JUL 28 1961

MASTER

NAA-SR-6302
TRW REPORT No. ER-4472
THE SNAP II POWER CONVERSION SYSTEM
TOPICAL REPORT No. 9
ALTERNATOR ANALYSIS, DESIGN AND DEVELOPMENT

AEC RESEARCH AND DEVELOPMENT REPORT

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

TAPCO a division of
Thompson Ramo Wooldridge Inc.
CLEVELAND, OHIO

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

PROJECT

512-128252-88

NAA-SR-6302
THE SNAP II POWER CONVERSION
SYSTEM TOPICAL REPORT NO. 9
ALTERNATOR ANALYSIS, DESIGN
AND DEVELOPMENT
TRW REPORT NO. ER-4472

PREPARED BY:

R. L. Bucklin
R. L. Bucklin

CHECKED BY:

R. J. Shafronek
R. J. Shafronek
Senior Project Engineer

APPROVED BY:

W. R. Chapman
W. R. Chapman
Manager, Engineering

J. W. Galysh
J. W. Galysh
Research Engineer

D. L. Southam
D. L. Southam
Project Manager

J. E. Taylor
J. E. Taylor, Manager
New Devices Laboratories

H. J. Morgan
H. J. Morgan
Research Engineer

C. G. Martin
C. G. Martin, Manager
Electrical Product Development

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

DATE

June 19, 1961

DEPARTMENT

8868

Thompson Ramo Wooldridge Inc.

CLEVELAND, OHIO, U. S. A.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A) Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employees or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

ABSTRACT

The 3 KW nuclear auxiliary power unit designated SNAP II is intended for use in a satellite vehicle. The system consists of a reactor heat source, a mercury Rankine engine, and a permanent magnet alternator. The design details, test results, and development of the SNAP II alternator presented in this analysis were accomplished under a subcontract to Atomics International as part of the Atomic Energy Commission Contract AT(11-1)-GEN-8.

TABLE OF CONTENTS

	<u>Page</u>
1.0 SUMMARY	1
2.0 INTRODUCTION	2
3.0 REQUIREMENTS AND SPECIFICATIONS	4
4.0 ALTERNATOR DESIGN	5
4.1 Initial Design Analysis	5
4.1.1 Rotor Design	8
4.1.1.1 Segmented Ring	8
4.1.1.2 Continuous Ring	10
4.1.2 Stator Design	11
4.1.2.1 Electrical and Mechanical Considerations	11
4.1.2.2 Mercury Seal	12
4.2 Development Design Approach	14
4.2.1 Operation With Series Capacitors	14
4.2.2 Electromagnetic Excitation	15
4.2.3 Polyphase Operation	16
5.0 ALTERNATOR PERFORMANCE RESULTS	19
5.1 Single-Phase Performance Without Capacitors	20
5.2 Single-Phase Performance With Capacitors	24
5.3 Two-Phase Operation Without Capacitors	29
5.4 Two-Phase Operation With Capacitors	37
6.0 TEST APPARATUS	39
6.1 Dynamometer	39
6.2 Instrumentation	39
6.3 Load Banks	42
7.0 CONCLUSIONS AND RECOMMENDATIONS	43
APPENDIX: COMPARATIVE ANALYSIS OF SINGLE-PHASE AND TWO-PHASE OPERATION	45

LIST OF FIGURES

	Page
FIGURE 1 SNAP II COMBINED ROTATING UNIT	3
FIGURE 2 SNAP II ALTERNATOR	6
FIGURE 3 SNAP II ALTERNATOR COMPONENTS	7
FIGURE 4 REVERSIBLE CHANGES IN MAGNET FLUX RETENTION TEMPERATURE	9
FIGURE 5 ALTERNATOR STATOR WITH GLASS BORE SEAL	15A
FIGURE 6 SINGLE-PHASE OPERATION	21
FIGURE 7 VOLTAGE REGULATION VS TOTAL WATTS OUTPUT, SINGLE- PHASE - OPEN SLOT - NO CAPACITORS - TEMPERATURE 650 °F	22
FIGURE 8 EFFICIENCY CHARACTERISTICS, SINGLE PHASE - OPEN SLOT - NO CAPACITORS - TEMPERATURE 650 °F	22
FIGURE 9 VOLTAGE REGULATION VS WATTS OUTPUT, SINGLE PHASE - CLOSED SLOT - TEMPERATURE 650 °F	23
FIGURE 10 EFFICIENCY CHARACTERISTICS, SINGLE PHASE - CLOSED SLOT - TEMPERATURE 650 °F	23
FIGURE 11 SINGLE-PHASE OPERATION WITH CAPACITORS	24
FIGURE 12 VOLTAGE REGULATION VS TOTAL WATTS OUTPUT, SINGLE PHASE - OPEN SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	25
FIGURE 13 EFFICIENCY CHARACTERISTICS, SINGLE PHASE - OPEN SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	25
FIGURE 14 VOLTAGE REGULATION VS WATTS OUTPUT, SINGLE PHASE - CLOSED SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	26
FIGURE 15 EFFICIENCY CHARACTERISTICS, SINGLE PHASE - CLOSED SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	27
FIGURE 16 EFFICIENCY CHARACTERISTICS, SINGLE PHASE - CLOSED SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	28

LIST OF FIGURES (Continued)

FIGURE 17	TWO PHASE OPERATION	29
FIGURE 18	VOLTAGE REGULATION VS TOTAL WATTS OUTPUT, TWO PHASE - OPEN SLOT - NO CAPACITORS - TEMPERATURE 650 °F	30
FIGURE 19	EFFICIENCY CHARACTERISTICS, TWO PHASE - OPEN SLOT - NO CAPACITORS - TEMPERATURE 650 °F	30
FIGURE 20	VOLTAGE REGULATION VS TOTAL WATTS OUTPUT, TWO PHASE - CLOSED SLOT - TEMPERATURE 650 °F	31
FIGURE 21	EFFICIENCY CHARACTERISTICS, TWO PHASE - CLOSED SLOT - TEMPERATURE 650 °F	32
FIGURE 22	EFFICIENCY CHARACTERISTICS, TWO PHASE - OPEN SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	33
FIGURE 23	VOLTAGE REGULATION VS TOTAL WATTS OUTPUT, TWO PHASE - OPEN SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	34
FIGURE 24	VOLTAGE REGULATION VS WATTS OUTPUT, TWO PHASE - CLOSED SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	34
FIGURE 25	VOLTAGE REGULATION VS TWO PHASE - CLOSED SLOT - SERIES CAPACITATORS - TEMPERATURE 650 °F	35
FIGURE 26	EFFICIENCY CHARACTERISTICS, TWO PHASE - CLOSED SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	35
FIGURE 27	EFFICIENCY CHARACTERISTICS, TWO PHASE - CLOSED SLOT - SERIES CAPACITORS - TEMPERATURE 650 °F	36
FIGURE 28	TWO-PHASE OPERATION WITH CAPACITORS	37
FIGURE 29	ALTERNATOR PERFORMANCE TEST FACILITIES	40
FIGURE 30	ALTERNATOR PERFORMANCE DRIVE STAND	41

LIST OF TABLES

TABLE 1	COMPARISON BETWEEN PERMANENT MAGNET AND BEEM ALTERNATOR	16
TABLE 2	ELECTRICAL PERFORMANCE COMPARISON	17
TABLE 3	SINGLE-PHASE PERFORMANCE VALUES AT DESIGN POINT	21
TABLE 4	TWO-PHASE PERFORMANCE VALUES AT DESIGN POINT	37
TABLE 5	TEST INSTRUMENTATION	42

1.0 SUMMARY

The work presented in this analysis of the SNAP II 3 KW alternator was performed under a subcontract to Atomics International. The prime objectives of the program were:

- a. Select the type of electrical generating system best suited to the SNAP II requirements.
- b. Design, fabricate and test the system selected to evaluate its performance at design point and off design point conditions.
- c. Determine areas of possible improvement and incorporate into the final design where possible.

