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2 TO 10 KILOWATT SOLAR OR RADIOISOTOPE BRAYTON POWER SYSTEM

by John L. Klann
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at Intersociety Energy Conversion Engineering Conference sponsored by the Institute of Electrical and Electronics Engineers
Boulder, Colorado, August 14-16, 1968

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E-4454

ABSTRACT

A second-generation Brayton power system has been defined. Hardware components are currently being assembled for complete, ground-based power system tests. The power systems to be tested are described. Maximum system efficiency is estimated at 0.19 for 2 kilowatts of output, rising to about 0.27 in the range from 6 to 10 kilowatts.

INTRODUCTION

Needs for electrical energy in space are growing. Some of our future space missions will probably need kilowatts of electricity for periods in excess of a year. Parker,[1] for example, has postulated an orderly progression of manned space flights. Within the next 10 years, he foresees electric power needs up to about 15 kilowatts with missions as long as 5 years.

NASA recognized the probable needs for long-life, kilowatt-level space power systems, and saw potential advantages in the Brayton cycle for satisfying such needs. Studies (as summarized by Bernatowicz[2]) showed that an extension of technology would be needed to successfully use the Brayton cycle in space. There were two major technology gaps. Thermodynamic analysis showed that highly efficient, small-diameter turbomachinery was needed. Sufficient performance data were not available. The second technology gap was that of bearings for the rotating machinery. For long life, gas lubricated bearings were felt to be needed. An extension of gas bearing technology would be required for this application. Therefore in 1963, NASA started a closed-Brayton-cycle component technology program at Lewis Research Center.

The early component work at Lewis centered about an 8-kilowatt, solar-powered system.[2] It was characterized by two, separate turbomachinery packages - a low-speed turboalternator and a high-speed turbocompressor. We contracted for the design and fabrication of some of the components that would be applicable to the system. These components were tested and most performance results were encouraging. (The 1966 Space Power Conference[3] at Lewis summarized the results at that time.) Small turbomachinery could be made with efficiencies of 80 percent or more. And gas bearings could be made to work for the Brayton cycle machinery.

Concurrent with the early component work, a NASA study group had investigated[4] concepts to exploit radioisotopes as a heat source for kilowatt-level space power systems. Radioisotope heat sources, even at the multikilowatt level, could be relatively compact. A Brayton system was particularly attractive in combination with isotopes. The potentially high conversion efficiency of a Brayton system would make good use of a limited radioisotope supply. (Analytical studies by Glassman,[5]

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[1] R. N. Parker, "Space Power and the Progression of Manned Space Flight Requirements," S.A.E. Aerospace Systems Conference Proc., pp. 169-183, Los Angeles, Calif., June, 1967.

[2] D. T. Bernatowicz, "NASA Solar Brayton Cycle Studies," paper presented at the Symposium on Solar Dynamic Systems, Solar and Mechanical Working Groups of the Interagency Advanced Power Group, Washington, D.C., September 24-25, 1963.

[3] W. L. Stewart, W. J. Anderson, D. T. Bernatowicz, D. C. Guentert, D. R. Packe, and H. E. Rohlik, "Brayton Cycle Technology," Part V, pp. 95-145 of "Space Power Systems Advanced Technology Conference," NASA SP-131, August, 1966.

[4] Ad Hoc Study Group, "Selection of Radioisotopes for Space Power Systems," NASA TM X-1212, March, 1966.

[5] A. J. Glassman, "Thermodynamic and Turbomachinery Concepts for Radioisotope and Reactor Brayton-Cycle Space Power Systems," NASA TN D-2968, August, 1965.

McKhann,[6] and myself[7] looked at the isotope-Brayton system. Parker's paper[1] shows potential advantages for the combination.)

In February of 1966, based on the earlier test results and further system studies, a new Brayton power conversion system was defined. The good performance of small turbomachinery and a potential need to extend Brayton system outputs down to about 2 kilowatts, led to the selection of a single-shaft, combined turbomachinery package. The new machinery required slightly smaller diameters. However, the number of bearings and shaft seals, in comparison to the earlier two-shaft system, were cut in half. Fewer bearings and seals reduce power losses which become more important to good system performance at low power outputs.

Design selections for the new Brayton power conversion system were made such that its rated power output could be adjusted within the range from 2 to 10 kilowatts. In space use it could be coupled to either a solar- or radioisotope-heat source.

In addition to new component tests, complete ground-based power system tests are planned. The purpose of this paper is to describe the new Brayton power conversion in its ground-test configuration. For completeness, a brief description of the heat sources intended to be used in the ground tests and some indications of the program status are also included. Power system efficiency estimates are presented.

GENERAL SYSTEM DESCRIPTION

Figure 1 shows a schematic diagram of the Brayton gas loop with the four major subsystems shown in phantom. The heat source subsystem adds heat to an inert working gas in its heat exchanger. The hot gas flows to a single-stage, radial-inflow turbine. Expansion of the gas through the turbine spins the machinery shaft and produces useful work. Part of this work is absorbed by driving a single-stage, radial-outflow compressor. Most of the remaining shaft work is available to a four-pole, brushless alternator. The rotating shaft is supported by journal and thrust bearings that are lubricated by the working gas itself.

