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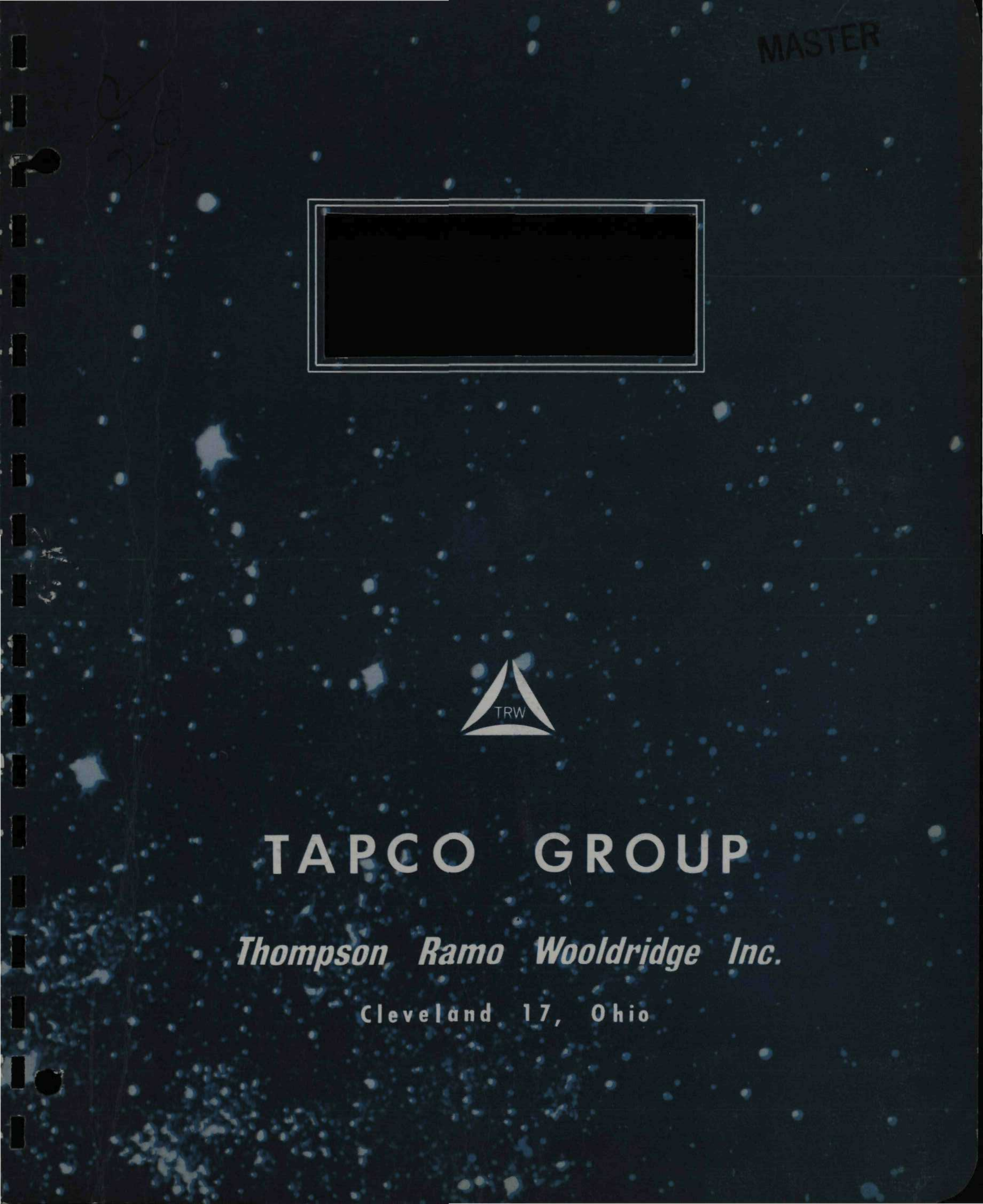

TAPCO GROUP

Thompson Ramo Wooldridge Inc.

Cleveland 17, Ohio

Special Distribution

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ENGINEERING REPORT 4052

SNAP I POWER CONVERSION SYSTEM ALTERNATOR DEVELOPMENT

PREPARED BY

NEW DEVICES LABORATORIES, TAPCO GROUP
THOMPSON RAMO WOOLDRIDGE INC.

AS AUTHORIZED BY

THE MARTIN CO. PURCHASE ORDER NO. OE 0101

FOR

THE UNITED STATES ATOMIC ENERGY COMMISSION
PRIME CONTRACT AT(30-3)-217

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FOREWORD

SNAP I is the first of a family of devices to convert nuclear energy to electrical for use in space. The SNAP Systems for Nuclear Auxiliary Power - programs are sponsored by the Atomic Energy Commission; the SNAP I prime contractor is The Martin Company. SNAP I was designed to utilize a radio isotope as the energy source.

The SNAP I Power Conversion System utilizes mercury as the working fluid for a Rankine cycle. A radioisotope is used as the energy source to vaporize mercury in a boiler; turbo-machinery extracts the useful energy from the vapor and converts it into electrical energy; the exhaust vapor is condensed by rejecting the waste thermal energy to space in a condenser-radiator.

During the SNAP I Power Conversion System development, Thompson Ramo Wooldridge has been responsible for the development of the following items:

- Turbo-machinery
    - Mercury vapor turbine
    - Alternator
    - Lubricant and condensate pump
    - Mercury lubricated bearings
- Speed Control
- Condenser-Radiator

A series of eight Engineering Reports have been prepared describing Thompson Ramo Wooldridge's SNAP I Power Conversion System development program. These are as follows:

ER-4050	Systems
ER-4051	Turbine
ER-4052	Alternator
ER-4053	Pump
ER-4054	Bearings
ER-4055	Control
ER-4056	Condenser-Radiator
ER-4057	Materials

The material in this report deals specifically with the developmental history of the alternator for the SNAP I Power Conversion System. This report is submitted as part of the requirements of Purchase Order OE-0101 from the Martin Company, issued under the Atomic Energy Commission prime contract AT(30-3)-217.

TABLE OF CONTENTS

1.0 SUMMARY

This report traces the developmental history of the SNAP I permanent magnet alternator from the original requirements to the design selected to fulfill these requirements. Representative performance data, such as voltage regulation, harmonic content and efficiency, are presented for each stator design. The design and performance of the rotor are discussed and the bore seal and motor startup problem areas are explained. A description of the test facilities for the alternator development program is included. Finally, conclusions and suggestions for design improvements to further increase performance are presented.

The SNAP I Power Conversion System alternator is a permanent magnet design which is simpler and more reliable than the conventional wound field alternator. A major advance in the state-of-the-art of high temperature materials, achieved during a TRW-sponsored materials development program, allows the alternator stator windings to operate at high temperature, thus eliminating the need for alternator cooling.

During the alternator development program, several design concepts were evolved and their performance evaluated. Although this unique application results in stringent operating conditions, the alternator performed satisfactorily in the 550°F mercury vapor atmosphere of the turbomachinery package. 2510 hours of full power endurance running demonstrated the operational capability.

2.0 INTRODUCTION

Figure 2-1 shows the turbomachinery package of the SNAP I Power Conversion System. This unique subminiature electric powerplant contains the alternator, turbine, and system pump, all mounted on a common shaft. Design rotating speed is 40,000 revolutions per minute and support is obtained from mercury lubricated bearings. Due to the requirement for long duration unattended operation in stringent environments, the SNAP I turbomachinery package represents advanced engineering concepts in analysis, design, fabrication, and experimentation.

This report describes the efforts which culminated in a successful alternator for meeting the SNAP I requirements.

The stringent environment in which the alternator is required to operate strongly influenced the type of alternator selected. The lack of moisture and oxygen make a brushless machine imperative to insure a long operating lifetime. A permanent magnet rotor is particularly well adapted for operation in the high temperature environment without cooling and in the presence of high temperature mercury vapor.

As a result of the evaluation for environmental, electrical, stress, and packaging considerations, a radial air gap, permanent magnet, 6 pole, single phase, 2000 cycles per second alternator, rated at 530 watts, 0.8 power factor, and 115 volts, was selected.

SNAP I TURBOMACHINERY PACKAGE

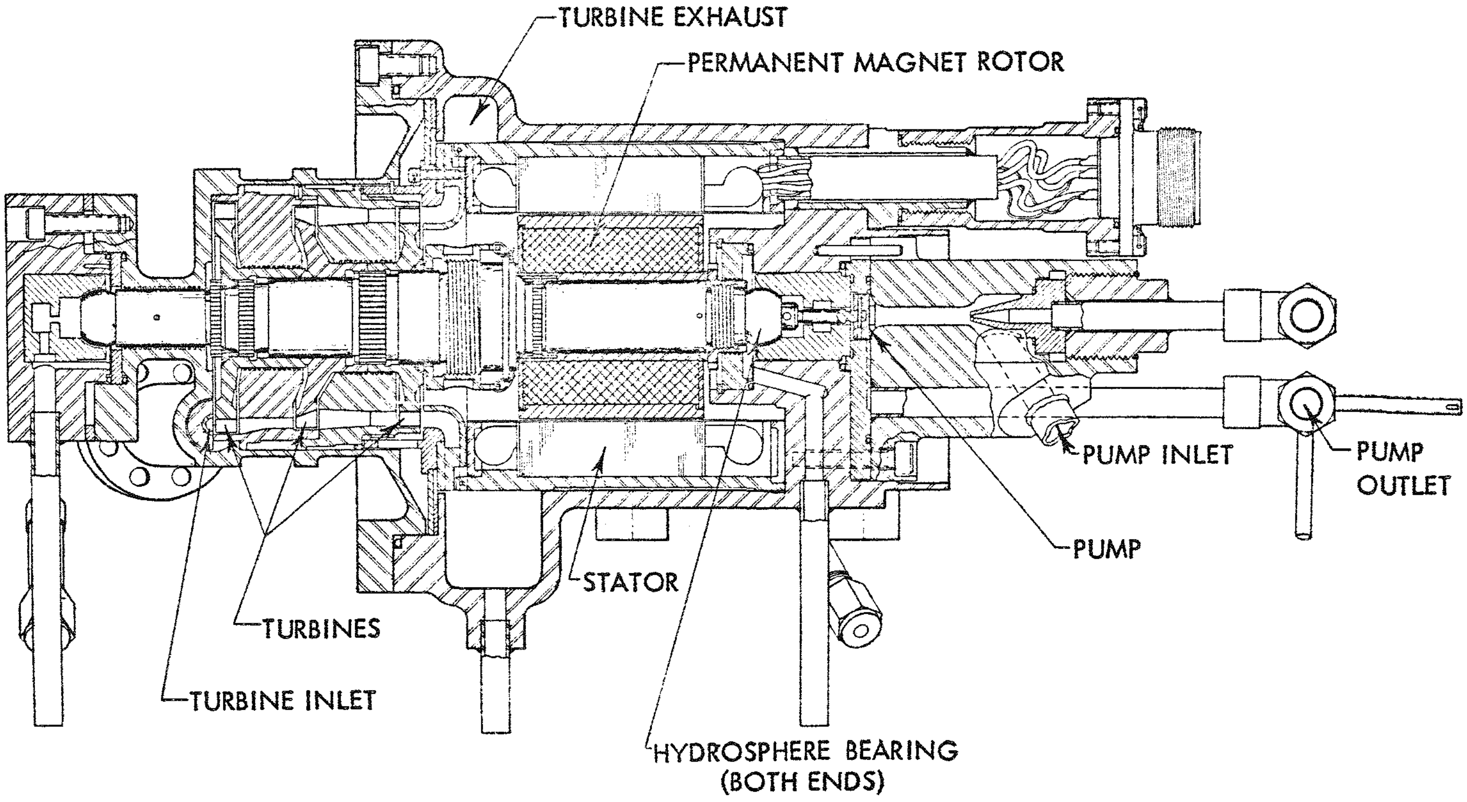


FIGURE 2-1

3.0 REQUIREMENTS AND SPECIFICATIONS

In order to arrive at a set of design specifications it was necessary to consider the operational requirements of the alternator. The environment imposed on the alternator made a permanent magnet, brushless machine attractive since the specialized environment to insure a long brush life is not present and a permanent magnet machine can operate satisfactorily at high temperatures. Operation at 600 to 700°F produces only a slight loss of magnetization, as shown in Figure 3-1. This effect is reversible, however, and can be considered in the magnet design. In addition, all rotating parts must be capable of operation in the presence of mercury vapor. Single phase power was specified by the user of the power output of the SNAP I system.

It is desirable to keep the voltage regulation of the alternator low in order to minimize control requirements. The determining factors of the regulation at constant speed are load current, load power factor, internal impedance, and demagnetizing armature turns. A power factor decrease reduces the terminal voltage by decreasing the vector angle at which the internal voltage drop is subtracted from the generated voltage. The regulation can be improved by varying the size of the unit thereby reducing the internal impedance and armature reaction, or by the addition of external capacitors for voltage correction.

