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DESIGN AND DEVELOPMENT OF A VOLTAGE REGULATOR-EXCITER FOR THE SNAP-8 NUCLEAR-ELECTRICAL POWER-CONVERSION SYSTEM

by

S. L. Bradley

AEROJET-GENERAL CORPORATION
Azusa, California

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS 5-417

Martin J. Saari, Project Manager

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Cleveland, Ohio

Martin J. Saari, Program Manager

SNAP-8 Program Office

FOREWORD

The work described in this report was performed at Aerojet-General Corporation, Azusa, California, as part of the SNAP-8 35 kw nuclear-electric power conversion System Contract being conducted within the Power Systems Department. General Electric engineered, developed and produced the actual hardware in accordance with specifications provided by Aerojet-General Corporation. The work was performed under NASA Contract NAS 5-417, with Martin J. Saari as Program Manager for NASA and Dr. W. F. Banks as Aerojet-General Corporation Program Manager.

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ABSTRACT

A voltage regulator-exciter was developed for the 60 kw alternator used in the SNAP-8, Rankine-cycle, nuclear space power system. Performance and endurance tests were conducted and the test results indicated that the voltage regulator-exciter subsystem would provide reliable, voltage regulation performance exceeding the specification requirements for load changes of no load to full load. This report covers the design and tests conducted including test results obtained during the development of the voltage regulator.

SUMMARY

A voltage regulator-exciter was developed for the SNAP-8 Rankine-cycle, nuclear space power system. The SNAP-8 power system is capable of providing 35 kw of usable electrical power to the system user at 400 ± Hz, 120 volts line to neutral, and 208 volts line-to-line. Voltage regulation is better than ± 1% for load changes of no load to full load (35 kw), and the regulation is expected to be better than ± 5% during 10,000 hours of operation in a space and radiation environment.

The design goal was achieved by use of components of proven reliability, derating of components, and use of redundancy of vulnerable electronic parts. All electrical connections were designed to permit welding where possible. Parts were potted and sealed in enclosures to protect against environmental conditions.

The test program consisted of laboratory testing of all parts of the voltage regulator-exciter prior to assembly, laboratory testing of the completed assemblies, testing with the alternator, and finally testing in a complete SNAP-8 power conversion system. An endurance test of the SNAP-8 alternator and associated controls including the voltage regulator-exciter was conducted for a period exceeding 12,000 hours.

The voltage regulator-exciter exceeded the reliability and performance requirements specified, and two of the regulators were operated for a total of 20,000 hours without failure. The voltage regulation was held within ± 0.6% for load changes from no load to full load. No sustained oscillations were observed during the endurance tests. During tests with the alternator, the voltage regulator-exciter performed at approximately one-half the specified 30% allowable dip and rise for sudden load application and removal. The recovery time for loads up to 60 kw at 0.75 PF, for field winding temperatures below 150°C, was within the original specification limit of 0.25 seconds. However, recovery time for

temperatures of 160°C, for applied loads of 60 kw at 0.75 PF, was greater than the original 0.25 second limit. To improve the recovery time, a larger saturable current potential transformer with a capability of producing a higher forcing voltage was designed and fabricated.

Tests were conducted on the new unit and the recovery time was 0.35 second for temperatures of 160°C when full load of 60 KW **at** 0.75 PF was applied. This recovery time was sufficient to meet the system requirements and therefore the specification limit was changed to 0.35 seconds for temperatures up to 160°C.

I. INTRODUCTION

SNAP-8 is a Rankine-cycle, nuclear-electric power system providing 35 kw usable power for space missions. The power conversion system 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. The basic SNAP-8 system is shown in Figure 1. Reactor heat is carried in the primary NaK loop to the mercury boiler. The mercury, vaporized in the boiler, drives the turbine alternator to produce electricity. Leaving the turbine alternator, the mercury vapor is condensed and pumped back to the boiler. Heat given up by the mercury as it condenses is carried by NaK in a heat transfer loop to a radiator where it will be radiated to space. Organic fluid in a fourth loop is circulated to the electrical components for cooling.

The voltage regulator-exciter subsystem discussed in this report regulates the output voltage of the alternator, and was designed, fabricated and acceptance tested by the General Electric Company.

II. DESIGN AND THEORY

A. ELECTRICAL CONTROL SUBSYSTEM

The SNAP-8 electrical control subsystem 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 2. The voltage regulator module and the saturable current potential transformer are shown in relationship to each other and in relationship to the rest of the electrical system. The voltage regulator provides a control signal to the static exciter to regulate the alternator output voltage at 208 ± 6 volts. This control signal is directly proportional to the alternator frequency. The static exciter, in conjunction with the voltage regulator, provides alternator field-current to control the alternator output voltage.

The speed control transformer assembly provides power to the speed control module. The speed control regulates the speed of the turbine-alternator by maintaining a load on the unit equal to the load capability of the SNAP-8 power conversion system. This is accomplished by operation of the speed control module, the saturable reactor, and the parasitic load resistor. The speed control module senses the alternator output frequency and controls the power dissipated in the parasitic load resistor by controlling the saturation level of the saturable reactor.

The programmer assembly controls the start, shutdown, and restart of the power conversion system. The programmer assembly also provides for internal and external fault protection by the use of a protective system. Three motor contactors, which are actuated by the programmer, initiate electrical inputs from the inverter output to start each of the pump motor assemblies. When alternator power is available, the programmer activates

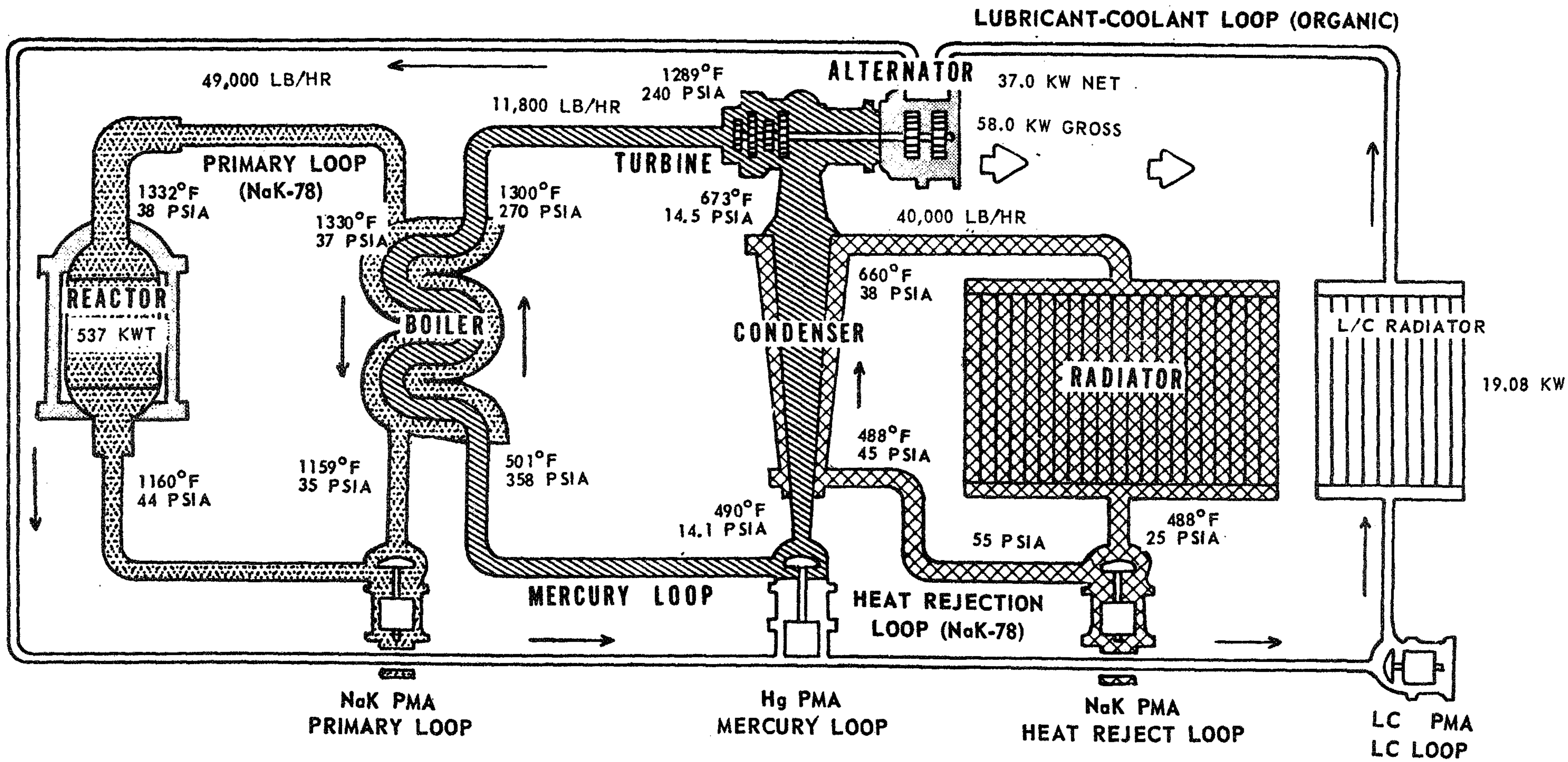


Figure 1. SNAP-8 System Schematic

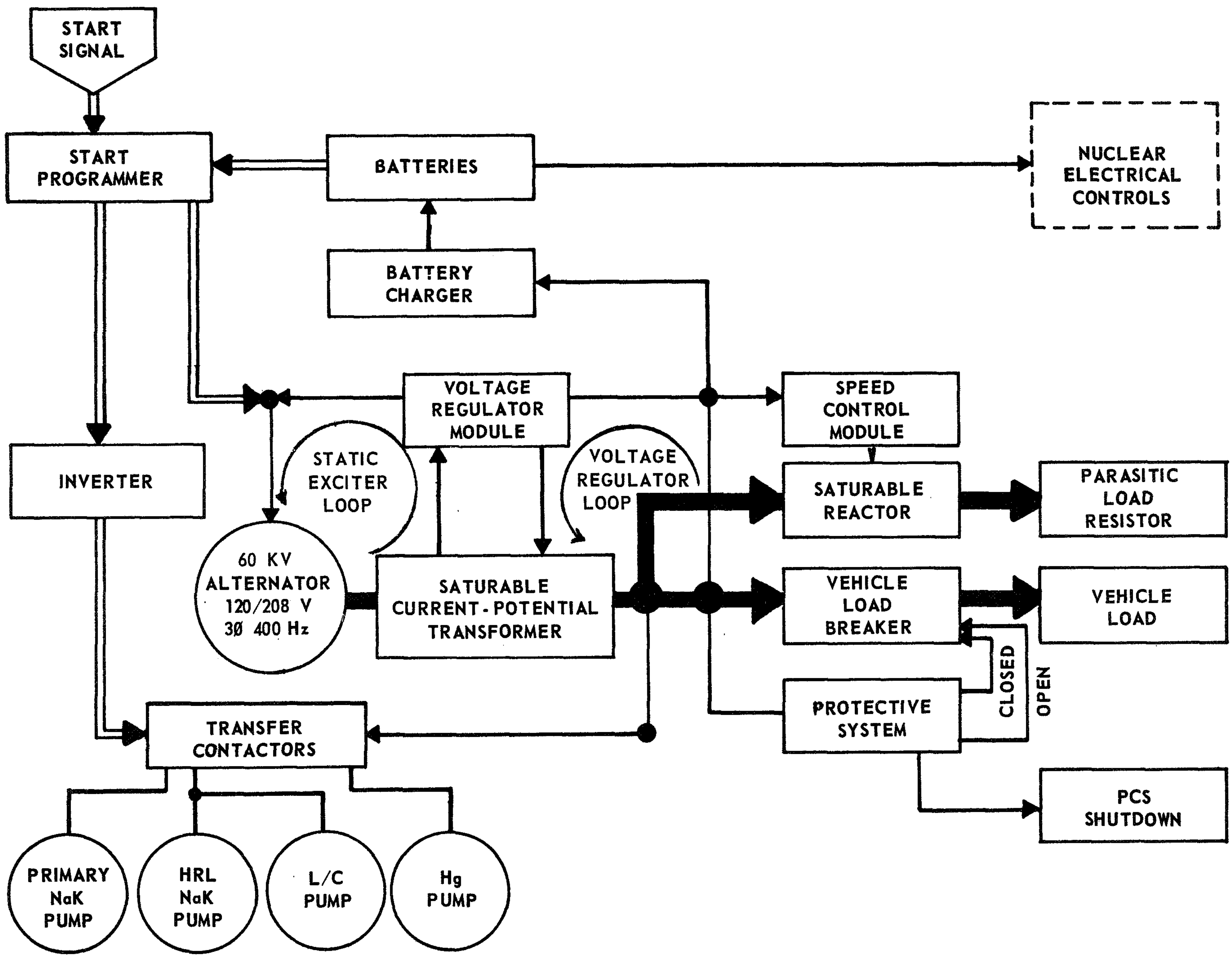


Figure 2. SNAP-8 Electrical Control System Block Diagram

the motor contactors switching the pumps from the inverter output to the alternator output. Upon shutdown, the programmer 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 power to start and operate the pumps during startup, shutdown, and nuclear system decay heat removal. A more detailed discussion of the electrical control system is presented in Reference 1.

B. VOLTAGE REGULATOR-EXCITER

1. Performance and Operation

The voltage regulator-exciter development goal for the SNAP-8 system was to produce a regulator which would provide ± 5% regulation from 3.5 to 35 kw at a load power factor of 0.85 lagging with a reliability of 99.9% for 10,000 hours of continuous operation in a space and nuclear radiation environment.

In general, the regulator maintains alternator line to line voltage at 208 ± 6 volts at 400 ± 4 Hz. At other frequencies from 320 to 480 Hz, the line voltage was to be held proportional to frequency. Furthermore, the regulator will supply a minimum of 2 per unit rated current during a short circuit. After removing the fault causing the short circuit, the line voltage recovers promptly and stabilizes with the load change. The electrical design and performance requirements from the voltage regulator component specification are summarized in Appendix A. A schematic diagram of the voltage regulator-exciter subsystem is shown in Figure 3.

The alternator voltage is regulated by an automatic adjustment of the alternator field current to compensate for changes in load and field temperature. The rating of the alternator was 60 kw, 0.75 power factor, and 400 Hz. The regulation is provided by the voltage regulator module and the saturable current potential transformer. The voltage regulator module (see Figure 4) senses the alternator output voltage and compares it to a reference which is proportional to the frequency. It then corrects the alternator field current to maintain voltage within specified limits by controlling the saturation level of the saturable current potential transformer.

