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**MOTOR STARTING TECHNIQUES FOR THE 2-TO-15 KW
BRAYTON SPACE POWER SYSTEM**

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ABSTRACT

The 2-to-15 kilowatt Brayton space power system currently under going development and testing at Lewis Research Center has been effectively started by motoring the rotating unit. The rotating unit is comprised of a radial-flow turbine which drives a radial-flow compressor and a Lundell-type alternator. This Brayton power system generates 120/208 volts, 1200 hertz electrical power at a rated speed of 36,000 rpm. The system is designed for a turbine inlet temperature of 1600° F (1145 K) and can be operated with a variety of heat sources such as a nuclear reactor or radioisotope.

• By applying 20 volts line-to-neutral, 400 hertz electrical power to the alternator terminals at standstill, the rotating unit can be motored to a speed of 12,000 rpm in about 20 seconds. Upon removal of the input electrical power, the system self-accelerates to its rated speed, provided that the turbine inlet temperature is 875° F (741 K) or higher.

THE BRAYTON POWER SYSTEM (1)* is a closed-loop Brayton-cycle engine designed for space applications. This engine was designed to deliver 2 to 15 kW of electrical power continuously over at least a five-year life with shutdown and restart capability (fig. 1).

The Brayton-cycle technology program at Lewis Research Center began in 1963. At the present time extensive ground tests of all major components, subsystems, and the complete engine have been or are being conducted (2). This testing includes investigations of means and methods of starting the engine conveniently. The results of motor starting testing on a complete Brayton gas loop test system are reported here.

• The Brayton power system can be started—that is, brought to a self-sustaining operating condition—by either of two methods: (a) gas injection or (b) motoring of the alternator. By injecting gas (the working gas, a mixture of helium and xenon) into a partially evacuated loop and raising the turbine inlet temperature to 330° F (440 K), the turbine can be driven to bring the system to a self-sustaining operating condition. Results of testing injection starting of the Brayton power system are described in Ref. 3.

A second method of obtaining self-sustaining operation is to use the alternator as a motor. In this operation the motor spins the compressor, circulating the working gas which is heated by the heat source. When sufficient pressure is developed by the compressor, and sufficient heat is absorbed from the heat source to provide enough energy to the turbine to drive the compressor and overcome windage losses, the operation becomes self-sustaining.

Motor starting permits a reduction in size and complexity of the gas management system.

BRAYTON POWER SYSTEM

The core of this power system (fig. 1) is the Brayton rotating unit (BRU) shown in Fig. 2. It consists of a gas turbine, an alternator, and a compressor mounted on a single shaft. The shaft is supported by pivoted three-pad gas journal bearings located just outboard of the alternator, and a gimbal-mounted double-acting step-sector gas thrust bearing at the compressor end of the shaft. Startup and shutdown of the unit are accomplished while the bearings and hydro-

*Numbers in parentheses designate References at end of paper.

statically supported by jacking gas externally supplied to the bearings at 100 to 150 psia (70 to 100 N/cm²). For normal design-speed operation, the jacking gas is turned off and the bearings, both thrust and journal, operate completely hydrodynamically.

Major subsystems (fig. 3) of the Brayton power system are the electrical subsystem and the heat rejection subsystem. The electrical subsystem regulates and distributes the generated electrical power as well as providing all control and logic functions required to operate the system. The heat rejection subsystem removes waste heat and rejects it to space from a radiator. A 400 hertz motor-pump assembly circulates liquid coolant (Dow Corning 200) through the system. The coolant is pumped through the alternator and through a series of four cold plates on which the electrical subsystem components are mounted.

SYSTEM STARTING EXPERIENCE - The practicality of operating the alternator of the Brayton power system as a motor was demonstrated in earlier testing described in Ref. 4. The Brayton alternator is a brushless stationary-coil solid-rotor modified-Lundell machine. In order to determine its characteristics as a motor, the alternator was tested with a variety of applied voltages. The no-load armature current and torque characteristics determined for motoring voltages of 20 and 30 volts (line-to-neutral), 400 hertz were within bounds that warranted their use as starting voltages for motor starting the closed loop system. These values are indicated in Figs. 4 and 5.

Motor starting the Brayton power system was first demonstrated in a closed "hot" gas loop in a test rig established for evaluation of the BRU only. In that installation the BRU was the only flight-type engine hardware under test. The tests were intended to exercise the unit over its complete operating range, determine any operational limitations, and evaluate the behavior of the BRU during startup and shutdown.

