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ISOTOPE BRAYTON SPACE POWER SYSTEMS AND THEIR TECHNOLOGY

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ABSTRACT

The objectives of the NASA-Lewis Research Center Brayton Space Power Program and the advantages of achieving an isotope Brayton space power system are enumerated. The paper describes the 2-15 kWe Brayton engine, its subsystems, and major components and summarizes the status of the test program. Two areas of Brayton constituent technology are discussed—gas bearings and heat exchangers. A summary is given of a 500-2500 W isotope Brayton space power system study that showed very attractive performance, simplicity, and low cost for a system in this power range.

INTRODUCTION

Since 1963 the Lewis Research Center has been conducting a technology program on a Brayton space power system. Mainly, industry has performed the component design and fabrication while the Lewis Research Center, the system manager and integrator, has performed the component and system tests. The objectives of this program have been to develop the technology for a space power system that has a lifetime exceeding five years, a high net conversion efficiency, and an appropriately low specific weight.

As a space power system, the isotope Brayton offers the advantages of low cost and long life. Its relatively high net conversion efficiency (20 to 30 percent) would reduce isotope heat source cost by about 75 percent as compared to radioisotope thermoelectric generators. With Curium-244, the isotope Brayton potentially competes in cost and weight with solar cell/ batteries in near earth orbit. In addition, the Brayton has the cost saving attribute that a specific engine design can cover a wide power range (at least a factor of five). This minimizes cost by avoiding the need for developing and qualifying a power system for each new application. The Brayton system, particularly in light of its use of gas bearings, has the potential for achieving long life operation. Other than from the isotope decreasing in power with time, an isotope Brayton space power system should not exhibit a loss in power output.

In developing the Brayton technology, a 2 to 15 kWe power system has been used as a focus. A very considerable part of this 2 to 15 kWe work is applicable to Brayton power systems at both lower and higher power levels. Since NASA mission studies for the 1980's indicate that the majority of the missions will require from hundreds of watts to about 2 kW, the program presently emphasizes a Brayton system that operates over a range of 500 to 2500 We. This system, called the mini-Brayton, would avail itself of the Multi-Hundred Watt heat source which is presently under development by the Atomic Energy Commission.

This paper first describes the 2-15 kWe Brayton engine, its subsystems and major components, and summarizes the test program conducted on the engine and its subsystems. Two areas of constituent technology from the Brayton Space Power Program are then discussed—the gas bearings and heat exchangers. Lastly, a summary is given of a study of the mini-Brayton space power system.

THE 2-15 kWe BRAYTON ENGINE

Description of Engine, Subsystem, and Major Components

In 1969, a Brayton engine using first generation components was assembled. The engine was originally designed to operate at 10 kWe. However, at increased pressure and with additional cooling to the alternator the power can be extended to 15 kWe. The engine is compactly configured and contains many of the components that would be on a flight system. It was tested in a vacuum environment in the Space Power Facility at the Lewis Plumbrook Station.

A schematic of this engine is given in Fig. 1. The working gas is either krypton or a mixture of helium-xenon having the same molecular weight as the krypton (83.8). The design temperatures are shown in the figure. In our laboratory test, the gas is heated by an electric resistance heater and then enters the turbine. The turbine extracts energy from the gas and drives a compressor and an alternator which are on the same shaft. The gas then enters the recuperator where it transfers heat to the cooler gas coming from the compressor. After rejecting heat to the waste heat exchanger, the gas goes to the compressor. The materials used in the engine were Inconel and Hastelloy N for the high-temperature section from the heat source to the turbine and stainless steel for the remaining part of the engine.

Cycle efficiency of the Brayton is dependent upon such factors as turbine and compressor inlet temperatures, turbine and compressor efficiencies, heat transfer effectiveness of the recuperator, friction pressure drop, and alternator efficiency. If the turbine and compressor inlet temperatures are maintained at design conditions, the power level of the Brayton system can be varied by changing the gas pressure or inventory.

In addition to the gas loop, where the power is converted, the 2-15 kWe engine requires a number of subsystems for operation. The electrical subsystem provides regulation of the alternator output voltage, allows variation of the user load by use of a parasitic load speed control and provides housekeeping power. The two principal functions of the gas management subsystem are to provide external gas pressurization to the bearings during engine startup or shutdown and to adjust the gas pressure (or power) of the power loop. The heat rejection subsystem consists of redundant coolant loops that circulate a silicone oil (Dow-Corning 200) to cool the waste heat exchanger, the electronic cold plates, and the alternator stator. Heat is then finally rejected to either a facility heat exchanger or to a flight-type radiator.

One of the more important components in the Brayton engine is the

Brayton Rotating Unit (BRU). A cross-section of this unit is shown in Fig. 2. Turbine, compressor, and alternator are all on the same shaft which rotates at 36 000 rpm. The BRU has a radial inflow turbine and a centrifugal compressor having nominal pressure ratios of 1.75 and 1.90, respectively. The main structural part of the BRU is the alternator to which the gas bearings and the turbine and compressor scrolls are attached. To provide pressure to the gas bearings, the cavity of this unit is connected to the compressor outlet. Close clearance seals at the turbine and compressor ends minimize the bypass flow. In the design (ref. 1) of the BRU, particular attention was given to minimize the heat flow from the turbine into such areas as the gas bearings and the alternator. A discussion of the gas bearings for this unit is included in a subsequent section of the paper.