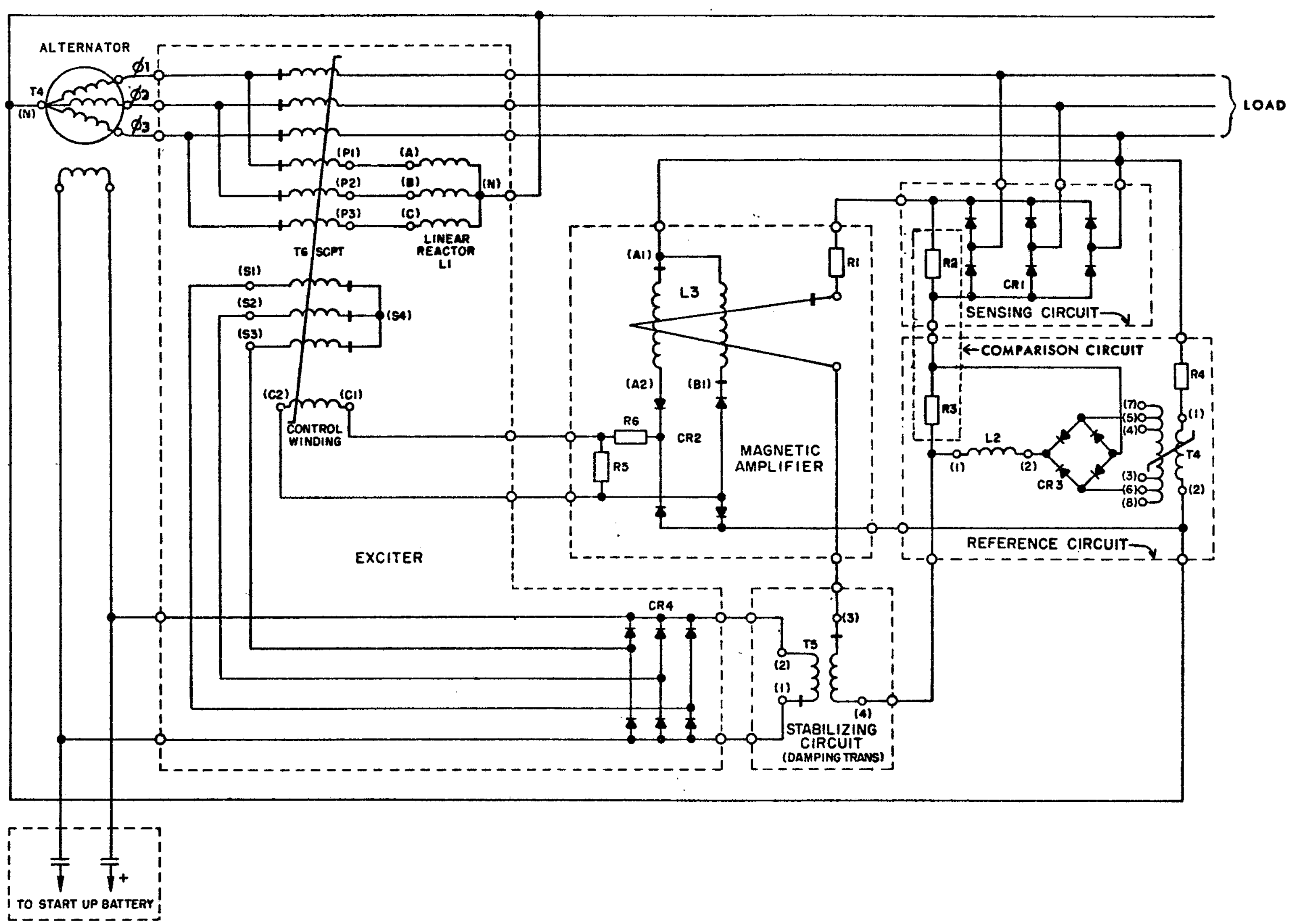


Figure 3. Voltage Regulator-Exciter Schematic

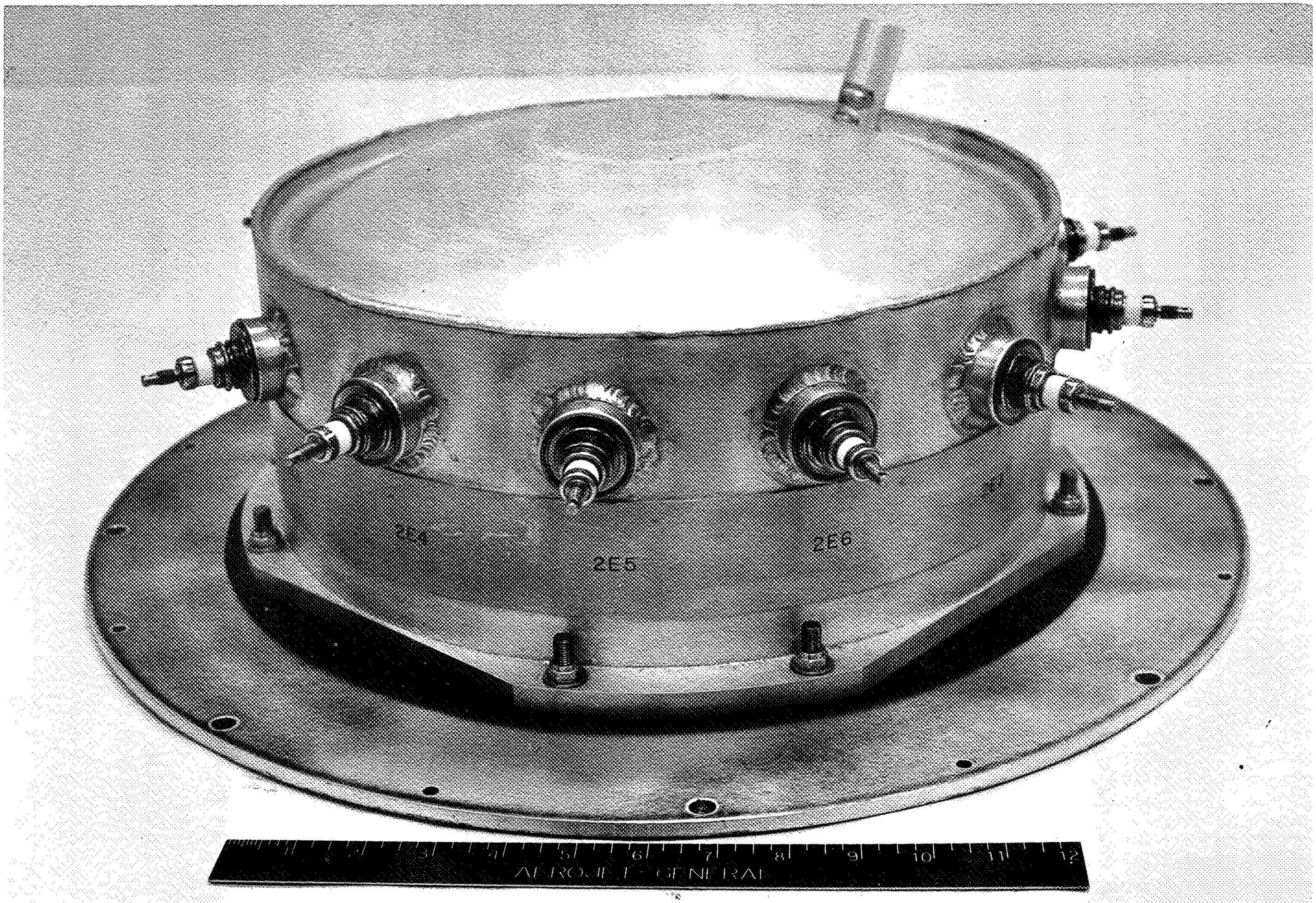


Figure 5. Voltage Regulator Module

During alternator operation at no load, all the field excitation is supplied by the voltage winding of the saturable current potential transformer. When load is applied to the alternator, the load current passing through the current winding of the saturable current potential transformer supplies additional excitation to the alternator field to compensate for the additional voltage drop in the alternator produced by such a load current. Lagging power factor current produces more excitation than in-phase or leading current, and since lagging power factor loads require more excitation than in-phase or leading loads, the increased excitation supplied by the load current tends to compensate for changing power-factor loads. Compensation is not precise, so a regulator control-circuit is provided to adjust the output of the saturable current potential transformer. When a load change occurs, and the compensation is too great or too little, the voltage output of the alternator rises or falls accordingly. The voltage regulator senses this change and supplies control current from the magnetic amplifier to the saturable current potential transformer. This changes the output of the saturable current potential transformer in the correct direction to return the alternator voltage to the rated level. For further descriptions of this type regulator-exciter, see References 2, 3, and 4.

2. Component Reliability

Primary design considerations are performance and reliability; weight is a secondary consideration. The design considerations employed to assure reliable performance were the following: circuit simplicity, use of components of proven reliability, reliable electrical connection performance testing, isolation of circuit elements from environmental hazards, redundancy and derating of components. Components of high reliability were specified for use in the subsystem, reference Table I. The diodes are controlled-avalanche silicon types which were tested for susceptibility to nuclear radiation. Germanium or selenium rectifiers were

TABLE I

RELIABILITY DESIGN CHARACTERISTICS

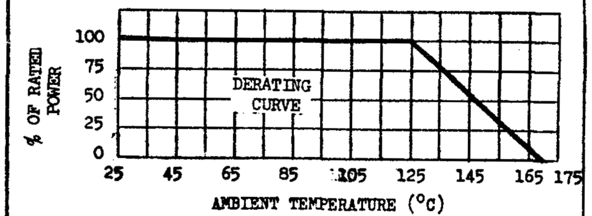
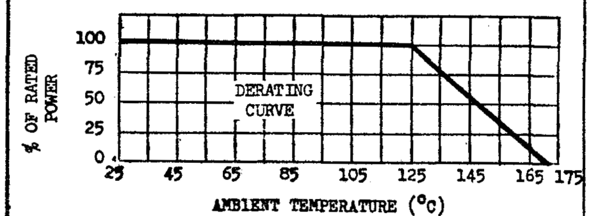
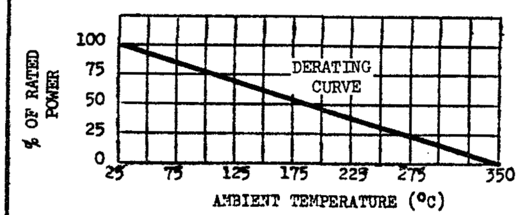
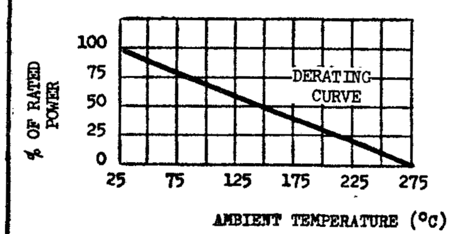
COMPONENTS	DEFINITION OF FAILURE	MAXIMUM FAILURE RATE	RELIABILITY CONSTRUCTION REQUIREMENTS	POWER RATING	ADDITIONAL DESIGN CHARACTERISTICS (for specific components)
Resistor					Resistor Derating Curves
1/8 watt	± 2% change in resistance from initial value	0.02% / 1000 hrs	LEADS: Nickel (Grade A) CORES: Ceramic or boron-free alkaline glass	1/8 watt @ 125°C	
1 watt	± 2% change in resistance from initial value	0.02% / 1000 hrs	PROTECTIVE COATING: Ceramic silicone or diallyl phthlate RESISTANCE ELEMENT: Metal film	1 watt @ 125°C	
7 watt	± 2% change in resistance from initial value	0.02% / 1000 hrs		7 watts @ 25°C	
10 watt	± 2% change in resistance from initial value	0.02% / 1000 hrs		10 watts @ 25°C	

TABLE I (cont.)

RELIABILITY DESIGN CHARACTERISTICS

DEFINITION OF FAILURE: Same for diode and rectifier:

Increase in forward voltage drop (FVD) or back leakage current (BLC) exceeding the following limits:

(all at 100°C junction temperature)

COMPONENT	DEFINITION OF FAILURE: FVD Increase	DEFINITION OF FAILURE: BLC Increase	MAXIMUM FAILURE RATE	RELIABILITY CONSTRUCTION REQUIREMENTS
Diode (semiconductor, silicon)	2.0 volts @ 0.25 amps	1 ma @ 600 volts	0.02% / 1000 hrs	ANODE: Kovar, tin dipped CATHODE: Nickel-plated copper
Rectifier				
(single unit)	0.7 volts @ 5 ma	up to 1 ma @ 500 volts	0.02% / 1000 hrs	ANODE LEAD: Grade A nickel, gold plated
(unit in series)	0.35 volts @ 10 ma	up to 1 ma @ 500 volts	0.02% / 1000 hrs	CATHODE LEAD: Grade A nickel, clad copper, gold plated

TYPICAL DESIGN CHARACTERISTICS

Characteristic	Component: DIODE	Component: RECTIFIER
1) Repetitive and working PRV	600 volts	500 volts
2) Avalanche voltage @ 25°C (max.)	1030 volts	750 volts
(min.)	750 volts	600 volts
3) D.C. current @ 135°C case (max.)	12 amps	———
4) One-cycle surge current (peak)	240 amps	10 amps
5) Reverse power surge (non-recurrent) @25°C	3.9 kw	———
6) Full load voltage drop (max.) @ 135°C for average full cycle	0.7 volts	———
7) Thermal impedance (junction to stud)	2.0°C/watt	———
8) I^2T rating	67 amps^2-sec-min	0.5 amps^2-sec
9) Average forward current (max.) @ 50°C		500 ma
10) Continuous reverse power dissipation (maximum)	———	0.5 watt
11) Forward voltage drop (max.) @ 400 ma	———	1.0 volt

TABLE I (cont.)

RELIABILITY DESIGN CHARACTERISTICS

COMPONENT	DEFINITION OF FAILURE	MAXIMUM FAILURE RATE	RELIABILITY CONSTRUCTION REQUIREMENTS		DESIGN CHARACTERISTICS	
			(For all transformers)	Core Material	Quality Test Variable(s)	Specified Response(s)
TRANSFORMERS:	(For all transformers)		1) Use only cut toroids 2) Use only layer-wound cores 3) Use no wire smaller than size 30			
Saturable Current Potential (IE)	Inability to comply with any design characteristic tested in performance tests before and after installation.	0.03×10^{-6} failures per hour		3½% grain-oriented silicon steel	For winding: A-N B-N C-N	1) Current 2.70 amps 2) Reactance 32 ohms ± 5 ohms @ 400 Hz 3) Induction saturation voltage 125,000 lines/in^2 = 140 volts + 20% - 0%
Magnetic Amplifier (L3)		0.01×10^{-6} failures per hour		Orthonol or equivalent	Magnetic Amplifier Test Performance Curve (Figure 31)	
Saturating Reference (T4)		0.01×10^{-6} failures per hour		48 Alloy or equivalent (stack initially with 57 laminations)	Winding Conformance	1) Current 20 ma 2) D.C. resistance 120-140 ohms 3) Inductance 18 + 40%-0% henrys
					1) Line voltage 120 volts rms	29.7 ± 1.0 volts
					2) Line voltage from 108 to 132 ohms	D.C. volts within ± 0.1% variation
					3) R_1 from 200 to 240 ohms	D.C. volts 0.6% or less increase
					4) R_2 from 20 K to 24 K ohms	D.C. volts 0.6% or less increase
					5) Temperature reduced to -55°C	10 volt (D.C.) or less increase
					increased to 71°C	9 volt (D.C.) or less decrease
Stabilizing (T5)		0.01×10^{-6} failures per hour		3.25% grain-oriented silicon steel	For winding: 1-2	1) Current 270 ma 2) Reactance 170-200 ohms

not used. Wirewound or film type resistors were used because the probability of failure of these types is lower than for other types. The cores were built up of laminations and coils were layer wound thus minimizing the possibility of turn to turn shorts. To minimize wire breakage, only wire of Number 30 or larger was used in the wire wound components. Insulating materials of glass silicone, Pyre ML treated glass, H-film layer insulation, magnorite filler and epoxy potting compounds were used (see Table II).

Lot control was applied to the following materials to facilitate identification, ensure in-process controls, and maintain performance dependability:

- Magnetic materials
- Insulations
- Hermetic Seals (i.e., stand-offs, feed-through bushings, etc.)
- Electrical Conductors (i.e., hook up wire, self leads, etc.)
- Polymers

New lot numbers were assigned when a break occurred in the continuity of manufacturing.

3. Component Redundancy and Derating

The use of redundancy and derating of components was utilized to achieve circuit reliability. Redundancy techniques were used for resistor and diode components. The diodes were connected in quads. For each rectifier in the circuit four diodes were connected in two branches with two diodes in series in each branch. If one rectifier in either or both branches shorted, the rectifier would continue to function. If one rectifier in either branch opened, the rectifier would function normally. See Appendix B, Tables B-IV, B-V, and Figures B-1 and B-2 for component reliability and failure probabilities.

In the case of the resistors in the circuit a parallel combination of ten resistors was used for each circuit resistor requirement. The circuit was designed so that two resistors could fail and the circuit

TABLE II

CONSTRUCTION MATERIALS

MATERIAL	FEDERAL AND/OR MIL. SPEC.	COMMERCIAL SPEC.	PART OR USAGE
Aluminum, sheet or plate	QQ-A-327 T6 HT and AGED	6061-T6	Voltage regulator chassis, housing, dome, reactor-transformer housing, module housings and magnetic component housings.
Aluminum, bar, rod, tube	QQ-A-325 QQ-A-270 T6 HT and AGED WW-T-789 T6 HT and AGED	6061-T6 6061-T6 6061-T6	Dome assembly tube, rectifier module housing, brackets on magnetic components and pins on main chassis asm.
Aluminum, tube		AA Type 3003(0)	Pinch-off tube on voltage regulator dome assembly
Aluminum, brazing sheet	#11 Brazing Sheet per MIL-B-20148A. Core material per QQ-A-359		Voltage regulator nameplate.
Brazing alloy, alum, sheet	QQ-R-556, Type 2	718 Brazing Alloy	Brazing on voltage regulator chassis, module housings.
Brazing alloy		ASTM-B260, Class B AG-6 ASTM-B260, Class B AG-8 ASTM-B260, Class B CU-P-5	Brazing leads to coils - magnetic components.
Brazing Filler Metal		ASTM-B-189	Brazing current coils - SCPT on Reactor-Transformer.
Brazing Filler Material		Alumibraze 400	Brazing on voltage regulator chassis, module housings.
Brazing Flux (Paste)	MIL-O-F-499		Brazing leads to coils - magnetic components.
Copper, strip	QQ-C-576, oxygen free copper		Terminal lugs and strips on voltage regulator assembly and on rectifier modules.
Copper, bar	QQ-C-504, hard, oxy. free cu.		Current coil terminal posts on Reactor-Transformer.
Copper, tubing	WW-T-775		Ferrules for welding wire to terminals.
Gas		Sulphur Hexaflouride	Inert heat-transfer back fill in voltage regulator housing.
Glass, silicone	MIL-P-997B, Class H		Core tubes in magnetic components.
Mica			Rectifier insulation in rectifier modules.
Nickel, Grade A, wire Nickel, Grade A, rod Nickel, Grade A, ribbon	(¼ hard) * B14H18B (cold drawn) *B14H21B (dead soft) *B14H35X		Wire leads on rectifier modules. Hermetic terminals on voltage-regulator and reactor-transformers. Terminal and component interconnections on rectifier and resistor module.
Potting:			Encapsulating compound used in assembly of modules, magnetic component, and voltage regulator assembly.
Epoxy resin	*44A258559	EPON 828 (Shell Corp)	
Curing agent Catalyst Filler	*44A258560 *44A258561 *44A258562	NMA (Allied Chem) DMP-30 (Rohm&Hass) Magnorite II (Miller Stephenson Chem.)	
Flexibilizer	*44A258562	Cardolite NC-513 (Norton Refractories Inc.)	
RTV Liquid	*A15F6	RTV-102	Sealing compound for magnetic components.
RTV Impregnation	*A15F5A	RTV-11	Magnetic component coil impregnation (protective coating).

* General Electric Code Ident. No.

TABLE II

CONSTRUCTION MATERIALS (CONT'D)

MATERIAL	FEDERAL AND/OR MIL. SPEC.	COMMERCIAL SPEC.	PART OR USAGE
Silicone Compound, RTU-30		RTV-30, RTV 60	Protective coating on rectifier component subassemblies prior to hard potting, and on interconnecting wires in voltage regulator final assembly.
Silicone, Laminated Sheet	MIL-P-997		Component holder (insulating board) in rectifier and resistor modules.
Sleeving, Fiberglass		PYRE ML	Insulation on magnetic component leads.
Steel, silicone, grain oriented, electrical		ALLEGHANY LUDLUM 4750 DELTAMAX HIMU 80	Core laminations in magnetic components.
Tape, Kapton, "Hs" film		Dupont Kapton	Insulation in modules, magnetic components, regulator asm.
Tape, adhesive backed		Parmacel type EE6579	Magnetic component coil and lead insulation.
Tape, Glass			Final assembly wiring cord ties. Wrap for metal cable clamps. (Final assembly)
Terminal, Hermetic	**094677		Hermetically sealed electrical terminals.
Wire, Hookup		Novathene NRRJ Novathene NRRC (Raychem Spec. 1240)	Magnetic component lead wires. Rectifier modules; voltage regulator interconnection wiring.
Wire, ML insulated	MIL-W-583, Type M, M2, M3	M. L	Magnetic component windings, rectifier module leads.
Wire, copper, magnet	MIL-W-583, Type M2	H.M.L.	Magnetic component windings.
Wire, Welding	*44B259905-001, 002, & 003		Welding on voltage regulator chassis and dome assemblies.

* General Electric Code Ident. No.
** Aerojet-General Corp. Code Ident No.

would still operate within the specified limits (see Appendix B, Tables B-IV, B-V, and Figure B-3).

The voltage, current, power, and temperature operating levels of all components were derated. The power ratio of resistors, P operated vs P rated, varies from 0.064 to 0.20. The junction temperature of all diodes was maintained below 194°F, however, operation at a junction temperature of 300°F would be conservative (see Appendix B, Table B-III).

4. Simplicity of Circuitry

The basic circuitry of the voltage regulator-exciter design was developed several years ago and has been used extensively in naval and aircraft applications, as related in References 3 and 4. This proven system was selected for the SNAP-8 voltage regulator-exciter because of the high reliability requirement established for the SNAP-8 system. The voltage regulator-exciter circuit was designed to be free of multiple amplifier stages, regulated power supplies and other complicating circuits to achieve the long life design goal of 10,000 hours. An external voltage set point adjustment was discarded in order to reduce complication and eliminate a failure mode.

Circuits with the least number of semiconductors and electrolytic capacitors were favored because of the vulnerability of these components to nuclear radiation and high temperature. A circuit was chosen which uses magnetic active components and excludes the use of transistors and silicon controlled rectifiers. A damping transformer was used instead of an R-C circuit to provide rate feedback and assure system stability. See References 2 and 5 for additional discussion of the damping transformer used as a stabilizing element.

