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MOTOR START OF A 2- TO 10-KILOWATT BRAYTON ROTATING UNIT OPERATING ON GAS BEARINGS IN A CLOSED LOOP

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16. Abstract

The Brayton rotating unit (BRU) was motor started in a closed-loop test facility using the alternator as a motor. This report presents the results obtained in terms of minimum required turbine inlet temperature and speed for self-sustaining operation and acceleration time required to reach the design operating speed of 36 000 rpm.

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SUMMARY

The Brayton rotating unit (BRU) was motored in a closed-loop test facility to simulate operation in a Brayton power system. The alternator was used as the motor. The objective of this investigation was to obtain the motor starting performance and operating characteristics of the BRU in a closed, hot test loop. The results of this investigation showed that

(1) Surge could not be detected when the BRU was motored in a closed loop.

(2) Self-sustaining system operation was obtained by motoring to 6600 rpm, with turbine inlet temperatures above 1440° R (800 K).

(3) An operating line with minimum turbine inlet temperature, no electrical load, and constant compressor inlet temperature was established for the BRU in the test loop. Above 15 000 rpm the operating line represents conditions of stable equilibrium, and below this speed the operating line represents conditions of unstable equilibrium.

(4) The higher the speed and turbine inlet temperature, the shorter the time required to reach rated speed. Small increases in speed or turbine inlet temperature above the minimum drastically reduce the time required to reach rated speed.

INTRODUCTION

The NASA Lewis Research Center is investigating the application of the Brayton cycle to electric power generation in space. As part of this program, a single-shaft turbine-compressor-alternator package was designed and built under contract. This package has been designated the Brayton rotating unit (BRU) and was designed for operation on self-acting gas bearings and a working fluid composed of a mixture of helium and xenon.

The first BRU delivered to Lewis was operated in a closed loop to simulate operation in a power generating system over a range of pressure levels and a range of inlet temperatures into the compressor and turbine. The total accumulated operating time was 1000 hours. Reference 1 presents the effects of operating parameters on BRU performance. Reference 2 presents the mechanical performance, and reference 3 presents the alternator performance of the BRU.

The method used to obtain self-sustaining operation in these tests was to inject gas into the partially evacuated loop, through the preheated heater, and then through the turbine to rotate the BRU rotor. The gas injection starting of the BRU is described in detail in reference 4.

Another method of obtaining self-sustaining operation within the BRU and closed loop is to use the alternator as a motor. In this case, the compressor circulates the working fluid around the loop where it picks up heat from the heater. When sufficient pressure ratio is generated by the compressor and sufficient heat is absorbed from the heater, enough energy is provided to the turbine to drive the compressor and overcome windage losses, and BRU operation becomes self sustaining.

The motor characteristics of the BRU alternator were investigated in reference 5 over a range of supply frequencies from 212 to 1200 hertz. Reference 5 showed that magnetic effects during motoring has no adverse effects on gas bearing operation. Also, the BRU alternator operating as a motor could develop enough torque to accelerate the BRU rotor to sufficient speed where self-sustaining operation is possible.

A possible motor starting problem peculiar to radial turbomachinery is that at low speeds and low flow rates the pressure rise associated with the centrifugal forces in the turbine can become quite large compared with the pressure forces developed by the compressor. This results from the fact that the turbine rotor (4.97-in. or 12.62-cm diam) is larger than the compressor impeller (4.25-in. or 10.79-cm diam). Thus it is possible that the turbine may establish flow around the closed loop in the reverse direction. On the other hand the centrifugal forces in the turbine opposing the compressor may send both turbomachinery components into surge and thus result in no flow in the loop. Still another possibility is that, since the compressor is designed for the compression process, it will at some point overpower the centrifugal forces in the turbine to establish flow in the proper direction around the closed loop.

Reference 5 showed that, when the anternator was used as a motor, there are high losses in the rotor. These high losses can become a problem if extended periods of motoring are required to achieve self-sustaining operation of the BRU in the closed loop.

In this investigation, the BRU was subjected to transients that may be encountered during a hot, closed-loop motoring start cycle. Observation of pressure and temperature were made to determine whether reverse flow or surge occurred.

This report presents the results obtained when the BRU alternator was motored by applying 28 volts at 400 hertz. The turbine inlet temperature (1340° to 1692° R or 744 to 940 K) and motoring period (3 to 6 sec) were varied independently. The compressor inlet temperature was maintained nominally constant at 535° R (297 K). Included also are observations made of the dynamic behavior of the BRU and system flow. A test to establish the minimum self-sustaining turbine inlet temperature as a function of speed with a compressor inlet temperature of 535° R (297 K) was made, and the results are included in this report.

