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DESIGN DESCRIPTION AND PERFORMANCE TEST RESULTS FROM TWO IDENTICAL BRAYTON HEAT EXCHANGER UNITS

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TECHNICAL PAPER proposed for presentation at Fifth Intersociety Energy Conversion Engineering Conference sponsored by the American Institute of Aeronautics and Astronautics
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

Two identical Brayton-cycle heat exchangers, each consisting of a high performance recuperator, a heat-sink heat exchanger, and interconnecting ducting, have been tested in combination with a Brayton turbine, alternator, and compressor. One test installation comprised the gas loop of the Brayton engine; the other was a complete Brayton engine containing all the system components with the exception of the heat source and radiator which were simulated. The design of the unit is described, and the results of the tests are compared to the anticipated-off design performance.

Introduction

NASA is currently engaged in the development of closed Brayton cycle system technology for the generation of space electric power for long durations. The system presently under consideration is chosen to investigate the means of producing power in the range of 2 to 15 kWe (Refs. 1, 2, 3).

A basic goal of this system is high conversion efficiency which is particularly advantageous when a radioisotope is considered for the heat source. A higher efficiency reduces the thermal input requirements (i.e., quantity of radioisotopes) of the heat source for producing a given level of electric power.

The concept selected for the Brayton power conversion equipment adopts the use of a single shaft Brayton Rotating Unit (BRU) coupled to a heat source and a Brayton Heat Exchanger Unit (BHXU). This paper will discuss the Brayton Heat Exchanger Unit, its role in the Brayton cycle system, design details, and performance achieved to date.

The BHXU consists of a recuperator, a heat sink exchanger, and ducting to interconnect all the gas loop components. The BHXU is paramount to obtaining high conversion efficiency and decreasing the size and weight of the radiator. The recuperator is a vital element which contributes approximately 70 percent of the gross thermal efficiency of the system.

The BHXU was designed and fabricated by the AiResearch Corporation of Los Angeles. Two of the units delivered have each been incorporated with a Brayton rotating unit (Ref. 4) into a power conversion loop. One unit was tested as part of a complete power system employing all flight-type components except the heat source and radiator. The other unit was tested coupled to the BRU predominately as a power conversion loop test. The total operating time accumulated on each unit, as of May 18, 1970, is 2080 hours in the complete engine test, and 239 hours in the power conversion loop test.

However, only data obtained through February 11, 1970 are analyzed. The results of both tests are presented to show the behavior of the BHXU. The BHXU performance characteristics are related to engine operating conditions which define output power level. The resulting off-design performance of the BHXU is determined over the range of power output from 2 to 13 kWe.

The results illustrate performance trends and compare the effects of using both krypton and a mixture of helium and xenon at the molecular weight of krypton as the working fluid. These preliminary results will provide an evaluation of the BHXU and indicate expected results for other operating conditions.

Brayton Cycle System

A basic diagram of the Brayton cycle system is presented in Fig. 1. The BHXU in this arrangement is the portion blocked out by the dotted lines. Direction of fluid flow in both the gaseous and liquid loop is indicated by the arrows. Gas leaving the turbine flows through the recuperator, then through the heat sink exchanger, and then on to the inlet of the compressor. Compressed gas from the outlet of the compressor flows through the recuperator, and then through the heat source heat exchanger in returning to the inlet of the turbine.

The gas and liquid loops are coupled by the heat sink exchanger. A liquid pump circulates coolant through the heat sink exchanger and then through the radiator.

The recuperator transfers heat from the low pressure gas leaving the turbine to the high pressure gas leaving the compressor. The heat sink exchanger transfers cycle waste heat from the low pressure gas leaving the recuperator to the liquid coolant.

Temperatures shown are indicative of the 2 to 15 kWe Brayton system being tested in the Lewis Research Center Brayton technology program.

Description of Design of Brayton Heat Exchanger Unit

The design conditions for the Brayton Heat Exchanger Unit are listed in Table I.

Parametric studies and trade-offs were conducted to select component geometries and various design layouts were performed to establish the overall packaging of the BHXU prior to detail design. Detail design optimization and integration resulted in a compact package of the BHXU and BRU representative of a flight-type configuration.

A complete assembly of the fabricated BHXU is shown in Fig. 2. The overall packaging of the BHXU with the Brayton Rotating Unit (BRU) is shown in Fig. 3. The overall dimensions of this package are 22 by 49 by 56 inches. The weight of the BHXU is 450 pounds.

Component Description

The main part of the BHXU consists of a gas-to-gas recuperator and a gas-to-liquid heat sink exchanger joined by a transition section which serves as a manifold and forms a rigid structure between the two components.

