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STEADY-STATE CHARACTERISTICS OF A 1200-HERTZ ALTERNATOR AND ELECTRICAL CONTROLS OPERATING IN A SINGLE-SHAFT BRAYTON-CYCLE POWER SYSTEM USING KRYPTON GAS

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16. Abstract

Steady-state performance of a 1200-Hz alternator, a voltage regulator, a series field controller, and a parasitic speed control is presented for an operating range of 1 to 10 kW. Test results show that the parasitic-load power factor (lagging) varied from 0.50 to 0.95. High neutral currents were measured with a maximum current of 21 A at 2.4 kW. Maximum voltage deviation from rated 120 V was 3.3 percent. Measured peak alternator hot-spot temperature was 495° F (257° C) at the rotor heat shield for an output of 10.1 kVA.

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SUMMARY

Steady-state performance of a 1200-hertz alternator, a voltage regulator, a series field controller, and a parasitic speed control is presented. These components operated for 200 hours in a closed-loop Brayton power system using krypton gas. Test results include alternator excitation requirements, speed control characteristics, parasitic-load power factor, neutral current, load voltage variation, and temperatures.

The parasitic-load power factor (lagging) varied from 0.50 to 0.95 for the tested operating range of 1 to 10 kilowatts. High neutral currents were measured with a maximum current of 21 amperes at 2.4 kilowatts. Maximum voltage deviation from rated 120 volts was 3.3 percent. Measured peak alternator hot-spot temperature was 495° F (257° C) at the rotor heat shield for an output of 10.1 kilovolt-amperes.

INTRODUCTION

As part of a program to develop a 2- to 10-kilowatt space power system, the Lewis Research Center is presently investigating the performance of a 1200-hertz Brayton power conversion system (refs. 1 to 3). One test program currently in progress is studying the performance characteristics of a Brayton rotating unit (BRU) and a Brayton heat exchanger (BHXU) operating in a closed loop using an inert gas as the working fluid. The BRU consists of a turbine, alternator, and compressor on a single shaft supported by gas-lubricated bearings. The BHXU is a recuperator and a waste heat exchanger. The alternator is integrated with an electrical subsystem which consists of a voltage regulator, series field controller, and a parasitic speed control.

The steady-state performance characteristics of the alternator and electrical subsystem were measured and are presented herein.

Performance data presented resulted from the first 200 hours of continuous closed-loop operation. To minimize costs, the working fluid used for this initial testing was krypton. Krypton has aerodynamic properties and molecular weight (83.8) close to that of the helium-xenon mixture which is the design working fluid for this system.

The normal operating characteristics of a breadboard voltage regulator, series field controller, and parasitic speed control are presented. Included are test data showing the effects of parasitic loading on the alternator output. Temperatures in the alternator for various load conditions and turbine-inlet temperatures are also presented.

APPARATUS AND PROCEDURE

Figure 1 is a schematic of the closed-loop single-shaft Brayton power conversion system. This system is capable of producing an electrical power output of 2 to 10 kilowatts. The only system hardware used in the test facility were the BRU, BHXU, and breadboard equivalents of the flight-type electrical system controls. The electrical heat source, gas management system, and heat rejection system used were test support equipment designed and built at the Lewis Research Center. Detailed descriptions of this Brayton power system may be found in references 1 and 2.