One area that required development was a circuit design which would maintain volts-per-cycle output (voltage output proportional to frequency) from the alternator. This required a voltage reference which varies directly proportional to frequency ± 3% over the operating temperature range of +134°F (+57°C) to +160°F (+71°C).

A saturating transformer was chosen to provide the volts-per-cycle reference (T4, Figure 3). A three-phase bridge rectifier was selected to provide the sensing signal to compare with the reference (Cr-1, Figure 3). A damping transformer, T5, Figure 3, was used instead of a resistor-capacitor circuit in the SNAP-8 application because of the reliability requirement.

5. Electrical Connections

Electrical connections (high and low resistance) are a cause of failures in electrical circuits, therefore, emphasis was placed on providing reliable electrical connections. This led to the use of welded connections where possible and special mechanical design of all other electrical joints and connections. All external connections to the voltage regulator-exciter were welded. Figure 5 shows terminals designed for combination mechanical and welded connections. Mechanical connections were used during test and checkout. Electrical connections were made to the modules through hermetically sealed feed-through terminals with ceramic insulators. These terminals were fitted with nickel skirts or flanges for mounting to the enclosures. A special process was developed to provide a hermetic seal as these materials are not normally weldable to aluminum. A copper transition piece was inert-arc-welded to the nickel flange of the terminal followed by pressure welding of the transition piece to an aluminum alloy adapter. The aluminum adapter was inert-arc-welded to the aluminum enclosure (see Figure 5).

Resistor and axial-lead diode assemblies were designed in a cordwood type construction, as shown in Figure 6, with nickel ribbon conductors connected by resistance welding.

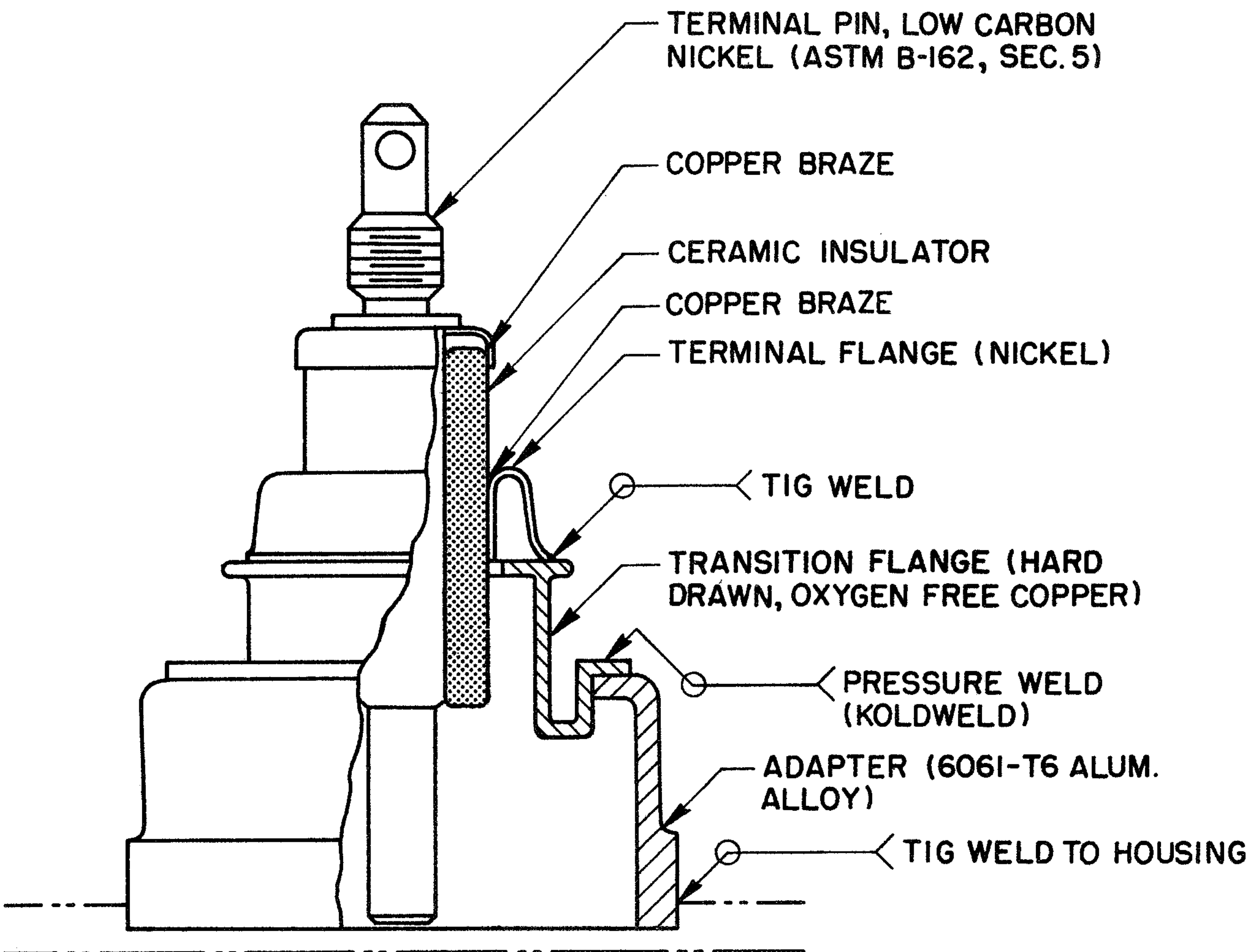


Figure 5. Typical Hermetic Terminal

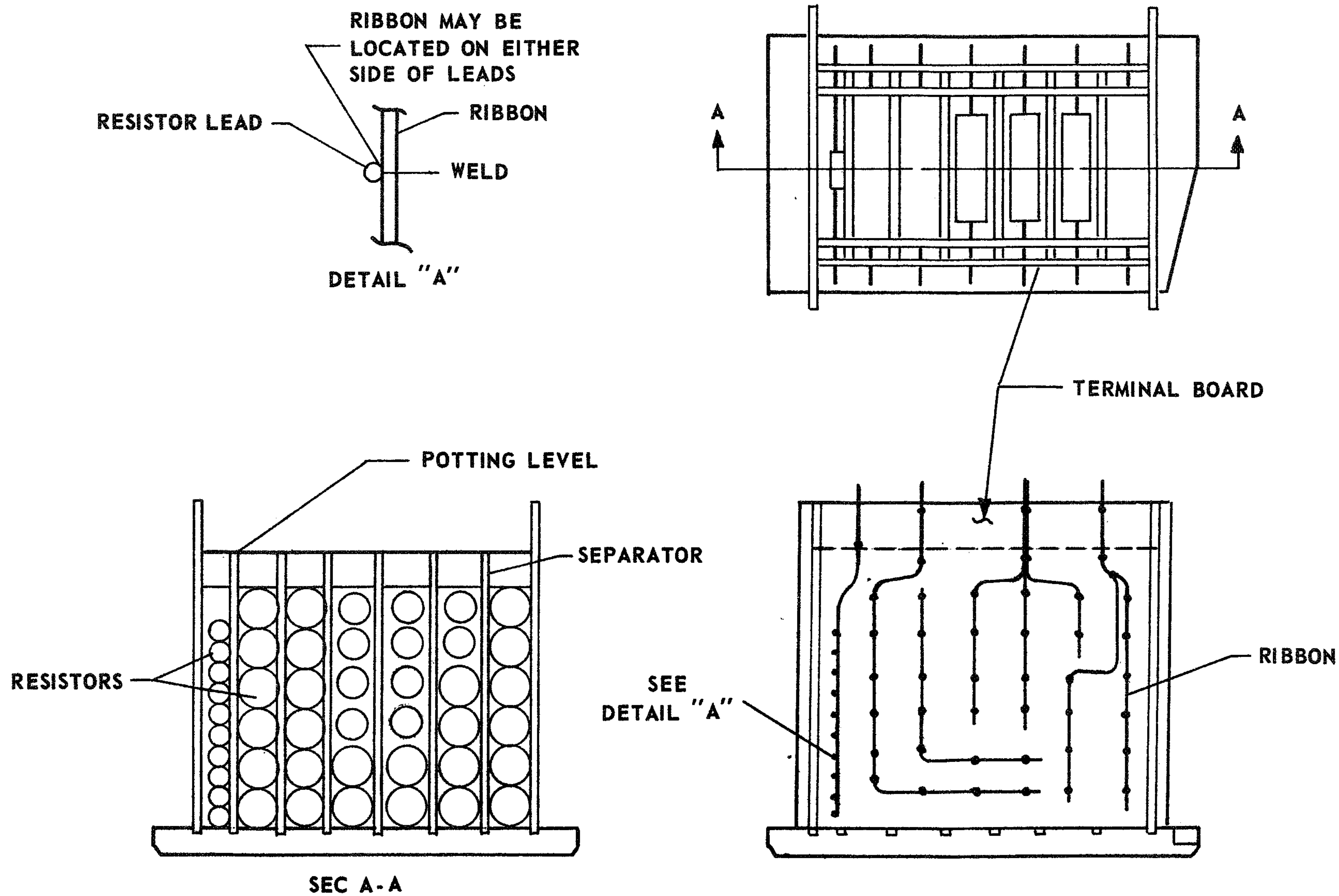


Figure 6. Resistor Assembly and Welding Detail

Module internal wiring terminations are stranded copper-hookup wire and were welded with an inert arc fusion process. Large current carrying conductors, as in the saturable current potential transformer, were lapped to give greater current carrying area and were then brazed. Pressure type electrical connections which depend on spring pressure to maintain contact were not used in the voltage regulator-exciter.

6. Environment Isolation

For a summary of the component specification environmental conditions, see Appendix A, Table A-I. The environmental conditions include the following:

- Earth bound conditions of salt fog, rain, humidity extremes, winds, sand and dust.

- Shock, vibration and acceleration forces of varying direction, duration and intensity, of an especially severe nature during launch and for short periods during extended time (10,000 hours) in space.

- External temperature extremes from -40 to 160°F, and internally produced temperatures reaching limits dependent upon the individual component location and specification.

- From normal atmospheric pressure at sea level to, essentially, a total vacuum (1×10^{-12} torr).

- Long exposure to radiation, especially from the nuclear reactor (which is potentially capable of producing a detrimental effect on component performance).

The voltage regulator module and the saturable current potential transformer module were designed as hermetically sealed packages to protect and isolate the components, wiring and insulation from the hostile environments. The exciter and regulator are cooled by conduction to cold plates, one at 155°F ± 20°F and one at 232°F ± 20°F. The saturable current potential transformer and the linear reactor are capable of operating at the higher temperature over the required life and therefore these two components are packaged as a complete assembly for mounting on the 232°F ± 20°F heat sink.

III. THEORY OF OPERATION

The Voltage Regulator-Exciter is made up of two basic functional circuits, the voltage regulator and the static exciter. The voltage regulator consists of the following circuits:

- Sensing Circuit
- Voltage Reference Circuit
- Comparison Circuit
- Magnetic Amplifier Circuit
- Stabilizing Circuit
- Static Exciter Circuit

A. SENSING CIRCUIT

The sensing circuit shown in Figure 7 measures the average of the three line voltages and produces a DC voltage proportional to this measured average. The circuit consists of rectifier CR1 and resistor R2. CR1 rectifies the AC line voltage and produces a DC voltage across R2. The voltage across R2 is applied to the comparison circuit.

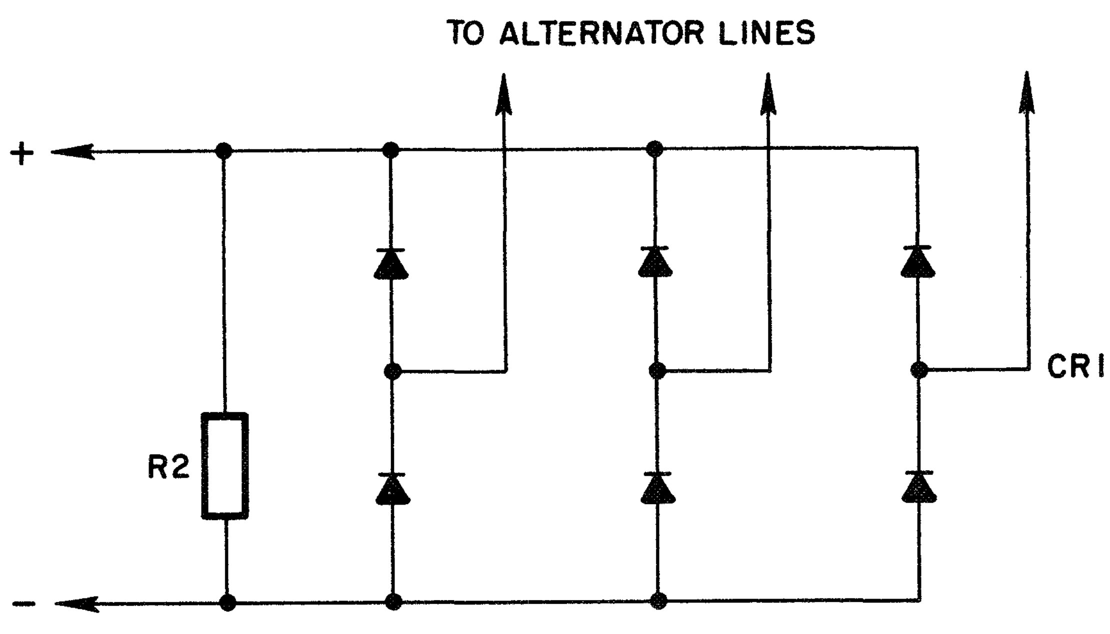


Figure 7. Sensing Circuit

The saturation voltage of magnetic devices is proportional to the frequency. To prevent saturation of magnetic devices connected to a variable frequency generator, the alternator line voltage must be regulated so that it too is proportional to frequency. This type of regulation is referred to as volts-per-cycle control.

The saturable transformer reference circuit shown in Figure 8 provides volt-per-cycle control. At rated line frequency, the saturating reference transformer sets a reference level equivalent to rated line voltage. At reduced line frequency, the transformer saturates at a lower voltage, producing a lower reference voltage and consequently a lower regulated line voltage.

Line-to-neutral voltage is applied to transformer T4 primary through dropping resistor R4. T4 is normally saturated with the magnetizing current automatically producing the drop across R4 required to maintain constant voltage across T4 primary.

The second voltage from T4, which is proportional to primary voltage and, therefore, also constant, is rectified by CR3, filtered by L2 and applied across resistor R3.

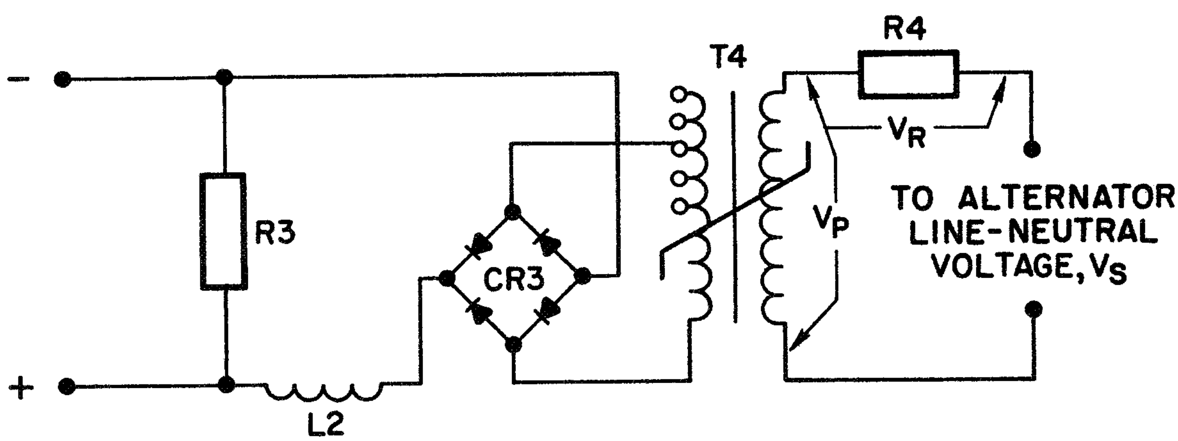


Figure 8. Volts Per Cycle Reference Circuit

B. VOLTAGE REFERENCE CIRCUIT

For the saturating transformer reference circuit shown in Figure 8, the voltage waveforms in Figure 9 are obtained.

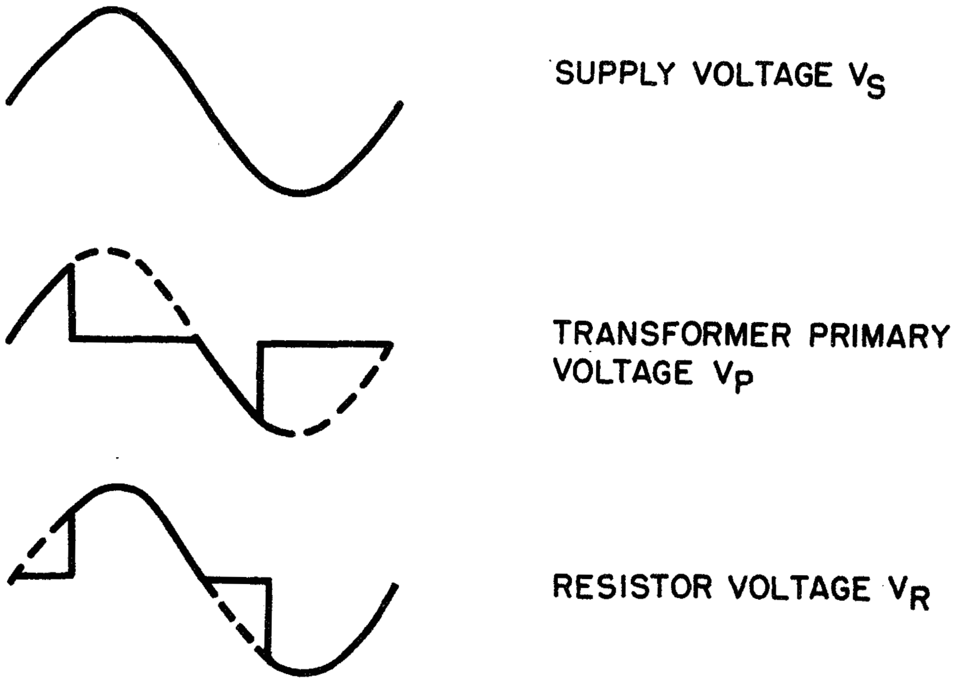


Figure 9. Reference Circuit Voltage Waveforms

Since the voltage waveforms across the transformer primary and the series resistor may be added together to make up the supply voltage waveform, the sum of the averages of these voltages also will be equal to the average supply voltage.

