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DEVELOPMENT OF A 60 KW ALTERNATOR FOR SNAP-8

by

M. G. Cherry and J. R. Pope

AEROJET-GENERAL CORPORATION
Azusa, California

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

FOREWORD

The work described in this report covers the design and development of an alternator for the SNAP-8 Power Conversion System. The work for the SNAP-8 power conversion system was accomplished in a joint effort by General Electric Company and Aerojet-General Corporation. The work was performed under NASA Contract NAS 5-417. Mr. A. W. Nice, of the Space Power System Division, NASA-Lewis Research Center, was project coordinator, Martin J. Saari NASA Program Manager and Dr. W. F. Banks as Program Manager for Aerojet-General Corporation.

ABSTRACT

This report describes the design philosophy, the mechanical and electrical design, and the development testing of an 80 KVA alternator driven by a mercury vapor turbine in the SNAP-8 mercury Rankine cycle. The alternator was designed using the latest technology compatible with high reliability, long life and good performance. Development tests on several alternators, including running time on one unit in excess of 19,000 hours at design conditions, have verified the design concept and demonstrated endurance capabilities exceeding the original objectives.

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SUMMARY

This report covers the design, development, fabrication, and testing of the alternator for the SNAP-8 Rankine-cycle, nuclear space power system. The alternator was developed to meet the SNAP-8 power generating system requirements which included the ability to start up and generate 60 kw of electrical power unattended in a space environment for 10,000 hours. Thirty-five (35) kw would be available to the system user.

The alternator configuration selected to meet these requirements was a solid pole, brushless, homopolar inductor type operating at 12,000 revolutions per minute (rpm) and producing 120/208 volts, 3 phase alternating current power, with an output frequency of 400 Hertz. The alternator is lubricated and cooled by a polyphenyl ether oil. Leakage of fluid into the rotor cavity is prevented by a system of (screw) seals on either side of the bearings. The electrical insulation system is an aromatic polyimide (ML) system coupled with an epoxy resin compound. The reliability goal was 97.35% for 10,000 hours of continuous operation.

During development of the alternator, design changes were made to improve excitation and efficiency. Rotor slot depths were increased, the frame and rotor area were increased, and the rotor material was changed. The net result was a field current reduction from 25 to 20 amperes and an increase in efficiency from 86 to 87.5 percent. A high field coil hot spot temperature and high stator end turn temperature were two problems on the early units. Reduction in these temperature levels was effected by reduction of thermal resistance from connector to conductor.

Endurance tests of the SNAP-8 turbine-alternator, in a breadboard system, were conducted to verify conformance with specified requirements. Accumulated testing time with the power conversion system was more than 11,200 hours and was achieved on a single unit. The testing included numerous start and stop transients as well as changes in loading and power factor conditions.

The alternator tests revealed two other problem areas; a cooling jacket weld failure and a visco seal seizure at turbine runaway conditions. The first problem, due to an embrittled weld joint, was resolved by using a more ductile weld filler metal and rewelding. The second problem was recognized as the result of operating the alternator outside of the normal design capability. This problem would be resolved with an improvement in bearing spring loading arrangement, reducing the tendency of the bearings to unload at speeds significantly above 12,000 rpm.

The alternator design was started in June 1963, and ten alternators were produced as of August 1966. One alternator was an experimental development model, four were a pre-prototype version, and five were prototype units which were developed as described in this report.

The SNAP-8 alternator has adequately demonstrated compliance with the specification requirements and has verified its capability to operate reliably for more than 10,000 hours of continuous operation.

I. INTRODUCTION

SNAP-8 is a 35 kw nuclear-electric power conversion system for use in a space environment. The system operates on a mercury Rankine-cycle using eutectic sodium-potassium mixture (NaK) and mercury as the working fluids. 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 power conversion system (Figure 1) uses mercury as a working fluid and is coupled to the reactor cooling loop by a boiler in which the mercury is vaporized. The vapor drives a turbine-alternator assembly which develops the electrical output of the system. The mercury vapor leaving the turbine enters the condenser, is liquified, and then returned by way of the mercury pump to complete its cycle. Condenser cooling is provided by a heat rejection NaK loop which couples the condenser and space radiator. Lubrication is provided by an organic working fluid (polyphenyl ether) to the bearings in the turbine-alternator assembly and the mercury pump-motor assembly. Cooling is provided for the alternator, pumps, and electrical controls. The organic loop fluid is pump driven and has its own heat-rejection radiator.

The alternator discussed in this report has been developed to supply 80 KVA at power factors between unity and 0.75 lagging. The alternator is a solid pole, brushless, homopolar inductor type operating at 12,000 revolutions per minute and producing 120/208 volts, 3 phase alternating current power with an output frequency of 400 Hertz. Leakage of lubricant coolant fluid into the rotor cavity is prevented by a system of screw seals on either side of the bearings.

The electrical insulation system is an aromatic polyimide coupled with an epoxy resin compound. The alternator mechanical and electrical design development characteristics are discussed and evaluated for compatibility with design performance requirements for unattended continuous operation in a space system. Development tests and endurance tests were conducted on components and on the complete assembly in the power conversion system test facility in excess of 10,000 hours to verify the alternator design reliability and endurance capability for use in the SNAP-8 power generating system.

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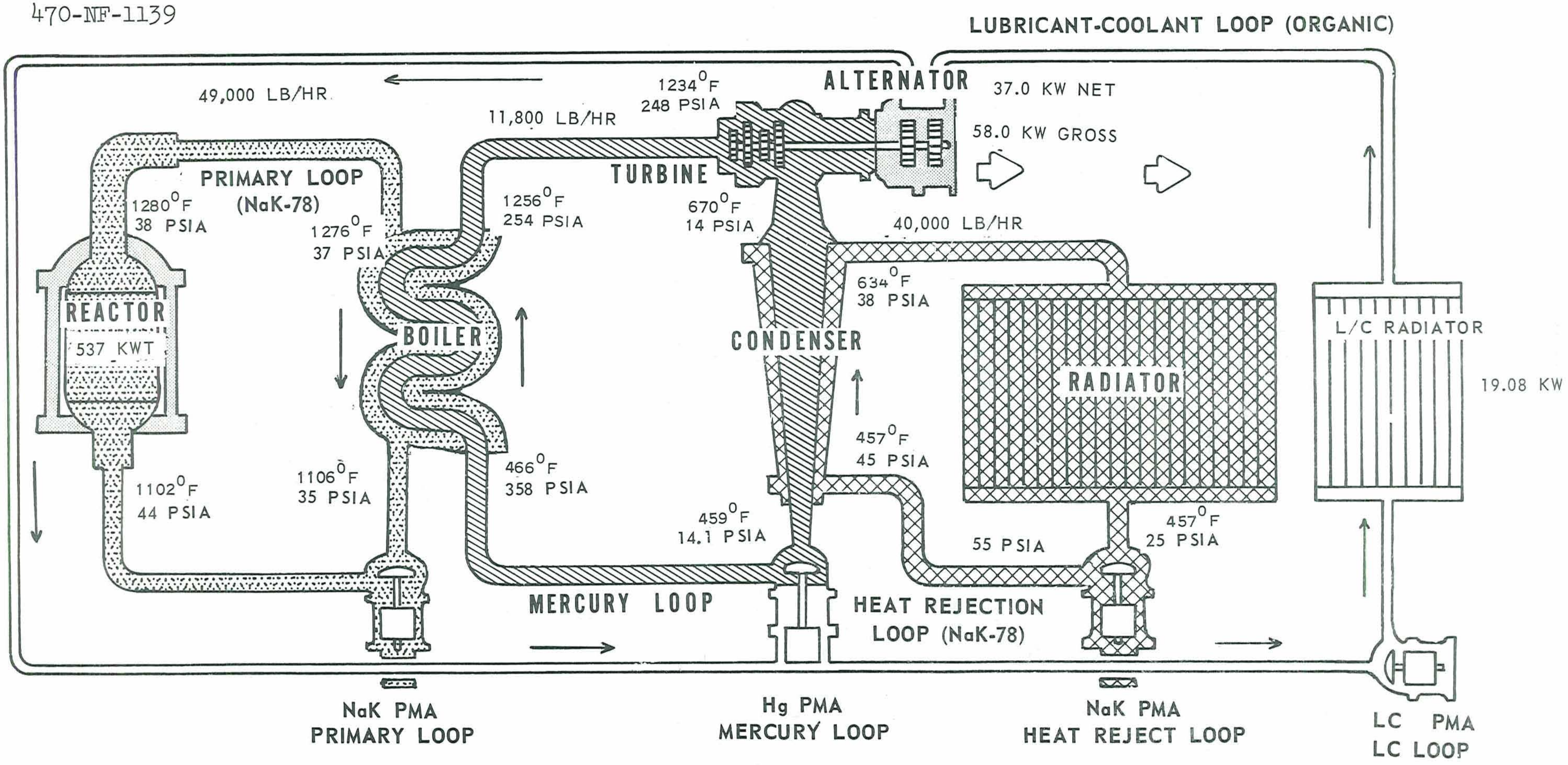


Figure 1. SNAP-8 System Schematic

II. DESIGN AND DEVELOPMENT

A. DESIGN PHILOSOPHY

The major requirement of all components in the SNAP-8 system was the ability to operate at design conditions in a space environment unattended for a period of at least 10,000 hours. Selecting an alternator was a choice of one of the various solid rotor brushless types or a salient pole rotating rectifier unit.

One of the areas of concern with the conventional wound rotor generator was the possibility of windings shorting or grounding due to dynamic stresses.

The homopolar inductor generator was selected for development rather than other solid rotor generators because of the structural advantages. An effort was made to accomplish the design changes on the first four alternators. The fifth and all subsequent units had all of the changes and improvements incorporated and were defined as "prototype" units.

III. DESIGN REQUIREMENTS

The alternator (Figure 2) used in the power conversion system was designed for compliance with the SNAP-8 requirements and the alternator specification requirements (Reference 1 and 2) which are summarized in Table I. Conventional ball bearings were selected as the bearing media with a slinger disc type backed up by a screw seal to minimize leakage and prevent lubricant coolant fluid from entering the rotor cavity.

The insulation system is producible by conventional manufacturing methods, compatible with polyphenyl ether oil (Mix-4P3F), and provides adequate dielectric strength, along with low thermal resistance between conductor and coolant. The insulation system should not break down while operating in a low vapor pressure or when exposed to the specified nuclear radiation environment (Table I and Reference 3 remain relatively free from outgassing.

The electromagnetic design minimizes magnetic bearing forces and rotor pole face losses, while the thermal design meets the life and reliability requirements with a low pressure drop cooling system.

The reliability of the alternator is specified at 97.35 percent in order to meet the requirement of a 10,000 hour mission life. The turbine and alternator are bolted together at a common flange and the power is transmitted through a flexible quill drive shaft. The flexible quill drive shaft is specified to minimize the spline loading and reaction forces on the bearings. The alternator housing and electrical connections are hermetically sealed.

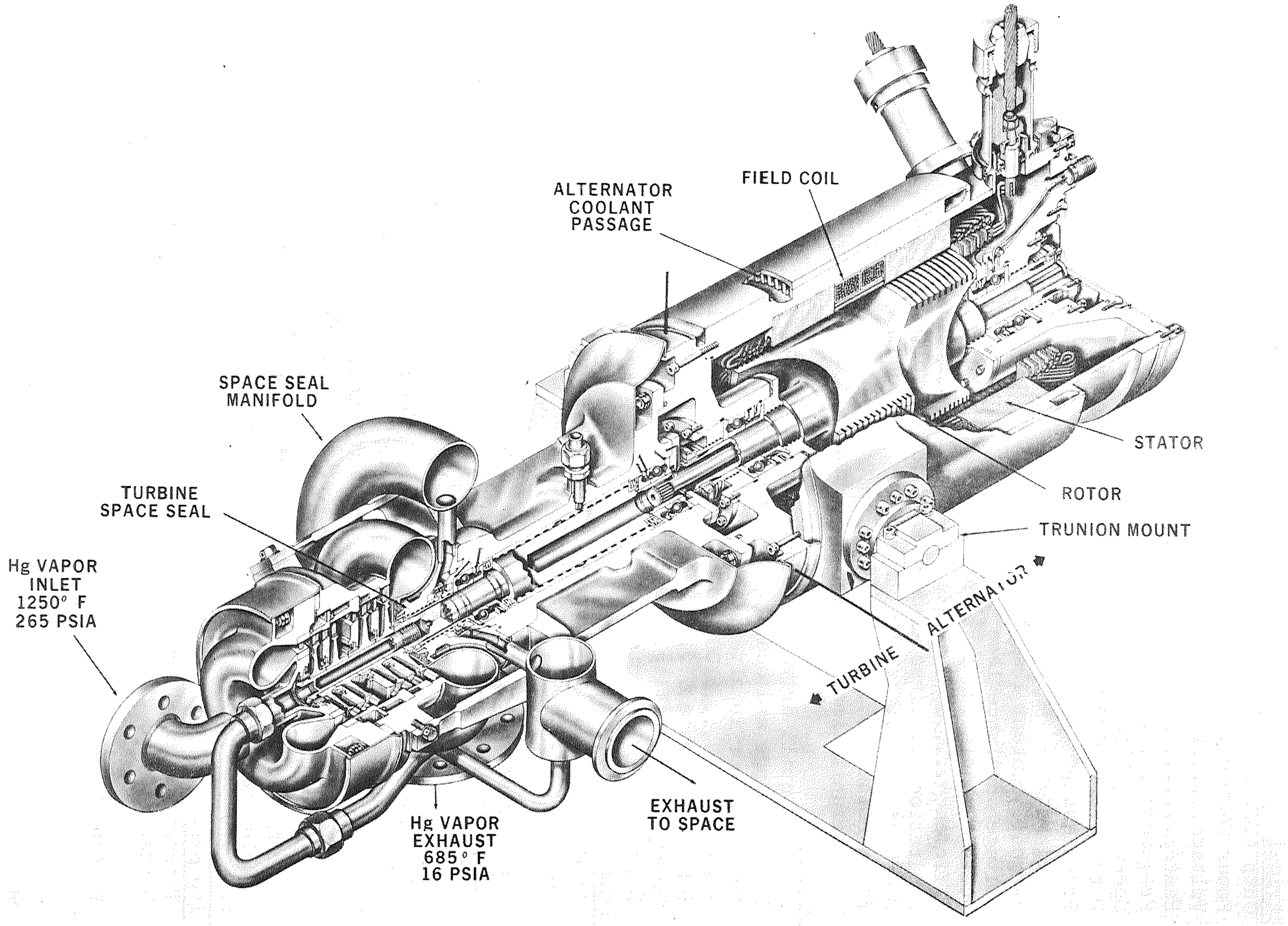


Figure 2. SNAP-8 Turbine Alternator Assembly

TABLE I. SUMMARY OF ALTERNATOR REQUIREMENTS

Electrical

Output......60 KW
Power factor......0.75 lagging to unity
Voltage......120/208 rms
Phases......3 phase, 4 wire
Frequency......400 Hz
Speed......12,000 RPM
Duty......10,000 hours continuous unattended
Brushless
Solid rotor
Harmonic content less than 7%
Voltage unbalance less than 1%
Voltage modulation less than 1%
Efficiency......87% at full load, rated speed and cooling
Excitation......less than 22 amps and 52 volts
Short circuit......2 PU current for 5 seconds
Radio noise......MIL-I-26600
Open circuit time constant......less than 0.60 second