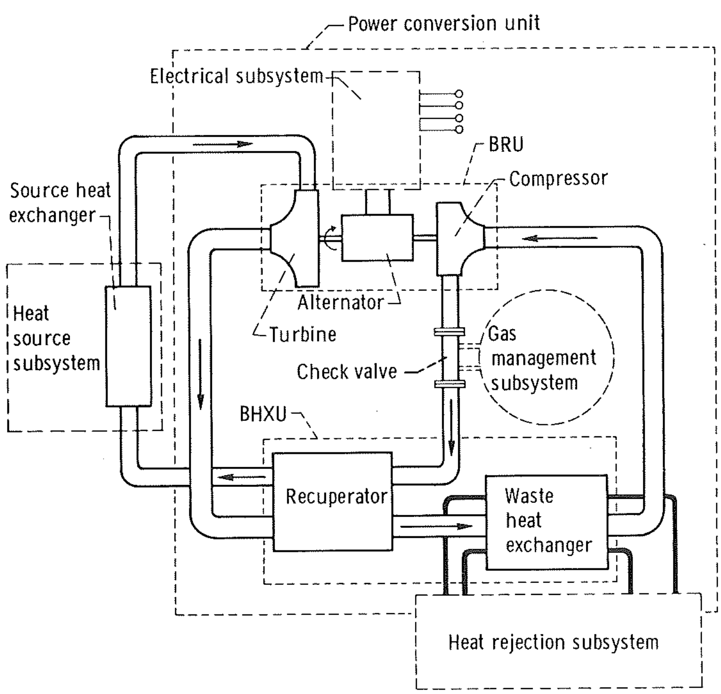

Figure 1. - Schematic diagram, Brayton power system.

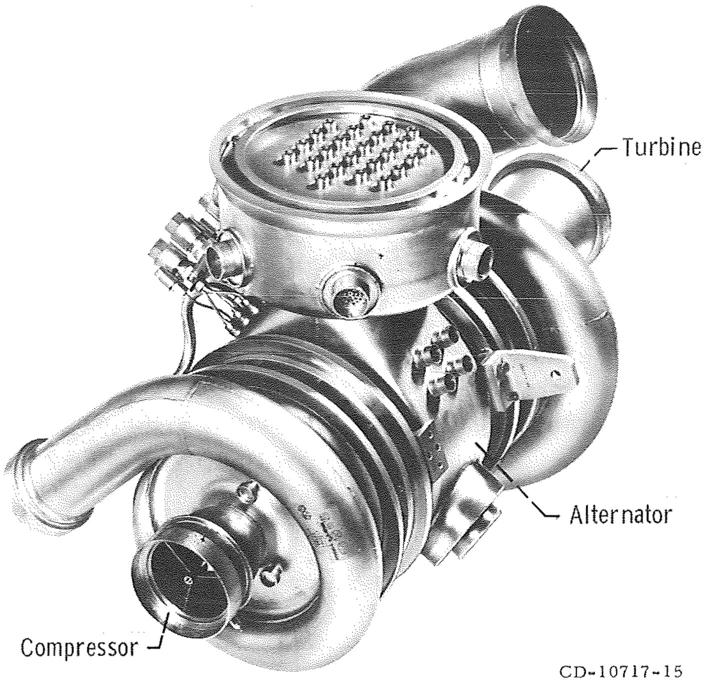

Figure 2. - Brayton rotating unit.

BRU Alternator

The BRU, shown in figure 2, consists of a turbine, alternator, and compressor mounted on a single shaft supported by gas-lubricated bearings. Figure 3 is a sectional view of the BRU alternator.

The alternator, which is described in reference 3, is a modified Lundell alternator

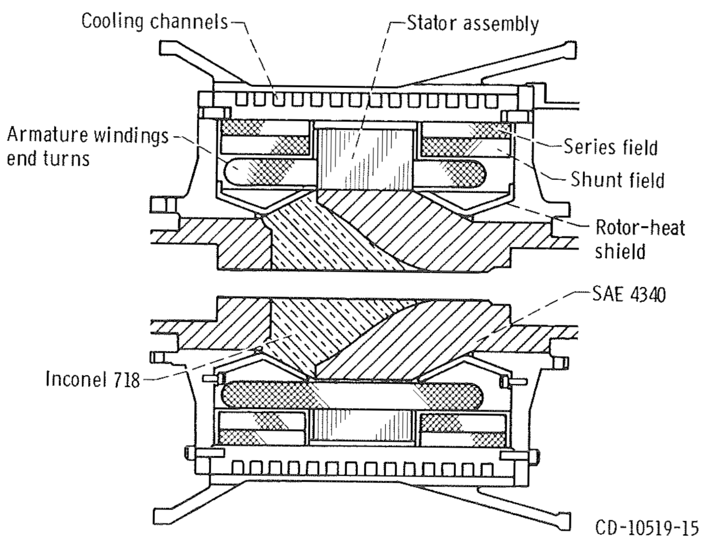

Figure 3. - Sectional view of BRU alternator.

having a solid-bimetallic-rotor, two stationary field windings, and a stationary armature winding. The rated output is 14.3 kilovolt-amperes at 0.75 lagging power factor and 120/208 volts. The frequency is 1200 hertz and the speed is 36 000 rpm.