A preliminary study resulted in the selection of a permanent magnet alternator as the electrical power source for SNAP II. The primary advantages of this type of machine are as follows:

1. High efficiency, small volume, low weight.
2. Proven dependability of permanent magnet alternators because of the absence of slip rings, brushes, and rotating field windings.
3. Ease of protecting rotor from mercury vapor corrosion.

Experimental data indicate that this type of alternator will fulfill design requirements. Initial tests on single-phase alternators have shown slight deficiencies in voltage regulation, harmonics, and efficiency. Various changes have been made in the design and construction to improve performance in these areas. Operation of the alternator as a two-phase machine has resulted in performance exceeding the original design objectives.

2.0 INTRODUCTION

The SNAP II 3 KW auxiliary electric power unit consists of a reactor heat source and a power conversion system. The power conversion system is a mercury Rankine engine which is composed of a mercury boiler heated by a NaK heat transfer loop, an axial flow impulse turbine which extracts energy from the superheated mercury vapor, a condenser which returns the vapor to a liquid state and a mercury pump which returns condensate to the boiler. The turbine directly drives the alternator, the mercury pump, and a permanent magnet induction NaK pump which is designed to circulate the NaK between the mercury boiler and the reactor. The combined rotating unit is shown in Figure 1.

The major problems confronting TRW in the design and fabrication of the electrical generating system for SNAP II were the requirements for continuous operation at temperatures approaching 700°F and continuous exposure of the major components to corrosive mercury vapors. Under these extreme operating conditions conventional alternators and materials are unsatisfactory. High temperature insulating materials and conductors are required and external materials must be impervious to mercury corrosion.

The intrinsic characteristics of the permanent magnet alternator offered the most promising solution to the problem. This report analyzes specific problem areas in alternator construction, performance, and sealing and shows how the present unit was established to give optimum design advantages.

SNAP II COMBINED ROTATING UNIT

3.0 REQUIREMENTS AND SPECIFICATIONS

The determining factors in establishing a set of specifications for the SNAP II alternator were the proposed operating conditions and the preliminary design analysis conducted by TRW. As a result of the design analysis nominal values were established for such performance parameters as voltage regulation, efficiency, and harmonics.

The following specifications are based on alternator performance at operating temperatures.

1. Electrical output	3.0 KW (net) useful power
2. Duty cycle	3.0 KW constant and continuous
3. Voltage (single phase)	110 volts ± 5 percent
4. Load power factor	Variable from 1.0 to 0.8 lagging
5. Electrical ground	One side of the power output to be grounded to the alternator frame.
6. Harmonics	7 percent maximum
7. Frequency	2000 cps ± 1 percent
8. Overload	140 percent of design current for 5 milliseconds.
9. Radio interference	Not to exceed specification MIL-I-6181-B
10. Operating life	One year minimum

4.0 ALTERNATOR DESIGN

A permanent magnet alternator was chosen to generate the electrical power. It is a synchronous, brushless, radial air gap design employing a nonsalient pole permanent magnet rotor for excitation. This design was chosen because of its superior electrical characteristics while operating in the environment imposed by the system. The particular advantages of this type of alternator are as follows:

- a. Absence of slip rings, brushes, and rotating windings provides excellent dependability. The need for external excitation and voltage control is also eliminated.
- b. Symmetry and simplicity of the rotor construction enhances operation at high speed, contributes to ease and reduced cost of fabrication, and simplifies the sealing of the magnet from mercury vapor corrosion.
- c. The permanent magnet alternator combines high efficiency with low weight and unit volume.

Original design objectives led to the design and fabrication of a single-phase permanent magnet alternator. The high speed, high temperatures, and extreme environmental conditions involved centered research about two major areas: (1) electrical, and (2) bore seal.

4.1 Initial Design Analysis

Certain basic assumptions, necessary before actually initiating the alternator design, were based primarily on past experience in permanent magnet alternators. The operating speed of 40,000 rpm was selected in view of the design of the combined rotating unit. A cylindrical permanent magnet rotor with 6 poles was used to obtain the desired 2000 cps frequency at this speed. A two-phase lap winding was selected so that (1) the unit could be used as a motor to initiate package start-up and (2) the unit could be reconnected externally to deliver single-phase electrical power as an alternator. The general configuration of the alternator stator and rotor are shown in Figures 2 and 3.

For motor start purposes, the alternator is operated as a synchronous motor driven by a variable frequency power supply. The power supply is set to a low frequency and input current is increased until the alternator pulls into synchronism with the input frequency. As the input frequency is increased, the alternator drives the package to design speed. The primary difficulties involved are (1) alternator demagnetization if the unit is driven out of synchronism by the turbine and (2) overspeed as a result of demagnetization. These problems required development of a tuned capacitive load contained in the power supply and connected across the alternator terminals. If the alternator is demagnetized, the tuned load will present a capacitive load to the alternator, causing a rising voltage characteristic. The residual magnetism in the rotor will be sufficient to prevent overspeed.

FIGURE 2

SNAP II ALTERNATOR COMPONENTS

Since mercury vapor is not a conductor, electrical problems were eliminated by the general configuration of the combined rotating unit which tends to prevent liquid mercury from condensing in the stator bore area. Rotor windage losses in mercury vapor at operating conditions were calculated to be 88 watts. The glass bore coating and exposed can materials have been successfully checked for mercury compatibility.

One of the most critical performance requirements of the alternator is that it be capable of operation in a nuclear environment of 1.5×10^9 fast neutrons/cm²/sec. Choice of inorganic insulation materials free from boron virtually makes the non-metallic components of the SNAP II alternator insensitive to radiation. The effect of nuclear radiation on stator laminations and on magnets is discussed in a report entitled "Magnetic Cores and Permanent Magnets in Hyper-Environments" written by D. I. Gordon of N. O. L. In this article silicon irons such as used for the alternator are listed as probably being "very good" in a combined temperature and radiation environment of 500°C and 10^{16} fast neutrons/cm²/sec. The same "very good" comment is listed also for the magnet material. The author also states that at normal temperatures, permanent magnets and silicon irons are "insensitive to nuclear radiation up to 10^{17} fast neutrons/cm²/sec." Present plans call for the testing of a stator in a radiation environment to further assure that no problem exists in this area.

4.1.1 Rotor Design

Choice of rotor material for the SNAP II alternator was based on the high energy product of the material at the operating temperature. Although magnetic strength varies with temperature, the material selected is suitable for operation up to temperatures of 500°C; the change with temperature is a reversible effect provided that the magnet is first cycled above the expected operating temperature. The expected variation in magnetic properties over the temperature range is shown in Figure 4. Design assumptions for the rotor were dictated largely by the high temperature, high speed operation, and the necessity of shielding the magnet from the mercury atmosphere. Rotor stresses encountered under actual operating conditions required the use of a high strength shrink ring on the magnet. The relatively high compressive strength of the magnet permitted the high strength shrink ring to be placed over the magnet with a heavy shrink fit. Thus the rotor is always in compression, even at operating speed and temperature. Shielding the magnet against mercury exposure was accomplished by completely encasing the magnet in the shrink ring.

4.1.1.1 Segmented Ring

A shrink ring made of alternate magnetic and non-magnetic segments is most desirable from the electrical standpoint in low-temperature or low-speed machines. This type of construction allows the magnetic sections of the ring to be placed over the magnet pole faces with the non-magnetic section

REVERSIBLE CHANGES IN MAGNET FLUX RETENTION VERSUS TEMPERATURE

FIGURE 4

between the pole faces. The magnetic section over the pole face presents a much greater permeance in the radial direction for the main working flux, and the non-magnetic section tends to limit the leakage flux between pole faces. The disadvantages of this sleeve are (1) extremely thick rings are required for high stress conditions, (2) highly stressed welds introduce reliability and mercury compatibility problems, and (3) matching expansion rates of welds and basic magnet stock is difficult.

