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DEVELOPMENT OF SPEED CONTROL FOR THE SNAP-8 ELECTRICAL GENERATING SYSTEM

by

S. L. Bradley

AEROJET-GENERAL CORPORATION

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 5-417
Martin J. Saari, Program Manager

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TOPICAL REPORT

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CONTRACT NAS 5-417

NASA Lewis Research Center
Cleveland, Ohio
Martin J. Saari, Project Manager
SNAP-8 Program Office

FOREWORD

The work described in this report was performed by Aerojet-General Corporation, Azusa, California, as part of the SNAP-8 electrical generating system contract being conducted within the Power Systems Department. The work was performed under NASA Contract NAS 5-417, with Mr. Martin J. Saari as NASA Program Manager, and Dr. W. F. Banks as the Aerojet-General Corporation Program Manager.

ABSTRACT

This report covers the design, fabrication and testing of the speed control used on the SNAP-8 electrical generating system. A total of more than 10,000 hours of operation with the electrical generating system has provided information which verified that the speed control was capable of regulating the speed of the system to within ± 1%, with an output frequency of 400 ± 4 Hz.

Test results are presented along with an evaluation of the speed control performance relative to the SNAP-8 electrical generating system.

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SUMMARY

A speed control system, developed for the SNAP-8 program, has operated for over 10,000 hours in a power conversion system test facility, and for more than 16,000 hours in an electrical component test facility. During power conversion system tests, stability was maintained with no measureable drift in alternator speed while being subjected to variations in vehicle loads. Regulation was better than ± 1% from no load to full vehicle load operation at 35 kw. Speed recovery time was two seconds following sudden full load application and one second for sudden load removal.

Tests were performed to evaluate both the packaging materials and the electrical characteristics of the speed control system. The reliability of Koldweld joints was determined to be more than adequate for attaching ceramic nickel terminals to the aluminum housing and for attaching copper to aluminum. New tungsten inert gas welding (TIG-Welding) applications were explored, and the electrical characteristics of components and individual assemblies were evaluated during each stage of fabrication. The harmonic content was measured and was found to be acceptable.

Simplicity was stressed in the design of the speed control circuitry which resulted in control system efficiency and reliability. This was demonstrated by the fact that no failures have occcurred during the entire test program. Components and materials have adequately demonstrated in simulated test environments, the capability and reliability of operation in the SNAP-8 environment.

I. INTRODUCTION

SNAP-8 is a nuclear-electric space power system utilizing a mercury Rankine cycle which is being developed by Aerojet-General Corporation for the National Aeronautics and Space Administration. The nuclear reactor is being developed for the Atomic Energy Commission by Atomics International. SNAP-8 can provide a minimum of 35 kw to the user for space missions.

Reactor heat is transferred by a sodium-potassium (NaK) loop to the mercury boiler. The mercury, vaporized at high pressure in the boiler, drives the turbine alternator assembly (TAA). Upon leaving the TAA, the mercury vapor is condensed and pumped back to the boiler. Heat given up by the mercury as it condenses is carried by a second NaK loop to a radiator and rejected to space. Polyphenyl ether is circulated to several of the system pump motors and to the electrical components for cooling. This low-temperature coolant is also used to lubricate the ball bearings of the turbine alternator and mercury pump-motor assemblies.

The speed control system discussed in this report controls the speed of the turbine-alternator assembly and, hence, the output frequency. The frequency regulation is 400 ± 4 hertz. The speed is held to the required regulation by maintaining a load on the alternator equivalent to the output of the electrical generating system. This operation is achieved by dissipating excess power in a parasitic load resistor which is cooled by the NaK in the heat rejection loop. The amount of power allowed to flow to the parasitic load resistor is controlled by the saturable reactor which, in turn, depends on the control current supplied by the magnetic amplifier. The frequency sensing circuit monitors the output of the turbine-alternator, and delivers a signal to the magnetic amplifier which increases or decreases its output to the saturable reactor. If the frequency of the turbine-alternator rises, the output of the magnetic amplifier is increased which, in turn, increases the power output of the saturable reactor to the parasitic load resistor. The opposite action occurs when turbine-alternator frequency drops. Any change in load or load power factor varies the alternator output voltage which is controlled by the voltage regulator. However, the regulator allows the alternator output voltage to vary in proportion to the frequency.

This report covers the design and test evaluation resulting in a satisfactory speed control system design for the SNAP-8 electrical generating system.

II. DESCRIPTION OF THE SNAP-8 SPEED CONTROL SYSTEM

A. DESCRIPTION OF SNAP-8 ELECTRICAL CONTROL SYSTEM

The SNAP-8 electrical control system provides voltage control, speed control, power conditioning and distribution, fault protection, and start and shutdown sequencing. A block diagram of the SNAP-8 electrical control system is shown in Figure 1. The voltage regulator module and the saturable current potential transformer are shown with respect to the rest of the electrical system.

The voltage regulator provides a control voltage to the static exciter which is proportional to the frequency to regulate the alternator output voltage at 208 ± 6 volts. The static exciter, in conjunction with the voltage regulator, provides the alternator field-current to control the alternator output voltage. The vehicle load breaker connects and disconnects the alternator to the vehicle load.

The programmer assembly controls all functions of the power conversion system including sequencing at start, shutdown and restart, and provides for internal and external fault protection by the use of a protective system. Three motor transfer contactors which are controlled by the programmer cause the electrical inputs of the pump motor assemblies to be supplied from either the inverter output or from the alternator output depending upon the inputs to the programmer logic circuitry.

When the TAA is delivering sufficient power, the programmer automatically transfers the pump power input from the inverter output to the alternator output. For shutdown, the programmer starts the inverter and actuates the motor contactors to transfer the pumps back to the inverter output for decay heat removal.

The inverter converts direct-current power to alternating current to start and operate the pumps during the period preceding, and subsequent to, alternator operation for startup, shutdown, and nuclear system decay heat removal. The speed control system, consisting of the speed control module, speed control power transformer, saturable reactor, and parasitic load resistor, senses turbine-alternator frequency variations and regulates the alternator speed within ± 1% of the desired operating speed of 12,000 rpm (400 hertz).

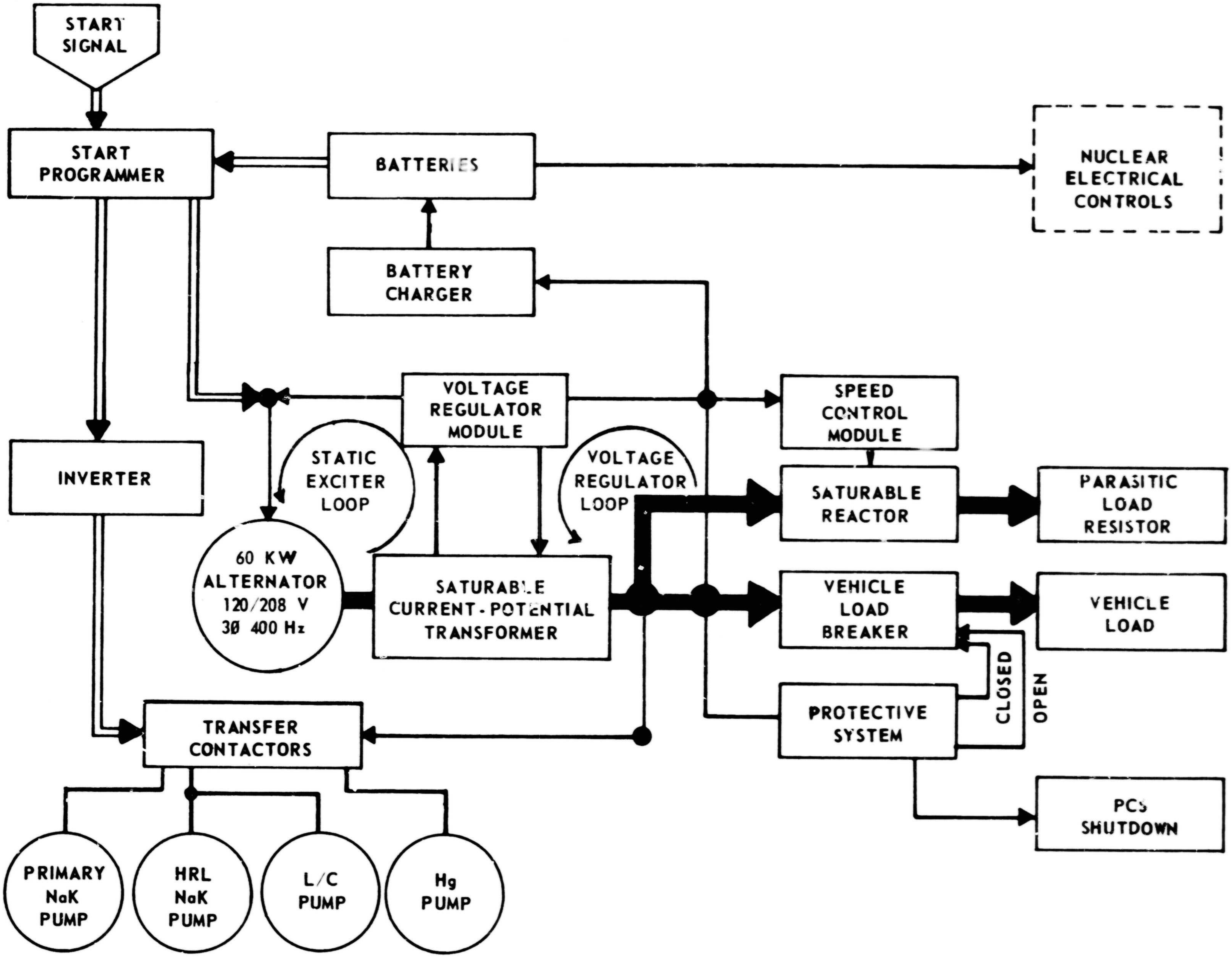

Figure 1. SNAP-8 Electrical Control System Block Diagram

B. DESCRIPTION OF SPEED CONTROL OPERATION AND DESIGN CONSIDERATIONS

1. Operation

The speed control system, shown schematically in Figure 2, regulates the speed of the turbine-alternator. Elements of the system include the speed control module (see Figure 3), the saturable reactor (see Figure 4), the parasitic load resistor (see Figure 5), and the speed control transformer (see Figure 6). The system senses the alternator output frequency and controls the power dissipated in the parasitic load resistor by controlling the saturation level of the saturable reactor. If the frequency of the turbine alternator rises, the output of the speed control module is increased, which increases the load transferred through the saturable reactor to the parasitic load resistor. If the frequency of the turbine-alternator drops, the opposite action occurs, decreasing the load delivered to the parasitic load resistor. Therefore, the total power load is continuously adjusted to control the turbine-alternator frequency output. The speed control module itself consists of a frequency sensing circuit and the magnetic amplifier (see Figure 2). The speed control power transformer assembly provides power to the speed control module. The frequency sensing circuit monitors the frequency output of the alternator and delivers a signal to the magnetic amplifier which controls the output of the speed control module to the saturable reactor.

2. Design Considerations

Four considerations were given design priority. These were simplicity in circuitry, redundancy of components potentially vulnerable to radiation and high temperatures, isolation of components from environmental hazards, and operation of components significantly below their current, voltage and temperature ratings.