Preliminary design calculations indicated that the total distortion would be approximately 5% with individual harmonics less than 3%. This was accomplished by selecting the winding pitch and distribution factors to minimize lower order harmonics and skewing the stator slots to reduce higher order harmonics. The harmonic content indicated is due to generated harmonics only and any nonlinearities in the load may increase it beyond these values.

It is necessary to maintain the insulation of the stator winding at a suitable temperature to prevent dielectric breakdown and insure reliable performance for the desired life of the unit. A heat balance indicated that it was necessary to fabricate the stator such that a solid molecular bond is provided for the dissipation of copper losses by conduction to the iron laminations by way of the slot cell. At the start of the program, the stator operating temperature dictated the use of class H insulating materials with silicone enamel wire and a silicone-mica combination in the stator. The wound stator was then impregnated with a silicone varnish. The final curing cycle was at 550°F. The stator was then potted and enclosed in a stainless steel jacket to provide protection from the mercury vapor and also provide maximum heat transfer from the windings to the coolant. The outer diameter of the canned stator was then surrounded by an annular passage, through which the coolant mercury flowed at 350°F. The coolant flow rate was sufficient to maintain the maximum hot spot temperature below 450°F.

However, during the course of the program, a major advancement in the state-of-the-art of high temperature insulation was made as part of a TRW-sponsored program on High Temperature Materials. This advancement allowed the maximum stator operating temperature to be raised well above 550°F, thereby eliminating any stator hot-spot problem and eliminating the need for alternator cooling. By eliminating the alternator coolant loop, the package design was greatly simplified and the required mercury inventory was reduced to approximately 85% of the original requirement.

REVERSIBLE CHANGES OF ALNICO VI VS. TEMPERATURE

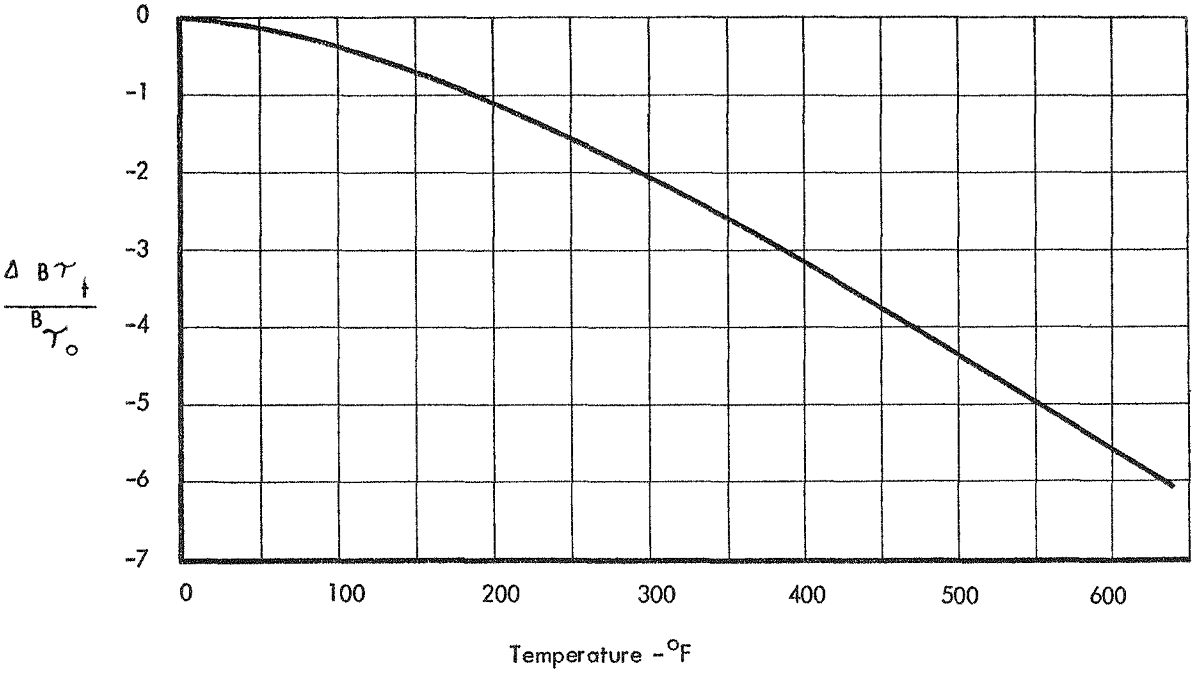


FIGURE 3-1

As a result of the above considerations and preliminary design studies, the following design specifications were formulated:

1.	Electrical output	530 watts, single phase
2.	Voltage	115 v ± 2% at operating temperature
3.	Frequency	2000 ± 2.5% (controlled externally)
4.	Power factor	must meet design requirements at .80 ±.02 lagging
5.	Voltage regulation	due to changes in load from 0 to 100% of nominal load at nominal frequency and power, voltage regulation must be less than 25% - due to frequency changes voltage regulation must be less than 2.5%
6.	Harmonics	less than 7% when operating into a linear load
7.	Efficiency	85% - a design objective
8.	Overload	must be capable of sustaining steady current overload of 20% above nominal with no permanent effects on performance when operating into a linear load of not less than 0.80 power factor
9.	Motor startup	must be capable of operating as a motor to start the package. During startup and load stabilization must be capable of current overload of 50% nominal
10.	Radio interference	must meet requirements of MIL-I-6181B
11.	Coolant	must operate without coolant as long as alternator winding temperature does not exceed 550°F.

4.0 DESIGN AND PERFORMANCE

The excitation field required by an ac generator may be provided either by an electromagnet, as in the conventional wound-field machine, or by a permanent magnet. The wound field is most common because only the recent development of the Alnicos has made the permanent-magnet generator practical in sizes larger than a tachometer generator.

The advantages of an ac generator without exciter, commutator, slip rings, brushes, and field winding are obvious for an application where reliability and unattended operation are prime considerations. These advantages make the permanent-magnet generator especially attractive for military applications, e.g., for guided missiles, piloted aircraft, and satellite power supplies, where size, weight and environmental requirements are stringent.

It is standard practice in the design of a permanent magnet to expose the magnet to the maximum demagnetizing influence that the magnet will encounter in in normal service. The magnet is then said to be "stabilized" and, providing the magnet is not subjected to a greater demagnetization, flux density remains within a narrow band.

Most permanent-magnet generators are designed to be air stabilized, i.e., stabilized by separating rotor and stator in air. Air stabilization imposes a weight penalty on the machine, so in this application the unit was load stabilized to conserve weight and space. A photograph of the alternator developed for this program is shown in Figure 4-1.

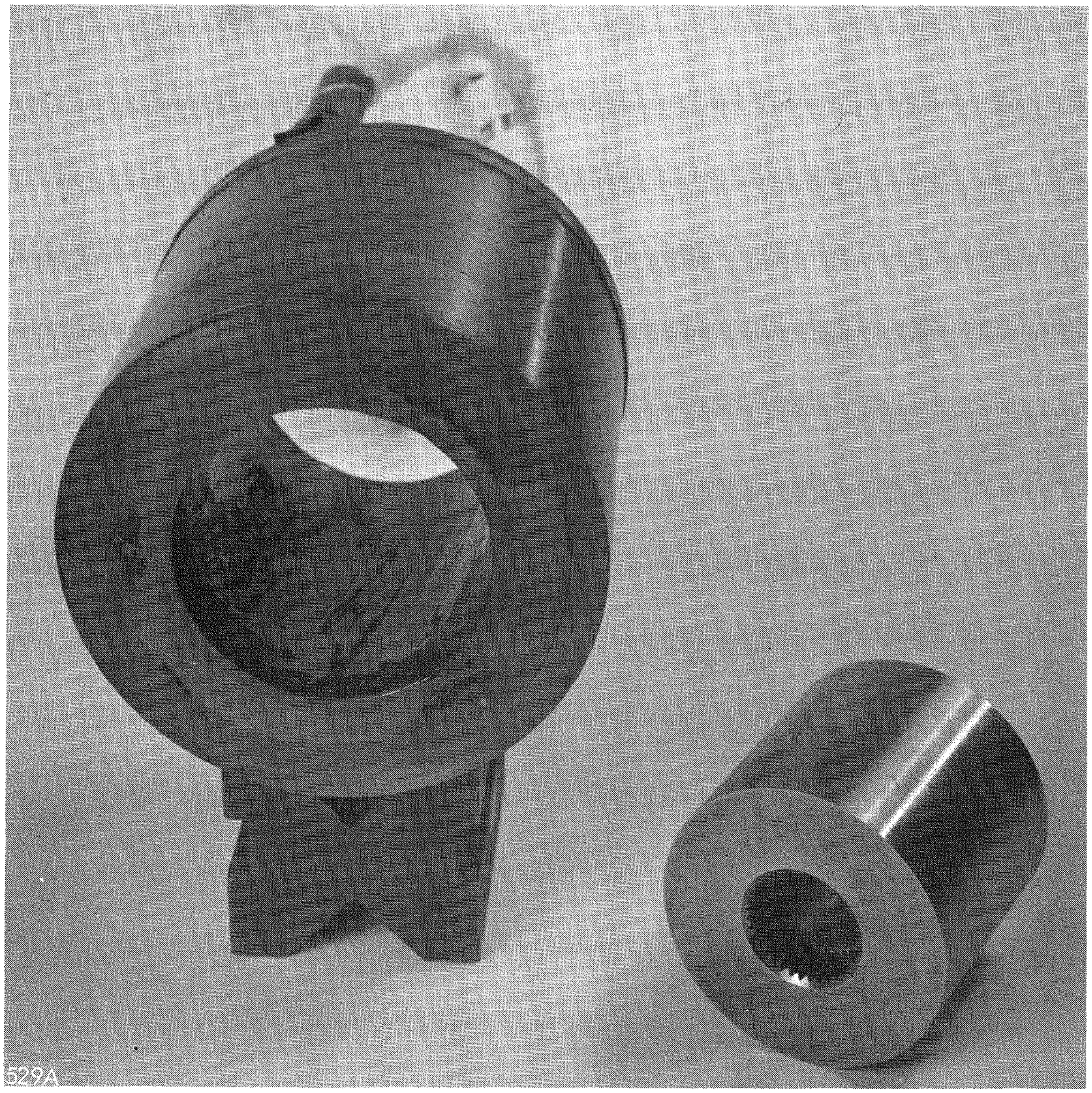
4.1 Stator Design

4.1.1 24-Slot Stator

The original stator design was one that incorporated 24 stator slots. The stator was wound as a two-phase unit and connected single-phase to take maximum advantage of the available magnetic steel. The pitch and distribution factors were selected to minimize the generated harmonics. Since originally there was no specification on voltage regulation, and since the external load was expected to be fairly constant, there was no great concern over the relatively high voltage regulation. The stator was wound with 4 turns per coil of silicone-glass wire and impregnated with a silicone varnish. The performance of this unit is presented in Figure 4-2 which shows that the output voltage at rated load, 530 watts at .8 PF, was 108 volts. Voltage regulation and harmonics data is presented in Table 4-1.

TABLE 4-1

Voltage Regulation	Load	%
	530 watts @ 1.0 PF	7.1
	530 watts @ .8 PF	27.1%



Stator Rotor

SNAP I ALTERNATOR

FIGURE 4-1

SNAP I ALTERNATOR PERFORMANCE

24 Slot Stator - 4 Turns/Coil
Voltage Regulation - 1.0 PF and 0.8 PF

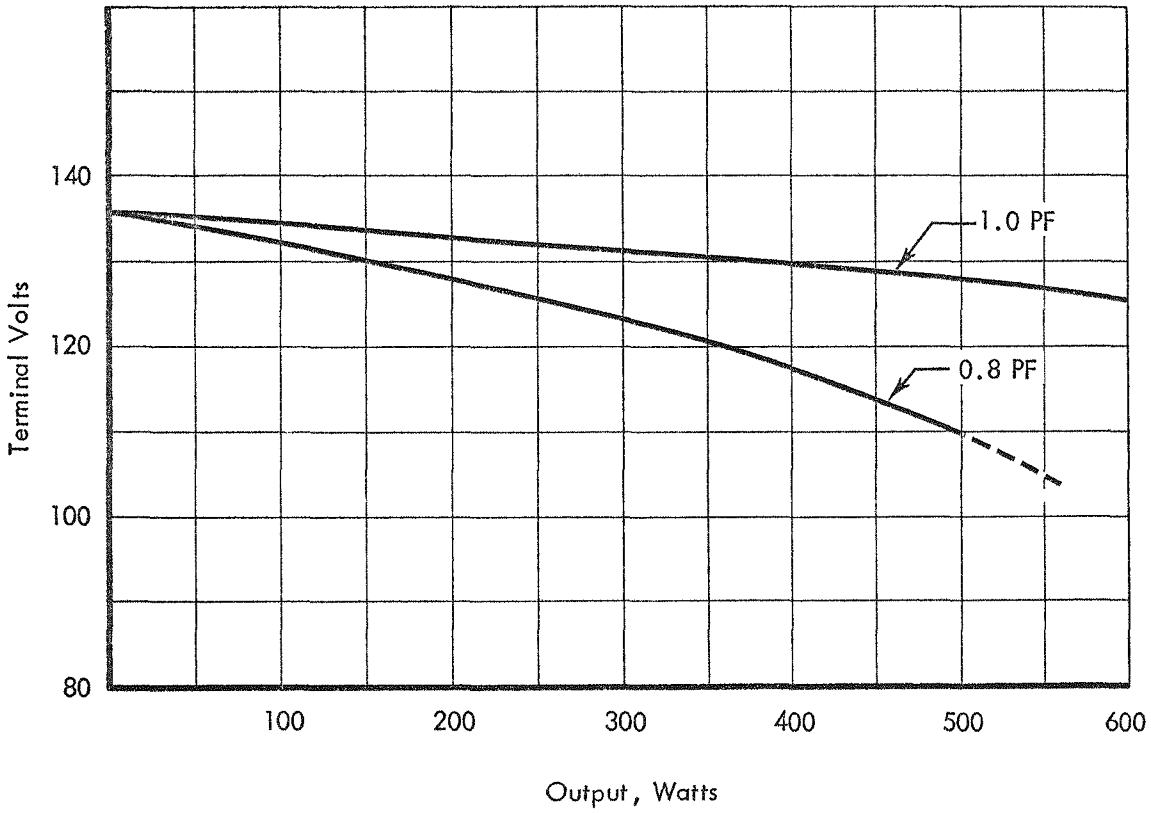


FIGURE 4-2

TABLE 4-1 (cont.)