4.1.1.2 Continuous Ring

Use of non-segmented rotor shrink rings presents different problem areas. A continuous non-magnetic ring would consume excessive magnet mmf while delivering flux through the ring radially. In addition, mercury-compatible non-magnetic materials possess thermal expansion rates so much higher than the magnet that at 700°F the ring would expand away from the magnet. Use of a ring made from a magnetic steel would solve the differential expansion problem but would cause undesirable flux leakage between adjacent poles on the magnet outside diameter.

Based on stress considerations, a decision was made to use the continuously magnetic shrink ring to assure overall system reliability. Leakage flux in the ring was kept to a minimum by (1) much greater permeance in the radial direction through the ring for the main working flux, (2) fairly high magnetic reluctance in the circumferential direction in the ring due to small area and longer leakage path in the ring, and (3) low magnetic permeability of the ring itself.

Thorough materials investigations resulted in selection of precipitation hardening steels for the ring based upon low expansion rate, mercury compatibility, low magnetic permeability, low leakage flux saturation level, high tensile strength, and excellent creep strength at elevated temperatures. The radial thickness of the shrink ring was established as a result of leakage flux considerations to obtain the required strength allowing a reasonable safety factor. To give an adequate margin of safety in the design calculations, the magnet itself was assumed to have zero tensile strength, a minimum safety factor of 2 was allowed for published data on material tensile strength at elevated temperatures, and an allowance in the calculation was made for an additional increase in shrink fit to compensate for creep. The configuration of the finished rotor assembly was such that it was supported on the shaft by end plates at each end. Clearance between the shaft and the magnet inside diameter prevented any additional stress from being introduced into the magnet material. Assumptions for material constants such as modulus of elasticity, thermal expansion rates, and Poissons ratio were taken from published literature or were determined experimentally where needed. An air gap length was chosen by allowing the maximum dimension that would not consume

excessive magnet mmf. The air gap allowed space for a stator bore seal, assembly tolerance stack-up, and running clearances.

4.1.2 Stator Design

4.1.2.1 Electrical and Mechanical Considerations

The design assumptions involved in the stator were based primarily on past experience in permanent magnet alternators. To minimize voltage regulation as a result of armature reaction and internal reactance drop, a minimum number of conductors were used which also resulted in excellent slot fill. The conductors were chosen on the basis of current density and loss considerations. The slot dimensions allowed for insulated conductors and slot insulation. The slot width and depth were selected to keep the slot reactance and harmonics low. The stator was designed to permit insertion of rigid slot insulator material. Harmonic distortion was reduced by proper selection of coil pitch, small stator slot opening, and the continuous magnetic rotor shrink ring. The choice of slots resulted in an optimum winding which also tended to reduce harmonics. A stator diameter and length were selected to give acceptable flux densities in the stator core and teeth. Iron losses were reduced by using laminations made of Armco Tran-Cor-T 0.005 inch thick electrical sheet steel.

A welded stator core was used in the original development units. Conductors are of hairpin design, allowing maximum ease of insertion and minimum end turn and connection spacing. The wound stator core is potted to eliminate the possibility of damage due to shock and vibration and to provide additional thermal transfer for the heat developed by internal losses. The entire stator assembly is then completely enclosed in a steel can, except for the stator bore. With the application of a glass coating to the stator bore, the stator assembly becomes a completely sealed unit. Electrical output leads are terminated in a steel tube integral with the stator housing. A hermetic A/N type connector can be adapted to the tube for sealing purposes.

The high temperature and mercury environment demanded a careful study and selection of both structural and insulating materials to give the required long life. Precipitation hardening steels were selected for the stator and rotor can materials because of their low thermal expansion rates, high strength, mercury corrosion resistance, and availability. The electrical conductors and output leads were selected to provide maximum conductivity and oxidation resistance at high temperatures.

Insulation materials suitable for continuous duty at temperatures of 700°F are few. Materials selected for use in early stators were chosen on the basis of mercury and temperature compatibility. The glass stator bore seal was developed after considerable experimentation using ceramics and metal tubes.

Leak checks and insulation tests were conducted on the stator after each step of fabrication to insure that no weak point in the unit developed which could be a future source of trouble.

More recent improvements in stator materials include use of ceramic slot insulators, higher temperature glass bore seals and improved potting compounds.

In developing an effective bore seal for the stator assembly, three areas were investigated: (1) metal sleeves, (2) ceramics, and (3) thin glass coatings. Extensive investigations and testing in these areas proved the glass bore seal is the most acceptable and reliable method.

4.1.2.2 Mercury Seal

Ceramic Bore Seals

The first attempt to provide a bore seal was made using a ceramic material which was suitable for operation at temperatures up to 500°C. This material was molded onto stator stacks supplied by TRW with the original intention of providing slot insulation, end lamination, and bore seal as one integral system. Because the material formed only mechanical bonds (not chemical) with metals, very little success could be achieved in forming a thin coating on the stator bore. Peeling, chipping, and cracking of the loose bore coating resulted in abandonment of this work. However, it is felt that if more time and money were available, approaches now suggested could still give an acceptable bore seal which would be mercury compatible, leak tight, and temperature resistant.

As a backup approach, considerable effort at TRW was expended toward fabrication and assembly of a thin ceramic tube which would fit into the stator bore and then be joined to the stator can at each end. Problem areas which accompanied this type of seal are the following:

1. The ceramic material was found to be porous in thin sections even though published literature gave data to the contrary. A glass glazing of the tubes failed to eliminate this problem.
2. The thin ceramic tube was too fragile in view of handling, assembly, vibration, and shock considerations.
3. Low thermal expansion of the ceramics presented differential expansion difficulties at the point where the tube was joined to the metal stator can at each end. Use of expansion-matching

nickel alloys such as Kovar proved unacceptable from the mercury corrosion standpoint.

4. Considerable scrapping of ceramic tubes was encountered during diamond grinding to thin-walled sections.

The ceramic bore tube approach was terminated when concurrent experimentation for application of a glass bore seal appeared much more promising. Investigation into new commercially available materials did not uncover any usable material which could meet the many environmental and fabrication requirements of the SNAP II alternator bore seal.

Metal Bore Seal

Another method that was pursued in developing a bore seal was the use of a thin metal tube in the alternator bore. This tube is a conductor, and therefore a voltage is generated along its length. The generated voltage produces a current that is limited only by the tube resistance; these eddy currents produce losses that can be prohibitive. Initial tests using thin metal tubes produced losses in excess of 2200 watts at design conditions. The efficiency as a result of these excessive tube losses would be about 50 percent. Based on these initial tests, a program was initiated to develop a metal bore seal of high-resistivity metal. Since the power loss is inversely proportional to the resistance, metal tubes with special configurations would result in decreased losses, due to increased length or resistance.

Considerable progress was made in butt welding thin metal sheet steels into tubes. These tubes were then formed to the correct configurations. Initial attempts were discouraging due to the lack of availability of high resistivity metals which could be formed and be impervious to mercury at elevated temperatures.

In addition, several attempts were made to apply a metal braze to the stator bore. These methods failed primarily because of the porous nature of the brazing materials and the high temperatures necessary in the brazing process. Applications of braze at 2000°F resulted in fairly deep penetration of the laminated stator stack, considerable distortion of the stack, and sintering of laminations into one solid mass.

Glass Bore Seal

Initial attempts to produce a glass seal in the stator bore were discouraging. Cracks in the glass coating appeared on the surface of the laminated stator stack and at the junction of the stator housing and stator stack. This effect

was thought to be caused by the difference in linear expansion between the stack and glass coating. However, later investigation indicated that the welded stack also distorted and introduced stresses in the glass bore.