The recuperator core and end section design is summarized in Table II. The recuperator is a pure counterflow plate-fin unit with cross-flow triangular end sections providing fluid access to the core.

The counterflow section utilizes rectangular offset fins sandwiched between plates as shown in Fig. 4(a). Fins 0.153 and 0.125 inch high are used respectively to form the low and high pressure passages in the core. Figure 4(b) shows schematically these two adjacent finned sandwiches including the inlet and outlet finned end sections. Single sandwiches of these fins are arranged alternately in a stack to produce the core. Figure 4(c) shows these sandwiches in the process of being stacked prior to brazing. Each sandwich contains flow divider strips that run the length of the core to prevent fluid crossflow. The sides of the flow passages are closed by 0.1 inch thick side strips, and the unit is entirely joined by brazing. Construction material is 347 stainless steel throughout the recuperator.

The heat sink exchanger design is summarized in Table III. This exchanger is an eight pass cross-counterflow, plate-fin unit. Gas flows in a single pass directly through the exchanger. The liquid makes eight passes through the exchanger. The passages consist of rectangular offset fins 0.125 inch high on the gas side and 0.050 inch high on the liquid side, in a single sandwich alternating arrangement. The gas side passages are similar in construction to the recuperator passages shown in Fig. 4. Two liquid circuits are provided in the exchanger. One liquid passage is placed on each side of the gas passage. Only one needs to be active at any time the other is redundant. Turning between successive liquid passes is accomplished with mitered fin turning section internal to the liquid sandwiches as shown in Fig. 5. The turning sections are triangular sections of the same fin geometry used in the liquid pass. Successive liquid passes within each sandwich are separated by side strips: each of the sandwiches are closed off with 0.1 inch thick side strips, and the unit is entirely brazed. The construction material is 347 stainless steel throughout the exchanger.

Manifolds are attached to the two heat exchangers and shaped to provide uniform flow. Ducts are attached to the manifolds which extend to the BRU and to the heat source. A section of the ducting between the compressor outlet and recuperator inlet is designed to incorporate a section containing a main flow valve and injection and vent lines which connect to the gas management system to be used during gas loop starts and stops.

Bellows are provided in the BHXU to accommodate the thermal growth of both the BRU and BHXU with minimum stresses, to protect the structural integrity of these components. A six-inch diameter bellows is located between the recuperator and turbine, a four-inch diameter bellows is located between the compressor and heat sink exchanger, and a three and one-half inch diameter bellows is between compressor and recuperator.

A lightweight mounting system is incorporated to support the BHXU with minimum loads and stresses and to minimize the thermal differential and stresses between the BHXU and the BRU. Mounts support the unit in six locations. A restraining pad is located on each of the two low pressure elbows to react out pressure forces on the bellows.

Instrumentation ports are provided throughout the BHXU at inlets and outlets for the measurement of temperatures and pressures which can be used to monitor operating performance.

Flanges are attached to both ends of all ducts which result in weldable connections with the mating equipment. Two types of flanges are utilized to accommodate fit-up of components and to facilitate assembly and disassembly within the BHXU and with other components of the Brayton system.

The BHXU was designed to withstand rapid startup transients imposed by system operation and to accommodate all the integration requirements of the power conversion equipment.

Considerable attention was devoted to obtaining a unit with leak tight containment. The manufactured units were leak checked and found very tight externally over the entire BHXU and internally between the gas and liquid circuits in the heat sink exchanger.

Description of Equipment and Tests

Two BHXUs were assembled in separate packages and hot tested in two different facilities. The equipment modules utilized in each of these test installations to form a power system are illustrated in Fig. 6. This figure identifies the various subsystems and their place in the system test.

The test system consists of a Brayton Rotating Unit (BRU), Brayton Heat Exchanger Unit (BHXU), heat source subsystem, Gas Management Subsystem (GMS), electrical subsystem, and a heat rejection subsystem. Briefly, the nature and function of these subsystems is the following: The BRU consists of a turbine driving an alternator and a compressor. All three components are mounted on a common shaft running on gas lubricated bearings. The alternator delivers the usable electric power. The BHXU consists of the recuperator, heat sink exchanger, and interconnecting ducting. The unit regenerates heat from the turbine exhaust fluid transferring it to compressor discharge fluid, rejects cycle waste heat and routes the working fluid to and from the BRU, GMS, and to the heat source.

The GMS stores and supplies the gaseous working fluid for startup, hydrostatic support of the BRU gas bearings during startup and shutdown, and provides for adjusting operating system inventory.