After expansion in the turbine, the gas flows through a recuperator. This heat exchanger transfers the majority (approximately 70 percent) of the energy that is potential waste heat back to the cooler gas flow leaving the compressor. Then a gas-to-liquid heat exchanger removes the unusable heat. The cooled gas is compressed, ducted back through the recuperator, and returned to the source heat exchanger.

The heat source subsystem provides thermal energy continuously at high temperatures to the working gas. The source heat exchanger is an integral part of the gas loop. However, since this heat exchanger is different depending on the heat source, it is also considered to be part of the heat source subsystem.

The electrical subsystem regulates and distributes the power and controls the power system. Output frequency is regulated, and hence, the rotating shaft operates at a constant speed. The gas management subsystem is used mainly to start and stop the power system. It also is used to adjust the working gas inventory.

The heat rejection subsystem liquid coolant is also used to cool the alternator and electrical subsystem components. For added reliability, two identical coolant loops are available for use. During normal power system operation, one loop is active while the other is passive. In our ground-tests, an auxiliary or "radiator-simulator" heat exchanger will be used to reject the heat from the liquid.

The Brayton power conversion system (PCS) consists of everything but the heat source subsystem and the radiator simulator. The PCS coupled to a heat source subsystem and the radiator simulator forms a ground-test, Brayton power system.

Any given power system must, on demand, be capable of producing power from zero up to its rated output. The rated power output of the closed-cycle Brayton system may also be adjusted. Its range of rated power output primarily results from sizing the alternator for the high power, and the ability of the gas bearings to support the shaft at the low power. Assuming the ability to control the system's heat-input and -output, the power rating would be adjusted by changing the working gas inventory in the Brayton loop. Setting the gas pressure level fixes the inventory and mass flow rate. Since the shaft speed is controlled, the shaft work and alternator output are proportional to the gas flow rate.

DESIGN CONDITIONS

Table I presents a list of the Brayton cycle design conditions. They were selected in the analysis of a radioisotope space power system.[7]

A working gas mixture of helium and xenon at the

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[6] G. G. McKhann, "Preliminary Design of a Pu-238 Isotope Brayton Cycle Power System for MORL. Vol. I: Technical Summary," Report No. SM-48832 (NASA CR-68809), Douglas Aircraft Company, Inc., September, 1965.

[7] J. L. Klann, "Analysis and Selection of Design Conditions for a Radioisotope Brayton-Cycle Space Powerplant," Proposed NASA Technical Note.

molecular weight of krypton (83.8) was chosen. The helium in the mixture causes increased heat transfer capability over that of pure krypton gas (Mason[8]).

The values of turbine- and compressor-inlet temperature resulted from considerations of space radiator area and total system weight.

Values for machinery shaft speed and turbine- and compressor-pressure ratios were picked to give high cycle efficiency (the ratio of gross shaft power to heat source thermal input) and reasonable pressure levels and rotor diameters. Rotational speeds were also restricted to those which would produce a multiple of 400 hertz from the four-pole alternator. At 36,000 rpm, the output frequency is 1200 hertz.

High values of heat transfer effectiveness were selected for both the recuperator and the waste heat exchanger. These choices gave near minimum system weight and still resulted in relatively compact heat exchangers.

These conditions have been used in the PCS hardware designs. They were applied to the designs at the gas pressure levels and mass flow rates that were estimated to give 10 kilowatts of net system output.

SYSTEM TESTS

NASA-Lewis plans to assemble complete Brayton power systems for ground testing. The site for the test programs is the Space Power Facility at NASA's Plum Brook Station in Sandusky, Ohio. This is a vacuum chamber 100-feet (30.5-m) in diameter and 120-feet (36.6-m) high. It is designed to handle nuclear tests.

Our ultimate intent in the ground-based programs is to integrate and test the PCS and radiator simulator with three different heat source subsystems. Figure 2 lists the heat sources. They include a test-support electric heater, and space-configured solar- and radioisotope-heat sources.

Electric Heater

The initial test program is planned with the electric heat source. It is designed to simulate operation of either space heat source. The test-support subsystem (being supplied[9] by the Solar Division of International Harvester Corp.) consists of two planar banks of quartz lamps, a central heat exchanger, ducts for mating with the PCS, and a power controller.

The quartz lamps transfer heat radiantly to the heat exchanger. The heat exchanger is a series of U-tubes manifolded into inlet and outlet headers. The lamps and heat exchanger fit into an insulated rectangular box. Lamp reflectors are water-cooled from an external supply. Voltage controls permit either manual or automatic operation. Two automatic control modes are available: either a constant source-heat-exchanger gas outlet temperature, or a constant lamp output heat flux.