The problem of sealing the stator bore of the alternator has been greatly reduced by modifying the stator construction. The stator assembly was designed so that the stack would be held in compression during every phase of operation. This was accomplished by first glass-bonding the laminations together in the housing with end plates at each end. The inside diameter of the stack was then compressed axially with a load great enough to prevent creation of tensile stresses in the bore seal by thermal expansion and distortion. The inside and outside diameters of the end caps were then welded to the end plates and stator housing respectively. This assembly technique allowed the end caps to function as a spring to keep the stator bore in compression. The glass coating was applied and fired on the stator bore. As the glass cooled from the firing temperature, a compressive stress was set up in the bore seal due to the difference in expansion between the glass and metal and this stress remained during all subsequent operations.

Recent tests have shown that the use of glass in the stator construction has resulted in reliable stator bore seals which meet the required leakage requirements under all environmental conditions. Figure 5 shows the alternator with the glass bore seal.

4.2 Development Design Approach

Alternator design improvements are continuing in an attempt to achieve optimum alternator performance reliability, and adaptability to the overall SNAP II system. Extensive refinements in state of the art of permanent magnet machine design, fabrication, and application techniques by TRW are being pursued.

4.2.1 Operation with Series Capacitors

Early in the SNAP II program, studies were made to find methods of controlling overload and short circuit currents applied to the alternator. Several complicated circuits were suggested for external control, but reliability and advantages of adding additional electronic control components were questionable. The most important consideration in controlling excessive alternator currents is that the control be capable of acting in the first half cycle of the voltage or current waveform, since demagnetization of the permanent magnet rotor occurs instantaneously when a specific number of armature ampere turns is exceeded. Thus relatively slow-acting relays, circuit breakers, fuses, and mechanical devices in general are automatically eliminated from consideration.

It is known that demagnetization of a permanent magnet alternator is a function, among other things, of both armature current magnitude and power factor. Use of series capacitors is immediately suggested as a means of power factor correction of lagging power factor load currents. In addition, use of series capacitors would block the direct current component of short circuit current and reduce demagnetization effects. By proper choice of series capacitor values, a short circuit stable alternator with improved overload and voltage regulation characteristics can be achieved.

The SNAP II permanent magnet alternator was experimentally evaluated with several possible capacitor values until a compromise was reached between short circuit stability and voltage regulation. Since the specification calls for load fluctuations between 0.8 and 1.0 pf, a compromising capacitor value had to be chosen which would power factor correct both extremes of load power factor. If load power factor changes were reduced or eliminated, a capacitor could be adopted which would give practically straight line voltage characteristics under real power changes.

In conclusion, use of series capacitors provides short circuit stability with simple control means, improves alternator overload capabilities and voltage regulation characteristics and requires no alternator design modifications. The improved performance characteristics are included in Section 5.0.

4.2.2 Electromagnetic Excitation

The possibility of short circuiting the permanent magnet alternator inadvertently and thus reducing its power-delivering capability either during test or due to a component failure in the load system has resulted in an investigation aimed at developing a short circuit stable alternator. The two methods under consideration are (1) operation of the present alternator with series capacitors to reduce the demagnetizing current, as outlined in the preceding section and, (2) the design of an alternator possessing inherent short circuit stability which would compare performance-wise with the permanent magnet alternator. Operation of the permanent magnet alternator with series capacitors has resulted in short circuit stability as pointed out in the performance section of this report, but this method has the disadvantage of requiring a large capacitor package external to the alternator.

The BEEM type alternator is a new concept. It employs a rotor construction which can withstand high-speed, high-temperature operation extremely well. The BEEM alternator is a "Brushless Electromagnetically Excited Machine." Excitation is provided by a direct current coil mounted around the stator frame. The flux generated in the excitation coil is transferred to the rotor through the stator housing and then to the stator. The BEEM alternator is ideally suited for operation in a mercury atmosphere due to the absence of windings on the rotor. The absence of permanent magnets as the main flux source also results in short circuit stability.

ALTERNATOR STATOR WITH GLASS BORE SEAL

Table 1 shows the advantages and disadvantages of this type alternator compared with the present permanent magnet alternator.

TABLE 1

COMPARISON BETWEEN PERMANENT MAGNET AND BEEM ALTERNATOR

	Permanent Magnet Alternator (Two-Phase)		Electromagnetic BEEM Alternator*
	Without Capacitors	With Capacitors	
Regulation	$\pm 3.41\%$	$\pm 5\%$	Inherently poor; requires external voltage regulator
Efficiency	89%	88%	Lower efficiency due to power requirement of excitation coil
Harmonics	2.5%	4.8%	Approximately 5%
Overload	175% of rated current	163% of rated current	Overload depends only on excitation available
Short circuit stability	No	Yes	Yes
Weight	9.4 lb	9.4 lb + approx. 12 lbs for capacitors**	Approx. 13 lb + 4 lbs for voltage regulator

*Based on preliminary calculations

** Room Temperature Operation

4.2.3 Polyphase Operation

The most outstanding design improvement has been the change from single to polyphase operation. The initial alternators were wound as two-phase units and utilized as single-phase units. Conversion to two-phase operation required but a change in load systems and instrumentation and an external reconnection of the alternator leads. The basic analytical comparison of single and two-phase operation is presented in the appendix in concise mathematical terminology.

The primary advantages of polyphase operation and the reasons for this design change are as follows:

1. The double frequency component of armature reaction inherent in single-phase machines produces air gap flux pulsations which establish large eddy current losses in the rotor shrink ring. Balanced polyphase operation results in armature reaction which distorts and reduces the effective main field flux without introducing air gap flux pulsations.
2. Polyphase operation improves voltage regulation since the total armature reaction for a given KVA output is only half under two-phase operation compared to single phase. In the present SNAP II alternator, armature reaction is much more important in determining voltage drop than winding impedance drop.
3. Harmonic distortion is greatly reduced by polyphase operation. The double frequency pulsations of air gap flux occurring under single-phase loading only produce a pronounced third harmonic voltage in the armature.
4. Alternator efficiency under polyphase operation is remarkably improved to such an extent that alternator internal heating and required turbine power are lowered considerably.
5. Because of reduced armature reaction under polyphase loading the alternator overload capability is increased far above 140 percent specification requirements. Single-phase operation at 0.8 pf loading showed less than 110 percent overload possibilities.

TABLE 2

ELECTRICAL PERFORMANCE COMPARISON

	Number of Phases		
	Single-Phase	Two-Phase	Three-Phase
Efficiency (3000 watts total at 0.8 pf)	73%	85%	87% (est)
Harmonic Distortion (3000 watts at 0.8 pf)	11.5%	5.25%	5% (est)
Voltage Regulation (300 watts - from 1.0 to 0.8 pf)	±7.0%	±6%	±5% (est)

It should be noted that the present SNAP II alternator was evaluated as a two-phase machine because a mere external connection was necessary to obtain this evaluation. However, the real and intrinsic qualities of polyphase operation can be realized only in three-phase operation. Some of the more general advantages of the three-phase machines are that they are more adaptable for rectification networks, motor drives and distribution of single-phase loads between several phases. Table 2 is an electrical performance comparison of single-phase, two-phase and three-phase operation.

5.0 ALTERNATOR PERFORMANCE RESULTS

This section covers alternator performance and design evaluation from the beginning of the SNAP II program. The discussion is divided into the four major operation areas: single phase, single phase with capacitors, two-phase, and two-phase with capacitors. The electrical discussion covers the various electrical parameters and is supported by data and graphs showing variations or off-design point conditions.

