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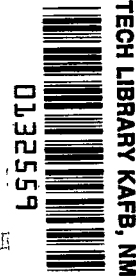


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**EFFECT OF OPERATING PARAMETERS
ON NET POWER OUTPUT OF A
2- TO 10-KILOWATT BRAYTON
ROTATING UNIT**

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16. Abstract The Brayton rotating unit was operated as part of a closed laboratory loop over a wide range of operating parameters. The operating parameters included compressor outlet pressure (15.0 to 45.0 psia or 10.3 to 31.0 N/cm ² abs), inlet temperature to the turbine (1460 ^o to 2060 ^o R or 811 to 1144 K), inlet temperature to the compressor (510 ^o to 580 ^o R or 283 to 322 K), and molecular weight, which varied the aerodynamic speed from 69 to 100 percent of design.					
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EFFECT OF OPERATING PARAMETERS ON NET POWER OUTPUT OF A 2- TO 10-KILOWATT BRAYTON ROTATING UNIT

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SUMMARY

As part of an investigation of the application of the Brayton cycle to space electric power generation, a single-shaft turbine-compressor-alternator package designed for operation on gas bearings has been under investigation at the NASA Lewis Research Center. This package was designated the Brayton rotating unit (BRU) and was operated as part of a closed laboratory loop over a wide range of operating parameters.

The results indicated that the net power output (gross alternator power minus power to excite the shunt and series fields) of the BRU in the laboratory loop varied from 3.6 to 13.6 kilowatts at design inlet temperatures to the turbine and the compressor of 2060° and 536° R (1144 and 298 K), respectively. This variation in power was obtained by varying the system pressure level, measured at the compressor outlet, from 15 to 45 psia (9.8 to 31.0 N/cm^2 abs), respectively.

The BRU was operated with a turbine inlet temperature of 1660° R (922 K) to simulate operation with the SNAP-8 reactor. Reducing the turbine inlet temperature from 2060° to 1660° R (1144 to 922 K) resulted in a 50-percent decrease in BRU net output.

The molecular weight of the working fluid was varied from 83.8 to 40. For this range of molecular weight, with constant compressor outlet pressure, the BRU net output decreased 24.7 percent.

INTRODUCTION

The NASA Lewis Research Center is investigating the application of the Brayton cycle to space electric power generation. As part of this program, a single-shaft

turbine-compressor-alternator package, designated the Brayton rotating unit (BRU) was designed and manufactured under contract for testing at the Lewis Research Center. The BRU was designed for operation on gas bearings and a mixture of helium and xenon. This mixture was specified for the system working fluid because of its heat-transfer properties (ref. 1). A molecular weight of 83.8 for the mixture was specifically chosen to be the same as krypton so that the aerodynamic properties, such as flow rate, equivalent speed, compressor pressure ratio, and specific work, would be identical for both fluids. Thus, krypton, which is less costly than the mixture, could be used for the testing of the machine at the same mechanical speed as that required by the mixture.

The BRU was designed for operation at a turbine inlet temperature of 2060°R (1144 K). Testing of the BRU at this temperature was conducted in a hot closed-loop test facility. The first hot tests were made with working fluids of krypton and argon (ref. 2). The total operating time was 525 hours. Testing with the design mixture of helium and xenon consisted of approximately 475 additional hours of operation for which the turbine inlet temperature (1460° to 2060°R or 811 to 1144 K), the compressor inlet temperature (510° to 580°R or 283 to 322 K), the compressor outlet pressure (15.0 to 45.0 psia or 10.3 to $31.0\text{ N/cm}^2\text{ abs}$), and the BRU rotor speed ($36\ 000$ to $37\ 000\text{ rpm}$) were systematically varied. These variations in operating parameters resulted in a large variation of net power output. Net power output is defined herein as the gross alternator power minus the power consumed to excite the field windings to obtain approximately 120 volts line to neutral. The purpose of this test was to determine the performance of the BRU and to accumulate a total of 1000 hours of running time.

This report presents the variations in net power output of the BRU in the laboratory loop as it was affected by changes in operating parameters. Also included is the effect on net power output of varying the molecular weight of the working fluid from 83.8 to 40 with a nominally constant mechanical speed of $36\ 400\text{ rpm}$, an inlet temperature to the turbine of 1960°R (1089 K), and an inlet temperature to the compressor of 540°R (300 K).

BRAYTON ROTATING UNIT DESIGN CONDITIONS

Turbomachinery

The 10.5-kilowatt design operating conditions for the BRU turbomachinery are as follows:

Working fluid	Helium-xenon mixture
Working fluid molecular weight	83.8
Mass flow rate, lb/sec (kg/sec)	
Turbine	1.31 (0.594)
Compressor	1.32 (0.599)
Turbine inlet temperature, °R (K)	2060 (1144)
Turbine inlet pressure, psia (N/cm ² abs)	43.2 (29.8)
Turbine total- to static-pressure ratio	1.75
Compressor inlet temperature, °R (K)	540 (300)
Compressor inlet total pressure, psia (N/cm ² abs)	23.7 (16.3)
Compressor total-pressure ratio	1.9
Shaft speed, rpm	36 000

The difference in turbine and compressor mass flow rate results from the fact that approximately 2 percent of the compressor flow is bled into the bearing housing to maintain bearing ambient pressure.