The alternator (ref. 2), shown in Fig. 3, is of the Lundell type in which the field windings are located in the stator. The rotor is of four pole construction using 4340 magnetic steel for the pole pieces and Inconel 718 as the nonmagnetic separator. This type of alternator eliminates the need for field brushes, reduces windage, and has no rotating winding or rectifiers. The direction of the magnetic lines through the alternator are shown in the figure. Output voltage (120 V l-n) of this three-phase machine is controlled by the shunt field which senses average peak voltage.

The other important component in the Brayton engine is the Brayton Heat Exchanger Unit (BHXU) (ref. 3), shown in Fig. 4. This unit incorporates both the recuperator and waste heat exchanger. Stacked plate-fin construction is used in both heat exchangers. In the recuperator the hot and cold gases run counterflow while in the waste heat exchanger the working gas and the silicone oil are in cross-counter flow. The heat transfer effectiveness of the recuperator and the waste heat exchanger for the helium-xenon mixture is 0.95.

Figure 5 shows the Brayton Rotating Unit and the Brayton Heat Exchanger Unit in its support frame during the engine buildup. The engine completely assembled and connected to test support equipment is shown in Fig. 6.

Extent of Tests

The objectives of the test program for the 2-15 kWe Brayton engine were to determine its performance over a broad range of operating conditions including simulated sun-shade transients and to obtain significant operational time on a complete system.

For both krypton and the mixture of helium-xenon, engine performance was obtained for turbine inlet temperatures from 1300° to 1600° F, compressor outlet pressures from 25 to 44 psia, and compressor inlet temperatures from 45° to 94° F. Figure 7 gives the performance (ref. 4) of the engine for the helium-xenon gas mixture for a turbine inlet temperature of 1600° F and a compressor inlet temperature of 80° F, with power variation being effected by changing the loop pressure.

During the first phase of testing in which the above mapping was performed, the waste heat from the engine was dumped to a facility heat exchanger. In the following phase, the engine was connected to a flight-type radiator (ref. 5). The effect of a simulated near earth orbit on engine performance was determined. The flight-type radiator, sized for a nominal 7 kWe output, was 22 ft in diameter and 10 ft high.

In the radiator tests the cooling loops of the engine were connected to the radiator as shown in Fig. 8. The liquid coolant from the waste heat exchanger passed through the entire radiator while the coolant from the alternator and electronic cold plates passed only through the low temperature section of the radiator. This splitting of the high and low temperature coolants minimizes the size of the radiator.

Figure 9 shows the engine and radiator installed within the Plumbrook Space Power Facility. The dark background is the cold wall which surrounds the radiator. The sun in these tests was simulated by a bank of iodine-quartz lamps, located between the cold wall and the radiator. The cold wall was held at -110° F and the intensity of the quartz lamps was varied to simulate sunlight in a near earth orbit. Results of this test are presently being analyzed. During both phases, the 2-15 kWe engine accumulated a total 3200 hours of testing.

In addition to testing the engine, a number of the subsystems have been individually tested to demonstrate long term operation and determine interaction of components. A test rig containing the BRU and BHXU, with the gas loop identical to that of the engine, has accumulated in excess of 10 000 hours of operation; over 9000 hours of this operation was unattended. In addition to demonstrating long term operation of the BRU and BHXU, this rig has been used to investigate methods for motor starting the engine and for performance mapping. Tests of more than 10 000 hours each have also been conducted on the electrical and gas management subsystems. During these tests the components have been periodically exercised. The electrical subsystem has been tested at pressures less than 10^{-5} torr and at temperatures ranging from -60° to 120° F, while the gas management subsystem has been tested only at ambient conditions.

With the exception of the recuperator in the BHXU which will be discussed in a following section, no obstacle of significance has been encountered in the engine and the subsystem tests. The difficulties which have arisen have been primarily associated with test support equipment rather than the Brayton hardware.

CONSTITUENT TECHNOLOGY

A considerable part of the Brayton Space Power Program at the Lewis Research Center has been concerned with constituent technology that potentially has a wide range of applications. Two areas of such constituent technology are gas bearings and heat exchangers, both of which are important to the isotope Brayton space power system. A discussion of these topics follows.

Gas Bearings

The Brayton Rotating Units which have been tested in the heated gas loops have employed conforming pivoted pad journal and Rayleigh step thrust bearings. Shown in Fig. 10 is the journal bearing and its carrier. Each pad is connected to a beam through a ball and socket. Two of the beams are rigid while the third can flex. Prior to start, the shaft is clamped by the pads. During start gas is externally applied to the journal through a hole in the face of each pad. The pad that is flex mounted pulls away from the shaft and the shaft in turn pulls away from the two fixed mounted pads. When rated speed is reached, external gas pressure is removed and the bearings become self-acting. Initially there was concern about the possibility of wear at the ball-socket pivot. However, inspection (ref. 6) of three Brayton Rotating Units indicates that after a short initial wear-in period, any additional wear is not measureable.