Total Distortion	Load	%
	0	1.22 %
	530 watts @ .8 PF	5.2 %

Since the 4 turns per coil configuration was low in voltage at rated load, the design was revised to incorporate 5 turns per coil. Also at this time, because an advancement in the state-of-the-art on wire insulation had been developed on a TRW sponsored program it was decided to build a stator that needed no coolant. This stator was constructed with silver conductors with a special glass insulation and had a capability of operating at 550°F without external coolant. This design performed satisfactorily with the exception of excessive voltage regulation and an efficiency lower than the design objective. The performance of this unit is presented in Figures 4-3 and 4-4 and in tabular form in Table 4-2. Overload data is also presented in Table 4-2.

TABLE 4-2

Voltage Regulation	Load	%
	530 watts @ 1.0 PF	8.4 %
	530 watts @ 0.8 PF	38.8 %
Total Distortion		
	0 watts	1.1 %
	530 watts @ 0.8 PF	6.25 %
Overload		
	1.0 PF	greater than 250%
	.8 PF	greater than 150%

4.1.2 Closed Slot Stator

In an attempt to simplify the bore seal problem, it was decided to build a stator with completely closed stator slots. It was known that voltage regulation and harmonics would increase appreciably in this design because of the relatively high reactance of the winding. In an attempt to decrease this reactance, the lamination was designed with 32 slots. Another

SNAP I ALTERNATOR PERFORMANCE

24 Slot Stator - 5 Turns/ Coil
Voltage Regulation - 1.0 PF and 0.8 PF

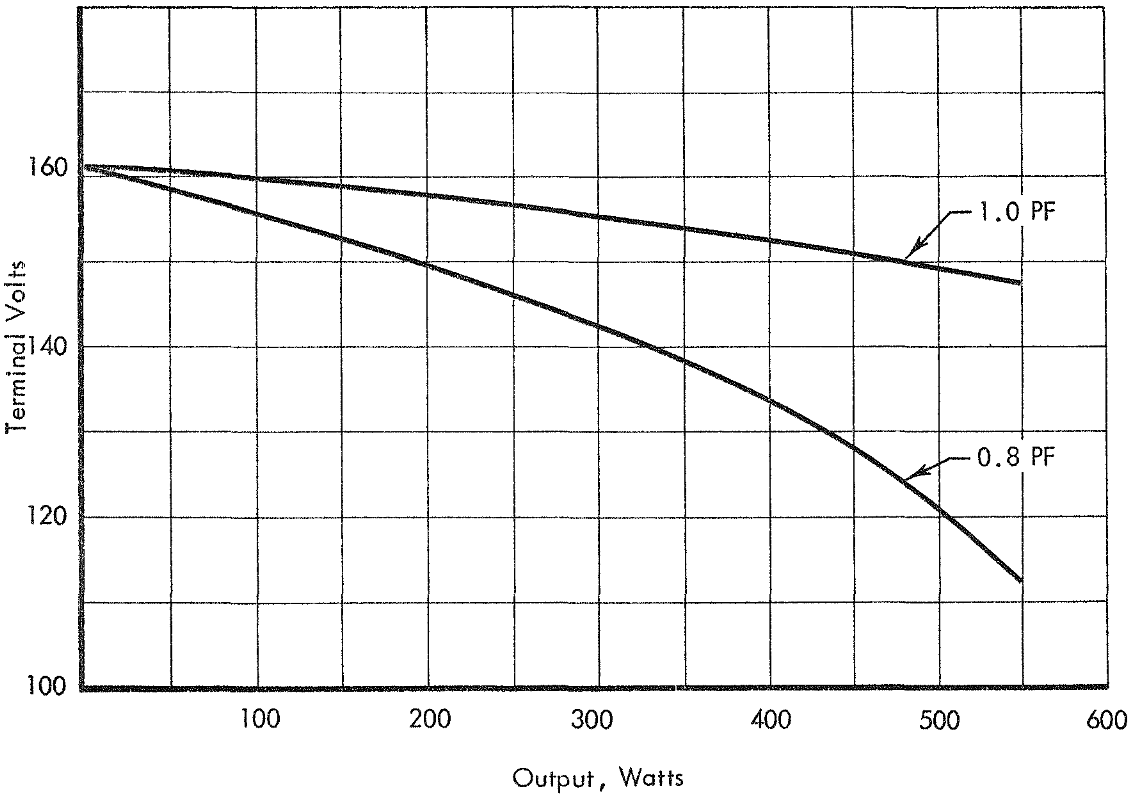


FIGURE 4-3

SNAP I ALTERNATOR PERFORMANCE

24 Slot Stator - 5 Turns/Coil
Efficiency Data - 1.0 PF and 0.8 PF

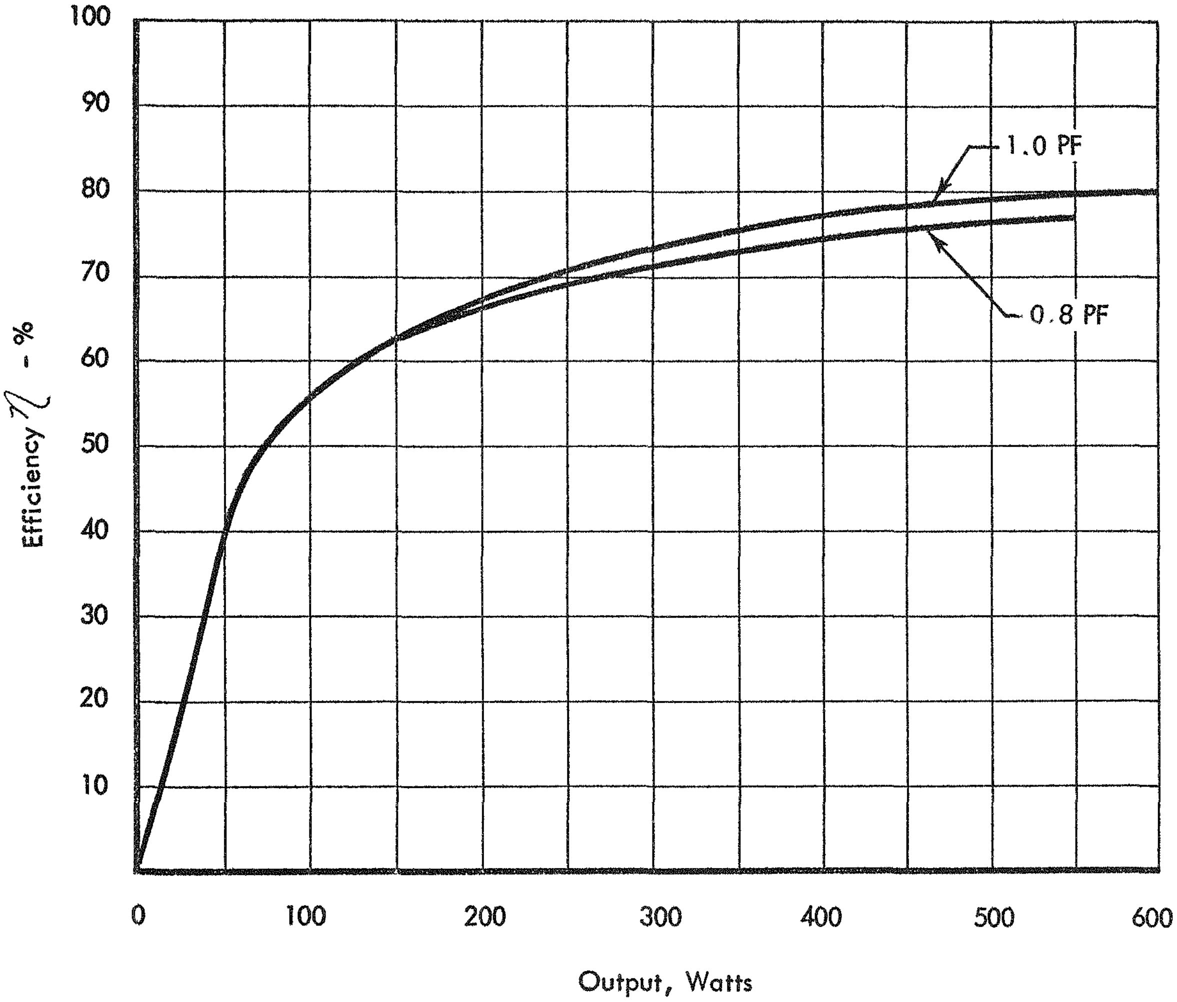


FIGURE 4-4

difficulty of the closed-slot design is that the stack had to be tunnel-wound, that is, since the stack had no slot openings, the winding had to be threaded through from the ends of the stack one turn at a time.

The voltage regulation data for this design is presented in Figure 4-5 and also in Table 4-3. As can be seen from this data, the voltage regulation was approximately 64% at rated load and the terminal voltage is very low. The voltage regulation was improved to nearly flat response by using a 6.25μ f capacitor in series with the output as shown in Figure 4-6. The total distortion, however, did not improve greatly with the external capacitor.

TABLE 4-3

Voltage Regulation	Load	%
	530 watts @ 1.0 PF	5.4
	530 watts @ .8 PF	64
With 6.25μF capacitor	530 watts @ 1.0 PF	0
	530 watts @ .8 PF	3.0
Total Distortion		
	0 watts	3.37
	500 watts @ 1.0 PF	17.2
With 6.25μF capacitor	500 watts @ .8 PF	16.1

4.1.3 32 Slot Stator

In an attempt to improve voltage regulation and efficiency of the 24 slot designs to meet design objectives, it was decided to revise the design to 32 slots with 3.5 turns per coil. Again, the main objective was to reduce stator reactance for improved voltage regulation. In order to improve efficiency, several changes were made: a) the lamination material was changed from .007 inch stock to .005 inch stock to decrease iron losses, b) the conductors were made of a larger diameter silver wire for a decrease in conductor losses. The data presented in Figures 4-7 and 4-8 and also in Table 4-4 indicate the voltage regulation was considerably improved but the efficiency was lower by approximately 2%.