Prior to this testing, detailed performance data were obtained for an electromagnetically equivalent machine. These data are presented in references 4 and 5.

Electrical Controls

Figure 4 is a block diagram of the Brayton electrical system tested. Photographs of the breadboard voltage regulator, series field controller, and speed controller are shown

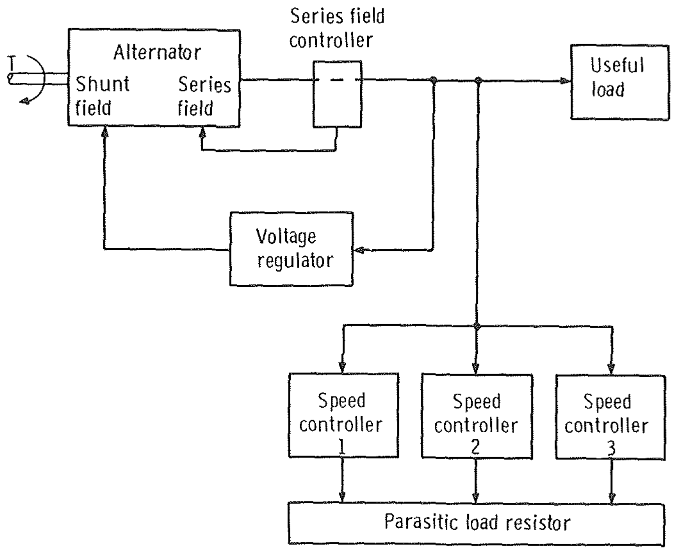

Figure 4. - Block diagram of Brayton electrical system.

in figures 5 and 6. The series field controller delivers current to the series field in direct proportion to armature current. The voltage regulator provides excitation to the shunt field to maintain constant voltage at the useful load. The three-speed controllers vary the current into the parasitic load resistor as a function of line frequency. The parasitic load automatically compensates for variations in the useful load and thereby maintains constant BRU speed. Table I gives design specifications for the voltage regulator and parasitic speed control. More detailed descriptions of these electrical controls may be found in references 3 and 6.

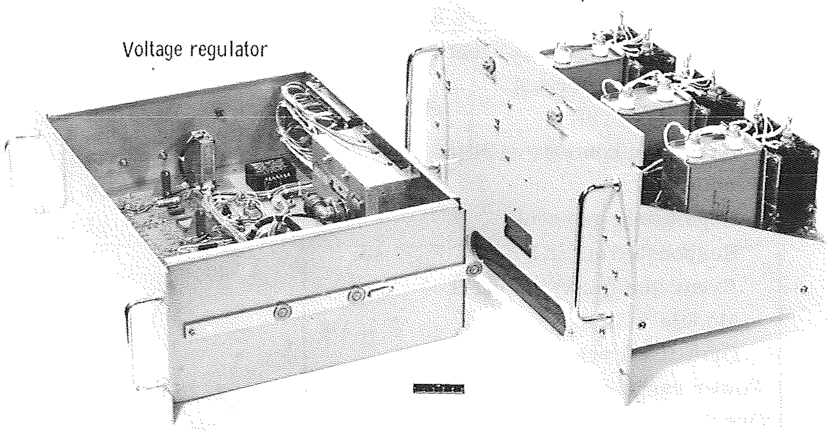

Figure 5. - Breadboard control devices.