Figure 11 shows the thrust bearing runner and each side of the Rayleigh-step stator. When the BRU is assembled, the runner is sandwiched between the stators and the stator assembly is connected to a flexure pivoted gimbal. Early in the BRU testing an instability was observed in the thrust bearing. This, however, was corrected by providing friction damping to the flexure gimbal.

As backup, work was started early in the Brayton program on other promising types of bearings for the Brayton Rotating Unit (ref. 7). This work consists of three types of journal bearings — a nonconforming pivoted pad, a cruciform pivot, and a ribbon-foil bearing; and one type of thrust bearing — a spiral grove. Each of these bearings have been cold tested in Brayton Rotating Units and have performed satisfactorily.

Presently, a Brayton Rotating Unit that includes leaf-type foil bearings for the journal and thrust bearings is in the final phase of assembly. Figure 12 shows the journal bearings with the foils inserted in the carriers. Figure 13 shows the thrust bearing with its foil stators. Prior to start, the foils are slightly spring loaded against the shaft. Upon start, the shaft rotates in contact with the teflon coated foils and at about 3000 rpm the foils deflect away from the shaft and the bearings become self acting.

With this type of bearing there is no need for external pressurization during start up and shutdown. Therefore, the gas management subsystem may be simplified or entirely eliminated. Furthermore, the leaf-type foil bearing does not require a thrust gimbal and appears to be resistant to wear and tolerant to shock and vibration. Although the bearings presently operating in the Brayton Rotating Unit have performed very satisfactorily, the foil bearings appear to have the advantage of simplicity. Further investigation of these bearings is planned.

Heat Exchangers

In the 2-15 kWe Brayton engine program, three identical Brayton heat exchanger units have accumulated a total of approximately 14 000 hours of operation. The recuperator sections of all three of these units have experienced external leaks. These leaks occur after nominally 15 start-stop cycles. The location of these leaks has been in a region of high thermal stress where the hot gas initially enters the recuperator from the turbine. Temperatures in this region are as high as 1200° F. The leak occurs in the braze joint between the plate and the header bar as shown in Fig. 14. These leaks have been fixed by field brazing and one of the heat exchangers also has a secondary containment built around the recuperator.

A second generation Brayton Heat Exchanger Unit (designated the BHXU-A), which is in the final phase of assembly, contains a number of changes that should minimize the possibility of external leaks from the recuperator. Referring to Fig. 15, a ductile gold alloy braze will replace the nicrobraz that was used in the first units. Also, the recuperator will be doubly contained by external plates that are brazed to the header bar surfaces and welded along its edges.

A comparison is shown in Fig. 16 of the waste heat exchanger designs for the BHXU and BHXU-A. The tube and fin construction of the BHXU-A reduces the number of braze joints between the liquid coolant and the gas which, therefore, further minimizes the chance of one fluid mixing with the other.

In 1971, a technology program was initiated to investigate key problems associated with Brayton heat exchangers. Investigations in this program include performance assessment of low-cost braze alloys, improved design and fabrication techniques to preclude leakage, and design and fabrication techniques to improve cyclic life.

THE MINI-BRAYTON SPACE POWER SYSTEM

Since a large number of projected missions require less than 2 kW of electric power, a feasibility study (ref. 8) was conducted on an isotope Brayton space power system specifically designed to operate from 500 to 2500 We. The assumptions in this study were conservative in that it was primarily based upon the technology of the 2-15 kWe Brayton Program which achieved high efficiency over a wide power range.

A schematic of this mini-Brayton Power System is shown in Fig. 17. The system has a number of simplifying features - the working gas rejects its heat by passing directly through the radiator; the alternator is cooled by the working gas itself; and the use of foil bearings eliminates the need for a gas management subsystem. The control module converts the alternator output to dc; provides voltage regulation; speed control; and conditions external power, such as from the shuttle, for motor starting. Table I gives a summary of the performance of the mini-Brayton using from 1 to 4 Multi-Hundred Watt heat sources. One rotating unit design was used for all the power levels while the remaining components were optimized for each power level. The performance summary shows that the bus-bar efficiency is 23 percent for 550 We output and increases to 28 percent for 2670 We output. Specific power for the five hundred watt level is 1 W/lb and 2.3 W/lb at 2.5 kWe.

As presently conceived each Multi-Hundred Watt heat source would have its own separate heat exchanger. These heat sources would be paralleled if more than one heat source were required. A mock-up of the mini-Brayton with all its components is shown in Fig. 18. The size of the radiator for the 550 We output is nominally 5 ft in diameter and 5 ft long.

Work subsequent to the above study indicates that, with the exception of the radiator, all the components of the mini-Brayton can be standardized to operate from 500 to 2500 W without a significant weight penalty. Such a standardized power system will reduce cost because one system would suffice for a number of different missions and would, also, negate the need for developing and qualifying each new power system.

CONCLUDING REMARKS

Testing of the 2-15 kWe Brayton engine has shown that a Brayton space power system can achieve high net conversion efficiency (up to 29 percent) and that this efficiency remains high over a broad power range. This engine has been tested for more than 3200 hours during which it was mapped over a wide range of operating conditions. Also, the engine with a flight-type radiator was tested in a simulated sun-shade earth orbit. The three major subsystems of the engine—gas loop, electrical, and gas management—have each been separately tested for more than 10 000 hours. With the exception of the recuperator problem, no major difficulty has been encountered in the testing program.