Solar Source

We plan to integrate the solar heat source subsystem with the PCS and radiator simulator for later tests. This source consists of a 30-foot-diameter (9.2-m) parabolic mirror with a cavity heat receiver located at the mirror's focal point. Test-support solar simulator lamps and mirrors are being developed as part of an in-house effort at Lewis.

The receiver absorbs energy reflected from the parabolic mirror. It stores part of this heat and transfers the rest to the Brayton working gas. Lithium fluoride is used as the heat storage and heat transfer material. The receiver is being built.

Details of this heat source concept and its associated technology were presented at the 1966 Space Power Conference.[3] However, it should be noted that the use of lithium fluoride, because of its 1560° F (1122° K) melting point, limits the turbine inlet temperature to about 1500° F (1090° K). This is 100° F (56° K) below the maximum PCS design temperature.

Radioisotope Source

A reference conceptual radioisotope heat source consists of a planar array of plutonium-238 fuel capsules rated at 25-kilowatts thermal. These capsules would be mounted in a reentry body and, normally, would radiate to an adjacent source heat exchanger.

This concept arose from the results of the NASA study group.[4] Oak Ridge National Laboratory (ORNL)

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[8] J. L. Mason, "Working Gas Selection For The Closed Brayton Cycle," paper presented at the Sixth AGARD Combustion and Propulsion Colloquium, Cannes, France, March 16-20, 1964.

[9] "Brayton Cycle Gas Heating System," contract number NAS3-10945, Solar, Division of International Harvester Co., San Diego, Calif., February, 1968.

extended the design concepts. (These studies were reported by Robinson.[10,11]) An initial design of high temperature fuel capsules resulted from this work.

Using the ORNL fuel capsule design, the Space Systems Division of AVCO Corporation is continuing[12] the studies. They are to provide a preliminary design of a complete radioisotope heat source and its reentry vehicle.

NASA has requested the AEC to provide plutonium-fueled capsules for use in a 25-kilowatt thermal source. This source would be integrated with the Brayton PCS and tested in the Space Power Facility. Preliminary plans for this ground test are being made.

POWER CONVERSION SYSTEM HARDWARE

All components for the first test program with the electric heat source subsystem are under contract. These same PCS components are also intended for the later tests with the space-configured heat source subsystems. Most of the PCS components are designed to be flight-type; and they are designed for a five-year life.

Figure 3 repeats the power system schematic diagram and shows some of the resulting design conditions.

Brayton Rotating Unit (BRU)

The combined rotating package (under contract[13] to AiResearch, Phoenix Div.) is referred to as the "Brayton Rotating Unit" or "BRU."

Design choices resulted in a turbine impeller tip diameter of 4.97 inches (12.6 cm), an alternator rotor diameter of 3.3 inches (8.4 cm), and a compressor impeller tip diameter of 4.25 inches (10.8 cm). These small machines were designed for relatively high efficiencies. At the 10-kilowatt power level, these efficiencies were 0.87 for the turbine, 0.92 (electromagnetic) for the alternator, and 0.80 for the compressor.

Initial component testing of the turbine and compressor at Lewis has shown that the design efficiencies were exceeded. Preliminary test results indicate a design-point efficiency of 0.90 for the BRU turbine, and a peak efficiency of 0.83 for the BRU compressor.

The BRU has a design temperature difference of about 1500° F (830° K) from the hot to the cold end. Design alternator stator, hot-spot temperature limit is 356° F (453° K). Dual liquid passages are looped around the alternator housing. Either liquid passage can provide the needed cooling.

One journal bearing is located between the turbine wheel and the alternator rotor, while a second is located between the alternator rotor and the compressor wheel. Each journal bearing includes three pivoted pads; two are fixed, while the third is spring loaded. A Rayleigh-step, thrust bearing is located between the compressor wheel and the compressor-end journal bearing. The thrust bearing includes stepped-stator plates on both sides of a flat-plate rotor.

During normal BRU operation, about 2 percent of the compressor discharge gas is ducted into the bearing and alternator cavity. This high-pressure gas provides the means for hydrodynamic (self-acting) bearing operation. Labyrinth shaft seals, located just inboard of both the turbine and compressor wheel, enclose the bearing and alternator cavity. However, the compressor bleed flow leaks through these seals (approximately 1 percent each) and reenters the turbine and compressor flow passages.

During BRU starts and stops, the bearings are designed for hydrostatic (pressurized) operation. The gas management subsystem provides the high-pressure jacking gas to each bearing pad.

The BRU is designed to perform efficiently over the net system power output range from 2 to 10 kilowatts. The compressor discharge pressure will vary from about 13 psia (90 kN/m^2) at 2 kW, to about 44 psia (300 kN/m^2) at 10 kW. At the low power level the pressure is high enough to provide satisfactory bearing operation. At the high power level, the pressure is not so high as to result in large alternator windage losses.

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[10] R. A. Robinson, et al., "Brayton-Cycle Radioisotope Heat Source Design Study. Phase I: (Conceptual Design) Report," Report No. ORNL-TM-1691 (NASA CR-72090), Oak Ridge National Lab., August, 1967.