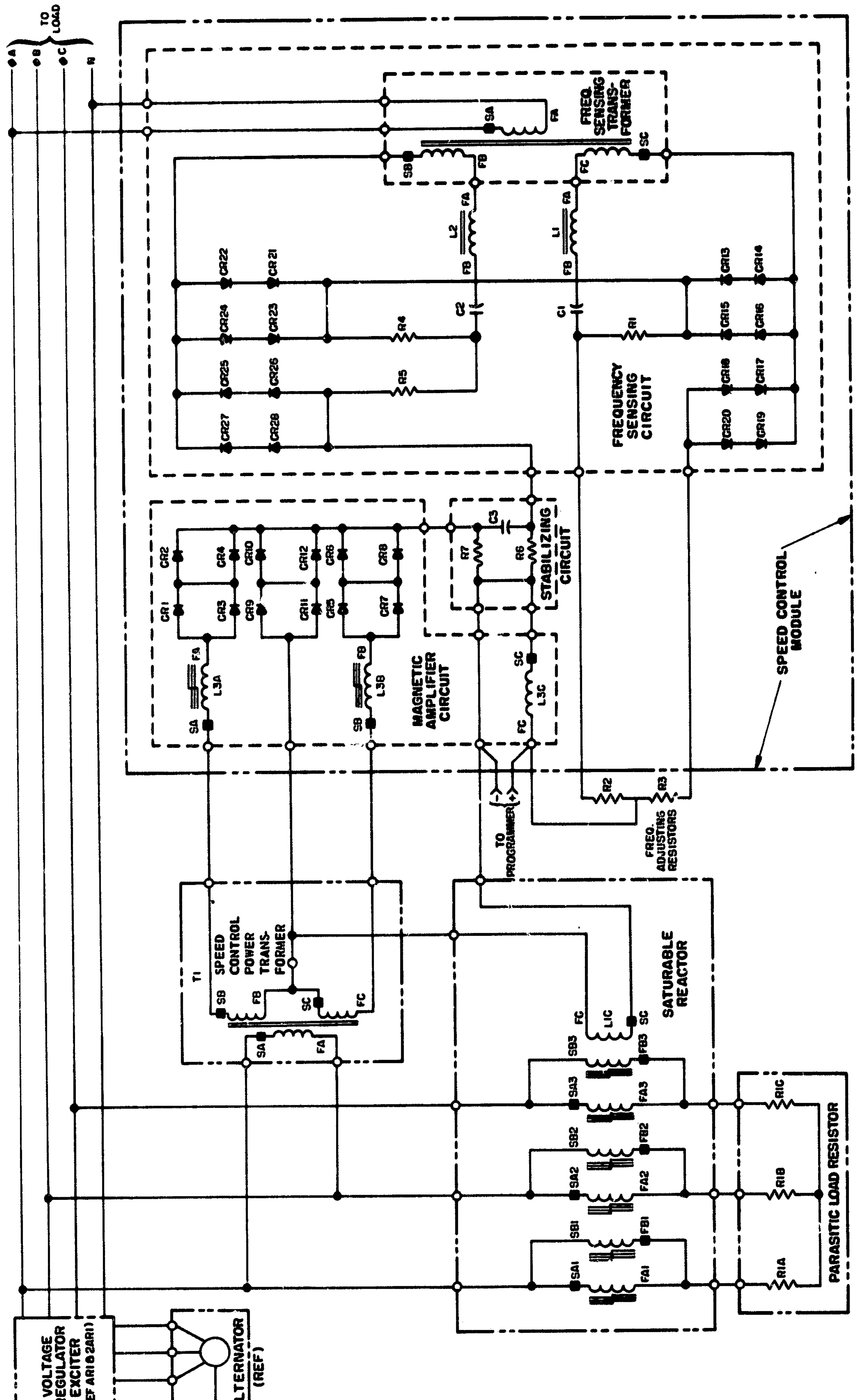

Figure 2. Speed Control System Schematic

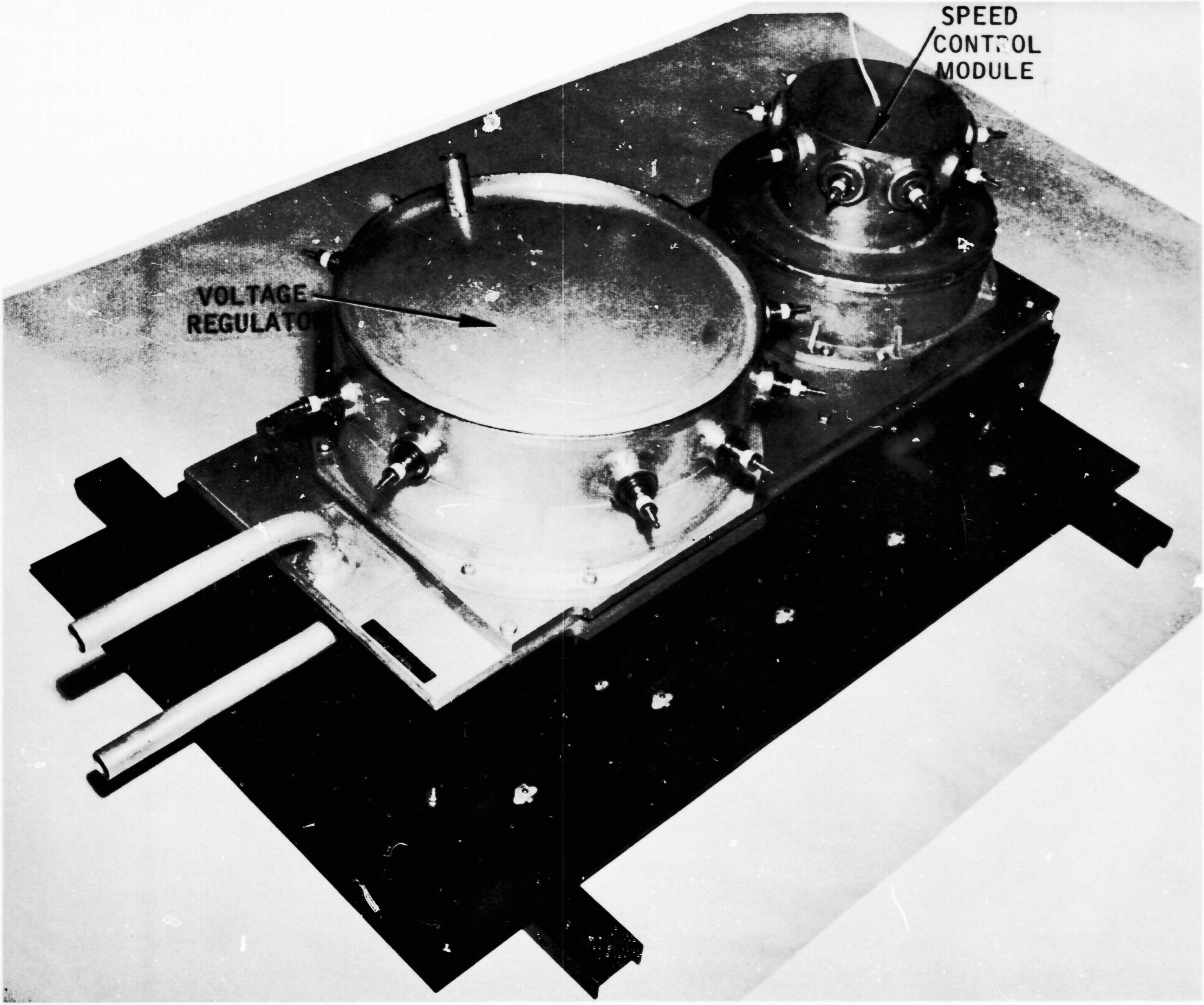

Figure 3. Speed Control and Voltage Regulator Modules Mounted on Heat Sink

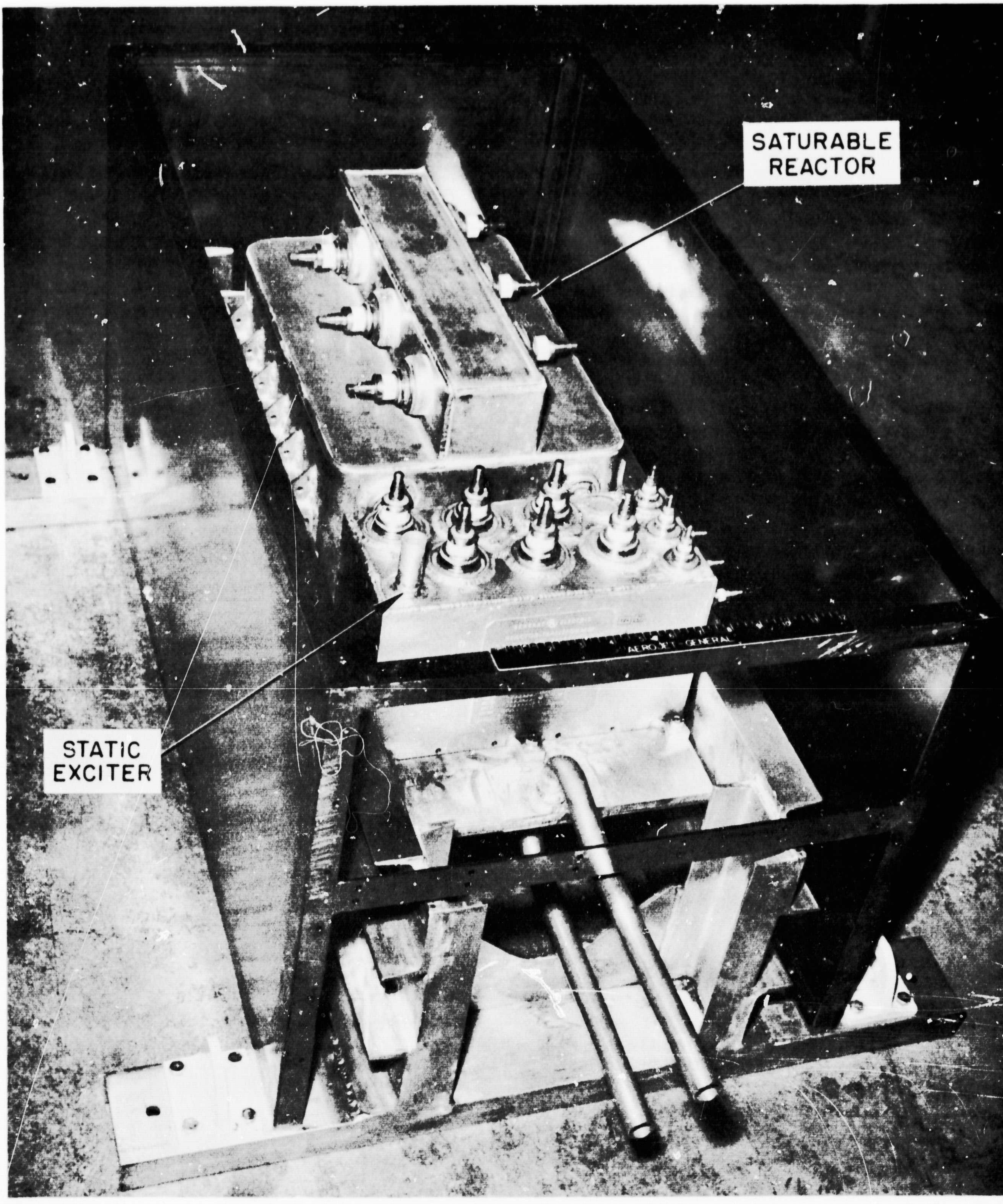

Figure 4. Saturable Reactor and Static Exciter Mounted on Heat Sink

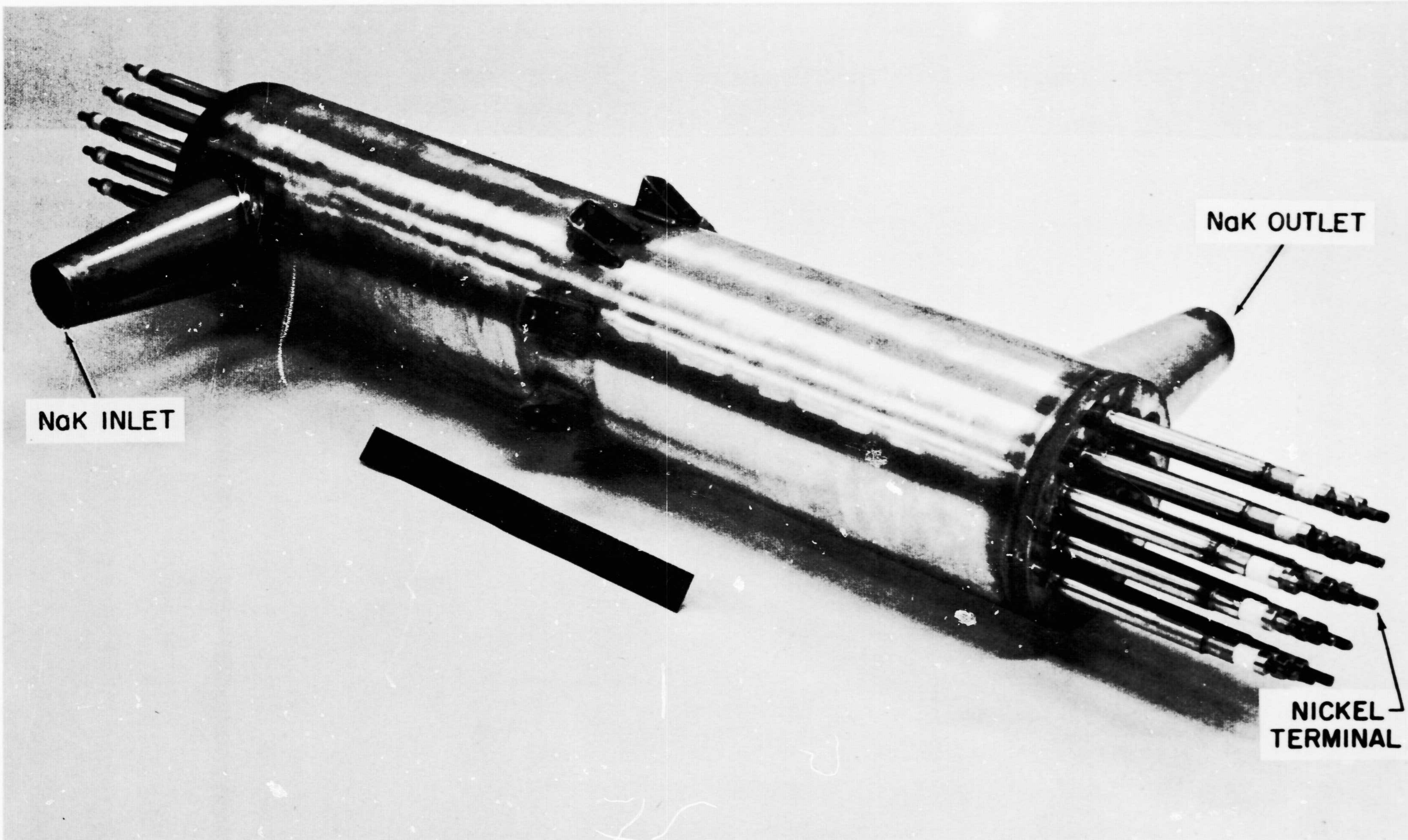

Figure 5. Parasitic Load Resistor

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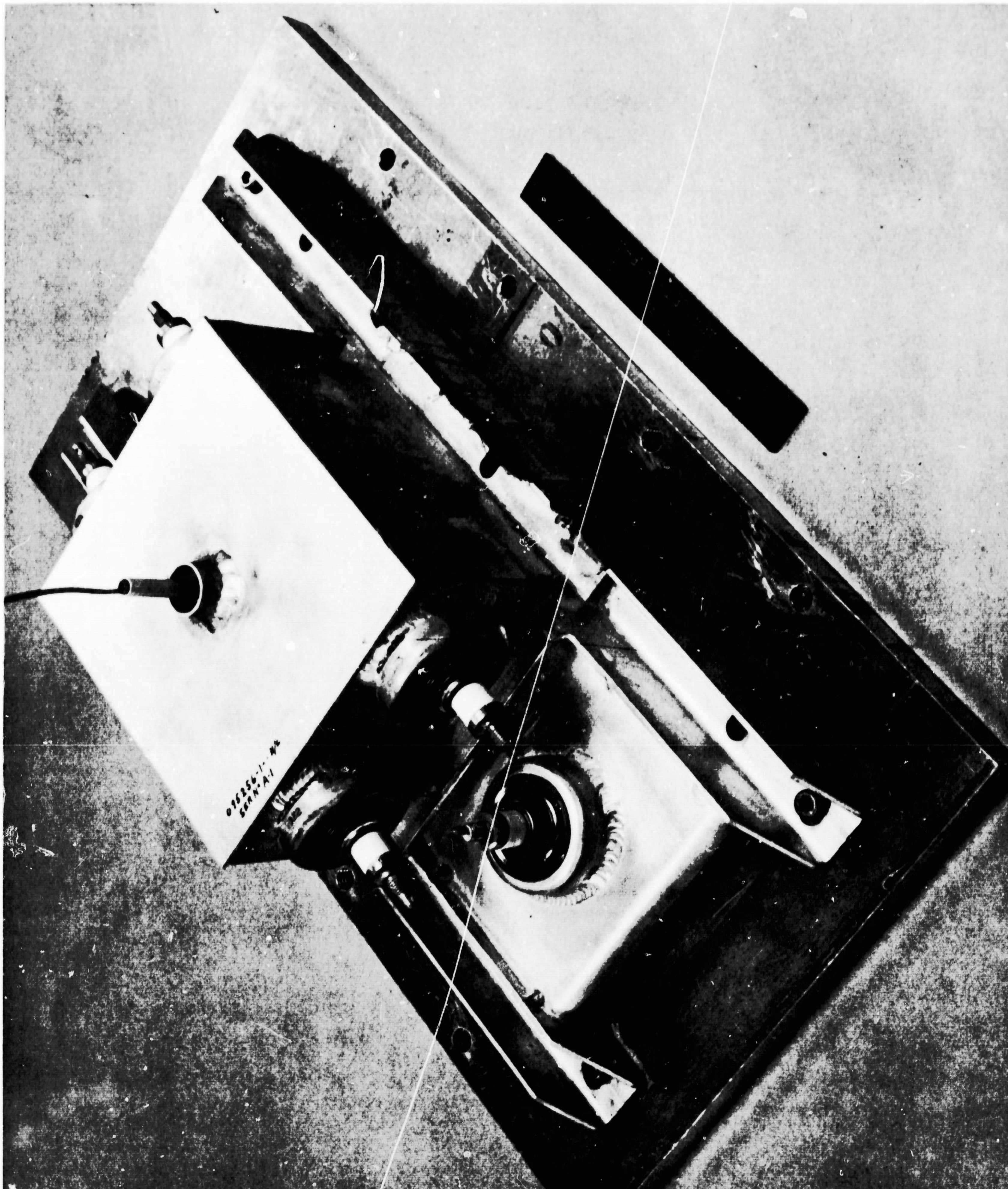

The frequency circuit was designed to produce sufficient power output to only require single stage amplification. Therefore, a single phase full-wave center-tapped magnetic amplifier circuit was selected for simplicity and reliability. This design uses fewer rectifiers than a bridge circuit and therefore has higher reliability and improved efficiency.