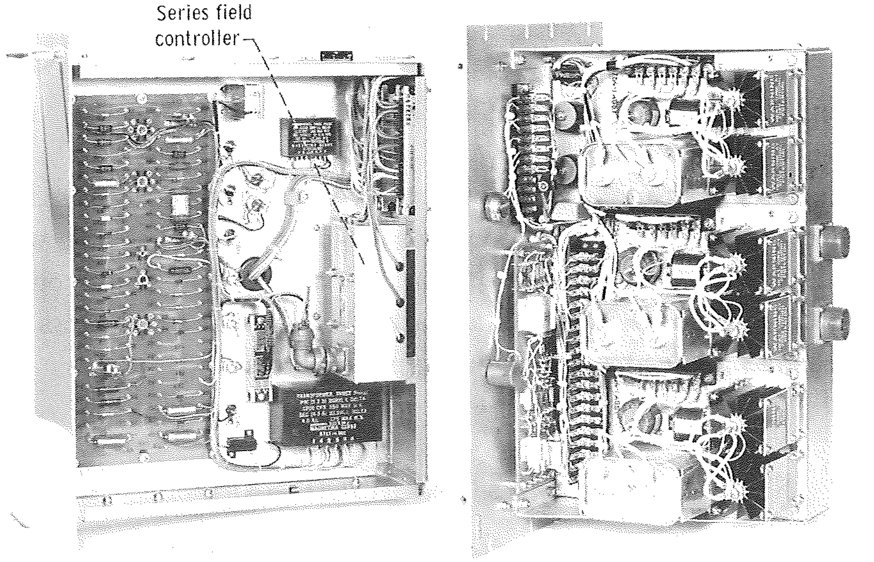

Figure 6. - Detailed view of breadboard control devices.

TABLE I. - SYSTEM REQUIREMENTS

Voltage	120/208
Regulation, percent	[a]±1
Response time ($\Delta E \leq \pm 5\% \; E_R$), sec	1/4
Excursion (max), percent	[a]136
Modulation, percent	[a]1/2
Drift ($t \geq 5$ yr), V	1
Harmonic content, percent	[a]5
Frequency, Hz	1200
Regulation, percent	±1
Response time ($\Delta F \leq \pm 2\% \; F_R$), sec	1
Excursion (max), percent	±2
Modulation, Hz	±2
Drift ($t \geq 5$ yr), Hz	±2
Power range-optimum, kW	2.25 to 10.5
Overload rating (for 5 sec), kVA	21
Short circuit rating (for 5 sec), per unit	3
Electrical interference	MIL-STD-826
Design life (min), yr	5
Coolant temperatures, $^{\circ}$F ($^{\circ}$C)(nom)	
Alternator	70 (21)
Controls	90 (32)
Environmental specification	NASA P1224-1, -2
Neutron flux, neutrons/cm^2	$\leq 10^{11}$
Integrated gamma dose (in 5 yr), rad	$\leq 10^{4}$

[a]Alternator-voltage regulator combination only.

Experimental Procedure

The procedures used for the 200-hour test were as follows: For given turbine- and compressor-inlet temperatures, the compressor-discharge pressure was adjusted to vary the total alternator output power. Then, for a given alternator output, the division between useful and parasitic loads was adjusted for several data points. In all cases the useful load was kept balanced and near unity power factor.

RESULTS AND DISCUSSION

Alternator Excitation Requirements

The curves in figure 7 show the series-field current and shunt-field current variation with alternator output power at 0.9 power factor. Series-field current supplied by the series-field controller is directly proportional to armature current. Hence, with

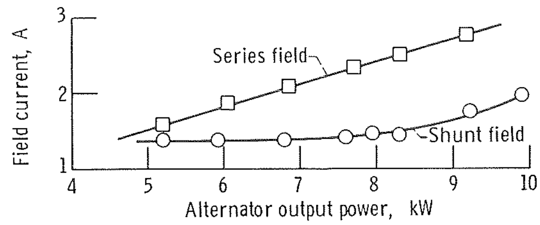

Figure 7. - 1200-hertz alternator excitation requirements for 0.9 power factor (lagging) loads.

constant voltage and power factor, the series-field current varies linearly with alternator output power. This series-field excitation supplies the ampere-turns for changes in alternator loading and short circuits.