SNAP I ALTERNATOR PERFORMANCE

Closed Slot Stator
Voltage Regulation - 1.0 PF and 0.8 PF

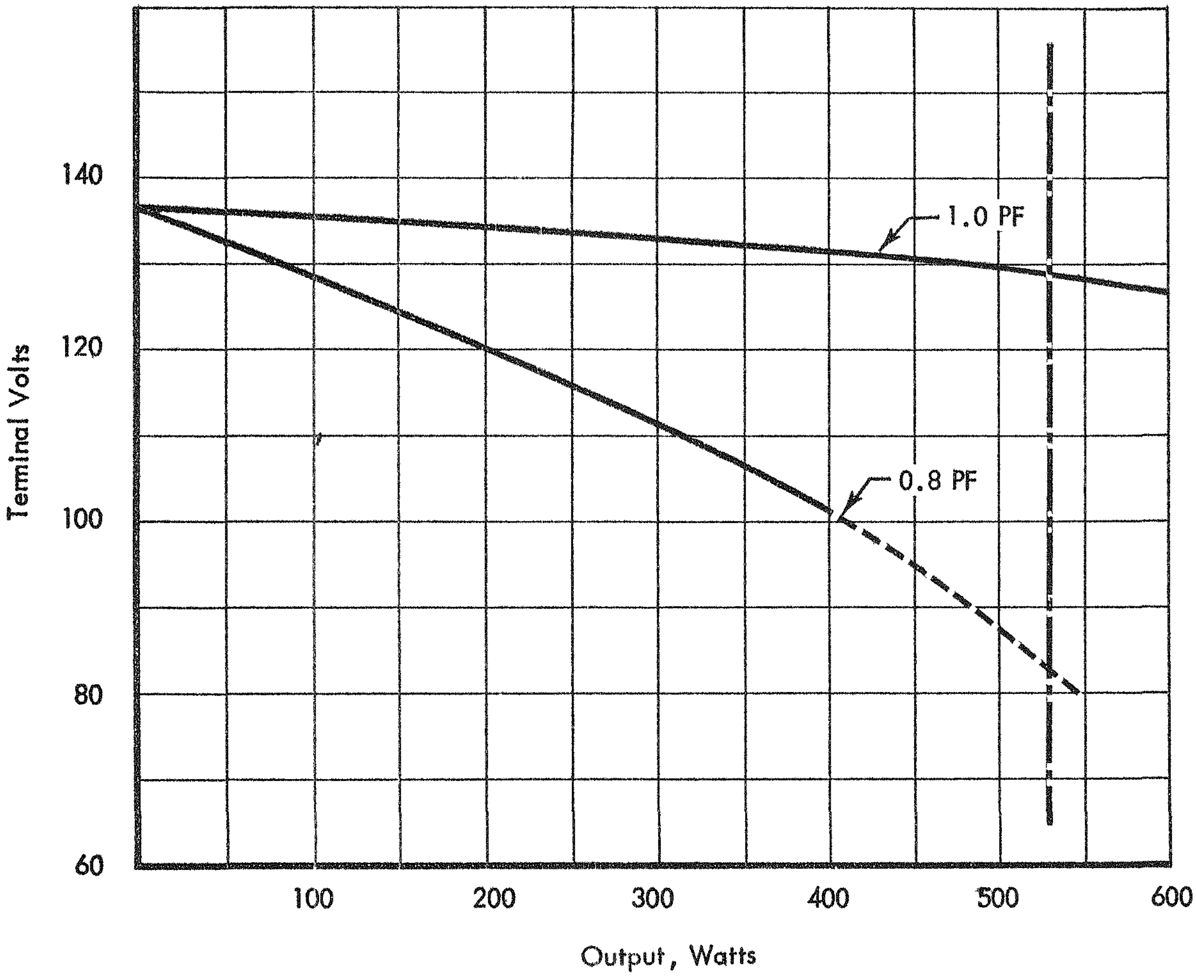


FIGURE 4-5

SNAP I ALTERNATOR PERFORMANCE

Closed Slot Stator
Voltage Regulation - 6.25μF Ext. Capacitor

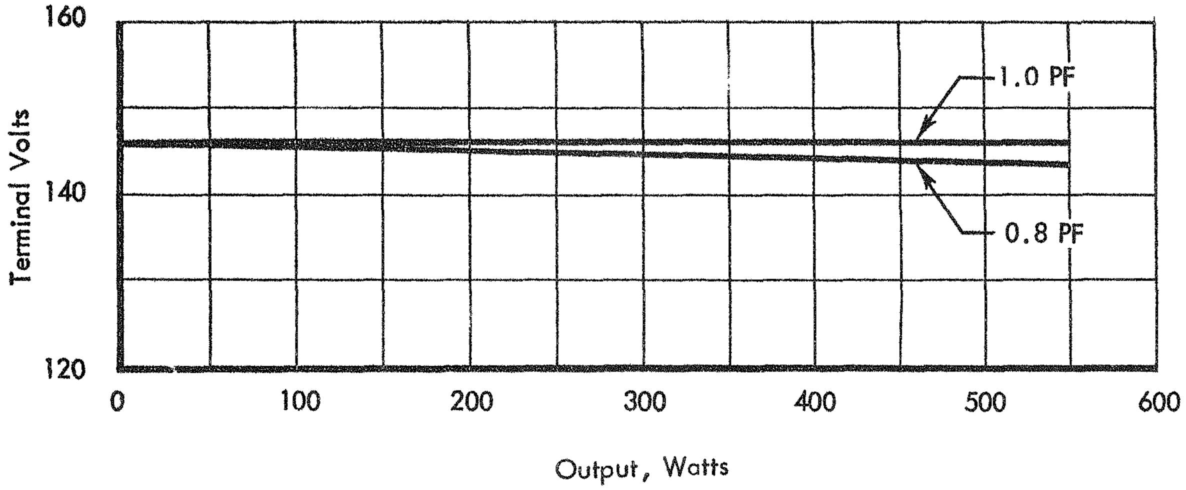


FIGURE 4-6

SNAP I ALTERNATOR PERFORMANCE

32 Slot Stator - .040 Slot Opening
Voltage Regulation - 1.0 PF and 0.8 PF

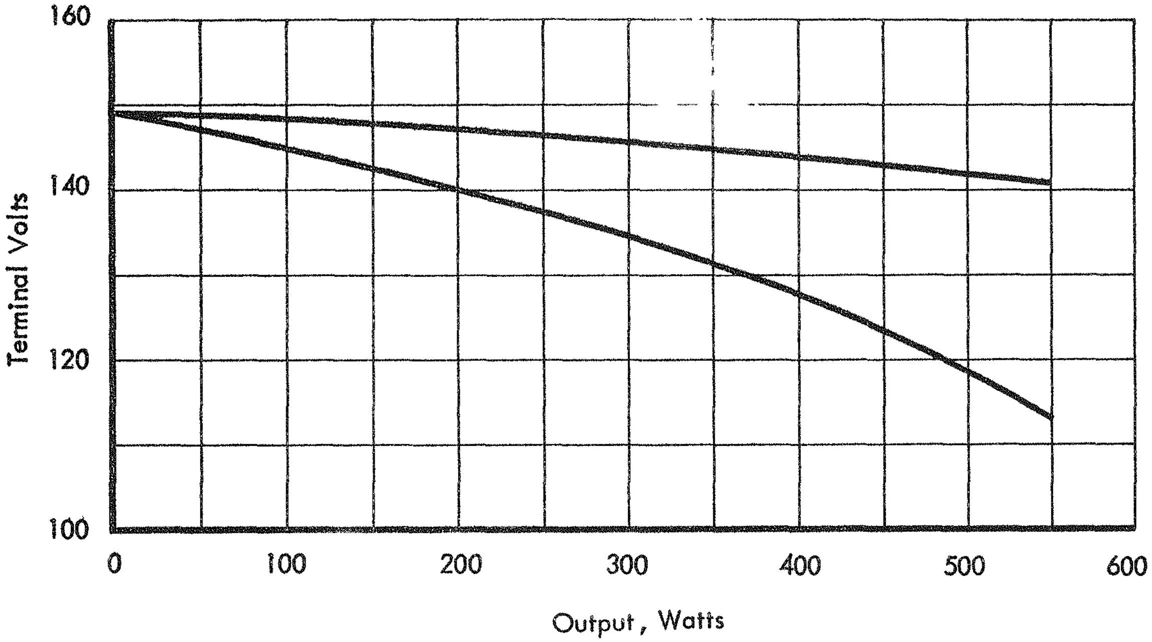


FIGURE 4-7

SNAP I ALTERNATOR PERFORMANCE

32 Slot Stator - .040 Slot Opening
Efficiency Data - 0.8 PF

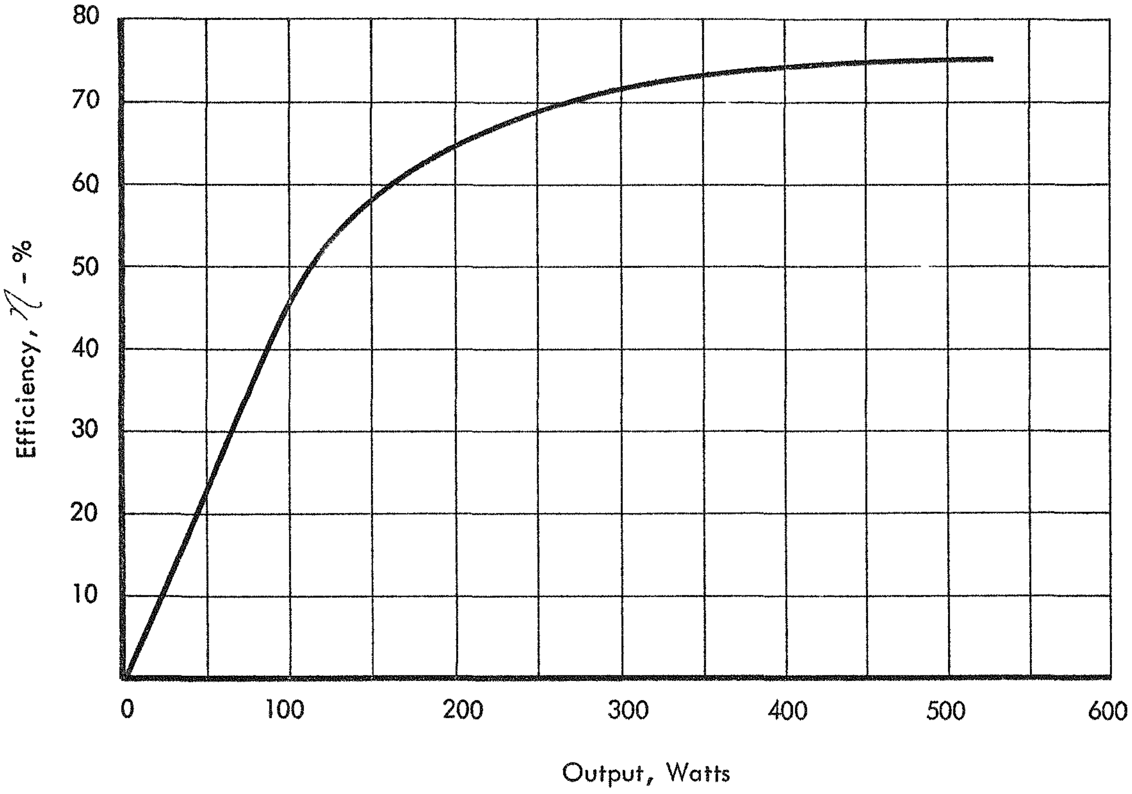


FIGURE 4-8

TABLE 4-4

Voltage Regulation	Load	%
	530 watts @ 1.0 PF	4.95
	530 watts @ 0.8 PF	28.9
Total Distortion		
	530 watts @ 0.8 PF	5.5
Efficiency		
	530 watts @ 0.8 PF	75

The causes of this lower efficiency were traced to two areas: a) the higher gap density, and b) the ratio of slot-opening (.040 inch) to air gap (.015 inch). Since the gap density could not be lowered without increasing the conductor losses, the most straightforward solution was to decrease the slot opening to .025 inch. This change increased voltage regulation slightly, but the efficiency objective was considered more important. A stator of this design was constructed and the performance is plotted in Figures 4-9 and 4-10 and in Table 4-5. The voltage regulation increased to approximately 31% and the efficiency improved over 7% to 82.5%. The rotor pole face losses were decreased from about 110 watts to approximately 50 watts.

