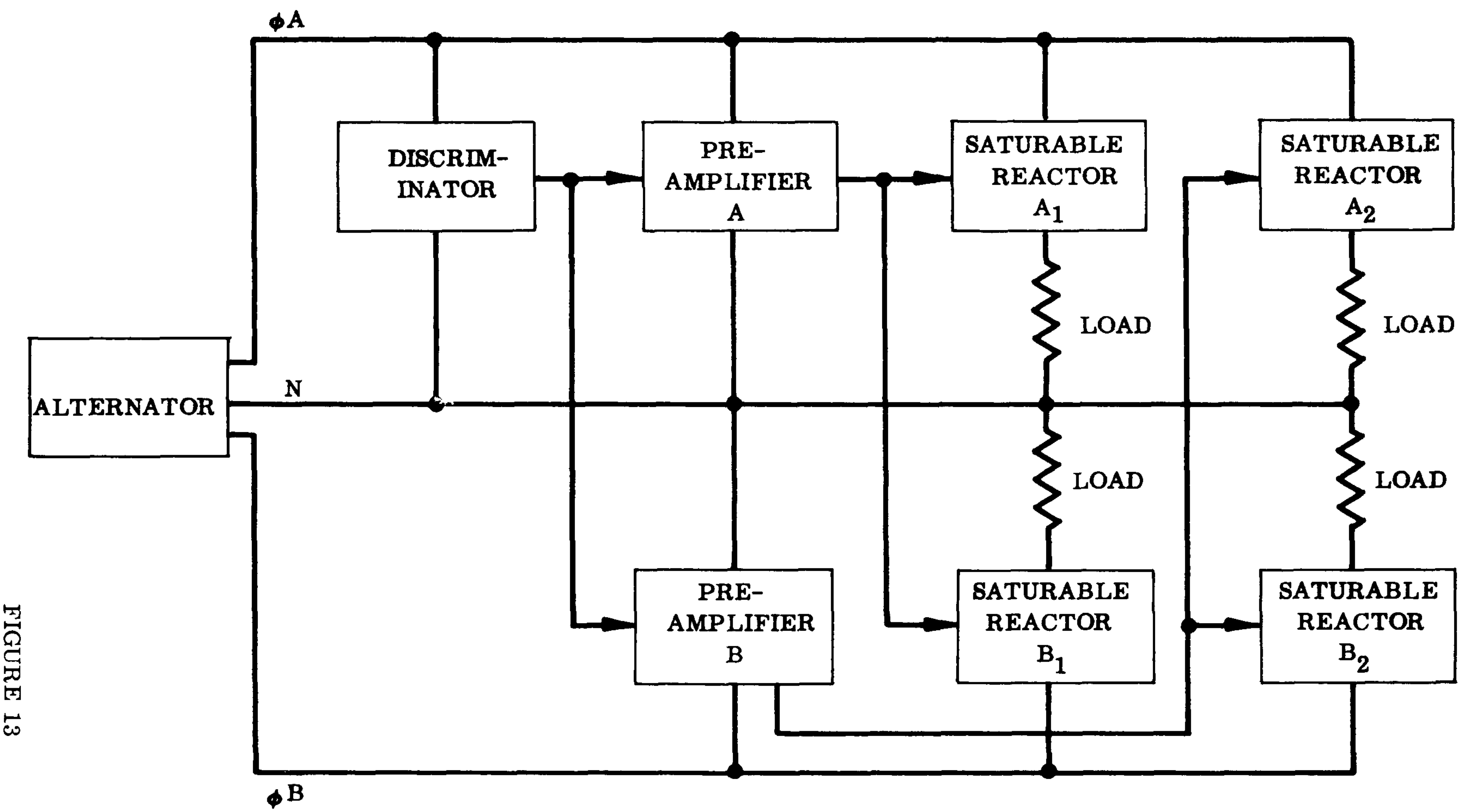
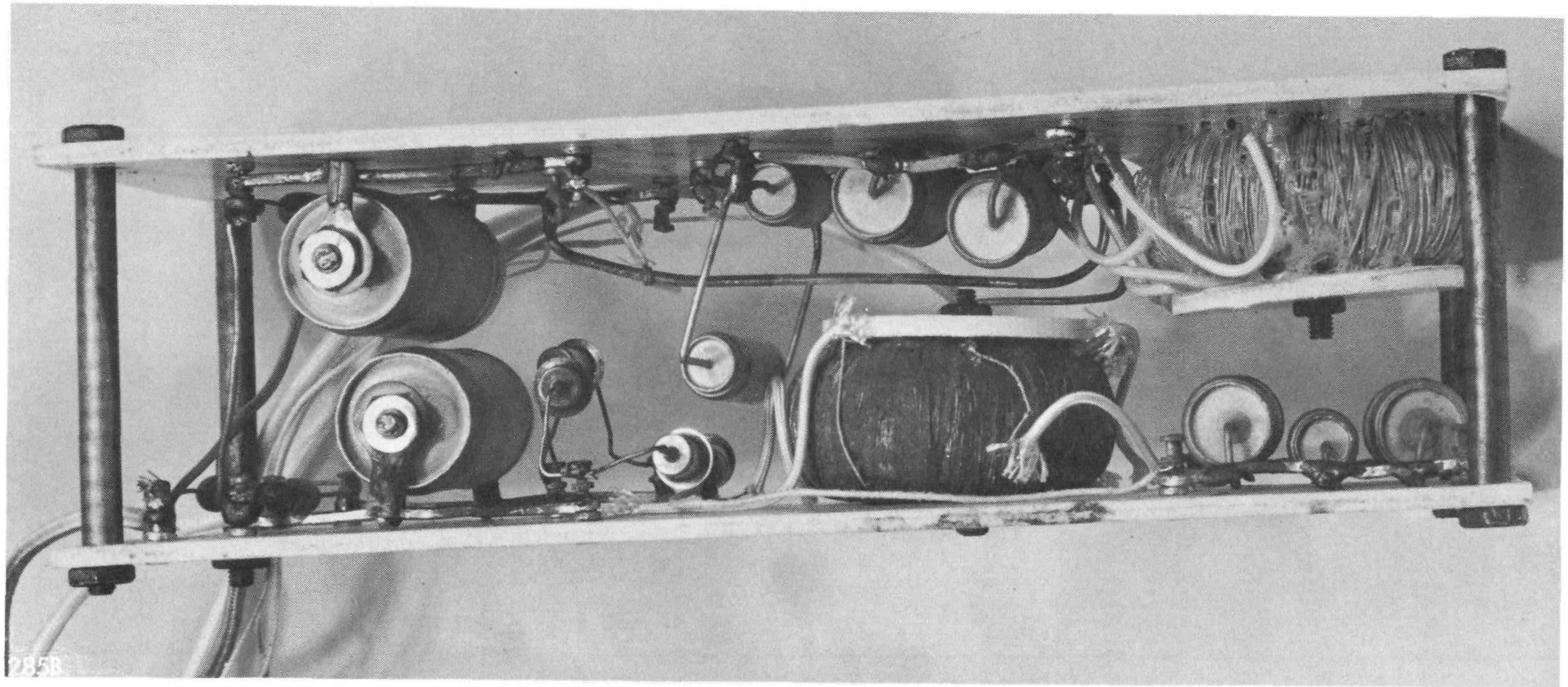