The shunt-field current is relatively constant and varies between 1.38 and 2.0 amperes over the power range from 5 to 10 kilowatts. Shunt-field excitation supplies the additional ampere-turns needed to maintain constant voltage at the useful load.

Speed Control Characteristic

Figure 8 shows data for up to 8 kilowatts of parasitic loading as a function of in-

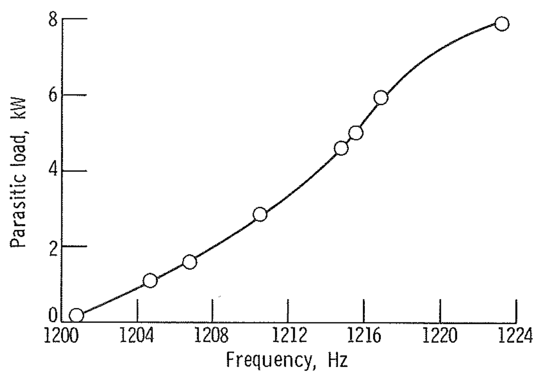

Figure 8. - Variation of parasitic load with frequency.

creasing frequency above 1200 hertz. Since each speed controller can apply a maximum of 6 kilowatts of parasitic load, this curve indicates that the first unit is turned fully on and the second unit is also absorbing approximately 2 kilowatts of load. The slope of this curve represents the gain of the speed control. For the curve shown, the average gain is 0.33 kilowatt per hertz and the overall change in frequency is 24 hertz (720 rpm) (2 percent). During the testing, the speed controllers were adjusted to provide maximum gain without introducing instabilities in the system. Speed controller instabilities were observed in earlier testing in another facility and are discussed in reference 7.

Parasitic-Load Power Factor

The power factor of the parasitic load is presented in figure 9. The curve shows

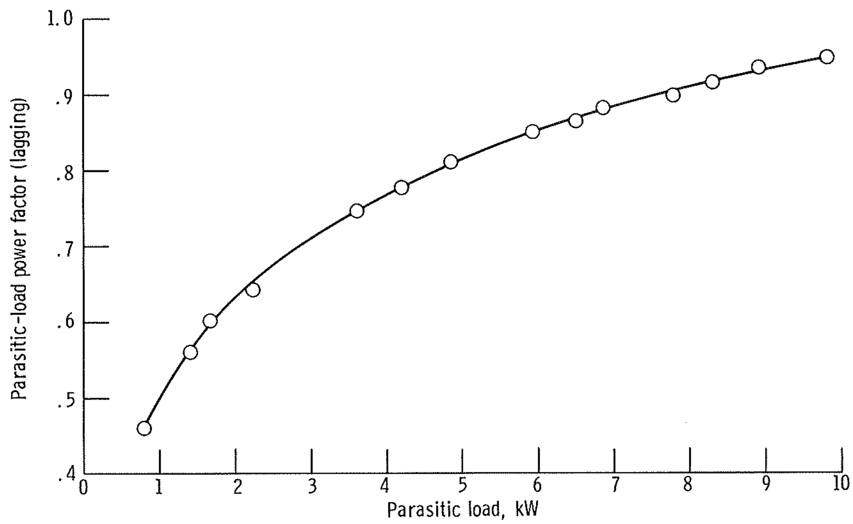

Figure 9. - Parasitic-load power factor as function of load.

that the power factor varied from 0.50 to 0.95 for the operating range of 1 to 10 kilowatts. The variation in power factor shown results from the effects of the phase-controlled parasitic load current. Phase-controlled currents are periodic, but nonsinusoidal. As a result, they introduce harmonic distortion into the alternator current and voltage. In addition the fundamental component of the phase-controlled current lags the applied voltage and thus causes the power factor to be lagging. Both of these effects vary with speed-controller firing angle which determines the parasitic power, and both are considered undesirable from the standpoint of increased alternator volt-ampere loading and output distortion. These effects are discussed in greater detail in references 8 and 9.