TABLE 4-5

Voltage Regulation	Load	%
	530 watts @ 1.0 PF	7.9
	530 watts @ 0.8 PF	31.5
Total Distortion		
	530 watts @ 0.8 PF	5.5
Efficiency		
	530 watts @ 1.0 PF	86
	530 watts @ 0.8 PF	82.5

SNAP I ALTERNATOR PERFORMANCE

32 Slot Stator - .025 Slot Opening
Voltage Regulation - 1.0 PF and 0.8 PF

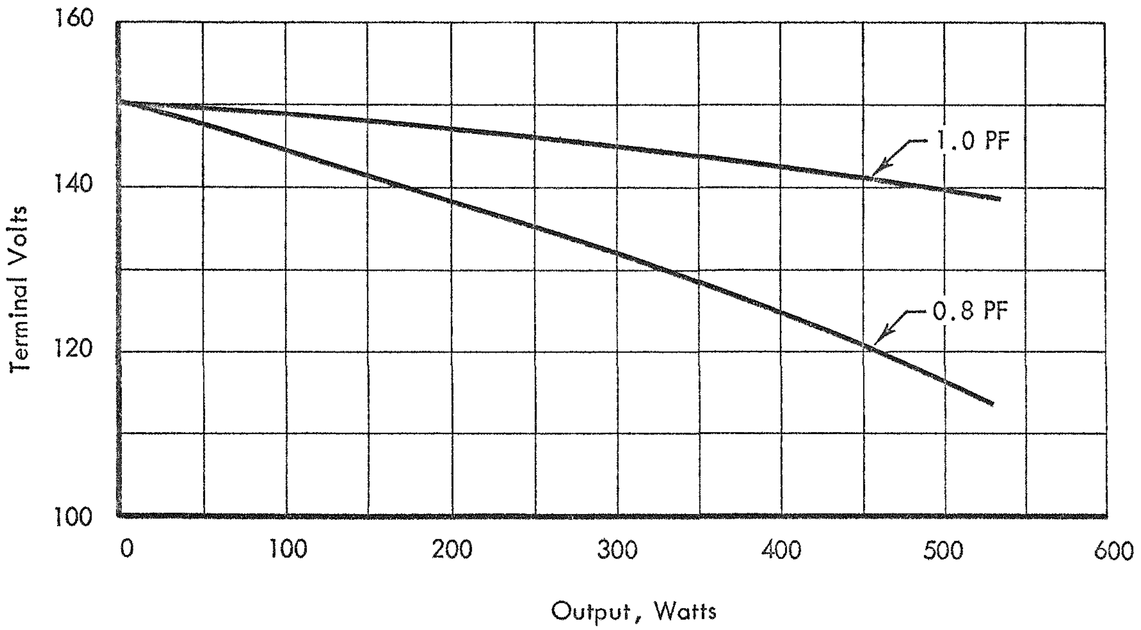


FIGURE 4-9

SNAP I ALTERNATOR PERFORMANCE

32 Slot Stator - .025 Slot Opening
Efficiency Data - 1.0 PF and 0.8 PF

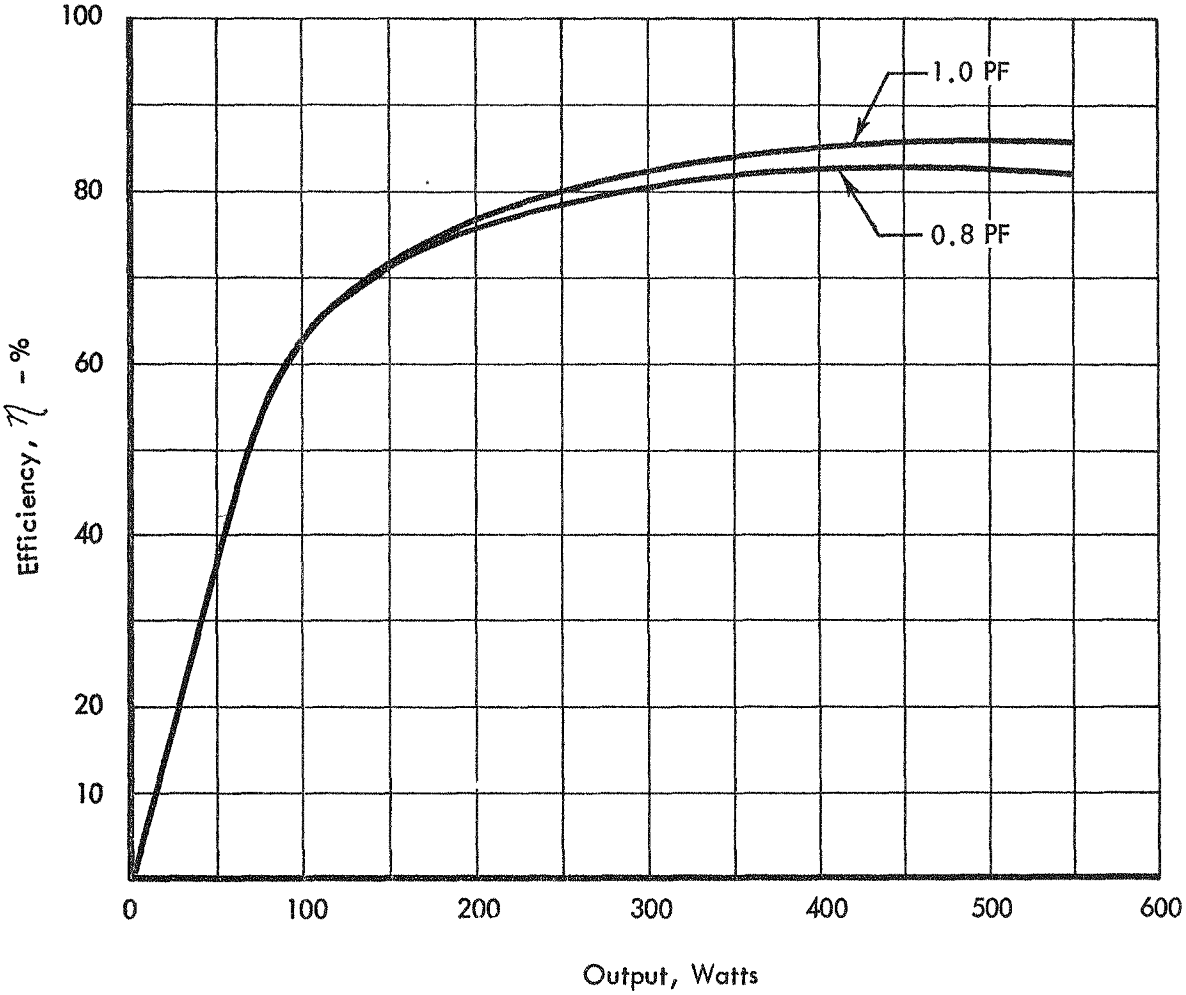


FIGURE 4-10

Although all the design objectives were not completely met, the efficiency was the only deficiency of any consequence. One method of increasing the efficiency is by design changes such as a further decrease in slot opening and an increase in stack length. But the most straightforward method of realizing a sizeable increase in the efficiency is to change to a multiple phase loading. An alternator efficiency of 90% is indicated when operating with two-phase loading. Changing to two-phase loading would entail no design changes since the alternator was designed as a two-phase unit and connected single-phase.

Voltage regulation was greater than the original objective, but this is not extremely important since the power required is relatively constant. The overload capability of the alternator exceeded the design objective. The alternator was operated at an output of 1200 watts with no adverse effects.

4.2 Rotor Design

4.2.1 Magnetic Material

Alnico VI was selected for the permanent magnet rotor, primarily because of its mechanical strength at high temperature. The published data for tensile strength of Alnico VI is 23,000 psi and that of Alnico V of approximately 5500 psi. Therefore, even though Alnico V has a higher energy product and would result in a slightly smaller rotor, the running stresses were higher than the maximum allowable stress in Alnico V. The magnetic strength of the Alnico materials varies with temperature and they are suitable for operation up to temperatures of 500°C. The change in magnetic properties 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 was shown in Figure 3-1.

Another important consideration in the alternator design was the selection of radiation resistant materials. Gordon (1) reports that, "Permanent magnets are insensitive to nuclear radiation up to at least 10^{17} neutrons/cm^2 (nvt). Magnetic core materials with coercive force values greater than 0.5 oersted (such as silicon irons) also show no appreciable changes in this environment." Gordon also reports that in a combination of radiation and high temperature environments, the stability of both Alnico VI and the silicon irons should be very good. The stator insulation system consisted entirely of inorganic materials and therefore should be relatively insensitive to radiation damage.

4.2.2 Shrink Ring

4.2.2.1 Segmented Ring

The shrink ring that bonds the permanent magnet rotor to prevent rotor rupture at the high operating speeds is an important element of the alternator design. The ring must be designed to support the magnet and keep the operating stress due to temperature and speed well below the maximum tensile value. The ring must also be designed so that no air-gap greater than the .015 inch design value is introduced between the rotor and the stator. The selected design incorporated alternate sections of magnetic and non-magnetic materials welded together to decrease losses. A cross-section of the rotor design is shown in Figure 4-11. The technique for fabrication of this ring is as follows:

a) Mill a blank of 410 stainless steel in six places to accomodate the non-magnetic section.

b) Fill the slots with 310 stainless steel weld rod.

c) Grind the ring for the design shrink fit on the magnet.

d) Orient the ring with respect to the magnet and then shrink together.

The design stress in the rotor at operating temperature and speed was approximately 20,000 psi which is well below the theoretical limit. These stresses were predicted on the assumption that the ring will be in contact with the magnet up to a speed of 50,000 rpm. A rotor of this design was spin-tested at 51,000 rpm at operating temperature and performed satisfactorily.

4.2.2.2 Solid Shrink Ring

Concern about the integrity of the weld on the segmented shrink ring was raised, and as a result, a design incorporating a solid shrink ring was investigated. The thickness of this shrink was held as thin as practical to minimize leakage between rotor poles. A ring of 15-7 MO steel of .040 inch thickness was designed and fabricated. Another objective of this design was to operate the magnet at zero stress at design conditions. In order to accomplish this objective, an interference fit between magnet and ring of .006 inch was required which resulted in a stress in the ring of 113,000 psi (the maximum allowable stress was assumed to be 130,000 psi). Fabrication problems with this interference fit were encountered and the fit was changed to .003 inch interference.

In order to compensate for the added leakage in the shrink ring, a magnet of Alnico V was used. Performance of this rotor was approximately the same as the segmented ring rotor using Alnico VI.

4.3 Stator Seal

The sealing of the stator bore is one of the most important aspects in the alternator design. Because the stator conductors are readily attacked by mercury vapor, every precaution was taken to insure that mercury vapor did not contact the stator windings. This protection was accomplished in three ways, and can be seen in Figure 4-12.

1) After the stator was wound it was impregnated twice with a special high temperature resin. Tests in an autoclave at operating temperature, indicated that coils impregnated with this resin were impervious to mercury.