Primary Voltage (V_P) must be set low enough so the transformer will still operate in the fully saturated region for the lowest supply voltage. As V_P is reduced, the losses in R4 increase. It was determined by test that the maximum average voltage for which full saturation could be guaranteed was 68Volts.

where:

$$V_R(av) = V_S(av) - V_P(av)$$

$$V_R(av) = \frac{120}{1.11} - 68 = 50V$$

For these same conditions, the measured average current across R4 was 250 ma:

$$R4 = \frac{50}{.25} = 200 \text{ ohms}$$

The required voltage output from the reference circuit was 302V, which is the sum of the sensing plus error voltages and the voltage drop in the diodes and filter choke. The turns ratio may then be calculated by:

$$\frac{N_S}{N_P} = \frac{302}{68} \cong 4.4$$

Using this ratio, with a DU37 transformer lamination, 360 primary and 1580 secondary turns could be fitted through the window opening using a wire size large enough to reduce losses to the required value. Two coils were used to reduce leakage reactance.

Five core materials were tested for use in the saturating reference transformer. Hy-Mu 80 and Orthonal were found to have too much output voltage change with temperature change. Selectron was considered to have too great a change in voltage output with change in input voltage and Supermendur was too strain sensitive. The core material selected, 48 alloy, was formed from laminations into a two legged configuration, and one-half the primary and one-half the secondary were wound on each leg to reduce leakage flux (Reference 2). This design provides an output voltage regulation of 1.2% for ± 10% change in input voltage and shows slightly more than 2.9% change in output for a temperature change of +46°C to +71°C.

The effects of line voltage change and temperature change on the output reference voltage is shown below:

	Variation	Change in Reference Voltage
Input Voltage	± 10%	1.2%
Temperature	-55°C to + 71°C	6.1%
	+46°C to + 71°C	2.9%

During normal operation, the temperature of the voltage regulator did not change more than 14°C, and the voltage change relative to temperature was less than 1.69%.

C. COMPARISON CIRCUIT

The comparison circuit shown in Figure 10 compares the sensing voltage to the reference voltage and provides an error current, I_E, to the magnetic amplifier control winding.

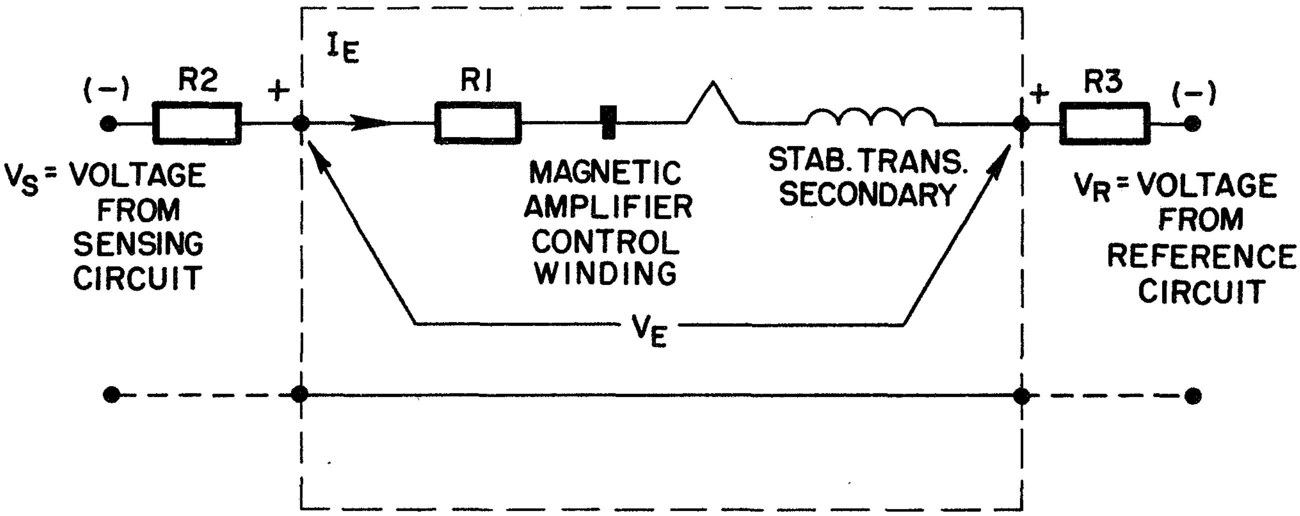


Figure 10. Comparison Circuit

When a sensing voltage appears across R2, a reference voltage appears across R3. The negative sides of these voltages were connected together directly while positive sides were connected together through R1, the magnetic amplifier control winding, and the secondary winding of stabilizing transformer T4. When V_S exceeds V_R, current I_E flows in the direction shown. Current in this direction turns on the magnetic amplifier, which turns off the exciter, reducing field current.

D. MAGNETIC AMPLIFIER CIRCUIT

Changes in line voltage produce error currents in the order of milliamperes while the exciter control winding requires changes in the order of amperes. This is accomplished by use of the magnetic amplifier circuit shown in Figure 11. The magnetic amplifier gate windings act as switches (gates) between the supply voltage and the load. If the core flux is on the steep slope (a) of the saturation curve, B-H Loop, Figure 12, the gate winding

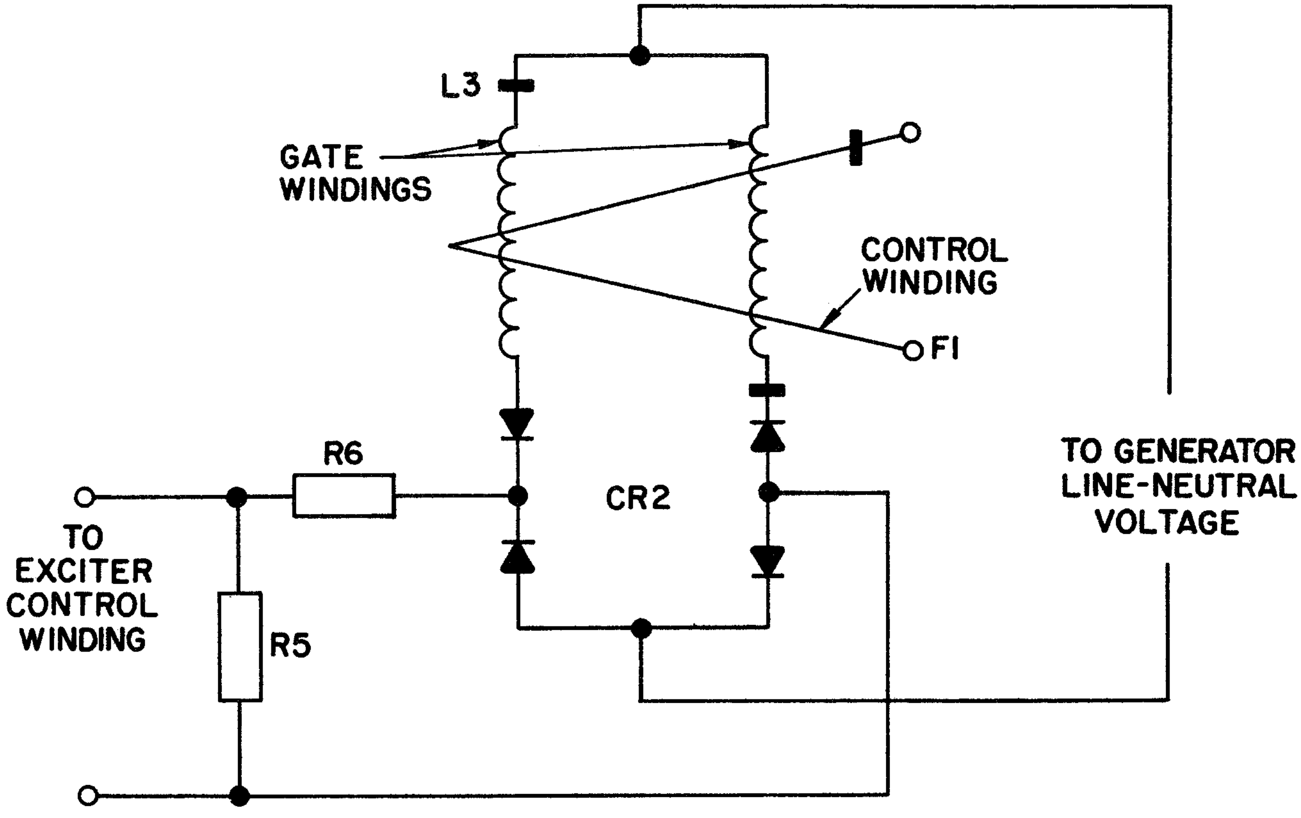
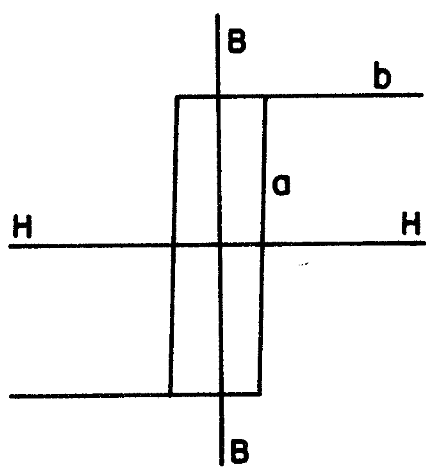


Figure 11. Magnetic Amplifier Circuit



(a) B-H LOOP

Figure 12. Characteristic Curves of a Magnetic Amplifier

has a very high inductance and the load current is limited to a very low value. If the core flux is on the flat portion (b) of the saturation curve, the gate winding has a low inductance and the load current is limited mainly by the load resistance. With the control winding connected as shown in Figure 11, control current into F1 produces flux which opposes the flux due to the magnetizing or load current. The magnetizing current must, therefore, increase to a larger value before the core saturates, so saturation occurs later in the cycle. If the control current is increased sufficiently, it will not allow the magnetizing current to saturate the core so the gates will remain "closed" to load current for the entire half cycle.

The supply voltage is applied to the gate windings in series with the load. After the supply voltage wave passes through zero and becomes positive, a small magnetizing current proportional to supply voltage flows in the gate windings. This small current is rectified and quickly saturates the core. With the core saturated, the gate winding inductance drops to a low value and gate (or load) current is determined only by the load resistance and supply voltage. Thus, with no control current, the cores are saturated for all but the first few degrees of the supply voltage wave and the output is a maximum.

The magnetic amplifier gate windings must withstand line-neutral voltage and were designed using the basic equation for the saturation voltage as shown below:

$$V_{sat} = 4.44 \text{ NAfB} \times 10^{-8}$$

where B is flux density in gauss, A is iron area in square centimeters, N is number of wire turns and f is frequency in Hz.

$$NA = \frac{V \times 10^{8}}{4.44fB} = \frac{120 \times 10^{8}}{4.44(400)(13,900)} = 486$$

It was desirable to use as small a core punching as possible. With a DU-37 punching, a stack height of 1-1/8 yields a gross cross sectional area of 2.7 square centimeters and a net gross area of 2.43 square centimeters.

$$N = \frac{486}{2.43} = 200 \text{ turns}$$

The window of the DU-37 punching will accommodate the required 200 gate turns with sufficient left for the control winding. A further trial and error solution confirms that the DU-37 is the smallest punching that can be used, with losses low enough to maintain a low temperature rise. A small punching has a small magnetic path length, which yields higher gain.

A magnetic amplifier gain of 37.5V/ma is required as determined by a stability and gain analysis. The maximum magnetic amplifier output voltage will be approximately 100V.

therefore:

$$G = \text{gain} = \frac{\text{output voltage}}{\text{control current}} = \frac{V_O}{I_C}$$

$$I_c = \frac{V_o}{G} = \frac{100}{37.5} = 2.7 \text{ ma}$$

Furthermore,

$$N_c I_c = 0.8 \text{ Hl}$$

where: N_c = number of control winding turns,

I_c = control current, amperes,

H = Half-width of B-H loop, oersteds, and

l = length of magnetic path, cm.

For DU-37 Orthonol lamination, at 400 Hz,

$$N_c I_c = 0.8(0.25)(17.2) = 3.44$$

and $$N_c = \frac{3.44}{2.7 \times 10^{-3}} = 1275 \text{ turns}$$

The magnetic amplifier gain characteristic is shown in Figure 13.

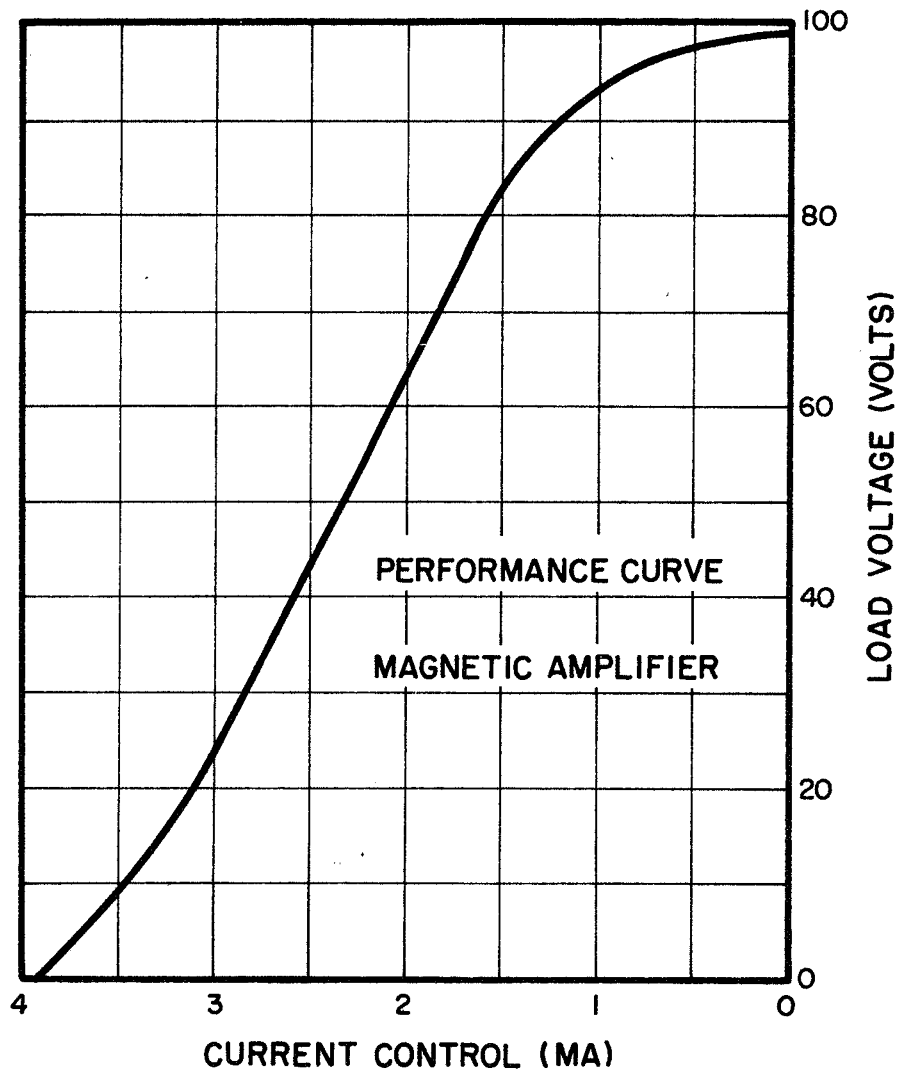


Figure 13. Magnetic Amplifier Gain Characteristics

E. STABILIZING CIRCUIT

In any closed-loop regulating system containing more than two significant time constants and having relatively high gain, there is a possibility of sustained oscillation, or "hunting." To control this condition, a stabilizing circuit was connected between the exciter output and the magnetic amplifier input as shown in Figure 14.

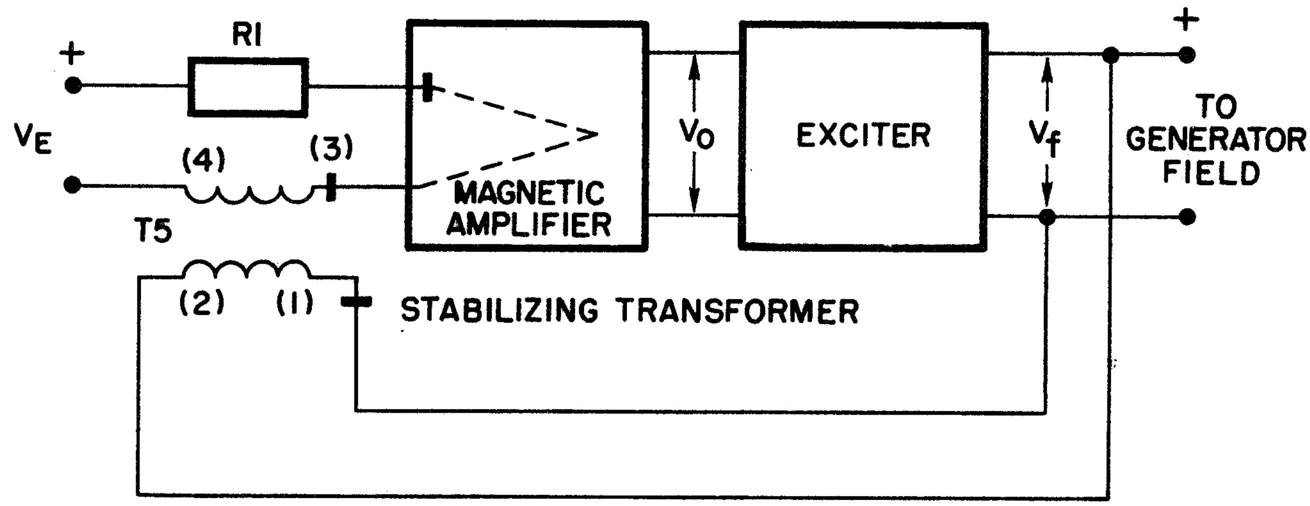


Figure 14. Stabilizing Circuit

An increase in line voltage causes a corresponding increase in error voltage V_E. This change increases the magnetic amplifier output voltage V_O and decreases the exciter output voltage V_f.

A decrease in V_f is equivalent to the addition of a negative voltage across V_f and, therefore, transiently makes terminal 1 of T5 positive with respect to terminal 2. A positive voltage at terminal 1 induces a positive voltage at terminal 3. Positive voltage at terminal 3 transiently opposes the initial increase in V_E providing negative feedback which stabilizes the system.

F. STATIC EXCITER CIRCUIT

The static exciter, Figure 15, supplies field excitation power for the alternator by rectifying a combination of voltage and current signals from the alternator output and feeding the result back to the generator field. The components of the static exciter are:

- Saturable current potential transformer (T6) in which the voltage and current signals are combined vectorially and into which a control signal from the regulator is introduced.
- Three-phase bridge rectifier (CR4) which rectifies the exciter output.

  Three-phase linear reactor L1 for shifting each line voltage input signal with reference to the current input signal.