Alternator

The 10.5-kilowatt operating conditions for the alternator are as follows:

Power, kW	10.5
Power factor	0.85
Frequency, Hz	1200
Liquid coolant flow, lb/sec (kg/sec)	0.12 (0.054)

Gas Bearings

The 10.5-kilowatt operating conditions for the gas bearings are as follows:

Lubricant	Helium-xenon mixture
Temperature, °R (K)	815 to 880 (450 to 489)
Ambient pressure, psia (N/cm ² abs)	42.6 (39.4)

BRAYTON ROTATING UNIT AND TEST FACILITY DESCRIPTION

A schematic drawing of the experimental test facility is presented in figure 1. The

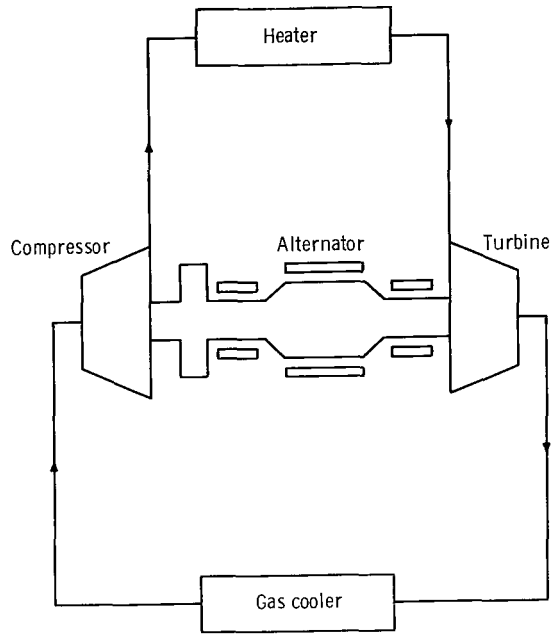


Figure 1. - Experimental test setup.

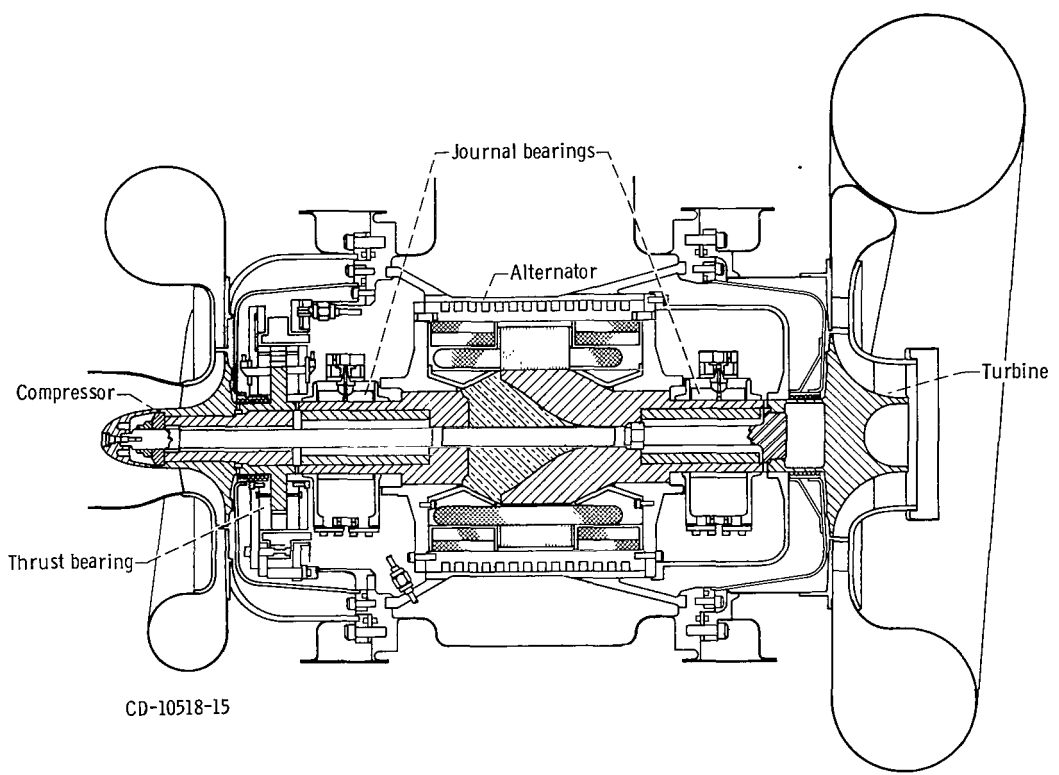


Figure 2. - Schematic of BRU.

BRU is shown installed between the heater and the gas cooler. The design working fluid is a mixture of helium and xenon with a molecular weight of 83.8. A schematic drawing of the BRU showing the salient features is presented in figure 2. There are two journal bearings and a double-acting thrust bearing all self-lubricated with the system working fluid. The compressor and turbine are mounted on the ends of a common shaft with an alternator between them. Descriptive and design information on the BRU and the test facility is given in reference 2. Descriptive information on the electrical system is given in reference 3.

Instrumentation

Instrumentation was provided to obtain net power output, total and static pressures and total temperatures at the inlet and outlet of the turbine and compressor, and weight flow and molecular weight of the working fluid.

Chromel-Alumel thermocouples were used to measure all temperatures. Strain-gage pressure transducers were used to measure all pressures. Data on performance of the turbine and compressor were determined from measuring stations near their inlet and outlet flanges. Each station contained a bare-spike total-temperature rake, static-pressure taps, and total-pressure probes.