PERMANENT MAGNET ROTOR

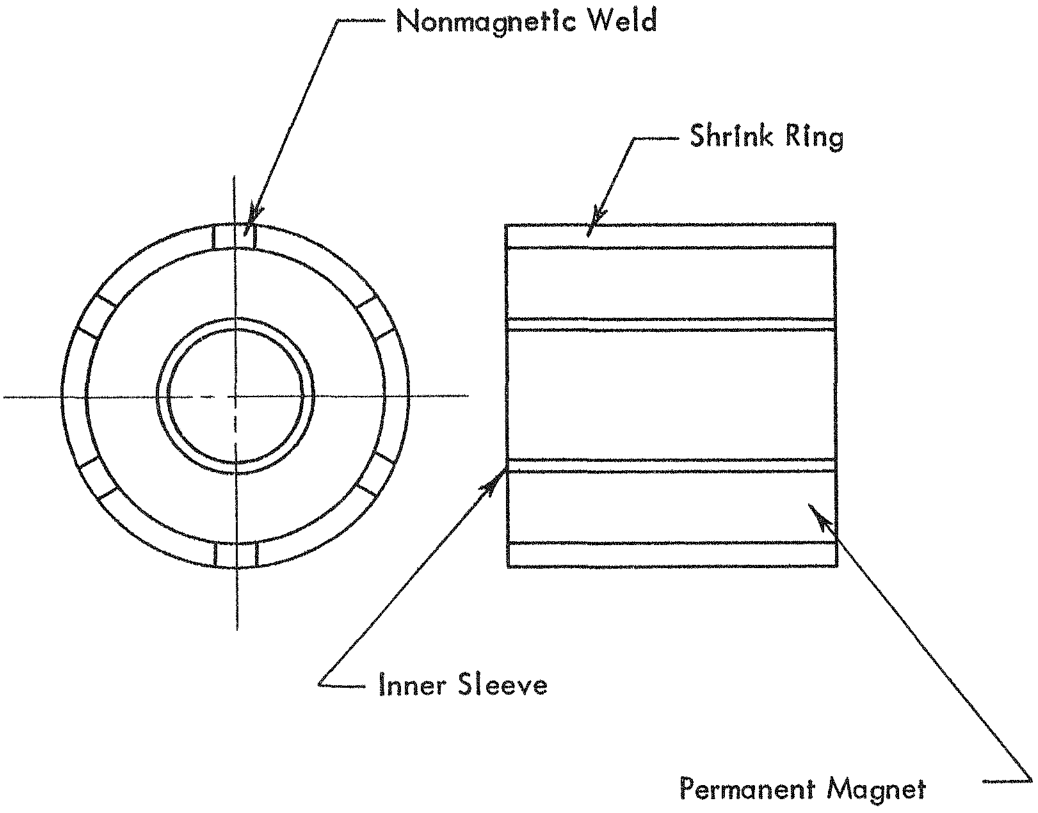


FIGURE 4-11

ALTERNATOR STATOR

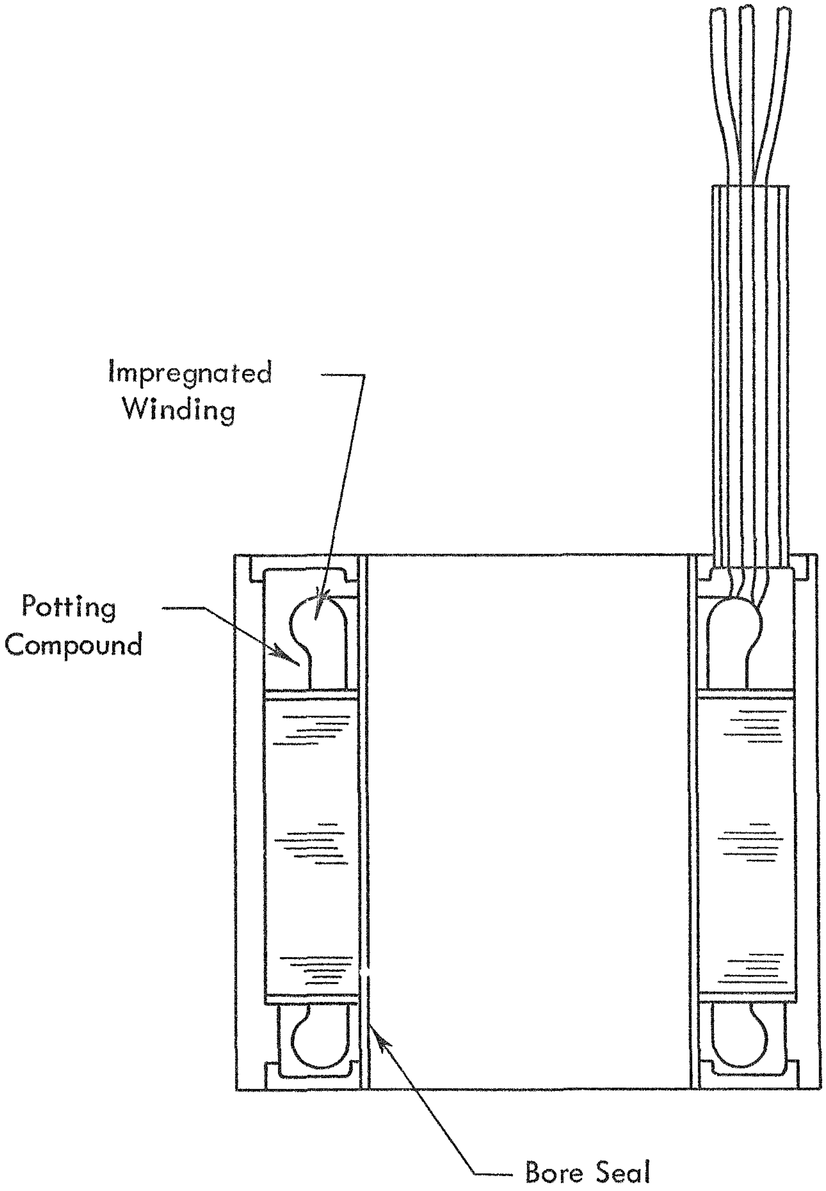


FIGURE 4-12

2) The end turn areas were then potted with high temperature potting compound. Although this potting compound was not completely impervious to mercury, it provided an added space factor that had to be penetrated before the mercury could contact the end turns. The potting compound also provided a relatively rough surface to which the final bore seal could adhere more easily.

3) The bore was then sealed with a thin (.010 inch thick) coating of material that was impervious to mercury. The two different materials which were successfully used for this final seal were pyroceram and alumina.

4.3.1 Pyroceram Cement

Pyroceram is a trade-name of the Corning Glass Company. This is a finely powdered glass in a vehicle that can be used for sealing many materials. When the cement is heated, the glass develops a partially crystalline structure which results in a devitrified glass seal much stronger and harder than the original glass. This seal is servicable at temperatures up to 450°C, which is well above the operating temperature of the stator.

The technique used in applying Pyroceram was as follows:

1) After the stator was potted as described above, the stator bore was ground to the lamination I.D. (The stator slot openings were also included in the potting procedure).

2) A layer of Pyroceram Cement was applied to the bore.

3) The glass coating was fired and cooled slowly.

4) Several coats of cement were applied until a uniform coat of glass covered the bore.

5) The bore was ground to final size. The performance of this seal was good; however, several fine cracks appeared at the ends of the stator due to differential expansion of the glass and the steel. These cracks were successfully sealed by applying a thin layer of the high temperature resin that was used as a stator impregnant. This method of sealing provided a leak-tight seal under a differential pressure of one atmosphere. This method was used in all of the SNAP I turbomachinery package alternators.

4.3.2 Alumina Tube

Another technique that was used to accomplish the bore seal utilized a thin ceramic sleeve in the bore. The material used in this attempt was Morganite Triangle RR, which is an aluminum oxide of 99.7% purity. Technical information from the manufacturer indicated that the material is leak-tight in thicknesses as small as .007 inch and the thickness used for this application was .010 inch. The technique used in the fabrication of the seal was as follows:

1) The O.D. of the ceramic was ground to fit the alternator bore with a clearance of a few ten thousandths of an inch.

2) The sleeve was then pushed into the bore and sealed on both ends with Pyroceram Cement.

3) The bore was ground to size.

The results of this method were also very promising, but several fine cracks appeared at both ends of the stack just as in the Pyroceram Cement seal described above. Although this approach was not pursued further, it is believed that if the ceramic sleeve were kept in compression at all times, the seal would be effective.

4.4 Motor Start-up

The feasibility of starting the alternator as a motor was investigated. Actually, a conventional permanent magnet alternator has no inherent starting characteristics with conventional power sources. However, if the alternator were pulled into synchronism at a low frequency (below 20 cps) and this frequency continuously increased, the alternator would remain in synchronism so long as the power source supplied the increasing power requirements of the alternator with speed.

A power source with a continuously variable frequency was fabricated using a Precise Super 80 universal motor driving a special permanent magnet alternator. The alternator consisted of a specially wound 24 slot SNAP I stator and rotor. The speed was controlled from 0 to 26,000 rpm by means of a variable transformer so that the power output of the special alternator could be varied from 0 to 1300 cps with voltage being proportional to speed. A design requirement of the special alternator was to have maximum possible volts per cycle at low frequencies which resulted in an optimum winding of 8 turns per coil to achieve maximum volts per cycle and maximum power transfer.

The SNAP I alternator was then tested as a motor for starting torque performance with the variable frequency power supply and the results are listed in Table VI.

TABLE VI

Five (5) turns/coil 24 slot stator

Ambient Temperature-°F	Minimum Starting Torque oz-in *	Frequency for Optimum Start-cps	Starting Frequency Range CPS
Room	.513	6	3-19
200 **	.408	5	4-13
400 **	.284	6	4-9
600 **	.140	5.5	3-7

Four (4) turns/coil 24 slot stator

Ambient Temperature-°F	Minimum Starting Torque oz-in *	Frequency for Optimum Start-cps	Starting Frequency Range CPS
Room	.85	9	3-13
600 °F ***	.23 approx.		

* 1) Breakaway torque of ball bearings not included (measured .1 oz.in. max.)

** 2) Room temperature tested; higher temperature tested by calculating stator resistance at higher temperature and inserting series resistors to simulate temperature conditions. Effects of stator iron temperature on starting torque are negligible since flux density is low. Loss of torque due to temperature effects on PM rotor flux density are 5% at 600°F, 3% at 400°F and 1% at 200°F.

*** 3) 600°F was obtained by assuming same ratio of torque between room and 600°F as measured in 5 turns per coil alternator.

The 3-1/2 turn per coil 32 slot stator was not tested; however, calculations show that this stator would have a starting torque of .16 oz. in. at 600°F.

When this power supply was connected to the first turbomachinery package (3-1/2 turns per coil 32 slot stator), it would not start the package. It was learned that more starting torque was required than could be provided with this power supply. At this time, the motor start-up program was cancelled because of budget limitations and no further work was done.

Performance tests were also conducted on the alternator for running torque by using a Magtrol absorption type dynamometer. These tests were run to establish power requirements and output characteristics during spin up. After start-up, the power supply and alternator performed satisfactorily. However, each spin up resulted in a slight demagnetization of the power supply. Performance characteristics of the alternator as a motor are shown in Figure 4-13.

PHASE WATTS VS. LOAD

5 Turns/coil 24 Slots

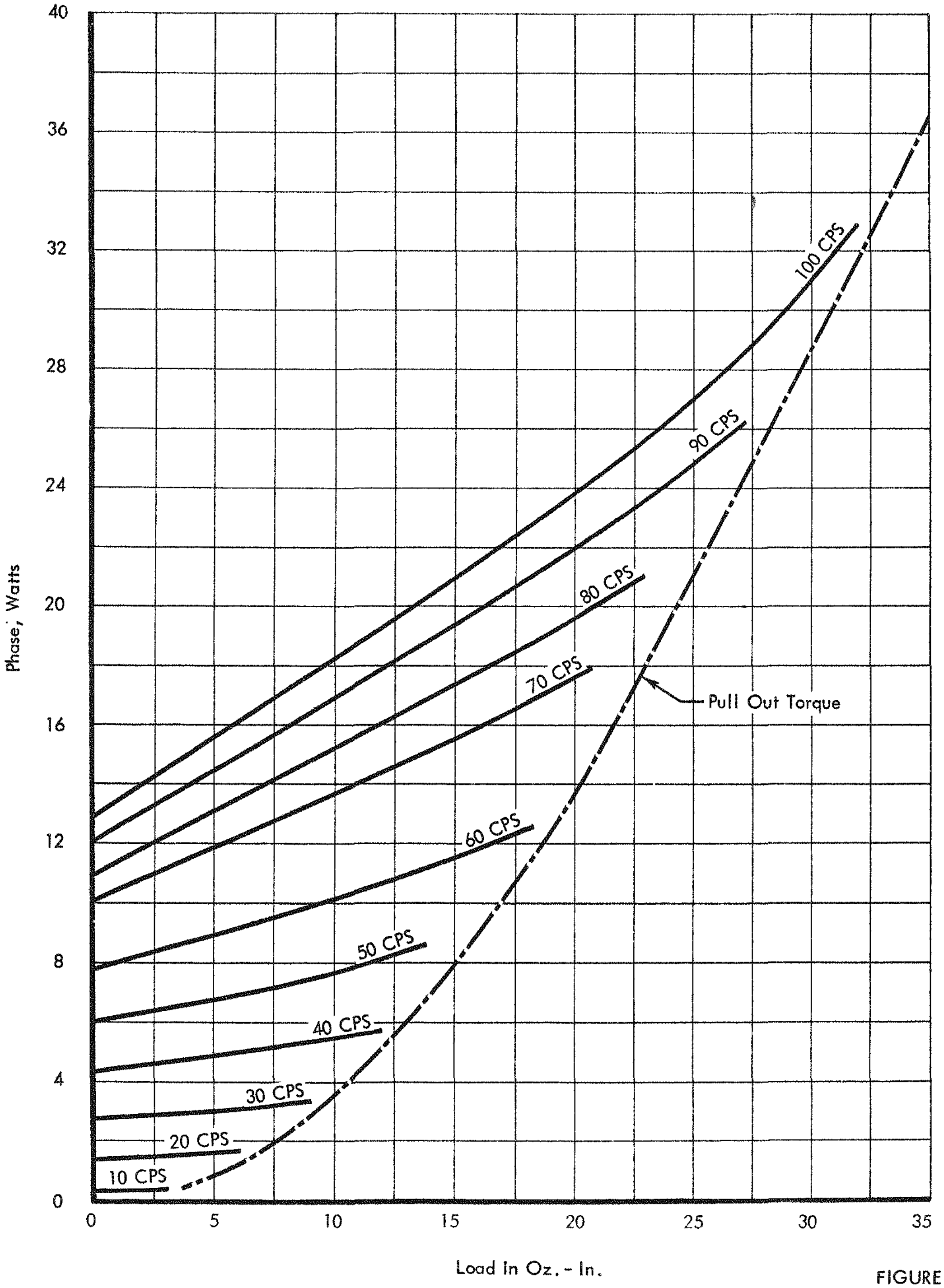


FIGURE 4-13

5.0 FLUX-SWITCH ALTERNATOR

At the beginning of the SNAP I program there was a requirement to provide a calibrated loading device for turbine evaluation. Since the lead time required to provide a permanent magnet unit would have been excessive and would have greatly delayed turbine testing, a flux-switch alternator was selected. The only requirement for the loading device was that it absorb 500 watts of power at 40,000 rpm and perform satisfactorily in the high temperature mercury vapor environment.

The flux-switch alternator is an inductor type alternator that is very well adapted to the high speed requirements of this application. The rotor consists of a laminated stack and thereby minimizes the rotor stress problem. The stator can be separately excited and as a result, the alternator load can be easily varied from no load to full load. With this type of unit, almost any load within the rating could be provided over a fairly wide speed range. This is not true of the permanent magnet type, because the load capabilities drop off quite quickly with speed. A photograph of the flux-switch alternator stator is shown in Figure 5-1.