A modified Brayton Rotating Unit with foil thrust and journal bearings is being assembled. This type of bearing should simplify the BRU and potentially eliminate the gas management subsystem. A second generation Brayton Heat Exchanger Unit (BHXU-A) is being assembled and will be tested to demonstrate the solution to the recuperator problem.

A feasibility study of a 500 to 2500 W isotope Brayton space power system (mini-Brayton) showed high net bus-bar efficiencies (~25 percent) and specific powers from 1 to 2.3 W/lb. This system has relatively few components and will make use of foil gas bearings. Its high net conversion efficiency reduces the isotope inventory and therefore the cost of the isotopes, and the suitability of use of a given power module over a wide range of powers reduces costs of development and flight qualification.

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TABLE I. - MINI-BRAYTON PERFORMANCE STUDY

	Number of MHW heat sources			
	1	2	3	4
Gross thermal power, W	2400	4800	7200	9600
Net system efficiency, $\frac{\text{Net power}}{\text{Gross thermal input}}$	0.24	0.27	0.29	0.29
Bus-bar efficiency, $\frac{\text{Conditioned power}}{\text{Gross thermal input}}$	0.23	0.26	0.28	0.28
Conditioned power to user at 120 V dc, W	550	1260	1990	2670
Total system weight, lb	570	710	970	1160
System specific power, W/lb	1.0	1.8	2.1	2.3

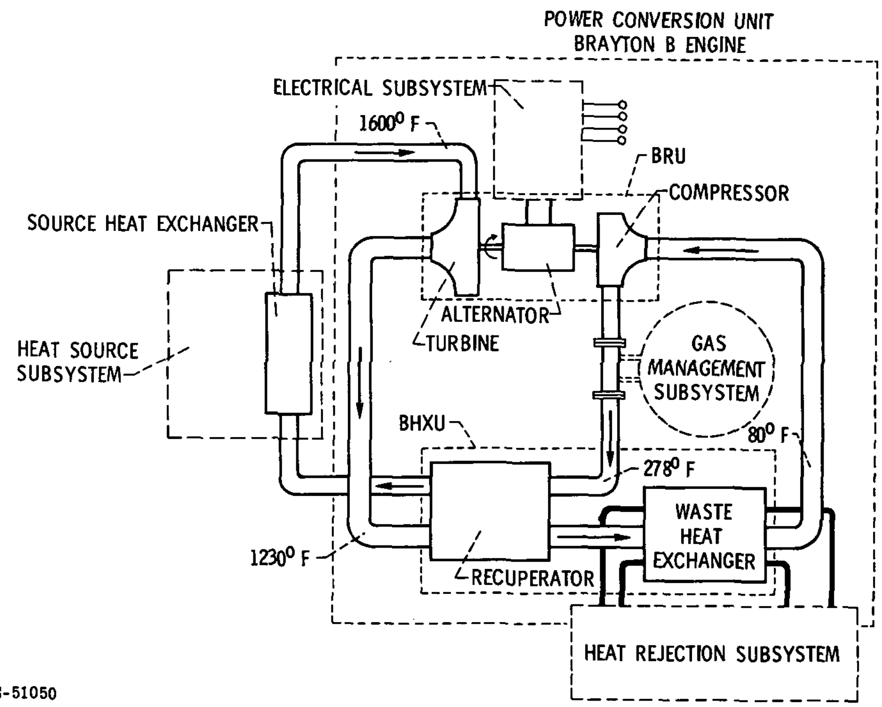

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Figure 1. - Schematic diagram, 2-15 kW(e) Brayton engine.

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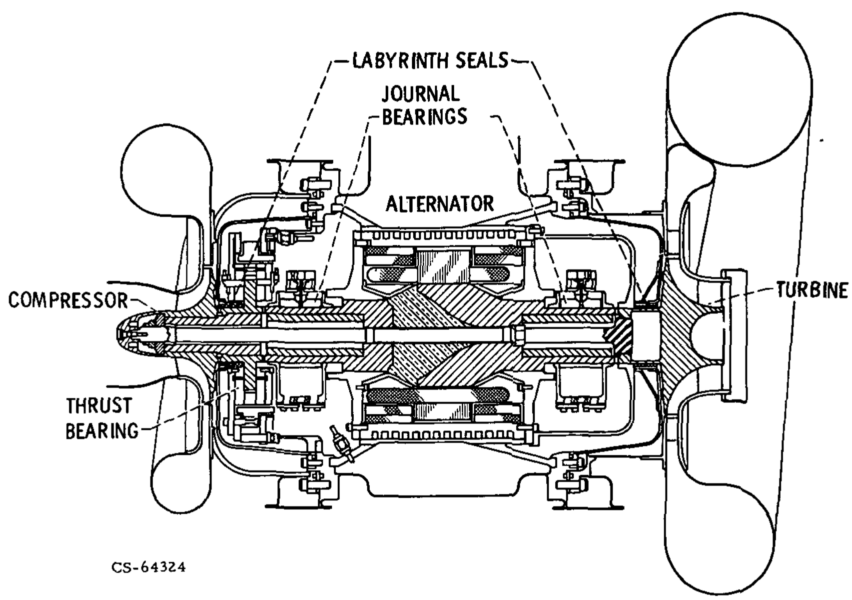

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Figure 2. - Brayton rotating unit cross section.