Neutral Current

Neutral-current variation with parasitic loading is shown in figure 10. The useful

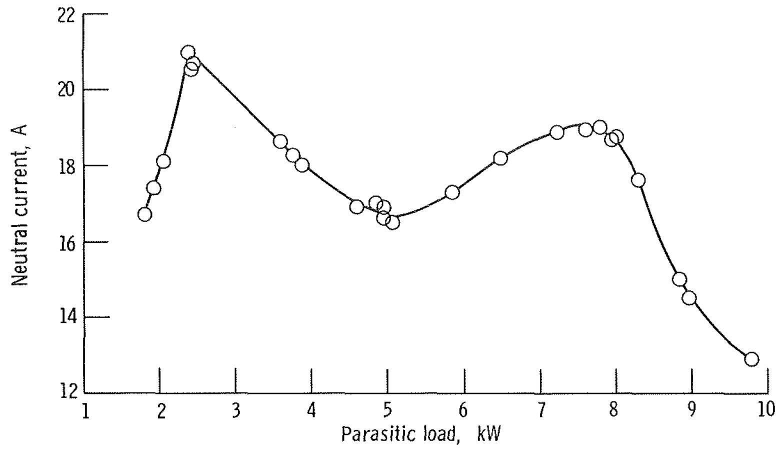

Figure 10. - Variation of 1200-hertz alternator neutral current with parasitic load.

load is zero. Maximum neutral current is 21 amperes at 2.4 kilowatts. The magnitude and variation of neutral current results from two effects. First is the effect of unbalanced parasitic loading caused by the differences in the individual firing circuits in the speed controllers. These differences affect the firing angles of the SCR's, thus producing unbalanced currents which vary in magnitude with parasitic power.

The second effect arises from the current harmonics caused by the firing of the SCR's, which also varies with the firing angles of the SCR's. These harmonics tend to add and result in the neutral current shown. Since the harmonics vary with the SCR firing angle, the neutral current varies with parasitic load.

Useful Load Voltage Variation

The variation of the useful load voltage is shown in figure 11 for a constant alternator load of 9 kilowatts. The voltage varies from approximately 116 to 121 volts. Ideally the useful load voltage should be constant at 120 volts. The maximum deviation from 120 volts is 3.3 percent. This deviation will be reduced during future tests by adjusting the voltage regulator such that the maximum deviations above and below 120 volts are about equal. The resulting deviation would be less than 2 percent.

The variation shown in figure 11 is probably due to the effects of the parasitic loads.

Alternator Temperatures

Figure 12 shows the alternator winding temperatures as a function of alternator

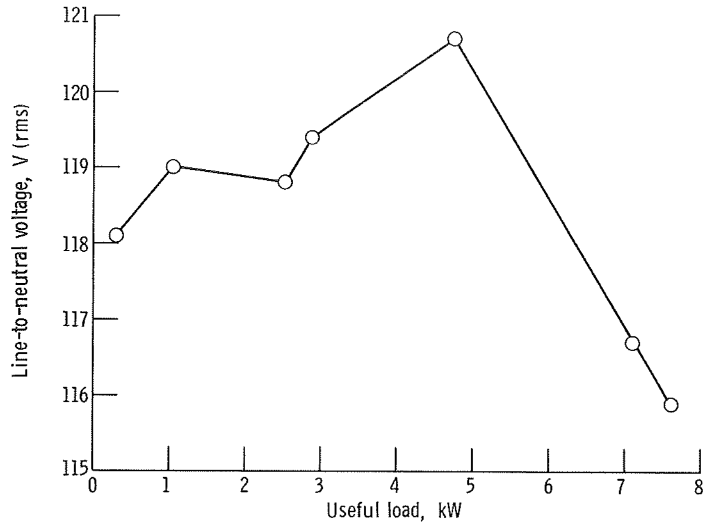

Figure 11. - Average useful load voltage. Alternator output, 9 kilowatts; useful load power factor, 1.0.

