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RECENT TECHNOLOGY ADVANCES IN THE NASA-LEWIS RESEARCH CENTER BRAYTON PROGRAM

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ABSTRACT

A review of the progress and milestones passed in the Brayton program during the past year is presented. The 2-to-15 kWe power system was successfully operated in a vacuum with a space-type radiator. Gas loop and electrical subsystem endurance tests have continued to demonstrate long-term operation with one rotating unit surpassing 10 000 hours of failure-free operation. Simplified gas-bearing designs for the rotating unit are being evaluated. Fabrication of an improved design of heat exchanger is nearing completion, and a study of more advanced heat exchanger technology is being conducted. A study was completed to investigate the applicability of Brayton technology applied to a lower power level (0.5 to 2.5 kWe) and showed potentially very attractive performance, simplicity, and low cost for a system in this power range.

INTRODUCTION

In 1963 the staff at NASA-Lewis Research Center (LeRC) began work on a closed-cycle-Brayton program whose major goal is to demonstrate technology for reliable and efficient generation of electric power in space with a life of at least 5 years of continuous operation. This effort to date has been focused on a power system with a useful output of 2 to 15 kWe. The original design power range for the system was 2 to 10 kWe but experimental testing indicated that the upper limit could be extended to 15 kWe by providing additional cooling to the alternator windings.

The status of the LeRC Brayton program was presented at the IECEC conference last year (ref. 1) and this paper presents further milestones achieved in this program. During the past year the 2-to-15 kWe power system was successfully operated in a vacuum with a space-type radiator. These tests included simulated sun-shade transient heat loads of a near-Earth orbit. Gas-loop and electrical subsystem endurance tests have continued to demonstrate long-term operation with one rotating unit surpassing 10 000 hours of failure-free operation. An experimental investigation of paralleling two 1200-Hz solid-rotor alternators was started and has indicated excellent inherent paralleling capability of this type of alternator. Work is continuing to provide additional cooling capability for the alternator for continuous operation at power levels up to 15 kWe, to simplify the bearing design for the rotating unit, and to thereby eliminate the need for hydrostatic jacking gas. Fabrication of an improved design of heat exchanger is nearing completion and a more advanced heat-exchanger-technology program is being conducted. The applicability of Brayton technology to lower powers (0.5 to 2.5 kWe) was studied, and the resulting isotope-Brayton concept is not only simple in concept but also has predicted efficiency four times that of competitive isotope power systems. This paper discusses these achievements in more detail and provides an overview of the LeRC Brayton program, some of the details of which are discussed by subsequent papers at this conference.

RECENT TESTING PROGRAM ACHIEVEMENTS

2-to-15 kWe Complete-Power-System Tests

The primary goals of these tests were to map the performance of the power conversion system over a broad range of operating conditions and to obtain significant operating time in a vacuum environment. The system tests were conducted in two phases. During the first phase of testing, completed in June 1970, the system was operated for 2561 hours using a facility type of heat exchanger for rejection of system waste heat. The performance data for this phase are summarized in references 2 and 3.

After completing the first phase of testing, two major modifications were made to improve the system. First, volts-per-hertz voltage regulation was incorporated in order to provide greater tolerance of transient overloads (ref. 4) by reducing voltage as speed is reduced due to overload. Secondly, provisions were made for motor-starting the system by using the alternator as a motor to bring the rotating unit up to self-sustaining speed. Previously, gas injection through the turbine was the mode of starting. The motor-start technique permits both reduced gas-storage requirement and a simplified gas-management subsystem.

When the modifications were completed, the power conversion system was connected to a newly designed full-scale space-type radiator for the second phase of testing. The radiator (ref. 5) was 21.7 feet in diameter and 10 feet high. The system and radiator are shown in figure 1. Operation began in February 1972 and was completed in July 1972, and during that period the system was operated for 736 hours. The primary objective of the second phase was to determine the interaction of the power conversion system and the radiator over a wide range of space-simulated operating conditions, including near-Earth-orbit sun-shade-transient radiator heat loads. Steady-state mapping of the power conversion system and radiator combination was completed for effective sink temperatures from -10° to -110° F. Simulated sun-shade radiator heat-load cycles of near-Earth orbits were simulated by using banks of iodine-quartz lamps installed between the cold wall and the radiator and directed at the radiator. With the cold wall maintained at a constant temperature, the lamp power was varied to simulate the sun-shade heat-load cycles.