The saturable current potential transformer is essentially a three-phase transformer with two primary and one secondary winding per phase and a single control winding which is used to vary the outputs of all three phases. The current and potential (voltage) windings are the two primaries and the secondary winding is the output winding.

A signal which is a function of line voltage is applied to the potential windings through the linear reactors and this input is combined with the current input obtained by running the entire line currents through each of the corresponding windings. The output of the saturable current potential transformer is fed via the secondary winding to the three-phase rectifier and from there to the alternator field.

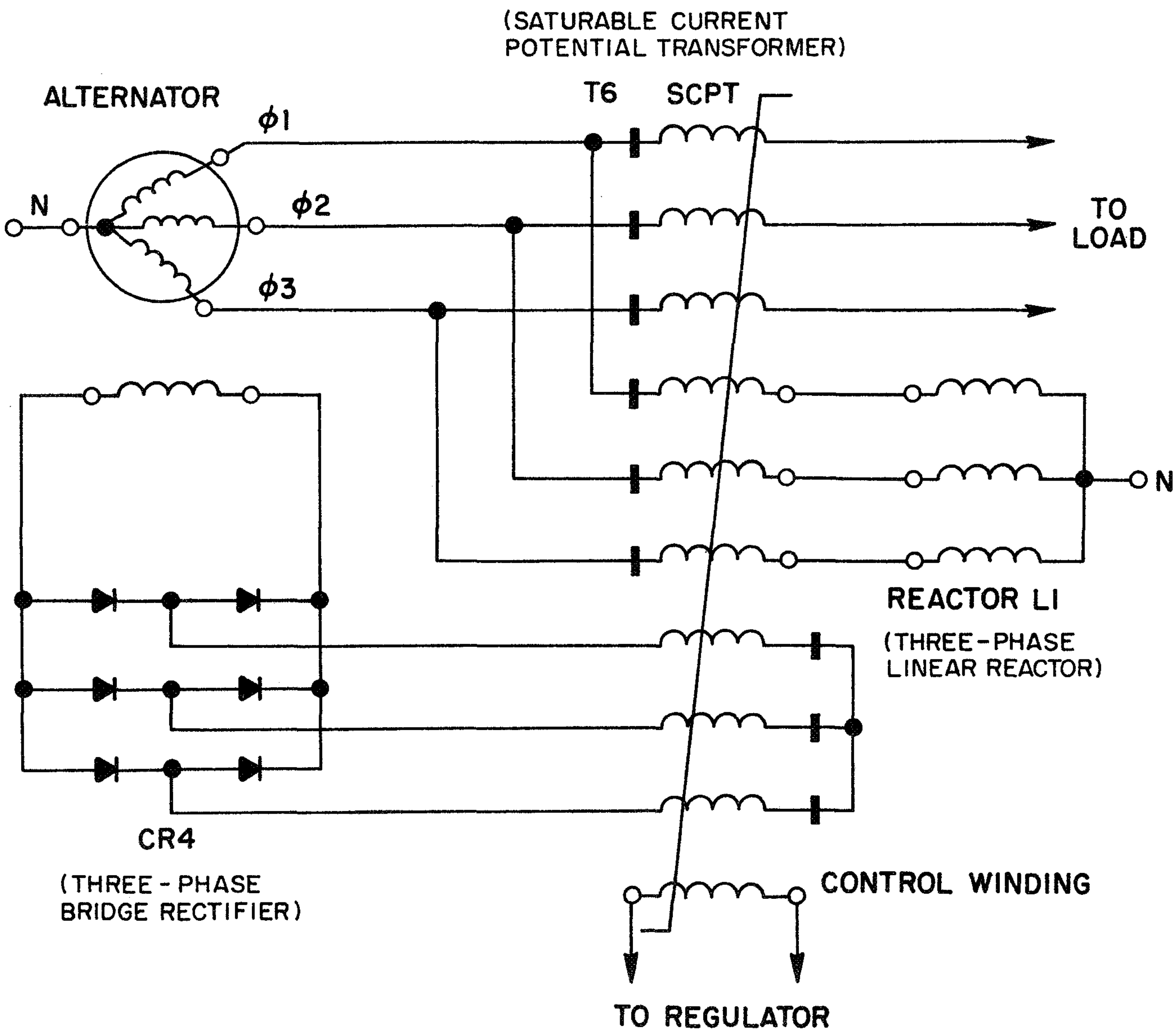


Figure 15. Static Exciter Circuit

The voltage and current signals are proportioned so that for normal loads at 400 Hz frequency the exciter will supply constant voltage. However, a control signal is furnished by the regulator to improve system accuracy, to compensate for field temperature and line drop variations, and to provide transient forcing. If the alternator output voltage tends to rise the following occurs:

- The control signal from the regulator increases.
- The saturable current potential transformer becomes more saturated.
- The exciter output decreases.
- The field current decreases lowering the alternator output.

If the alternator output voltage tends to fall, the opposite changes take place.

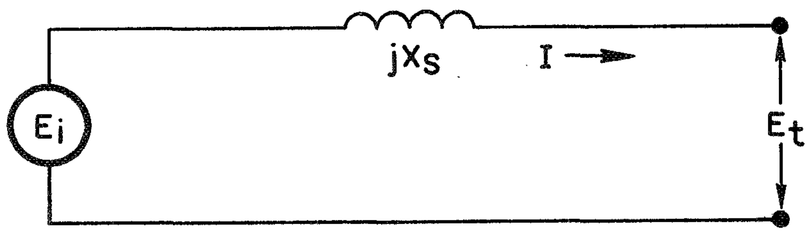
The exciter is a compensator because it holds the alternator voltage constant at constant frequency for all loads within the rating of the alternator. It utilizes both the voltage and current input of the alternator in such a manner that the output of the exciter is approximately correct for any load. The alternator internal voltage drop V_x can be represented by the equation:

$$V_x = jX_s I$$

where X_s is the synchronous reactance and I is the line current. This equation assumes a cylindrical rotor, no saturation, and no resistance in the armature winding. To compensate for the voltage drop V_x, the excitation must provide an internal voltage E_i as shown by the vector diagram in Figure 16.

$$E_i = E_t + jX_sI$$

This internal voltage E_i is proportional to the field excitation when no saturation is present.



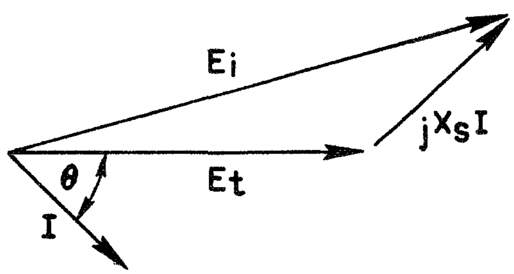


Figure 16. Vector Diagram of Voltages in Alternator

The single phase equivalent circuit for the exciter is shown in Figure 17. This circuit has a voltage source and a current source that represent the excitation obtained from the generator voltage and generator current. X_L is the reactance in series with the voltage source, X_M is the magnetizing reactance of the saturable current potential transformer that is varied by the DC control current, and R is the equivalent AC resistance of the alternator field. With no load on the alternator, the excitation is supplied entirely by the voltage source. When the load is applied, the current source supplies a current that divides between X_L, X_M, and R. The current source can be made to supply the synchronous impedance drop by applying

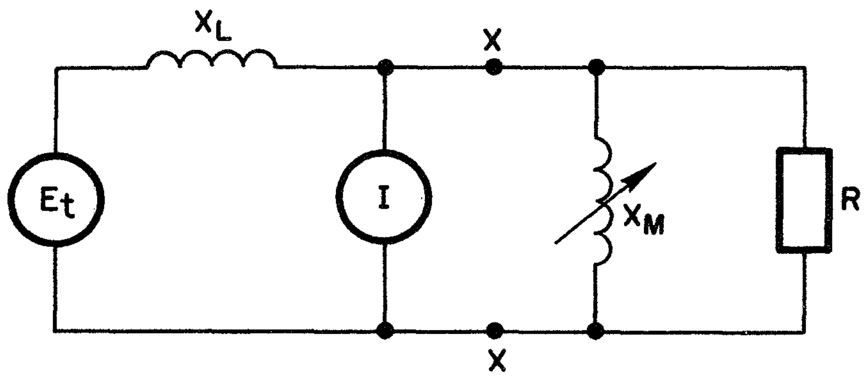


Figure 17. Single Phase Equivalent Circuit

Thevenin's Theorem at points X in Figure 17. By use of Thevenin's Theorem, the revised equivalent circuit is shown in Figure 18. If X_M is constant, it is evident that the current through R will be proportional to $E_t + jX_L I$. By selecting the proper values for X_L and the turns ratio, $jX_L I$ can be made proportional to $jX_s I$ and the exciter will provide the correct excitation at all loads.

To use this equivalent circuit for design, the alternator excitation characteristics were converted to their AC equivalents using the following equations:

Field Voltage	$V_{fac} = 0.429\ V_{fdc}$
Field Current	$I_{fac} = 0.78\ I_{fdc}$
Field Resistance	$R = 0.55\ R_{fdc}$

Table III indicates the calculated alternator excitator requirements.

TABLE III

ALTERNATOR EXCITATION REQUIREMENTS

LOAD	Field Temp.	DC VALUES				AC VALUES		
		Field Ohms	Field Amps	Field Volts	Corr. Field Volts	Field Volts	Field Amps	Field Ohms
No Load	Cold	1.45	7.5	11.9	12.9	5.52	5.85	
	Hot	2.35	7.5	17.6	18.6	7.97	5.85	1.36
Rated Load	Cold	1.45	21.7	31.5	33.5	14.36	16.90	
	Hot	2.35	21.7	51.0	53.0	22.70	16.90	1.34
3 Short Circuit	Hot	2.35	32.0	75.0	77.0	33.0	24.9	1.32

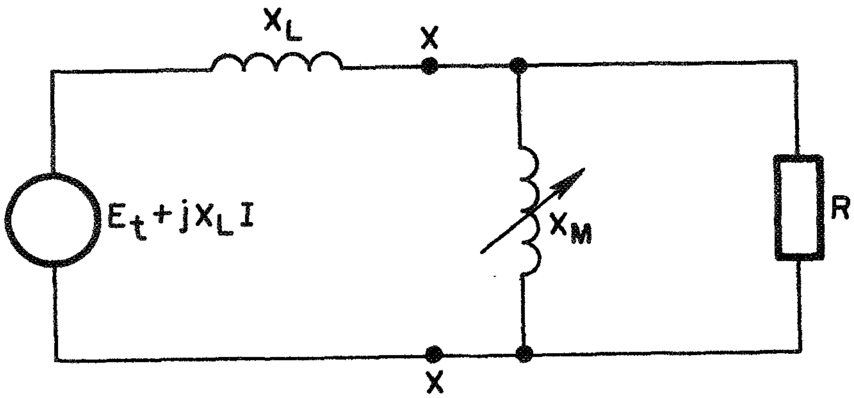


Figure 18. Equivalent Thevenin Circuit

The equivalent circuit for the no load condition with numerical values inserted is shown in Figure 19.

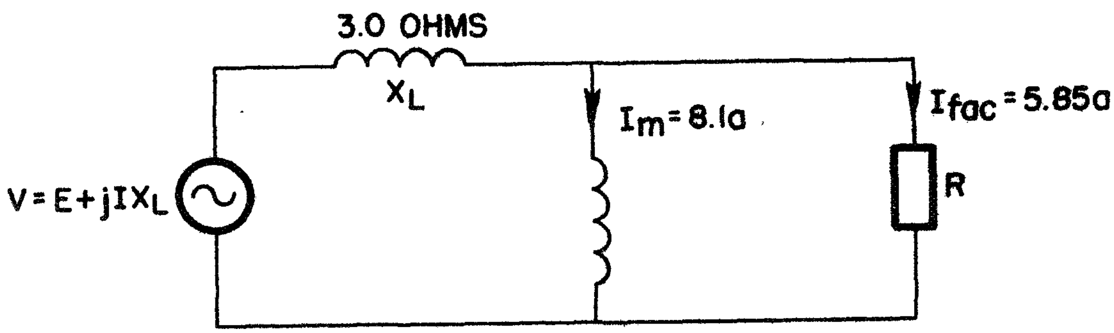


Figure 19. Equivalent Circuit, No Load

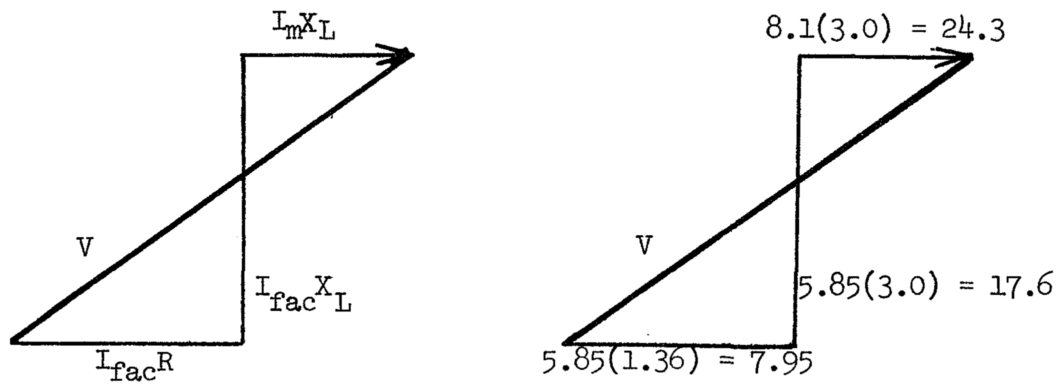
At no load, I = 0, and all excitation comes from the primary voltage winding as stated above. The vector diagram is shown in Figure 20.

The exciter, therefore, must supply 36.7 volts at its secondary terminals at no load. Since the primary voltage is 120V,

$$\frac{N_P}{N_S} = \frac{120}{36.7} = 3.27$$

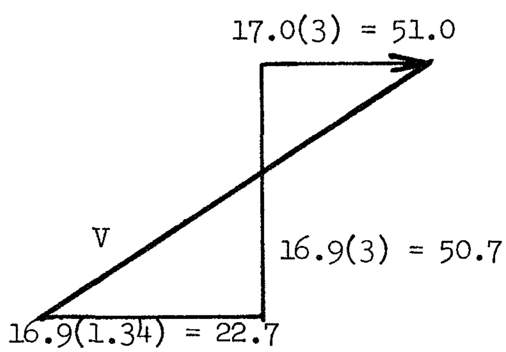
where N_P = primary turns and N_S = secondary turns.

At full load, a higher field current is required, and the excitation is furnished from both primary (voltage) and current windings. Also, I_m will automatically increase since the voltage across it will increase, and some provision should be made for this, if the exciter is to compensate automatically. From experience, I_m at full load is 1 to 2 times I_m at no load. In this design, I_m = 17.0a. The excitation requirements at full load are shown in Figure 21.



$$V = \sqrt{(7.95 + 24.3)^2 + (17.6)^2} = 36.7 \text{ v}$$

Figure 20. Vector Diagram



$$V = \sqrt{(22.7 + 51.0)^2 + (50.7)^2} = 89 \text{ v}$$

Figure 21. Full Load Excitation

V, in the secondary, will be supplied by both primary and current windings according to the relation $V = E + jIX_L$. The phase angle θ by which line current lags line-neutral voltage is the power factor angle and is specified as $41.4°$ for the voltage regulator rated power factor of 0.75. See Figure 22.

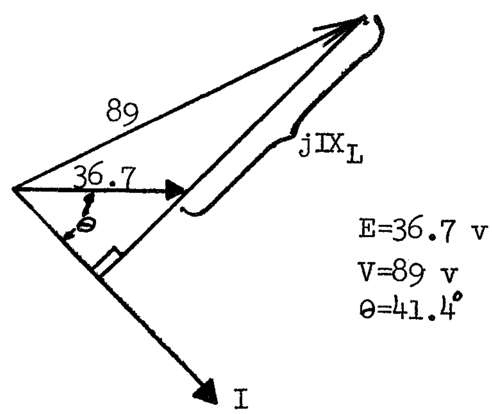


Figure 22. Phase Angle Power Factor Relationship

By graphical methods, it is determined that $jIX_L = 60.3$.

$$I = \frac{60.3}{X_L} = \frac{60.3}{3.0} = 20.1$$

For reliability, at this high current, a one turn current winding is used.

$$\frac{N_S}{N_I} = \frac{I_I}{I_S} = \frac{223}{20.1} = 11.1$$

Where the subscript I refers to the current winding. It was previously shown that $\frac{N_P}{N_S} = 3.27$

Choosing $N_I = 1$, $N_S = 11$

$$N_P = 11.0\ (3.27) = 36 \text{ turns}$$

The saturation voltage of the exciter was required to be 33V. Silicon steel was used which has a saturation flux density B = 125,000 lines per square inch.

$$V_{sat} = 4.44\ N_S AfB \times 10^{-8}$$

where:

A = effective iron area (square inches)

f = frequency (Hz)

$$A = \frac{V \times 10^8}{4.44 N_S fB} = \frac{V \times 10^8}{4.44(11)(400)(125,000)} = 1.35\ \text{inch}^2$$

Core AH-31 with a gross area of 1.50 inches and a stacking factor of 0.9, has the correct net iron area.

The exciter gain characteristics at no load were as shown in Figure 23.

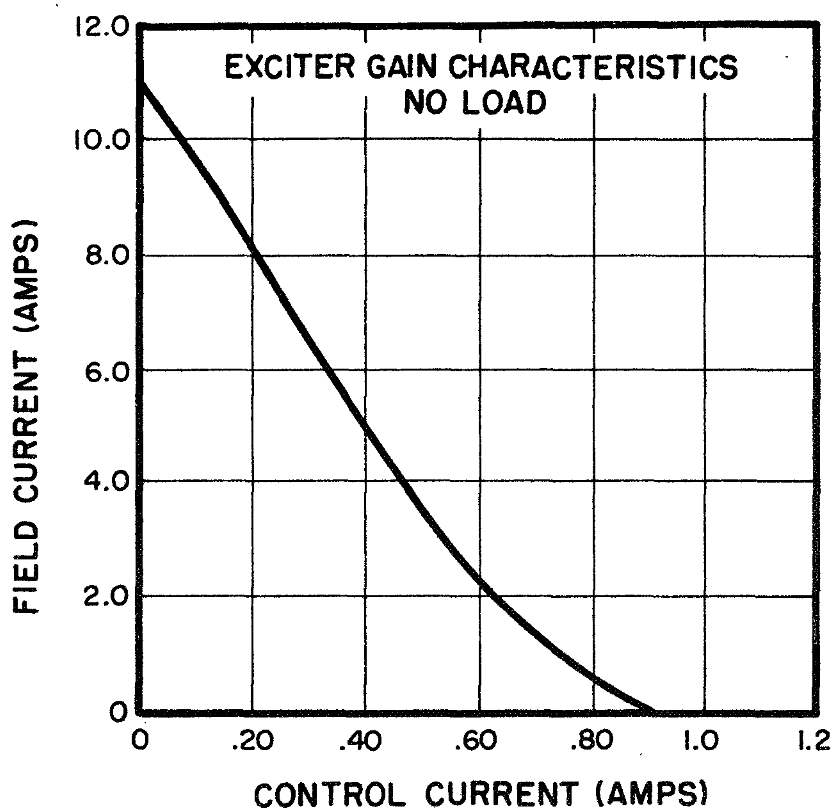


Figure 23. Exciter Gain Characteristic

IV. PERFORMANCE TESTING

The performance of the voltage regulator-exciter was determined by conducting the following tests:

- Laboratory tests of components, subassemblies and complete modules.
- Motor driven alternator tests.
- Operational tests with the SNAP-8 power conversion system.
- Operational and endurance tests with the alternator.