Mechanical

Flexible quill drive shaft and coupling spline
Ball bearings and scavenging system - oil cooled
Organic vapor in alternator cavity
Bearing life......100,000 hours with 99.5% reliability
Helium leak rate......2×10^{-7} cc/sec. or less
Overspeed Capability......18,000 RPM
Counterclockwise rotation

Cooling

Cooling fluid......Shell Mix 4P3E - polyphenyl ether
Flow rate......2000 lb/hr maximum (1600 lb/hr Frame, 400 lb/hr bearings and seals
Inlet pressure......20 psia $\pm$ 1 psia
Inlet temperature......$210^{\circ}F \; {}^{+\,0^{\circ}F}_{-\,60^{\circ}F}$
Pressure drop......14 psi max.
Max. fluid hot spot temperature......$500^{\circ}F$
Winding hot spot temperature......$392^{\circ}F$ maximum during steady state operation except 180° bus ring to be $410^{\circ}F$ max.
Winding hot spot temperature......$480^{\circ}F$ max. during transient operation for 5 seconds
Bearing temperatures......$300^{\circ}F$ maximum during steady state operation
Bearing temperatures......$500^{\circ}F$ maximum during transient operation

Reliability......97.35% for 10,000 hours

Environment

Transportation shock......4 g's
Transportation vibration......2 - 10 Hz @ 0.4 inch DA displacement
10 - 500 @ 2 g peak
Launch Shock......35 g's in three directions
Vibration ......16-100 Hz @ 6 g; 100-180 Hz @ 0.0118 in. DA displacement
180-2000 Hz @ 19 g peak
Acoustic noise......148 db Re 0.0002 micro bar
Acceleration......3, 4.5, and 7 g's in various directions

Nuclear Radiation......5×10^{12} nvt fast neutrons
and 10^{7} rads gamma total dosage

Explosion proof

IV. ELECTRICAL DESIGN

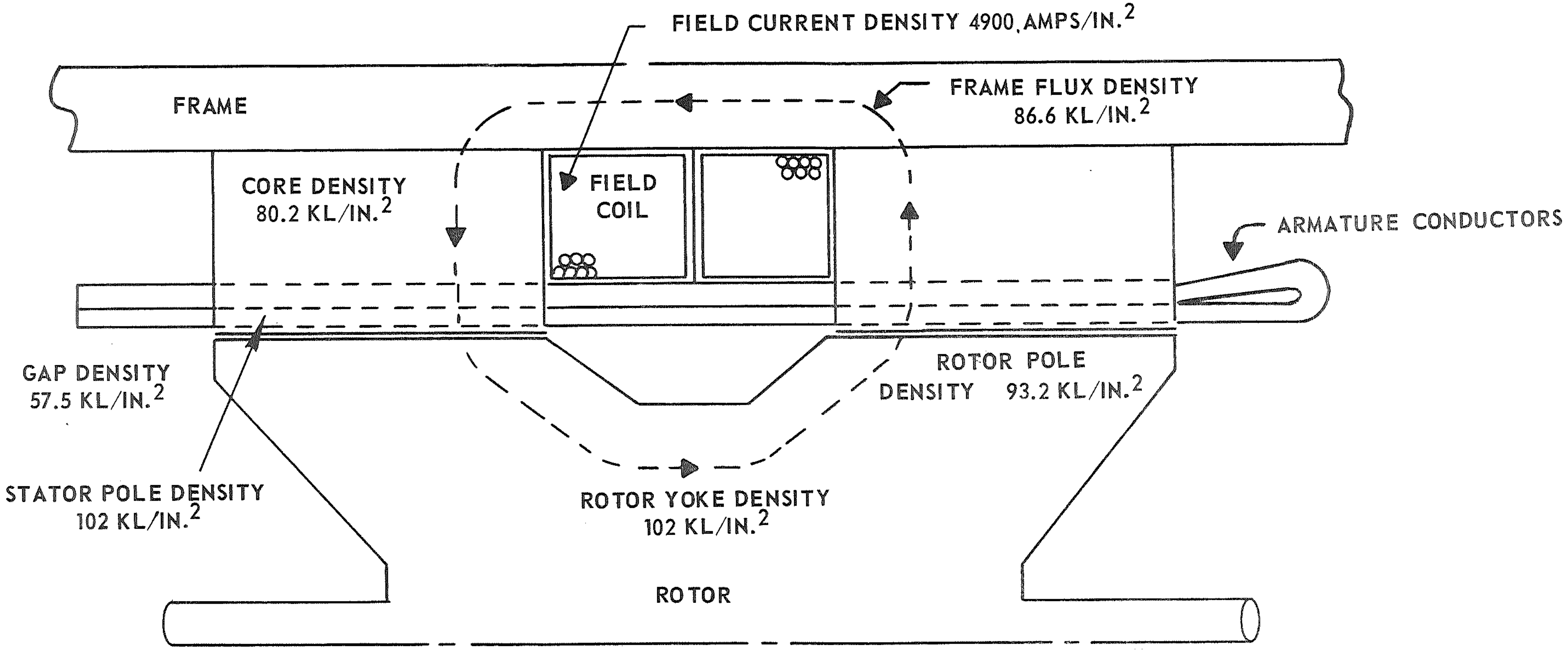
A. ELECTROMAGNETICS

The alternator is a brushless solid rotor generator of the homopolar inductor type with a radial air gap. Figure 3 shows the electromagnetics. The field coil, which produces the direct current working flux, is positioned between two identical sets of laminated cores. The electromagnetic circuit, shown within the dashed lines, consists of the frame, which surrounds the core and field coil, the core sections, the radial air gaps, the solid rotor poles and the hub of the rotor. As the rotor rotates, the lines of flux flow through a path of varying permeability resulting in a pulsating flux across the armature conductors thus, producing a voltage in these conductors.

The stator consists of two 3.3 inch long laminated core assemblies having a toroidal field coil between them and assembled in a common frame bore. The 0.014 inch thick laminations are made of 3.25 percent silicon cold rolled electrical steel (AISI Type M-19). Each of the laminated cores was assembled, welded at the outer diameter, and bonded with an epoxy resin. This configuration was selected to prevent flare and vibration of the teeth in the end punchings. The stator core outside diameter is 10.375 inches. The output windings, made of hairpin formed rectangular copper conductors, were inserted into the slotted cores from one end and connected by welded joints at the other end.

A two circuit design was chosen to minimize the radial bearing forces resulting from possible eccentricity between rotor and stator. After connections were made, the wound stator cores and field coil were assembled into a frame made of low carbon steel tubing. The field coil was designed to fit between the stator cores with the same outside diameter, thus achieving the reliability and simplicity associated with one piece stator housing construction.

The rotor was machined from an AISI 4620 steel forging to provide good strength and magnetic material properties. Slots were machined circumferentially in the rotor poles to reduce pole face losses. The rotor poles overhang the stator cores axially at both ends to decrease the magnetic forces on the bearings.



FLUX AND CURRENT DENSITY AT 80 KVA, 0.75 POWER FACTOR

ARM CONDUCTOR AREA – 0.025675 IN.^{2}
FIELD CONDUCTOR AREA – 0.00407 IN.^{2}
ARM CURRENT/CONDUCTOR – 111.0 AMPS
FIELD CURRENT/CONDUCTOR – 20.0 AMPS

Figure 3. Alternator Electromagnetics

The stator punchings are partially closed slots to reduce the pole face losses caused by flux pulsations in the air gap. The relatively large radial air gap (0.060 inch) decreases the radial bearing forces caused by eccentricity of the rotor and stator, and the pole face losses to a low level.

A further effect of the large air gap is the need for a high magnetic potential between rotor and stator, leading to considerable leakage flux in the region between the rotor poles. This flux is limited by contouring the rotor between the four machined poles projecting from the hub in order to increase the effective depth of the rotor slot opposite the stator cores. The calculated flux and current densities at rated conditions are shown in Figure 3.

B. INSULATION

1. Design Concepts

The insulation system was designed to meet the reliability and life requirements encountered in space nuclear environment. The primary requirements were as follows:

- Operation in a nuclear radiation of 5×10^{12} nvt fast neutrons and 10^7 rads gamma total dosage.
- Operation in a low vapor pressure.
- Exposure to a polyphenyl-ether synthetic type oil in the alternator cavity.

The preceding requirements as well as temperature, life, cooling, space and producibility led to the selection of the following basic system:

- Slot insulation: 0.0105 aromatic polyimide impregnated and coated glass cloth.
- Conductors: Heavy coated aromatic polyimide insulated OFHC copper.
- Slot phase insulation: 0.016 silicone-glass laminate.

- Top sticks: Aromatic Polyimide
- Winding impregnation: Thin, clear, unfilled epoxy Novalac resin compound.
- Potting compound: Black, filled, thixotropic epoxy Novalac resin compound.
- Lead cable: Glass braid, reinforced mica insulated OFHC copper stranded cable.
- Tapes and sleeving: Heat cleaned fiberglass.

2. Development of Insulation Joints

a. Joint Insulations

Contamination of the alternator cavity and possible resulting change in vapor pressure at vacuum operation through "out-gassing" of adhesive in joint insulation tapes, was considered a disadvantage in the joint insulation system specified. This system consists of three thicknesses (wraps) of 0.0065 inch silicone- glass thermosetting adhesive tape with an over-wrap of three thicknesses 0.005 inch untreated glass tape.

A program was initiated to investigate other joint insulation systems and establish by weight loss measurements at accelerated operating temperatures the comparative performance. Seven systems tested included a combination of such materials as desized glass tapes over ML-glass cloth and sleeving, Du Pont "H" Film and silicone treated glass adhesive tape. From these tests, it was concluded that the system first specified was the most stable and would result in least "out-gassing" effects.

b. Effects of Cooling Fluid

The fluid selected for alternator cooling was a polyphenyl ether (Shell 4P3E). Hot fluid or vapors contacting conductors and insulation material during alternator operation could result in damage by corrosion and chemical attack. Data on the compatibility of 4P3E fluid with materials selected for use in the alternator were not available and a program was initiated to obtain data to assure that the materials would not be adversely affected. The primary concern in the use of 4P3E as a coolant fluid was compatibility with alternator materials and dielectric effect in the alternator cavity. Tests conducted early in the program, simulating conditions and time contemplated in the machine, established that hot oil had no deteriorating effect on the insulating and conductor materials selected for use in the alternator. The combination effects of oil mist, low vapor pressure and radiation on air dielectric were considered. It was postulated that because of the low voltage levels the net effect would not produce corona or effects detrimental to the reliability of the alternator. These conclusions were confirmed by insulation tests conducted at the Georgia Nuclear Laboratories.

c. Materials Selection

Requirements considered of primary importance and the material selected to satisfy these requirements are described below. A detailed description of conductors and insulation for all components of the alternator is shown in Tables II and III.

Twenty-six insulated conductors and insulating materials in simple combination, (See Tables II & III), specified for use in the alternator, were studied in hot fluid and vapor at temperatures of 392° and 572°F for periods up to 4,000 hours. These tests demonstrated that all materials specified for use in the alternator were compatible with hot polyphenyl ether fluid (4P3E).

d. Environmental

(1) <u>Alternator Environment</u>

A system test program was initiated which involved several specific materials adapted for use in the alternator. The test program involved construction of two "statorettes," built from alternator stator cores and fields, and evaluated in simulated SNAP-8 environments at the Georgia Nuclear Laboratories, Dawsonville, Georgia. The specified nuclear radiation environment of 5×10^{12} nvt fast neutrons and 10^7 rads gamma total dosage would damage materials such as the fluorocarbons (Teflon, Viton) commonly used in lead wire, seal constructions. A study of available data revealed materials of the silicone, epoxide and polyimide chemical families were not significantly affected

Table II. Alternator Field Insulations and Conductor Materials and Processes

	MATERIAL DESCRIPTION			SOURCE OF SUPPLY	
Component	Size	Type, Composition	G. E. Co. Spec.	Commercial Source	Mfg's Designation
1. Coil Box Inner	0.0055"	Aromatic Polyimide impregnated and coated fiber glass cloth	A50CD227C	EI DuPont Co., Fairfield, Conn.	No. 6507-0055
2. Box corner fill	0.026" dia.	Untreated glass cord	A4L1B2	Owens-Corning Fiberglass Corporation	EC9-20
3. Box side lead Insulation	86A226289 Tube	Silicone-glass Laminate	A19B22A1	General Electric Co. Coshocton, Ohio	No. 11556 Textolite
	Plus - No. 13	Aromatic Polyimide coated fiber glass	A50CD307A	Bentley Harris Mfg. Co., Conshohocken, Pa.	BH 963 ML
	Plus - No. 9	Aromatic Polyimide coated fiber glass	A50CD307A	Bentley Harris Mfg. Co., Conshohocken, Pa.	BH 963 ML
4. Conductor	0.0720" dia.	Heavy coated aromatic polyimide insulated round OFHC copper	B50CD117E	General Electric Co., SAC Wire Section, Schenectady, New York	HML
5. Coil box liner cement	Compound	Thin, clear, unfilled epoxy Novolac resin compound	A50CD240A	General Electric Co., DCM&G Dept., Erie, Pa.	
6. Conductor bond	Compound	Black, filled thixotropic epoxy Novolac resin compound	A50CD241A	General Electric Co., DCM&G Dept., Erie, Pa.	
7. Insulation between coil O D and copper band	0.0055" (2 layers)	Aromatic polyimide impregnated and coated fiber glass cloth	A50CD227C	EI DuPont Co., Fairfield, Conn.	No. 6507-0055
8. Lead cable - power lead	12 AWG	Glass braid, reinforced mica insulated OFHC copper stranded cable	B50CD180A12	Rockbestos Wire & Cable Co., New Haven, Conn.	"Mica-Temp"

Table III. Alternator Armature Insulations and Conductor Materials and Processes

	MATERIAL DESCRIPTION			SOURCE OF SUPPLY	
Component	Size	Type, Composition	G.E.Co. Spec.	Commercial Source	Mfg's Designation
1. Slot insulation	0.0105"	Aromatic polyimide impregnated and coated fiber glass cloth	A50CD227E	EI DuPont Co., Fairfield, Conn.	No. 6508-0105
2. Conductor	0.125" x 0.212"	Heavy coated aromatic polyimide insulated rect. OFHC copper	B50CD116E	EI DuPont Co., General Electric Co., SAC-Wire Section Schenectady, N. Y.	HML
3. Slot phase insulation	0.016"	Silicone-glass laminate	A19B22A1	General Electric Co., Coshocton, Ohio	No. 11556 Textolite
4. Insulation end punchings	0.020" 3 per end	Silicone-glass laminate	A19B22A1	General Electric Co., Coshocton, Ohio	No. 11556 Textolite
5. Top-sticks	36A227152 0.032" thick	Aromatic polyimide	A50CD337A	EI DuPont Co., Wilmington, Delaware	Polymer SP
6. Coil side end turn phase insulation	3 AWG	Heat cleaned fiber glass sleeving	A50CD76A	Bentley Harris Mfg. Co., Conshohocken, Pa.	BH Special Treated
7. Coil top-to-bottom end turn phase insulation	0.0105"	Aromatic polyimide impregnated and coated glass cloth	A50CD227E	EI DuPont Co., Fairfield, Conn.	No. 6508-0105
8. Lead Cable - power leads	8 AWG (3 per phase)	Glass braid, reinforced mica insulated OFHC	B50CD180A8	Rockbestos Wire & Cable Co., New Haven, Conn.	Mica-Temp
9. Lead and phase joint insulation	0.0065" (3 layers)	Pressure sensitive thermosetting silicone adhesive coated glass cloth tape	A23B5A3	Minnesota Mining and Mfg. Co., Irvington, Ill.	Scotch No. 69
	Plus - 0.005" (3 layers)	Heat cleaned fiber glass woven tape	A50CD305A	Hess, Goldsmith & Co., New York, N. Y.	