The use of twenty-eight diodes (rectifiers), is an example of redundancy of vulnerable components to improve reliability. While only seven diodes are necessary for the efficient operation of the speed control system, the use of twenty-eight diodes allowed for the possible failure of as many as 21 diodes without affecting speed control performance. The diodes are connected in quads. Each rectifier uses four diodes connected in two branches with two diodes in series in each branch. If one rectifier in either or both branches shorts, the rectifier will continue to function. If one rectifier in either branch opens, the rectifier will again function normally. Figure 7 illustrates how the failure rate is reduced by redundancy. If the failure rate of an individual rectifier is .01%, the quad will have a failure rate of .00001%.

The requirement for isolation of components from hostile environments resulted in a packaging design capable of sealing all components while providing effective heat transfer, and adapting to the use of welded connections.

High reliability of the speed control system was further enhanced by the operation of components at less than rated current, voltage, and temperature. The diodes selected are operated at 25 percent of the rated operating voltage with a forward current of less than 1/10 of the rated current. The capacitors used in the circuit are operated at 50 percent of rated voltage and the resistors at 25 percent of their power ratings.

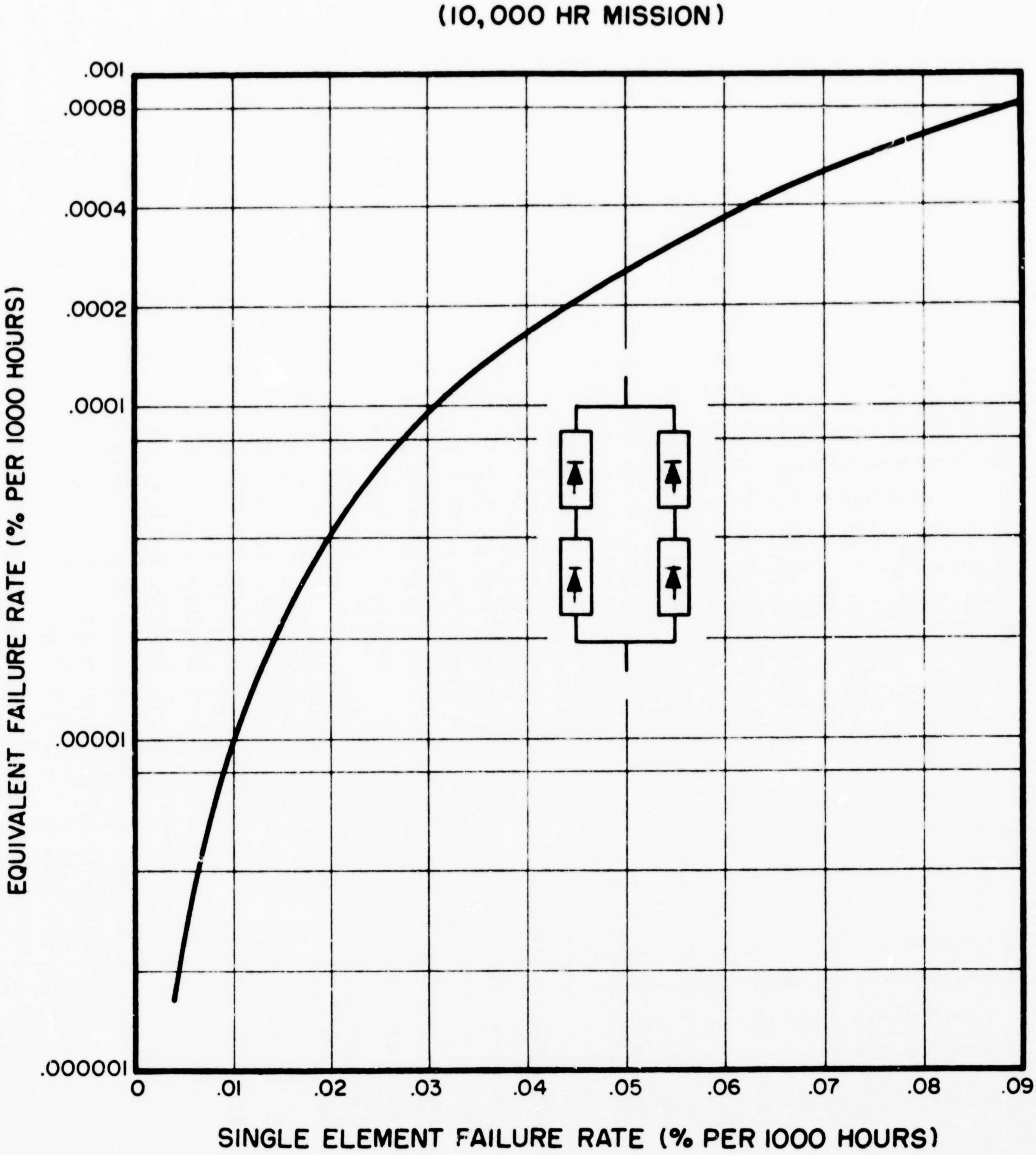

Figure 7. Failure Rate for Rectifier Quad

III. DESIGN

A. SPEED CONTROL SYSTEM DESIGN REQUIREMENTS

General operating design parameters for the speed control system are as follows:

Power, (maximum control) KW	47
Power, (vehicle load range) KW	0 to 35
Frequency, Hz	400 ± 4
AC voltage, rms (3-phase)	120/208 ± 5%
Life, hours	10,000
Shelf life, years	2
Reliability (for 10,000 hours continuous rated operation), %	99.64
Power dissipation, watts	
Speed control module	75
Speed control power transformer	25
Saturable Reactor	650

1. Performance

For normal operation, the power dissipated in the parasitic load resistor varies directly with changes in turbine speed (see Figure 8).

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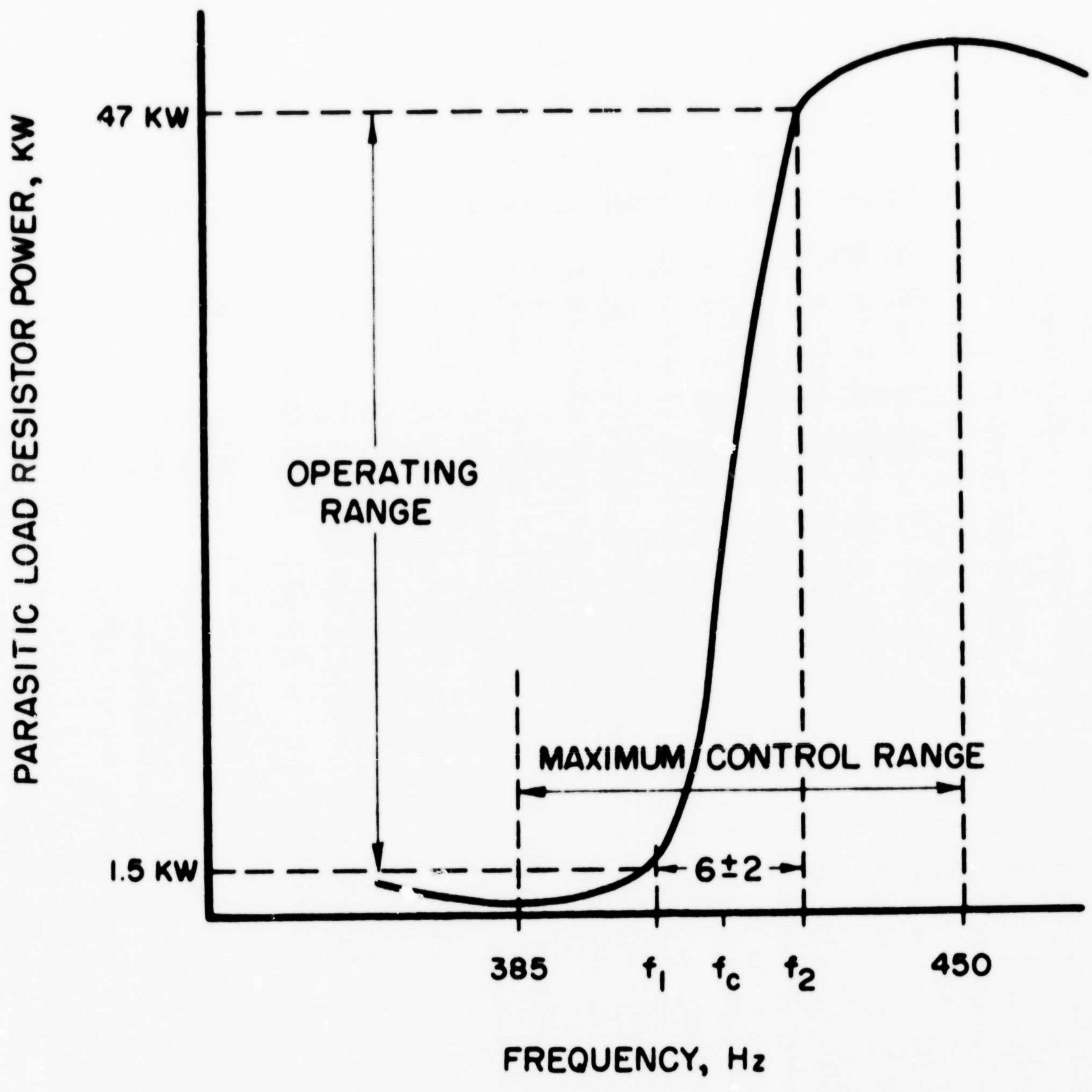

Figure 8. Speed Control Operating Range

2. Maximum Control Range

The maximum control range (385 to 450 hz) is that portion of the alternator frequency versus the parasitic load resistor power transfer curve wherein the slope is greater than or equal to zero (see Figure 8). A positive slope is defined as one wherein the parasitic load resistor power varies directly with the frequency of the alternator voltage. Provisions are included for applying a direct current bias to the control winding of the magnetic amplifier of the SCM from the programmer, and was incorporated to prevent power dissipation in the parasitic load resistor when the frequency is below 385 hertz. A bias current of 20 to 25 milliamperes is sufficient to perform this function.

3. Normal Operating Range

The normal operating range is that portion of the maximum control range at or near 400 hertz where the total 3 phase parasitic load resistor power is between 1.5 kw and 47 kw for a frequency change of 6 ± 2 hertz (see Figure 8).

4. Frequency Set Point Adjustment

The frequency set point adjustment is located externally to the speed control module and provides a minimum adjustment range of 8 Hz. When the control is set midway between its adjustment limits, the arithmetic center frequency of the normal operating range is 400 ± 2 Hz (see Figure 8) when computed as follows:

$$F_c = \frac{F_1 + F_2}{2}$$

where F_c is the center frequency

F_1 is the frequency at 1.5 kw PLR power

F_2 is the frequency at 47 kw PLR power

5. Center Frequency Drift

Center frequency drift is defined as the change in the value of the arithmetic center frequency of the speed control after it has been temperature stabilized and its center frequency set at 400 hertz. This change is limited to the range 396 to 404 hz corresponding to parasitic loads of 1.5 to 47 kw, respectively. Conditions that could cause a change in speed control components during the rated life of the speed control assembly would include but is not limited to the following:

a. Extended exposure to the environments specified in paragraph III-A-10 and Table II.

b. Operation at different points within the environmental limits.

c. Local thermal changes caused by operating at different points within the normal operating range.

6. Transient Response

The speed control has been designed for a time constant of less than 0.50 seconds. This time constant is defined as the arithmetic sum of the saturable reactor time constant and the speed control amplifier and sensing circuit time constant. The time constant of each component was measured at or corrected to a constant 120/208 v rms and 400 Hz and is defined as one-fifth the time for the component output change to complete 99 percent of the change when a step change input is applied. This time constant was predicted to be adequate for controlling the turbine-alternator assembly speed when step vehicle loads of 35 kw were added or removed, if after the vehicle load change, the operating parasitic load resistor power was between 1.5 kw and 47 kw. Transient speed dips and rises greater than ± 1 percent were permissible as long as the speed returned to within the ± 1 percent band in less than 5 seconds. The speed control must maintain the turbine-alternator assembly speed below 13,200 rpm (440 Hz) during such a transient.

7. Rated Temperature

The rated temperature of each speed control component is the maximum internal hot spot temperature at which the most temperature sensitive part in the assembly will reliably operate continuously and comply with the system design requirements. Materials were selected which had the highest rated operating temperatures available commensurate with other design considerations. The maximum internal hot spot temperature and hence the rated temperature for each speed control assembly is as follows:

a. Speed Control Module - 275°F (125°C)

b. Speed Control Transformer - 425°F (220°C)

c. Saturable Reactor - 425°F (220°C)

d. Parasitic Load Resistor - 660°F (349°C)

8. Heat Transfer

The speed control assemblies are designed to transfer the internally generated heat to actively cooled heat sinks and maintain acceptable internal hot spot temperatures. The temperature at the surface of the speed control module heat sink is 155° ± 20°F (68° ± 11°C). The temperature of the surface of the speed control transformer and saturable reactor heat sink is 232° ± 20°F (111° ± 11°C). When the assemblies are operated at these temperatures, none of the assemblies has hot spot temperatures in excess of their rated temperatures.

9. Nuclear Radiation Resistance

The materials selected for use in the fabrication of the speed control system withstand total integrated radiation including direct, scattered, and secondary radiation from all nuclear sources as follows:

a. Fast neutrons (0.1 MEV or greater)

10^{11} nvt (n/cm^2), integrated dose for 10^4 hours

b. Gamma rays

10^6 rads (C), integrated dose for 10^4 hours

10. Isolation from Environments and Packaging Design

The environment in which the speed control system must operate, as a part of the total SNAP-8 system is summarized in Table I. Isolation is accomplished by hermetically sealing all parts and circuits in an atmosphere to exclude contaminants and protect against natural and human hazards. The module also includes a 6061-T6 aluminum housing and base plate designed to provide maximum heat transfer into the heat sink.