The electric subsystem, consisting of the dc power supply and controls, provides power during starts and stops and regulates field excitation, alternator output voltage; controls BRU speed, distributes electrical power output to the various loads, and monitors engine operation.

The heat rejection subsystem using a pump circulates coolant fluid through the BRU to cool the alternator, the BHXU to dissipate cycle waste heat and through the coldplates to cool the electric system components. The coolant returns to a simulated radiator for dissipation of heat. The heat source supplies the energy to heat the gas discharged from the recuperator before it returns to the inlet of the turbine.

One BHXU was tested in a Brayton power system employing all flight-type engine components. The system was operated in the Space Power Facility at NASA-Lewis Plum Brook Station. This first operation of a complete Brayton engine was conducted in a vacuum environment maintained at approximately 10^{-6} torr. Both krypton and helium-xenon were used as the working fluids. The other BHXU was tested in a power conversion loop employing the flight-type BRU and BHXU. The remaining subsystems employed were test support equipment. This test was performed in open atmosphere. To date, only krypton has been used as the working fluid in this system.

In both tests, Dow Corning 200 (2CS) was used as the liquid coolant through the heat sink exchanger. During both tests the power systems were operated over a range of turbine inlet temperatures, compressor discharge pressures, and compressor inlet temperatures.

Measurements

Pressure measurements were made using static pressure taps with strain gage transducers. Gas temperature measurements were made using chromel-alumel thermocouples, and liquid temperatures were measured using iron-constantan thermocouples. Liquid flow measurements were made using turbine-type flowmeters. Gas flow rates were measured with a venturi.

Results and Discussion

The Brayton engine tested under vacuum was operated using both krypton and helium-xenon as the working fluid. In the data reported herein, the turbine inlet temperature was varied from 1250° to 1450° F, compressor discharge pressure varied from 25 to 44 psia and compressor inlet temperature varied from 45° to 95° F.

The Brayton power conversion loop utilizing krypton as the working fluid was operated over a turbine inlet temperature range from 1200° to 1600° F, a compressor discharge pressure from 15 to 56 psia, and a compressor inlet temperature range of 55° to 100° F.

System performance is presented in Ref. 3. The performance characteristics of the BHXU have been determined for the operating conditions associated with these tests. The performance of the BHXU is expressed in terms of the heat transfer effectiveness and total pressure drop ratio; i.e., pressure drop divided by inlet pressure through each heat exchanger flow stream.

To illustrate the behavior of the BHXU in relation to system operating conditions, the performance is presented as a function of the system pressure level at the discharge of the compressor. Both power and the mass flow rate of the system increase directly with increasing compressor discharge pressure.

Recuperator Performance

The variation of recuperator heat transfer effectiveness with compressor discharge pressure is shown in Fig. 7 at a turbine inlet temperature of 1400° F utilizing krypton as the working fluid. The results are displayed for each unit tested.

The effectiveness of the recuperators are nearly identical and, consequently, shown as one curve. The effectiveness decreases slowly with increasing compressor discharge pressure, because of the offsetting effects of an increasing heat load and an increasing heat transfer coefficient in the recuperator. The effectiveness is reduced from 0.93 to 0.89 as the discharge pressure increases from 15 to 50 psia.

The effect of turbine inlet temperature on the recuperator effectiveness using krypton as the working fluid is shown in Fig. 8. The compressor inlet temperature was held constant. A change in turbine inlet temperature from 1300° to 1600° F resulted in a very slight to insignificant effect on the recuperator effectiveness. This change in turbine inlet temperature represented approximately a 300° F change in the inlet gas temperature on the low pressure side of the recuperator. At a given compressor discharge pressure the flow rate is the same for both temperatures. Therefore, the effect of turbine inlet temperature on effectiveness is a viscosity effect on heat transfer coefficient which is apparently small.

The same temperature effect can be expected when the working fluid is a mixture of helium and xenon. As shown in Fig. 8, the measured recuperator effectiveness is 0.90 at a compressor discharge pressure of 45 psia and a turbine inlet temperature of 1600° F. The predicted effectiveness at this condition is 0.89.

The effect on recuperator effectiveness due to a change in the working fluid from krypton to the mixture of helium and xenon is illustrated in Fig. 9. The effectiveness is plotted as a function of the compressor discharge pressure for both fluids. The resulting effectiveness with helium-xenon is higher than with krypton at all pressure levels. The improved thermal conductivity of the helium-xenon over krypton is responsible for the increase in effectiveness.