Table III. Alternator Armature Insulations and Conductor Materials and Processes

		MATERIAL DESCRIPTION			SOURCE OF SUPPLY	
	Component	Size	Type, Composition	G.E.Co. Spec.	Commercial Source	Mfg's. Designation
10.	Inter-coil joint insulation	3/8" dia.	Heat cleaned fiber glass sleeving	A50CD76A	Bentley Harris Mfg. Co. Conshohocken, Pa.	BH Special Treated
		Plus- Compound	Black, filled thixotropic epoxy Novolac resin compound	A50CD241A	General Electric Co., DCM&G Dept., Erie, Pa.	
11.	Winding impregnation	Compound	Thin, clear, unfilled epoxy Novolac resin compound	A50CD240A	General Electric Co. DCM&G Dept., Erie, Pa.	
12.	Insulation end punching cement	Compound	Thin, clear, unfilled epoxy Novolac resin compound	A50CD284A	General Electric Co., DCM&G Dept., Erie, Pa.	
13.	Fill between stator core sections	Compound	Black, filled thixotropic epoxy Novolac resin compound	A50CD241A	General Electric Co., DCM&G Dept., Erie, Pa.	
14.	Reinforcement to item No. 13	0.007"	Leno weave, heat cleaned glass cloth tape (3 layers)	A50CD286A	Columbia Electric Tape & Mfg. Co. - Philadelphia, Pa.	
15.	Bus conductors	0.080 x .500	Heavy coated aromatic polyimide insulated OFHC copper	B50CD116E	EI DuPont Co., General Electric	HML
16.	Bus insulation	0.0105"	Aromatic polyimide impregnated and coated glass cloth	A50CD227E	EI DuPont Co., Fairfield, Conn.	6508-0105
17.	Tapes and Sleeving	Plus - 0.005" (3 layers)	Heat cleaned fiber glass tape	A50CD305A	Hess, Goldsmith & Co.	
18.	Lead cable - phase equalizer-leads	12 AWG (one per phase)	Glass braid, reinforced mica insulated OFHC copper stranded Cable	B50CD80A12	Rockbestos Wire & Cable Co,, New Haven, Conn.	Mica-Temp

by this dosage level. Du Pont "ML" polyimide resins showed satisfactory tolerance to levels of 1.85 x 10^8 rads, a dosage which exceeded the requirements.

The two completed "statorettes" simulated a wound alternator stator and field, sectioned axially at the center, (see Figure 4). Since the insulation system test results indicated no failures or failure modes, it was concluded that the alternator insulation system would provide reliable performance in SNAP-8 environments.

(2) Rotor Cavity Pressure

A vapor pressure, in the range of 0.05 to 8.0 mm Hg (equivalent to 100,000 to 250,000 ft. altitude), is expected in the alternator cavity. This range is critical with respect to air dielectric breakdown. Although all voltage operating conditions are expected to be below the theoretical dielectric breakdown level, it was concluded materials having good resistance to corona, and impregnating materials and processes providing solid fill to the windings should be used in the insulation system of the alternator. The polyimide and epoxy materials and thorough impregnation of coils and insulations satisfied these requirements.

e. Design Producibility

Information relating to configuration and producibility are presented below.

(1) Field Coil

An annular field coil, positioned between the stator cores (Figure 5) was selected to provide the necessary electromagnetic and thermal performance. Heat transfer, coil bond, and insulation reliability were considered of primary importance for design of the coil. An epoxy bonded double-coil wound into a double cavity copper annular bobbin was selected for the field coil winding. The construction featured winding each coil side from the bobbin bottom, with a well insulated joint at the center bottom of the bobbin, in order to minimize crossovers and bulky joints at the coil outside diameter.

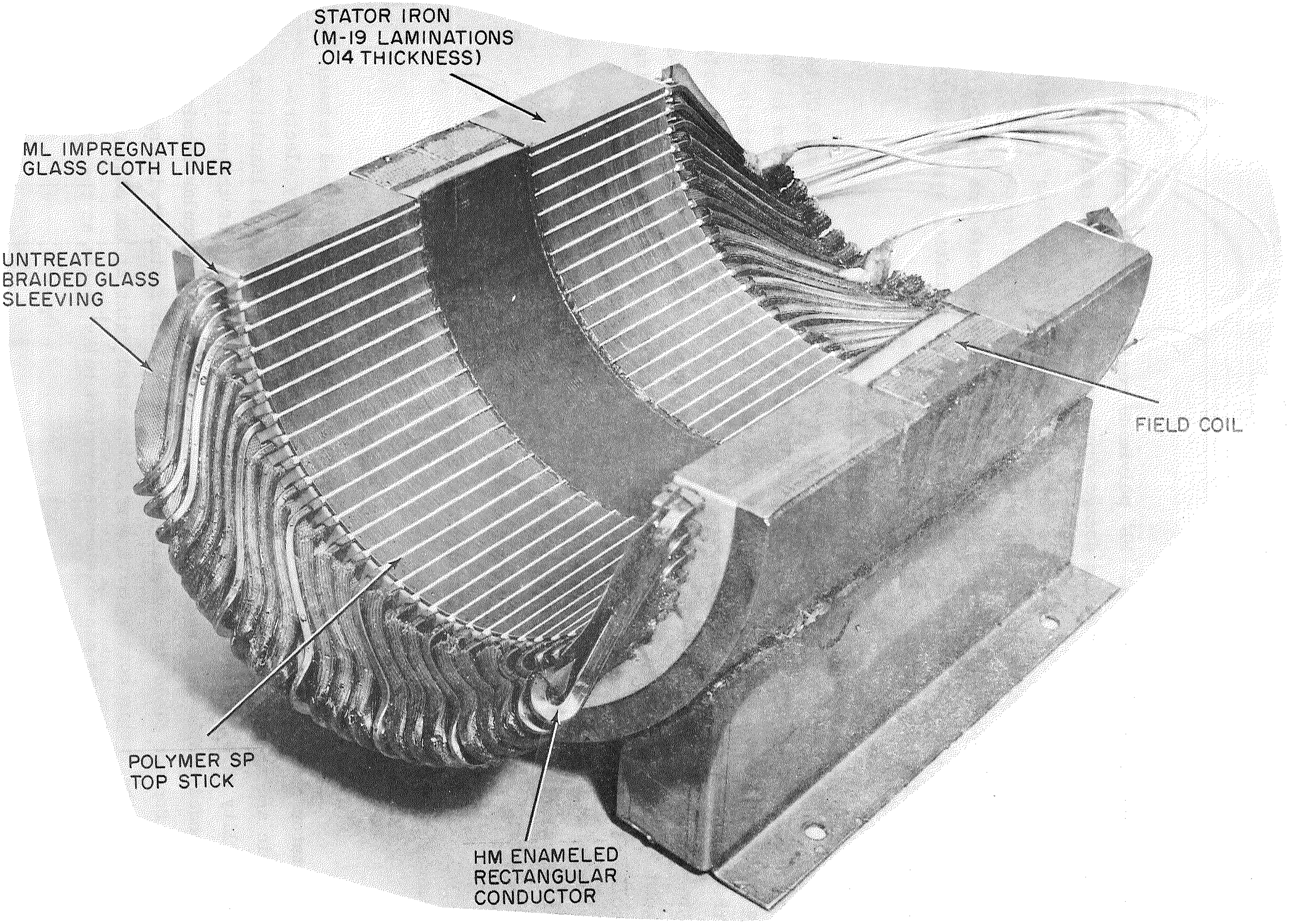


Figure 4. Statorette Involute End

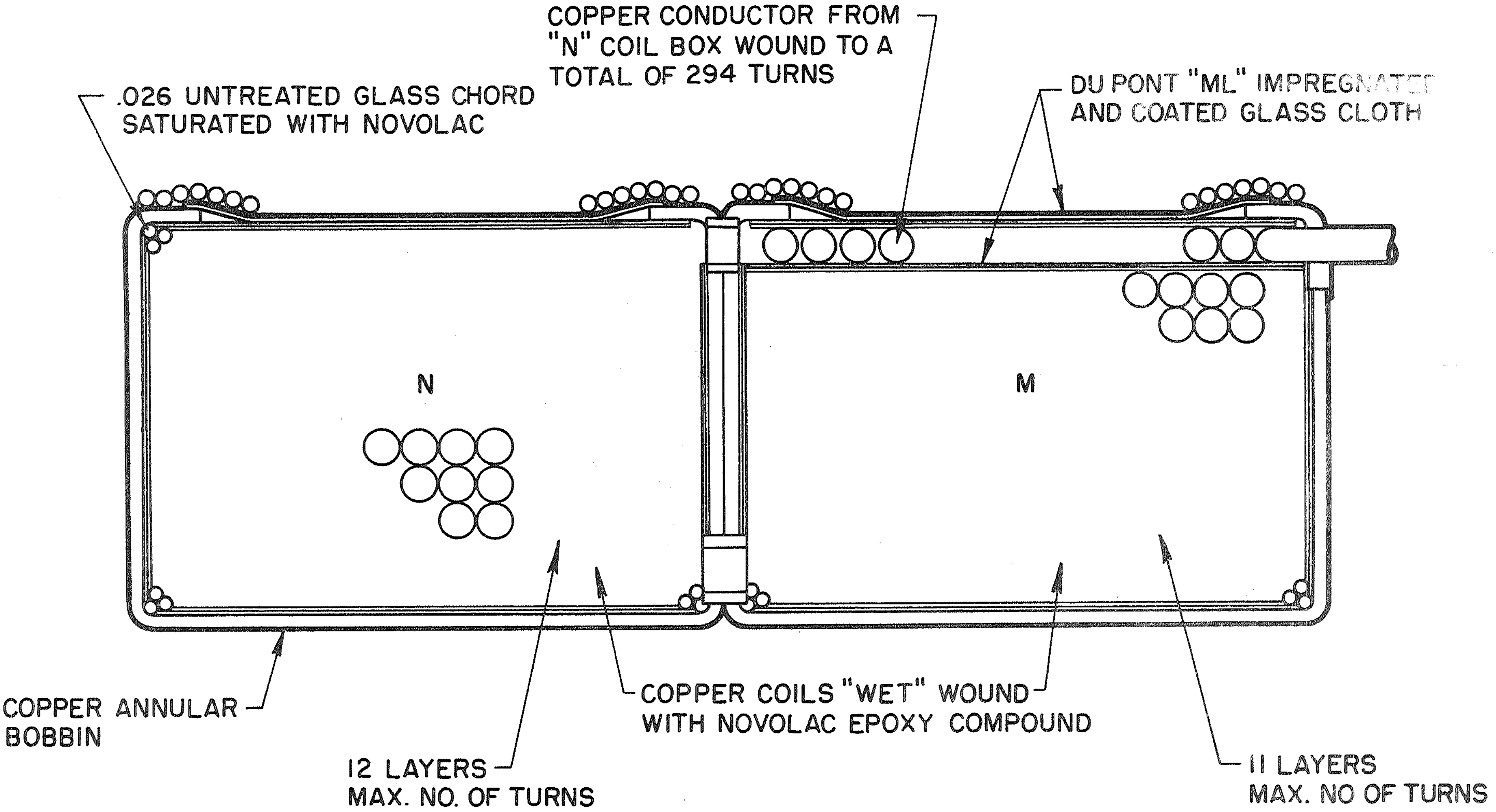


Figure 5. Alternator Field Coil

Materials selected for the field windings included fabricated insulation of two thicknesses of 0.0055 inch Du Pont "ML" impregnated and coated glass cloth cemented to the box sides and bottom with Novolac epoxy. The corners of the box were insulated with three wraps of 0.026 inch untreated glass cord saturated with Novolac epoxy compound. The insulated box was dielectric inspected prior to winding. The coils were "wet wound" using Novolac epoxy compound, to minimize voids in the system. The coil outside diameter was completed by placement of two layers of 0.0055 inch glass cloth impregnated around the coil prior to application of the copper/solder heat transfer structure.

In-process dielectric tests at levels substantially higher than conducted on conventional rotating machines were conducted on the field winding for the following reasons: the winding was finally positioned "behind" armature coils, and "buried" to the extent that repair of a fault would require removing all armature coils.

(2) Armature

The alternator electromagnetic design required a double-core construction of square-bottom, semi-closed slot configuration with a high copper fill, which provided efficient electromagnetic performance and effective heat transfer.

The semi-closed slot (see Figure 4) and high fill factor, which required one turn per slot per phase (i.e., 2 conductor per slot) dictated use of a rectangular conductor inserted from the core end in contrast to the more conventional insertion from the bore. The ML impregnated and coated glass cloth, having smooth surface and semi-rigid features conformed well in the slot, and offered ideal properties permitting conductors to be slipped into the insulated slot without displacing the slot liner. The smooth texture of HML enameled rectangular conductors was also an aid to insertion.

Slot phase separation (see Figure 4) for the two-conductor per slot design is accomplished by anchoring a strip of 0.016 inch silicone-glass laminate to one end of the bottom conductor with silicone cement.

The cement is washed out in a cleaning process prior to impregnation of the windings. The phase separators are positioned on the conductors prior to insertion and then inserted with the armature coil assembly. The thickness for separation was selected to provide adequate margin for insulations reliability, particularly for operation at the expected low alternator cavity pressures.