The initial alternator performance was affected largely by several compromises that were required to meet the design objectives. These included the following compromises:

1. Closed-slot stator
2. Single-phase operation
3. Package size limitations

The closed-slot stator was required to simplify the bore seal problem. As a result of the closed slot, the stator reactance was high and resulted in poorer voltage regulation and higher harmonics. The single-phase design requirement introduced high losses in the rotor pole faces and thereby decreased the alternator efficiency. The single-phase operation also limited the overload capabilities of the unit because the output for a given size is lower for a single-phase unit than for a polyphase unit. The package size limited the rotor length to maximize the CRU shaft critical speed, and also limited the rotor diameter to prevent excessive stresses at the high rotational speed. Several problems were found to exist after initial performance tests were conducted at 650°F. While these problems did not seriously affect the overall performance of the machine, they did require solution to meet the original design objectives. The basic deficiencies were as follows:

1. Voltage regulation was 12.5 percent
2. Efficiency was 76 percent
3. Overload capability was not adequate.

Recent test results have indicated that motor startup may be feasible. The unit has been successfully driven to half design speed and slightly above this point the power supply output becomes distorted, causing the alternator to go out of synchronism. At the present time this is the major difficulty in the motor start effort and steps are being taken to correct the power supply output.

The total weight of the permanent magnet alternator is 9.4 pounds. Seven pounds is in the stator assembly with only 2.4 pounds comprising the rotor. Because minimum weight was one of the original design objectives, further weight reduction possibilities are limited to redesign using better magnetic materials in the stator and rotor.

The alternator efficiency information included in this report is a net efficiency which results from experimental dynamometer testing. To obtain the net alternator efficiency value, the dynamometer ball bearing, coupling, and windage losses were determined using a dummy alternator rotor and then subtracted from the total indicated drive motor torque values (converted to watts) taken during the various alternator dynamometer runs. The subtraction of dynamometer losses as a lump also inherently included alternator rotor air windage losses. In order to charge mercury vapor windage losses to the alternator net efficiency, calculated values of mercury vapor windage losses were then added to indicate drive motor torque values (converted to watts) during alternator runs. In summary, net alternator efficiency is defined as follows:

$$\text{Net efficiency} = \frac{\text{Alternator electrical output, watts}}{\text{Total drive motor watts-dynamometer losses + calculated mercury vapor windage loss}}$$

The harmonic distortion data discussed in earlier paragraphs was measured by a total distortion analyzer sensitive to the frequencies up to 100 kc. Individual harmonics were sometimes checked using a wave analyzer, but the instruments available would measure frequencies up to 16 kc or only up to the eighth harmonic of the alternator. As a double check on values obtained from the distortion analyzer, individual harmonics were summed up using the square root of the sum of the squares method. Close agreement between distortion analyzer values and summated individual harmonics was realized. Display of the waveform on an oscilloscope also served as a rough check on waveform distortion values measured.

The specification for alternator voltage regulation of 110 volts $\pm$ 5 percent is interpreted to mean that a voltage span between 104.5 and 115.5 volts is permissible between power factor ranges of 0.8 to 1.0 under constant 3000 watts load at design speed and temperature. Voltage regulation data presented in percentages in this report were obtained from experimentally derived curves using the formula:

$$\text{Voltage Regulation} = \pm \frac{\text{Full load volts} - 110 \text{ volts}}{110 \text{ volts}} \times 100$$

in percent

5.1 Single-Phase Performance Without Capacitors

The original design called for operation of the alternator as a single-phase unit, entailing an open-slot stator construction. The initial test results are based on the diagram shown in Figure 6 for both open and closed-slot stator configurations.

Single-phase performance is shown graphically in Figures 7 through 10 for both open and closed-slot stators. Performance values at design point are tabulated in Table 3 for ease of comparison. These performance values indicate that improvement is needed to meet the original design objectives. Variation in performance between open and closed-slot stators shows approximately the same voltage regulation and

SINGLE-PHASE OPERATION

FIGURE 6

TABLE 3

SINGLE-PHASE PERFORMANCE VALUES AT DESIGN POINT

Parameter	Spec.	Without Capacitors		With Capacitors	
		Open Slot	Closed Slot	Open Slot	Closed Slot
Regulation	$\pm 5\%$	$\pm 12.5\%$	$\pm 12.4\%$	$\pm 5.87\%$	$\pm 7.0\%$
Efficiency 0.8 p.f.	80%	73%	75%	70%	73%
1.0 p.f.	80%	80%	81%	74%	77%
Harmonics	7%	4.3%	11.3%	4.8%	11.5%
Overload	140%	120%	111%	163%	160%
Short Circuit Stability	No	No	No	Yes	Yes

VOLTAGE REGULATION VS TOTAL WATTS OUTPUT
SINGLE PHASE - OPEN SLOT - NO CAPACITORS
TEMPERATURE 650°F

FIGURE 7

EFFICIENCY CHARACTERISTICS
SINGLE PHASE - OPEN SLOT - NO CAPACITORS
TEMPERATURE 650°F

FIGURE 8

VOLTAGE REGULATION VS WATTS OUTPUT
SINGLE PHASE - CLOSED SLOT
TEMPERATURE 650°F

FIGURE 9

EFFICIENCY CHARACTERISTICS
SINGLE PHASE - CLOSED SLOT
TEMPERATURE 650°F

FIGURE 10

efficiency. However, harmonics show a marked increase. This results from the presence of the leakage flux in the slot bridge. These performance data, while indicating that the original units did not meet the original design objectives, did bear out the feasibility of the general alternator configuration and construction.

5.2 Single-Phase Performance With Capacitors

Because an alternator short circuit caused a failure during package testing, an investigation was initiated into methods of making the alternator short circuit stable. The purpose of this investigation was twofold: (1) to guarantee that any alternator fault would not damage the package due to overspeed and (2) to improve the overload capabilities of the alternator. The results of this study indicate two methods can solve these problems:

1. Inclusion of series capacitors between the alternator and load.
2. Use of an electromagnetically excited machine. (This type of machine has been discussed in Section 4.2.2.)

When inserted between the alternator and load, as shown in Figure 11, capacitors prevent the flow of excessive demagnetizing current. The capacitors raise the effective power factor on the alternator from near zero lagging where the current is all demagnetizing to near unity where the demagnetizing effect is negligible. Use of capacitors results in improved voltage regulation, overload, and short circuit stability. Performance is shown graphically in Figures 12 through 16.

SINGLE-PHASE OPERATION WITH CAPACITORS

FIGURE 11

VOLTAGE REGULATION VS TOTAL WATTS OUTPUT
SINGLE PHASE - OPEN SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 12

EFFICIENCY CHARACTERISTICS
SINGLE PHASE - OPEN SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 13

VOLTAGE REGULATION VS WATTS OUTPUT
SINGLE PHASE - CLOSED SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 14

EFFICIENCY CHARACTERISTICS
SINGLE PHASE - CLOSED SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 15

EFFICIENCY CHARACTERISTICS
SINGLE PHASE - CLOSED SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 16

5.3 Two-Phase Operation Without Capacitors

As a result of the comparative analysis between single and two-phase operation as indicated in Section 4.2.3, the alternator was evaluated as a two-phase unit. The results are improved regulation, efficiency and harmonics. The two-phase performance is covered in the following section.

Since the original SNAP II unit was actually wound two-phase for motor startup and the flux densities in the stator were conservatively designed, operation of the alternator on either single phase with a nominal 110 volts line-to-line voltage or operation on two-phase with nominal 110 volts line-to-neutral was conveniently achieved with identical alternator constructions. The diagram in Figure 17 shows the two-phase configuration.

FIGURE 17

Accurate performance comparison between open-slot stators and closed-slot stators, use of series capacitors, and single-phase versus polyphase operation is hindered by the fact that additional variables in the form of construction and material changes were made in these test units. This variation shows up considerably in later units where stack lengths have been shortened slightly and improvements have been made in insulating the laminations. Figures 18 through 21 show the performance characteristics of stator utilizing the latest design improvements. The data in Figures 20 and 21 reveal performance far exceeding the original design objectives when the unit is operated as a two-phase machine.