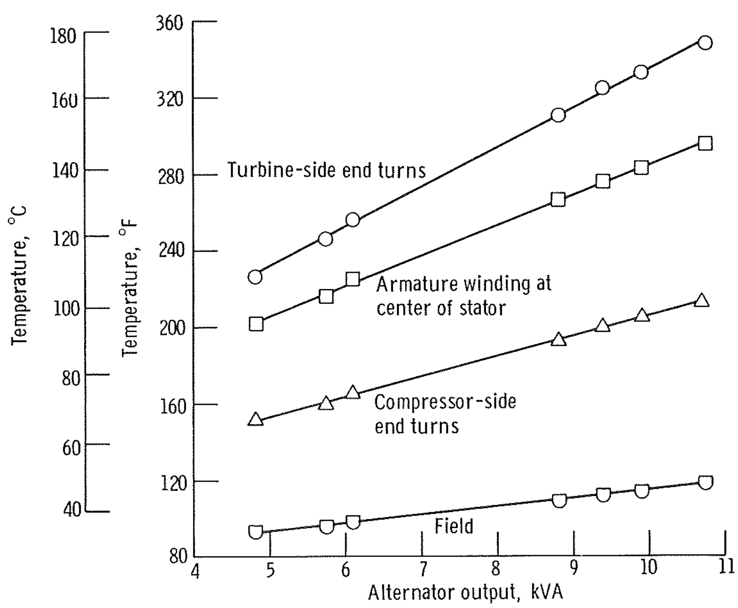

Figure 12. - 1200-Hertz alternator winding temperatures. Turbine inlet temperature, 1600° F (871° C); compressor inlet temperature, 70° F (21° C); coolant inlet temperature, 55° F (13° C); coolant flow rate, 3.3 gallons per minute.

output (kVA). The end turns on the turbine side are hotter than the end turns on the compressor side. The maximum end-turn temperature was 348° F (175° C) at 10.75 kilovolt-amperes. The data also indicate that the field temperature was lower and varied only 26° F (14° C) over the range of loads investigated. This results from the fact that the field has low losses (ref. 4) and is in close proximity to the stator cooling channels which resulted in good heat transfer.

The alternator-rotor heat-shield temperature at the turbine side is presented in figure 13. Measured peak hot-spot temperature was 495° F (257° C) with design

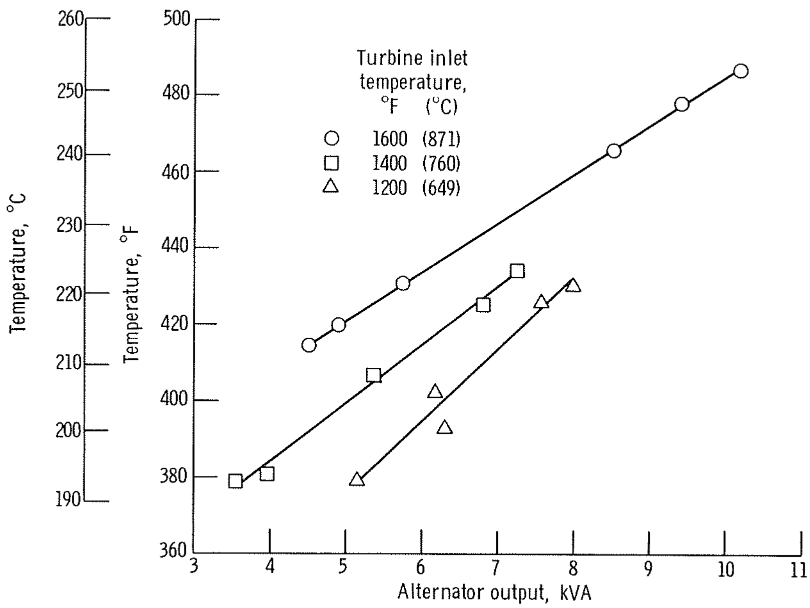

Figure 13. - 1200-Hertz alternator rotor heat-shield temperature. Coolant inlet temperature, 55° F (13° C); compressor inlet temperature, 70° F (21° C).