End turn phase insulations are provided through use of a wrap-around of 0.0105 inch (ML-glass) positioned between the involute of the armature coil and the extensions of the slot liners. Coil side phase insulations are accomplished by use of 0.020 inch wall untreated braided-glass sleeving, positioned on frog-legged coils prior to insertion. The sleeving provided sufficient separation between the coil sides, and is later impregnated with epoxy to provide added dielectric and coil support.

A roof-shaped topstick was machined from Polymer SP. This material is of polyimide chemical base and offers essentially the same properties as the ML family in a moldable solid form. Topsticks fabricated from this material provide high strength and ease of insertion without damaging slot liners or conductors, primarily due to the material's low coefficient of friction.

Armature winding and insulation mechanical support, environmental protection and corona resistance are achieved by vacuum impregnation with Novolac epoxy varnish compound. The vacuum process is applied to the windings after attachment of the phase connections and bus bar assemblies. Vacuum processing is essential to assure compound fill in the slots and saturation of the untreated glass tapes and sleeving.

The viscosity of Novalac is extremely high at room temperature. Therefore, impregnation required preheat of the windings and the compound to a temperature (100°C) that reduced viscosity but did not activate the resin (this temperature was established at 212°F).

(3) Between Core Structure

To provide environmental protection and mechanical support, the volume between the core structure and conductors is filled with a trowelable Novolac epoxy compound. The space between folded slot liners and the bore is filled with a laminated glass, fabricated in place by wet lay up of three layers 0.006 inch leno weave glass cloth and epoxy.

(4) Connections

Solid connections are achieved by using TIG welding and oxygen free high conductivity copper. Oxygen free, high conductivity copper is used for all flexible lead cables, bus bars, and field coil conductors. The intercoil connections are protected with a short section of untreated glass sleeving positioned over the joint, then filled with an epoxy compound to provide a bond. All other joints and joint areas are insulated by a double tape comprised of three thicknesses 0.0065 inch silicone-glass adhesive tape over the joint plus three layers of 0.005 inch de-sized glass tape. The tapes provided a strong dielectric joint.

The phase connections, as shown in Figure 6, consisted of a bus bar arrangement to provide numerous cross-overs and routing of the phase windings. The bars are positioned together to save space. Insulation is provided by placing a strip of 0.0105 inch (ML-glass) on the bar at adjacent bus bar sides. Each insulation strip is taped in place and then the composite bars are also taped together with de-sized 0.005 inch tape.

Insulation and winding quality is assured by dielectric inspection of the sheet insulations before use, inspection of windings after insulation of coils, and inspection at subsequent process stages where insulations could be affected.

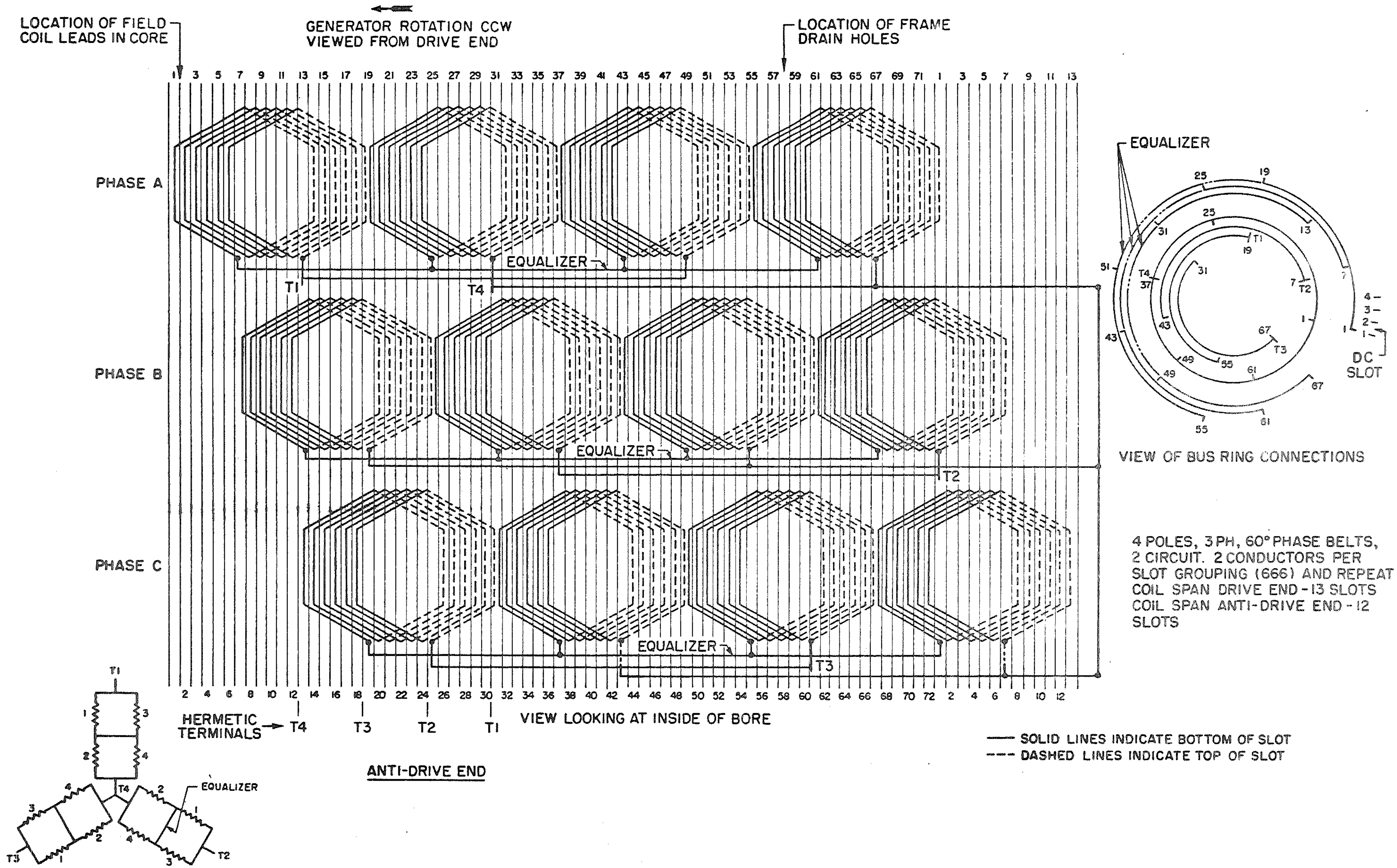


Figure 6. Alternator Intercoil Connection Diagram

V. MECHANICAL DESIGN

A. THERMAL

A thermal analysis of the alternator was performed during the design phase and the resulting thermal map is shown in Figure 7. The alternator is cooled and lubricated by the polyphenyl ether synthetic oil (4P3E). The windings are cooled by introducing the oil into the frame and passing it through axial slots in the frame outer diameter (see Figure 8). Preliminary investigations revealed that a laminar flow regime was required to limit the thermal resistance of the oil and to keep the pressure drop low. The large area required with a laminar flow system was obtained by machining 192 slots (0.05 by 0.375 in.) the full length of the stator core. The frame was divided into 8 paths of 24 slots each. A shroud covered the frame outside diameter and provided a header at each end of the slots. Barriers in the header direct the flow into proper paths.

Heat flows into the frame from the stator core and the field coil. Heat flows from the field coil to the copper enclosure of the coil end then to the frame and oil. The field coil within the frame was designed to ensure low thermal resistance contact under operating conditions with a vacuum in the generator cavity.

Stator core and armature copper losses flow through the stator cores to the frame and oil. The stator core is assembled with an interference fit to minimize contact resistance. Some rotor pole face losses are radiated to the stator, then pass through the stator core and frame to the oil. The remaining rotor losses and some radiation losses from the end turns to the end shields are removed by the bearing lubrication oil. The bearing and lubrication system was designed to remove heat from the shaft ends and to transfer heat generated by the seals and bearings.

The connections and leads are cooled by conduction through the conductors to the stator core and the generator terminals and by radiation to the frame and end shields. Convection cooling is eliminated by the vacuum in the generator rotor cavity.

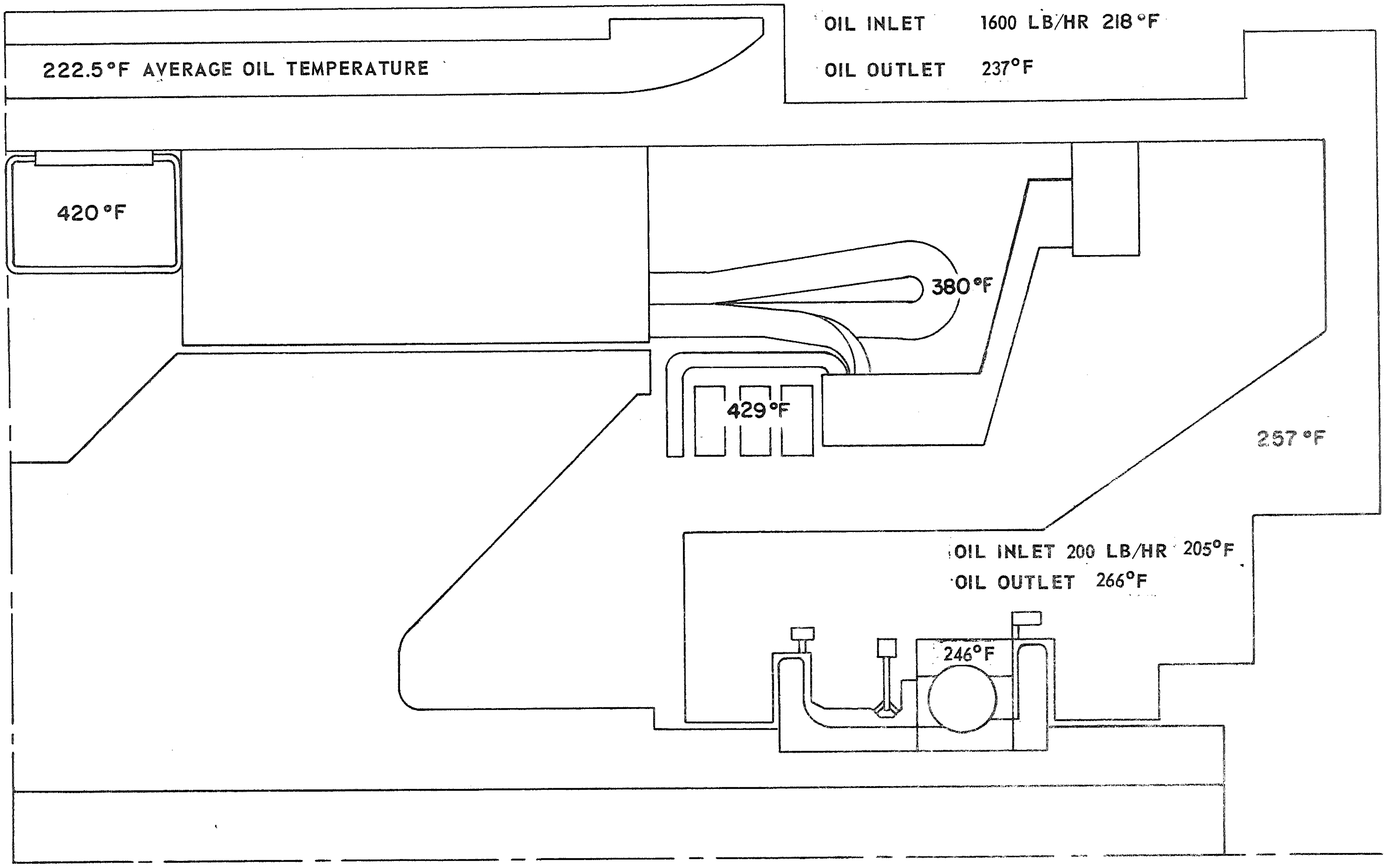
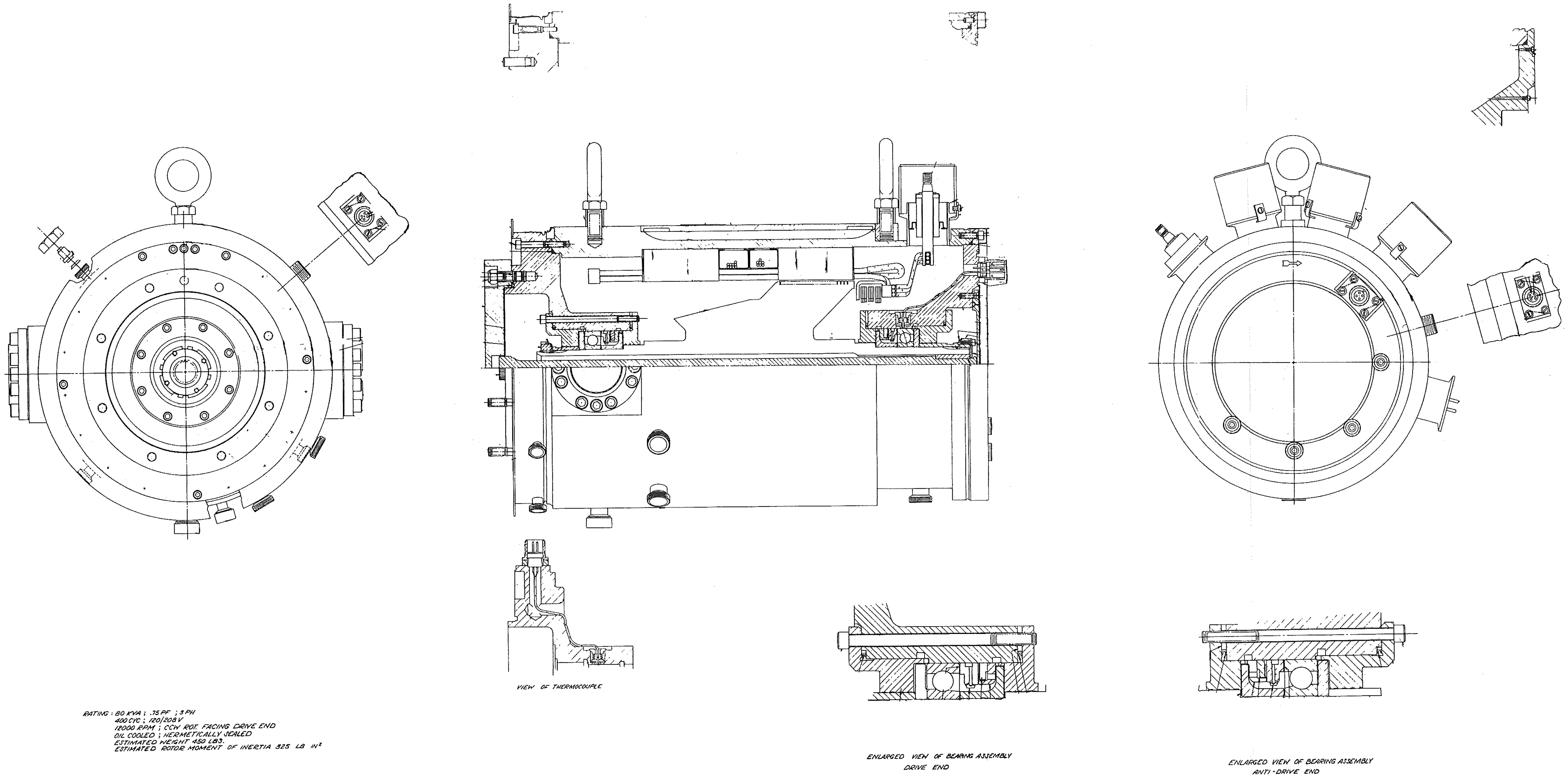


Figure 7. Alternator Thermal Map



RATING : 80 KVA ; .75 PF ; 3 PH
400 CYC ; 120/208 V
12000 RPM ; CCW ROT. FACING DRIVE END
OIL COOLED ; HERMETICALLY SEALED
ESTIMATED WEIGHT 450 LBS.
ESTIMATED ROTOR MOMENT OF INERTIA 325 LB IN^2

Figure 8. Alternator Schematic

B. BEARINGS AND SEALS

1. Bearings

The angular contact ball bearing was selected as the best type for high speed operation, long life, and with high reliability (see Figure 8). This type provides a maximum ball complement for increased bearing load capacity and high radial stiffness, and permits the use of a one-piece, light weight ball separator. The low, nonthrust shoulder is on the inner ring and the separator is piloted on both lands of the outer ring. This configuration provides a full width radial interface at the outer ring for the oil slingers, and precluded the balls approaching the low shoulder at high speed. With axial preload, the bearing is designed to operate without internal looseness, thus aiding rotor assembly dynamic balance and close running clearances for the dynamic slingers.