The difference in effectiveness due to the change in fluids is 0.035 at a compressor discharge pressure of 25 psia and increases to a difference of 0.05 at a compressor discharge pressure of 45 psia.

Heat Sink Exchanger Performance

The change in heat transfer effectiveness of the heat sink exchanger with compressor discharge pressure is shown in Fig. 10. The variation is shown for the working fluid krypton and helium-xenon at a turbine inlet temperature of 1300° F.

The flow of gas and liquid through the heat sink exchanger could be regulated independently of one another. Consequently, flow on both sides of the heat sink exchanger were not duplicated between one test and the other and matched operating conditions were not obtained over the range of compressor discharge pressure.

Two conditions related to liquid flow are depicted in Fig. 10. In the complete system test with helium-xenon as the working fluid, liquid flow rate was held constant. In the power conversion loop test with krypton as the working fluid, the liquid flow rate varied in proportion to the compressor discharge pressure.

The effectiveness decreases with increasing compressor discharge pressure for both helium-xenon and krypton. As with the recuperator, this occurs because of the combined increase of both the heat load and heat transfer coefficient. The reduction in effectiveness is more appreciable when the liquid flow rate is held constant. As witnessed in the recuperator, the performance with helium-xenon is higher at all levels of compressor discharge pressures. The singular effect of a change in working fluid can be shown for an individual compressor pressure of 35 psia, where equal flow rate ratios are obtained. At this point the difference in effectiveness between krypton and helium-xenon is about 0.04. This value is within the range experienced in the recuperator.

Pressure Drop Performance of BHXU

The variation of total pressure drop ratio for the BHXU with compressor discharge pressure is shown in Fig. 11 for both units tested with krypton. The total pressure drop ratio decreases with increasing compressor discharge pressure. There appears to be little difference (0.002) between the units throughout the range of pressures shown.

The variation of liquid side pressure drop with liquid flow rate through the heat sink exchanger is shown in Fig. 12. For the range shown, the pressure drop increases linearly with flow rate. At the design flow rate of about 0.19 pound per second, the resulting pressure drop is 4.3 psi. The expected design pressure drop at this condition was 4.5 psi.

Operating Experience

Through May 18, 1970, one BHXU has been tested in an engine test in a vacuum environment for 2080 hours of operation with krypton and with helium-xenon as the working fluid. In this period of testing, the unit experienced twelve startup and shutdown cycles. The other unit tested in atmosphere with krypton as the working fluid accumulated 239 hours of operation. In this sequence there were two startup and shutdown cycles.

During test operations the temperature and pressure experienced by the BHXU reached a value of 1240° F and 50 psia, corresponding to operation at a turbine inlet temperature of 1600° F and an alternator output power of approximately 13 kilowatts. At these peak conditions, the BHXU performed with a temperature gradient of nearly 1200° F, from the hot to cold end. These conditions slightly exceed the original design requirement.

Concluding Remarks

Two BHXUs have been hot tested in conjunction with the operation of a Brayton power system. The units have operated over a range of inlet temperatures and pressures with krypton and helium-xenon as the working fluids and under both an atmospheric and a vacuum environment. The range of this operation corresponded with an alternator output power of approximately 2 to 13 kWe. Use of the gas mixture helium-xenon as compared to krypton increased the recuperator effectiveness by as much as 0.05. Changing the turbine inlet temperature had little effect on the recuperator effectiveness.

This investigation was conducted at conditions resulting in off-design operation of the BHXU. This phase of operation has been very satisfactory with demonstration of a performance slightly better than expected. No significant difference in performance was obtained between the two units tested. Design temperatures and pressures were achieved although the data was not available in time for this paper; however, these operating levels have demonstrated the mechanical, structural, and thermal capability of the unit.

Several startups and shutdowns have been experienced. No adverse effects have been observed and the structural integrity of the unit has been preserved. The results of operation as part of a power system have not produced any objectionable interactions indicating that the BHXU design has adequately handled the integration requirements. Fluid containment ability of the units remains unaffected.

Based on the demonstrated results, it is reasonable to anticipate that the performance objectives of the BHXU will be met at design conditions.

References

1. Klann, J. L., "Steady State Analysis of a Brayton Space Power System," TN D-5673, 1970, NASA, Cleveland, Ohio.

2. Brown, W. J., "Brayton-B Power System - A Progress Report," Proceedings of the Fourth Intersociety Energy Conversion Engineering Conference, AIChE, New York, 1969, pp. 652-658.

3. Klann, J. L., Vernon, R. W., Fenn, D. B., and Block, H. B., "Performance of the Electrically Heated 2 to 15 kWe Brayton Power System," To be presented at this conference.