turbine-inlet temperature of 1600° F (871° C) and an output of 10.1 kilovolt-amperes. For this test krypton gas was present in the rotor cavity. As the cavity pressure increases with increasing alternator output, the windage loss increases. The windage loss is significant and causes heating of the rotor heat shield as load increases. Figure 14 shows the effect of parasitic loading on alternator output and rotor heat-shield temperature for constant alternator load of 9 kilowatts. The useful load power factor was unity. As parasitic load increases to approximately 5 kilowatts, the temperature also rises. Since the total load power was held constant, the low parasitic-load power factor causes an increase in armature current and a reduction in alternator power factor as indicated by the increasing alternator kilovolt-amperes. Thus, the armature copper losses within the alternator increase and contribute to the heating of the rotor heat

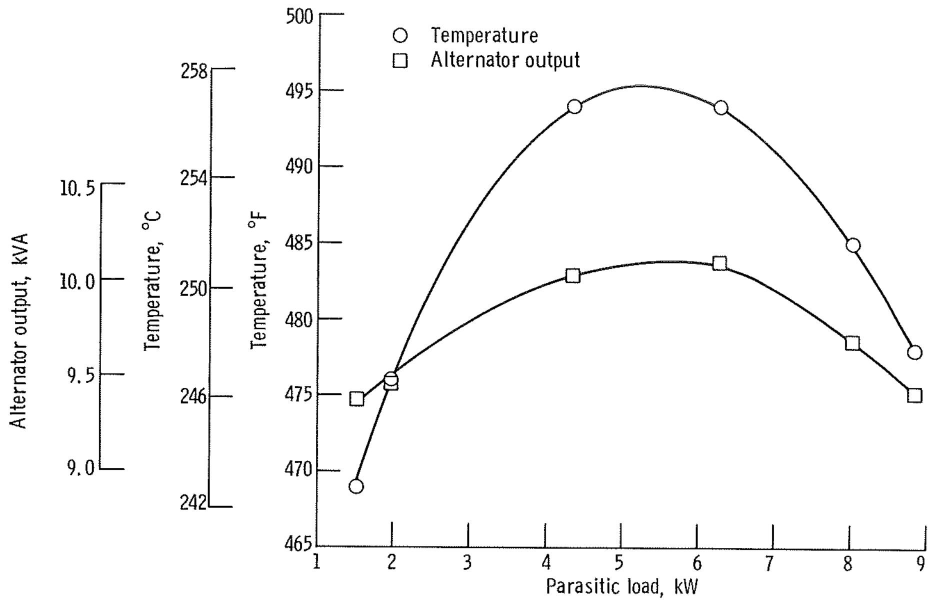

Figure 14. - Effect of parasitic load on 1200-hertz alternator output and rotor heat-shield temperature for a 9-kilowatt total load. Turbine inlet temperature, 1600° F (871° C); compressor inlet temperature, 70° F (21° C); coolant inlet temperature, 55° F (13° C); coolant flow rate, 3.3 gallons per minute; useful load power factor, 1.0.

shield. Above 5 kilowatts parasitic load, the alternator power factor increases which causes a corresponding reduction in armature current and losses.

SUMMARY OF RESULTS

The significant test results obtained during the 200-hour test on the alternator and electrical controls are as follows:

1. The power factor (lagging) of the parasitic load varied from 0.50 to 0.95 for the operating range of 1 to 10 kilowatts.

2. Maximum neutral current was 21 amperes at 2.4 kilowatts.

3. The average useful load voltage varied from 116 to 121 volts with parasitic loading for a total load of 9 kilowatts.

4. Measured peak alternator hot-spot temperature was 495° F (257° C) at the rotor heat shield with design turbine-inlet temperature (1600° F or 871° C) and an output of 10.1 kilovolt-amperes.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 19, 1970,
120-27.

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