5.1 Design and Performance

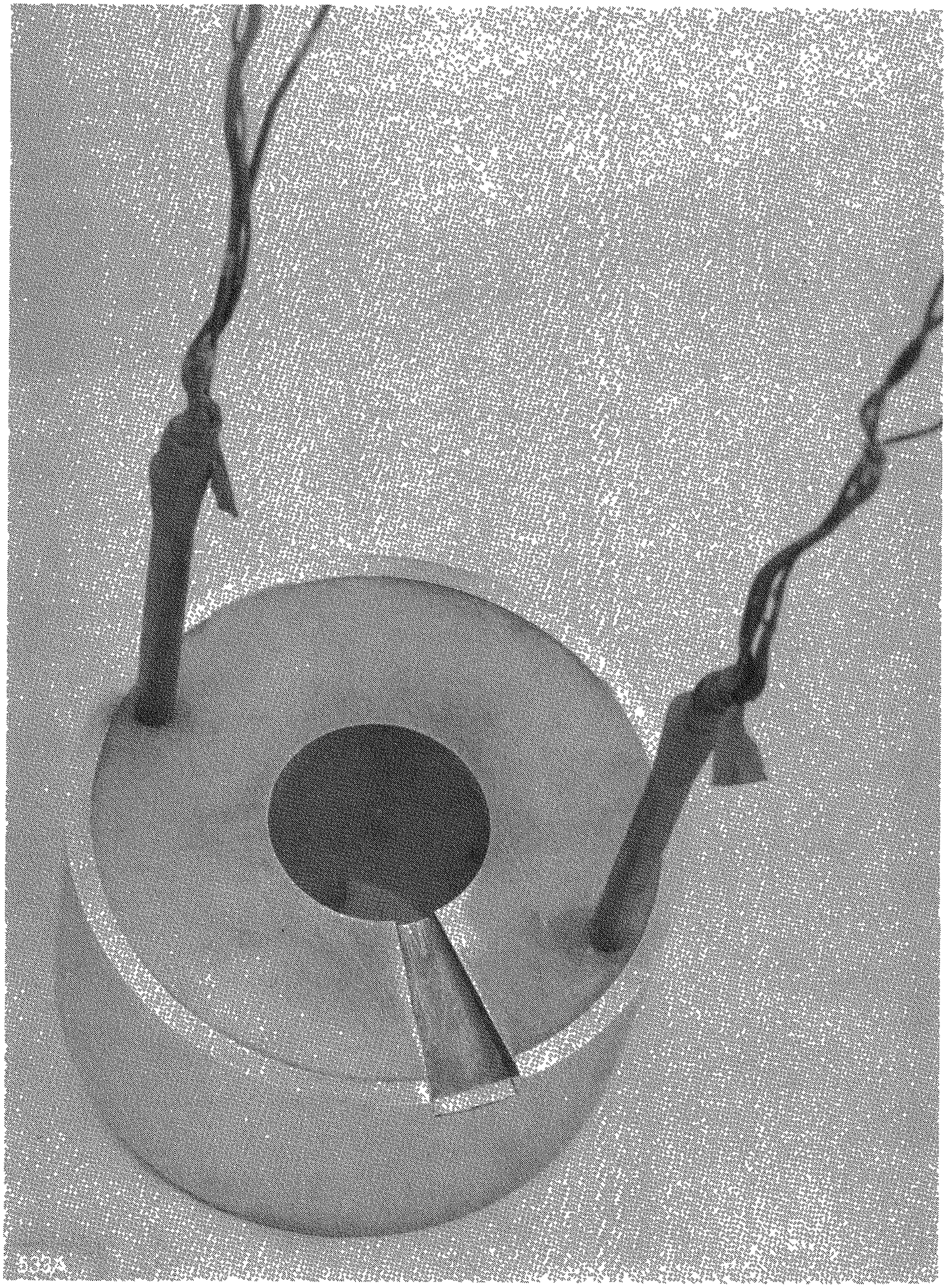
The design of the flux-switch unit was predicated on available laminations which were a part of a production item at TRW. The unit was designed and fabricated using commercially available class H materials.

The stator was completely sealed using a nonmagnetic stainless steel tube in the bore. Although the eddy current losses in this tube were quite high, the losses could be dissipated. It must be noted that nearly all the alternator loading on the shaft takes place in the bore tube, and could result in buckling of the bore tube if the heat were not dissipated quickly.

Cooling was provided through an annular passage around the O.D. of the stator. The coolant was liquid mercury at an inlet temperature of 250°F which kept the alternator stator winding temperature below 500°F by controlling the mercury flow.

The performance of this unit at both design and off-design speeds is shown in Figure 5-2. The alternator was designed to operate at a terminal voltage of 120 volts and to absorb 500 watts at that level. It should be noted that the performance data shown on Figure 5-2 were taken with no external load so that all the input power appears as losses in the alternator. Approximately 95% of these losses occur as eddy current losses in the bore tube which points out the need of a nonmetallic bore seal for the permanent magnet unit.

Because the motoring dynamometer (described in Section 6.2) was not available, other methods of calibrating the alternator were required. The two methods evaluated were the measurement of input power to the test stand turbine and deceleration tests on the turbine.



TOTALLY ENCLOSED FLUX - SWITCHING ALTERNATOR STATOR

FIGURE 5-1

FLUX SWITCH ALTERNATOR

Power Absorption Vs. Terminal Volts
20000 and 30000 RPM

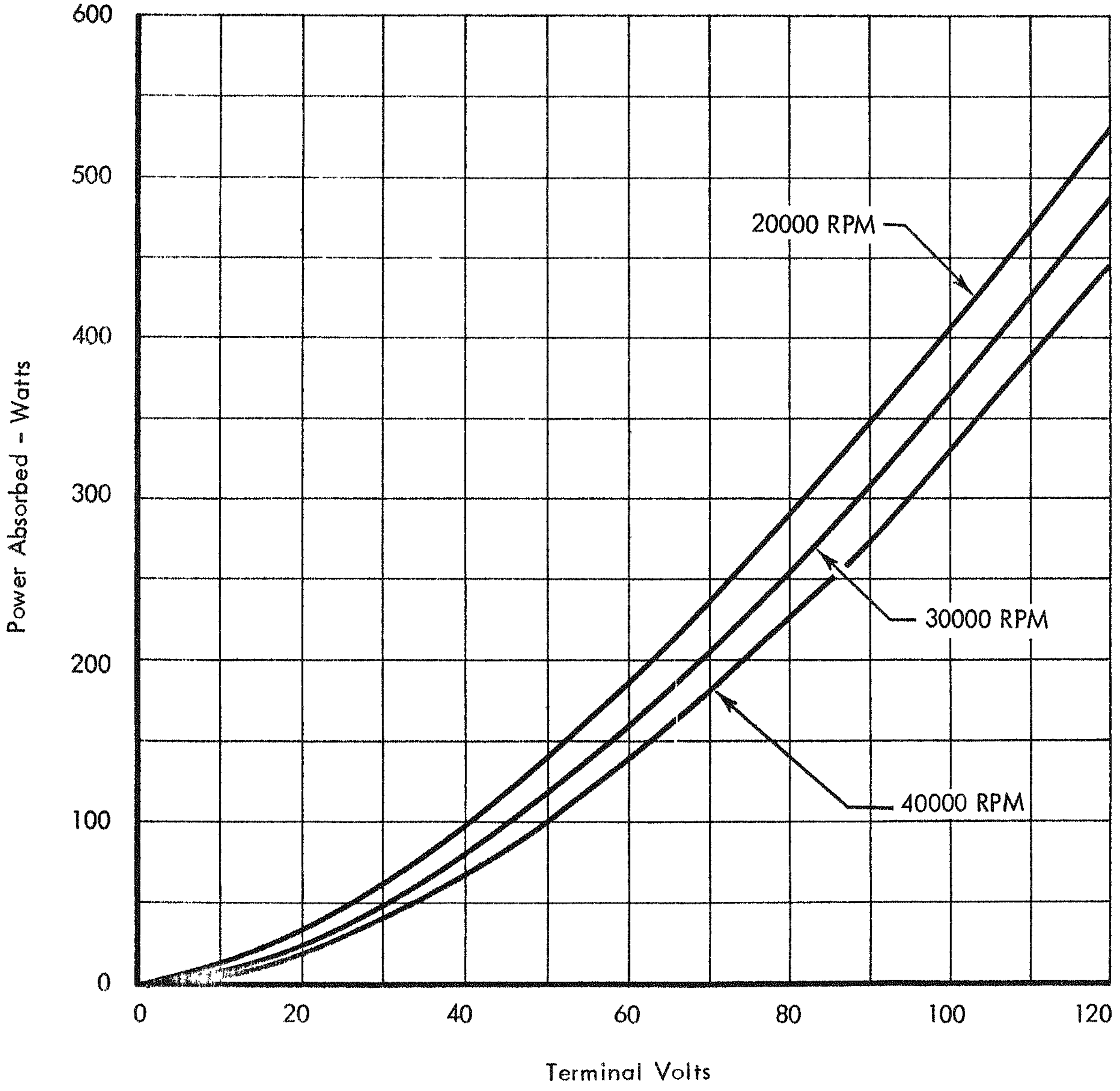


FIGURE 5-2

The measurement of turbine inlet power by evaluating input air flow and temperature drop, did not provide consistent results. The cause of these inconsistencies was traced to the variation of turbine efficiency with load, and this method had to be abandoned.

The speed decay tests provided repeatable results within 5% accuracy. In this method the measurement or calculation of three parameters are required: the moment of inertia of the shaft assembly, the angular velocity, and the shaft deceleration. The moment of inertia of the shaft was calculated and then measured by the torsional pendulum method with very close agreement of the results. The angular velocity was easily calculated at any speed. In order to measure rotor deceleration, a trace of the shaft speed decay versus time was taken at a given load condition. The slope of this curve was then calculated to find the deceleration. The power supplied to the alternator from the shaft was the product of these three parameters.

6.0 TEST FACILITIES

The test facilities for the SNAP I alternator development consisted of three test rigs: (a) Performance Test Rig, (b) Motoring Dynamometer, (c) Motor Startup Rig. The Motor Startup Rig has been described previously.

6.1 Performance Test Rig

The Performance Test Rig is shown schematically in Figure 6-1 and pictorially in Figure 6-2. The rig consisted basically of an air-driven turbine which was adapted from a turbine-driven fuel pump that was in production at TRW. It had the capability of providing the necessary power at the required high operating speeds. At the beginning of this program, a study of available electric motors in the required output range was made, but no suitable supply was commercially available.

The turbine power was metered so that the alternator efficiency could be estimated. The parameters measured for this determination are: inlet pressure, air flow and inlet and outlet temperature. This data however did not provide consistent results, which was partially due to a great variation in turbine efficiency over the load range.

The test rig also contained an oil coolant loop which was instrumented to provide a measurement of the stator losses by metering the inlet and outlet pressures and temperatures, and the coolant flow rate. This coolant loop was obseleted when the alternator design was changed so that no external coolant was required.

The test rig also included a speed indicator and an overspeed control. Although not an integral part of the Performance Test Rig, the load bank is described here. The load bank had a rating of 800 watts and 800 var at 120 volts 4000 cps, single phase. The reason the load bank was rated at 4000 cps is that it was first used for evaluation of the flux switch alternator which operated at the higher frequency. The load bank was a special design by Avtron Manufacturing Company for this program.

6.2 Motoring Dynamometer

A study was made to establish procurement problems of a motoring type dynamometer. Because it was found that extremely long lead time and expense were required, it was decided to design and fabricate this dynamometer at TRW.