A 200 series bearing was selected to ensure adequate ring sections for minimum distortion during assembly and operation. The 208 size (40 mm bore) light series, angular contact ball bearing provides maximum load capacity, a more rigid shaft for high rotor critical speed, and a conservative drive spline size. The early units used bearings with rings and balls made from consumable electrode vacuum single melt (C.E.V.M.) M50 steel. The prototype alternators have bearings of triple C.E.V.M. M50 steel.

The alternator rotor is straddle mounted between the two double spring loaded bearings in a back-to-back arrangement, i.e. with contact angles diverging toward shaft axis. The dual spring loading arrangement permits equal thrust capability in either direction.

The bearings are lubricated and cooled by four oil jets spraying on the inner ring. The bearing cavity is scavenged to prevent the bearings from running flooded. The bearing bores in each end shield are ground in one setup when the end shields are assembled to the frame, thus assuring alignment. The end shields are sized for an interference fit with the main stator frame and doweled for angular location, to maintain alignment.

The following types of loads were considered during bearing analysis:

- Rotor weight when in ground operation.
- Residual unbalance forces.
- Magnetic forces.
- Axial loads transmitted through the spline coupling.
- Maximum shock load during launch.

The bearing analysis was conservative since allowances were not made for the following factors:

- Increase in life due to the lubricant, polyphenyl ether.
- Use of a triple vacuum melt M-50 steel.
- Increase in life due to lack of a good fit of actual bearing failures to the Weibull distribution in the high reliability range.

2. Seals

The seal system (Reference 4) used in the alternator to provide lubricating and cooling oil containment was a plain slinger type which was coupled with a screw seal return type. Both are non-contacting and offer zero leakage.

These seals were unique for certain operating conditions as it was possible to maintain a stable liquid-to-vapor interface on the rotating parts, and thus limiting leakage to the evaporation loss from the liquid-to-vapor interface. Leakage in both types of seals was minimized primarily by the introduction of external forces on the leakage fluid. The slinger seal, see Figure 9, acts as a centrifugal separator. Since the pressure on both sides of the slinger is the vapor pressure of the saturated liquid, the slinger seals against a low pressure differential. Its main function is then to form a stable interface between the vapor and the liquid, and to pump the liquid up to the return line pressure.

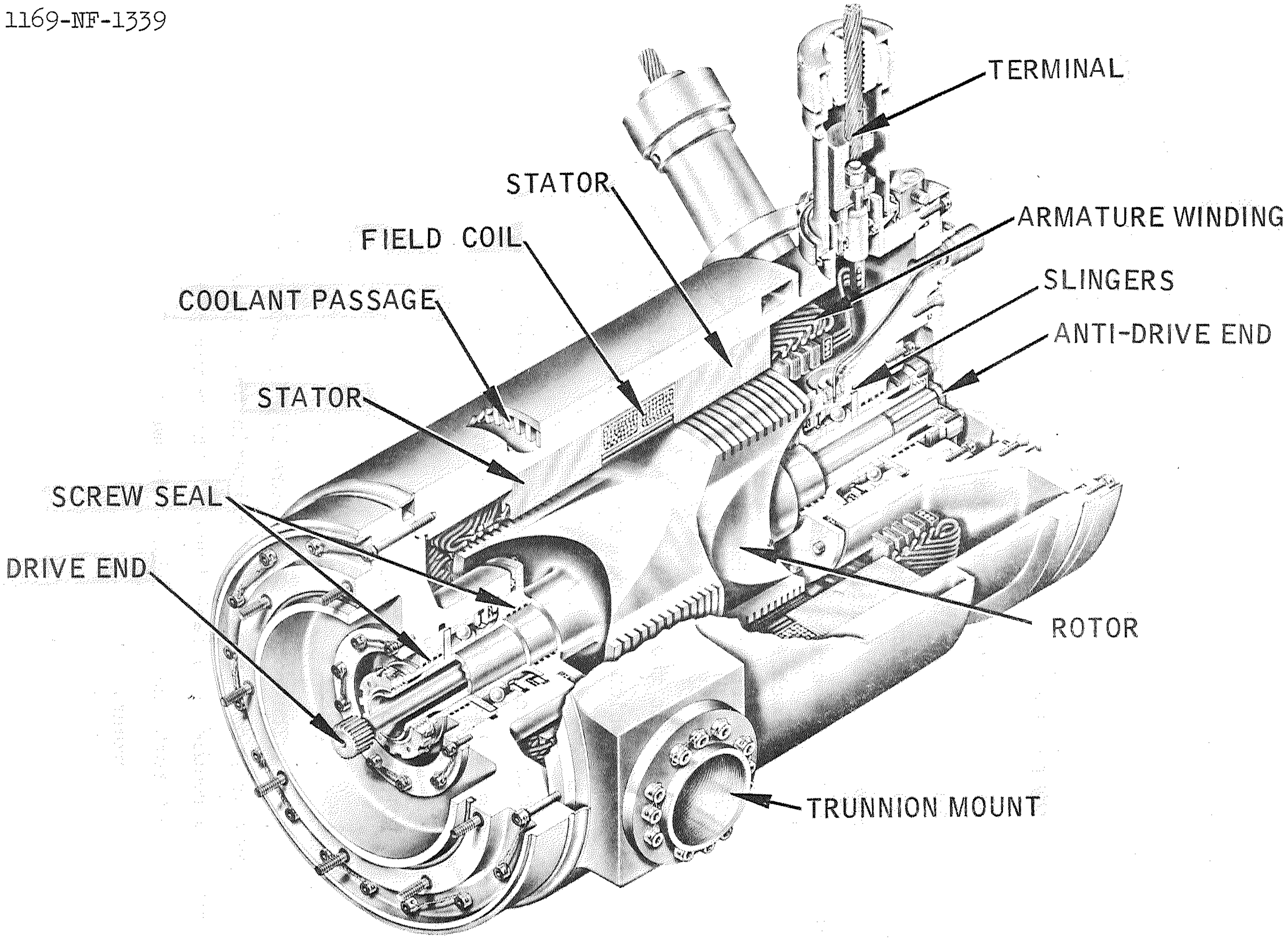


Figure 9. SNAP-8 Alternator

The screw seals function is to return drops of fluid escaping from the slinger/liquid interface, back to the interface. A rectangular thread form was chosen for the final design prototype machines because of its higher pumping efficiency over the triangular threads used on the earlier machines.

C. LUBRICATION

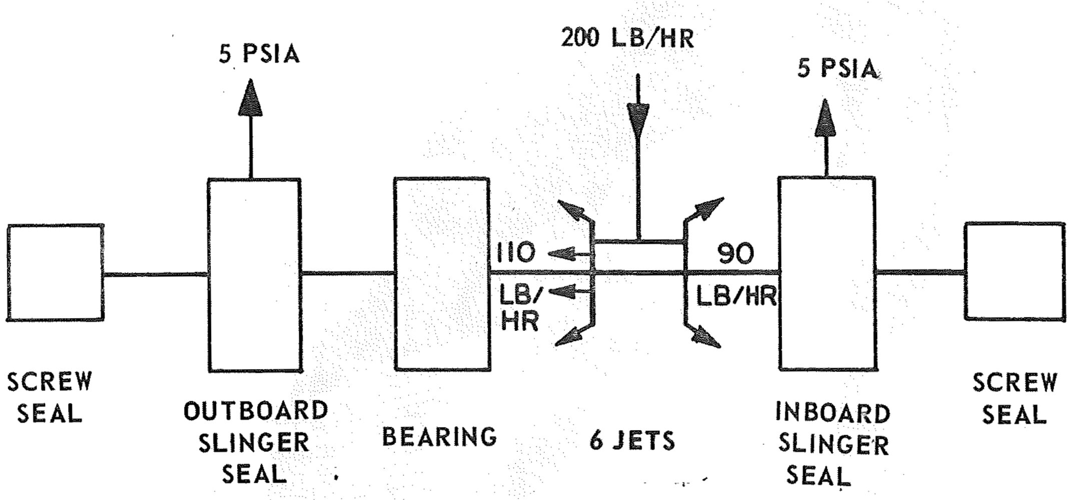
The bearings are lubricated by multiple-jet injection of the oil directed at an angle between the separator and the innerface. Scavenging slingers, on both sides of the bearing, ensure nonflooding operation and return the lubricant to the suction side of the lubricant-coolant loop. Lubrication of all the bearing elements, maximum bearing through flow, and effective cooling were achieved by injecting the lubricant from the low, non-thrust shoulder of the bearing. The design flow for each bearing and slinger is 200 pounds per hour; 55% of the total inlet lubricant-flow is directed at the bearings; and 45% at the inboard slinger, to dissipate heat generated in the alternator rotor which is conducted along the rotor to the slinger (see Figure 10).

A 0.040 inch diameter nozzle was selected, based on a maximum diameter to minimize clogging and still provide an adequate jet velocity of oil at the design flow.

D. ROTOR AND FRAME DESIGN

1. Rotor

The rotor, see Figure 11, is made from an AISI 4620 forging to provide good strength and magnetic properties. Slots are machined in the rotor to reduce pole face losses. The rotor poles overhang the stator cores axially, at both ends, to reduce the magnetic forces on the bearings produced by misalignment.