A typical system motor-start from this second phase of testing is shown in figure 2. The electric heat source was first brought up in temperature ($\sim 1500^{\circ}$ F), and the alternator-load contactor was opened. The alternator voltage regulator was turned off and the series field was shorted to put the alternator in a "motoring" mode; then jacking-gas flow to the bearings was initiated. The alternator was then motored by a motor-start inverter powered from the system DC bus. Synchronous motoring speed (12 000 rpm at 400 Hz inverter frequency) was obtained in about 20 seconds. The motoring at 12 000 rpm was continued until the turbine inlet temperature reached approximately 850° F, the total motoring time being about 2 minutes. The motor-start inverter was then disconnected from the alternator and the rotating unit bootstrapped itself to rated speed

(36 000 rpm) in about 40 seconds. The voltage regulator was turned on when motoring was terminated and the series field short was removed at approximately 24 000 rpm. As the rotating unit reached rated speed, the parasitic-loading speed control took control of rotational speed. Jacking-gas flow to the bearings was then terminated, and the motor-starting was complete. These tests confirmed the motor-starting concept as the reference startup method for all future testing.

An unwelcome result during this 736-hour second phase of testing was when the recuperator developed external leaks at a number of braze joints between the header bars and the plates (refer to fig. 3). These leaks were localized to two high-temperature and highly stressed areas of the recuperator and were attributed to low-cycle thermal fatigue from system startups. The fix consisted of brazing over the leak-affected areas and then welding plates over the two faces of the recuperator where the leaks existed in order to act as a containment vessel should any further leak develop. While this repair permitted continued system operation, a program to develop the technology required to provide heat exchangers with better thermal-cycle fatigue characteristics is being pressed forward and is discussed later in this paper.

Subsystem Tests

Three subsystems are being performance-life tested with goals of 20 000 hours of operation. Recent achievements from these tests are summarized next.

Gas-loop tests. - The gas-loop test comprises the Brayton Rotating Unit (turbine, compressor, and alternator) and the Brayton Heat Exchanger Unit (recuperator and waste heat exchanger). A computer monitors and controls the gas-loop tests. This test facility (fig. 4) is also used to test new concepts before being incorporated into the complete system. For example, the motor-start technique was investigated extensively in this facility prior to system application. As of August 15, 1972 over 10 000 failure-free hours were accumulated on a rotating unit and 3540 hours were accumulated on the heat exchanger unit. The original recuperator used in this facility developed leaks similar to the engine unit and was replaced with a spare; the spare also developed a leak. Thus, all three identical recuperators developed leaks after about 20 to 30 thermal cycles.

Electrical subsystem tests. - This subsystem provides the required regulation and control of the generated electric power as well as control of the entire Brayton power system. The electrical subsystem is being tested using a three-phase generator to simulate the BRU alternator, and the initial results were presented at last year's conference (ref. 6). No major milestones have been passed during the past year; however, testing has continued to accumulate operational hours to a total of 9689 hours as of August 15, 1972. Of this total, 9433 were accomplished during unattended operation. A computer, similar to one used for gas-loop tests, monitors and controls the electrical subsystem tests.

All electrical hardware modifications and additions are tested in this facility, pictured in figure 5, before they are incorporated into the power conversion system. The inverter required for the motor-start technique and the volts-per-hertz regulation circuitry were qualified for power system operation by first testing in this facility.

Gas-management tests. - A duplicate of the gas management subsystem used on the power conversion system (fig. 6) is also being tested. The gas subsystem consists of the gas supply tank, valves, and required piping. A total of 8605 hours has been accumulated as of August 15, 1972.

Component Tests

Coolant pump and inverter. - A motor-driven coolant pump and inverter have now completed 20 000 hours of operation with no failures or degradation of performance. Upon disassembly and inspection after completion of the 20 000-hour test, the pump was well within tolerance specifications for a new pump.