The speed control module assembly (Figure 3), the saturable reactor assembly (Figure 4), and the speed control power transformer assembly (Figure 6) are hermetically sealed packages. The parasitic load resistor assembly (Figure 5), due to its mode of heat transfer, is remotely located in the heat rejection loop. Each of the first three assembly packages consists of an aluminum base plate for heat transfer, an aluminum housing and hermetically-sealed ceramic insulated terminals. Aluminum was selected for the module housing and base plate because of ease in fabrication, excellent heat transfer characteristics, and adaptability to welding.

ENVIRONMENTAL CONDITIONS (At Maximum Stress)	POSITION OF MODULE	MAXIMUM ENVIRONMENTAL FACTORS DESIGNED TO WITHSTAND			
Atmospheric Contaminants	Launch-pad and lift-off	Salt fog, rain, 100% relative humidity, winds, sand, dust, and fungus.			
Temperature	All phases	Non-operational (external): -40 to 160°F Operational (internal): 32-260°F - Short periods 260°F - Continuous			
Thermal Shock	Launch-pad and lift-off	Maximum increase and decrease of 18°F/hour of solar radiation from 110 to 410 Btu/ft^{2}hr.			
Pressure	All phases	One (normal) atmosphere pressure to 1 x 10^{-12} torr.			
Explosive Atmosphere	All phases	Designed to avoid reaction with strong concentrations of hazardous gases (according to requirements specified at altitudes to 5,000 feet, in Procedure I, Method 511 of MIL-STD-180.)			
Radiation (reactor induced)	Space (operational)	Fast neutrons 1 x 10^{11} nvt Gamma rays 1 x 10^{6} rads			
Electromagnetic interference	Space (operational)	(According to MIL-STD-826, Method 1001, Class Am., Type C.)			
		PULSE AMPLITUDE (and type)	DURATION	DIRECTION	FREQUENCY RANGE
Shock	Lift-off and space	35g half-sine 35g triangular 35g rectangular	8 milliseconds 10 milliseconds 5 milliseconds	(3) in each axis and either direction (18 total)	Not applicable
		20g half-sine	10 milliseconds	Each axis, either direction	Not applicable
Acceleration	Lift-off and space	6g	5 minutes	In longitudinal axis (parallel to gravity vector)	Not applicable
		3g	5 minutes	In a direction opposite to the longitudinal axis	Not applicable
		4.5g	5 minutes	In mutually perpendicular transverse axes	Not applicable
Vibration	Lift-off and space	0.25g	5 minutes	All	5-2000
	Lift-off	2.0g	Peak periods	All	16-42
		0.022 in. displacement amplitude	Peak periods	All	42-95
		10g	Peak periods	All	95-2000
Acoustic Noise	Lift-off	Maximum 152db	Peak periods	All	65-150
		Greater Than 115db	Peak Periods	All	16-8000

TABLE I. ENVIRONMENTAL REQUIREMENTS

Packaging with provision for adequate heat transfer was especially important in the mechanical design of the saturable reactor assembly, since it produces the greatest power loss of the three assemblies. Low thermal resistance paths are provided from the saturable reactor to the base plate which also serve to provide the required mechanical support.

All electrical connections in the three speed control assemblies are tungsten inert gas welded (TIG-welded) to ensure maximum reliability or electrical joints. Since few TIG-welded electrical joints had been used in this type of electrical equipment, it was necessary to develop new techniques in each welding application. Typical welded joints are shown in Figure 9. Mounting assembly and connection techniques of the speed control module are shown in Figure 10. Electrical connections are made through ceramic insulated feed through nickel terminals. The Koldweld process (Kelsy-Hayes Company) was used to attach the copper transition flange on each ceramic terminal to the aluminum housing and provides the transition from the nickel skirts of the terminals to the aluminum housing of the modules (see Figure 11). The joining of copper to 6061-T6 aluminum was evaluated by mechanical testing and metallographic examination after thermal exposure at 350°F for periods up to 3000 hours. From this test it was observed that there was a decrease in tensile strength (7.8%) and an increase in ductility (20%). The yield strength, however, remained unchanged.

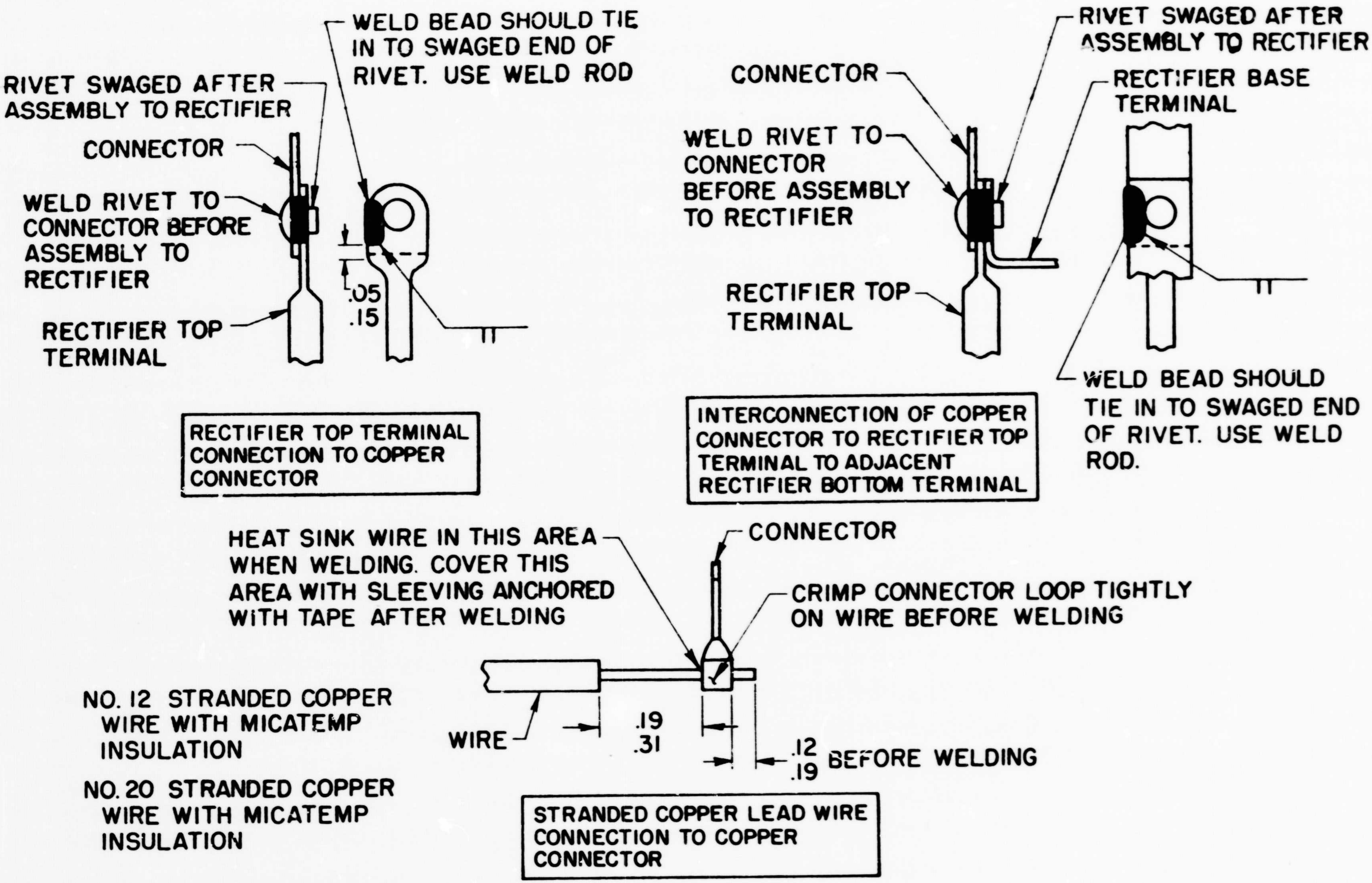

Figure 9. Typical TIG Welded Joints

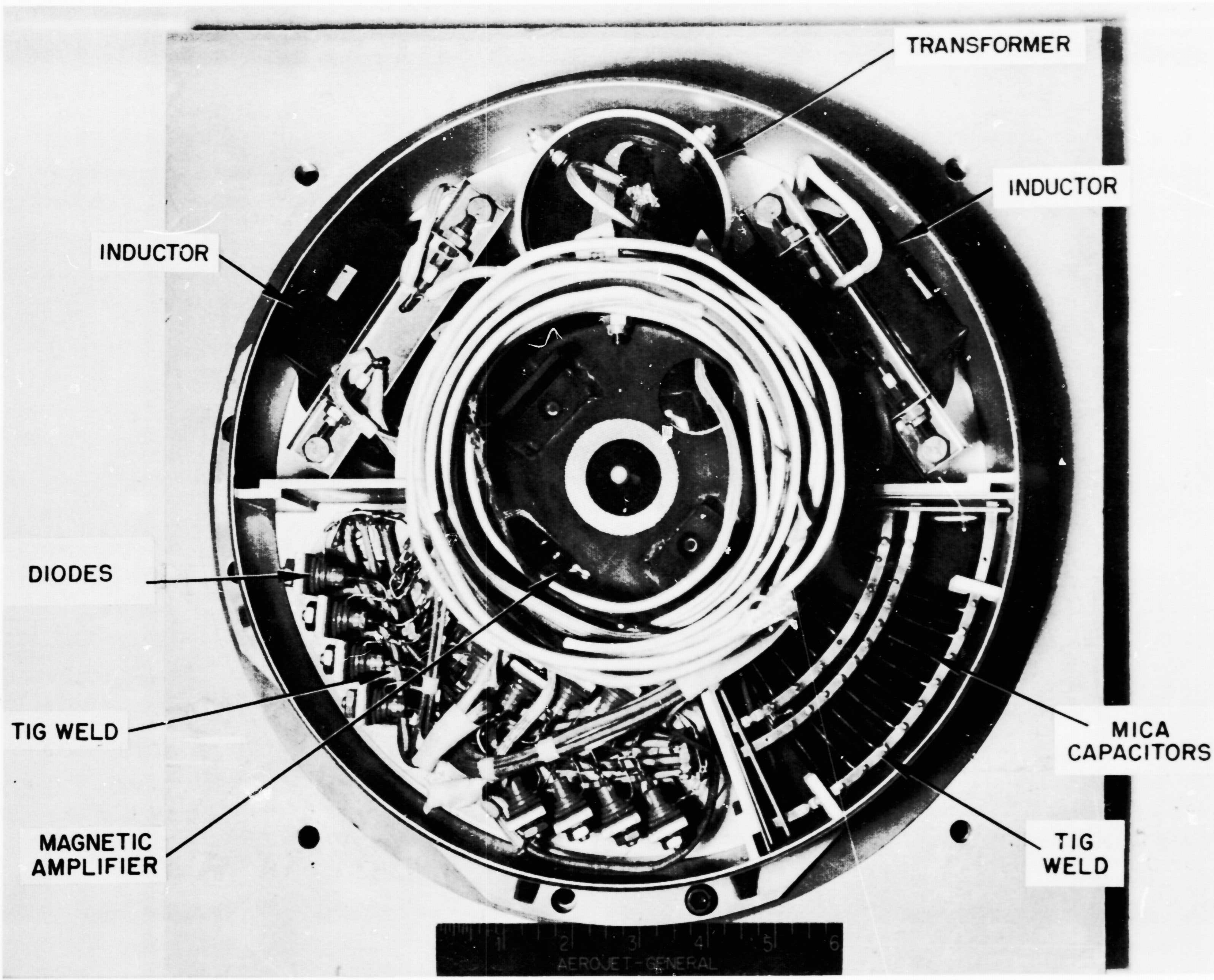

Figure 10. Inside View of Speed Control Module Showing

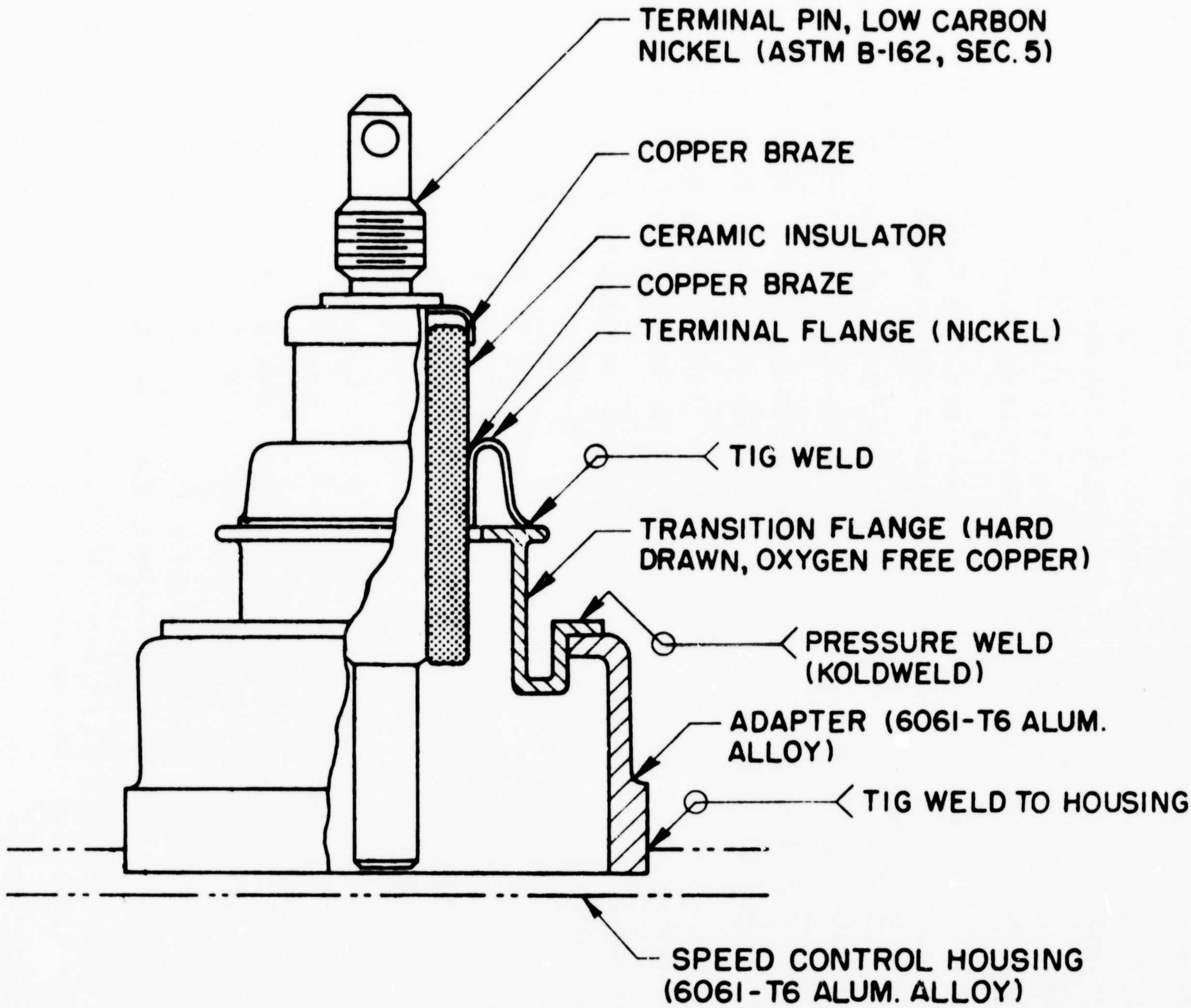

Figure 11. Ceramic Insulated Terminal

11. Magnetic Component Materials

The following materials were selected for use in fabrication of the magnetic components: magnet wire-HML insulated copper wire, lead wires - either self-leads or Rockbestos insulated stranded bare copper wire, sheet insulation-ML impregnated glass fabric, Doryl-Glass laminate and Silicon Glass laminate, impregnating material-Furane 17A, dipping compound-Sylgard 183, potting material-Epoxolite 813-9. All the magnetic components except the saturable reactors were fabricated by winding with HML insulated magnetic wire, impregnating with Furane 17A and covered with Sylgard 183. The saturable reactors were fabricated in the same manner except that they were not coated with Sylgard 183.