[11] R. A. Robinson, T. G. Chapman, S. T. Ewing, A. J. Miller, and J. P. Nichols, "Brayton-Cycle Radioisotope Heat-Source Design Study. Phase II (Preliminary Design) Report," Report No. ORNL-TM-1829 (NASA CR-72151), Oak Ridge National Lab., August, 1967.

[12] "Design of an Isotope Reentry Vehicle - Brayton Cycle Space Power System," Contract number NAS3-10938, Avco Corp., Space Systems Div., Lowell, Mass., September, 1967.

[13] "Brayton Cycle Rotating Unit and Associated Research Hardware," Contract number NAS3-9427, AiResearch Mfg. Co., a division of the Garrett Corp., Phoenix, Ariz., June, 1966.

Brayton Heat Exchanger Unit (BHXU)

The "Brayton Heat Exchanger Unit" or "BHXU" (under contract[14] to AiResearch, Los Angeles Div.) consists of the recuperator, waste heat exchanger, and ducts for connection to the BRU (fig. 3). (A short section of the duct between the compressor and recuperator, called a "spool piece," is supplied as part of the gas management subsystem.)

The BHXU, as well as the BRU, is designed to operate with large temperature differences. The hot end sees the turbine gas exit temperature of 1230° F (939° K), while the cold end provides 80° F (300° K) gas to the compressor. The recuperator itself operates between 1230° F and the compressor outlet temperature, 278° F (410° K).

The recuperator core is a counter-flow heat exchanger. Plate- and fin-surfaces or "sandwiches" are used for both gas flows. The core is formed by alternate stacking of hot- and cold-gas-flow sandwiches. The overall core dimensions are 8.5 by 20 by 20 inches (21.5 by 50 by 50 cm).

The waste heat exchanger has a cross-counterflow arrangement. There are eight liquid passes back and forth across a single gas flow pass. Again this core uses plate-and-fin sandwiches for both the liquid and gas flows. Each liquid sandwich has 8 separate passages about 20-inches-long (50-cm) perpendicular to the gas flow direction. The gas flow length is about 16 inches (40 cm). The core is formed by alternate stacking of liquid- and gas-flow sandwiches. And the overall core stack-height is about 6 inches (15 cm). Since there are dual liquid passages, the order of sandwich stacking is active-liquid, then gas, inactive-liquid, then gas and so on.

The BHXU is designed for the nominal 10 kilowatt output conditions. Overall design system pressure loss is 8 percent (which is consistent with the design ratio of turbine-to-compressor pressure ratios, see table I). The BHXU itself is designed not to exceed $4\frac{1}{2}$ percent pressure loss.

Since these heat exchangers are designed for 0.95 effectiveness at the 10-kilowatt conditions, they have increased effectivenesses at the lower power levels. The lower system power levels have smaller gas mass flow rates. With reduced flow, the heat transfer coefficient drops. However, the amount of heat to be transferred over the fixed core area also drops. The net effect is the increase in heat transfer effectiveness for both exchangers at the lower power levels.

Gas Management Subsystem

The gas management subsystem (under contract[15] to TRW systems) consists of a gas supply tank and fill- and vent-lines which connect to the Brayton gas loop in the spool piece. Supply lines are also connected to the BRU housing for pressurizing the bearing cavities. The full and vent lines are filtered and fitted with valves. A flow check valve, located in the spool piece prevents reverse gas flow during power system starts.

Functions of the gas management subsystem are listed in Fig. 4. They are associated with power system *starts*, *output adjustments*, and *stops*.

Initial power system starts are planned to be made by "gas injection." (Starts by "motoring the alternator" are being planned for later tests.) In the start sequence, both the heat-source- and heat-rejection-subsystems are prepared and functioning. Then the gas management subsystem supplies jacking gas to each bearing pad. Next it injects gas downstream of the closed check valve into the recuperator. The gas flows through the loop and is vented upstream of the check valve at the exit of the compressor. This flow rotates the BRU shaft and, for a short time, we have an open Brayton cycle. Somewhat above self-sustaining BRU speed, the vent valve is closed, the check valve is opened, and the main injection is stopped. The BRU accelerates to design speed, and the bearing jacking gas flow is stopped.

During power system operation after a start, the gas management subsystem provides a means for gas inventory control. Gas may be added or removed by valve sequencing.

The planned power system stop sequence includes: stopping the heat-source subsystem input, supplying bearing jacking gas, loading the alternator, and venting the gas loop. The gas management subsystem provides jacking gas until the BRU shaft reaches essentially zero speed. A control subsystem also provides an automatic sequence of these events for emergency power system stops.

Heat Rejection Subsystem

Figure 5 shows a schematic diagram of the heat rejection subsystem to be used in the test programs. The three parallel and dual coolant flows pass through the

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14 "Design, Development and Fabrication of Brayton Cycle Heat Exchangers," Contract number NAS3-10607, AiResearch Mfg. Co., a division of the Garrett Corp., Los Angeles, Calif., May, 1967.