Alternator paralleling tests. - The use of multiple generators operating in parallel permits a modular approach to power-system design and application. In conventional multiple-generator power systems, speed control is accomplished by a turbine-flow throttling valve. Unlike conventional power systems, our space power system uses an electronic speed control with a parasitic-load resistor.

In the 2-to-15 kWe Brayton power system, the turbine drives both the alternator and compressor mounted on a common shaft. The alternator load comprises the user load and the parasitic load. As the user load changes, the parasitic load is varied by the speed control in order to maintain constant alternator frequency. During the past year an experimental investigation began to determine the suitability of this type of speed control for synchronizing and operating two alternators in parallel. The two alternators, with independent speed controls, were successfully paralleled over a wide range of conditions and were stable after paralleling. This investigation is continuing, and the current results presented at this conference (ref. 7) include the transient effects of synchronizing two alternators with various phase-angle, voltage, and frequency differences.

COMPONENT IMPROVEMENT PROGRAM

Further work is being conducted to provide technology for a simpler Brayton system and more reliable components. The major efforts are directed at the heat exchangers and the rotating unit.

Brayton Heat Exchanger Unit (BHXU)

The BHXU consists of a gas-to-gas recuperator and a gas-to-liquid waste heat exchanger, both utilizing a plate-and-fin design. Three units were initially fabricated and tested. As mentioned earlier, all three recuperators developed leaks after thermal cycling 20 to 30 times. A second-generation improved design, designated BHXU-A, is presently being fabricated. The BHXU-A incorporates modular plate-fin construction for the recuperator and finned-tube construction for the waste heat exchanger. A comparison of the BHXU and BHXU-A construction is shown in figures 7 and 8. The BHXU-A is designed to provide double containment against leaks for both the recuperator and the waste heat exchanger.

In addition to the BHXU-A effort, there is a more-advanced heat exchanger technology program. The objective of this program is to develop design and fabrication techniques to improve cyclic life and preclude leakage and also to evaluate low-cost, ductile braze alloys.

Brayton Rotating Unit (BRU)

The rotating unit includes the turbine, alternator, and compressor all mounted on a single shaft. All the bearings in the BRU are lubricated by the system (gas) working fluid. The original journal bearings are tilting-pads pivoted on fully conforming ball-and-socket pivots. The thrust bearing is a double-acting Rayleigh-step design. While the performance of the original bearings indicates that design should operate satisfactorily for 5 years there is a BRU technology program that includes an investigation of alternate bearing designs. The original bearings require external pressurization (jacking gas) during starts and stops. Hopefully, this requirement will be eliminated with an alternate design and a simplified gas management subsystem would result. A summary of the BRU program is being presented at this conference (ref. 8).

Inspection at various test hours of four BRU's with original bearings indicates minor wear occurred within the first 700 hours and no additional wear was detected after the next 5000 hours. Apparently some initial wear-in through polishing of surface asperities occurred and then little, if any, additional wear took place. There was no change in bearing performance detected with bearing instrumentation used on the BRU that accumulated over 10 000 hours of operation.

In the BRU technology program several alternate bearing designs are being investigated. The alternate journal designs include nonconforming, pivoted pad bearings; a flexure-supported pad bearing; and both ribbon and leaf types of foil bearing. The alternate thrust-bearing designs include spiral-groove bearing and a leaf type of foil bearing.

A promising alternate design is the leaf type foil design. Both journal and thrust bearings of this design were assembled and tested in a BRU simulator. Repeated starts and stops have been accomplished with no external pressurization of the bearings. This bearing design, if incorporated in the power conversion system, could result in a much simplified gas management subsystem. Repeated shock loads in excess of 100 g have been applied to the housing in a direction normal to the shaft with the unit running at design speed with no adverse effect noted in bearing performance.

A BRU is being retrofitted with leaf type foil journal and thrust bearings and will be tested under design thermal conditions. The same BRU is also being modified to provide additional cooling to the end turns of the alternator stator windings so that 15 kWe can be obtained continuously without over-temperaturing the insulation on the windings.