In startup tests the BRU was motored and brought to self-sustaining system operation. This operating condition was attained by motoring the BRU to 6600 rpm with turbine inlet temperatures above 980° F (800 K). The tests are fully described in Ref. 5.

As a result of these tests, a set of limiting conditions for self-sustaining operation for given speed and turbine inlet temperature at a constant compressor inlet temperature (80° F) (300 K) was established for the BRU in this test loop. The function representing these conditions

is illustrated in Fig. 6. The solid right half of the curve represents combinations of temperature and speed which were stable operating points for the loop under test. At any speed and temperature combination above 15,000 rpm and 680° F (633 K) the system reverted to conditions indicated by the curve. At speeds below 15,000 rpm the system accelerated or decelerated depending upon whether temperature and speed conditions were represented by a point above or below the left (or dashed) side of the operating line. From a consideration of this operating line, an acceleration to design speed is predictable if the BRU is spun to a speed of 12,000 rpm at temperatures above 800° F (700 K).

TEST OBJECTIVE - The alternator-motoring starting described in Ref. 5 was performed by applying 28 volts line-to-neutral, 400 hertz, to the engine. In order to simplify the design of a starting inverter, it is desirable to start the Brayton power system with 20 volts, 400 hertz. At this level the battery voltage (± 28 volts) is high enough so that no voltage boost is needed, and no converter or transformer stage is required in the inverter.

The motor starting tests performed to determine the feasibility of using 20 volts line-to-neutral, 400 hertz, are described in this report.

TEST FACILITY - The motor starting tests were performed in a complete Brayton gas loop test system. The BRU is installed with the flight-type Brayton heat exchanger unit (BHXU). The BHXU consists of a recuperator, waste heat exchanger, and connecting ducting to the BRU, and is constructed as a single unit. The BRU and the BHXU, in conjunction with an electric (nonflight-type) heat source, form the complete Brayton gas loop. Reference 6 describes the features of the facility.

TEST PROCEDURE - Prior to motoring, guard heaters on the piping between the system electrical heat source and the scroll of the turbine inlet were used to elevate the temperature at the turbine inlet to the desired running value. This procedure was followed in order to raise the temperature of the BRU and to heat by natural convection the gas inventory so that the turbine inlet temperature was constant during the startup. The gas inventory was adjusted to set the desired initial system pressure.

A few moments before energizing the alternator, the gas bearings were pressurized and the system heat source was turned on. During the motor starting operation, this heat source control was adjusted to maintain the turbine inlet

temperature at the desired running value.

Prior to motoring, a 50-ohm resistor was connected across the field coil of the alternator in order to limit the voltage induced in the coil by the motoring electrical machine. The selected alternating voltage was then applied to the terminals of the alternator to drive it as a 3-phase solid rotor induction motor. At synchronous speed the motoring power was disconnected, the field loading resistor removed, and the BRU electrical system reconnected. While the system was bootstrapping, the voltage regulator-exciter (VR-E) was turned on at about 18,000 rpm so that the integral system electrical controls would be effective.

RESULTS AND DISCUSSION

The time for a motor start of the Brayton power system is the time required to accelerate the BRU from standstill to rated speed. This time includes motoring time (or the time to reach the synchronous speed for the applied electrical frequency) and bootstrap time (the time to accelerate from synchronous speed to rated speed).

Motoring time is determined by the torque-speed characteristics of the alternator functioning as a motor. Bootstrap time is a function of system pressures and temperatures. The torque developed by the motoring machine accelerates the lightly loaded BRU to synchronous speed. When the motoring power is removed, if the system conditions (speed, pressure, and temperature) are adequate, the turbine develops a torque in excess of the compressor, bearing, and windage load torques. The BRU bootstraps and speed is limited only by the system speed control circuitry.

A set of motor starting tests were conducted by applying 20 volts RMS line-to-neutral, 400 hertz to the alternator. The gas loop was initially pressurized to 15 psia (10 N/cm²) and preheated to turbine inlet temperatures of 875° F (741 K), 950° F (783 K), and 1200° F (922 K).

In each test hydrostatic jacking gas was supplied to the bearings prior to motoring to ensure against bearing rub. This gas was externally supplied continuously until design speed was reached. Thus, there was an excess gas inventory as well as an increase in gas temperature and pressure as a result of system operation. The resultant system pressure was allowed to build up to 18 psia (12 N/cm²) at the compressor discharger before excess gas was bled.