VOLTAGE REGULATION VS TOTAL WATTS OUTPUT
TWO PHASE - OPEN SLOT - NO CAPACITORS
TEMPERATURE 650°F

FIGURE 18

EFFICIENCY CHARACTERISTICS
TWO PHASE - OPEN SLOT - NO CAPACITORS
TEMPERATURE 650°F

FIGURE 19

FIGURE 20

EFFICIENCY CHARACTERISTICS
TWO PHASE - CLOSED SLOT
TEMPERATURE 650°F

FIGURE 21

EFFICIENCY CHARACTERISTICS
TWO PHASE - OPEN SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 22

VOLTAGE REGULATION VS TOTAL WATTS OUTPUT
TWO PHASE - OPEN SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 23

VOLTAGE REGULATION VS WATTS OUTPUT
TWO PHASE - CLOSED SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 24

VOLTAGE REGULATION VS WATTS OUTPUT
TWO PHASE - CLOSED SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 25

EFFICIENCY CHARACTERISTICS
TWO PHASE - CLOSED SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 26

EFFICIENCY CHARACTERISTICS
TWO PHASE - CLOSED SLOT - SERIES CAPACITORS
TEMPERATURE 650°F

FIGURE 27

TABLE 4

TWO-PHASE PERFORMANCE VALUES AT DESIGN POINT

Parameter	Spec.	Without Capacitors		With Capacitors	
		Open Slot	Closed Slot	Open Slot	Closed Slot
Regulation	$\pm 5\%$	$\pm 4.5\%$	$\pm 3.41\%$	$\pm 4.1\%$	$\pm 5\%$
Efficiency 0.8 p.f.	80%	79.2%	88.5%	87.5%	88%
1.0 p.f.	80%	81.0%	90%	88.8%	88%
Harmonics	7%	0.40%	2.5%	0.5%	4.8%
Overload	140%	120%	175%	163%	163%
Short Circuit Stability	No	No	No	Yes	Yes

5.4 Two-Phase Operation with Capacitors

Alternator performance with capacitors required for short circuit stability is shown graphically in Figures 22 through 27 and is tabulated in Table 4. Figure 28 shows the configuration used in testing the alternator as a two-phase, short circuit stable machine.

TWO-PHASE OPERATION WITH CAPACITORS

FIGURE 28

The addition of capacitors in the two-phase alternator has little effect on voltage regulation and efficiency, but it does result in a slight increase in harmonics. The overload capability is greatly increased, and the unit is short circuit stable.

A closed-slot alternator is currently under construction which employs a smaller slot bridge. The reduction in slot bridge width is expected to improve efficiency by reducing iron losses in the stator and also to effect a reduction in harmonics.

6.0 TEST APPARATUS

This section describes the test apparatus used in evaluation of alternator components. Considerable experience was obtained in this area during the SNAP I program. Included in this section are the major improvements in SNAP II facilities. The test facilities are illustrated in Figure 29 and by a closeup view of the alternator drive stand (Figure 30).

6.1 Dynamometer

A motoring type dynamometer capable of driving the alternator at 40,000 rpm was selected for the SNAP II program. The high frequency induction motor is powered by a variable speed power supply which permits operation at off-design point speeds. Torque measurements are made as follows: A torque arm attached rigidly to the drive motor housing actuates a linear variable differential transducer (LVDT). The LVDT consists of a movable core mounted on cantilevered springs. The LVDT output signal is fed to an amplifier which supplies an output signal to a direct current voltmeter calibrated directly in ounce-inches.

Initial tests using a high-speed induction motor employed in the SNAP I program resulted in poor repeatability, due to torsional vibration caused by the extreme sensitivity of the drive motor to frequency modulation in the power supply. These vibrations caused oscillations in the torque measuring system which made reading difficult. To improve the overall system reliability, the original motor was replaced with a high-speed grinder motor. The grinder motor is less sensitive to frequency modulation; as a result, the amplitude of the torsional vibrations does not cause appreciable readout error.

Also improved was the dynamometer motor life. Originally motor bearing life was approximately 8 to 10 hours, at which time the entire test stand had to be dismantled for bearing replacement. The grinder motor has reduced the shutdown time for bearing replacement by a factor of 15 to 1. Further improvements were made by installing verniers on the transducer amplifier, resulting in improved calibration and linearity.

6.2 Instrumentation

Instrumentation was selected in accordance with the original design objectives. The reliability and accuracy of the instrumentation of the component test facilities is such that design variations and performance may be accurately measured. Table 5 lists various instrumentation used and the accuracy of each. The instrumentation is calibrated periodically using Thompson Ramo Wooldridge facilities to assure reliable performance data.

ALTERNATOR PERFORMANCE TEST FACILITIES

40

FIGURE 29

TAPCO GROUP

Thompson Ramo Wooldridge Inc.

ALTERNATOR PERFORMANCE DRIVE STAND

TABLE 5
TEST INSTRUMENTATION

Item	Range	Accuracy	Model	Vendor
Voltmeter	0-150, 0-300 volts	$\pm 1/4\%$	Dy-Voca-25	Sensitive Research
Ammeters	0-5 Amps	$\pm 1/4\%$	Dew	"
Wattmeters	0-750 watts	$\pm 1/4\%$	BWEW	"
Current transformer	100-50-20-10 amp primary	-----	461-2	Weston
Temp. indicator	0-1200°F	$\pm 1/4\%$	400	Wheelco
Counter	0-100 kc	$\pm 1\text{cps}$	7150	Berkeley
Differential amplifier	$\pm 500\text{ mv}$ output	-----	401	Daytronic
Distortion analyzer	0-100 kc	$\pm 3\%$	33013	Hewlett Packard

6.3 Load Banks

The alternator load system used in component testing is an Avtron model T167 load bank. The use of this load bank permits application of simulated loads from 0 through 5000 watts at power factors ranging from 1.0 to 0.70 lagging. The load bank has been modified so that balanced loading can be applied to a two-phase alternator. An order has been placed with Avtron Manufacturing Co. for a three-phase load bank for testing a three-phase version of the SNAP II alternator.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the SNAP II alternator development program.

1. A permanent magnet alternator can be constructed to meet electrical, mechanical, and environmental specifications for the SNAP II alternator.
2. The stator bore seal was the most difficult problem area. Both mechanical design and material considerations were important in achieving an acceptable seal.
3. Alternator short circuit stability can be obtained through use of series capacitors with the permanent magnet alternator.
4. Electrical performance of the alternator was accurately predictable by analytical design.
5. A closed-slot stator was acceptable from the electrical performance standpoint. The present glass bore seal was aided measurably through use of a laminated smooth bore construction not interrupted by slot openings.

Some general recommendations for improvement of the SNAP II alternator are presented in the following paragraphs.

The many alternator performance advantages experimentally determined from two-phase operation indicate that the specifications for the SNAP II alternator should be modified from single-phase to polyphase electrical output. No basic change in alternator configuration, dimensions, insulation, conductor size or turns would be required. In addition, based on preliminary information, it is suggested that a three-phase version of the SNAP II alternator be developed. Conversion to three phase will require design calculations and internal modifications. In all designs based on mathematical calculations, it is desirable to evaluate the design by experimentation. In the case of the present SNAP II alternator design, certain areas such as leakage reactance and armature reactance require additional empirical constants to support various design calculations. A more detailed experimental analysis of the alternator is planned in the near future.

Although the presently developed glass-coated stator has given a successful seal, a backup or alternate seal system would be preferable in case future environmental stator testing reveals mechanical weaknesses or shortcomings. Perhaps a system could be devised so that stator conductors alone would be protected from mercury, allowing use of a smaller air gap. It has already been determined that the stator lamination material is entirely compatible with mercury.