A. COMPONENT LABORATORY TESTS

The components to be used in the voltage regulator-exciter were tested in the laboratory before being installed in the control circuits. The magnetic components were checked for correct turns, correct core characteristics and insulation integrity. Examples are the saturable current potential transformer and the magnetic amplifier (saturable reactor) which were checked for input-output characteristics. Components were subjected to radiation exposure and dielectric strength tests. Resistors and semiconductors were given special laboratory tests to assure the acceptability of each component.

In addition, an irradiation effects test program of selected sample components of the types to be used in the voltage regulator-exciter was conducted at the Georgia Nuclear Laboratories of Lockheed-Georgia Company to determine if the components would be suitable for use in a radiation environment of 1×10^{11} n/cm^2 and 1×10^6 Rads(c) as required for the SNAP-8 power conversion system. The components tested were the same types used in the voltage regulator-exciter and were the components expected to be most susceptable to radiation damage.

All components were tested at two temperatures 100°F and 160°F. The resistors received a maximum integrated exposure of 4.4×10^{13} n/cm^2 and 4.7×10^6 Rads(c). The capacitors received a maximum integrated exposure of 8.2×10^{13} n/cm^2 and 7.2×10^6 Rads(c). The physical and electrical characteristics of the capacitors and resistors did not change due to the irradiation exposure.

The diodes tested were rated at 100 milliamperes, 2.5 amperes and 7.5 amperes. The diodes were irradiated to a maximum integrated exposure of 4.4×10^{13} n/cm^2 and 4.7×10^6 Rads(c). There was no appreciable change in forward voltage drop or in reverse leakage current until an exposure level of 1×10^{13} n/cm^2 was reached. At a radiation level higher than 1×10^{13} n/cm^2 both the reverse leakage current and the forward voltage drop increased rapidly.

The specified exposure of the SNAP-8 controls is 1×10^{11} n/cm^2 and 1×10^6 Rads(c). At these levels of irradiation the diodes were not affected by the radiation. See References 6 and 7 for detailed discussion of the SNAP-8 radiation effects test program.

B. MOTOR DRIVEN ALTERNATOR TESTS

Preliminary tests of the first alternator revealed that the system did not meet the specified recovery time limit of 0.25 seconds. The tests indicated that the alternator excitation requirements were 20% higher than had been predicted. Based on these data a larger saturable current potential transformer was designed and fabricated which had a 27 ampere ceiling as compared to a 23 ampere ceiling on the first model. When the new saturable current potential transformer design was tested with the alternator, recovery time was 0.23 to 0.32 seconds. Tests conducted later with the SNAP-8 system demonstrated that the recovery time was sufficiently fast so there was no problem of slowing or stalling induction motor driven pumps.

The performance of the voltage regulator-exciter established by acceptance tests with a motor-driven alternator is summarized as follows:

1. A voltage regulation of ± 0.6% from no load to full rated load, 60 kw, 0.75 PF was achieved at a constant frequency of 400 Hz, (see Figure 24)

2. When full rated load (60 kw at 0.75 PF) on the alternator was suddenly applied and removed, the time for the voltage to recover and remain within 5% of the final voltage was:

Load application	0.27 to 0.35 seconds
Load removal	0.20 to 0.27 seconds

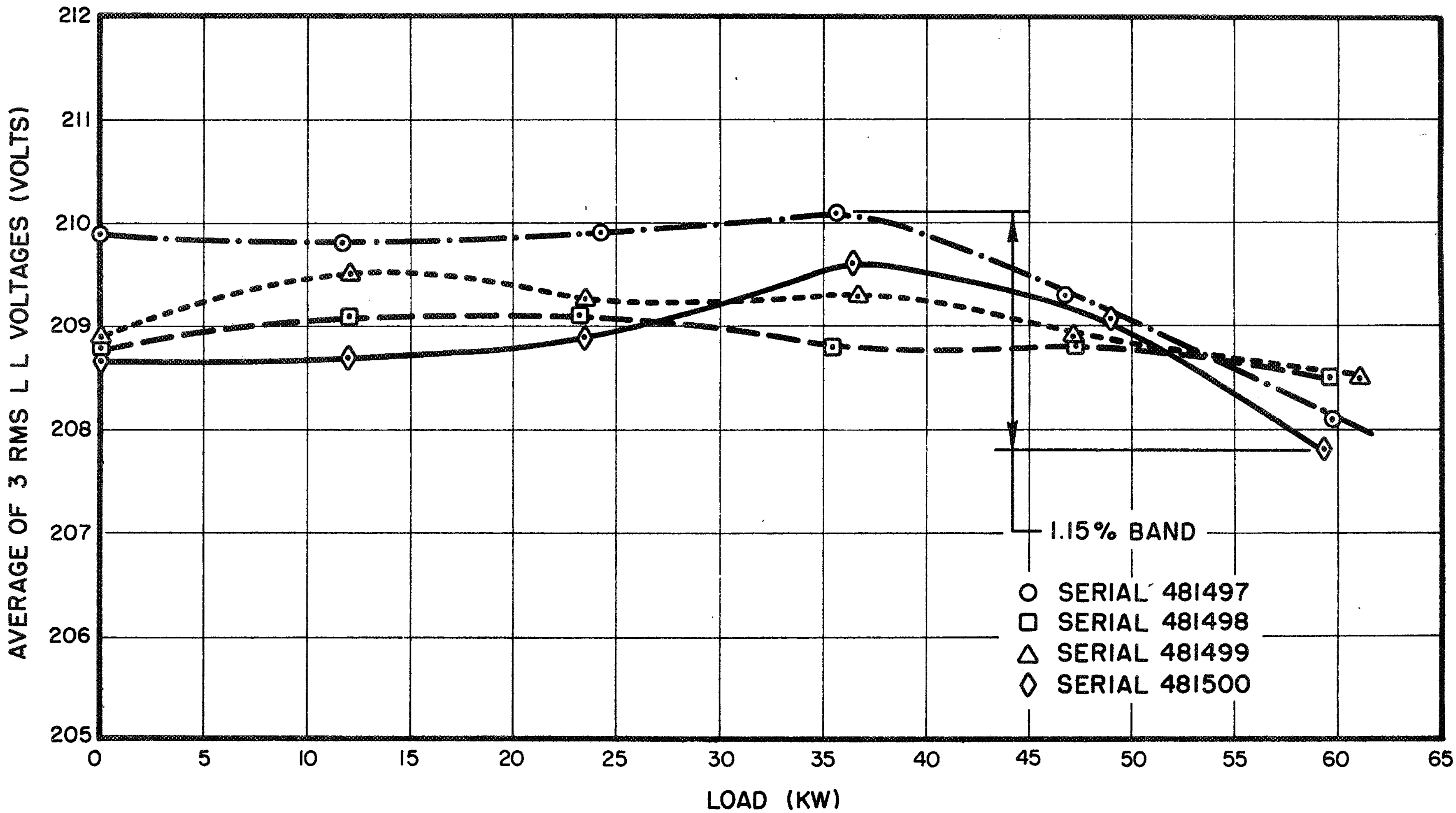


Figure 24. Voltage Regulator Test (Variable Load)

The maximum dip and rise in voltage resulting from the above load changes were:

Load application	34% voltage dip
Load removal	20% voltage rise

Figure 25 is a typical curve showing voltage dip and recovery after application of full rated load, 60 kw at 0.75 PF.

3. With the voltage regulator-exciter regulating the voltage of the alternator the minimum sustained short circuit current obtained on a line to line fault was 2.85 per unit and the maximum short circuit current obtained on a line to neutral fault was 4.23 per unit, see Table IV.

4. The voltage was maintained within the regulation band determined by the formula $E = \frac{F}{400} \times 208 \pm 6.24$ v, with no load on the alternator, from 200 Hz to 480 Hz.

5. The voltage was maintained within the regulation band determined by the formula $E = \frac{F}{400} \times 208 \pm 6.24$ v, with rated current delivered by the alternator, from 320 Hz to 480 Hz.

A comparison of test results vs system requirements is shown in Table V.

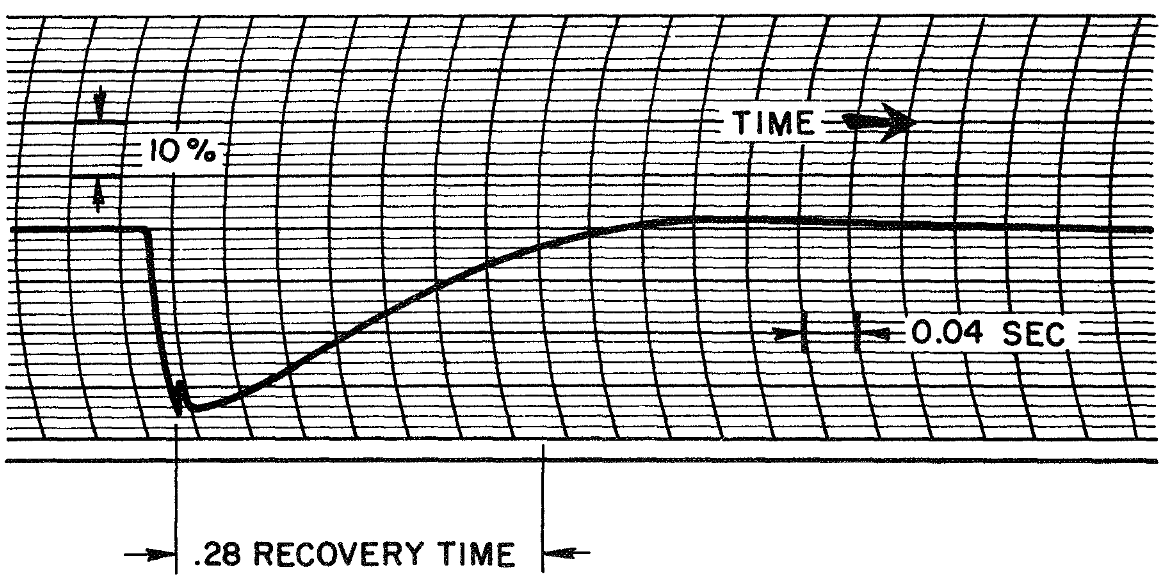


Figure 25. Typical Recovery After Load Application

TABLE IV

SHORT CIRCUIT TESTS

Type of Short Circuit	Lines Shorted	Per Unit Steady State Current
L-L[a] 3 phase	1-2-3	2.85
L-L 1 phase	1-2	3.06
L-L 1 phase	1-3	3.05
L-N[b] 1 phase	1-N	4.23
L-N 1 phase	3-N	4.19

[a] L-L Line to Line

[b] L-N Line to Neutral

TABLE V

COMPARISON OF TEST RESULTS WITH SPECIFICATIONS

Performance Requirements	Specification Limit	Test Results: Development ** Unit	Test Results: Serial 481497	Test Results: Serial 481498	Test Results: Serial 481499	Test Results: Serial 481500
1a. Voltage regulation - variable frequency, no load	$\frac{208}{400}f \pm 6.24V$		$\frac{208f}{400}{}^{+3.4}_{-5.5}$	$\frac{208f}{400}{}^{+2.6}_{-5.9}$	$\frac{208f}{400}{}^{+2.7}_{-6.2}$	$\frac{208f}{400}{}^{+2.5}_{-5.8}$
1b. Voltage regulation - variable frequency, load	$\frac{208f}{400} \pm 6.24V$		$\frac{208f}{400}{}^{+2.5}_{-0.9}$	$\frac{208f}{400}{}^{+1.4}_{-6.0}$	$\frac{208f}{400}{}^{+1.4}_{-6.7}$	$\frac{208f}{400}{}^{+1.6}_{-1.7}$
2a. Voltage regulation, rated frequency, 0.75 p.f.	$208 \pm 6.24V$		208.1-210.1	208.5-209.1	208.5-209.5	207.8-209.6
2b. Voltage regulation, rated frequency, 1.0 p.f.	$208 \pm 6.24V$		209.4-210.1	209.0-209.7	209.3-210.0	209.4-209.9
3a. Short circuit capacity, three phase	2.0 pu min.*	2.85				
3b. Short circuit capacity, single phase L-N	2.0 pu min.*	4.21				
4. Short circuit recovery time	.25 sec. max.	.22 sec.				
5a. Voltage modulation, no load	1% max	.0194%				
5b. Voltage modulation, rated load	1% max	.0776%				
6a. Voltage dip, 2 pu imp. load	30% max	15%				
6b. Voltage rise, 2 pu imp. load	30% max	12%				
7a. Recovery time, load application	.35 sec. max		.34	.35	.26	.27
7b. Recovery time, load removal	.35 sec. max		.27	.22	.20	.20

* Per Unit (pu)= X times the normal steady state value for a variable.

** Tests required for the development units only.

C. SYSTEM TESTS

1. Mercury Loop Test of Prototype System

Endurance testing of a prototype Voltage Regulator-Exciter regulating the voltage of the SNAP-8 turbine alternator operating with the Power Conversion System No. 1 (PCS-1) was conducted. The voltage regulator was mounted on a heat sink along with the speed control module (see Figure 26). The static exciter or saturable current potential transformer and the speed-control saturable reactor, were mounted on another heat sink. Each of these heat sinks were held at the temperatures expected in actual space operation. By holding the temperatures near the expected space service levels, the endurance tests being conducted provided the most meaningful information relative to performance and life expectancy of the Voltage Regulator-Exciter system. Table VI is a tabulation of the data taken during the PCS-1 tests.

At the conclusion of over 11,000 hours of operation, transient performance of the Voltage Regulator-Exciter was tested. Loads of 36 kw at .83 power factor and 1.0 power factor were suddenly applied and then removed. Figures 27 and 28 are recordings of the voltage transients experienced.

2. Electrical Component Test Facility Endurance Test

An endurance test of the SNAP-8 alternator driven by an electrical drive stand was conducted (see Figure 29). A prototype voltage regulator-exciter system was used in this test to regulate the voltage of the alternator. The voltage regulator-exciter operated for over 12,000 hours without failure. Table VII shows data taken during this test.

865-237

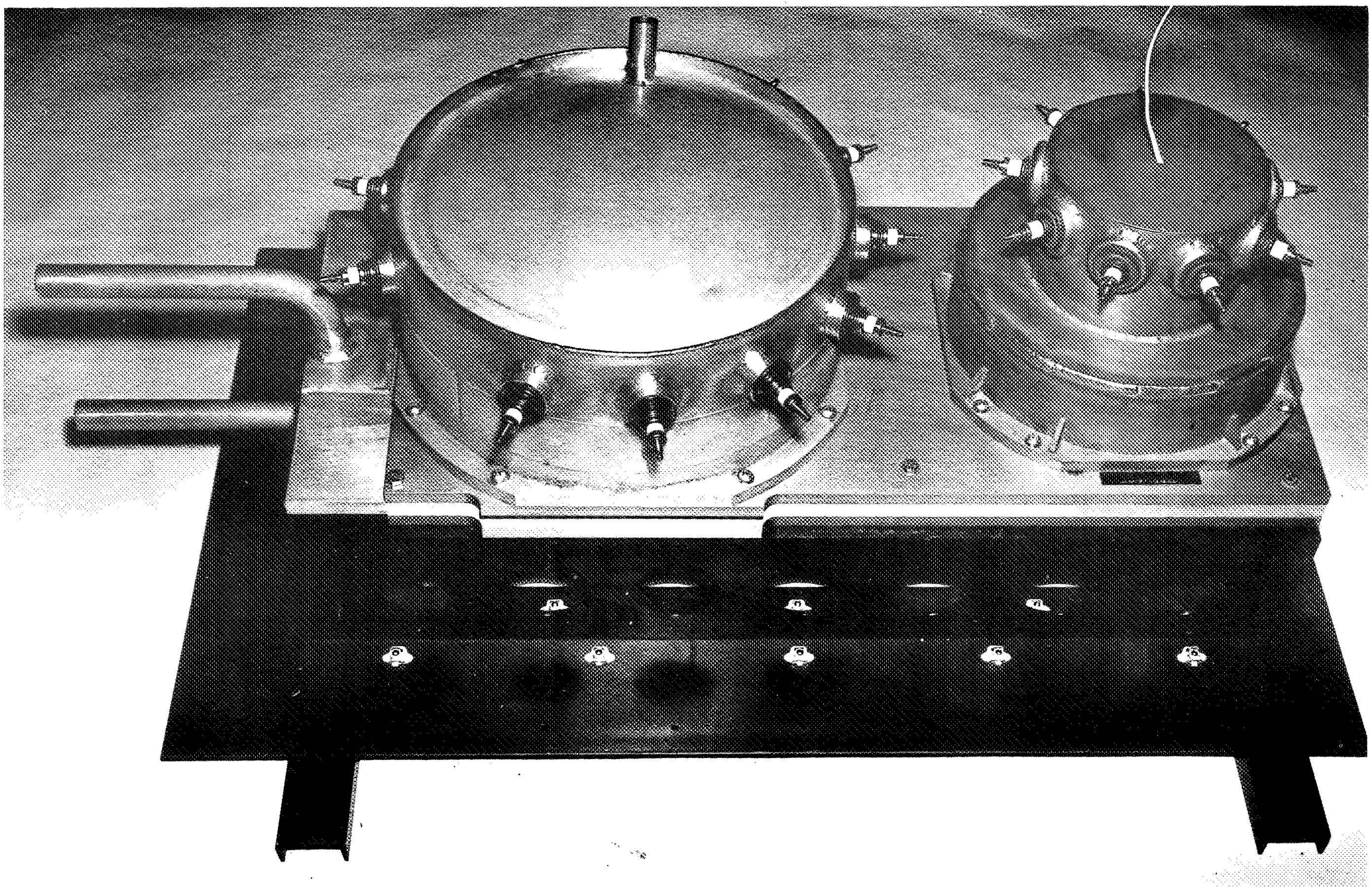


Figure 26. Photograph of the Voltage Regulator Module Mounted on a Heat Sink in PCS-1

TABLE VI - VOLTAGE REGULATION DATA OBTAINED IN POWER CONVERSION SYSTEM 1 TEST FACILITY ENDURANCE TEST

Voltage Regulator Exciter S/N 481499

Alternator S/N 481489

Date	Cum. Hours	Average of 3 Phase Line to Neutral Voltages	Total Alternator Load		Parasitic Load	Frequency	Voltage Regulator Module Base Temp.	Saturable Current Potential Transformer Base Temp.
		Volts	Kw	Power Factor	Kw	Hz	°F	°F
8-6-66	67.4	119.42	35.36	.773	25.13	400.00	125.00	---
4-19-67	483.1	120.13	52.92	.771	9.64	400.00	125.00	172.00
7-28-67	939.0	118.67	52.66	.765	13.29	---	128.00	176.00
9-9-67	1864.1	120.07	55.49	.784	12.19	400.00	115.00	176.00
4-9-68	3027.4	119.43	57.86	.829	16.09	400.46	145.39	200.75
10-31-68	4220.8	119.88	53.64	.768	12.18	400.00	156.82	201.46
11-30-68	4822.2	119.44	53.20	.759	14.43	400.11	151.32	199.75
1-31-69	6179.4	119.70	51.63	.744	13.21	400.19	153.07	199.72
3-23-69	7197.5	119.30	52.83	.750	14.60	400.25	152.97	199.03
5-4-69	8253.0	119.37	53.40	.762	15.03	400.22	149.62	198.67
5-11-69	8420.0	120.02	50.12	.752	11.82	400.17	147.11	198.11

NOTE: No adjustments were made on the Voltage Regulator-Exciter during this endurance test.