The speed curve for a turbine inlet temperature of 875° F (741 K) is shown in Fig. 7. Syn-

chronous speed (12,000 rpm) was reached in 30 seconds and motoring power was disconnected immediately. Shaft speed continued to increase, due to the bootstrapping action, to about 18,000 rpm at which speed the voltage regulator-exciter (VR-E) was turned on. The load of the VR-E was sufficient to cause the shaft to decelerate noticeably. Design speed (36,000 rpm) was reached in about 280 seconds.

Figure 8 shows the speed curve obtained at 950° F (783 K). At this condition, synchronous speed was reached in 25 seconds. The effects of the VR-E on shaft speed are noticeably less than at the lower temperature conditions of Fig. 7. Time to reach design speed decreased to 142 seconds.

At 1200° F (922 K) turbine inlet temperature (fig. 9), the time to reach synchronous speed was 20 seconds and the effects of the VR-E were negligible. The shaft speed reached 36,000 rpm in 72 seconds.

One motor start was performed with the initial gas pressure in the system at 25 psia (17 N/cm²). The resulting acceleration is shown in Fig. 10. Although the evidence is limited, the result indicated that increased system pressure produced a faster start. The motoring time to reach synchronous speed remained at twenty seconds, but the bootstrap time decreased to thirty seconds for a turbine inlet temperature of 1100° F (866 K).

These data are combined in Fig. 11 to show total motor starting time as a function of turbine inlet temperature. The data includes time to reach synchronous speed plus bootstrap time. The slope of the curve is very steep to about 1000° F. Above this temperature the slope changes more gradually. For an initial loop pressure of 15 psia, a reasonable selected minimum turbine inlet temperature is in the order of 1000° F (811 K). This temperature results in a total motor starting time of about 2 minutes.

The magnitude of the alternator current during motoring is shown in Fig. 12. The curve represents the line-to-neutral RMS current per phase for the 20 volts, 400 hertz starts. The results are typical for all temperature investigated. The starting current reaches 50 amperes and gradually decreases until just before reaching synchronous speed. Upon reaching synchronous speed, the current steps down to 17.5 amperes.

SUMMARY OF RESULTS

Motor starting the Brayton gas loop test

system with 20 volts line-to-neutral, 400 hertz, power is feasible at turbine inlet temperatures of 875° F (741 K) or higher. The alternator attains synchronous speed (12,000 rpm) in about 20 seconds. The system will then bootstrap, accelerating continuously until design speed (36,000 rpm) is reached and limited by the system speed control.

Motor starting time for an initial turbine inlet temperature of 950° F is less than two and one-half minutes.

Motor starting time is appreciably shortened by higher turbine inlet temperatures. The motoring time to synchronous speed varies only slightly from 20 seconds, but the acceleration of the BRU is a positive function of the turbine inlet temperature.

There is limited test data indicating that the acceleration of the BRU from synchronous speed is increased by higher system starting pressures. The load which results from application of the system electrical controls (at about 18,000 rpm) produces a momentary reduction of the bootstrap acceleration. But, at the selected system conditions tested, this load is not sufficient to stop the acceleration.

Starting motoring inrush currents are in the order of 50A, decreasing abruptly at synchronous speed to a value of 17.5A.

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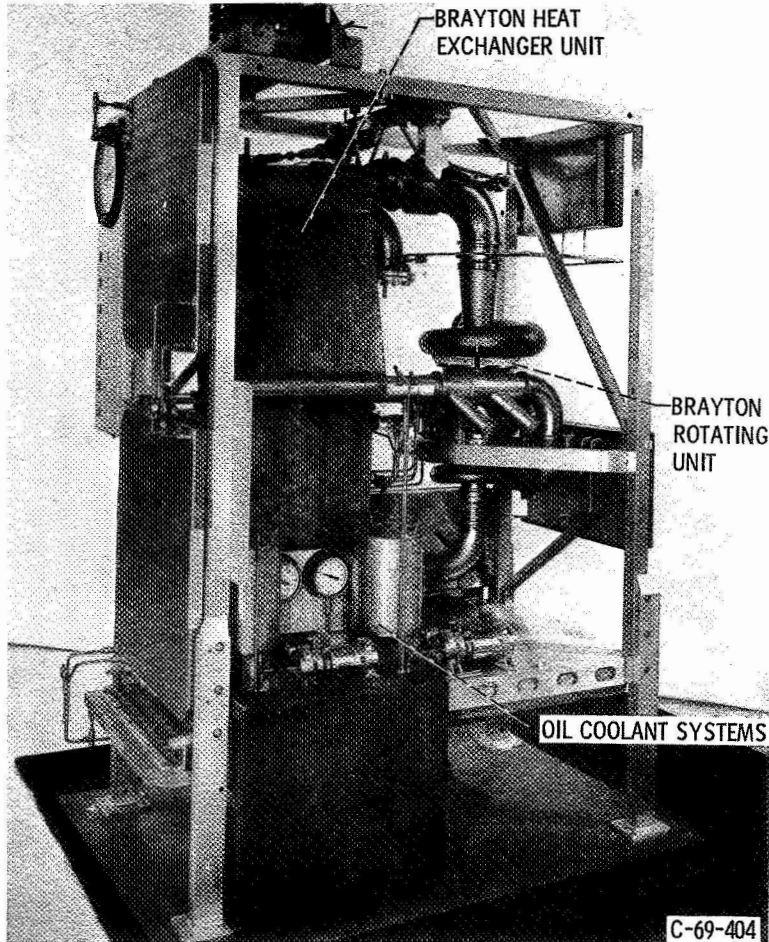