Also included in the BRU technology program is an effort to investigate foil bearings for larger rotating machines. This effort will investigate what effect size has in areas such as rotor-bearing rub and windage losses. This additional work includes: development of empirical techniques to predict foil gas-bearing performance, and fabrication and testing of a dynamic simulator which includes foil bearings and a Lundell alternator. The simulator will permit dynamic performance of a rotor-bearing system over a wide range of thermal, electro-mechanical, and pressure conditions.

BRAYTON SYSTEM FOR THE 500 TO 2500 We RANGE

A study of the applicability of the Brayton technology to the power range of 500 to 2500 We was recently conducted at Lewis (ref. 9). This study incorporates much of the technology described herein. The high efficiency, simplicity, and low cost makes the selected system attractive for a variety of space missions.

The study focused on power systems with overall efficiencies (conditioned power output/gross thermal input) ranging from 0.23 to 0.28 over the power range studied. Additional studies seek even higher efficiencies.

Concepts were chosen to provide a simple, highly reliable system capable of long life (10 yr or more). These concepts included: (1) a one-loop system incorporating a gas radiator and a gas-cooled alternator, (2) a rotating unit using gas bearings that do not require jacking gas, and (3) very simplified electrical and control systems. The flexibility of packaging makes the 0.5 to 2.5 kWe Brayton system attractive for systems utilizing either the space shuttle or a variety of launch vehicles (ref. 10).

CONCLUDING REMARKS

During the past year several encouraging accomplishments within the Brayton program have been achieved. A complete power conversion system was successfully operated with a space-type radiator. Test conditions included both steady-state performance evaluation and sun-shade transients. Subsystem tests have continued with well over a year of total operational time accumulated to date on the gas-loop subsystem and over a year on the electrical subsystem. Continuing efforts are in progress to provide a simpler bearing system for the rotating unit and to provide more reliable heat exchangers. Gas leakage from the heat exchanger is the most critical area in the Brayton technology program.

The new NASA emphasis is on standardization to reduce costs. The Brayton cycle system has demonstrated an inherent advantage in that a large power range can be covered with a single set of hardware simply by changing the energy input and the system pressure level and/or temperature. Therefore, a very few Brayton-cycle power conversion systems, differing only in size, could cover the entire power range required for future space missions. Component technology advances in the Lewis-Brayton program are tending toward simpler, more reliable system concepts.

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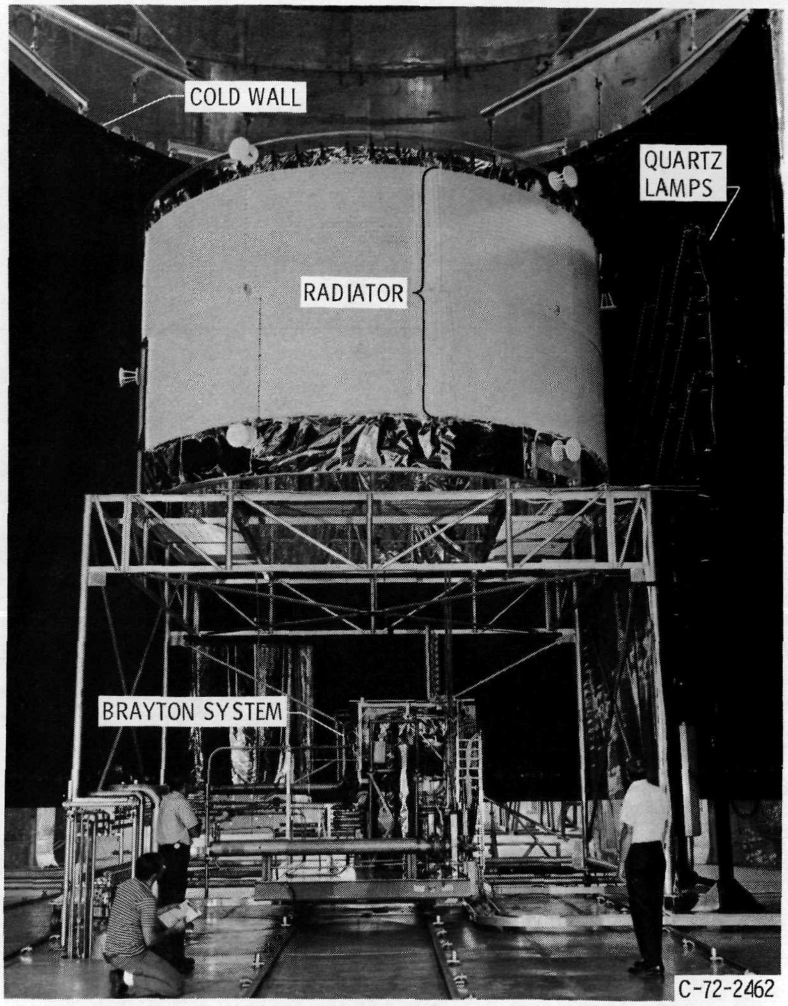