BEARING & SEAL SYSTEM SCHEMATIC

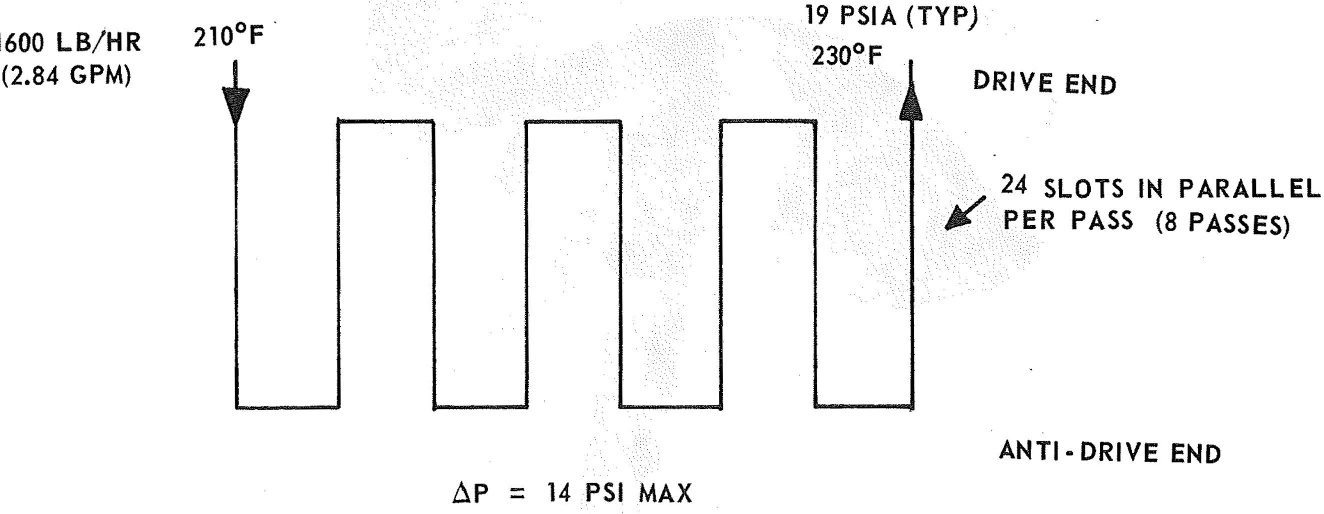


Figure 10. Alternator Cooling and Lubrication Schematic

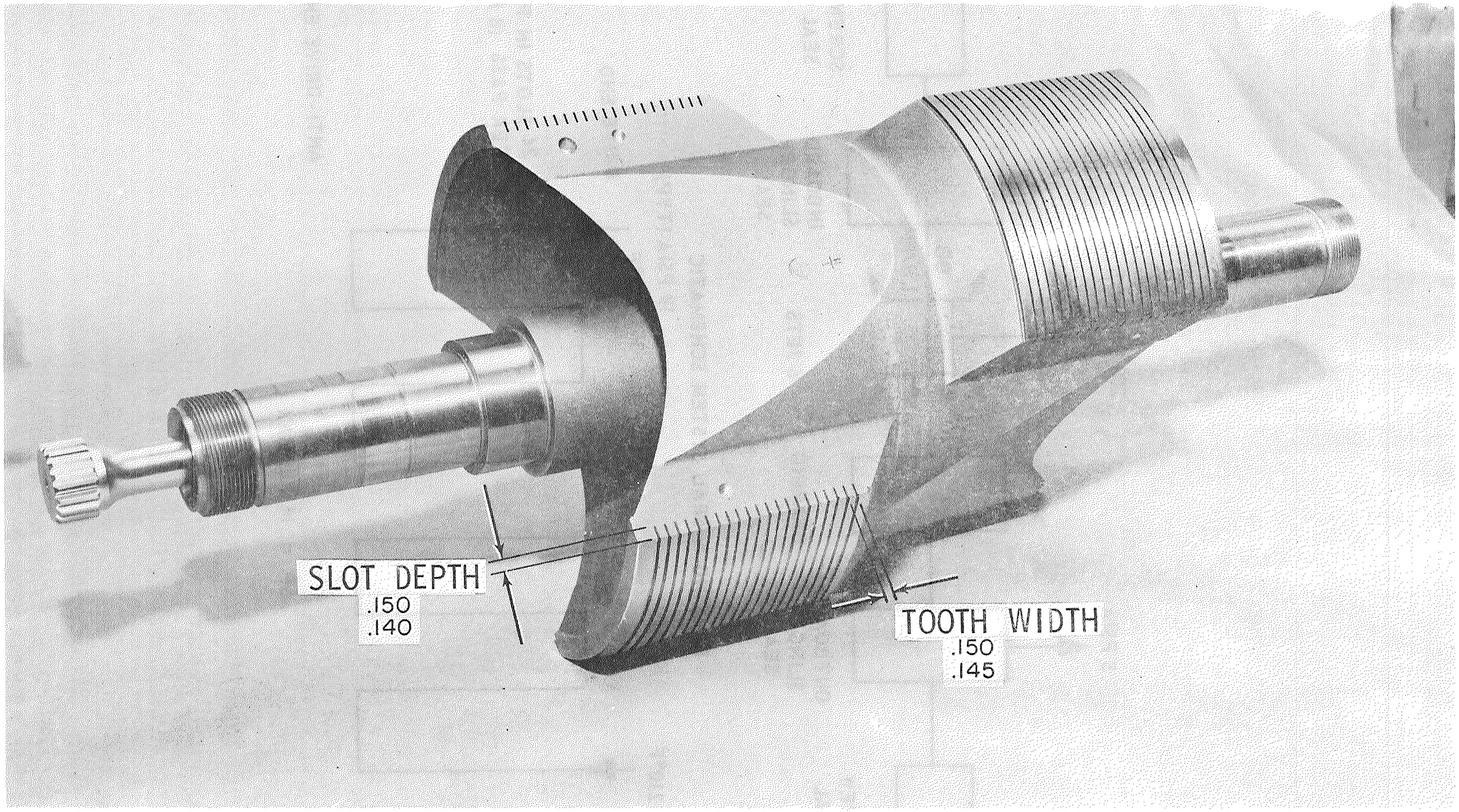


Figure 11. Rotor with Inner Shaft Assembled

2. Frame and End Shields

The frame was designed as a one-piece straight cylinder which permitted straight forward machining for the cooling passages, and also achieved the reliability and simplicity associated with one-piece construction.

The frame is composed of a HY-80 alloy steel-forged flange welded to a low-carbon, seamless steel pipe frame shell. This provides the necessary strength in the trunnion support area and suitable magnetic properties in the frame.

The cooling passages (192 slots, 0.05 by 0.375 in.) are machined axially along the outer surface of the frame. These passages are again divided into 8 paths of 24 slots each (Figure 10). A shroud covers the frame and provides a header at each end of the slots.

The end shields are composites of Inconel X forged hubs welded to 304 stainless steel flanges. Each shield is nonmagnetic; the hub material coefficient of thermal expansion matches that of the bearing and shaft. The shields also provide the bearing and seal supports, turbine bearing housing interface, and all passages for the cooling oil.

VI. ALTERNATOR DEVELOPMENT

One experimental alternator, four preprototype alternators and five prototype alternators were produced during this development period. Prototype alternators differ from the preprototypes in the design of the trunnion mounts, terminals, instrumentation and housing seal system. In addition, they have improved performance as a result of electromagnetic design changes made during the preprototype development phase. Following acceptance tests, several of the units were tested as part of a turbine-alternator assembly in the SNAP-8 system. Endurance tests were also conducted on a single unit for over 19,000 hours.

A. FABRICATION AND PERFORMANCE REQUIREMENTS

1. Reliability

The alternator reliability was established at 97.35 percent for a 10,000-hour mission with a reliability apportionment as shown in Table IV. The failure rate for the components to meet the required alternator reliability is equivalent to a mean time between failure (MTBF) of 373,000 hours or a failure rate of 2.68 per million hours.

2. Electrical

Testing of the early units revealed two areas where improvements were required; efficiency and excitation.

An analysis revealed that the air gap (0.060 in.) resulted in a large magnet-motive force, causing excessive flux to pass between the rotor and stator in the region between rotor poles. This leakage flux tends to saturate the rotor and frame, thus decreasing the induced voltage. Additional flux is required to generate rated voltage which, in turn, increases the total saturation in the rotor and frame. Design changes were made to correct this problem. The rotor was contoured between the rotor poles to increase the length of flux path from the stator to the inter-pole region, thus reducing the leakage flux. The frame was made thicker and the rotor hub diameter was increased to accommodate more flux without saturation.

Table IV. SNAP-8 Component Reliability Apportionment

Component	Quantity	Failure Rate/10^6 hours	
Electrical			
Main Stator Windings	3	0.41	
Stator Leads	4	0.10	
Stator Terminals	4	0.06	
DC Field Winding	1	0.14	
Field Leads	2	0.05	
Field Terminals	1	0.03	
Thermocouples	3	0.05	
Total Electrical			0.84
Mechanical			
Frame		0.10	
End Shield DE		0.05	
End Shield ADE		0.05	
Stator Core		0.02	
Inner Shaft		0.05	
Rotor and Shaft		0.02	
Seal Rings		0.03	
Dynamic Seals		0.20	
Assembly		0.14	
Hermetic Terminals		0.18	
Bearings		1.00	
Total Mechanical			1.84
Total Alternator			2.68
MTBF		373,000 hours	

The rotor material was changed from AISI 4130 to AISI 4620, the latter having superior magnetic properties. The result was a reduction of field current from 25 amperes to less than 20 amperes, which decreased the field power by 40 percent and dropped the field coil hot spot temperature approximately 86°F. The efficiency of the prototype alternators (87.5 percent) is 1-1/2 percent higher than the average of the early units. As a result of these changes, the prototype units meet all electrical requirements, including efficiency and excitation limits (see Table V).

3. Thermal (Hot Spot Temperatures)

Test results of the first four alternators indicated two problem areas:

- Field coil hot spot temperature exceeded hot spot allowable temperature of 352°F
- Stator connection wire exceeded hot spot allowable temperature of 392°F

A review indicated that the field coils were not being constructed in accordance with the design requirements, resulting in a detrimental heat transfer condition. This was corrected and verified prior to assembly of the generator by conducting a field coil thermal resistance test in a test frame with rated cooling. Based on the results of this test, it was possible to predict the actual field coil temperature when the completed generator was tested.

The second problem concerned a stator winding hot spot temperature of 437°F, compared with the specification limit of 392°F. Detailed analysis and test indicated that most of the temperature rise was in the conductor joining the bus bar to the winding, and in the flexible lead joining the bus bar to the terminal. The area of the flexible lead was doubled, and a thermal resistance test initiated.

Tests on the stator prior to assembly of the third completed unit verified the analysis. Based on the thermal resistance test, the end turn temperature was predicted to be 374°F, and the stator winding

Table V. Alternator Design Changes

		Prototype		
Variable	Design (Max)	No. 1 S/N 481489	No. 2 S/N 481490	No. 3 S/N 481491
Overall efficiency @ 80 KVA, 0.75 PF (see Figure 12)	87.7%*	87.5%	87.5%	87.5%
Field Coil Hot Spot @ 80 KVA, 0.75 PF	352°F*	324°F	340°F	338°F
End Turn Hot Spot (Stator)	392°F	406°F	437°F	388°F
Excitation Current in Amps Self Excited	21.35*	19.6	19.85	19.8
Electrical				
Losses without regulator (KW)	10.1*	8.6	8.6	8.7
Excitation Voltage (Volts)				
(a) With Regulator	48.7	43.3	43.8	43.5
(b) Without Regulator	48.6	41.9	42.2	41.4
Mechanical				
(a) Rotor Material (AISI)	4,130	4,620	4,620	4,620
(b) Slotted	No	Yes	Yes	Yes
(c) Contoured	No	Yes	Yes	Yes
(d) Flux Yoke, Thicker	No	Yes	Yes	Yes
Field Coil				
(a) Single Heat Path		No	No	No
(b) Double Heat Path		Yes	Yes	Yes
(c) Lower Thermal Resistance		Yes	Yes	Yes
Leakage Rate CC/HR (Goal)				
(a) ADE Inboard	0.02	0.86	0.37	0.16
(b) ADE Outboard	0.02	0.00	0.00	0.00
(c) DE Inboard	0.02	0.31	0.29	0.47
(d) DE Outboard	0.02	1.70	2.81	0.00
Slinger				
(a) Radial	0.010	0.017	0.017	0.017
(b) Axial Clearance	0.020-0.048	0.018	0.018	0.018
(c) Teflon Coating	No	Yes	Yes	Yes
Screw Seal - Inboard				
Teflon Coated	No	Yes	Yes	Yes
Screw Seal - Outboard				
Teflon Coated	No	Yes	Yes	Yes
Seal Weld	Yes	No	No	No
Bearings	Vacuum Melt	Triple	Triple	Triple
Weight in Pounds	330 (goal)	446	446	446

*At 80 KVA and 0.75 PF

180 degree bus bar to be 418°F. Subsequently, the stator wound thermal resistance test was conducted on each stator prior to assembly of the generator. The change in lead area was incorporated as a design improvement on the prototype alternators.

4. Cooling and Lubrication

Bearing and seal losses are approximately 2500 watts and pole face losses approximately 750 watts. Tests indicated that rotor pole faces were at approximately 550°F full load. Heat is removed from the shaft by oil flowing over the slingers and the bearings. The remaining rotor losses and some radiation losses from the end turns to the end shields are removed by the bearing lube oil.

During development testing, oil inlet temperature was controlled at 205°F to the alternator and the flow was set at 2.84 gallons per minute to the alternator stator cooling circuit. The steady state, measured pressure drop was 13.6 psi and compares to the specified maximum of 14.0 psi.

Regarding the bearing lubrication and temperature levels, there were no bearing problems, and the bearing temperatures were moderately above the incoming oil temperature. Typical bearing temperatures measured during acceptance tests are shown in Table VI. In the prototype alternators, the thermocouples were potted in drilled holes extending approximately 0.068 inch from the bearing bore, in each end shield at the bearing location. The thermocouple junction was insulated so that the thermocouple was ungrounded.

The prototype units utilized a floating thermocouple well to measure bearing temperatures (see Figure 8). A metal bellows fitting was welded into each end shield. The bellows served to seal the opening, preventing oil leakage, and as a keeper to hold the tip containing the thermocouple junction in contact with the bearing outer race. The metal wall at the tip was 0.025 to 0.015 inch thick. The thermocouple was insulated from the tip, with an insulation thickness of 0.010 to 0.005 inch.

Table VI. Bearing Temperatures

Serial No.	Drive End °C	Drive End °F	Anti-Drive End °C	Anti-Drive End °F
481489	118	244	117	243
481490	121	250	122	252
481491	120	248	117	243
481492	117	243	116	241
481510	115	239	117	243

5. Insulation

There have been no insulation malfunctions in a total of 29,000 hours operation, during acceptance and qualification tests of preprototype and prototype alternators. One alternator has accumulated over 19,000 hours of operating time. Approximately 50 hours of acceptance testing was accumulated on each prototype alternator. This total experience indicates that the insulation design is capable of meeting the 10,000-hour life required for SNAP-8 application.

a. Space Between Armature Cores

Protection and support of armature conductors between armature cores, and the space between the field box inner periphery and stator bore was achieved on the first alternators with numerous silicone-glass laminations. These insulation pieces resembled core insulation end punchings and were stacked and bonded to fill this volume with solid insulation. Later machines used Novolac epoxy compound which closed the space over the folded slot liners at the bore with three layers of 0.006 inch leno weave glass cloth applied by wet layup technique. This effected a strong, smooth, continuous loop at the bore to provide the required environmental protection and the mechanical support of conductors and insulation.

b. Armature Topsticks

Topsticks formed and sintered from dense alumina were applied to the first alternators. The ceramic topstick was provided in a 53/64-inch length in order to obtain a straight and flat stick without need for expensive lapping of the hard material. This resulted in insertion difficulty, and occasional damage to the folded slot liner from multiple insertion (4 per slot) of this somewhat abrasive material.

A moldable polyimide material (Polymer SP) was studied for possible topstick application in the alternator. The new material, machinable to desired configuration from molded slabs, is of the same chemical family, and provides essentially the same properties as the ML used for wire enamel and coating of glass cloth insulations. In addition, the moldable polyimide material provides high strength and a low coefficient of friction offering ease of insertion into tight slots without breakage.

Topsticks could be inserted in core lengths (3-5/16 inch) without breakage or damage to insulations. Performance of this stick to date has been excellent, with no change or negative effects in alternator operation.

6. Seals

The thread form used in prototype units is rectangular shaped, 0.012 inch radial by 0.092 inch axial, 8 starts, with lead angle of 14-1/2 degrees. The screw seals used were coated in the threads and on the slinger face with Teflon. The coating is used for its anti-wetting properties to minimize the secondary leakage from the slinger and screw seals. The first alternators had axial clearances of over 0.030 inch at operating conditions; subsequent units had operating clearances less than 0.020 inch. The last change involved the radial clearance over the rim of the slingers. The first alternator built had slingers installed with radial clearance of approximately 0.010 inch. Later units had a radial clearance of 0.017 inch. This change decreased the power loss of the seals.

The leakage rates of the prototype alternators varied from zero at the anti-drive end outboard seal to as much as 2.8 cc/hr. at the drive end outboard seal (see Table V). This is significantly less than that occurring in earlier units and apparently is the result of the change in screw seal thread form and the smaller slinger axial clearance. The effect of Teflon coating seemed to be inconclusive.

7. Alternator Weight

The SNAP-8 prototype alternator, as shown in Figure 9, weighs 446 pounds. Electromagnetic weight is 210 pounds or about 47 percent of the alternator weight. Table VII shows the electromagnetic and structural weights of the prototype alternator. The component designated as "other" includes miscellaneous hardware.

Table VII. Electromagnetic and Structural Weights of Prototype Alternators*

	Prototype - Serial No. 481490		
Component	Electro-Magnetic Weight	Structural Weight	Total
Rotor	52.52	7.60	60.12
Inner Shaft		2.00	2.00
Slingers and Seals		13.80	13.80
DE End Shield		51.00	51.00
ADE End Shield		29.00	29.00
Bearings		1.76	1.76
Frame	55.00	119.00	174.00
Stator Wound	101.00		101.00
Terminals	2.05		2.05
Other		11.16	11.16
Total	210.57	235.32	445.89

*Nominal Design Weight in Pounds

8. Performance

a. Preprototype

The specified rating of the alternator was 80 kva, 0.75 lagging to unity power factor, 120/208 volts, 3-phase, 4-wire, 400 Hz, at 12,000 revolutions per minute. The alternator had a hermetically-sealed frame and the mechanical joints were designed to permit complete hermetic sealing when assembled to the turbine.