Figure 1. - Brayton power system test engine.



Figure 2. - Brayton rotating unit.

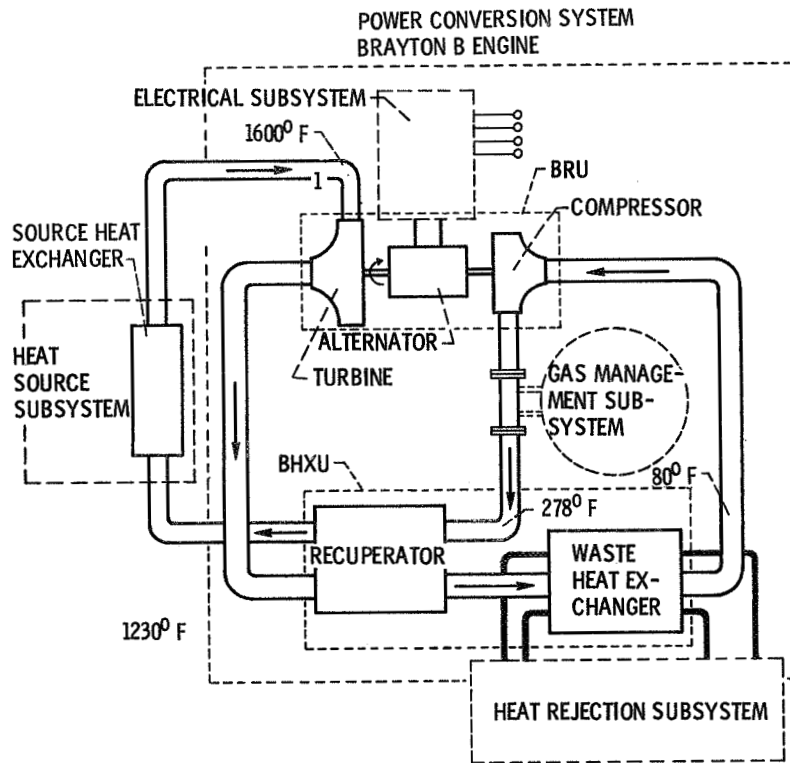
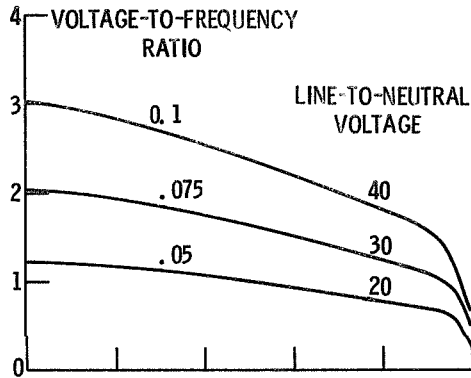
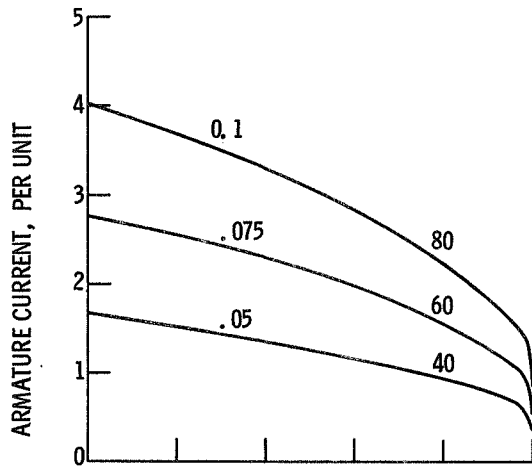