A continuous search for new permanent magnet materials as they become commercially available would do much for improving alternator overall mechanical and electrical performance. A new magnet material having very high tensile strength and improved magnetic qualities would permit removal of the rotor shrink ring and make possible more effective use of available magnet flux for improving such electrical characteristics as voltage regulation, overload capability, and efficiency.

Stator insulation, potting compounds, and fabrication techniques require further improvement. The winding is now considered to be well insulated within the slot, but the close proximity between adjacent end turns demands extra safety precautions to insure freedom from shorts during temperature cycling, shock, vibration, and acceleration. Present usage of glass sleeving and natural mica on the end turns leaves room for improvement through selection of materials possessing greater mechanical strength at elevated temperatures. The potting compound now incorporated into the end turns also has relatively little mechanical strength and is not readily applied in the tight spaces between adjacent end turns, jumper connections, and lead connections. A potting compound which is very fluid during application but not porous and brittle after curing is the ideal material. The fabrication procedure now used requires that the glass bore seal be applied as the last operation. Since this means thermal cycling the completely wound stator to as high as 1100°F, the glass sleeving over the lead wires and end turns deteriorates somewhat. Again improved insulation and fabrication methods should be more thoroughly investigated.

Evidence from recent tests shows that the present permanent magnet alternator will meet all the specifications listed in Section 3.0 when operated as two phase. The permanent magnet unit when operated with series capacitors will also give the added performance advantage of being short circuit stable. However, capacitor requirements are of large microfarad value (30 to 40 mfd) and if these capacitors must be adaptable for elevated temperature applications, a development effort would be required. An alternate method of obtaining a short circuit stable machine would be adoption of a Brushless Electromagnetically Excited Machine (BEEM alternator) now in the preliminary design stage. If a definite need is established for short circuit stability, the BEEM unit would be more advantageous than the permanent magnet unit with series capacitors. As another approach, additional studies should be made on the permanent magnet unit for increasing overload in order to approach short circuit stability through rotor construction and/or stator design modifications.

As the alternator must operate in a radiation environment, steps should be taken to determine the long-term effects of radiation on alternator materials and performance. Present plans call for testing a stator statically in a radiation atmosphere, but the only tests possible statically are (1) megger tests to check insulation to ground, (2) winding resistance measurements, and (3) material information and assumptions based on the data obtained if the unit is disassembled. It is suggested that consideration be given to performance testing this particular stator to completely determine the effects of radiation and to corroborate published data cited in the reports stating that most inorganic materials are suited to radiation environments.

APPENDIX

COMPARATIVE ANALYSIS OF SINGLE-PHASE AND TWO-PHASE OPERATION

SINGLE-PHASE OPERATION

To simplify mathematical analysis of single-phase armature reaction, it is assumed that the flux set up in the stator is distributed sinusoidally in space at any given time, and also that at any given point it varies sinusoidally in time, as represented in Figure A-1. Actually, the flux will vary from the sine curve due to the winding distribution and the various flux paths.

FIGURE A-1

With the above assumption, the maximum value of the flux density at point $\frac{\pi}{2}$ is B_m and at point 2ϕ is B_A where

$$B_A = B_m \sin \phi \quad (1)$$

and ϕ is measured as shown. Also at point ϕ the flux density varies sinusoidally with time.

$$B = B_A \cos wt \quad (2)$$

or more generally,

$$B = B_A \sin (wt - \alpha) \quad (3)$$

combining equations (1) and (2) we have,

$$B = B_m \sin \phi \cos wt \quad (4)$$

This equation gives the value of the flux density at any time and any place along the air gap. Using a well-known trigonometric formula, equation (4) can be rewritten as,

$$B = \frac{B_m}{2} \sin (\phi - \omega t) + \frac{B_m}{2} \sin (\phi + \omega t) \quad (5)$$

To interpret this equation, consider the first part of the expression

$$B^1 = \frac{B_m}{2} \sin (\phi - \omega t) \quad (6)$$

For a point moving along the air gap at a speed such that ϕ increases as fast as ωt , the quantity $(\phi - \omega t)$ is a constant and as such B^1 is also a constant. For such a point, B^1 represents a rotating magnetic field with sinusoidal distribution, which rotates synchronously with the field poles.

For another point rotating backward at such a rate that ϕ decreases as fast as ωt increases, we have

$$B^{11} = \frac{B_m}{2} \sin (\phi + \omega t) \quad (7)$$

which is also a constant representing the second part of the expression in Equation (5), and hence there is also a backwardly rotating field. Thus, Equation (5) represents two equal fields with sinusoidal distribution rotating in opposite directions, and these two fields are equivalent to one stationary alternating field having double the maximum value of either of the rotating fields. The component of single-phase armature reaction which rotates synchronously with respect to the field poles distorts the field (except at zero power factor). The other component which rotates backwards at twice synchronous speed with respect to the field poles sets up in the poles double frequency or second harmonic flux variations. Double frequency flux pulsations through electrically conducting materials (in this case rotor shrink ring and pole face) theoretically establish the necessary conditions for inducing voltages which result in eddy current losses.

This double frequency component of the field flux, in combination with the rotation of the field poles, also induces a third harmonic voltage in the armature turns which appears at the alternator terminals. The third harmonic cannot be eliminated by use of fractional pitch armature coils. A simple mathematic treatment will explain why a third harmonic is generated by double frequency flux pulsation in combination with field pole rotation.

The voltage generated in any armature turn is,

$$e = K \Phi \sin \omega t \quad (8)$$

where K is a constant, Φ is the pole flux. Ordinarily, Φ is constant for any given excitation and load. If it varies in time, it must be inserted in the formula for the voltage

as a function of time. Assume that the double frequency flux variation due to armature reaction is sinusoidal.

Then if $\Phi = \Phi_m \sin 2 \omega t$ is the value of flux at each instant. The voltage induced by it in the armature is

$$\begin{aligned} e &= K \Phi_m \sin 2 \omega t \sin \omega t \\ &= \frac{1}{2} K \Phi_m (\cos \omega t - \cos 3 \omega t) \end{aligned} \quad (9)$$

Inspection of the terms of Equation (9) above shows that the double frequency component of the flux therefore produces voltages of both fundamental and triple frequency in each armature turn.

The analysis of single-phase armature can be applied directly to the Snap II alternator. Excessive rotor shrink ring losses observed during experimental testing of the alternator under single-phase loads confirms the above analysis. A large third harmonic was also measured during alternator performance testing under single-phase loading.

TWO-PHASE OPERATION

For a two-phase machine there are two equal windings 90° apart in space, carrying equal currents 90° apart in time. The flux due to one winding is as before,

$$B_A = \frac{B_m}{2} \sin (\phi - \omega t) + \frac{B_m}{2} \sin (\phi + \omega t) \quad (10)$$

The field produced by the second phase is 90° from this in both time and space and may be represented by a similar equation in which ϕ and ωt are increased or decreased by 90° . Increasing both by 90° gives,

$$\begin{aligned} B_B &= \frac{B_m}{2} \sin \left(\phi + \frac{\pi}{2} - \omega t - \frac{\pi}{2} \right) + \frac{B_m}{2} \sin \left(\phi + \frac{\pi}{2} + \omega t + \frac{\pi}{2} \right) \\ &= \frac{B_m}{2} \sin (\phi - \omega t) - \frac{B_m}{2} \sin (\phi + \omega t) \end{aligned} \quad (11)$$

Adding Equations (10) and (11) gives the flux density produced by both windings,

$$B = B_m \sin (\phi - \omega t) \quad (12)$$

This is the equation of a single rotating magnetic field and it is noted that B_m produced

by the two phases is the same as that which would be produced by either phase alone. Hence, under two-phase operation a rotating field is produced which rotates synchronously with the field poles and distorts the main field flux only. No backward rotating component nor double frequency flux pulsation is produced by polyphase armature reaction under balanced loading. Thus, rotor pole face losses due to armature reaction effects are absent and no third harmonic is induced in the armature winding. The total armature reaction produced under balanced two-phase loading is only one-half that produced by single-phase operation (for the same generator KVA output) since current per phase is half on two-phase compared to single phase.