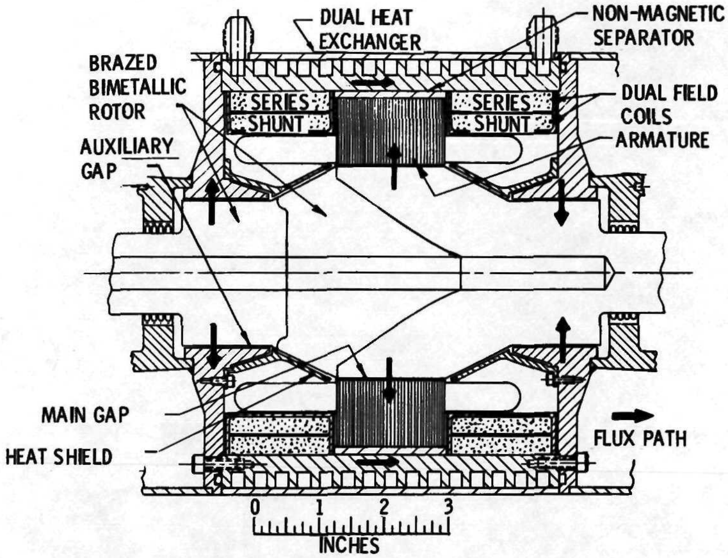

Figure 3. - Lundell alternator cross section.

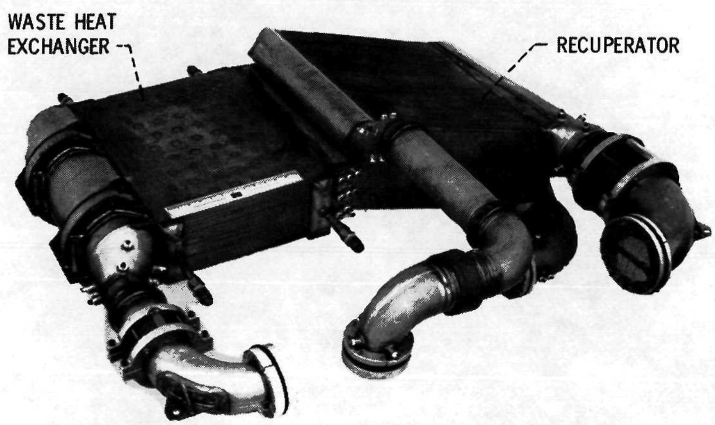

Figure 4. - Brayton Heat Exchanger Unit.

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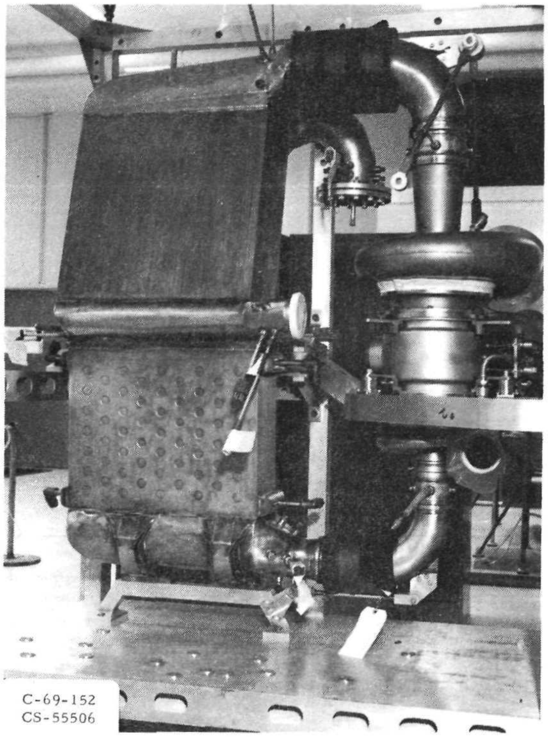

Figure 5. - BRU and BHXU in support frame.

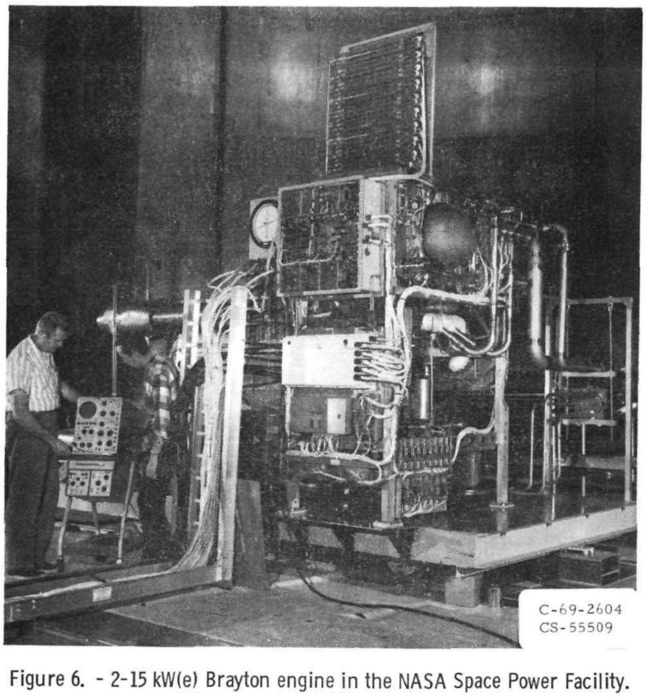

Figure 6. - 2-15 kW(e) Brayton engine in the NASA Space Power Facility.