The first alternators met the electrical requirements for SNAP-8 service (see Table V) except for excitation and efficiency; these two deficiencies were closely related.

A detailed analysis revealed that air gap (0.060 inch) caused excessive flux to pass between the rotor and stator in the interpolar region. This leakage flux tended to saturate the rotor and frame. It also reduced the effective voltage induced in the armature windings requiring more flux in the real pole axis to generate rated voltage, thereby, further increasing the total saturation in the rotor and frame.

To overcome these deficiencies, several changes were made:

- The rotor interpolar depth was increased by contouring between poles.
- The frame area and the rotor hub area were increased.
- The rotor material was changed from AISI 4130 to AISI 4620.

These changes resulted in a reduction of the field current from 25 to 20 amperes and an increase in efficiency from 86 to 87.5 percent.

b. Prototype

Performance curves and tables for the prototype alternator are shown in Figures 12 and 13 and Tables VIII, IX, and X. The response to sudden application of rated load is shown in Figure 14. The acceptance tests indicate that prototype alternators meet the SNAP-8 Alternator requirements.

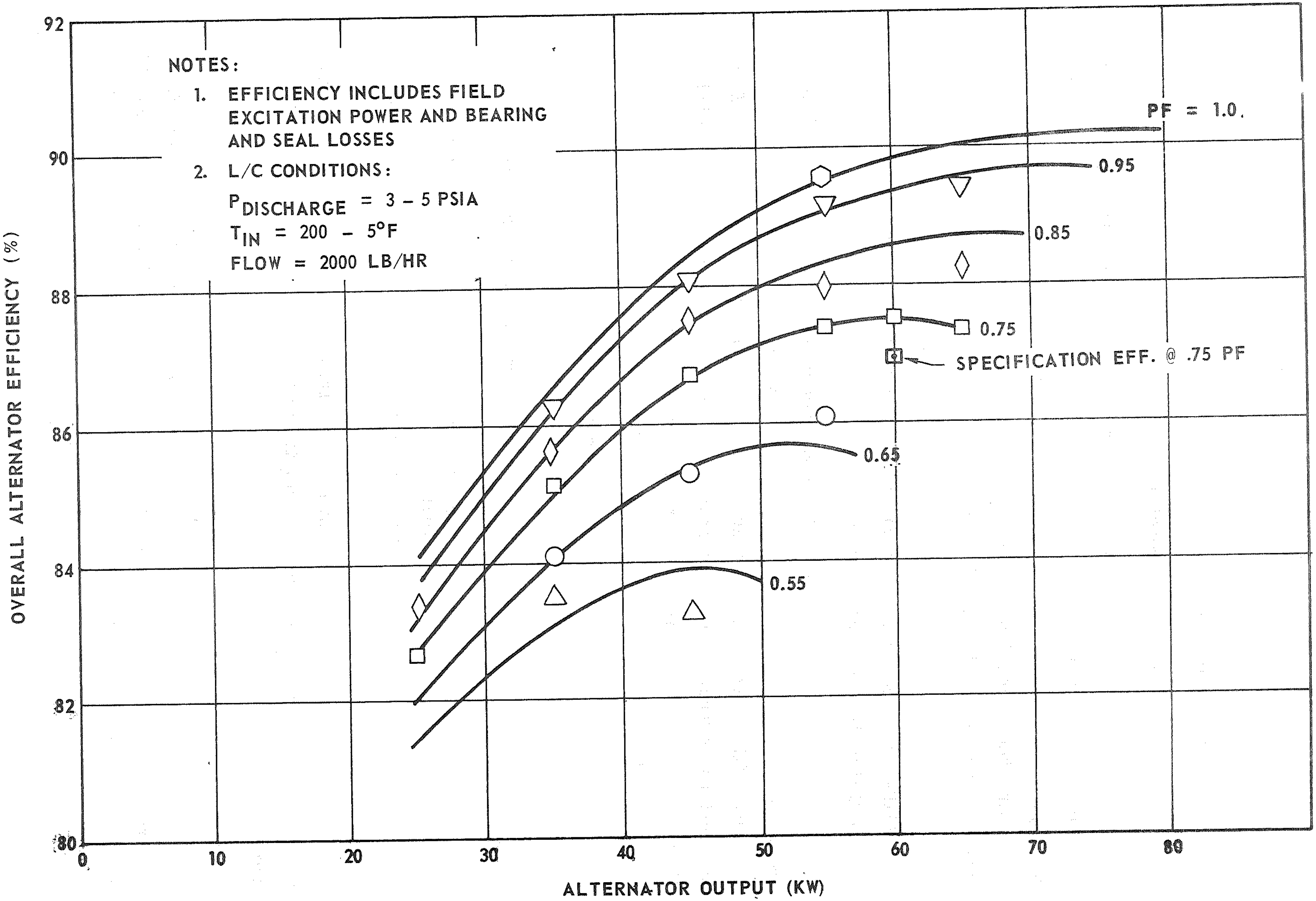


Figure 12. Alternator 481489 Efficiency Characteristics

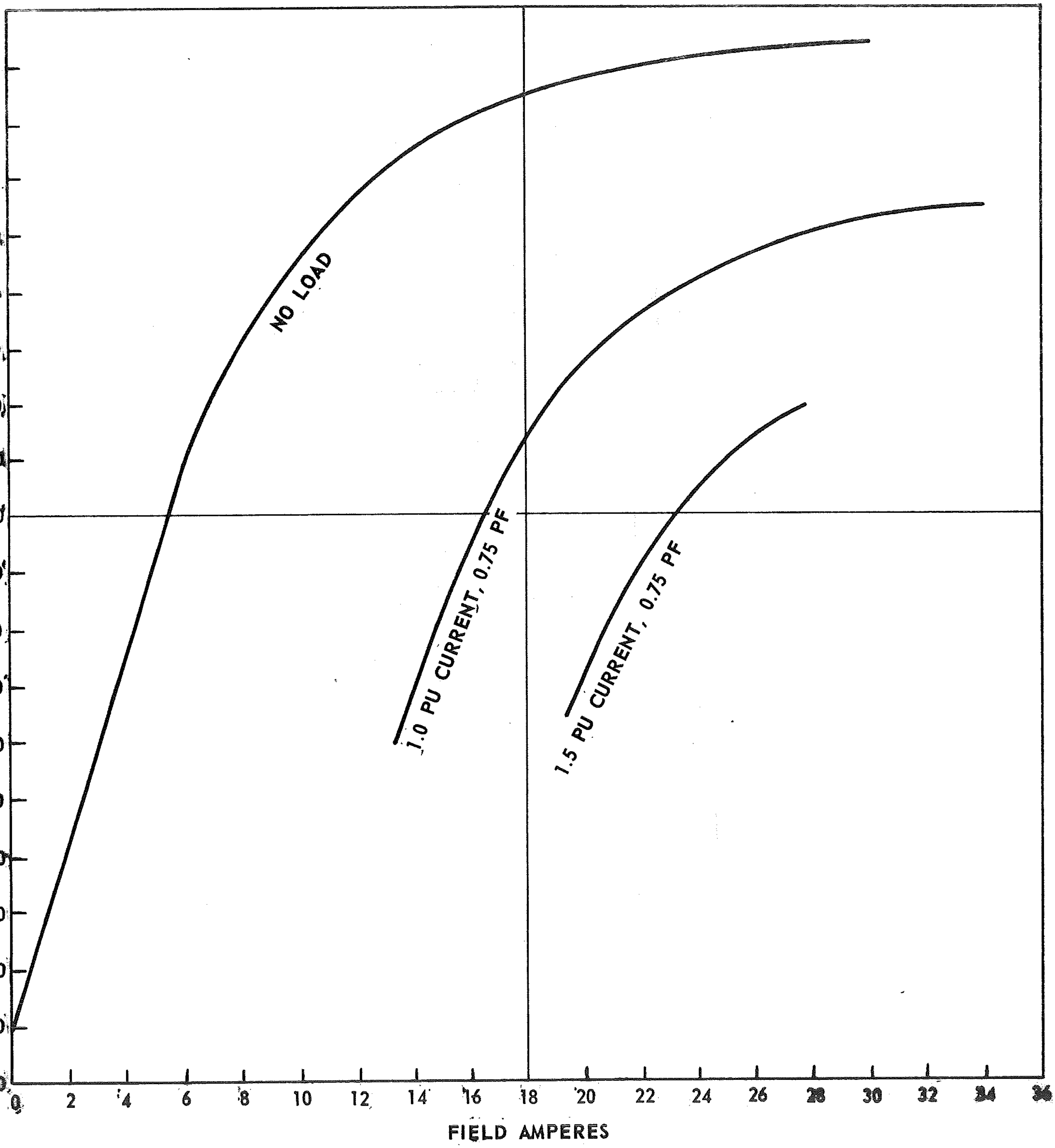


Figure 13. Alternator 481489 Saturation Curves

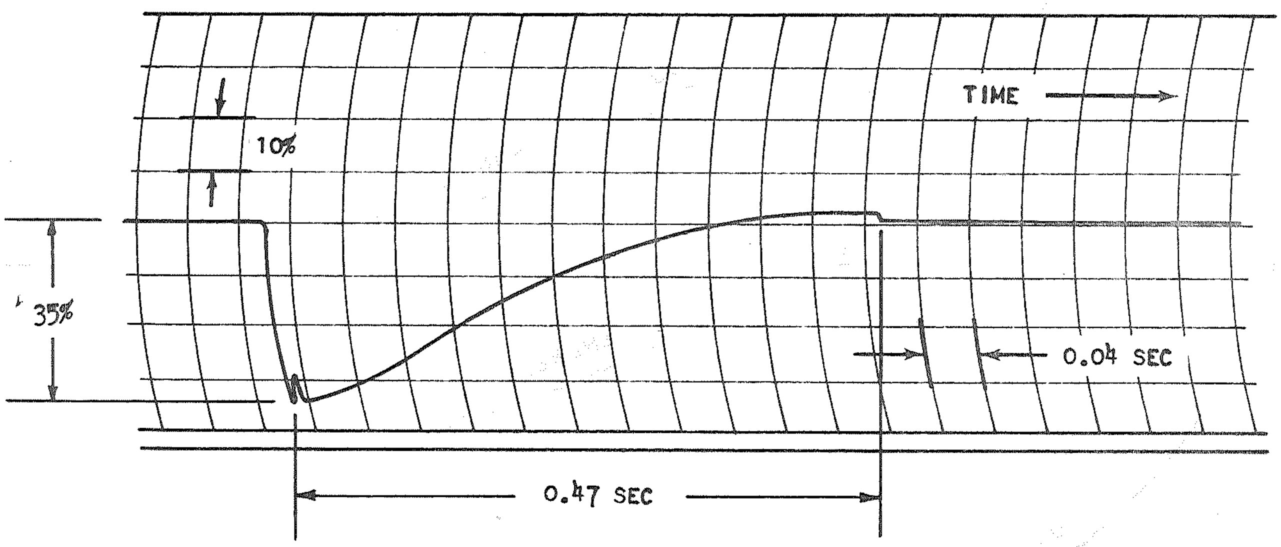


Figure 14. Recovery After Rated Load Application

Table VIII. Alternator Electromagnetic Performance Versus Specification Limits

Performance Item	Specification	Performance-Prototype Alternator #1
Open circuit time constant (T'do)	0.60 sec. max at steady-state temperature	0.57 sec. at 307°F
Short circuit ratio	0.25 min.	0.67
Short circuit capacity for 5 secs.	2 PU min.	2.94 PU (3 phase) 3.96 PU (1 phase)
Instantaneous voltage drop on sudden application of 2 PU impedance load	Voltage not to drop below 0.70 PU	Voltage dropped to 0.83 PU
Excitation	52 volts max. 22 amps max.	43.3 volts 19.6 amps
Wave form - total rms harmonic content (L-L at 1 PF)	7% max.	2.33%
Symmetry of construction (max. voltage difference between phases)	1 volt max.	<1 volt
Output voltage modulation	1% max.	0.14%
Efficiency, including field losses, at rated load, 0.75 PF	87% min.	87.8%
Field Coil Resistance	-	1.46 ohms
Stator Phase Resistance	-	.00583 ohms
Full load (80 kva, .75 PF) Excitation		
voltage	52 volts max.	42.0 volts
current	22 amps max.	18.9 amps
Loss Breakdown		
Field I^2R - KW	-	0.79
Stator I^2R - KW	-	1.31
Bearings and Seals - KW	-	2.20
Core and Stray Load - KW	-	4.00
Total KW	8.96 max	8.30

Table IX. Comparison of Specified Thermal Requirements with Test Results

Item	Specification	Test *	
Cooling Oil	Polyphenyl ether	Polyphenyl ether	
Flow gpm	2.84	2.84	
Inlet pressure psia	-	21.9	
temperature °F	205°F	205°F	
Outlet pressure psia	-	8.3	
temperature °F	-	230°F	
ΔP psi	14 psi max.	13.6	
		**DE	***ADE
Bearing			
Inlet flow gpm	0.35	0.338	0.320
pressure psia	20 psia ± 1 psi	20.2	20.2
temperature °F		196.0	198
Outlet flow - inboard gpm		0.155	0.138
flow - outboard gpm		0.175	0.176
pressure - inboard psia		6.7	6.5
pressure - outboard psia		6.7	6.7
temperature - inboard °F		225.0	248
temperature - outboard °F		259.0	258
Bearing cavity pressure psia		0.8	0.8
Winding Temperatures			
Field coil average	-	307°F	
Field coil hot spot	392°F max.	324°F	
Stator winding end turn	392°F max.	367°F	
Stator winding 180° bus bar	410°F max.	406°F	
Bearing temperature DE	300°F max.	244°F	
ADE	300°F max.	243°F	

* Based on Prototype Serial Number 481489

** DE = Drive End

*** ADE = Antidrive End

Table X. Prototype Alternator Performance Summarized

Parameter	Specification	Test
Cooling Oil Flow	2.84 GPM	2.84 GPM
Cooling Oil Inlet Press	33 psia	21.9 psia
Cooling Oil Pressure Drop	13 psi max.	13.6 psi
Cooling Oil Inlet Temp.	200 - 210°F	205°F
Speed	12,000 RPM	12,000 RPM
Output	80 KVA	80 KVA
Power Factor	0.75 lagging	0.75 lagging
Voltage	120	120 - 120.1
Frequency	400 Hertz	400 Hertz
Excitation Current	22 amps max.	19.1 amps
Excitation Voltage	52 volts max.	41.9 volts
Phase Unbalance	1% max.	1%

B. TESTS AND TEST RESULTS

1. Turbine Alternator Tests

The alternator is utilized as part of a turbine-alternator assembly, and is operated in a power conversion system with mercury vapor as the working fluid. The electrical control system used in conjunction with the alternator is shown in Figure 15. The primary objective of the mercury vapor tests was to evaluate all static and rotating components of the power conversion system rather than specific evaluation of any one component. Electrical tests conducted were directed toward speed control and voltage regulation characteristics under varying load conditions. Alternator electrical parameters were monitored along with winding and bearing temperatures, lubricant and cooling flow, and temperatures and pressures. The performance of the alternators was satisfactory, and all operating parameters relative to the SNAP-8 requirements were met.