Actual performance testing of the SNAP II alternator with two-phase loads revealed a striking reduction in rotor shrink ring losses as evidenced in the efficiency comparison discussed earlier in this report. The third harmonic was almost negligible under test with two-phase load. The much improved alternator voltage regulation for two-phase versus single-phase operation again confirms the above mathematical analysis, showing armature reaction is one-half that of single-phase operation.

In conclusion, it has been shown analytically that important alternator performance advantages can be realized under two-phase operation. Actual experimental test data included in Section 5.0 of this report dramatically support mathematical reasoning discussed above.

DISTRIBUTION LIST

Advanced Research Projects Agency

Advanced Research Projects Agency
The Pentagon, 3D154
Washington 25, D.C.
Attn: Fred A. Koether

Aerojet General, Azusa

Don Forrest
P.O. Box 573
Azusa, California
Attn: Evelyn Henry/AT(10-1)-880/

Air Technical Intelligence Center

Commander
Air Technical Intelligence Center
Wright-Patterson Air Force Base, Ohio
Attn: H. Holzbauer, AFCIN-4Bla

Air Force Ballistic Missile Division, Inglewood

Air Force Ballistic Missile Division
Hq. Air Research and Development Command
Air Force Unit Post Office
Los Angeles 45, California
Attn: Lt. Col. Melvin M. Burnett, WDAT
(Inside Envelope) For: Major George Austin

Air Force Special Weapons Center

Commander
Air Force Special Weapons Center
Technical Information and Intelligence Office
Kirtland Air Force Base, New Mexico
Attn: Delmer J. Trester

Air University Library

Director
Air University Library
Maxwell Air Force Base, Alabama
Attn: Major Lee C. Free

AiResearch Manufacturing Co. of Arizona

AiResearch Manufacturing Co. of Arizona
P.O. Box 1927
Phoenix, Arizona
Attn: M.H. Currey

Argonne National Laboratory

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois
Attn: Dr. Hoylande D. Young

Army Ballistic Missile Agency

Commanding General
Army Ballistic Missile Agency
Redstone Arsenal, Alabama
Attn: ORDAB-HSI

Atomic Energy Commission, Washington

U.S. Atomic Energy Commission
Technical Library
Washington 25, D.C.
(inside envelope) For: Lt. Col. G.M. Anderson, DRD
Capt. T.L. Jackson, DRD
Lt. Col. C.M. Barnes
R.G. Oehl, DRD
Technical Library

Atomic Energy Commission, California Patent Group

U.S. Atomic Energy Commission
San Francisco Operations Office
2111 Bancroft Way
Berkeley 4, California
Attn: William E. Elliott, Chief
California Patent Group

Bureau of Yards and Docks

Bureau of Yards and Docks (Code 440)
Department of the Navy
Washington 25, D.C.
Attn: Security Officer

Bureau of Naval Weapons

Bureau of Naval Weapons
Department of the Navy
Washington 25, D.C.
Attn: Code RR-12 and RA-8

Bureau of Ships

Bureau of Ships
Code 1500
Navy Department
Washington 25, D.C.
Attn: Melvin L. Ball

Jet Propulsion Laboratory

Jet Propulsion Laboratory
California Insitutute of Technology
Pasadena 3, California
Attn: J.E. Newlan, Supervisor
Technical Reports Dept.

Lawrence Radiation Laboratory

University of California
Lawrence Radiation Laboratory
Technical Information Division
P.O. Box 808
Livermore, California
Attn: Clovis G. Craig
(inside envelope) For: T.C. Merkle

Lockheed MSD, Sunnyvale

Lockheed Missiles and Space Division
3251 Hanover Street
Palo Alto, California
Attn: Miss Kathleen P. Kolan

Chicago Operations Office

Mr. Kenneth A. Dunbar, Manager
Chicago Operations Office
U.S. Atomic Energy Commission
9800 South Case Avenue
Argonne, Illinois
(Inside envelope) For: T.A. Nemsek

Chief of Naval Operations

Office of the Chief of Naval Operations (OP-75)
Department of the Navy
Washington 25, D.C.

Continental Army, Command

Office of Special Weapons Developments
U.S. Continental Army Command
Fort Bliss, Texas
Attn: Chester I. Peterson, Capt. AGC

Department of the Army

The Atomic Division
Office of the Chief of Research and Development
Department of the Army
The Pentagon
Washington 25, D.C.

Diamond Ordnance Fuse Laboratories

Commanding Officer
Diamond Ordnance Fuse Laboratories
Washington 25, D.C.
Attn: ORDTL 06.33, Mrs. Elizabeth W. Channel

Institute for Cooperative Research

The Institute for Cooperative Research
University of Pennsylvania
3400 Walnut Street
Philadelphia 4, Pennsylvania
Attn: Dr. Donald S. Murray

Security Officer

TO BE OPENED BY ADDRESSEE ONLY

Los Alamos Scientific Laboratory

Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico
Attn: Report Librarian
(Inside envelope) For: Dr. George M. Grover

National Aeronautics and Space Administration, Ames

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California
Attn: Dr. S.J. Defrance, Director

National Aeronautics and Space Administration, Cleveland

Lewis Research Center
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland 35, Ohio
Attn: George Mandel

National Aeronautics and Space Administration, Langley

Langley Research Center
National Aeronautics and Space Administration
Langley Field
Hampton, Virginia
Attn: Dr. R.J.E. Reid, Director

National Aeronautics and Space Administration, Washington

National Aeronautics and Space Administration
1512 H Street, N.W.
Washington 25, D.C.
Attn: Dr. Addison M. Rothrock

Naval Ordnance Laboratory

Commander
U.S. Naval Ordnance Laboratory
White Oak
Silver Spring, Maryland
Attn: Eva Liberman

Naval Research Laboratory

Director
Naval Research Laboratory, Code 1572
Washington 25, D.C.
Attn: Mrs. Katherine H. Cass

Oak Ridge National Laboratory

Union Carbide Nuclear Company
X-10 Laboratory Records Department
P.O. Box X
Oak Ridge, Tennessee
(inside envelope) For: Eugene Lamb

Office of Naval Research

Office of Naval Research
Department of the Navy, Code 735
Washington 25, D.C.
Attn: E.E. Sullivan
(inside envelope) For: Code 429

Project RAND

Director, USAF Project RAND
Via: Air Force Liaison Office
The RAND Corporation
1700 Main Street
Santa Monica, California
Attn: F.R. Collbohn
(inside envelope) For: Dr. John Nuth

Rome Air Development Center

Commander, Rome Air Development Center
Griffiss Air Force Base, New York
Attn: RCSG, J.L. Briggs

School of Aviation Medicine

School of Aviation Medicine
Brooks Air Force Base, Texas

Thompson Ramo Wooldridge Inc., Cleveland

Thompson Ramo Wooldridge Inc.
P.O. Box 1616
Cleveland 4, Ohio
Attn: D.L. Southam

Wright Air Development Division

Commander
Wright Air Development Division
Wright-Patterson Air Force Base, Ohio
Attn: WCACT
(Inside envelope) For: Capt. Clarence N. Munson WCLEPCNW-1
WCOSI - 2

Technical Information Service Extension, Oak Ridge

U.S. Atomic Energy Commission
Technical Information Extension
P.O. Box 62
Oak Ridge, Tennessee

Chicago Patent Group

U.S. Atomic Energy Commission
Chicago Operations Office
9800 South Cass Avenue
Argonne, Illinois
Attn: George H. Lee

AI Library

Atomics International
P.O. Box 309
Canoga Park, California