4. Beremand, D. G., "Performance Characteristics Based on Testing Three Identical Brayton Turbo-Alternator-Compressor Units on Gas Bearings," To be presented at this conference.

TABLE I. - BHXU DESIGN CONDITIONS

Working fluid (gas)	Xe-He mixture Molecular weight, 83.8 (krypton)
Liquid coolant	Dow Corning 200 fluid (2 centistokes at 25° C)
Recuperator hot side	
Gas flow rate, lb/sec	1.28
Inlet temperature, °R	1701
Inlet pressure, psia	24.1
Recuperator cold side	
Gas flow rate, lb/sec	1.267
Inlet temperature, °R	738
Inlet pressure, psia	43.1
Recuperator effectiveness	0.95
Heat sink heat exchanger	
Gas exit temperature, °R	540
Effectiveness	0.95
Capacity-rate ratio, (hot side/cold side)	0.87
Maximum liquid pressure drop, psi	25
Overall BHXU gas pressure drop, percent	4.5

TABLE II. - RECUPERATOR DESIGN SUMMARY

Counterflow Section	
Flow length, in.	19.7
Flow width, in.	8.45
Hot-side fins	
Height, in.	0.153
Fins per inch	16
Thickness, in.	0.004
Type	Offset rectangular
Cold-side fins	
Height, in.	0.125
Fins per inch	16
Thickness, in.	0.004
Type	Offset rectangular
Nominal plate thickness, in.	0.008
Number of sandwiches, each side	66
Stack height, in.	19.8
Side plate thickness, in.	0.06
Triangular End Sections	
Height, hot end, in.	3.85
Height, cold end, in.	1.3
Ratio,[a] hot end	0.65
Ratio, cold end	0.55
Fin configuration	
Height	Same as counterflow section
Fins per inch	10
Thickness, in.	0.004
Type	Plain rectangular

[a]Ratio of projected width of hot-side passage to core width.

TABLE III. - HEAT SINK EXCHANGER DESIGN SUMMARY

Gas flow length, in.	16.15
Liquid flow length (per pass), in.	20.0
Number of liquid passes	8
Gas-side fins	
Height, in.	0.125
Fins per inch	16
Thickness, in.	0.004
Type	Offset rectangular
Liquid-side fins	
Height, in.	0.05
Fins per inch	20
Thickness, in.	0.002
Type	Offset rectangular
Nominal plate thickness, in.	0.010
Number of gas sandwiches	31
Number of liquid sandwiches	32
Stack height, in.	6.4
Side plate thickness, in.	0.06

E-5773

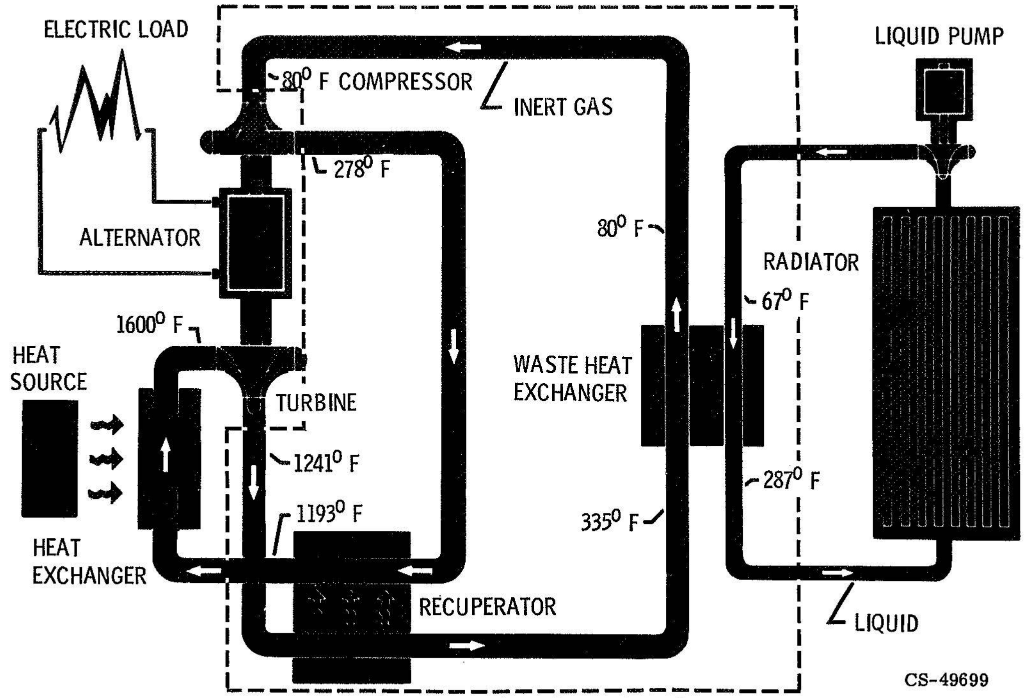

Figure 1. - Basic diagram of Brayton cycle system.