Figure 1. - Brayton system with space-type radiator in the space power facility.

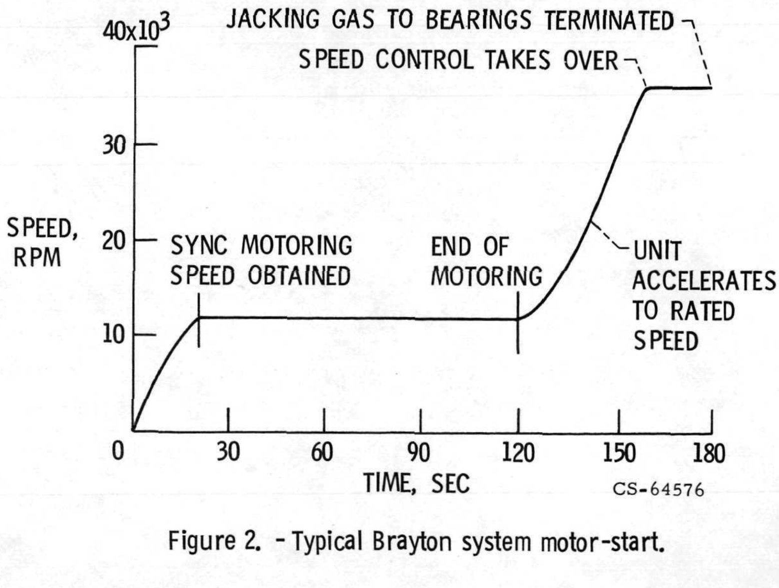

Figure 2. - Typical Brayton system motor-start.

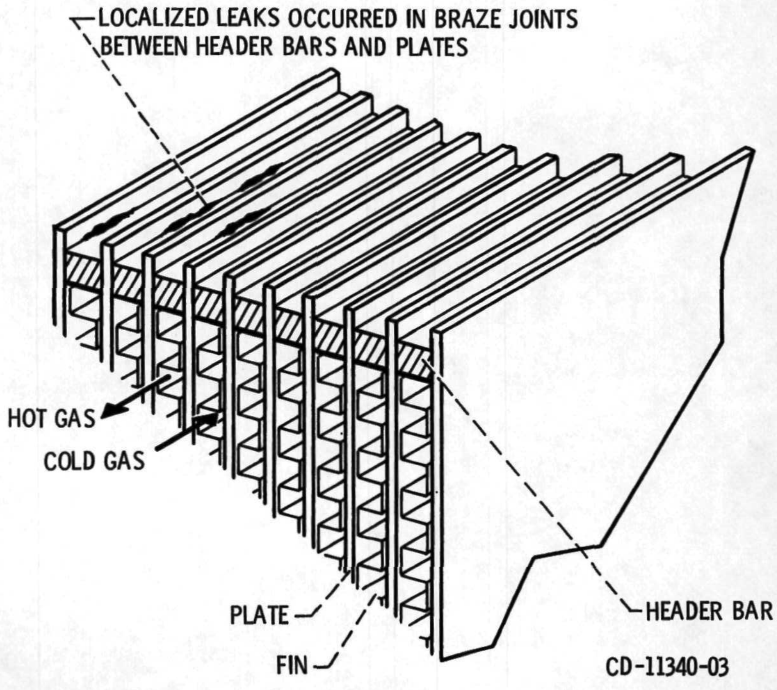

Figure 3. - Location of leaks in recuperator portion of the Brayton heat exchanger unit (BHXU).