DESCRIPTION OF BRU AND TEST FACILITY

A photograph and a schematic of the BRU are shown in figure 1. The turbine and the compressor are mounted on opposite ends of a common shaft, with the alternator in the center. A schematic of the closed loop test facility is shown in figure 2. Descriptive and design information on the BRU and the test facility are presented in reference 4. A block diagram of the electrical system is shown in figure 3. The auxiliary dc field supply was used to excite the alternator field to prevent reverse shaft rotation when the bearings were pressurized before motoring. The field loading resistors were used to reduce the voltage induced in the field windings when motoring.

PROCEDURE

Twenty-eight volts at a frequency of 400 hertz was selected for motor starting. At this voltage and frequency reference 5 indicated that the maximum starting current will not exceed 80 amperes (2 times the rated alternator current). The 400-hertz frequency gives a maximum motoring speed of 12 000 rpm. Gas injection starting data indicate that with a turbine inlet temperature as low as 1410° R (783 K) self-sustaining operation could be achieved at speeds above 8000 rpm.

The method used to motor start the BRU is as follows: The heater was preheated to the selected test temperature. The flow control valve was opened, and the compressor bypass valve closed. The alternator field was then excited to hold the shaft at zero speed, and the gas bearings were pressurized. The supply voltage and frequency were set to the desired ratio. To commence motoring, the field excitation was removed, the loading resistor contactor was closed, and then the motor-generator contactor was closed. At a preselected motoring time period (motor cutoff speed), the motor-generator contactor and the field loading resistor contactor were opened, and the BRU alternator electrical system was reconnected.

At various motor cutoff speeds (4600 to 10 200 rpm) observations were made of the effect of turbine inlet temperature on achieving self-sustaining operation. At a nominally constant turbine inlet temperature, the motoring period was increased from 3 to 6 seconds to vary the speed at the end of the motor period. By doing this the effect of cutoff speed on the time required for the BRU to reach the design operating speed of 36 000 rpm was determined.

Tests were made to determine the minimum turbine inlet temperature for self-sustaining steady-state operation at speeds above 15 000 rpm. Starting at a steady-state speed of 30 000 rpm, the turbine inlet temperature was reduced in small increments. After each reduction, the temperature was held constant to allow BRU speed to stabilize. Once the speed stabilized, that turbine inlet temperature was recorded as the minimum temperature for self-sustaining steady operation at that speed.

All tests described herein were conducted with the voltage regulator and speed controller disconnected from the BRU and the compressor inlet temperature held nominally constant at 535° R (297 K).

Although a test to determine the minimum turbine inlet temperature for BRU self-sustaining operation with the voltage regulator and speed controller connected was not an objective of this investigation, data of this nature are considered to be of interest and therefore will be presented. These data were obtained during previous tests but were not reported. The method used to obtain these data was somewhat different from that described in the previous paragraphs. For these tests the turbine inlet temperature was reduced very slowly, and speed drifted down very slowly. The change in speed, however, was slow enough so that the operating conditions were very close to steady-state conditions.

RESULTS AND DISCUSSION

The objective of this investigation was to subject the BRU to such transients as would be encountered in a motor start of the hot, closed test loop. The motor start performance of the BRU will be discussed in three sections as follows: (1) Dynamic Behavior of the BRU and Direction of Flow in the Loop, (2) Effect of Turbine Inlet Temperature and Speed on Self-Sustaining Operation, and (3) Effect of Turbine Inlet Temperature and Speed on System Startup.

Dynamic Behavior of the BRU and Direction of Flow in the Loop

As discussed in the INTRODUCTION, possible motor start problems peculiar to radial turbomachinery at low speeds are surge and reverse flow. During motoring, bearing and shaft motions were monitored, and transient recordings were made of pressures and temperatures in the loop. These data did not show any evidence of surge.

Reverse flow within the loop could not be detected with the bare-spike thermocouple used at the heater inlet. Also, the transient recording of the compressor mass flow rate does not show the change that would occur if the flow were initially in the reverse direction.

Effect of Turbine Inlet Temperature and Speed on Self-Sustaining Operation

The turbine inlet temperatures and speeds at which self-sustaining operation was attempted with motor starting in the closed-loop test facility are shown in figure 4. These data cover a range of speed from 4600 to 10 200 rpm and a range of turbine inlet temperature from 1340° to 1692° R (745 to 940 K). Also shown in figure 4 is the minimum turbine inlet temperature required for self-sustaining steady-state operation at a given speed from 15 000 to 30 000 rpm. The range of turbine inlet temperature covered by these data is 1140° to 1240° R (633 to 689 K). All these data, as discussed in the procedure, were obtained with the voltage regulator and speed controller disconnected from the BRU and the compressor inlet temperature held nominally constant at 535° R (297 K).