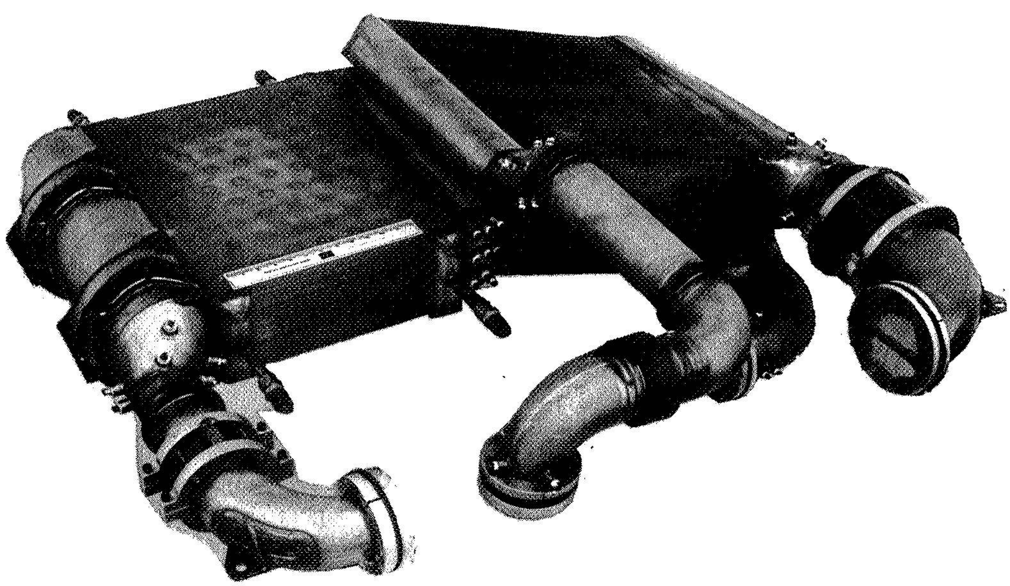

Figure 2. - Brayton heat exchanger unit.