12. Speed Control Component Weights

Speed control component weights are approximately as follows:

Speed Control Module - 25 pounds

Speed Control Transformer - 10 pounds

Saturable Reactor - 200 pounds

Parasitic Load Resistor (Dry) - 60 pounds

B. COMPONENT DESIGN REQUIREMENTS

1. Parasitic Load Resistor (PLR)

General design parameters for the parasitic load resistor are:

Power, kw	47
Power density, watts/sq in.	75
Power factor, lagging	0.99 minimum
Frequency, Hz	400

Operating temperature, °F	660
Reliability	0.99
Coolant fluid	Sodium-potassium Eutectic(NaK)
Coolant fluid flowrate, lb/hour	40,000 ± 4000
Coolant fluid inlet temperature, °F	650 ± 10

a. PLR Performance

The parasitic load resistor is a balanced three-phase, wye connected fixed resistance load capable of dissipating a maximum load of 47 kw. When the parasitic load resistor is at rated temperature, the line-to-neutral resistance of each phase is such that 47 kw would be dissipated, if the applied line-to-neutral voltage is 105 vrms, and the equivalent line-to-line voltage is 182 vrms.

b. PLR Phase Balance

Each set of resistors are matched and marked for balanced resistance between the phases within five percent as follows:

$$R_{max} - R_{min} \leq 0.05 \times \frac{R_1 + R_2 + R_3}{3}$$

where: R_{max} = highest value of phase resistance

R_{min} = lowest value of phase resistance

R_1, R_2, R_3 are values of phase resistance for each phase

c. PLR Internal Pressure

The parasitic load resistor must be capable of adjusting to the sudden load changes of the speed control system and the resultant changes in system pressures and temperatures. The parasitic load resistor is designed to withstand an internal proof pressure of 500 psid, without leakage damage, or permanent distortion. At maximum operating temperature, the PLR must withstand an internal pressure of 80 psid for 10,000 hours. At design conditions and short term operation (40 seconds, 20 times), it is designed to withstand an internal pressure of 75 psid at 1350°F.

d. PLR External Pressure

The parasitic load resistor is designed to withstand an external pressure of 15 psia while evacuated for testing, cleaning, or other processing at any temperature up to 795°F.

e. NaK Pressure Drop Through PLR Coolant Passages

The pressure drop through the parasitic load resistor while operating at temperatures between 640° to 660°F does not exceed 1.0 psi at rated flow.

f. PLR Temperature Transients

The parasitic load resistor is designed to operate without incurring any damage or distortion when subjected to a transient of 8°F per second for 60 seconds, in the temperature range of 200° to 700°F for a minimum of 100 times.

2. Magnetic Amplifier

The magnetic amplifier is designed to provide full rated saturable reactor control current at a gate firing angle of 90°. During severe transients with a vehicle load step change from 35 KW to zero and back to 35 KW, a gate firing angle near zero degrees could be obtained (if sufficient magnetic amplifier control current is available) producing sufficient magnetic amplifier output to obtain twice the rated saturable reactor control current. This improves the system transient response over what might normally be expected from the individual components' time constant. Figure 12 shows that for a frequency change from 396 to 404 hertz, a 14 milliampere change in magnetic amplifier control current can be obtained. Figure 12 also shows that the sensing circuit can produce control currents from plus values to -30 milliamperes. From test data it was determined that a 10 milliampere change in magnetic amplifier control current was sufficient to produce a change in saturable reactor control current from minimum to rated value. This verifies that there is sufficient magnetic amplifier control drive to realize the 2 times forcing capability from the magnetic amplifier output. The magnetic amplifier is designed to operate from a power transformer supplying 58 v rms either side of center tap and is capable of delivering output currents equivalent to those flowing at zero degree firing angle for extended periods of time.

The power input to the magnetic amplifier is supplied from the output of the power transformer. The magnetic amplifier control signal comes from the frequency sensing circuit to which is added a rate feedback stabilization signal from the saturable reactor input current. The output of the magnetic amplifier then becomes the control signal to the saturable reactor control winding. A single phase full-wave centertap magnetic amplifier circuit was selected for the following reasons:

- It uses fewer rectifiers than a bridge circuit.
- Fewer rectifiers mean lower power losses and better efficiency.
- Fewer parts mean circuit simplicity and improved reliability.

A centertapped power transformer was selected for the magnetic amplifier circuit. This particular design is heavier than a bridge circuit, which does not require a power transformer. However, the following desirable features are associated with the use of a power transformer:

- The input is electrically isolated from the output.
- The magnetic amplifier output voltage can be matched to the actual requirements of the saturable reactor control windings.
- The amount of self-generated electrical noise in the magnetic amplifier feeding into other circuits through the power distribution system is reduced. This capability could be further improved if necessary by adding an electrostatic shield between the transformer primary and secondary windings.

The choice of core materials was of particular importance in the magnetic amplifier for it determined the minimum value of output current. The higher value of minimum output current that occurs because of the higher core losses in core materials having the higher saturation flux densities is insignificant if the magnetic amplifier power output is high. However, the core material could be quite limiting at lower power output levels. For example, a minimum "off" current of 0.5 ampere would not be a problem, if the "on" current were 10 amperes or more. However, a serious problem would exist if the "on" current was 1 ampere. Since the minimum power dissipated in the parasitic load is quite important during system "start up", it is desirable to have the minimum possible "off" current from the magnetic amplifier controlling the saturable reactor.

Deltamax, a trade name for a grain-oriented 50% nickel and 50% iron, was the selected material for the magnetic amplifier core. The other two alternate choices, Silectron and Supermendur, permit 10% to 25% higher saturation flux densities than Deltamax. Their core loss factors are on the order of four times that of Deltamax, making Deltamax the most logical choice.

To obtain optimum utilization of the core properties of Deltamax, a tape-wound toroidal core configuration was selected. A four mil thick tape was used to reduce the core loss due to eddy currents at 400 hertz. This helps keep the core excitation low without serious degradation of other magnetic properties.

3. Frequency Sensing Circuit

The frequency sensing circuit design is a single phase, stagger-tuned four-diode half-bridge circuit. For the frequency versus current output of this circuit, see Figure 12. The circuit input is provided by the single phase, line-to-neutral output from the alternator. The sensing circuit detects changes in turbine speed as a change in the frequency of the alternator output voltage. This circuit has a high source impedance which makes the power source for the control winding of the magnetic amplifier a current supply resulting in an improved magnetic amplifier time constant. The frequency sensor output current is amplified by the magnetic amplifier which causes the saturable reactor to adjust the load on the alternator by increasing or decreasing the load dissipated in the parasitic load resistor. The maximum frequency control range for the speed control system (see Figure 8) is that portion of the curve from approximately 385 to 450 hertz.

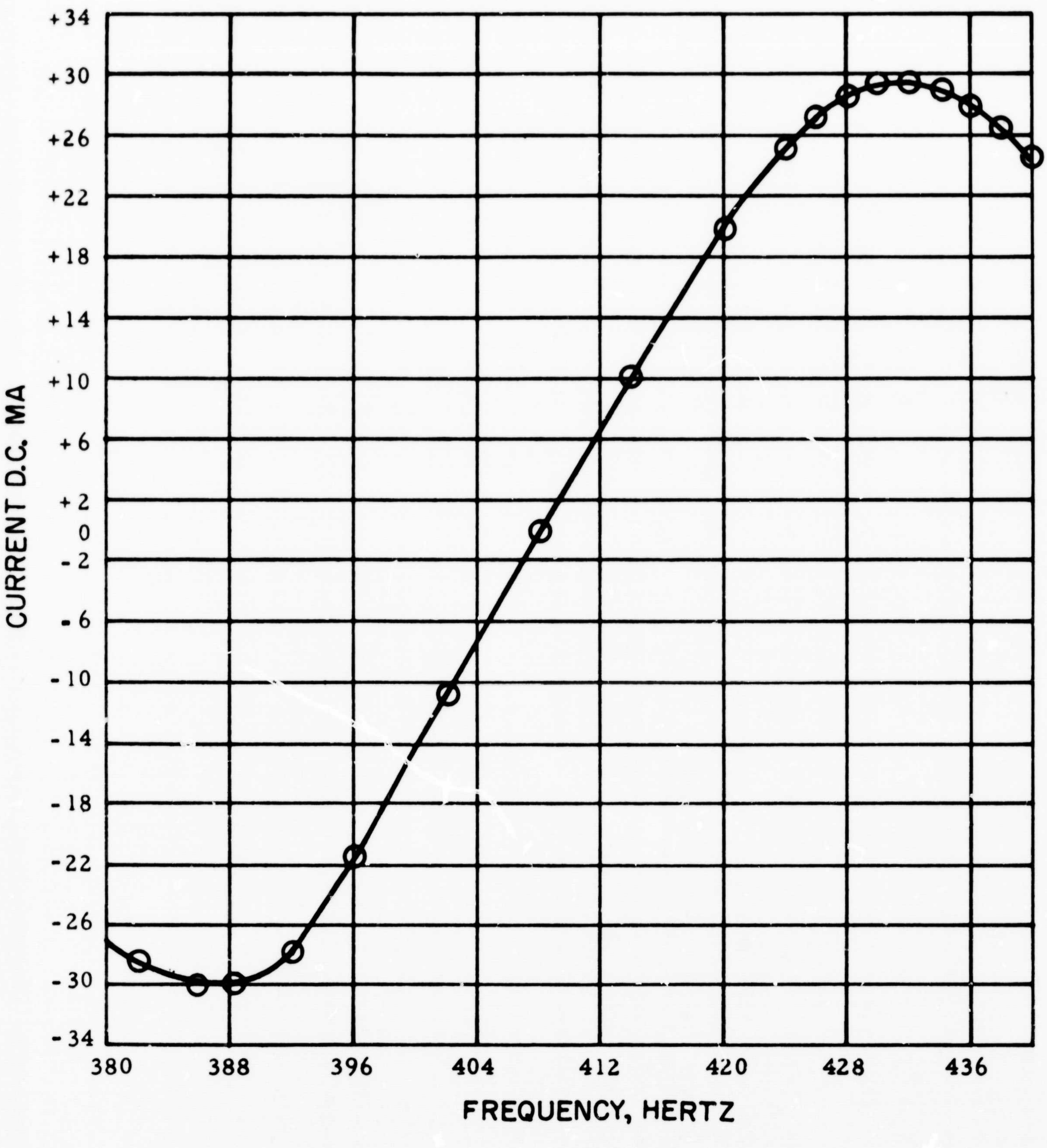

Figure 12. Sensing Circuit Output vs Frequency

5. Saturable Reactor (SR)

The saturable reactor is built in one assembly with six grain-oriented silicon steel cores, six gate windings, and one control winding. The power input to the saturable reactor comes from the 3 phase output voltage of the turbine-alternator. The control input signal is the full-wave rectified dc from the speed control magnetic amplifier. This signal causes the saturable reactor to maintain the load on the alternator by increasing or decreasing the load dissipated into the parasitic load resistor. The normal load operating range of the saturable reactor is from 1 kw to 47 kw.

IV. DEVELOPMENT

A. ELECTRICAL

1. Startup Loading

The speed control system exhibits an undesired loading action at and below frequencies of 385 hertz. At frequencies below 385 hertz, the slope of the sensing circuit's transfer curve for frequency input versus current output, reverses direction (see Figure 12). This results in reversal of the normal regulating operation, increasing rather than decreasing parasitic load below 385 hertz. An external bias circuit from the programmer is incorporated which automatically overrides the signal from the frequency sensing circuit below 385 hz thus preventing application of parasitic load until normal operating frequencies are reached.

A speed control sensing circuit change to eliminate the need for an external bias circuit was considered. The modified circuit would have replaced one of the series tuned circuits with a low-pass filter. This would have required one extra inductor and a larger capacitor accompanied by considerable rework of the speed control module packaging design. Such a modification is recommended for incorporation at a future date.

The speed control system design includes an R-C negative rate feedback circuit to obtain improved system damping and operating stability (see Section C.1.a).

2. Harmonic Distortion

An analysis of the harmonics made on the output of the alternator system during laboratory motor-driven alternator tests showed that the total harmonic content for both line-to-line and line-to-neutral voltage was less than 7.5% under the most unfavorable conditions. The NASA Specification required that the harmonic content should not exceed 8% line-to-line with balanced linear 100 percent load at 1.0 power factor; therefore, the results achieved were considered satisfactory for the SNAP-8 system.

3. Output Linearity

Performance tests determined that the transfer curve of the magnetic amplifier was less linear than the design requirements. It was established that this was caused by changing the relative phasing of the magnetic-amplifier power supply and the frequency sensing circuit. Tests showed that if the input to the sensing circuit was phase A to neutral, then the input to the magnetic-amplifier gate circuit should be phase A to phase B. Alternate connections were phase B to neutral and phase B to phase C, respectively, or phase C to neutral and phase C to phase A. Any other connection results in reduced gain and nonlinear operation. The method of phasing presently used is phase A-to-neutral to the sensing circuit and phase A to phase B to the magnetic amplifier resolving the non-linearity problem.