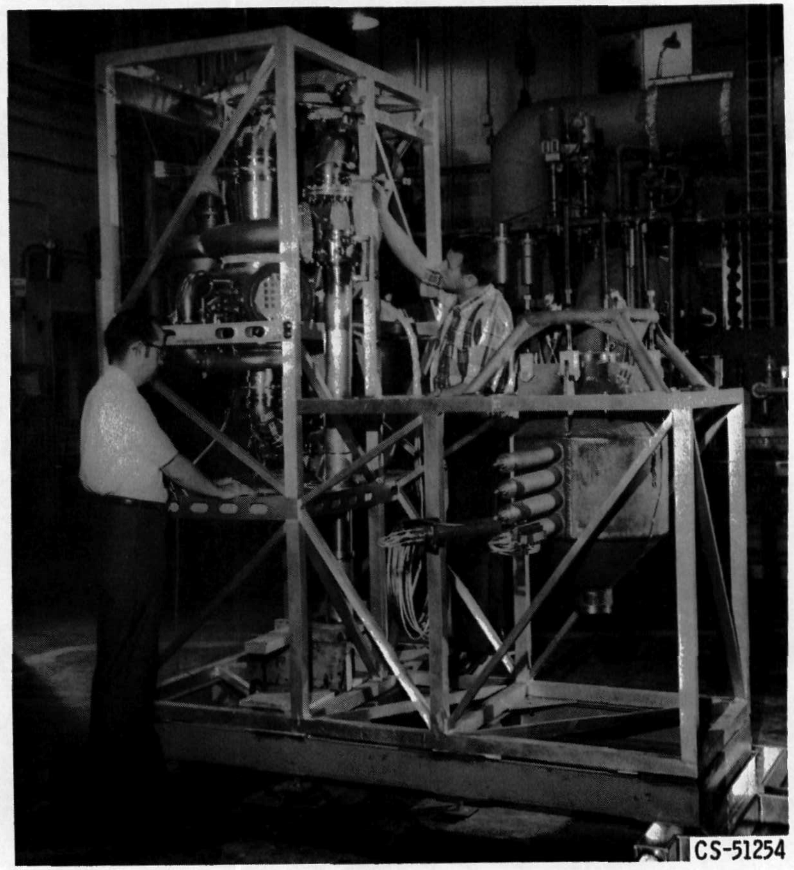

Figure 4. - Brayton gas-loop test facility.

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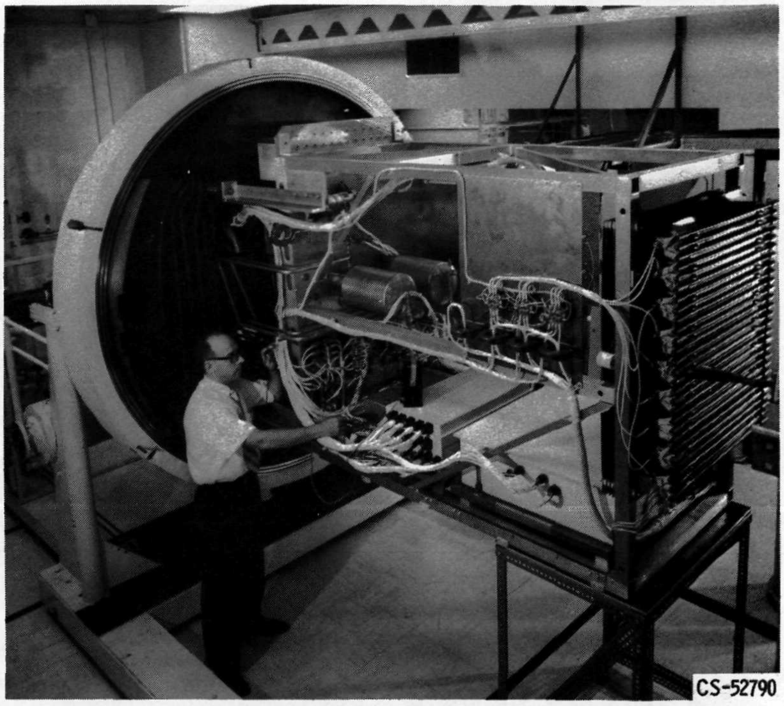

Figure 5. - Brayton electrical subsystem test facility.