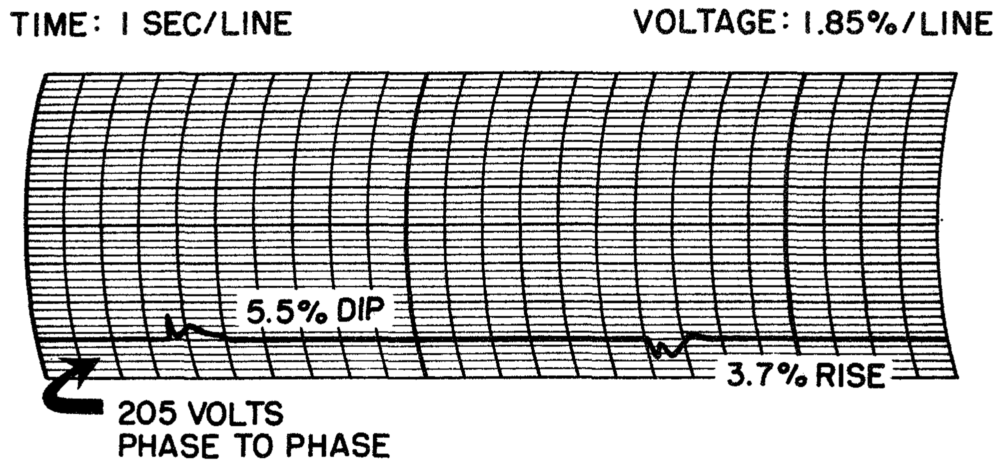


Figure 27. Load, 36 kw, 1.0 PF Suddenly Applied and Removed

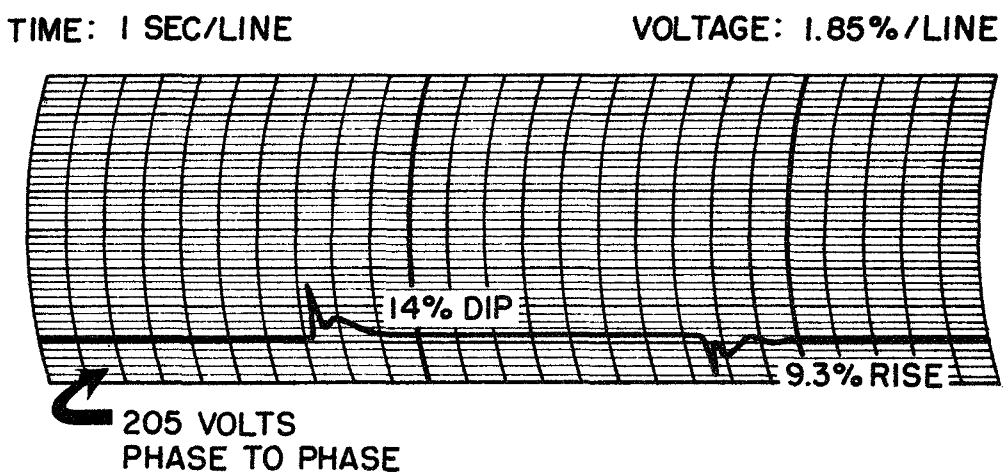


Figure 28. Load, 36 kw, .83 PF Suddenly Applied and Removed

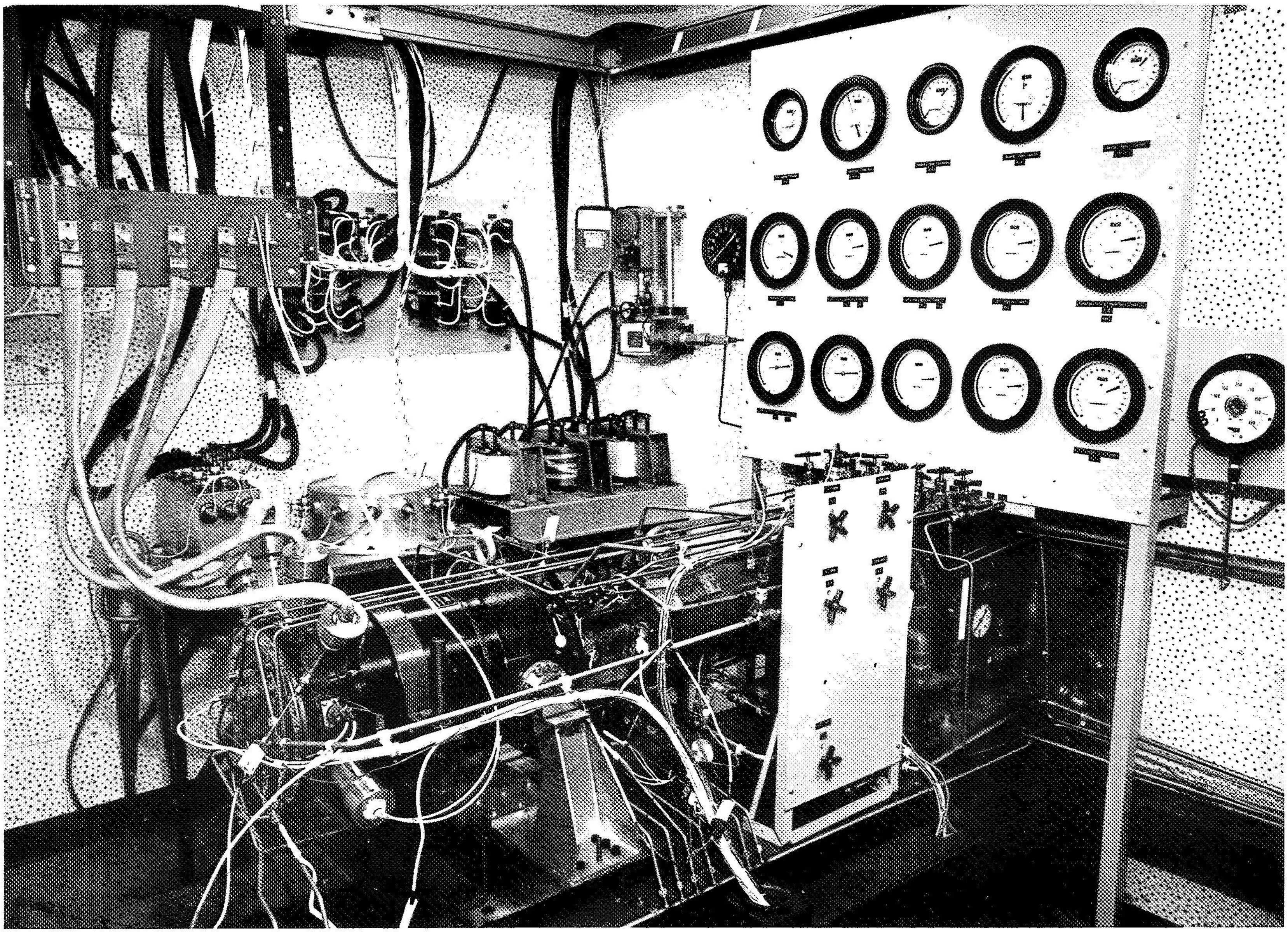


Figure 29. Photograph of Electrical Component Test Facility

TABLE VII - VOLTAGE REGULATION DATA OBTAINED IN ELECTRICAL COMPONENT TEST FACILITY ENDURANCE TEST

Voltage Regulator Exciter S/N 481497 Alternator S/N 091490								
Date	Running Time Meter	Average of 3 Phase Line to Neutral Voltages	Total Alternator Load		Parasitic Load	Frequency	Voltage Regulator Module Base Temp.	Saturable Current Potential Transformer Base Temp.
	Hours	Volts	Kw	Power Factor	Kw	H_z	°F	°F
3-20-67	12	120.0	60.0[a]	.76	6.0[a]	400	178	169
6-19-67	954	119.0	58.5[a]	.75	30.0[a]	400	180	180
8-21-67	2307	120.0	59.0	.75	4.5	400	174	180
11-15-67	2385	122.0	60.0	.75	40.0	400	141	202
3-13-67	3896	122.0	59.8	.75	20.5	400	139	224
7-1-68	6161	122.0	60.0	.90	5.0	400	148	230
10-10-68	8248	123.0	59.5	.90	6.0	400	143	226
12-9-68	9591	123.0	60.0	.90	21.5	400	141	227
3-7-69	11351	123.0	60.0	.90	6.0	398	143	225
3-28-69	11780	122.7	60.5	.90	41.0	402	143	223
4-16-69	12134	123.7	60.0	.90	20.5	400	143	225

[a] Calculated from other measured data.

NOTE: No adjustments were made on the Voltage Regulator-Exciter during this endurance test.

V. DISCUSSION OF RESULTS

A. VOLTAGE REGULATOR-EXCITER SUBSYSTEM PERFORMANCE

1. Reliability

A voltage regulator-exciter regulated the voltage of a SNAP-8 alternator running in a test facility for over 12,000 hours. It held the voltage well within the specified regulation range of ± 3% for changes in vehicle load from 0 kw to 35 kw (changes in parasitic load from 40 kw to 5 kw). A voltage regulator-exciter regulated the voltage of a SNAP-8 alternator driven by the SNAP-8 turbine operating in a hot gas loop, and performed successfully for over 8000 hours without failure and with no adjustment (see Table VI).

2. Regulation

NASA specification 417-1 required that the voltage be held within ± 5% of the nominal voltage for a minimum unattended operating time of 10,000 hours. This included the normal frequency regulation of ± 1%. The voltage regulator-exciter operated in the electrical component test facility for over 12,000 hours. During this operation the voltage was held to better than ± 5% of the set point of 120.4 volts; this included the effects of load, temperature and time changes (see Table VII).

3. Stability

The absence of oscillation, that is, the stability of the voltage-regulator exciter was demonstrated in all tests conducted. No sustained oscillations were observed for any operating condition. The stabilizing element, the damping transformer, demonstrated the capability of maintaining stability during development tests and for over 20,000 hours of operation.

4. Recovery Time

The original specification required that the voltage controlled by the regulator during load changes between full, 60 kw at 0.75 PF, and no load recover to, and remain within, 5% of its steady-state condition within 0.25 seconds. Preliminary combination tests on the regulator and alternator demonstrated that the regulator and alternator subsystem could not meet this requirement. Modification of the saturable current potential transformer to provide a higher ceiling voltage improved the performance to an acceptable value. The recovery time of the four prototype voltage regulator-exciters, on load application, 60 kw at 0.75 PF, varied from 0.27 seconds to 0.35 seconds, and on the same load removal the recovery time varied from 0 to 0.27 seconds (see Table VII). A typical recovery time curve after load application is shown in Figure 25.

Tests conducted in the hot gas loop with the turbine alternator assembly under the control of the SNAP-8 speed control and voltage-regulator exciter indicated a voltage recovery time of approximately .20 seconds when a 36 kw load at 0.83 lagging power factor was suddenly applied (Figure 28).

5. Voltage Dip and Rise

The performance specification (Appendix A) required that the alternator voltage, controlled by the voltage regulator-exciter, should not dip more than 30% when two per unit impedance load was applied or removed. The voltage regulator-exciter alternator subsystem easily met this requirement demonstrating a dip and rise capability approximately one-half that required by the specification. The possibility of sudden load changes causing disturbance to the electrical generating system or to the load being supplied is decreased as a result of this dip and rise capability.

6. Short Circuit Capacity

The performance requirements, Appendix A, required that the minimum sustained short circuit current of the alternator voltage regulator-exciter subsystem shall be 2.0 per unit. The minimum value achieved was 2.85 per unit on a three-phase line to line to line short circuit. Table IV shows the short circuit currents obtained during the test.

B. PROBLEMS

1. Major Problems Encountered

a. The volts-per-cycle reference transformer was an electrical design problem because of the requirement to develop a unit with acceptable tolerance to both temperature and voltage change.

b. A full hermetic seal of the saturable current potential transformer as presently designed was not achieved.

c. Voltage recovery time when load was suddenly applied was longer than originally specified for certain load and temperature conditions.

2. Voltage Reference Circuit

To provide a volts-per-cycle reference a saturating transformer was chosen. If a transformer with a core which has a nearly flat saturating characteristic is operated in the saturated region very small voltage changes in the secondary will be produced for large changes in the primary current flow. Temperature causes change in magnetization of magnetic materials. In high fields, that is at saturation, induction falls with increasing temperature, so in a saturating transformer the voltage delivered at the secondary decreases as temperature increases. The magnitude of this characteristic is not the same for all materials; so sample transformers were built of five different magnetic materials, and tests were run over the required temperature range, -55°C to + 71°C. The sample transformers were also tested for output voltage change when input voltage was changed ± 10%.

For the final design a 48 alloy core made of punchings was chosen, and half the primary and half the secondary was wound on each leg of the core to reduce leakage reactance, see Reference 2.

This design provides output voltage regulation of 1.2% for ± 10% change in input voltage and shows slightly more than 2.9% change in output for a temperature change of +46°C to +71°C.

During normal operation the temperature of the voltage regulator is expected to change no more than 14°C, so the voltage change with temperature will be no more than 1.65% which is satisfactory.

3. Saturable Current Potential Transformer Hermetic Seal

The voltage regulator-exciter is housed in two sealed enclosures, one for the regulator and one for the saturable current potential transformer. The regulator enclosure was successfully sealed but the saturable current potential transformer was not.

In the regulator the various components have their own terminals with separate hermetic terminals installed in the wall of the enclosure. The component terminals are then connected to the hermetic terminals with welded wires. In the saturable current potential transformer some terminals are much larger and are an integrated part of the magnetic device. The large terminals pass through the casing and a hermetic seal is then welded from terminal to case. Most of the problems experienced were due to the close spacing of the terminals which resulted in weld overlaps. Numerous small changes in design and manufacturing procedures were tried, but hermetic sealing could not be achieved. A change in design which allows more space for the terminals will be required to obtain a hermetic seal.

4. Voltage Recovery Time

As discussed in Section IV, tests on the first alternator with the voltage regulator-exciter demonstrated that the system did not meet the originally specified recovery time of 0.25 seconds when load was suddenly applied. To improve the recovery time a larger saturable current potential transformer with capability of producing a higher forcing voltage was designed and built. Tests run on four prototype units of the redesigned saturable current potential transformer demonstrated that the alternator, regulator-exciter subsystem performed as follows:

a. Recovery time was within 0.25 seconds for all load changes up to rated load, 60 kw, at rated PF, 0.75, for alternator field temperatures up to approximately 140°C (284°F).

b. Recovery time following load removal was always within 0.27 seconds.

c. Recovery time did not exceed 0.35 seconds for 160°C (320°F) field temperature when rated load, 60 kw at rated PF 0.75 was applied.

d. Recovery time did not exceed 0.25 seconds at 160°C field temperature after application of 45 kw at 0.80 PF.

e. Voltage dip on suddenly applied rated load, 60 kw at 0.75 PF, was approximately 31%, which is about one-half the maximum anticipated.

It was demonstrated that small circuit changes such as the addition of a lead circuit would not improve the recovery time an appreciable amount. It was concluded that increased field forcing voltage was required which could only be obtained by redesign of the saturable current potential transformer. Because of the nature of the regulator-exciter, this redesign would result in an increase in sustained short circuit current. The maximum short circuit current occurs on a single phase line to neutral fault. The existing saturable current potential transformer design, is 4.2 per unit (4.2 times the normal steady state value for a variable). To limit magnetic and thernal stresses of alternator windings, on the distribution system and on protective devices, it was desirable to limit the maximum current to the existing 4.2 per unit level. A redesigned saturable current potential transformer would require two turns on the current winding instead of the existing one turn.

As tests were run on the SNAP-8 system it was clearly extablished that when full rated vehicle load of 35 kw at 0.85 PF was suddenly applied the voltage dip and recovery time did not cause slowing or stalling of the motor-driven pumps nor were there any other effects detrimental to the system operation. Therefore, the voltage regulator-exciter specification was changed to allow a recovery time of 0.35 seconds rather than the original 0.25 seconds specified.

VI. CONCLUSIONS

The voltage regulator-exciter developed for the SNAP-8 space power system meets the requirements for an application which requires reliability and operation in a space and radiation environment. The circuit is simple, requiring only three basic components, diodes, resistors and magnetic components. The active elements are magnetic components which have established a long history of reliability, and to further improve reliability the most vulnerable components were connected in redundant configurations. The voltage regulation, recovery time, stability, dip and rise of voltage are fully satisfactory for the required service. Endurance tests indicated that this system has a long life potential. During 20,000 hours of operation no failures have occurred; no adjustments were required, and performance was completely satisfactory.

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7. Electrical Insulation Materials SNAP-8 Radiation Effects Test Program, Volume II, NASA CR-54387.

APPENDIX A

VOLTAGE REGULATOR-EXCITER

DESIGN OBJECTIVES
AND
PERFORMANCE REQUIREMENTS

APPENDIX A

VOLTAGE REGULATOR-EXCITER
DESIGN OBJECTIVES,
PERFORMANCE CHARACTERISTICS,
AND ENVIRONMENTAL REQUIREMENTS

I. Design Objectives

A. Simplicity of construction to attain the specified degree of reliability.

B. Objective of 99.78% reliability for the duration of operating life and shelf life.

1. Designed for 10,000 hours continuous, unattended operating life, under specified environmental conditions (Table A-I) while continuously satisfying all minimum operational performance specifications.