Figure 4 shows that self-sustaining operation was achieved with motoring in the speed range from 6600 to 10 200 rpm. At 6600 and 8200 rpm, it was achieved with turbine inlet temperatures as low as 1440° R (800 K) and 1340° R (745 K), respectively. At 4600 and 4800 rpm, it was not achieved with 1430° R (794 K) or 1626° R (904 K), respectively. The minimum turbine inlet temperature for self-sustaining steady-state operation in the speed range from 30 000 to 15 000 rpm can be seen to decrease from 1240° to 1140° R (689 to 633 K), respectively. The drop in minimum temperature with speed is caused by the reduction in windage and bearing friction loss as speed is reduced. Apparently, there is a minimum in this curve in the range of speed from 12 000 to 15 000 rpm. This conclusion was drawn from the fact that speed could not be stabilized at 12 000 rpm even with an increase in turbine inlet temperature to the temperature corresponding to 15 000 rpm. The turbine inlet temperature could not be increased by more than this in a short period because of the large thermal inertia in the system.

A method of arriving at an indication of the minimum turbine inlet temperature for self-sustaining operation in the speed range from 6600 to 15 000 may be obtained from the fact that at the minimum temperature the acceleration will be zero. At any temperature above this minimum, the acceleration will be positive. The higher the temperature is above this minimum, the greater the acceleration. Motoring data were recorded at 6600 and 8200 rpm at various turbine inlet temperatures. These data were plotted as a function of acceleration and extrapolated to a zero value of acceleration. Temperatures of 1425° R (791 K) and 1315° R (730 K) at 6600 and 8200 rpm, respectively, were obtained from the plot. These points were used to draw the dashed curve in figure 5 which joins the minimum self-sustaining temperature data from figure 4 at 15 000 rpm. The solid line represents an operating line at conditions of stable equilibrium for the BRU. At any temperature above 1140° R (633 K) and at a speed to the right of the dashed line, the BRU, with no load on the alternator and the voltage regulator and speed controller disconnected, will operate on this line. The dashed line represents an operating line at conditions of unstable equilibrium. At any condition off this line BRU operation will move either to the solid line or to zero speed. For the BRU operating in the Brayton space power system this curve would shift to a higher temperature because of the higher pressure losses designed into that system.

A study of the relationship among speed, temperature, pressure, and flow was made to determine what changes occur within the loop to cause the required turbine inlet temperature for self-sustaining operation to rise rapidly as speed is decreased below 15 000 rpm. Figure 6 shows the variation of the compressor helium-xenon weight flow rate (corrected to standard sea level condition) and of compressor total pressure ratio as a function of BRU speed for all points in which self-sustaining operation was attempted with motoring. Figure 6(a) shows a gradual increase in corrected compressor weight flow from about 0.09 pound per second (0.04 kg/sec) at 4600 rpm to 0.219 pound per second (0.10 kg/sec) at 10 200 rpm. The gradual increase confirms the earlier observation that flow reversal did not occur. The compressor pressure ratio (fig. 6(b)) increases from 1.012 at 4600 to 1.060 at 10 200 rpm. The slope of the pressure ratio curve changes between 5100 rpm and 6500 rpm. This indicates that the compressor is beginning to function more efficiently at the higher speed. In spite of the fact that the turbine inlet temperature was varied from 1340° to 1692° R (745 to 940 K), figure 6 appears to indicate that compressor weight flow and pressure ratio are a function of speed and independent of turbine inlet temperature in this temperature range.

Closer inspection of both the compressor and turbine pressure ratio data indicated that at 4600, 4800, and 6600 rpm the pressure ratio increases as the turbine inlet temperature is decreased. This trend is the opposite of the trend that was expected and observed at higher speeds. This reversal occurs because at low speeds the centrifugal force acting on the working fluid within the turbine rotor are approaching the same order of magnitude as its pressure forces generated by the compressor. When this happens the losses in the turbine and compressor increase rapidly. The compressor operating point also moves toward surge. Another factor that contributes to losses is that at low speeds the flow rate and Reynolds number are low for both turbomachinery components. Thus, when self-sustaining operation was attempted at just below 5000 rpm, the losses were so high that the turbine could not develop enough power to meet the power requirements of the compressor and other parasitic losses. Increasing the turbine inlet temperature would reduce the turbine losses by reducing the density and therefore the pressure rise associated with the centrifugal forces in the turbine rotor. Thus, self-sustaining operation at speeds below 6600 rpm cannot be completely discounted for higher turbine inlet temperatures than investigated herein.