2. Development and Improvement

Two alternator malfunctions were revealed as a result of the tests:

- Alternator cooling jacket weld hardening resulting in a cracked weld.
- Outboard screw seal seizure at overspeed.

Examination of the seal welds between the (HY 80) trunnion ring and the mild steel case revealed that variations existed in the type and amount of weld filler metal used for this joint (see Figure 4). Analyses of filings taken from the alternator seal weld, which cracked, indicated a weld composition which was hardenable. Weld hardening appeared to be accentuated by the chilling effect of the massive (HY 80) trunnion boss. Chemical tests of the four other alternators indicated that the seal welds in these units would probably be subject to seal weld cracking. The potential for cracking

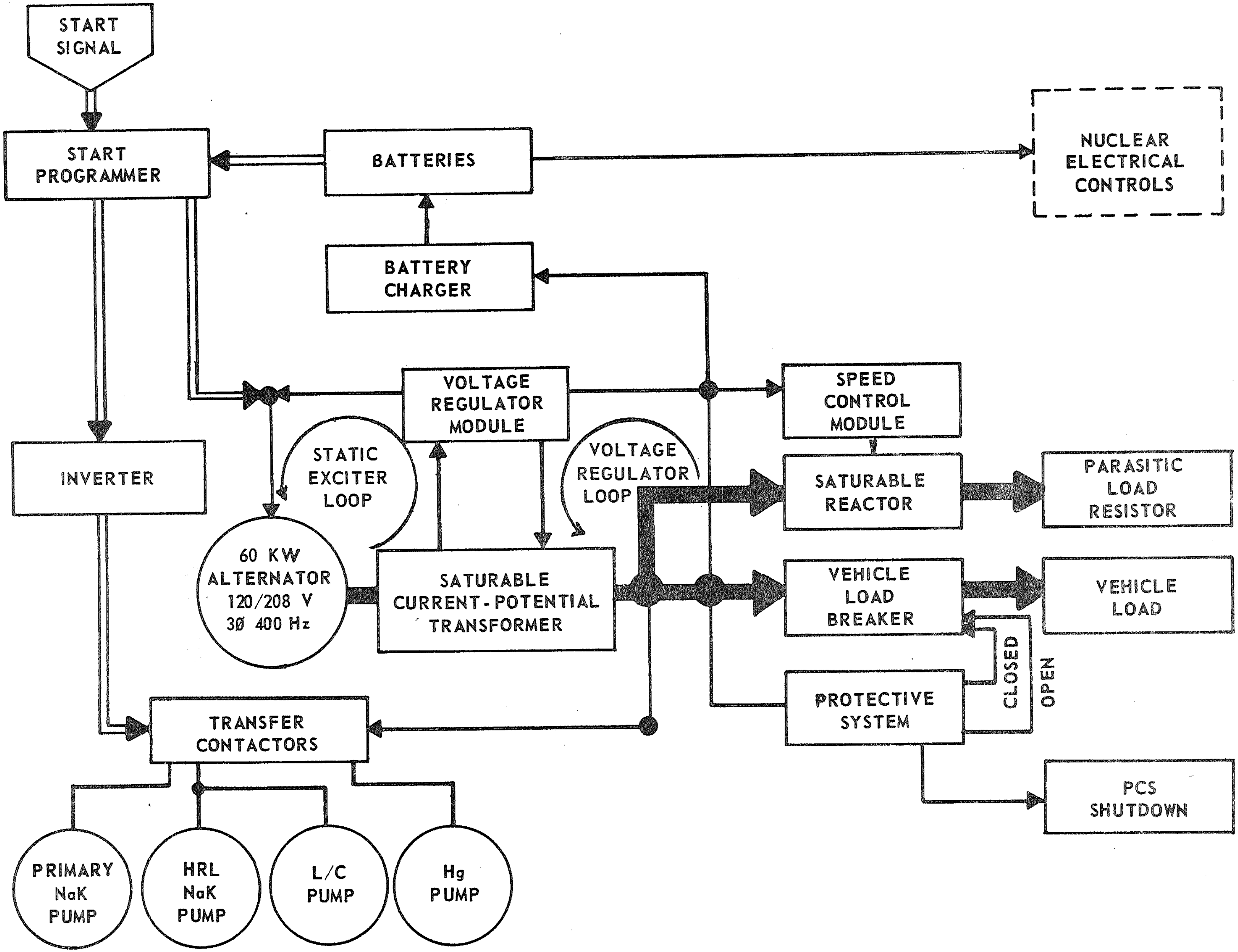


Figure 15. SNAP-8 Electrical Control System Block Diagram

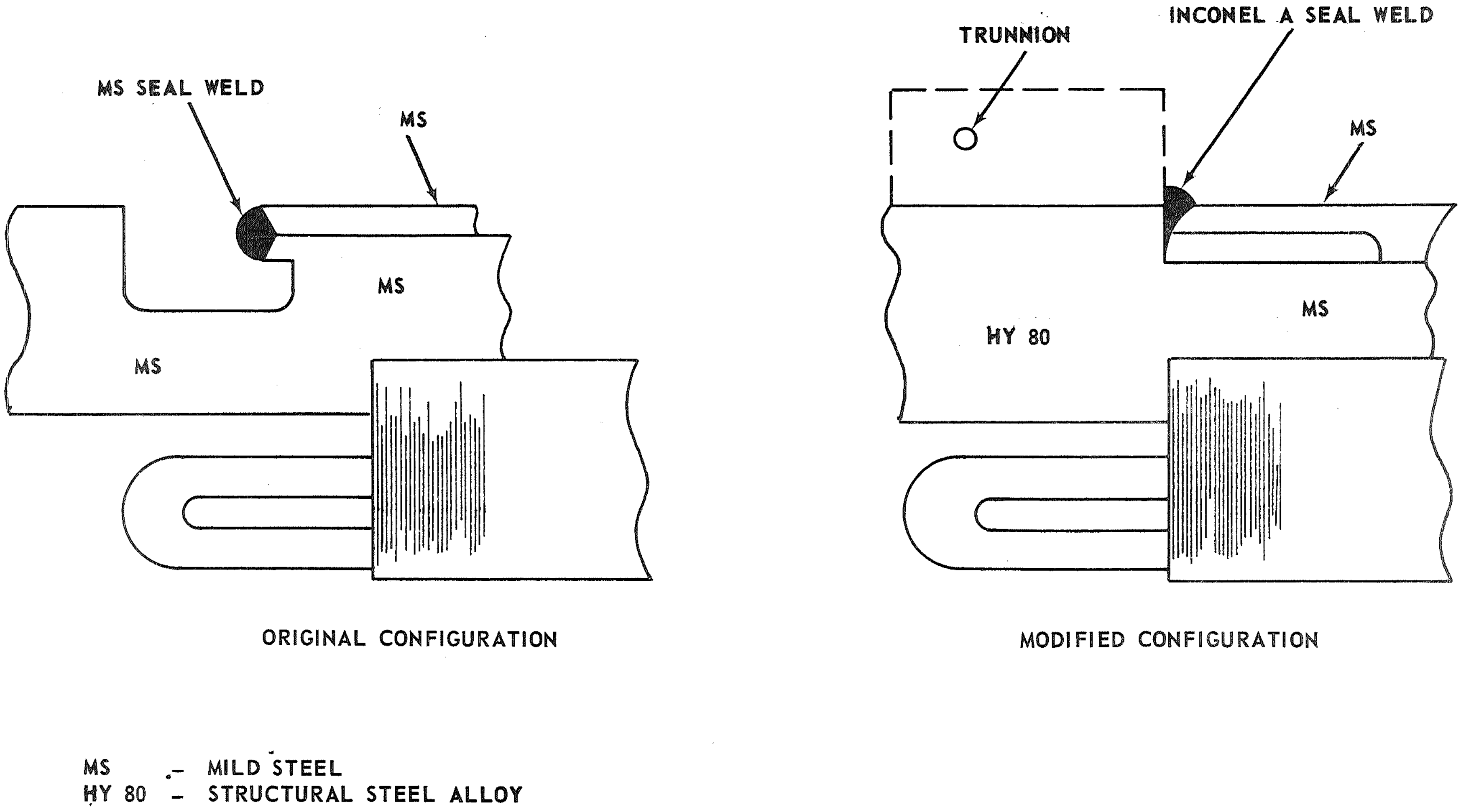
varied according to the weld configuration and weld filler metal used in each unit. Since stress relieving of these units was not practical, it was decided that a multiple pass overlay weld be deposited on the existing seal weld using Inco A filler metal which is non-hardenable and ductile. Pressure and temperature cycling tests followed to ensure weld integrity. A design modification to obtain a more reliable mechanical joint on future units was initiated (see Figure 16). Since this corrective action was applied, no malfunctions have occurred during 18,000 hours of service.

The outboard screw seal seizure occurred as a result of turbine overspeeds to approximately 19,000 rpm and 17,000 rpm, respectively, on two alternators. An analysis conducted on the alternators indicated that at speeds above 13,500 rpm, there was a progressive loss of bearing preload. The normal first critical speed with the bearings under their designed preload of 60 lb was 22,000 rpm. Examination of the bearings from the unit indicated that the bearings had indeed operated without preload. With the preload, the effective bearing stiffness was reduced and the rotor became unstable. Under these circumstances, the angular contact bearings were operating at virtually zero contact angle; the effective radial clearance was increased allowing the rotor to orbit.

Table XI shows the computed effect of reduced bearing preload on bearing stiffness and eventually on the first critical speed. Under these conditions, with the lowered first critical reached or approached, the situation was aggravated and the deflection amplitudes became large enough to cause the screw seals to rub.

Table XI. Effect of Bearing Preload

Bearing Preload (lb)	Bearing Stiffness (lb/in)	1st Critical Speed (rpm)
100	1.45×10^6	26,000
60	7.2×10^5	22,000
0	3.78×10^5	18,000



ORIGINAL CONFIGURATION

MODIFIED CONFIGURATION

Figure 16. Mechanical Joint Modification

It was concluded that the two malfunctions were caused by rotor instabilities due to loss of bearing preload and operating the unit at or near its first critical speed. The critical speed was lower than normal because the bearing stiffness had been reduced by loss of preload. The high amplitude which would be expected under these conditions would rub, and produce a wear pattern which would be the same as that acutally observed.

These malfunctions were a result of operating the alternator outside of the design envelope. Design modifications have been made with the object of reducing the tendency for the bearings to unload at speeds above design using a system of belleville washers with a higher length to diameter ratio for the bearing system preload.

A total of four alternators have been tested as part of complete turbine-alternator assemblies in a power conversion system. Apart from the two previously mentioned malfunctions, the performance has been satisfactory and has fulfilled the design requirements. The longest accumulated run time on a single unit has been in excess of 11,200 hours. The maximum number of startup and shutdown cycles experienced on a single unit was 43.

Testing of a complete turbine-alternator assembly in a mercury system was also conducted at NASA, Lewis Research Center, in which a unit satisfactorily completed over 1,400 hours of continuous operation.

3. Endurance Testing

An Electrical Component Test Facility (ECTF) was established to provide long-term endurance testing of the SNAP-8 electrical components. The components under test include the alternator, the voltage regulator and static exciter, the speed control, and the saturable reactor assembly. The primary objective of this test facility is to obtain endurance history for electrical components, including the alternator without the operational problems of a hot mercury facility.

The alternator performed satisfactorily during the initial 2,500 hour endurance test. The only observable anomally was an increase in the winding temperature which occurred after 880 hours of accumulated operation, following 350 hours of continuous operation and a planned shutdown. Initially, the winding temperature was 405°F for the first 880 hours of operation. Following the shutdown and restart, the temperature was observed to increase up to an average value of 425°F by 2,500 hours. Subsequent observation has led to the hypothesis that the high temperature is the result of the winding insulation aging. This results in less flexibility so that as the alternator cools (particularly on the first thermal cycle) to room temperature, separation between the stator coils and stator iron occurs. This would cause an increase in thermal resistance between the windings and coolant passages. Since the stator winding is cooled by means of conduction from the winding through the insulation to the stator iron, an increase in thermal resistance would naturally result in an increase in winding temperature.

Disassembly and inspection of the unit at 2,500 hours revealed the alternator to be in good condition. The insulation had darkened and a few cracks were observed in the end turn impregnating varnish. The insulation resistance of the stator winding to frame decreased from 9×10^9 ohms at the start of the test to 4.9×10^9 ohms at 2,500 hours. The field to frame showed a decreased resistance of 2×10^{11} ohm to 4.5×10^9 ohm over the same period. These lower values of insulation resistance indicated only minor electrical degradation which was typical of used alternators. Values of 1×10^6 ohm and larger are generally considered acceptable.

The alternator was reassembled and returned to the facility and testing was continued. A further 16,500 hours of satisfactory operation was achieved bringing the total accumulated run time on the 1 unit to over 19,000 hours.

VII. CONCLUSIONS

A reliable long life 80 kva alternator has been successfully developed for the SNAP-8 system.

Some significant accomplishments during this development were:

- Electromagnetic design balance was improved by contouring the rotor interpolar region.
- Low pressure drop and low thermal resistance was achieved by utilizing a "Laminar flow" stator oil cooling scheme.
- Application of dynamic seals - radial slingers backed up by a screw seal.
- Satisfactory completion of a 19,000 hour (accumulated time) endurance test at rated conditions on a prototype unit.

Future effort remaining to completely verify all the design features are:

- Evaluate the effectiveness of the dynamic sealing system over a long period of continuous operation with a space vacuum level maintained in the alternator cavity.
- Endurance testing on the other alternators to 12,500 hours to statistically demonstrate the life, reliability of components such as the bearings, insulation system, and drive spline.
- Alternator system tests with regard to vibration and shock.

In considering basic design improvements some possibilities would be:

- A weight reduction by material change and design optimization.
- An improvement in the Homopolar Inductor Alternator design could be made by increasing the rotor diameter and shortening the length. Thus the bearing span would be decreased which would improve the rotor stability at runaway conditions.
- The installation of a static and startup sealing system that would prevent the loss of oil film from the bearings during storage in space.

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