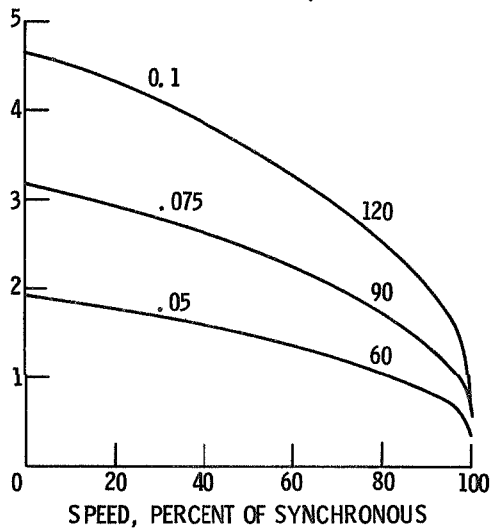
Figure 3. - Schematic diagram, Brayton power system.



(a) APPLIED FREQUENCY, 400 HERTZ;
SYNCHRONOUS SPEED, 12 000 RPM.



(b) APPLIED FREQUENCY, 800 HERTZ;
SYNCHRONOUS SPEED, 24 000 RPM.



(c) APPLIED FREQUENCY, 1200 HERTZ;
SYNCHRONOUS SPEED, 36 000 RPM.

Figure 4. - No-load motor starting armature current characteristics of 1200-hertz Lundell alternator. One per-unit current, 39.7 amperes.

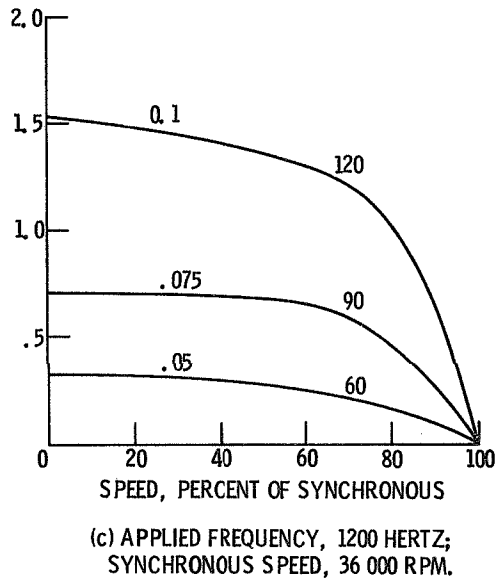
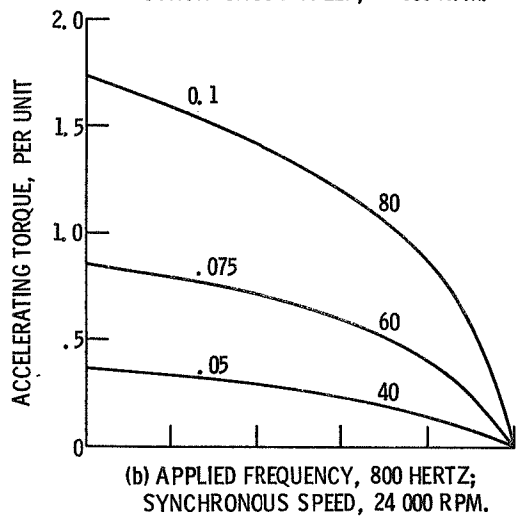
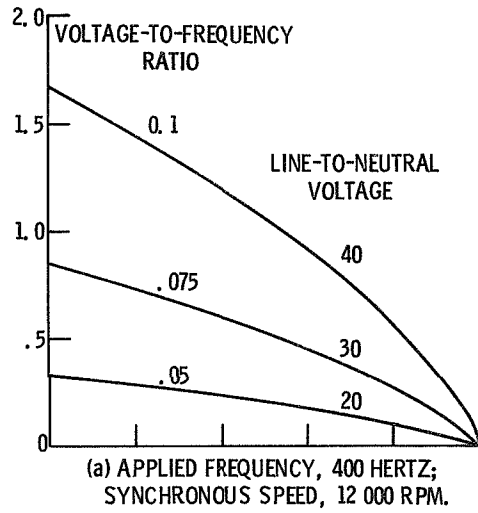


Figure 5. - No-load motor-torque characteristics of 1200-hertz Lundell alternator. One per-unit torque, 2.09 pound-feet (2.83 N-m).