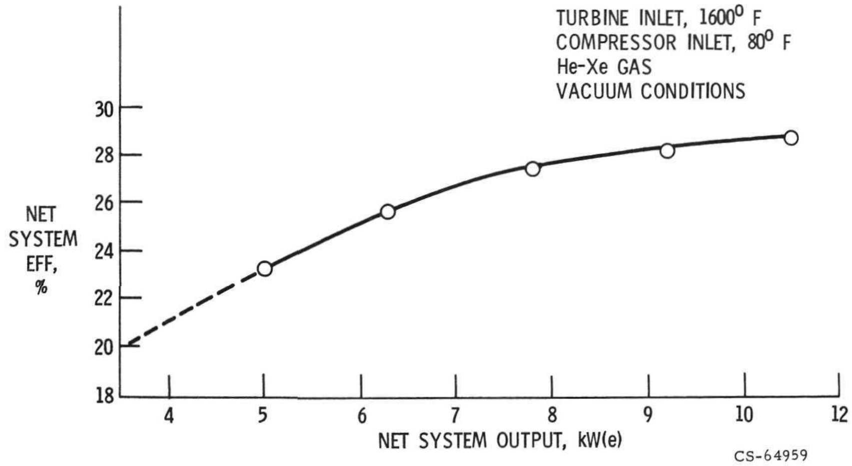

Figure 7. - Performance of 2-15 kW(e) Brayton engine.

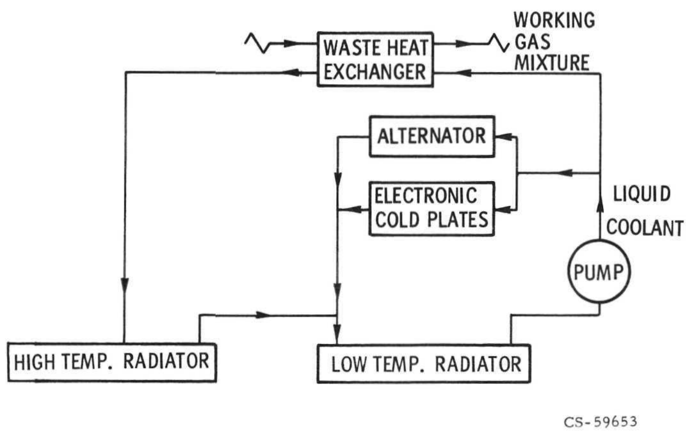

Figure 8. - Radiator and cooling-loop arrangement in Space Power Facility test.

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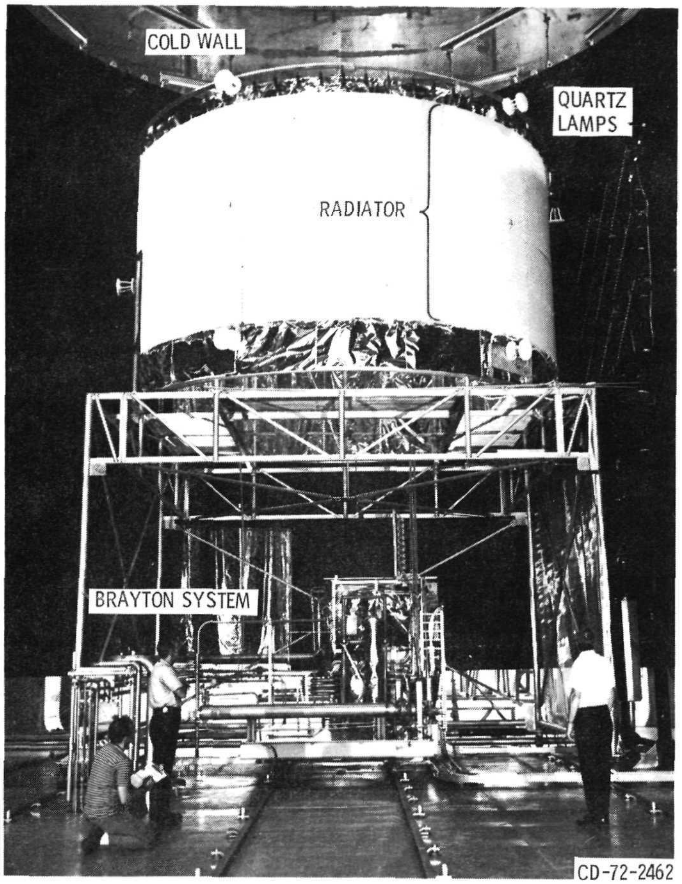

Figure 9. - Brayton engine with space-type radiator in the Space Power Facility.