Compressor inlet weight flow was measured with a calibrated low-pressure-loss converging-diverging flow nozzle. Flow bled from the compressor discharge into the bearing housing to maintain adequate bearing ambient pressure was measured with a calibrated rotameter. Alternator output was measured with electro-dynamometer-type wattmeters.

The molecular weight of the working fluid was determined by use of a gas mass spectrometer. Speed was measured with a capacitive-type pickup and six 0.050-inch (0.127-cm) slots milled into the shaft. The frequency of the output wave from the pickup was measured with an electronic frequency counter.

Procedure

The BRU was operated using a mixture of helium and xenon with a molecular weight of 83.8. Because of the long period of time required to start up and shut down, the system was operated continuously except for weekends. For all tests, an electronic speed control was used to maintain the speed nominally constant as a function of load (ref. 3). The power factor of the speed controller was 0.94 to 0.95 in the range of 5 to 15 kilowatts.

The investigation was conducted in three phases. The first phase, called general performance, consists of independently varying the compressor output pressure, the compressor inlet temperature, the turbine inlet temperature, and the rotor speed. The compressor outlet pressure was varied from 15.0 to 45.0 psia (10.3 to 31.0 N/cm² abs) in increments of 2.0 psi (1.4 N/cm²), while the inlet temperatures to the turbine (2060° R or 1144 K) and the compressor (536° R or 298 K) were held nominally constant.

For tests where the inlet temperatures of the turbine and compressor were varied, two compressor outlet pressures were investigated (25.0 and 42.0 psia or 17.2 and 29.0 N/cm² abs). For each of these pressures, the compressor inlet temperature was varied from approximately 510° to 580° R (283 to 322 K) in increments of about 10° R (5.6 K), while the turbine inlet temperature was held nominally constant at 2060° R (1144 K). For each of these pressures, the turbine inlet temperature was varied from 2060° to 1460° R (1144 to 811 K) in increments of 100° R (55.6 K), while the compressor inlet temperature was held nominally constant at 536° R (298 K). At a compressor outlet pressure of 45.0 psia (31.0 N/cm² abs), the turbine inlet temperature was also varied from 1660° to 2060° R (977 to 1144 K) in the same increments, and the compressor inlet temperature was 536° R (298 K). A zero power point at approximately 36 000 rpm was also established for the design value of compressor inlet temperature, a compressor outlet pressure of 26.0 psia (17.9 N/cm² abs), and a minimum turbine inlet temperature.

Up to this point in the testing, a limit of 465° F (241° C) was placed on the winding temperature in the alternator. This limit was imposed on the basis of the life consideration of the insulating materials, and it limited the net power output to about 13.5 kilowatts. The temperature limit was raised to make a short-duration test at 15 kilowatts. This was accomplished by setting the compressor outlet pressure at 45.0 psia (31.0 N/cm² abs), the compressor inlet temperature at 516° R (287 K), and the turbine inlet temperature at 2060° R (1144 K). This condition was held for a period of 5 hours to achieve a steady-state operation.

The variation in net power output as a function of BRU speed was investigated from 37 000 to 36 010 rpm. This was done with the nominal system net power output of 15 kilowatts. Since the speed controller controls speed as a function of load, speed variations were accomplished by transferring balanced-three-phase load from the speed control to a resistance load bank. The resistance bank was described as the system load in figure 8 of reference 3. The speed was varied in increments of approximately 200 rpm.

The second phase of testing was conducted to determine net output for operation at temperature limits imposed by operation with a SNAP-8 reactor. This series of tests is called performance at SNAP-8 conditions. For this series, the turbine inlet temperature was held nominally constant at 1660° R (922 K). The compressor inlet temperature was varied from 520° to 580° R (289 to 322 K) in increments of 20° R (11 K).

At each one of these compressor inlet temperatures, the compressor outlet pressure was varied from 29.0 to 45.0 psia (20.0 to 31.0 N/cm² abs) in increments of 4.0 psi (2.8 N/cm²).

The third phase of this investigation consisted of varying the working fluid molecular weight from 83.8 to 40. This series of tests was completed during the krypton-argon phase of testing but was not reported. The molecular weight was varied by the dilution of krypton with argon during the switch over from krypton to argon reported in reference 2. The compressor inlet temperature (540^o R or 300 K), the compressor outlet pressure (26.0 psia or 17.9 N/cm² abs), and the turbine inlet temperature (1960^o R or 1089 K) were held nominally constant.

Tests of radial turbomachinery research packages (ref. 4 and unpublished Lewis Research Center compressor research package data) have shown that the blade axial clearance has only a small effect on aerodynamic performance. Thus, it was decided to increase the axial clearance of the BRU to give added assurance of adequate axial clearance. To assist in the evaluation of the data, a measurement of the blade tip axial clearance was made. The minimum axial clearance in the turbine was 21.6×10⁻³ inch (54.9×10⁻³ cm) and was 15.0×10⁻³ inch (38.1×10⁻³ cm) in the compressor. At operating conditions, the axial clearance in the turbine was calculated to be 23.7×10⁻³ inch (60.2×10⁻³ cm) and in the compressor was 15.4×10⁻³ inch (39.1×10⁻³ cm). All tests were conducted with these values of clearance. The value of axial clearance for the turbine research package was 10×10⁻³ inch (25.4×10⁻³ cm) and for the compressor research package was 8×10⁻³ inch (20.3×10⁻³ cm).