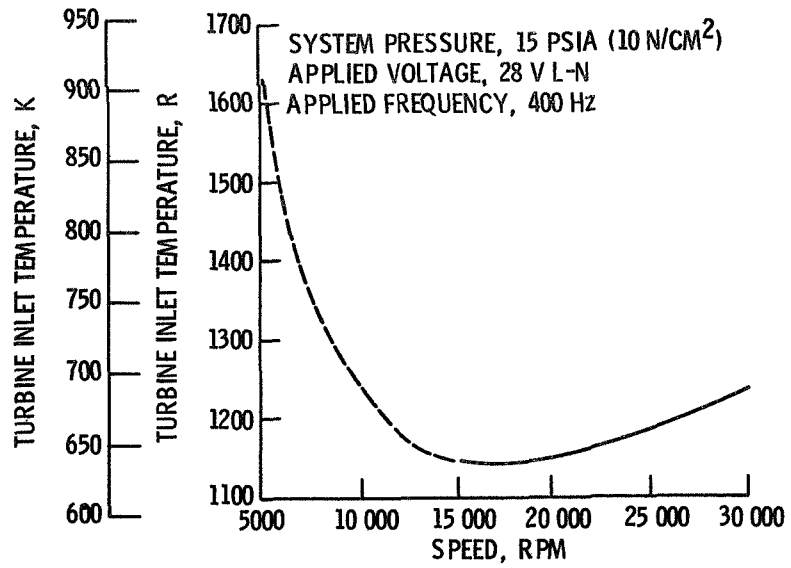


Figure 6. - Minum turbine inlet temperature and speed re-quired for self-sustaining operation.

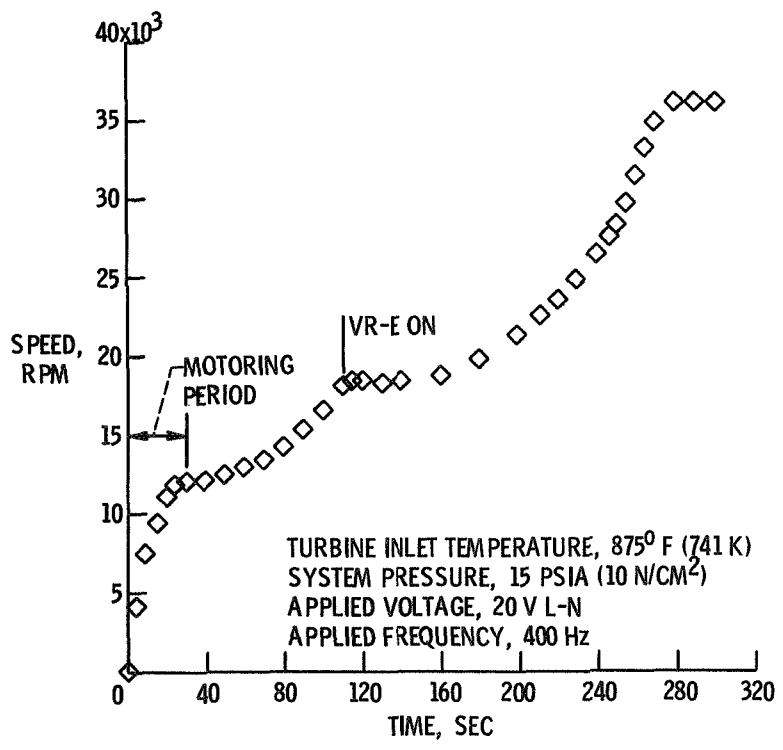


Figure 7. - Motor starting characteristics of Brayton gas loop test system, turbine inlet temperature of 875⁰ F (741 K).

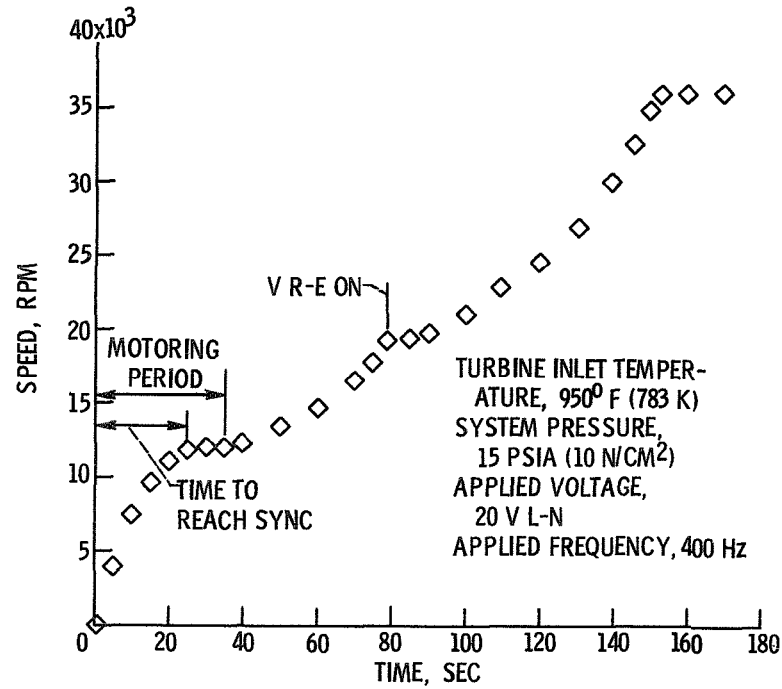


Figure 8. - Motor starting characteristics of Brayton gas loop test system. Turbine inlet temperature of 950° F (783 K).