Although the effect of voltage regulator and speed controller operation on the minimum turbine inlet temperature for self-sustaining operation was not an objective of this investigation, this information is presented in figure 7 together with similar data from figure 4. These data were obtained during shutdown while the turbine inlet temperature was reduced gradually. Therefore these data were taken during a very slow transient and do not represent true steady-state conditions. Calculations based on steady-state data from figure 4, and known characteristics of the voltage regulator and speed controller indicate very close agreement with the slow transient data. Figure 7 shows that as the BRU speed is reduced, the turbine inlet temperature required for self-sustaining operation does not decrease as rapidly with the voltage regulator and speed controller connected as without these components connected to the BRU. This is due to the operating characteristics of the voltage regulator which draws more and more power as it tries to maintain line voltage at 120 volts.

Effect of Turbine Inlet Temperature and Speed on System Startup

The time required to start the BRU in a closed, hot loop system is a function of BRU speed at motor cutoff and the turbine inlet temperature. Figure 8 shows the effect of the turbine inlet temperature on the time required to reach the rated speed of 36 000 rpm. From these curves it can be seen that the turbine inlet temperature has a significant effect on the time required to reach 36 000 rpm. The BRU speed at the end of the 3-second motoring period was 6600 rpm. The time required for the BRU to reach 36 000 rpm decreased from 4.2 minutes at 1525° R (847 K) to 2.3 minutes at 1678° R (932 K). The effect of turbine inlet temperature on total startup time decreased as the temperature was increased. The percent decrease in startup time was much greater between 1525° and 1612° R (847 and 895 K) than from 1612° to 1678° R (895 to 932 K). The test shown for a turbine inlet temperature of 1440° R (800 K) was ended at 5.7 minutes and at a speed of 20 500 rpm since it was certain that the BRU would reach rated speed. In order to keep the BRU speed under control at high turbine inlet temperatures, all tests were run with the voltage regulator and the speed controller reconnected to the BRU at approximately 12 000 rpm. The voltage regulator became energized by the alternator at approximately 20 000 rpm (ref. 5). The slope of the curves in figure 8 changes in the range of speed from 10 000 to 15 000 rpm. This change in slope is due to a decrease in losses, which were associated with centrifugal effects in the turbine and Reynolds number effects as discussed earlier.

The BRU was motored for three different time periods with a constant voltage-to-frequency ratio and a constant turbine inlet temperature. The BRU reached speeds of 6600, 8700, and 10 200 rpm for motoring periods of 3.0, 4.5, and 6.0 seconds, respectively. Figure 9 shows the effect of the motoring period on the maximum motor speed at cutoff and the time required for the BRU to reach 36 000 rpm. For a 3-second increase in motoring time, the total startup period decreases from 2.3 minutes to 0.96 minute.

The motoring period required to achieve self-sustaining operation in the test facility were not longer than those reported in reference 5. Since the temperature rise of the alternator stator and rotor was not a problem in reference 5, it was not considered to be a problem in this investigation. However, since both the turbine inlet temperature and the speed at motor cutoff play an important part in starting, the Brayton space power system may require a longer motoring period because of a different thermal inertia.

SUMMARY OF RESULTS

The results of motor starting the BRU in a closed-loop test facility are summarized as follows:

1. No evidence of compressor or turbine surge or reverse flow was found when motoring in the closed loop.

2. Self-sustaining operation of the BRU in the closed loop was obtained by motoring the alternator to 6600 rpm, with turbine inlet temperature as low as 1440° R (800 K).

3. Self-sustaining operation was not obtained at 4800 rpm with turbine inlet temperatures as high as 1626° R (903 K).

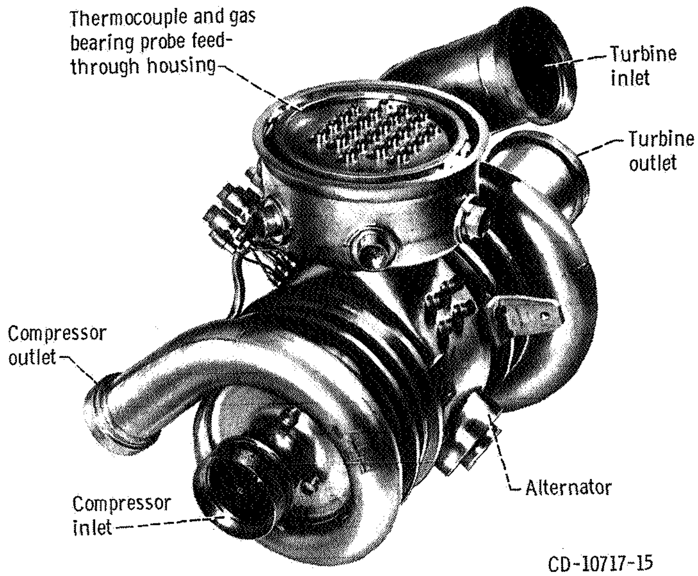
4. An operating line with minimum turbine inlet temperature, no electrical load and constant compressor inlet temperature was established for the BRU in the test loop. Above 15 000 rpm the operating line represents conditions of stable equilibrium, and below this speed the operating line represents conditions of unstable equilibrium.