RESULTS AND DISCUSSION

As discussed in the INTRODUCTION, the purpose of this investigation was to determine the performance of the BRU and to accumulate 1000 hours of operating time. This was accomplished by operating the BRU in the laboratory loop over a wide range of operating parameters. The results of this investigation are presented in the following sections: General Performance, Performance at SNAP-8 Conditions, and Effect of Molecular Weight Variations on Net Power Output.

General Performance

Presented in figure 3 is the variation in BRU net power output in the laboratory loop with compressor outlet pressure. For this series of tests, a turbine inlet temperature of 2060^o R (1144 K) and a compressor inlet temperature of 536^o R (298 K) are nominally

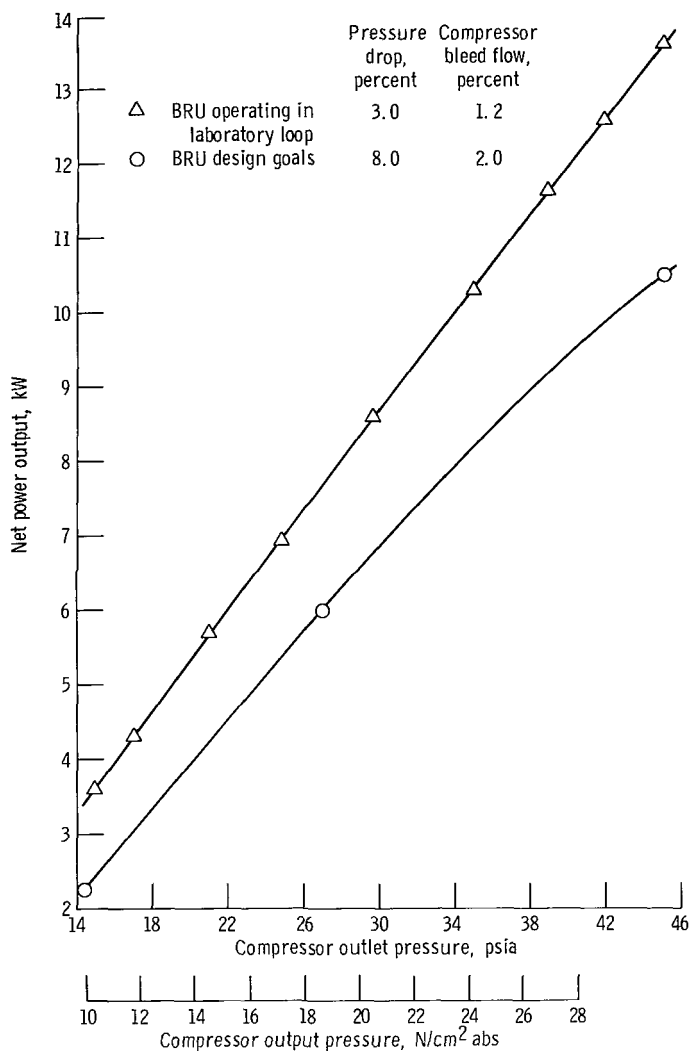


Figure 3. - Variation in BRU net power output with compressor outlet pressure. Compressor inlet temperature, 536° R (298 K); turbine inlet temperature, 2060° R (1144 K).

constant at the design values. Shown also are the design goals for the BRU at three values of compressor outlet pressure, an 8-percent system pressure loss, and an alternator power factor of 0.85. As discussed in the Procedure section, the power factor for these tests was 0.94 to 0.95. The difference in power factor between the test and design conditions will change the alternator output by approximately 1.0 percent.

Figure 3 shows that at 15.0 psia (10.3 N/cm² abs) the net power output is about 3.6 kilowatts and increases to about 13.6 kilowatts at 45.0 psia (31.0 N/cm² abs). At the design compressor outlet pressure of 27.0 psia (18.6 N/cm² abs), the net output is 7.7 kilowatts as compared with the BRU design goal of 6.0 kilowatts. The BRU design goals at compressor outlet pressures of 45.0 and 14.8 psia (31.0 and 9.8 N/cm² abs)

were 10.5 and 2.25 kilowatts, respectively. Thus, the BRU net output in the laboratory loop exceeds the original BRU design goals by about 51 percent at the 2.25-kilowatt pressure level and by about 30 percent at the 10.5-kilowatt pressure level.

The increase in power obtained from operation in the laboratory loop is primarily the result of pressure losses between the turbine and compressor being much lower than assumed in the design. A loss pressure ratio of 0.92 was assumed compared with an actual value of 0.97 in the laboratory system. This difference results from the fact that no recuperator was used and piping was not laid out for compactness. This reduction in pressure loss shifted the compressor operating point slightly toward open-throttle conditions, which in turn increased the flow through the turbine. The increased system flow along with the increased turbine inlet pressure and turbine pressure ratio drastically increased the net power output of the BRU. For a change in system pressure loss from 8 to 3 percent, it was computed that the alternator output would increase by about 19 percent. All the data included in this report are for the BRU in the laboratory loop. Lower power outputs would be expected for the BRU in the Brayton engine because of higher loss pressure ratios in the engine. Another factor that tends to increase the net power above the BRU design goal is that the seal leakage was only 1.2 percent of the system flow instead of the 2 percent assumed in the design. Also determined from figure 3 is that the net output increases at a slightly faster rate than the compressor output pressure. This is caused by the fact that the alternator efficiency is increasing to a peak near 10.5 kilowatts and the total power consumed by the bearings and field excitation are relatively constant.