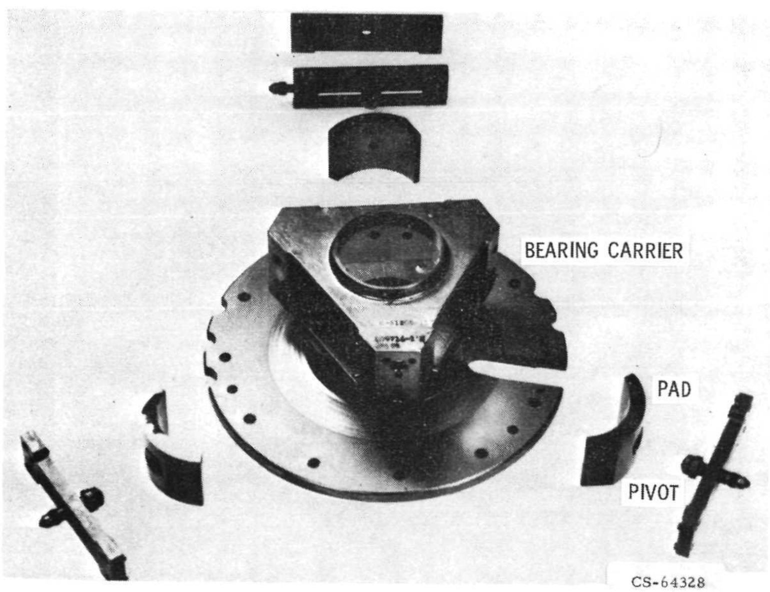

Figure 10. - BRU journal bearing assembly.

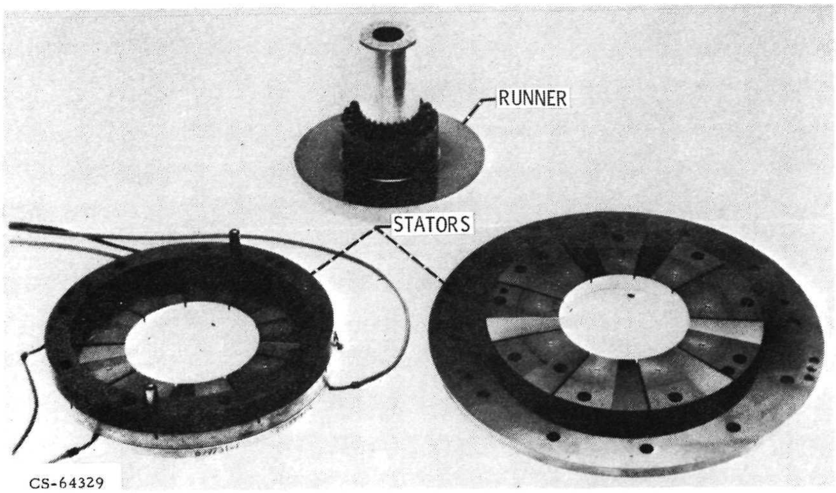

Figure 11. - BRU thrust bearing stators and runner.

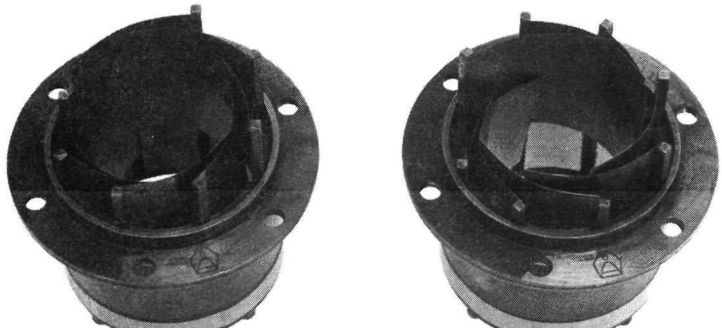

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Figure 12. - Leaf foil journal bearing.

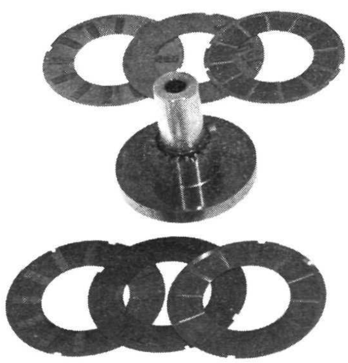

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Figure 13. - Leaf foil thrust bearing.

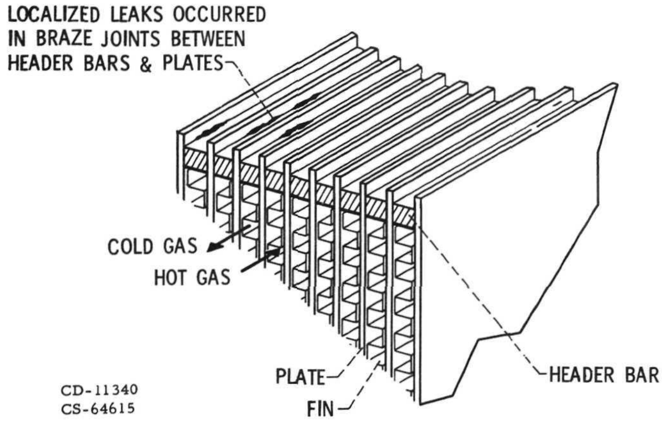

Figure 14. - Location of recuperator leaks.