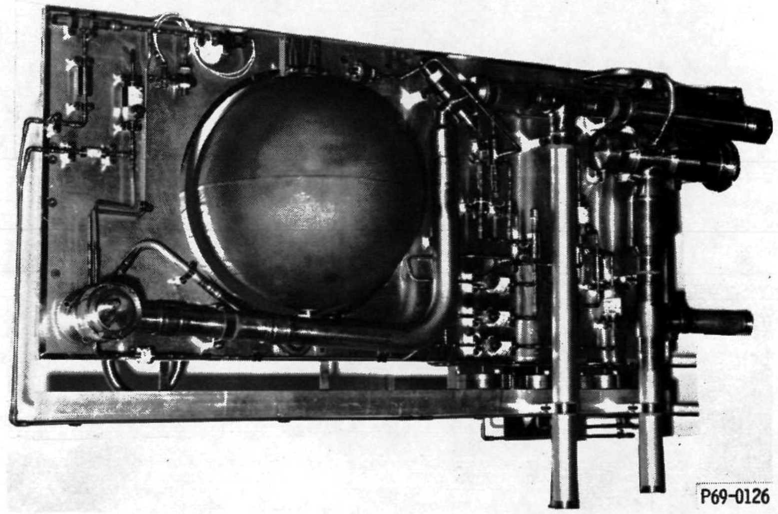

Figure 6. - Brayton gas-management subsystem.