15 "Design and Development of Gas Management Subsystem for Brayton Cycle Space Power Systems," Contract number NAS3-10937, TRW, Inc., Systems Group, Redondo Beach, Calif., September, 1967.

waste heat exchanger, the alternator housing of the BRU, and a series of four cold plates on which the electrical subsystem components are mounted. The three coolant flows then merge and pass through the radiator simulator heat exchanger. The flow is then filtered and sent to a pump for recirculation. Each loop has its own separate and independent pump. Although not shown in Fig. 5, an accumulator is planned to be used upstream of each pump inlet. Flow rates through each leg of the coolant loops will be adjustable.

The heat rejection subsystem coolant is a "Dow Corning-200" silicone liquid. This liquid can be obtained within a large range of room temperature viscosities. We have initially selected the blend with a viscosity of 2 centistokes (2×10^{-6} m^2/sec) at 77^o F (298^o K).

The radiator simulator heat exchanger is planned to have a liquid-to-liquid core design. The secondary liquid may be cooled at a remote location.

The pump-motor assemblies (under contract(16) to the Pesco Products Div. of Borg Warner Corp.) are supplied with 400-hertz power from inverters in the electrical subsystem.

The temperatures and heat loads shown in Fig. 5 are for 10 kilowatts of net system output. The temperature rise on the liquid side of the waste heat exchanger is about 220^o F (120^o K); while the temperature rise across both the BRU and the cold plates is about 30^o F (17^o K). The waste heat exchanger load is 20.5 kW, while the BRU heat load is 1.8 kW and the electric component heat load is about 1 kW.

At less than 10 kilowatts of system output, each of these heat loads decrease. Over the entire power range from 2 to 10 kilowatts, more than 85 percent of the total heat rejection subsystem heat load is from waste Brayton cycle heat.

Electrical Subsystem

Figure 6 shows a schematic diagram of the electrical subsystem. It contains an electrical control package, the user's load bus, a parasitic load, a d.c. power supply, a signal conditioner, and two inverters.

The control package regulates alternator output voltage, provides alternator excitation and controls the BRU speed. It also distributes the power output among the user load bus, the parasitic load and the d.c. power supply. (The BRU voltage-regulator and -exciter and speed control are provided as breadboard components under the BRU contract(13) with AiResearch.)

The user load bus supplies alternating current at 208 volts, line-to-line, or 120 volts, line-to-neutral.

The parasitic load contains three banks of resistive elements. It is used with the control package to regulate output frequency (and hence, BRU speed). Each load bank is used for discrete frequency changes. (The parasitic load is being supplied(17) by The Heat Engineering and Supply Company.)

During normal power system operation the d.c. power supply rectifies part of the a.c. output to provide internal direct current needs at ±28 volts. During starts and stops, silver-cadmium batteries supply the d.c. needs. Direct currents are used in the signal conditioner, the control package, the inverter, and a battery charger. (The d.c. power supply is under contract(18) to Gulton Industries.)

PCS control modules will be located in the Space Power Facility control room. They permit the operator to choose between manual or automatic system operations. Functional controls are provided for: starting by gas injection, stopping, bearing jacking gas flow, valve operation, gas-loop inventory regulation, and coolant loop operation. Also, protective control modules are provided for: emergency stops, gas-loop overpressures, and electrical subsystem overspeeds, underspeeds, or overcurrents. The signal conditioner forms an interface between the PCS instrumentation and its control and monitoring panels. Signals-from and commands-to the PCS pass through this component. (The signal conditioner and PCS control modules are under contract(19) to AiResearch.)

The static inverters provide 400-hertz power to the pump-motor assemblies in the heat rejection subsystem. (These inverters are being provided by Gulton Industries under a subcontract with Pesco Products.)

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[16] "Design and Development of Pump-Motor Inverter Assembly for Brayton Cycle Systems," Contract number NAS3-10935, Pesco Products, division of Borg-Warner Corp., Bedford, Ohio, June, 1967.

[17] "Parasitic Load Resistor Assemblies," Contract number NAS3-10777, Heat Engineering and Supply Co., San Gabriel, Calif., June, 1967.

[18] "Design and Development of a DC Power Supply for Brayton Cycle Space Power System," Contract number NAS3-10936, Gulton Industries, Inc., Engineered Magnetics Div., Hawthorne, Calif., August, 1967.

[19] "Brayton Cycle Engine Control Systems," Contract number NAS3-10943, AiResearch Mfg. Co., a division of the Garrett Corp., Phoenix, Ariz., January, 1968.

The electrical control package, signal conditioner, d.c. power supply, battery packs, and the inverters all mount on cold plates. Four 30 by 30 inch (76 by 76 cm) plates are planned for use in the ground tests.

Packaging

Figure 7 shows a photograph of a full-size PCS wooden mockup at an early stage of assembly. The BRU and BHXU are shown in place.

The overall size of the main framework is 55 by 66 by 33 inches (140 by 168 by 84 cm). The BRU is mounted vertically with the turbine end up. The turret on the right side of the BRU contains connectors for the power output and BRU instrumentation.