5. The higher the speed and turbine inlet temperature, the shorter the time required to reach rated speed. Small increases in speed or turbine inlet temperature above the minimum drastically reduce the time required to reach rated speed.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 14, 1971,
120-27.

REFERENCES

1. Wong, Robert Y.; Klassen, Hugh A.; Evans, Robert C.; and Winzig, Charles H.: Effect of Operating Parameters on Net Power Output of a 2- to 10-Kilowatt Brayton Rotating Unit. NASA TN D-5815, 1970.
2. Klassen, Hugh A.; Winzig, Charles H.; Evans, Robert C.; and Wong, Robert Y.: Mechanical Performance of a 2- to 10-Kilowatt Brayton Rotating Unit. NASA TM X-2043, 1970.
3. Evans, Robert C.; and Meyer, Sheldon J.: Electrical Performance of a 2- to 10-Kilowatt Brayton Rotating Unit. NASA TM X-2062, 1970.
4. Wong, Robert Y.; Klassen, Hugh A.; Evans, Robert C.; and Winzig, Charles H.: Preliminary Investigation of a Single-Shaft Brayton Rotating Unit Designed for a 2- to 10-Kilowatt Space Power Generation System. NASA TM X-1869, 1969.
5. Evans, Robert C.; Meyer, Sheldon J.; and Wong, Robert Y.: Motoring Characteristics of a 2- to 10-Kilowatt Brayton Rotating Unit. NASA TM X-2154, 1970.



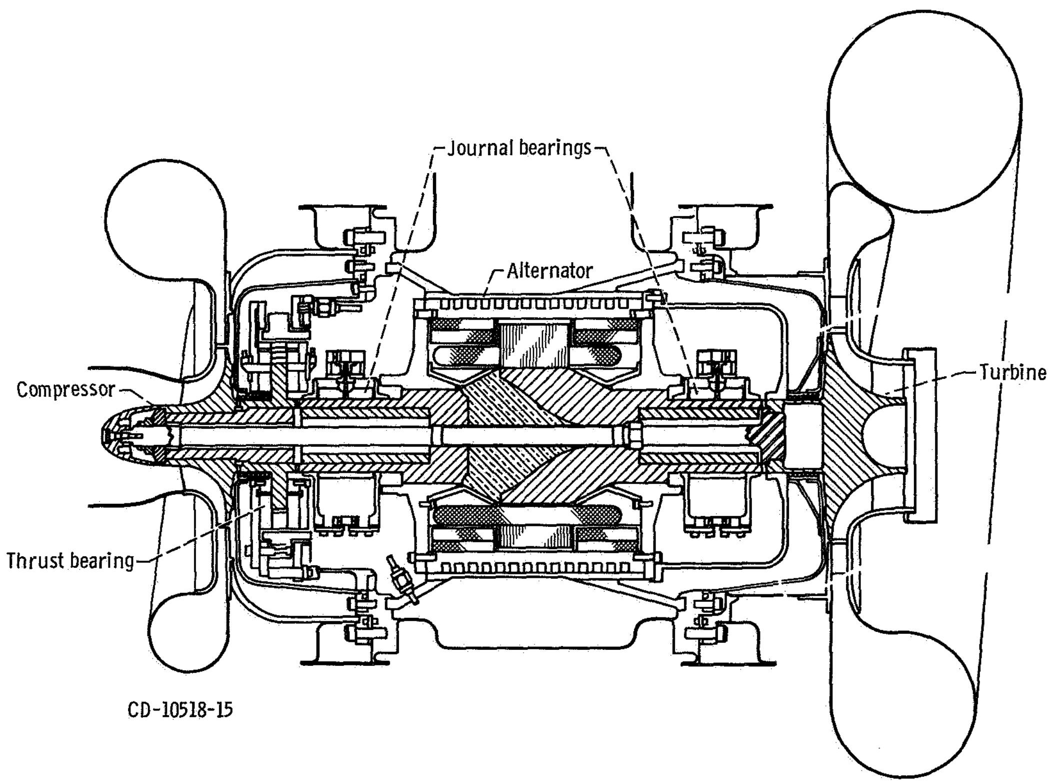


Figure 1. - Brayton rotating unit.