As discussed in the Procedure section, the blade axial clearances were about twice that of the research packages. As indicated in reference 4 and from unpublished compressor research package data, the performance of both the turbine and the compressor were degraded by doubling the axial clearance. Calculations made from the research package data revealed that there was a penalty of about 6 percent in the net power for doubling the axial clearances. Thus, it is indicated that, at the 10-kilowatt pressure level, the BRU would exceed the design goals by about 17 percent with the design values of system pressure loss and axial clearances.

Presented in figure 4 are the variations in net power output with compressor inlet temperature. Tests at compressor outlet pressures of 25.0 and 42.0 psia (17.2 and 29.0 N/cm² abs) were made. The turbine inlet temperature was held nominally constant at 2060° R (1144 K). At a compressor outlet pressure of 25.0 psia (17.2 N/cm² abs), the compressor inlet temperature was varied from 510° to 581° R (283 to 323 K), and the net power varied approximately linearly from 7.9 to 5.5 kilowatts. At a compressor outlet pressure of 42.0 psia (29.0 N/cm² abs), the compressor inlet temperature was varied from 525° to 584° R (292 to 324 K), and the net power varied from 13.4 to 10.0 kilowatts. At this compressor outlet pressure, the compressor inlet temperature

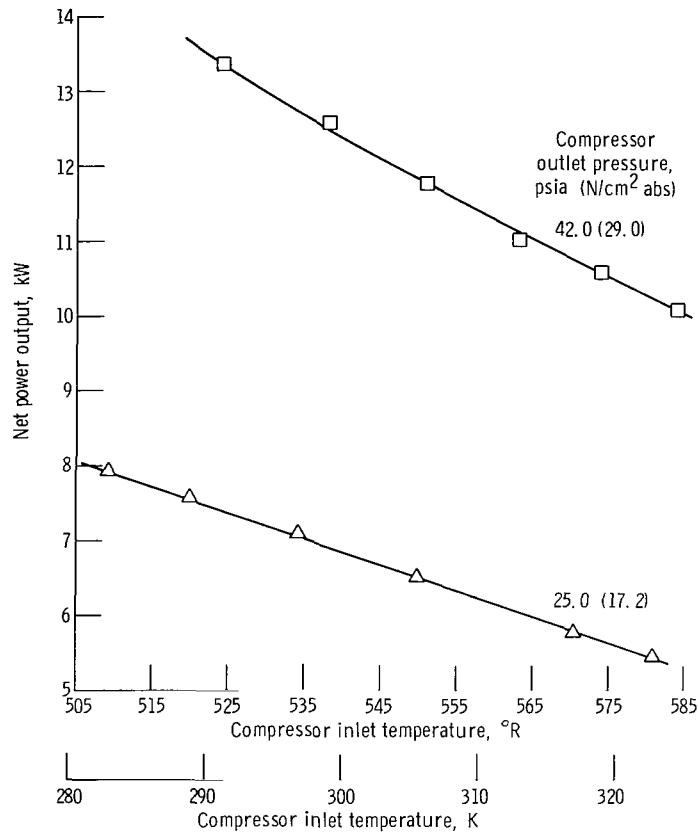


Figure 4. - Variation of BRU net power output in the laboratory loop with compressor inlet temperature. Turbine inlet temperature, 2060° R (1144 K).

was limited to a minimum value of 525° R (292 K) because of a limit of 465° F (241° C) placed on the alternator winding temperature. This temperature limit was based on predicted alternator insulation life.

Figure 5 is a cross plot of figure 4 and shows net output against compressor outlet pressure. Straight lines of constant compressor inlet temperature are shown since this variation is approximately consistent with figure 3. This plot was made to show where the 15-kilowatt run fit with respect to the data already presented. The operating conditions for this point are given in the Procedure section and can be seen in figure 5. For this point, the maximum winding temperature was 500° F (260° C).

Presented in figure 6 is the variation in net power as a function of turbine inlet temperature. Curves for constant compressor outlet pressures of 25.0, 42.0, and 45.0 psia (17.2, 29.0, and 31.0 N/cm² abs) are shown. A zero net power point is shown for a compressor outlet pressure of 26.0 psia (17.9 N/cm² abs). From the curves, it appears that at both 25.0 and 42.0 psia (17.2 and 29.0 N/cm² abs) the zero net power turbine inlet temperature is about 1345° R (747 K). From zero net power, the power increases to 7.0, 12.7, and 13.6 kilowatts at compressor outlet pressures of 25.0, 42.0,