B. FABRICATION

1. Cracking of Powdered-Iron-Core Inductor

During the early development phase of the frequency sensing circuit powdered iron mo-permalloy cores were used in the tuned inductors. When these units were wound and temperature cycled, the cores cracked, damaging the inductor. In order to eliminate this problem, grain-oriented silicon iron "C" cores with "air gaps" were substituted for the powdered iron.
The air gap material used was alumina which is a very stable material, maintaining its dimensions over wide temperature and pressure changes. These inductors have made possible a low drift frequency sensing unit.

2. Poor Capacitor Connections

The silvered mica capacitors originally obtained for use in the frequency sensing circuit were made up of several units mounted in a single can and connected together. The internal connections of these units were found to be very poor. To eliminate this problem, individual capacitors were purchased and connected into parallel combinations within the speed control module. Figure 10 shows the capacitor connections within the module.

3. Inductance Change Due to Potting

The first inductors, made with silicon grain-oriented steel with an "air gap", performed successfully before being impregnated but experienced a shift in inductance after impregnation. This problem was caused by the impregnating compound penetrating into the "air gap", changing its length and the stresses induced in the iron after potting. The problem was solved by tuning the inductors after impregnation and then coating them with a resilient material, Sylgard 183. The Sylgard material absorbed the effect of the shrinkage forces of the potting resin. When the inductors were processed in this manner, the inductance shift was very small, well within the trimming range available in the sensing circuit. All tuned inductors are now being fabricated in this manner.

4. Packaging

Packaging of the speed control module presented a unique fabrication task since matching of all the electronic components of the speed control module was required before assembly. There were no potentiometers for setting the operational points of the speed control, and the operational limitations were very stringent. Therefore, the components of the speed control module such as the transformer, the reactors, the capacitors, and the magnetic amplifier had to be assembled on a pre-fabrication-checkout board and tuned to the proper operating point before final fabrication. The components were then removed from the pre-fabrication-checkout board and installed in the speed control module.

5. <u>Magnetic Components</u>

The saturable reactor assembly and the speed control module assembly presented no problems when the magnetic components were fabricated, and no problems were encountered while assembling the capacitors or the resistors in the speed control module. However, the assembling of rectifiers in the speed control module presented some fabrication problems. It was necessary to develop a technique for welding the diodes into the assembly, and then develop a method for testing the diodes and wiring to determine whether damage had been caused during installation and welding. To prevent diode damage, it was necessary to limit the diode temperature to less than 350°F when TIG welding. Figure 13 shows the diode heat sink and a pictorial indication of the technique employed to resolve the difficulties encountered in fabricating this assembly.

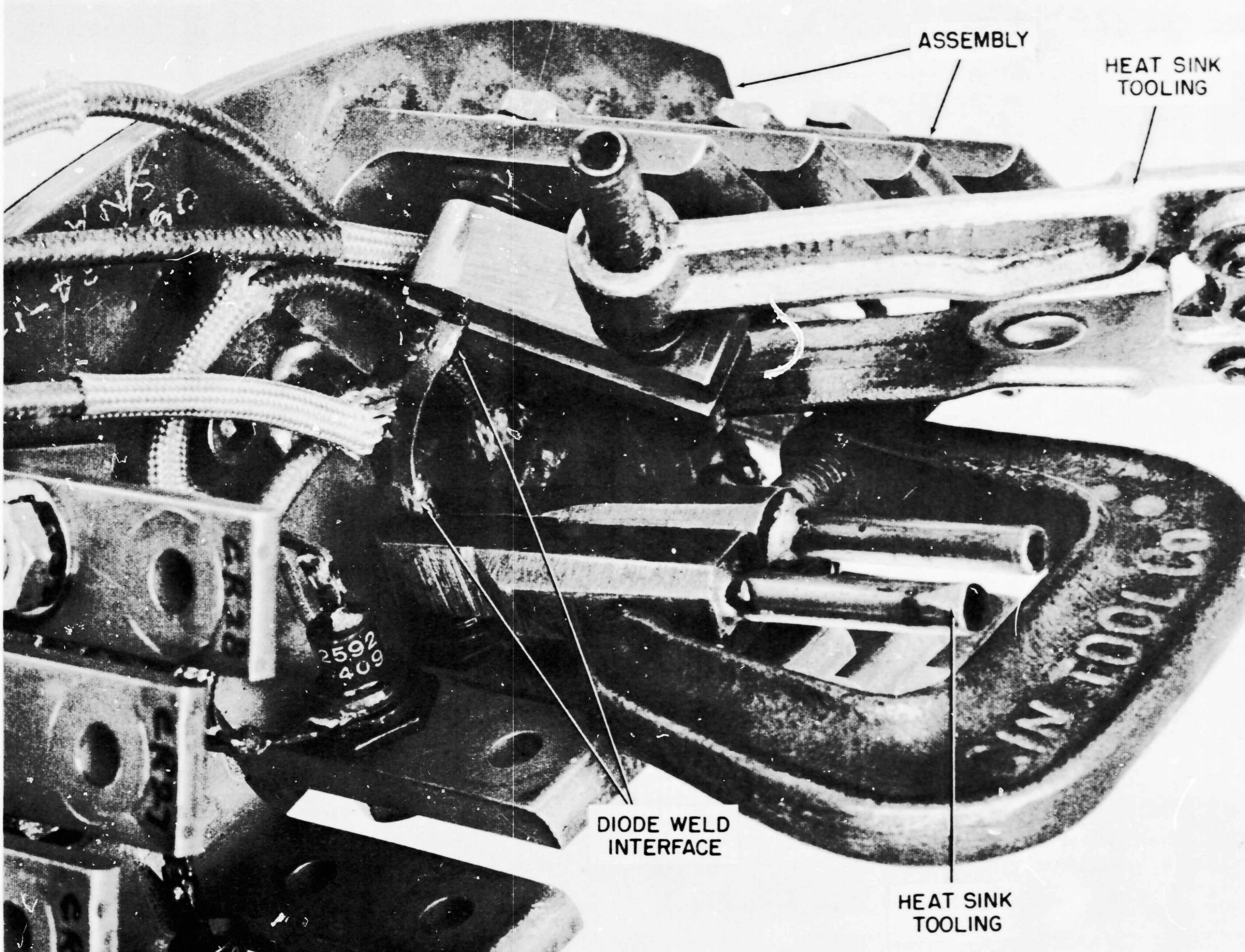

Figure 13. Diode Assembly on Heat Sink

V. TESTING

A. RADIATION EFFECTS TESTS

An irradiation effects test program on selected electrical control components and subassemblies was conducted at the Georgia Nuclear Laboratories of Lockheed-Georgia Company. The components tested were: low and high current silicon diodes, silicon-controlled rectifiers, resistors, and capacitors. The following subassemblies were tested: voltage sensing circuit, four-diode and eight-diode frequency sensing circuits, magnetic amplifier, and a silicon-controlled rectifier circuit. The following materials were tested: magnet wire with insulation of heavy pyre-ML-film, Anaconda H97M film, ceramic enamel over nickel clad copper, flexible lead wire, fibrous material, organic fluids, glass laminate, organic cubes, inorganic cubes, ceramic through type terminals, statorettes, and Teflon sheet and coating (see References 1, 2, and 3).

The integrated exposure of the SNAP-8 speed control system was expected to be 1×10^{11} nvt for a period of 10,000 hours. Most of the data was accumulated over the exposure range to about 1×10^{12} nvt. During the final few hours of the run, the lithium hydride shield was raised to increase the neutron flux. A final exposure of about 6×10^{13} nvt was reached. The results are summarized as follows:

- No significant changes in the performance characteristics of any of the diodes occurred prior to an exposure of about 1×10^{12} nvt.

- The performance of the high-current diodes appeared to be equal to, or better than, that of the low-current diodes. Both types were checked over their respective operating range, which included derating. This information on the high-current diodes was important to the design of the SNAP-8 electrical control system, because it essentially removed an area of concern about the use of diodes in the magnetic amplifier circuit for operation at relatively high-power levels. It was expected that the high-current diodes would be more susceptible to a nuclear environment than would the relatively low-current diodes. Figures 14 and 15 show the range of observed values of forward voltage drop and reverse leakage current for irradiated units of both high and low-current diodes as a function of neutron exposure.

B. DEVELOPMENT PROCESS TESTS

Development process tests were conducted during fabrication to verify the capability of the electrical characteristics of the speed control and the saturable reactor functioning independently. These tests included insulation resistance tests, dielectric strength tests, and electrical response tests. The tests were conducted at various stages of fabrication to determine any possible change in electrical characteristics due to component impregnation or the welding process. The speed control system frequency versus control current, and frequency versus output current fell within the specified range bounded by the respective curves of Figures 16 and 17 The direct current control input versus alternating line current output for the saturable reactor fell within the limits shown in Figure 18. The speed control sensing circuit transient and sustained operating characteristics were verified to be within specified design requirements.

C. SPEED CONTROL SYSTEM TESTS

The individual assemblies of the speed control module, speed control power transformer, and saturable reactor were tested as a system while connected to a hot mercury-vapor-driven turbine. A major objective of these tests was to investigate stabilizing circuits previously defined by analysis and to select the most effective circuit. To accomplish this, steady-state and transient performance data on the speed control system was obtained. A curve of steady state data was prepared to show the effect of parasitic load versus speed control frequency (see Figure 19). The plotted information indicated that the speed control system was functioning adequately.