An electric drive was selected because it offered the finest control and maximum flexibility for use at different speeds. To drive the alternator at 40,000 rpm, an aircraft, two-pole induction motor was purchased from the Bekey Electric Company. A low slip type was selected in order to obtain good speed regulation. As a power source for this motor, a variable frequency power supply was purchased from the Hertner Electric Company to the following specifications:

PERFORMANCE TEST RIG SCHEMATIC

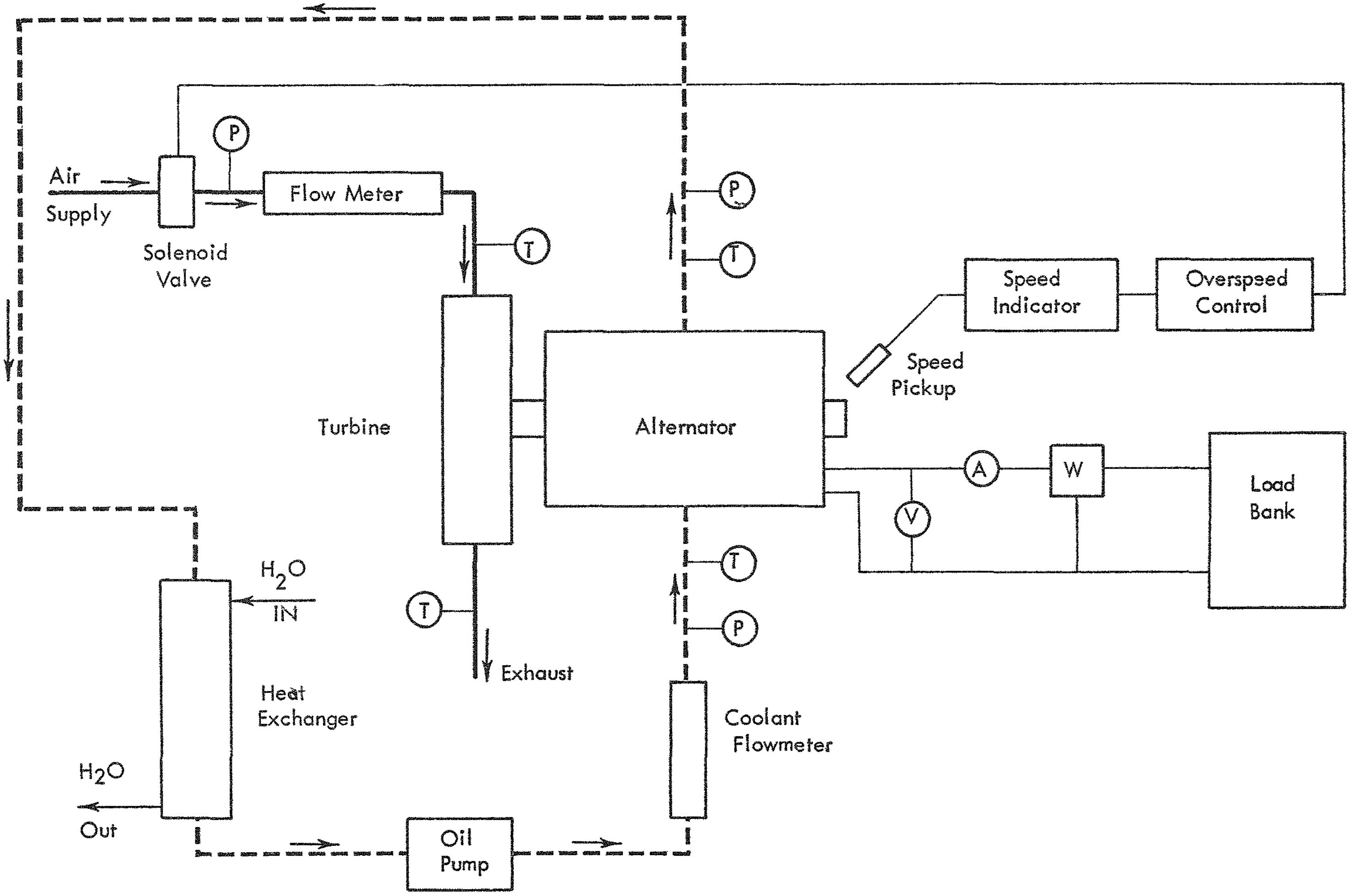
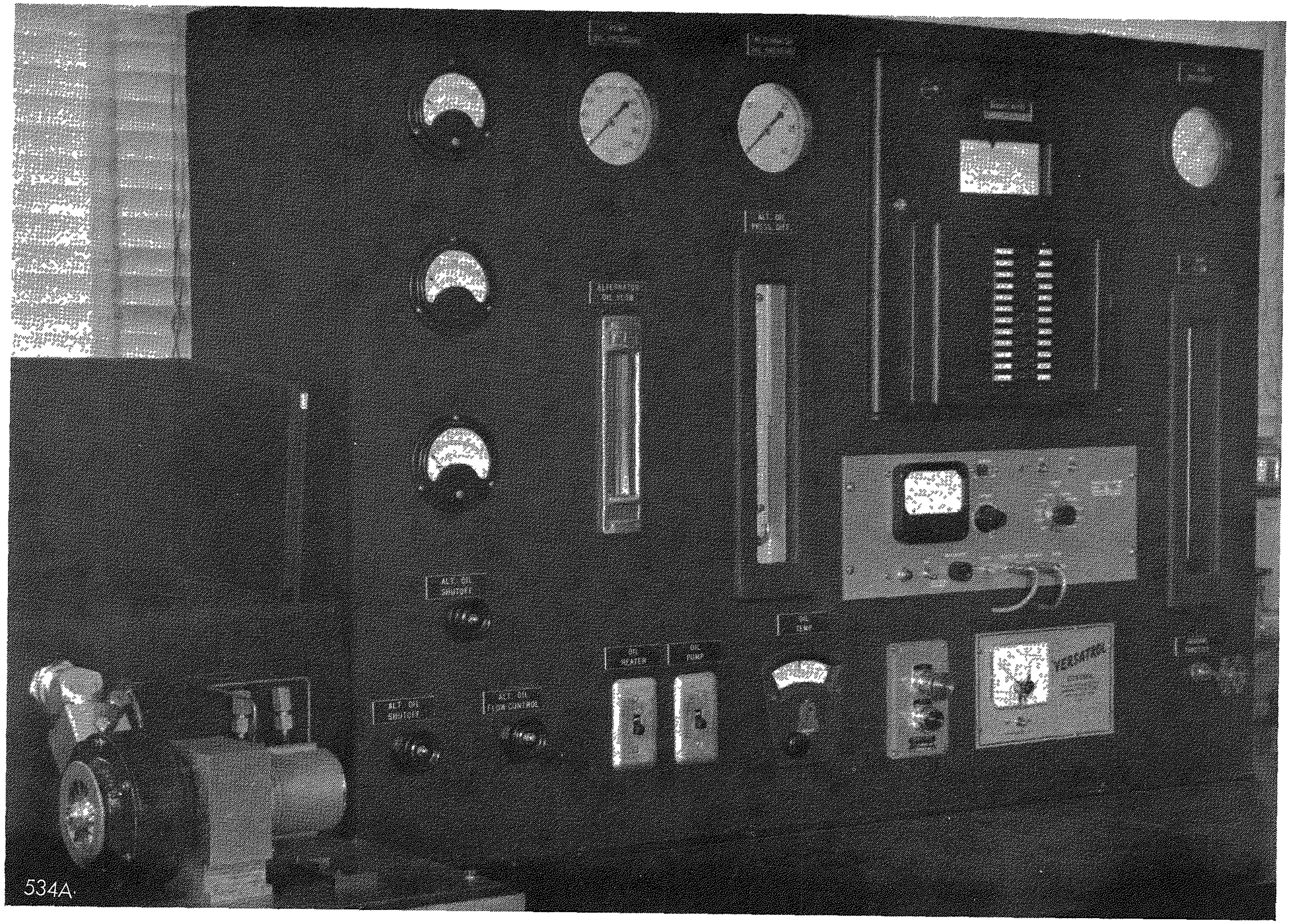


FIGURE 6-1



PERFORMANCE TEST RIG

FIGURE 6-2

Rating: 10 kw @.8 pf 3 ph 120/208 or 240/416 volts, 400 to 800 cycles (rating at 800 cps; rating proportional to frequency). Alternator direct coupled to and driven through a Reeves (8000 frame) varispeed mechanical speed-changer by a nonexcited synchronous motor. Unit was furnished with electric push button type remote frequency adjusting device, static d.c. exciters, magnetic amplifier voltage regulation, voltage adjusting rheostats and tachometer generator.

Voltage regulation: ±2% at any preset frequency from no load to full load, and ±4% over the frequency range.

Frequency regulation: With 60 cycle input frequency, the output frequency variation is between 0% at no load and -1% at full load.

Voltage adjustment: The output voltage is continuously adjustable from 70% to 110% of the rated value with the voltage regulator in operation and from +40% to 110% by direct manual control.

Frequency adjustment: The output frequency is continuously adjustable from 400 to 800 cycles.

The torque measuring device consisted of a linear variable differential transformer (LVDT) which received the reaction force transmitted from the cradled drive motor through a tee bar. The LVDT consisted of a movable core mounted on cantilevered springs. The output signal of the LVDT was fed to an amplifier. The amplifier output was fed to an indicator which was calibrated in torque. A block diagram is shown in Figure 6-3.

SNAP II ALTERNATOR DYNAMOMETER TEST STAND

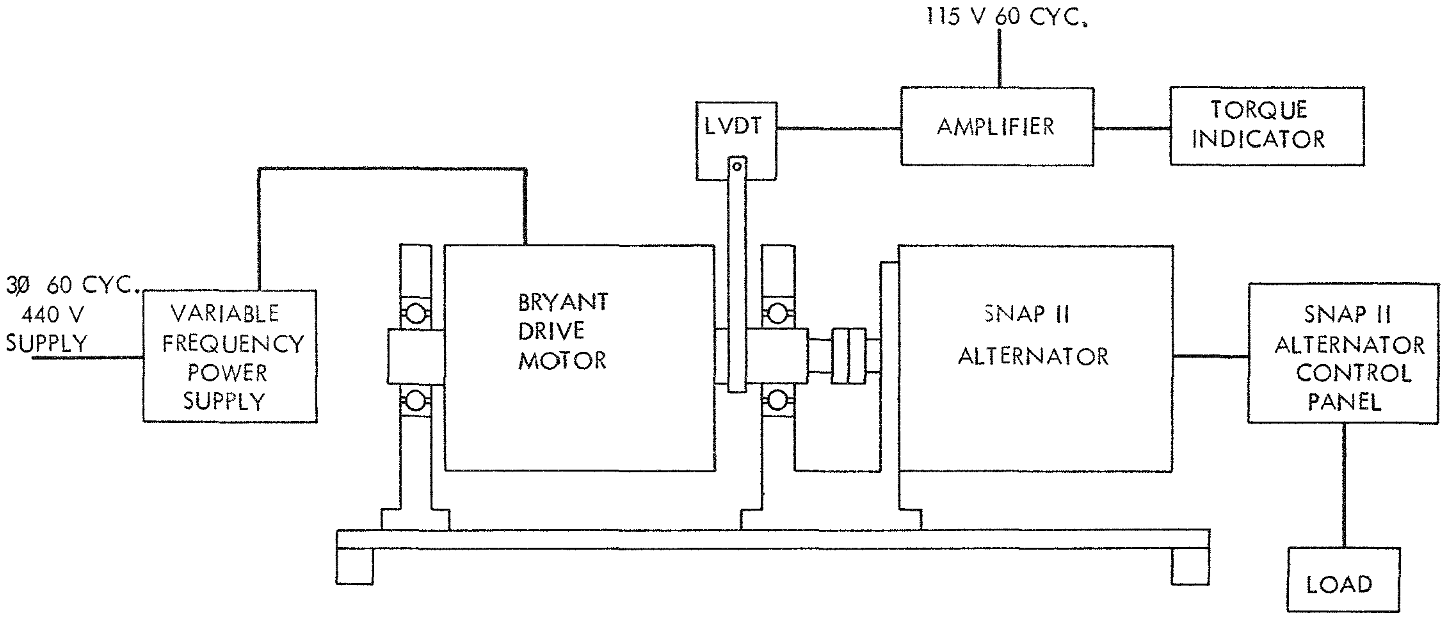


FIGURE 6-3

7.0 CONCLUSIONS

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

1. A permanent magnet rotor was constructed for operation in a high temperature mercury vapor atmosphere. This rotor functioned satisfactorily under the high temperature and mechanical stress conditions that were present. The performance of the rotor was close to design predictions.

2. Insensitivity to nuclear radiation was considered in the alternator design. Although no material investigations were conducted, care was taken to use materials whose reported radiation resistance properties were satisfactory for the SNAP I application.

3. The stator for the alternator also performed satisfactorily in the adverse environment. Although all performance objectives were not completely met, the only serious deficiency in performance was efficiency. Because the alternator load was to be constant, the voltage regulation was not considered a serious problem. One method of increasing efficiency is by a design change, but a far easier solution is to utilize multiple phase loading. An alternator efficiency increase to approximately 90% would be realized by loading the machine two-phase. No design changes would be required since the alternator was designed as a two-phase unit and then connected single-phase. A similar efficiency increase has been realized on the SNAP II alternator by utilizing two-phase operation.

4. The bore seal is probably the greatest problem area. A leak-tight bore seal has been realized which performed satisfactorily for long durations, but the fabrication methods leave much to be desired. Future work is required to guarantee the integrity of the seal.

5. The motor startup capabilities is also a possible problem area. However, with a properly designed power supply of sufficient capability, it has been established that satisfactory startup can be accomplished. A two-phase electronic source was purchased for the SNAP II program and is presently being evaluated.

6. The endurance capability of the alternator was successfully demonstrated in a system endurance test lasting 2510 hours. At the end of the endurance test, the alternator performance was within design limits and did not decay with time.

BIBLIOGRAPHY

The reports listed in the bibliography are not available for general distribution. Any inquiries concerning the availability of this information should be directed to the AEC.

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EN 546	Calibration Data - PTP II Alternator	5/4/59	Secret
EN 618	Alternator Calibration Data - PTP Spare	6/29/59	Secret
EN 619	Performance VIP - I Alternator	6/29/59	Secret