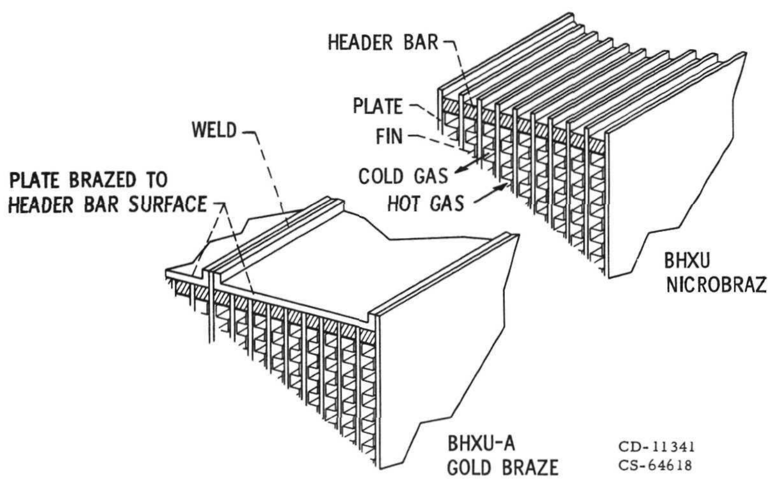

Figure 15. - Comparison of recuperator construction of BHXU-A with BHXU.

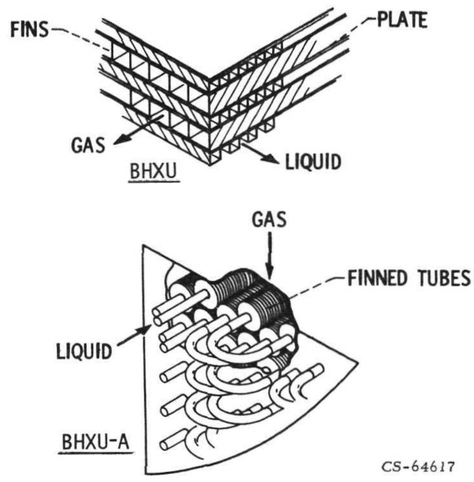

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Figure 16. - Comparison of waste heat exchanger construction of BHXU-A with BHXU.

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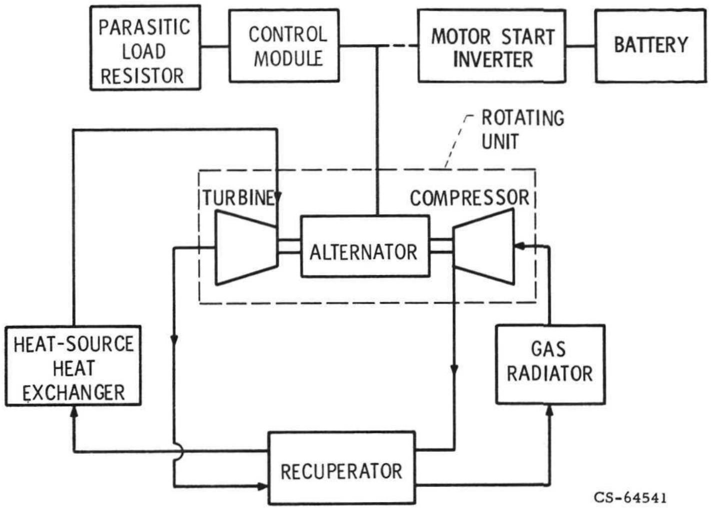

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Figure 17. - Mini-Brayton system schematic.

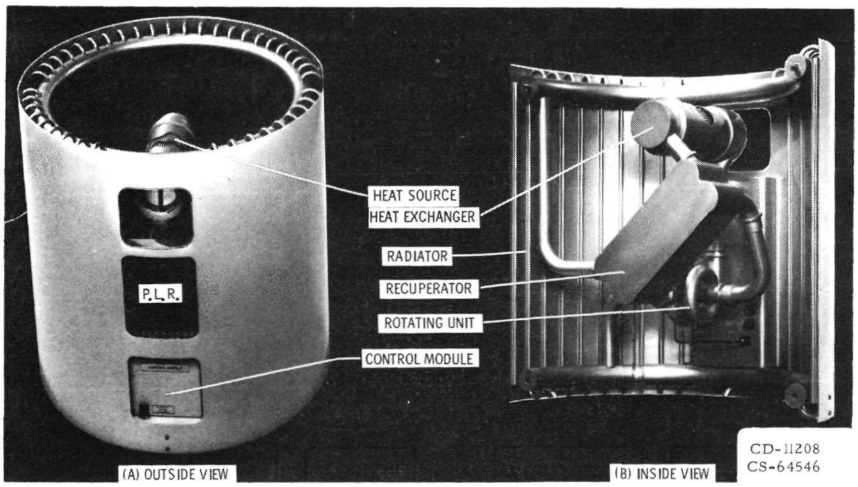

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Figure 18. - Mini-Brayton power system (550 We).