E-5773

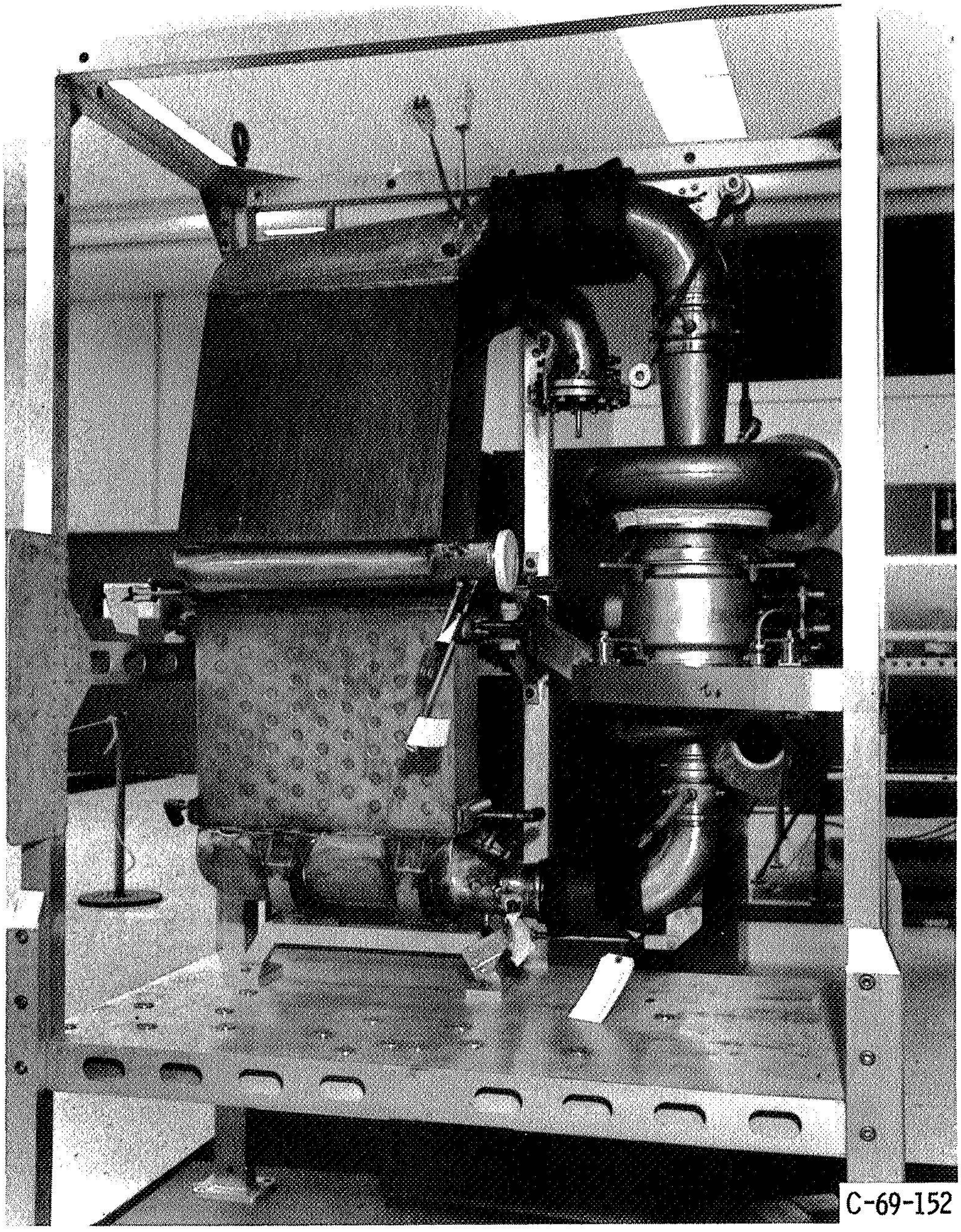

Figure 3. - Package of Brayton heat exchanger unit and Brayton rotating unit.

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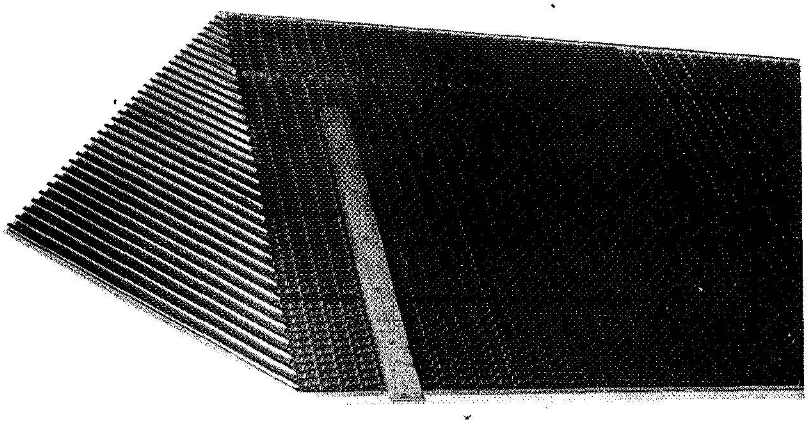
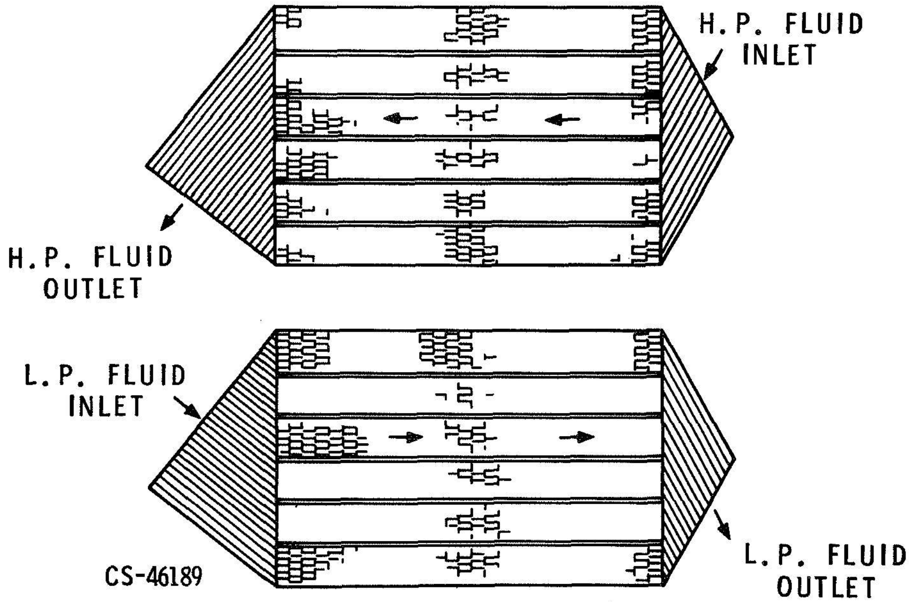
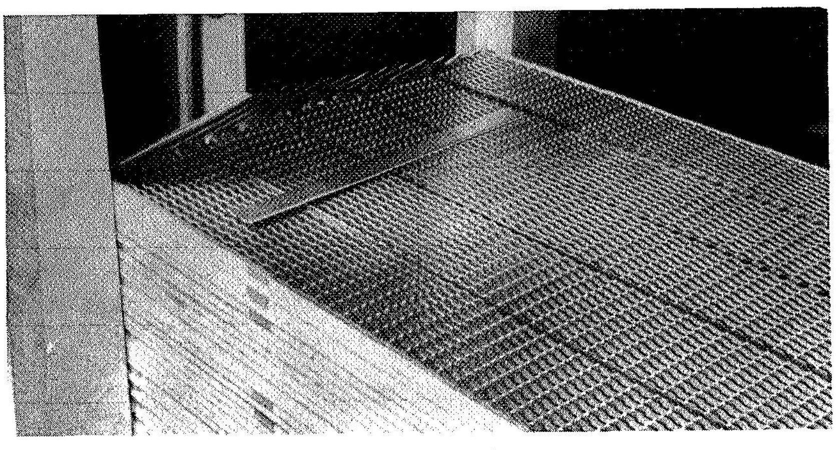