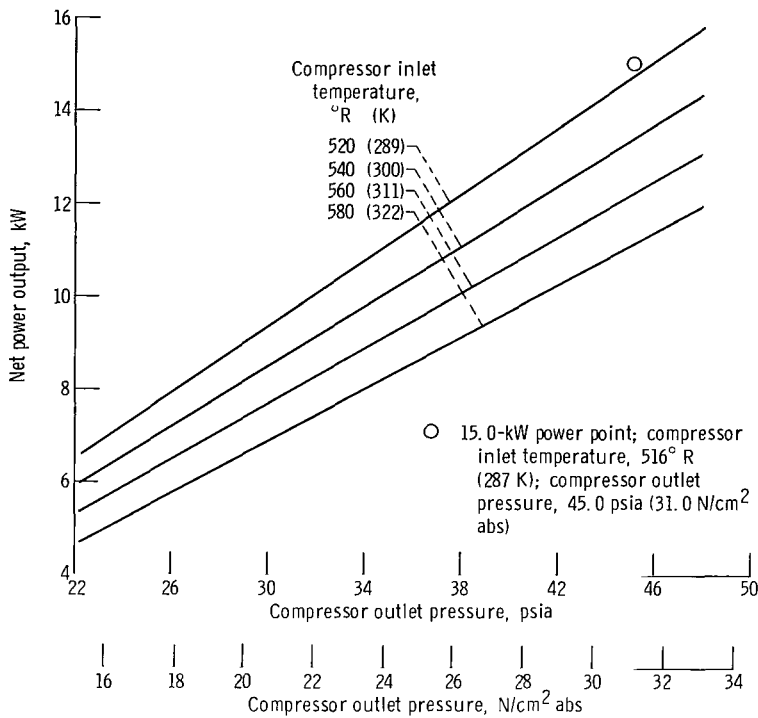


Figure 5. - Variation of BRU net power output in the laboratory loop with compressor outlet pressure. Turbine inlet temperature, 2060° R (1144 K).

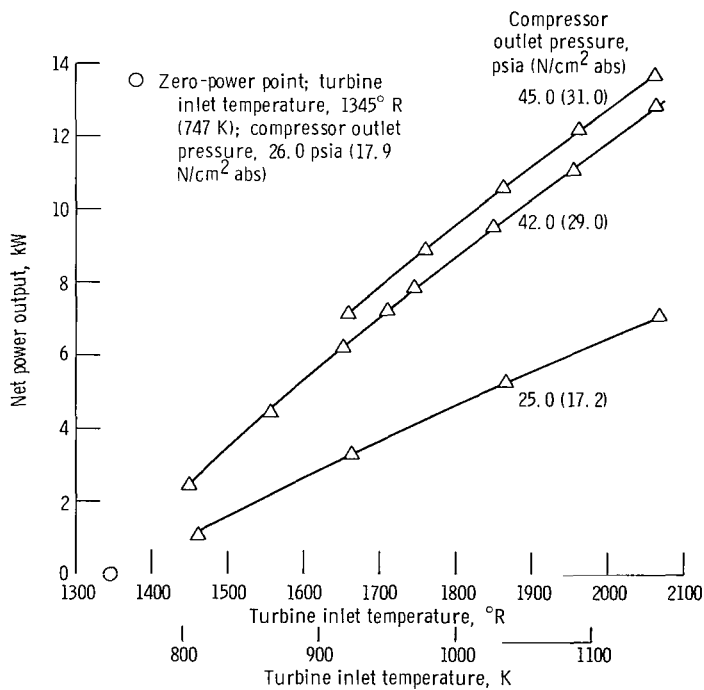


Figure 6. - Variation of BRU net power output in the laboratory loop with turbine inlet temperature. Compressor inlet temperature, 536° R (298 K).

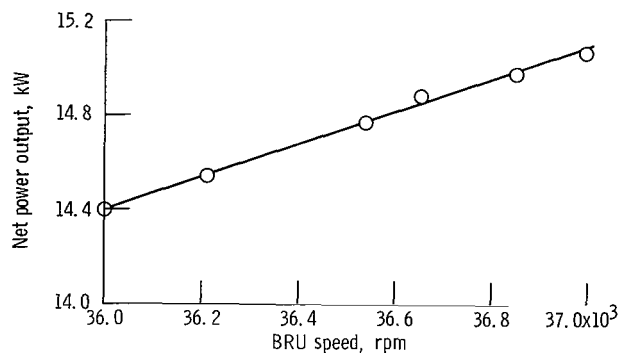


Figure 7. - Variation in power output as function of BRU speed.

and 45.0 psia (17.2, 29.0, and 31.0 N/cm² abs), respectively, for a turbine inlet temperature of 2060^o R (1144 K).

The variation in net power output with speed from 36 010 to 37 000 rpm is presented in figure 7 for constant inlet temperatures into both the turbine (2060^o R or 1144 K) and the compressor (515^o R or 286 K) and for constant gas inventory in the loop. The net power output varied from 14.4 to 15.1 kilowatts, a change of 4.6 percent for this speed range. The turbine power changed 6.0 percent, and the compressor power changed 7.2 percent over this speed range. The difference between the turbine and compressor power changed only 4.7 percent, which is consistent with the actual change in alternator power.

Performance at SNAP-8 Conditions

Plotted in figure 8 is the variation in BRU net power output in the laboratory loop as a function of compressor outlet pressure for a nominally constant turbine inlet temperature of 1660^o R (922 K). This temperature limit would be imposed when operating the Brayton system with a SNAP-8 reactor. Curves of constant compressor inlet temperature are presented for 520^o, 540^o, 560^o, and 580^o R (289, 300, 311, and 322 K). These curves show that the net power varies linearly with the compressor outlet pressure, and a reduction in compressor inlet temperature from 580^o to 520^o R (322 to 289 K) increases the net output by 75 to 80 percent. This compares to about a 35-percent increase for operation at a turbine temperature of 2060^o R (1144 K). The greater change in net output results because the compressor is using a greater percentage of the turbine power. This effect is even more pronounced if the higher pressure losses assumed in the design goals are imposed. The net power output would drop to near zero at a compressor inlet temperature of 580^o R (322 K).