The recuperator is placed toward the top of the package. And the waste heat exchanger is directly below the recuperator. The waste heat exchanger mates to the recuperator end section with a short, wedge-shaped transition piece. Tapered gas-flow manifolds are used on the BHXU heat exchangers to maintain uniform gas pressure drops across the width of the flow passages and to turn the flow into or out of the cores.

There are three sets of bellows in the BHXU ducting to allow for thermal growth and contraction. They are located in the turbine exhaust duct, the duct between the waste heat exchanger and the compressor inlet, and in the compressor discharge duct upstream of the gas management subsystem spool piece.

All other PCS components are to be fitted about this framework.

POWER SYSTEM EFFICIENCY ESTIMATES

Figure 8 shows an estimated variation of overall power system efficiency with net output power. System efficiency is defined here as the ratio of the 1200-hertz power available at the user's load bus to the total heat source thermal power. For a radioisotope heat source, the total thermal power includes an allowance for heat leakage from the array of fuel capsules. For the solar heat source, the total thermal power is that collected by the mirror. This total, therefore, includes reradiation as well as other thermal losses.

The curve in Fig. 8 was estimated assuming variable-sized radioisotope sources with the turbine and compressor inlet temperatures at design conditions. Overall system efficiency decreased from about 27 percent at 10 kilowatts to about 19 percent at 2 kilowatts. At 6 kilowatts, efficiency still exceeded 26 percent.

System losses were estimated and they include: thermal losses (both heat source and PCS); cycle losses; alternator losses (both electromagnetic and windage); bearing friction losses; and electrical subsystem power needs.

For fixed turbine and compressor inlet temperatures, cycle losses are dependent on the estimated values of turbine and compressor efficiency, heat exchanger effectiveness, and system pressure loss. Over the net system power range, the effects of variations in system pressure losses were estimated to be small and were neglected. Turbine and compressor efficiency were assumed to decrease at the lower power levels due to Reynolds number effects. This tends to increase cycle losses at the low power levels. However, at less than 10 kilowatts of system output, the increased heat exchanger effectiveness tends to decrease the cycle losses. The net effect was that cycle efficiency was nearly constant (about 37 percent) over the entire net system output range.

Since the alternator is sized for its best performance at the 10-kilowatt system power level, it has a reduced electromagnetic efficiency at the lower outputs. Alternator electromagnetic losses become a larger percentage of the system output at the low power levels.

System thermal losses, alternator windage loss, bearing friction losses, and electrical subsystem power needs all decrease with decreasing system power output. However, they have been estimated to decrease at a slower rate than the system output. Hence, at the lower power levels, these system losses also become a larger percentage of the output.

Although cycle efficiency was estimated to be nearly constant over the net output power range, system efficiency was not.

The conceptual 25-kilowatt-thermal radioisotope source would produce about 6.7 kilowatts at the user's load bus; while the 30-foot-diameter (9.2-m) mirror and heat receiver in a 300-nautical-mile (5.55×10^5-m) Earth orbit with an assumed collector-absorber efficiency of 79 percent, would yield a little over 10 kilowatts. The estimated efficiency for the solar-powered system is 22.7 percent. This reduced efficiency results from larger heat source thermal losses and the 100° F (56° K) reduction in turbine inlet temperature.

CONCLUDING REMARKS

Over the past five years, NASA-Lewis has been actively engaged in Brayton-cycle component tests. In particular, the performance of small compressors and turbines have exceeded their design goals.

We have defined a second-generation Brayton power conversion system. In space it could be coupled with either a solar- or radioisotope-heat source. And it has the capacity to be rated for net power outputs within the range from 2 to 10 kilowatts. Maximum power system efficiency is estimated to be 0.19 at 2 kilowatts of output, rising to about 0.27 in the output range from 6 to 10 kilowatts.

All hardware components for this new power conversion system are currently under contract for design and fabrication. This hardware will not only be used for more component tests, but will also be assembled for complete, ground-based power system tests. The first system tests are planned with the use of an electric heater. It is designed to simulate operation with the space-type heat sources. A 30-foot-diameter (9.2-m) mirror and associated solar heat source components are being built for a later system test. And, NASA has requested 25-thermal kilowatts of plutonium-238 from the AEC for a third ground test with the power conversion system. Preliminary plans are being made for this test.

Currently this effort is not tied to any particular mission and is in the early stages of ground testing.