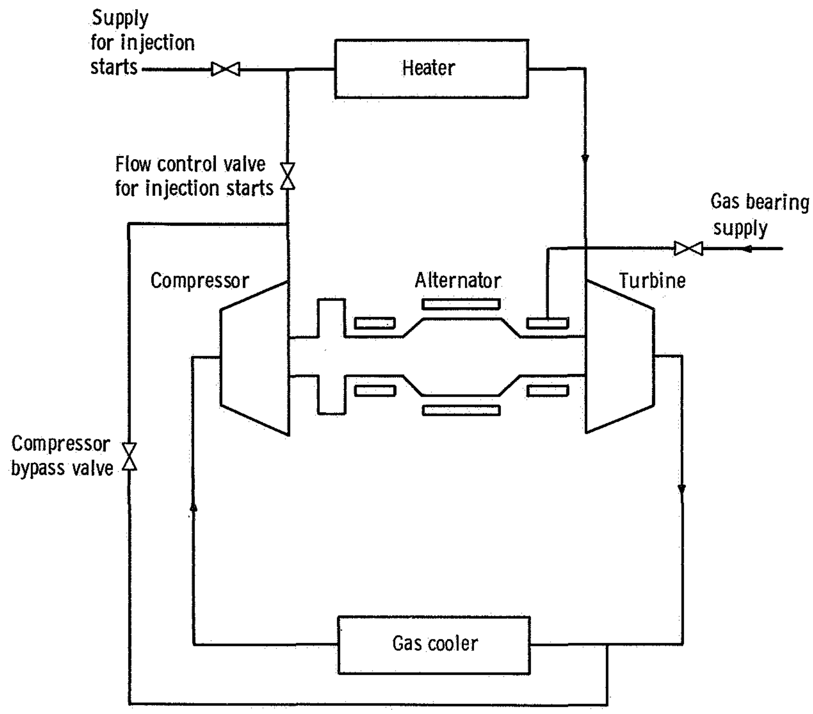


Figure 2. - Schematic of test loop.

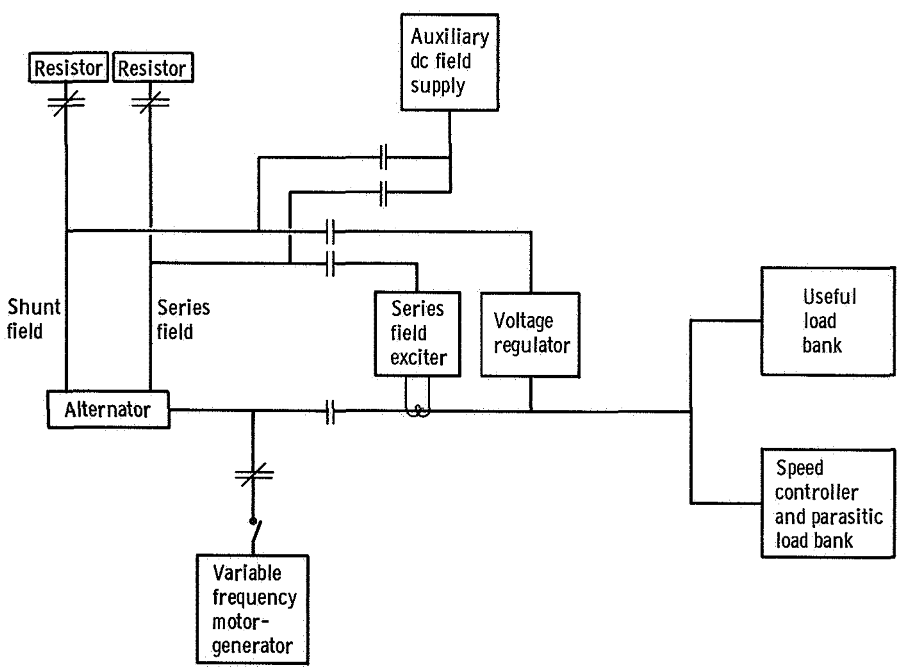


Figure 3. - Block diagram of electrical system.

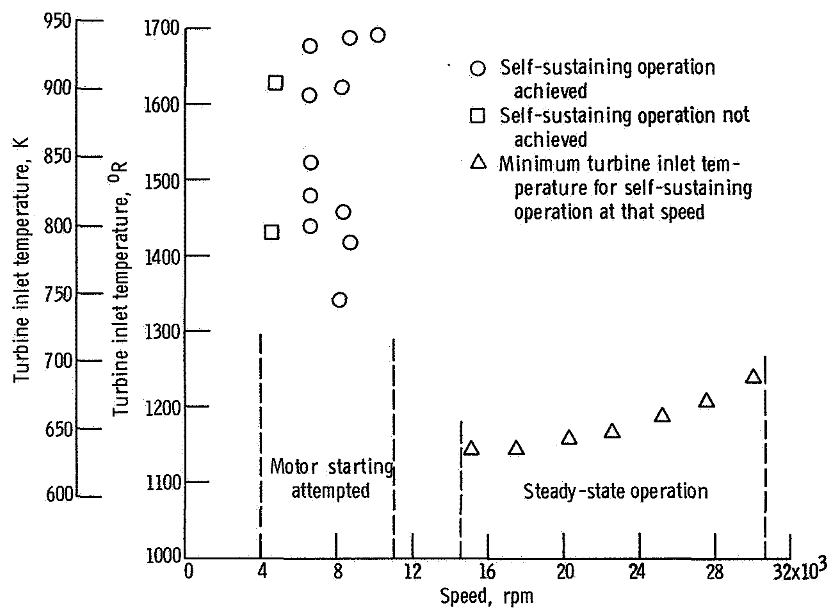


Figure 4. - Turbine inlet temperatures and speeds investigated for self-sustaining operation.