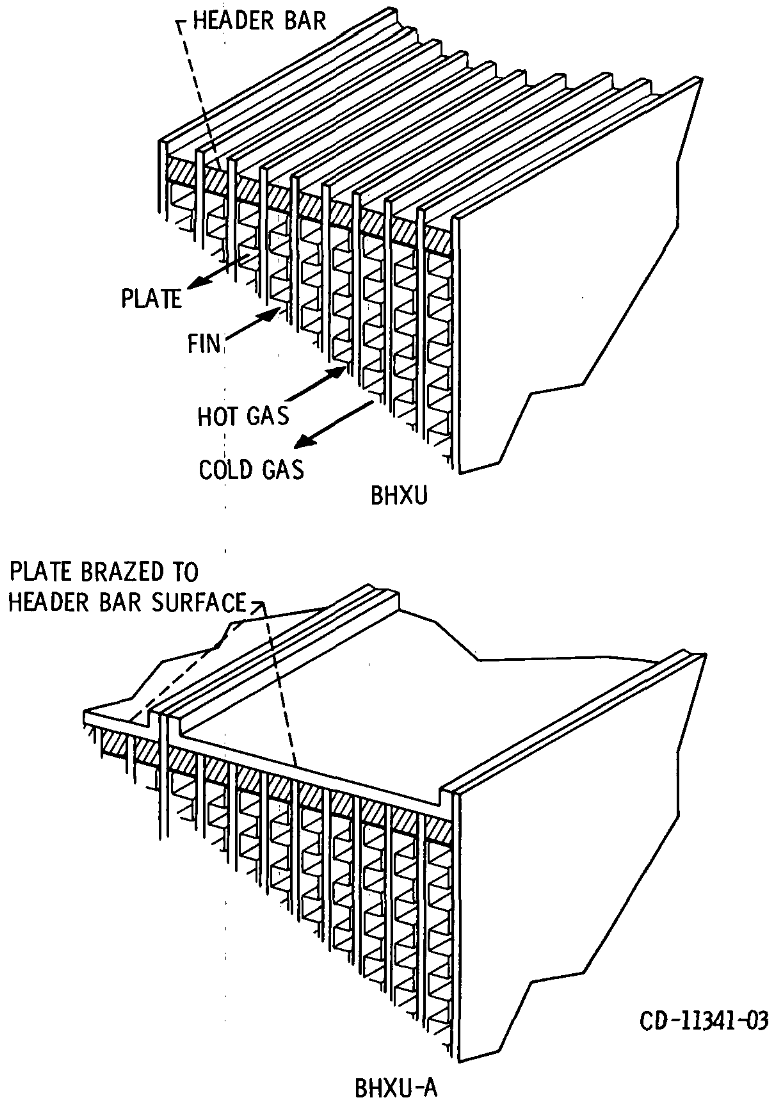

Figure 7. - Construction of recuperator for the Brayton heat exchanger unit (BHXU) and alternate unit (BHXU-A).

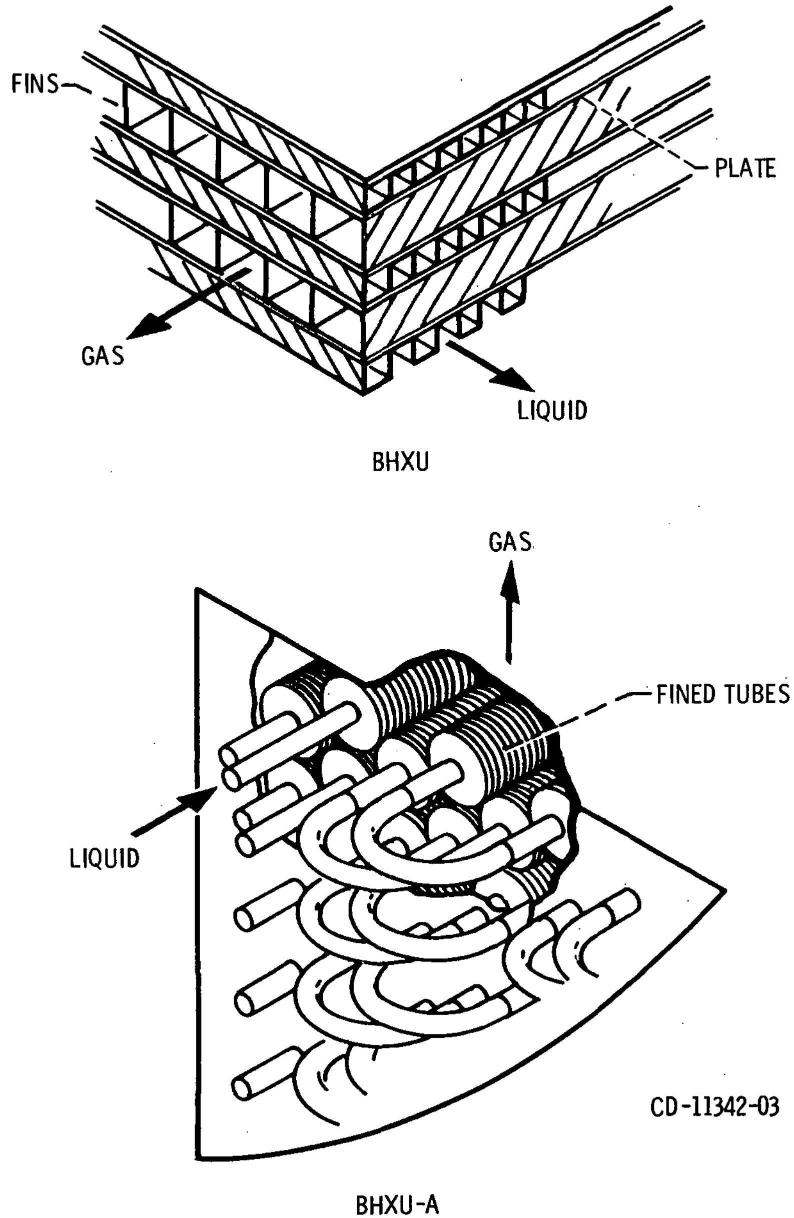

Figure 8. - Construction of waste heat exchanger for the Brayton heat exchanger unit (BHXU) and the alternate unit (BHXU-A).