TABLE I. - BRAYTON CYCLE DESIGN CONDITIONS

Working gas	He and Xe mixture
Gas mixture molecular weight	83.8
Turbine inlet temperature	1600° F (1144° K)
Compressor inlet temperature	80° F (300° K)
Machinery shaft speed	36 000 rpm (3769 rad/sec)
Compressor pressure ratio	1.90
Turbine pressure ratio	1.75
Recuperator effectiveness	0.95
Waste heat exchanger effectiveness	0.95

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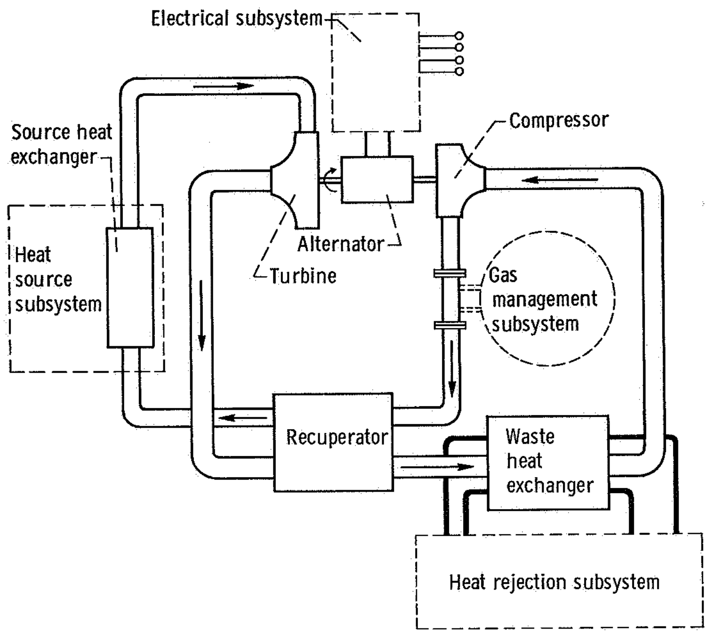

Figure 1. - Power system schematic diagram.

Electric heater

Quartz lamps
Central heat exchanger

Solar source

30-foot-diameter (9.2-m) mirror
Cavity heat receiver

Radioisotope source

25-kWt array of Pu^{238} fuel capsules
Mounted in a reentry body

Figure 2. - Heat source subsystems.

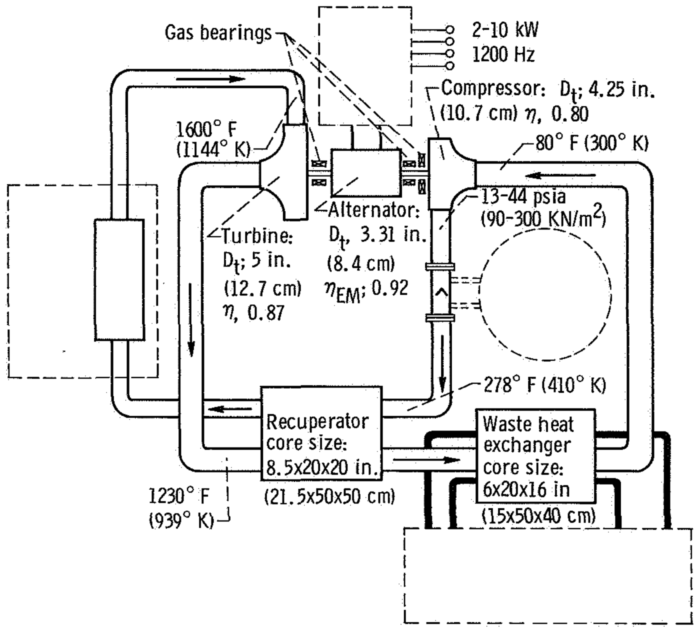

Figure 3. - Schematic diagram with some PCS design conditions.

Supplying bearing jacking gas
Injecting gas for power system starts
Controlling gas inventory
Venting gas for power system stops

Figure 4. - Functions of the gas management subsystem.

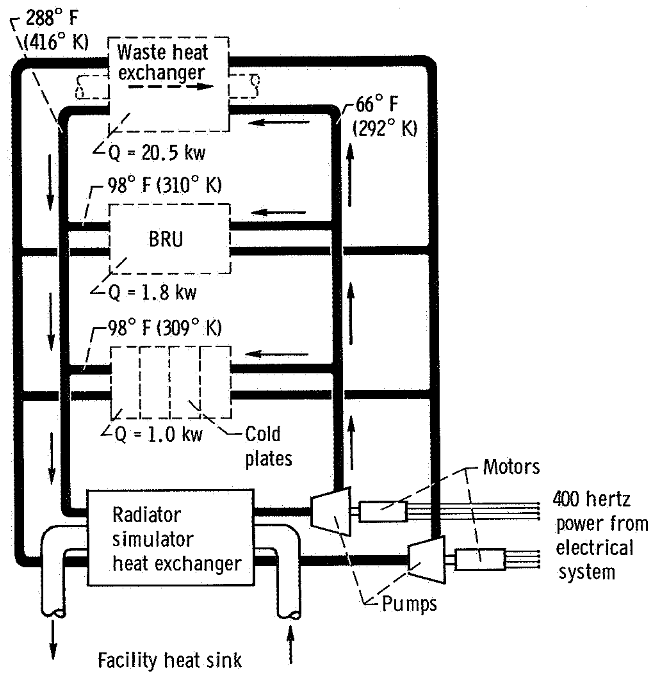

Figure 5. - Heat rejection subsystem schematic diagram.