The variation in net power output with compressor outlet pressure is presented in

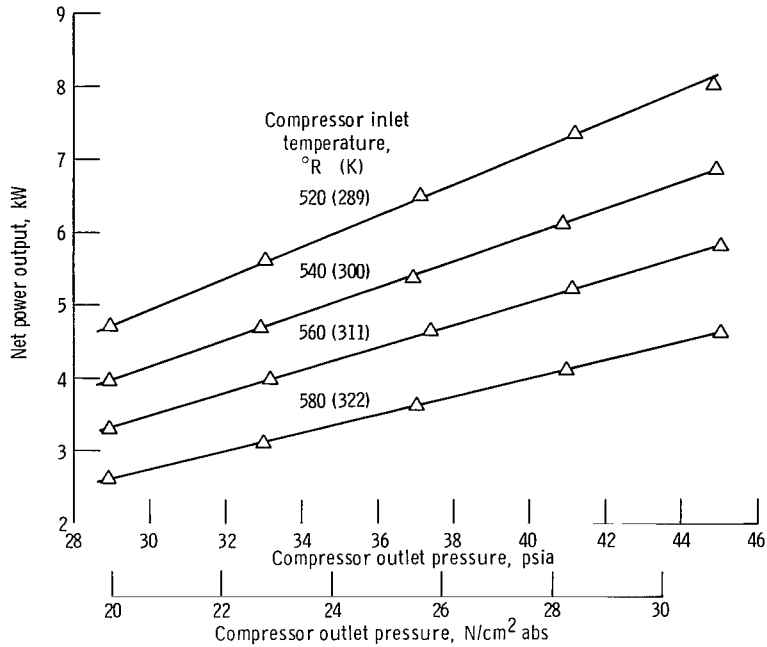


Figure 8. - Variation of BRU net power output in the laboratory loop with compressor outlet pressure at SNAP-8 conditions. Turbine inlet temperature, 1660° R (922 K).

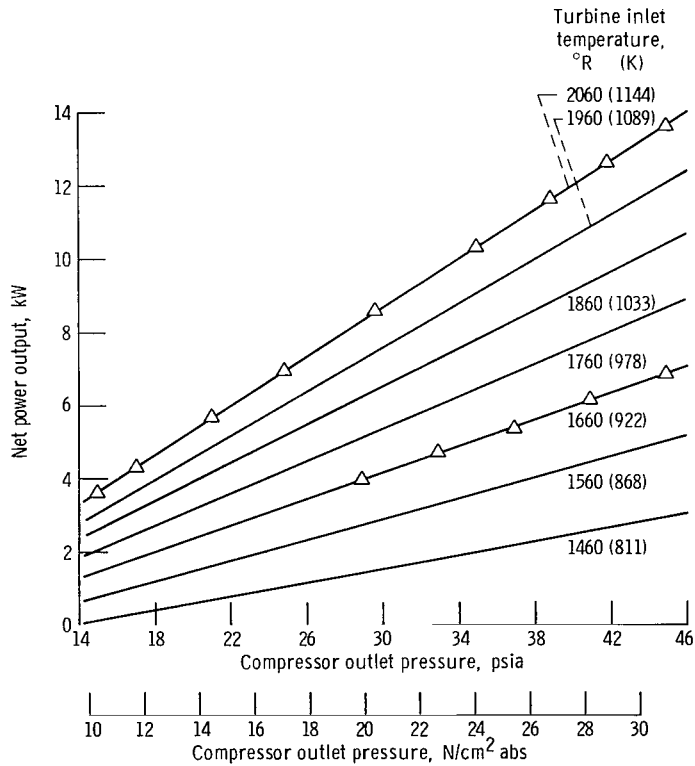


Figure 9. - Variation in BRU net power output in the laboratory loop with compressor outlet pressure. Compressor inlet temperature, 536° to 540° R (298 to 300 K).

figure 9. This figure is a cross plot of figure 6. Curves of constant turbine inlet temperature are shown from 1460° to 2060° R (811 to 1144 K) in increments of 100° R (55.6 K). Data from figures 8 and 3 are shown for turbine inlet temperatures of 1660° R (922 K) and 2060° R (1144 K), respectively. These curves show the penalty for operation at a reduced turbine inlet temperature. A loss of about 50 percent in net output is indicated for a 400° R (222 K) reduction in turbine inlet temperature from 2060° R (1144 K). The reduction in net power results from an increase in turbine aerodynamic speed to 111 percent of design and the reduction in inlet absolute temperature by 20 percent, which proportionately reduces the specific work.