2. Designed to be maintenance-free for 2 years, including the 10,000 hours operational period and the remaining nonoperational period.

(When used in conjunction with the SNAP-8 alternator, a suitable drive mechanism, and an electrical load, the voltage regulator-exciter shall meet the following characteristics:)

II. Performance Characteristics

A. Electrical

1. Voltage Reference - The voltage reference shall be a volts-per-cycle type which shall maintain the voltage output of the controlled alternator proportional to frequency within ± 3 percent of the voltage setting.

2. <u>Voltage Regulation</u> - The regulator shall maintain the alternator steady state line-to-line voltage within ± 3 percent of the voltage setting at frequencies from 396 Hz to 404 Hz.

3. <u>Short Circuit Capacity</u> - The regulator (in combination with the alternator) shall be capable of delivering a minimum of 2 per unit (200 percent) rated current at average rated speed on a three-phase line-to-line or single-phase line-to-neutral short circuit for a minimum of 5 seconds.

4. <u>Short Circuit Removal</u> - When the short circuit is removed from the alternator the output voltage shall recover to and remain within ± 5 percent of the nominal voltage within 0.25 seconds or less.

5. <u>Output Voltage Modulation</u> - When the alternator is operated at minimum, average, and maximum rated speeds both at no load and rated current at rated voltage, the percent modulation (with the regulator in proper operation) shall not exceed 1 percent.

6. <u>Voltage Deviation</u> - The alternator voltage controlled by the regulator shall not deviate by more than 30 percent of the nominal voltage when 2 per unit impedance load is applied or removed. The regulator shall not develop sustained oscillations under any of these load conditions.

7. <u>Time of Recovery</u> - The voltage controlled by the regulator during load changes between full load and no load shall recover and remain within 5 percent of its steady state condition within 0.350 second.

8. <u>Low Temperature Operation</u> - The regulator shall not permit the alternator voltage to rise above 223 vrms line to line during warm-up from -55°C (-67°F).

9. Rated Temperature - The regulator shall be capable of operating within the above electrical performance requirements throughout its service life with a continuous temperature environment of 260°F. For short time periods, the regulator will be required to operate at temperatures between 32°F and 260°F.

10. Dielectric Strength - The regulator shall be capable of withstanding a dielectric test voltage of 1500 volts, 60 Hz (rms) applied between the following points for one minute at sea-level pressure:

    a. Between all terminals and the enclosures.

    b. Between all mutually isolated terminals.

11. Insulation Resistance - The insulation resistance of the regulator shall be measured between all mutually isolated terminals at a potential of 500 vdc with a megohm bridge. The resistance shall be at least 100 megohms at the rated operating temperature.

B. Packaging

1. Enclosure - The enclosures of the regulator and exciter shall be hermetically sealed by welding to prevent leakage.

   The enclosures shall be purged and filled with dry, gaseous sulphur hexafluoride (SF_6), C.P. grade or better.

2. Leakage - The maximum leakage rate from either enclosures shall not exceed 1×10^{-7} standard cubic centimeters per second of helium as measured with a mass spectrometer.

3. Heat Transfer - The mechanical design of the enclosures shall be such as to transfer the heat load to an aluminum heat sink maintained at a temperature of 232°F ± 20°F.

III. Environmental Requirements

A. The voltage regulator shall be capable of withstanding the environmental requirements specified in Table A-1 and thereafter meet the performance requirements in Section II above.

Table A-1. Environmental Requirements

ENVIRONMENTAL CONDITIONS (At Maximum Stress)	POSITION OF MODULE	MAXIMUM ENVIRONMENTAL FACTORS DESIGNED TO WITHSTAND			
Atmospheric Contaminants	Launched 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/ft²hr.			
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

APPENDIX B

THERMAL, STRUCTURAL AND RELIABILITY ANALYSIS

APPENDIX B

THERMAL, STRUCTURAL AND RELIABILITY ANALYSIS

I. Thermal Analysis

A thermal analysis of the magnetic components and voltage regulator module were conducted. The calculated maximum temperatures are shown in Table B-I below.

TABLE B-I

CALCULATED MAXIMUM TEMPERATURES

COMPONENT	MAX. TEMP. (°F)	COLD PLATE TEMP. (°F)
Rectifier (CR1)	155	150
Rectifier (CR2)	155 (Stud)	150
Rectifier (CR3)	167	150
Rectifier (CR4)	198 (Stud)	150
Resistor (R1)	169	150
Resistor (R2)	157	150
Resistor (R3)	161	150
Resistor (R4)	187	150
Resistor (R5)	173	150
Resistor (R6)	171	150
Transformer (T4)	188	150
Transformer (T5)	205	150
Choke (L2)	252	150
Magnetic Amplifier (L3)	192	150
Linear Reactor (L1)	302	250
SCPT	314	250

II. Structural Analysis

These calculations for the SCPT and for the voltage regulator module were made. The results of these analysis are shown in Table B-II below.

TABLE B-II

COMPONENT "g" LEVELS

(10 "g" INPUT)

COMPONENT	MAX. "g" LEVEL			
Frequency (Hz)	2000	1750	1500	1250
Reactor Transformer	10.0	10.0	10.0	10.0
T5	15.5	13.5	12.3	11.4
L3	13.6	12.1	11.5	10.9
CR2A Module	13.6	12.1	11.5	10.9
CR2B Module	13.6	12.1	11.5	10.9
T4	14.2	12.7	11.8	11.1
L2	14.2	12.7	11.8	11.1
R1-4-5-6 Module	15.0	13.1	12.0	11.2
R2-3 Module	15.0	13.1	12.0	11.2
CR4-A Module	11.7	11.1	10.7	10.4
CR4-B Module	14.5	12.8	11.9	11.1
CR4-C Module	14.5	12.8	11.9	11.1
CR1 Module	11.7	11.1	10.7	10.4
CR3 Module	11.7	11.1	10.7	10.4

A reliability analysis was conducted, and some of the results are shown in the following tables and figures.

A summary of the control component stresses, the application limits for these parameters and the calculated or measured stresses are tabulated in Table B-III. This table confirms that all component stresses are very low.

TABLE B-III

COMPONENT STRESSES

COMPONENT	CRITICAL STRESS	APPLICATION LIMIT	CALCULATED OR MEASURED STRESS
R1	Operating Power	0.2	.064
R2	Rated Power		.11
R3			.20
R4			.20
R5			.14
R6			.14
CR1	Operating PRV	Not Specified	.60
CR2	Rated PRV		.28
CR3			.56
CR4			.35
CR1	Junction Temperature	194°F	155°F
CR2			155°F (Stud)
CR3			167°F
CR4			198°F (Stud)
CR1	Operating Current	Not Specified	.008
CR2	Rated Current		.016
CR3			.017
CR4			.20

TABLE B-III (cont'd)

COMPONENT STRESSES

COMPONENT	CRITICAL STRESS	APPLICATION LIMIT	CALCULATED OR MEASURED STRESS
SCPT	Operating Temperature	Not Specified	314°F
T4			188
T5			205
L1			302
L2			252
L3			192

Complete part application lists giving all application data and part ratings was completed. Results of this analysis are summarized in Table B-IV.

TABLE B-IV

PREDICTED RELIABILITY

PART	FAILURE RATE FAILURES PER 10^3 HRS.
Magnetics	
Exciter (SCPT) 3 x .03 + (Linear Reactor) .03	.1200
T4 (Sat Transformer)	.0100
T5 (Stab Transformer)	.0100
L3 (Saturable Reactor)	.0100
L-2 (Reactor)	.0100
Resistors	
R1-10, 1/8 W Film in Par. (.2 ea)	.0001
R2-10, 1 W Film in Par. (.2 ea)	.0001
R3-20, 1 W Film in Par. (.2 ea)	.0001
R5-16, 10 W WW in Par. (.2 ea)	.0001
R5-10, 7 Watt WW in Par. (.2 ea)	.0001
R6-10, 10 W WW in Par. (.3 ea)	.0004
Rectifiers	
CR1 a, b, c, d, e, f Quad. (.2 ea)	.0012
CR2 a, b, c, d, Quad. (.2 ea)	.0008
CR3 a, b, c, d, Double Quad. (.2 ea)	.0004
CR4 a, b, c, d, e, f, Quad. (.2 ea)	.0012
TOTAL	.1645

$$MTBF = \frac{10^6}{.1645} = 6.0790 \times 10^6 \text{ Hours}$$

Reliability For 10,000 Hours

$$R = 1 - 10^4 \times .1645 \times 10^{-6} = .9984$$

The extremely high reliability goal could not be approached by standard methods, so redundancy techniques were investigated. In the field of reliability, a redundant circuit is one which has extra components so connected that the circuit will operate normally when a component or components fail.

A typical example is the rectifier quad shown in Figure B-1.

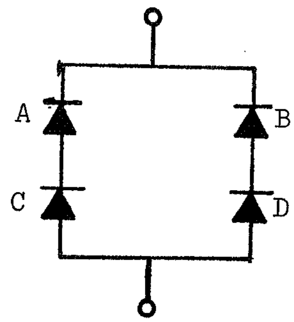

Figure B-1

A quad is used for each rectifier in the circuit. If rectifier A opens, rectifiers B and D will still fulfill the rectifier function and allow the circuit to operate. If rectifier A shorts, rectifier C will still allow normal operation. Certain multiple failures, such as shorted A plus open B or D, may occur without destroying the component function.

The rectifiers are applied so that any one rectifier in the quad will carry the required current and voltage by itself, so a failure will not overload another component. In the tabulations shown in this report, the total stress can be taken by a single component.

Figure B-2 illustrates how the failure rate can be reduced by redundancy. If failure rate of an individual rectifier is .01%, the quad will have a failure rate of .00001%.

The regulator circuit is designed so it will tolerate a 20% change in resistance. A parallel combination of ten resistors is used for each resistor, so any two may fail without exceeding the circuit tolerance. The increase in reliability due to this configuration is shown in Figure B-3.

Using a resistor with a failure rate of .02%/1000 hrs., if a failure rate of 10 in parallel becomes .00001%, a 20% increase in resistance is allowable.

FAILURE RATE FOR REDUNDANT RECTIFIER QUAD

(10,000 HR. MISSION)

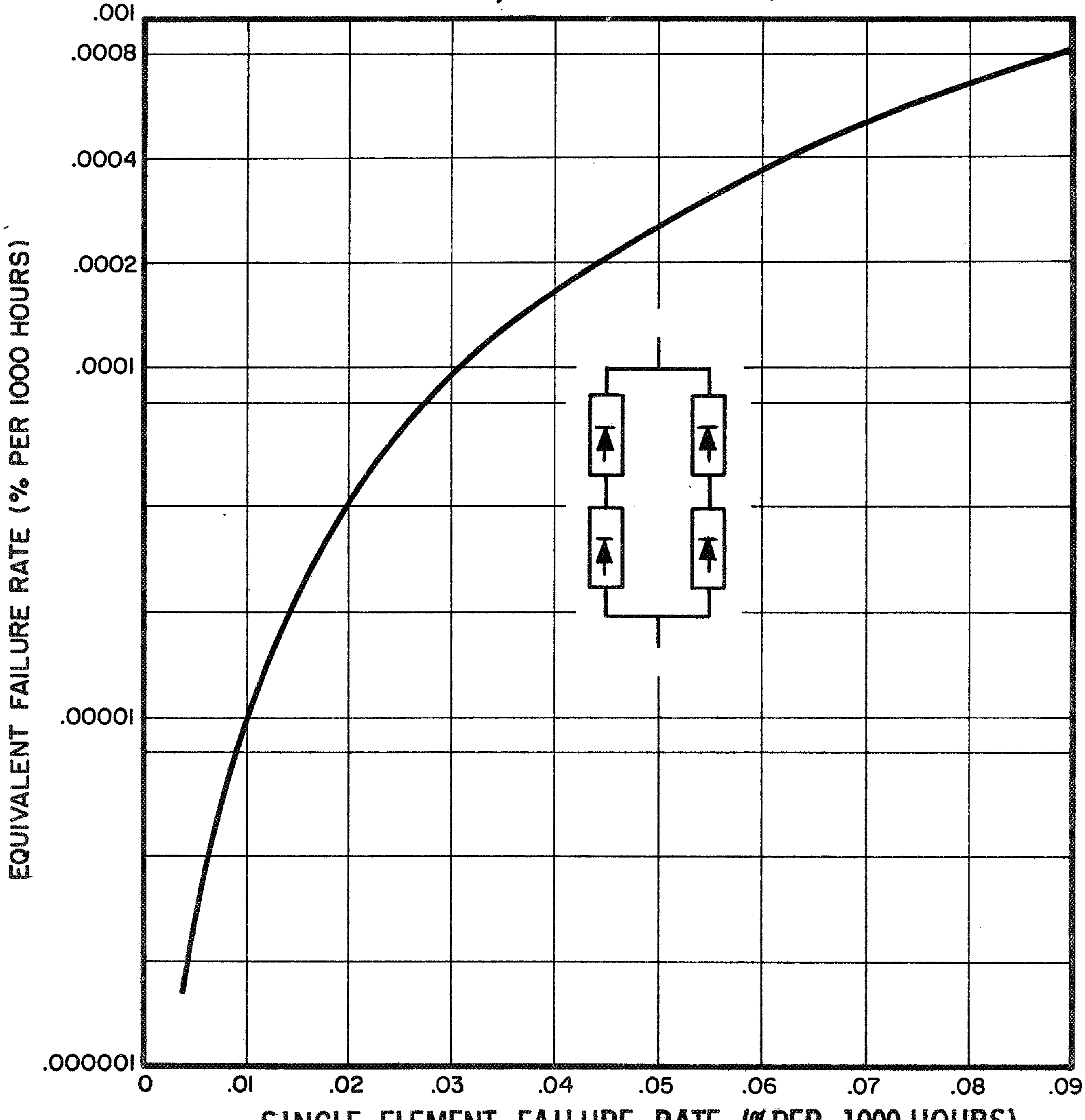

FIGURE B-2

FAILURE RATE FOR TEN RESISTORS IN PARALLEL

(SURVIVAL OF 8 OUT OF 10 PARALLEL UNITS - OPEN FAILURE MODE ONLY)

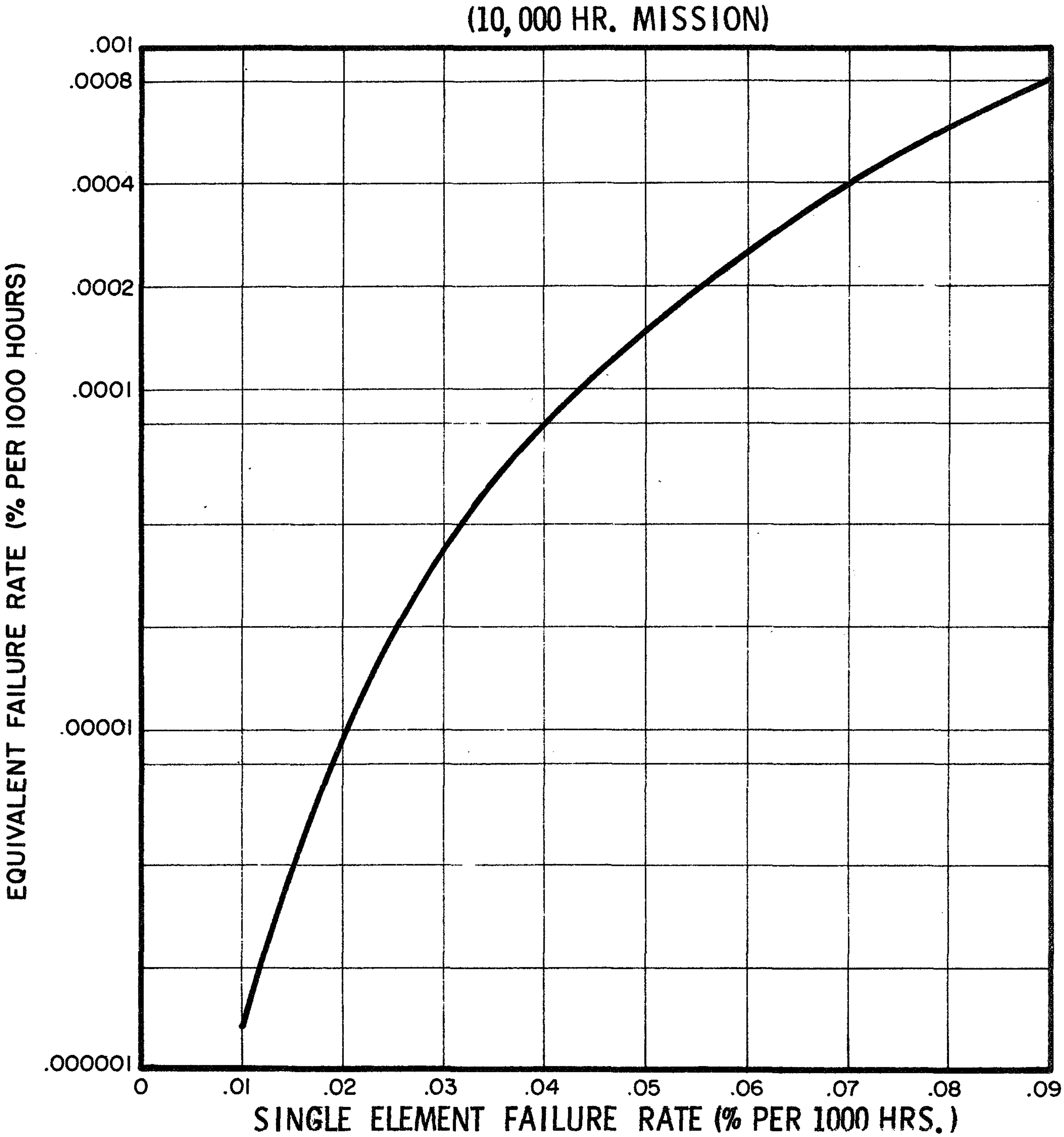

FIGURE B-3

Tests were conducted on the complete regulator to prove that the performance would remain within the specification limits when individual components in the redundant assemblies were short or open circuited.

The results are tabulated in Table B-V.

TABLE B-V

COMPONENT	CIRCUIT	FAILURE	CHANGE IN LINE VOLTAGE
CR1	Sensing	Short 1 cell in quad	-.3V
		Open 1 cell in quad	+.1V
CR3	Reference	Short 1 cell in quad	+.5V
		Open 1 cell in quad	-.4V
CR2	Mag. Amp.	No test	----
CR4	Field	No test	----
R1	Comparison	No test	----
R2	Sensing	Open 2 of 10 parallel resistors	+0.2V
R3	Reference	Open 4 of 20 parallel resistors	+0.6V
R4	Reference	Open 4 of 20 parallel resistors	-1.6V
R5, R6	Mag Amp Output	No test	-----

No tests were run for failures in power circuit elements, since it is known that large variations here will not effect circuit performance significantly.