FIGURE 13



HIGH TEMPERATURE FREQUENCY DISCRIMINATOR

FIGURE 14

saturation flux level decreased with an increase in temperature. Mo-Permalloy, which has desirable characteristics at room temperature, proved to be quite unsatisfactory for use at 370° C. In the case of Silectron, the degree of change from room temperature to 370° C was much less. For this reason, it would be acceptable for high temperature use as a magnetic amplifier despite its relatively low gain. Other core materials yet to be investigated are Supermendur* and Deltamax*. Deltamax is known to be strain sensitive, but this trait could be minimized by proper packing or packaging of the core material.

A saturable reactor power stage would be used in the high temperature control because high current rectifiers are not available. The saturable reactor gain is not as sensitive to temperature variations as a magnetic amplifier circuit because its gain is less dependent on the core material properties. The reactor, however, is penalized by large size and slow response. Some stabilizing and compensating technique will undoubtedly be necessary to stabilize the loop and to improve response of the control system. A computer simulation may be necessary to determine the transient response that can be expected of this control system.

To date, a saturable reactor designed to control 800 watts has been operated satisfactorily at 315° C.

* Arnold Engineering Company, Marengo, Illinois.

6.0 CONCLUSIONS

The breadboard speed control having a steady-state tolerance of ± 1% and a response time of less than 20 milliseconds has proven quite satisfactory for ground operation and test cell use where it is not required to be subjected to the extreme temperatures of the SNAP 2 system.

The high temperature control design will be subjected to a much more severe environment than the breadboard version. For this reason the steady-state tolerance will be broader and the response of the control will be slower. Also, because of the temperature environment along with shock and vibration specifications, the size and weight are expected to increase.

The flight package control for the SNAP 2 system will evolve from the information and test data obtained during development of both the breadboard and high temperature controls. Only circuits and components that testing has shown will meet all required specifications and exhibit a high degree of reliability can be used.

7.0 RECOMMENDATIONS

Although satisfactory progress has been made to date, certain areas have not been sufficiently covered thus far in the program. Areas that still require much work are those involving the life of materials and components in both vacuum and nuclear radiation environments. Although many papers and much information are available in both areas, the data are general. Questions with regard to the operation of the SNAP 2 rotational speed control in these environments can only be answered by data obtained from specific tests in these areas.

Prior to final packing of the flight version, thermoanalysis will be required to insure equal heat distribution throughout the control, thus preventing internal hot spots. Correct location of the control with respect to ambient temperatures and ease of heat dissipation also warrant consideration.