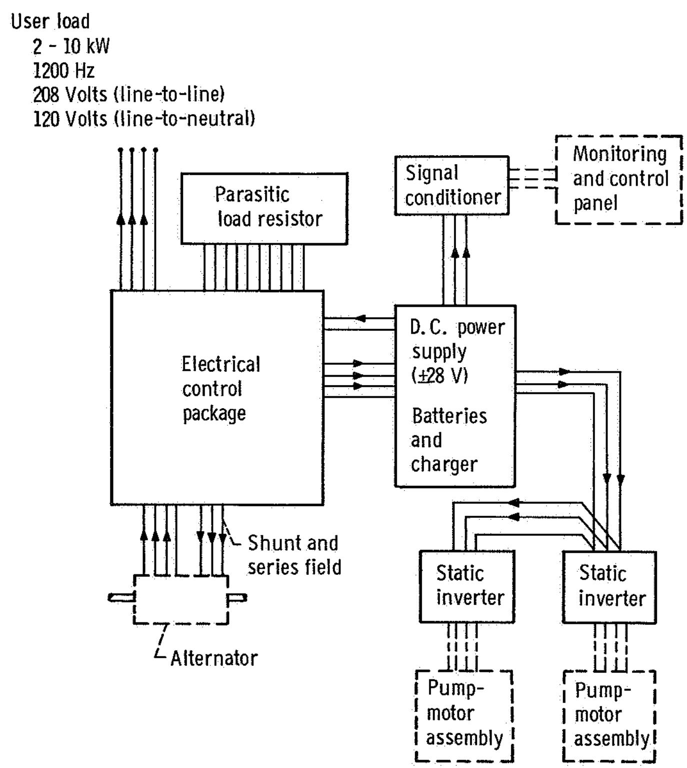

Figure 6. - Electrical subsystem schematic diagram.

E-4454

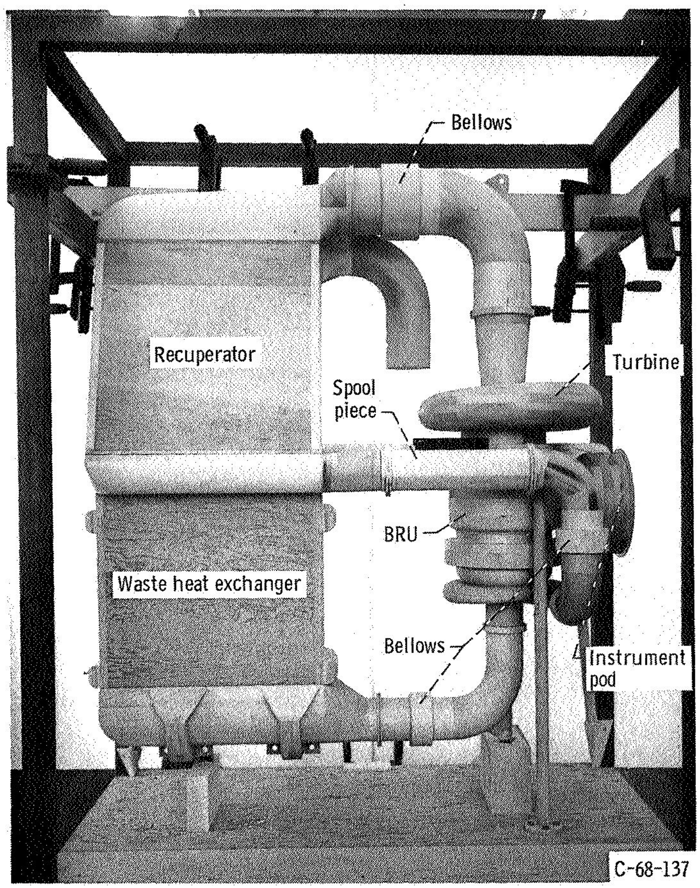

Figure 7. - Full-size mockup of BRU and BHXU in the test configuration.

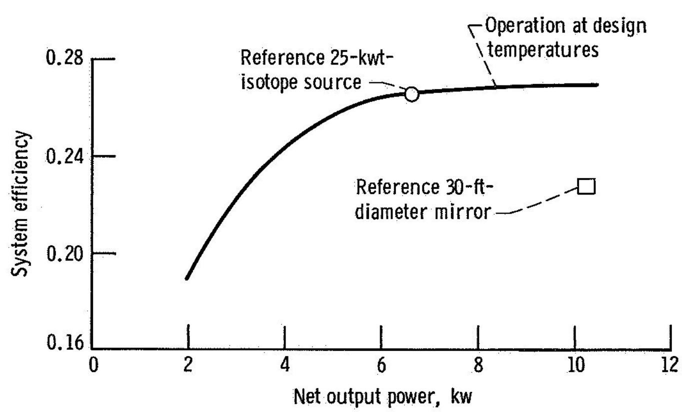

Figure 8. - Estimated efficiency.