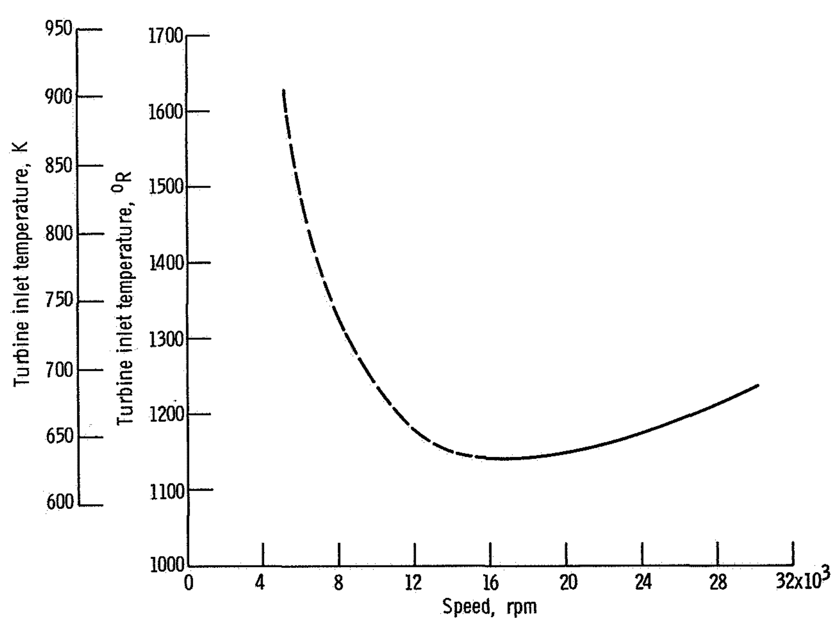
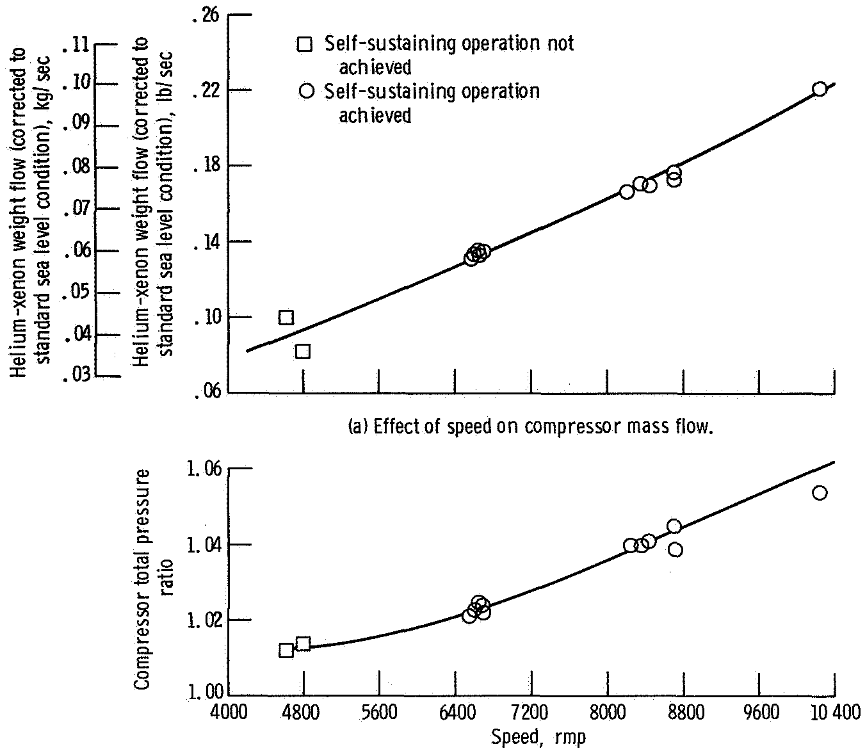


Figure 5. - Minimum turbine inlet temperature and speed required for self-sustaining operation.



(a) Effect of speed on compressor mass flow.

(b) Effect of speed on compressor pressure ratio.

Figure 6. - Compressor operating characteristics.