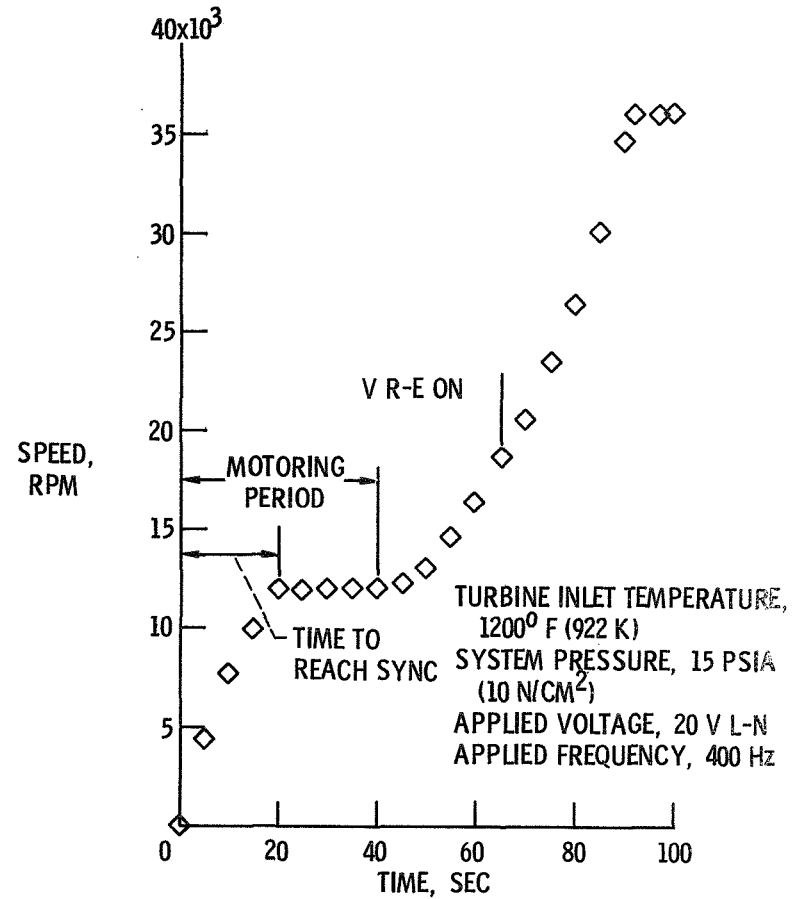


Figure 9. - Motor starting characteristics of Brayton gas loop test system, turbine inlet temperature, 1200° F (922 K).