Effect of Molecular Weight Variations on Net Power Output

Presented in figure 10 is the variation in BRU net power output in the laboratory loop with a variation in molecular weight of the working fluid for a constant compressor outlet pressure of 26.0 psia ($17.9 \text{ N/cm}^2 \text{ abs}$). Shown also is the net power output for a constant compressor inlet pressure of 14.0 psia ($9.7 \text{ N/cm}^2 \text{ abs}$). This curve was obtained from the constant outlet pressure curve by assuming that net power is proportional to compressor outlet pressure. This assumption is approximate since there is a second-order effect due to alternator efficiency and other parasitic losses. The two curves differ because, as molecular weight is reduced with a constant inventory in the system and a constant mechanical speed, the compressor inlet pressure rises and the outlet pressure

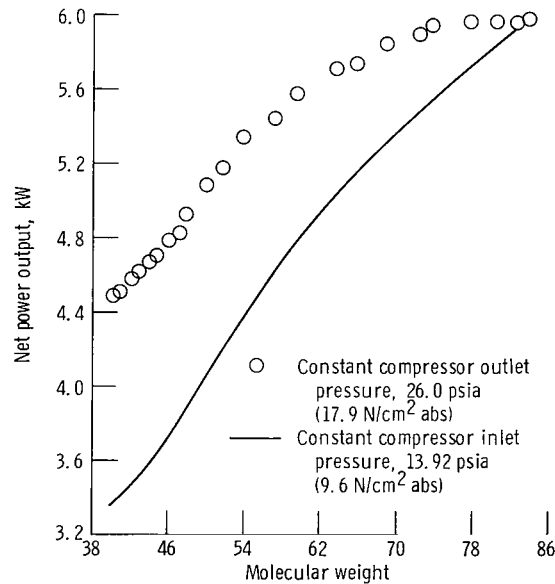


Figure 10. - Variation in BRU net power output in the laboratory loop with molecular weight of working fluid.

decreases. Thus, for a constant compressor outlet pressure, gas must be added to the system, and for a constant inlet pressure, gas must be removed. The mechanical speed (36 400 rpm), the turbine inlet temperature (1960^o R or 1089 K), and the compressor inlet temperature (540^o R or 300 K) were maintained nominally constant.

Figure 10 shows that, with a constant compressor outlet pressure of 26.0 psia (17.9 N/cm² abs), the net power output is 5.96 kilowatts at a working fluid molecular weight of 83.8 and drops to 4.49 kilowatts at a molecular weight of 40. Thus, with a constant compressor outlet pressure, there is a 24.7-percent reduction in net power for a reduction in molecular weight from 83.8 to 40. For a constant compressor inlet pressure, the net power drops from 5.96 to 3.36 kilowatts, a 43.6-percent reduction. The difference in the power reduction is caused by the change in inventory discussed in the previous paragraph.

The reduction in net power associated with the reduction in molecular weight of the working fluid is caused by a reduction in aerodynamic speed of the turbine and compressor. At a constant mechanical speed (36 400 rpm) and constant inlet temperature to the turbomachinery, a reduction in molecular weight from 83.8 to 40 reduces the aerodynamic speed from 100 percent of design to about 69 percent of design.

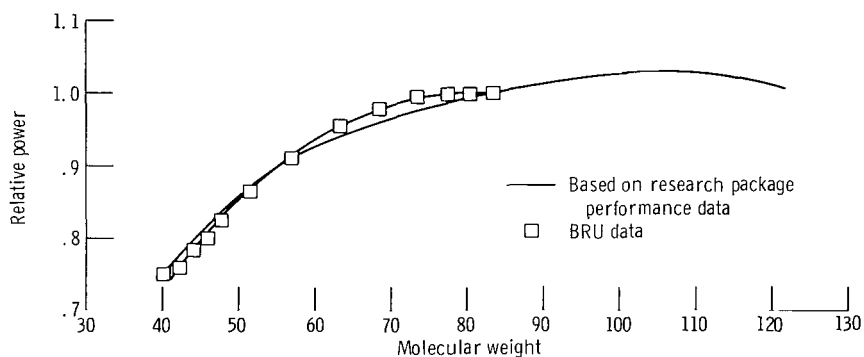


Figure 11. - Variation in relative power output with molecular weight of working fluid for constant compressor outlet pressure.

Presented in figure 11 is the variation in relative power computed from turbomachinery research package data as a function of molecular weight for a constant compressor outlet pressure. At the design molecular weight of 83.8, the relative power was taken as 1.0. For comparison, the data presented in figure 10 are replotted in figure 11, which shows that the BRU experimental data agree quite well with the research package data. Further, it is indicated that for a molecular weight of 70 up to 120 the net power varies only 6 percent.

SUMMARY OF RESULTS

The Brayton rotating unit (BRU) was investigated as part of a closed laboratory loop. The investigation included a study of a range of system operating parameters, such as compressor outlet pressure (15.0 to 45.0 psia or 10.3 to 31.0 N/cm² abs), inlet temperature to the turbine (1460⁰ to 2060⁰ R or 811 to 1144 K), compressor inlet temperature (510⁰ to 580⁰ R or 283 to 322 K), and a molecular weight of the system working fluid (83.8 to 40), and their effect on system net power output. The results of this investigation may be summarized as follows:

1. At design inlet temperature into the turbine and compressor, the net power output of the BRU in the laboratory loop varied from 3.6 to 13.6 kilowatts when the system pressure level, measured at the compressor outlet, was varied from 15 to 45 psia (10.3 to 31.0 N/cm² abs).

2. Operation of the Brayton system with a SNAP-8 reactor would impose a limit of 1660⁰ R (922 K) on turbine inlet temperature. This limit reduced the BRU net power output in the laboratory loop by about 50 percent from that obtained with the design temperature of 2060⁰ R (1144 K).

3. The net power output decreased by 24.7 percent when the molecular weight of the working fluid was varied from 83.8 to 40 with a constant compressor outlet pressure.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 24, 1970,
120-27.

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