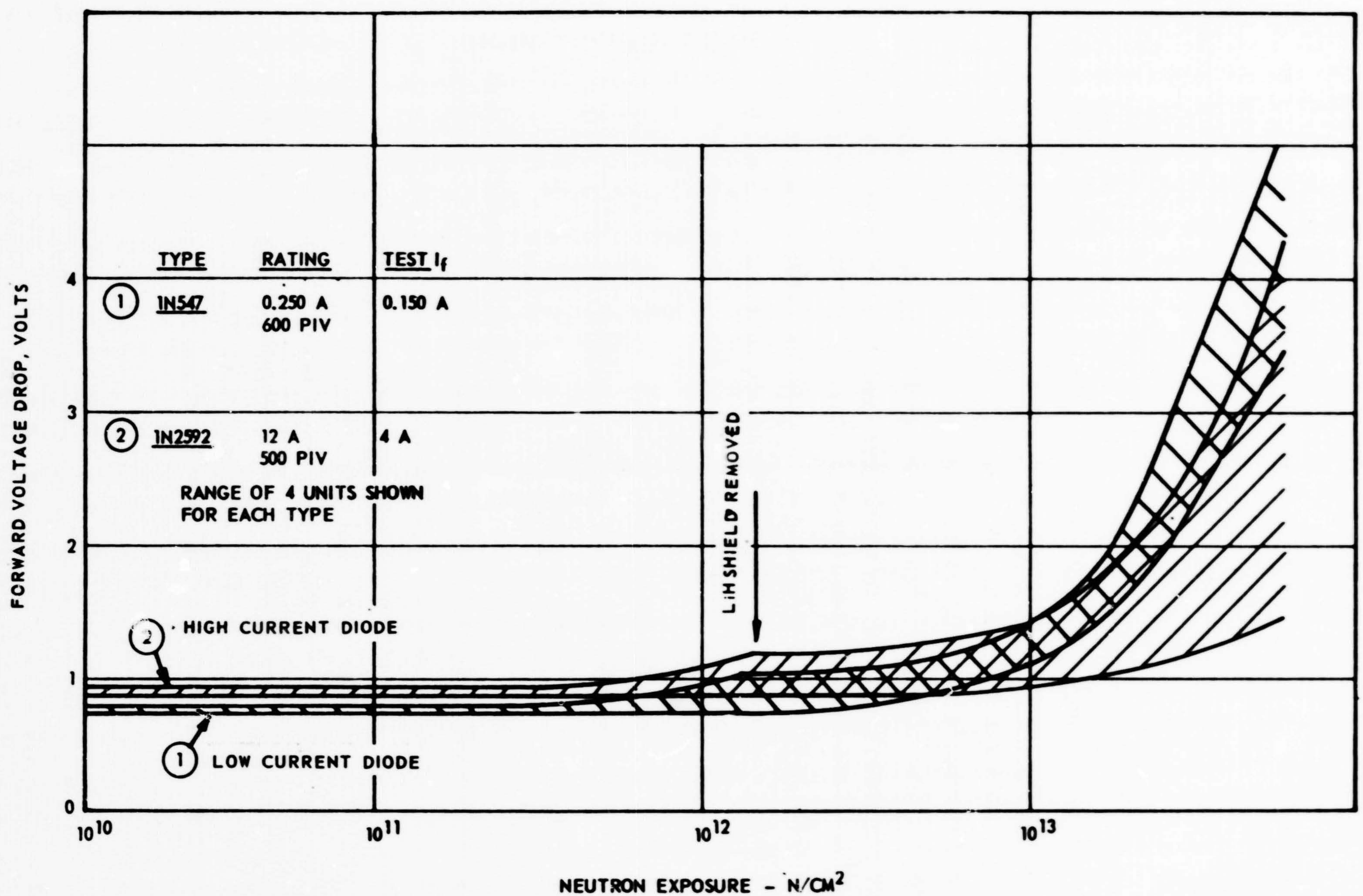

Figure 14. Diode Forward Voltage Drop vs Neutron Exposure

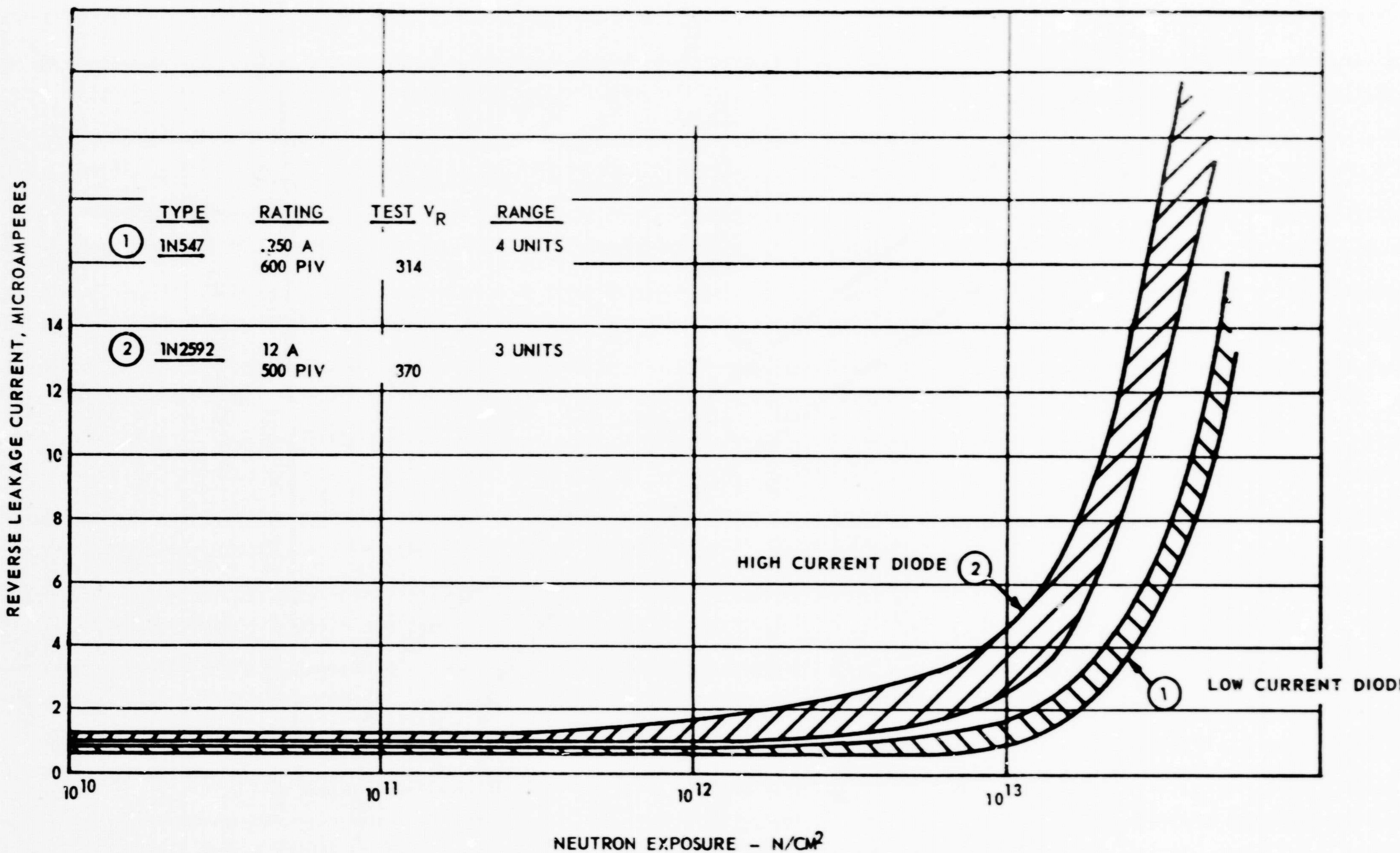

Figure 15 Diode Reverse Leakage Current vs Neutron Exposure

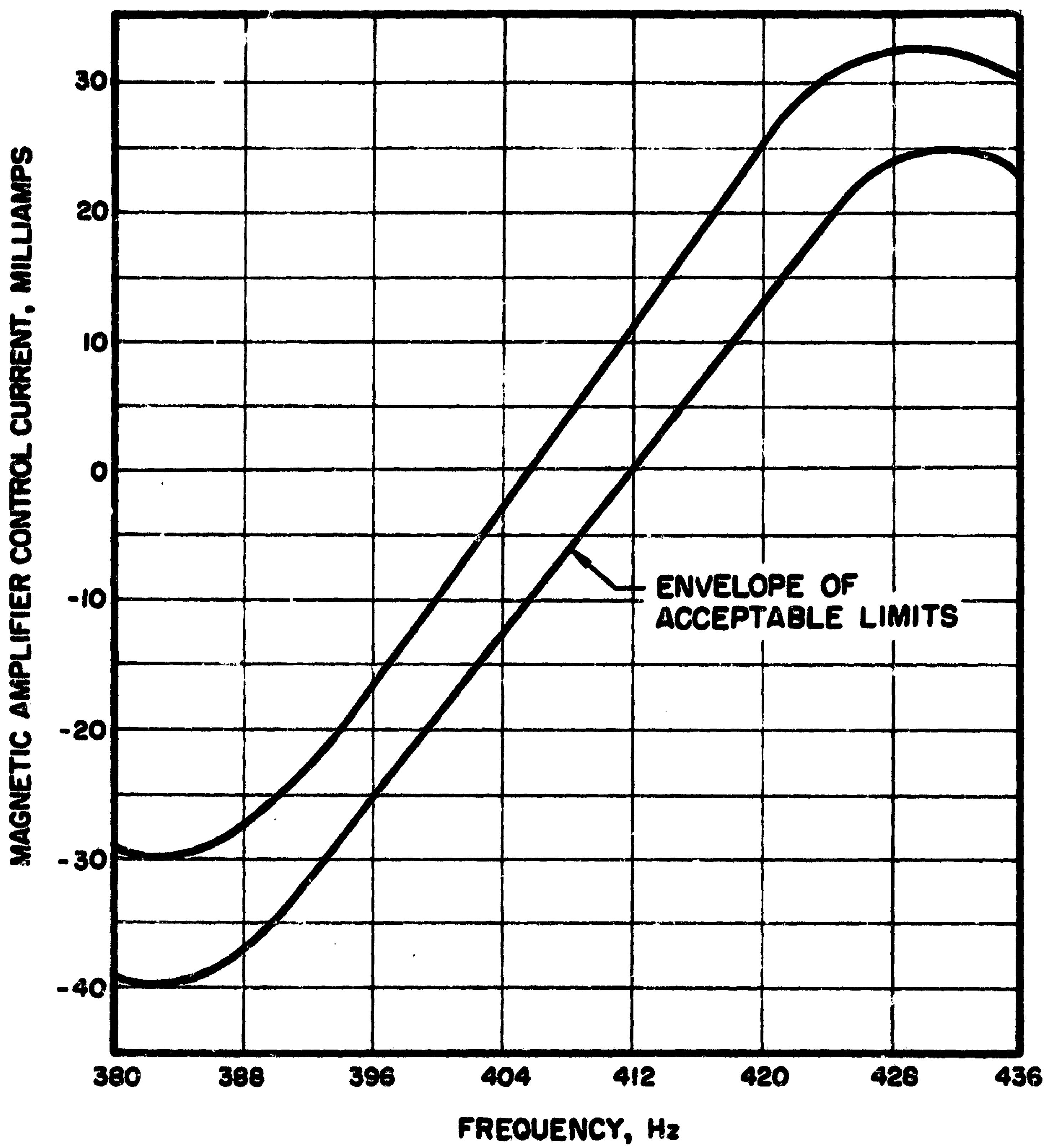

Figure 16. Frequency vs Magnetic Amplifier Control Current

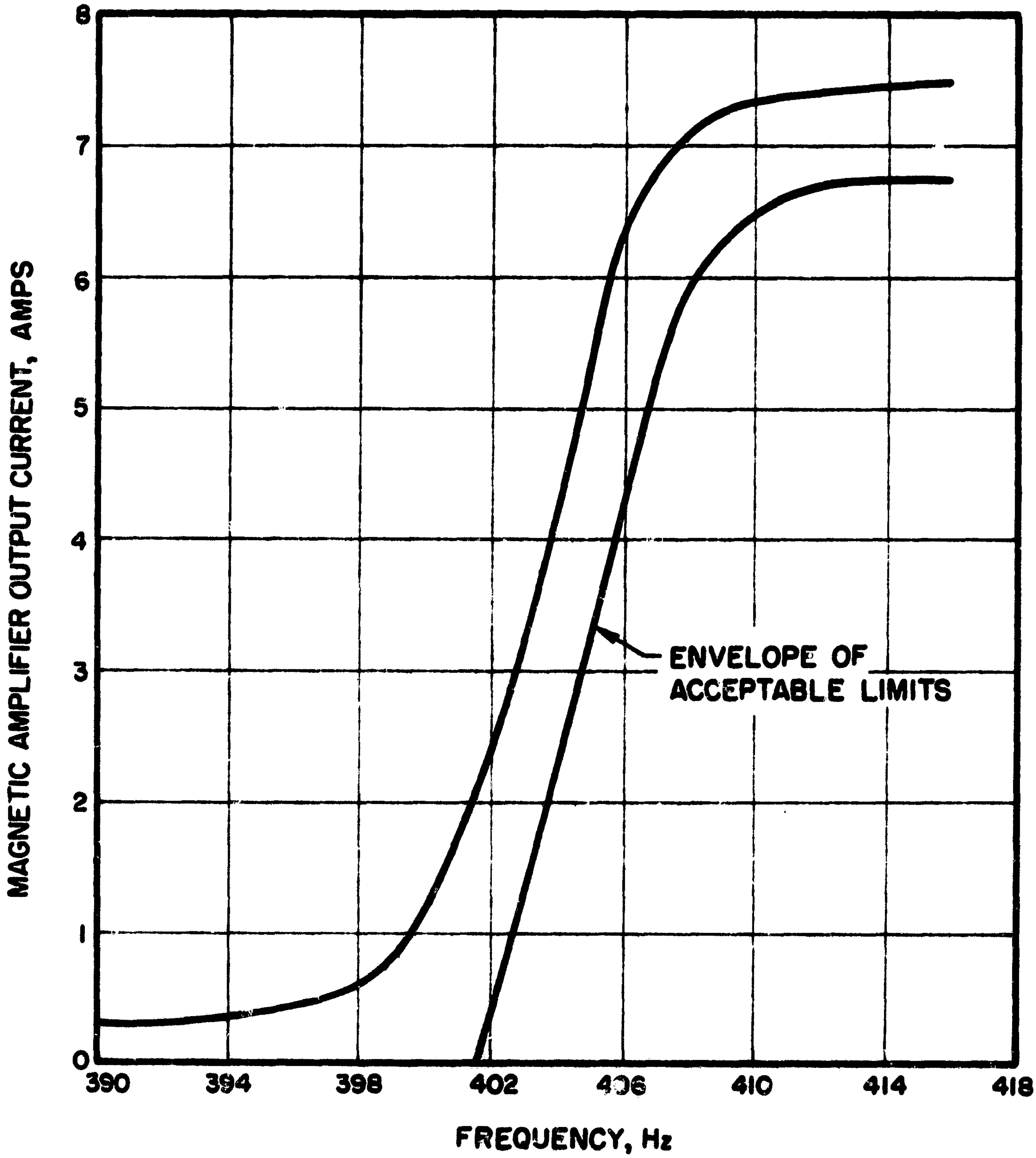

Figure 17. Frequency vs Magnetic Amplifier Output Current

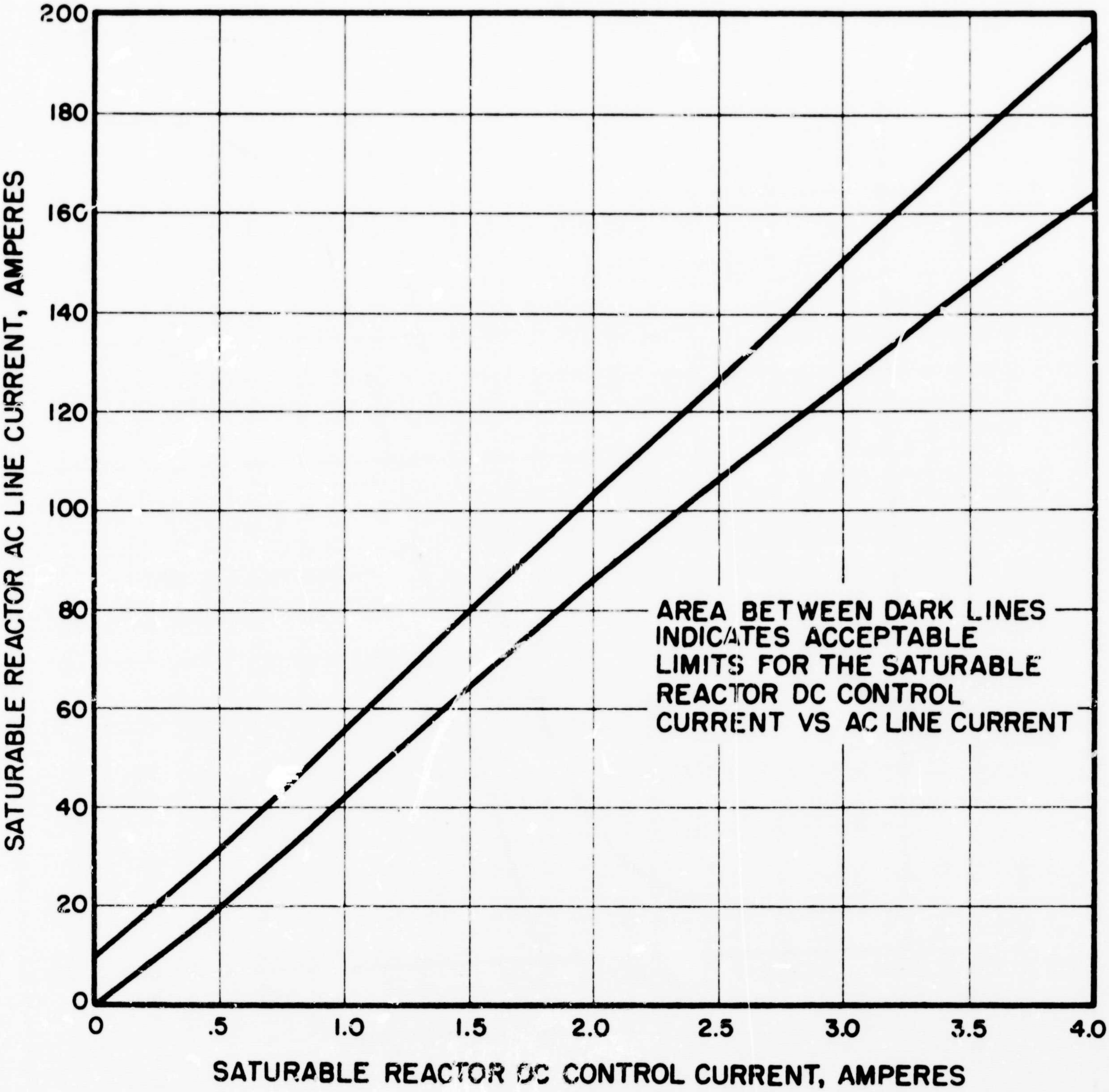

Figure 18. DC Control Current Input vs AC Line Current Output

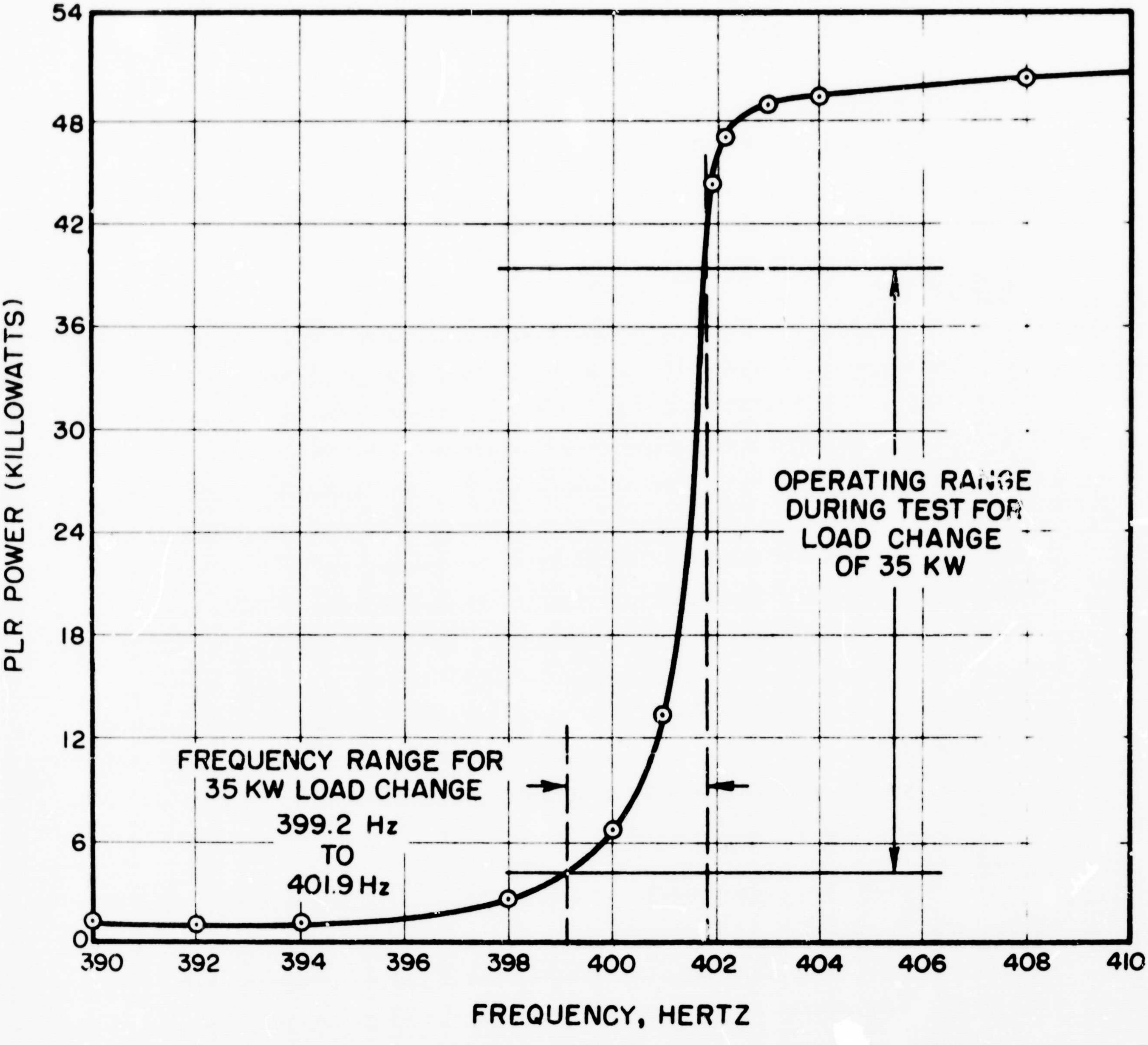

Figure 19. Speed Control Frequency vs Parasitic Load Power

1. <u>Transient Response Tests</u>

Transient response tests were conducted by transferring 35 kw from the parasitic load to the vehicle load, and then back to the parasitic load. Transient tests employing different feedback networks were conducted, some producing an overdamped response, others an underdamped response (see Figure 20). Test results showed that a system slightly underdamped would operate better than a critical or overdamped system because the recovery time was less and the amount of dip was reduced.

a. Stabilization

To ensure stable operation three types of rate feedback circuits were tested. These were a current and a voltage feedback from the parasitic load resistor, and a current feedback from the control winding of the saturable reactor to a resistor in series with the control winding of the magnetic amplifier. Tests indicated that the three circuits were functionally equivalent for use in the speed control. In transient response tests conducted by transferring 35 kw from the parasitic load to the vehicle load and then back to the parasitic load, the performance of these circuits was identical. The frequencies for each circuit dipped to approximately 380 hertz when adding step loads and rose to 415 hertz when the load was suddenly removed. Full recovery time from transient surge for each of the three circuits was about 2 seconds. The feedback circuit in Figure 21 was chosen because it did not require a three-phase full-wave bridge.

b. Improved Response

The result of the addition of the current feedback circuit was a substantial improvement in the control system stability margin. The phase margin was improved, increasing from 26 to 62 degrees, and the gain margin was nearly doubled, rising from 15 to 23 decibels. The increased phase margin indicated an effectively damped system.

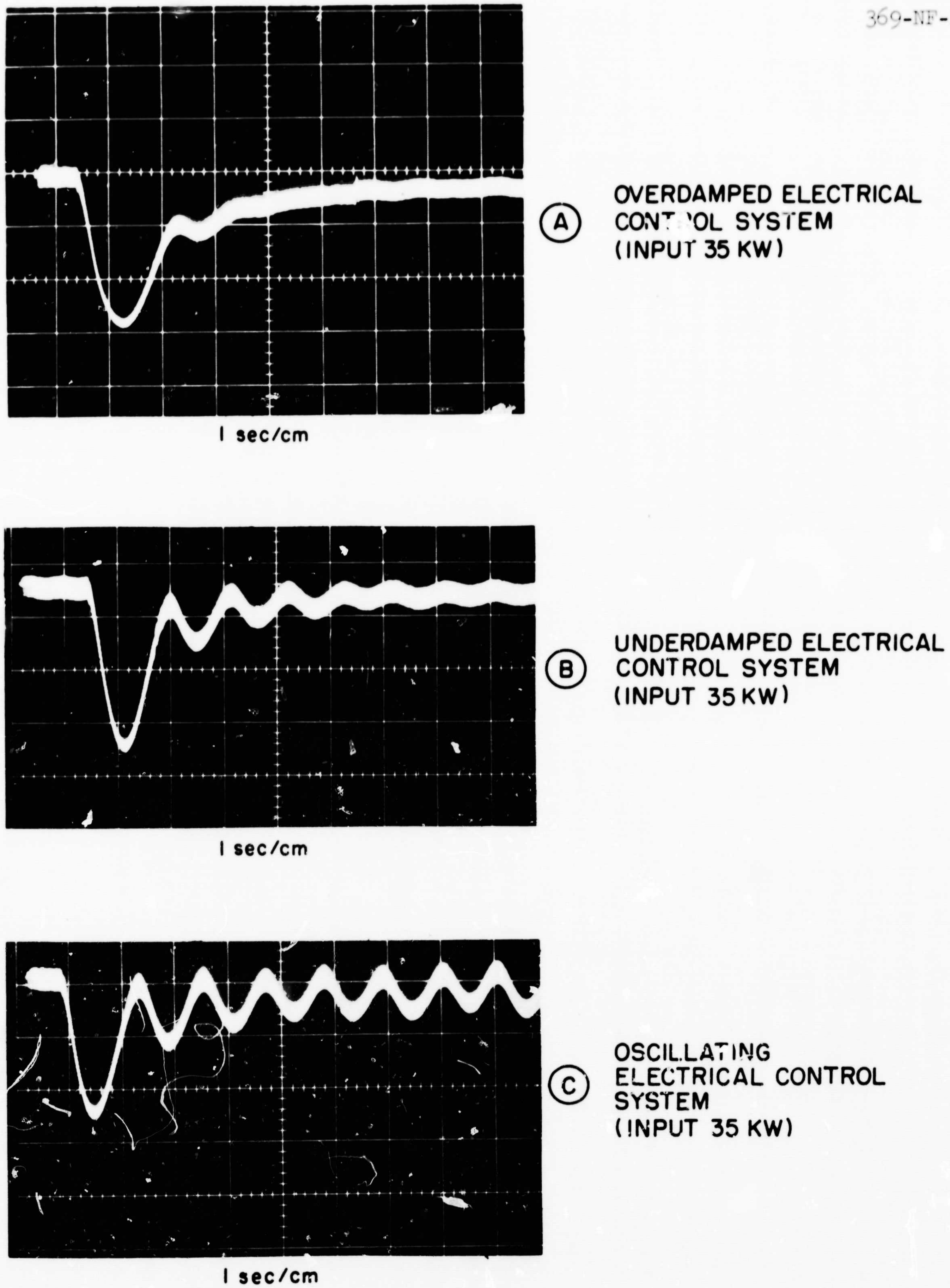

Figure 20. Electrical Control System Transient Response Test Results

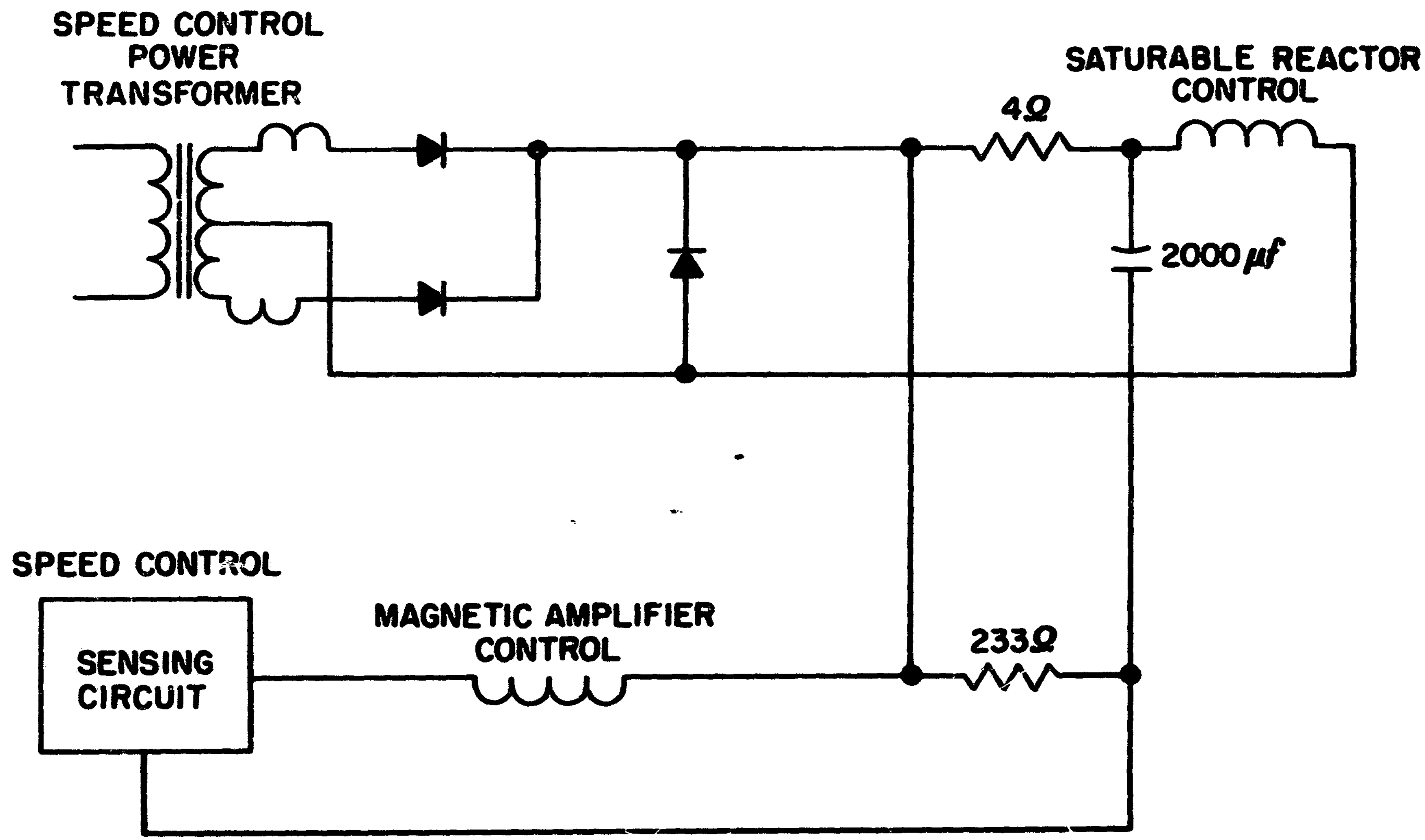

Figure 21. Saturable Reactor Control Current Feedback System