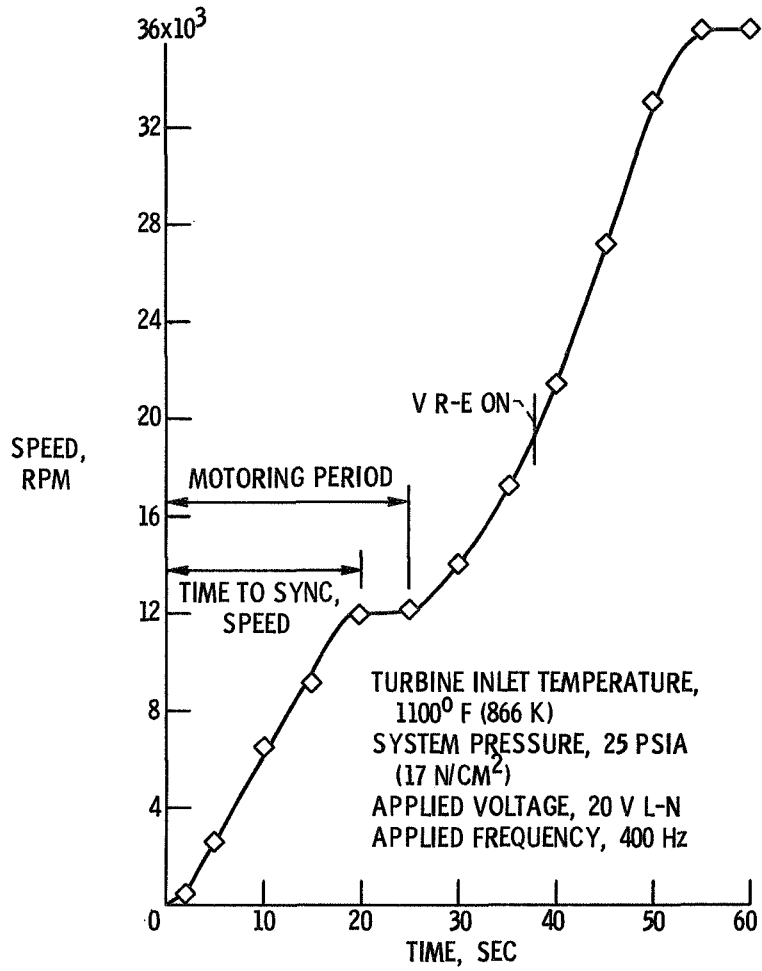


Figure 10. - Motor starting characteristics of Brayton gas loop test system, inlet temperature, 1100⁰ F (866 K).

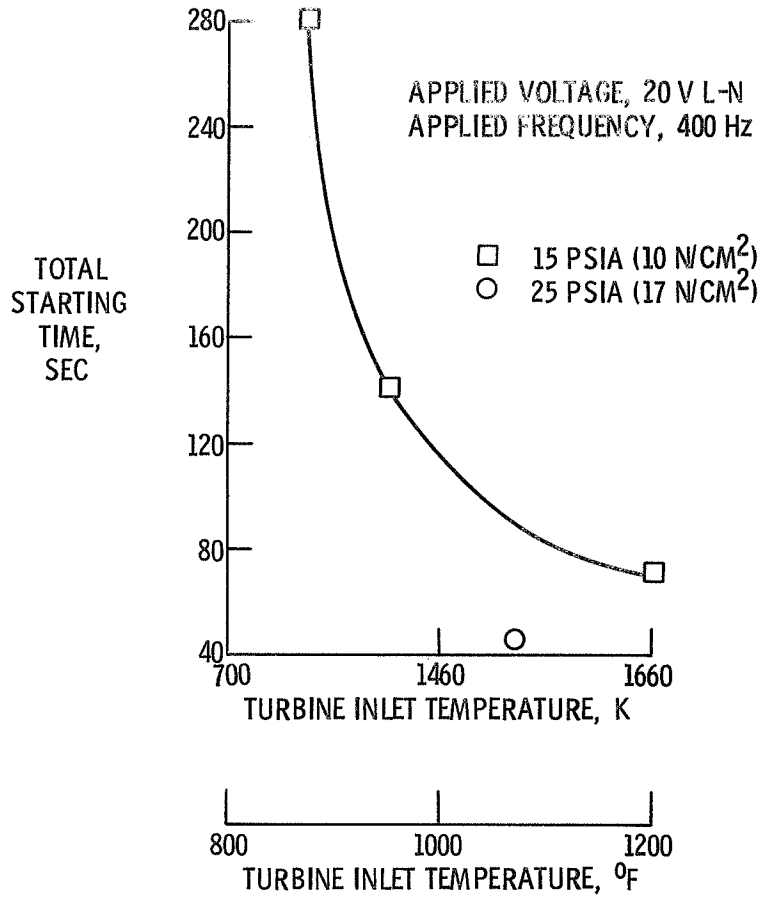


Figure 11. - Starting time of Brayton gas loop test system as a function of turbine inlet temperature.

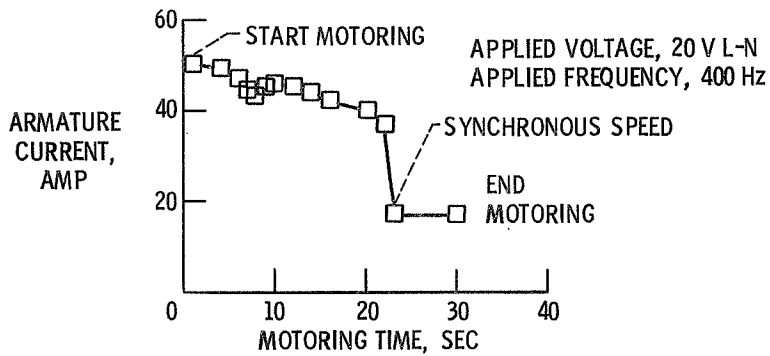


Figure 12. - Motor starting current for Brayton gas loop test system.