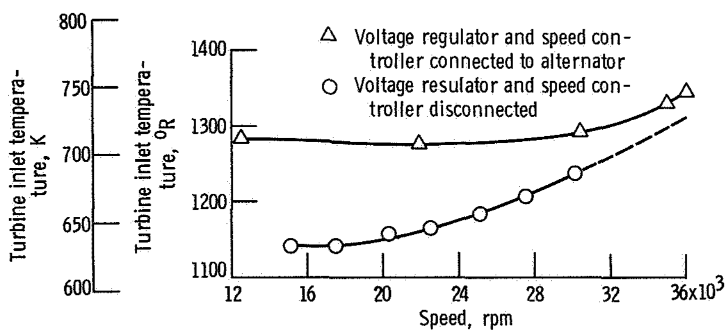


Figure 7. - Effect of voltage regulator and speed controller on turbine inlet temperatures for self-sustaining operation.

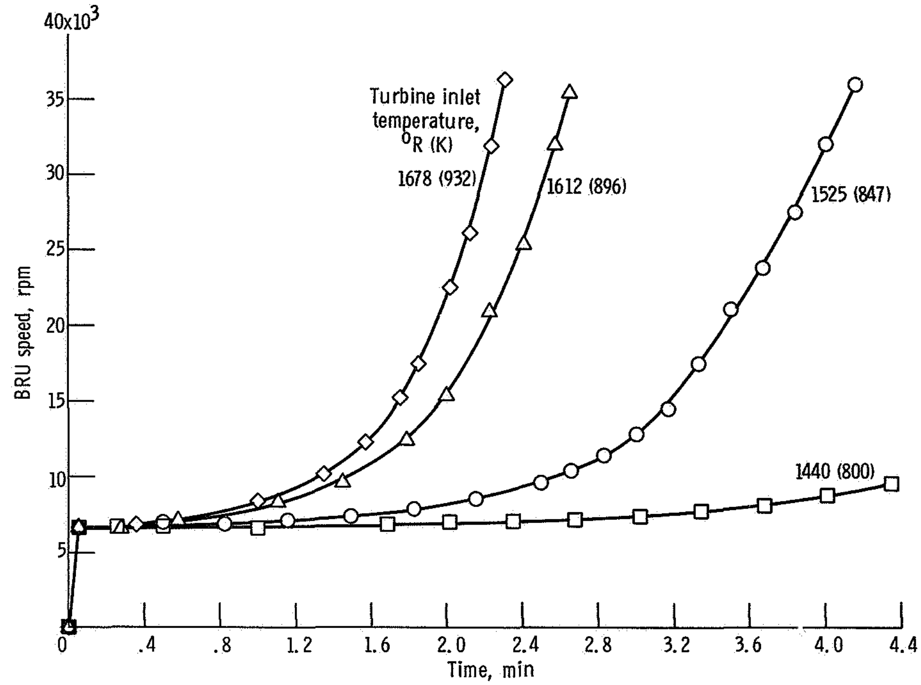


Figure 8. - Time required for BRU speed to reach 36 000 rpm for various turbine inlet temperatures. Loop pressure, 15.0 psia (10.3 N/cm); supply voltage, 28 volts at 400 hertz; motoring period, 3 seconds.

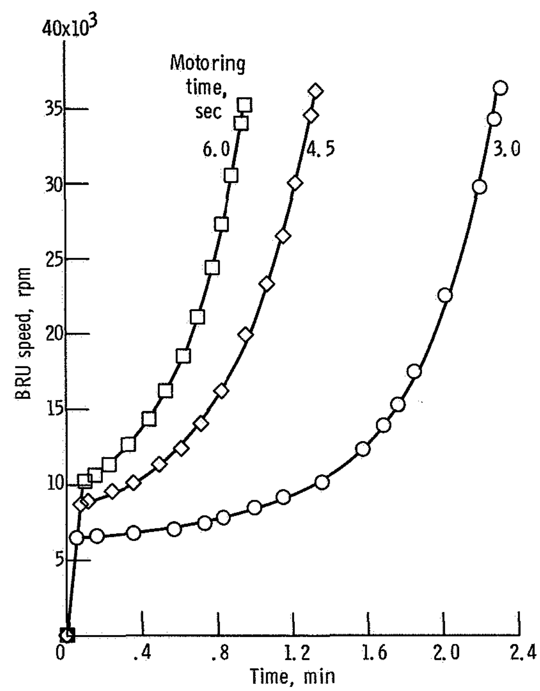


Figure 9. - Time required for BRU speed to reach 36 000 rpm for various motoring periods. Turbine inlet temperature, 1678° to 1692° R (932 to 940 K); loop pressure, 15.0 psia (10.3 N/cm); supply voltage, 28 volts at 400 hertz.

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