With an effective feedback system, the speed control system regulated steady state speed better than ± 1% (or ± 4 Hz) at 400 hertz for a change in vehicle load of 35 kw. The speed dip, rise and recovery time were all within system load requirements. Maximum speed dip and rise of 3.8 and 3.3%, respectively, were achieved when full load was suddenly applied and removed. A speed recovery time of less than two seconds was demonstrated after the sudden application of full load, and a recovery time of less than one second was demonstrated after removal of the load.

2. Endurance Tests

a. Power Conversion System Test Facility

The speed control system was installed in the power conversion system test (PCS) facility, and endurance tests were conducted with the speed control regulating the speed of the turbine-alternator driven by hot mercury vapor. The speed control system has been in operation in the PCS test facility for over 10,000 hours with no failures experienced.

The speed control module was mounted with the voltage regulator module on a liquid-cooled heat sink for these tests (see Figure 3). The saturable reactor was mounted on another heat sink with the static exciter (see Figure 4). Each of these heat sinks was held at the design temperature expected in actual space service. The temperature of the speed control heat sink was approximately 150°F and that of the saturable reactor heat sink was approximately 210°F.

b. Electrical Component Test Facility (ECTF)

An endurance test of the SNAP-8 alternator driven by an electrical drive under SNAP-8 simulated conditions was conducted. The speed control system was included in this test operation and operated in this loop for over 16,000 hours with no failures experienced.

VI. CONCLUSIONS

The speed control system developed for the SNAP-8 power conversion system has demonstrated performance which is completely satisfactory for the design service. The steady state operation of the system for over 10,000 hours displayed no measurable drift in speed regulation. For operation from no vehicle load to full vehicle load, 35 kw, speed control regulation of better than ± 1 percent was demonstrated. A maximum speed dip of 3.8 percent and a rise of 3.3 percent was achieved when full load was suddenly applied and then removed. A speed recovery time of less than two seconds after the sudden application of full load and a recovery time of less than one second after the sudden removal of full load was demonstrated by test operation in the power conversion system test loop. Since the installation and optimizing of the stabilizing circuit, no instability has been observed for a wide variety of operating conditions.

Simplicity was stressed in the design of the speed control circuitry which resulted in control system efficiency and reliability. This was demonstrated by the fact that that no failures have occurred during the entire test program. Components and materials have adequately demonstrated in simulated test environments, the capability and reliability of operation in the SNAP-8 space environment.

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