(a) Brayton cycle recuperator core.



(b) Recuperator core and end sections.



(c) Stack-up recuperator core.

Figure 4. - Recuperator.

E-5773

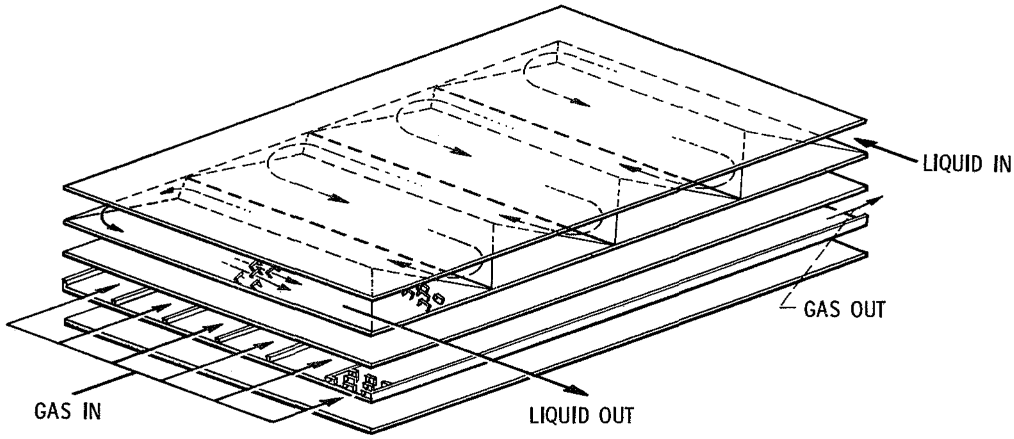


Figure 5. - Gas to liquid heat exchanger core.

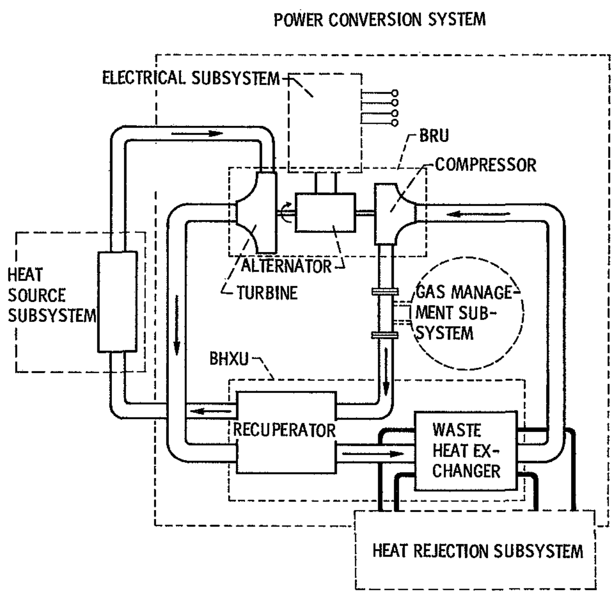


Figure 6. - Schematic diagram, Brayton power system.

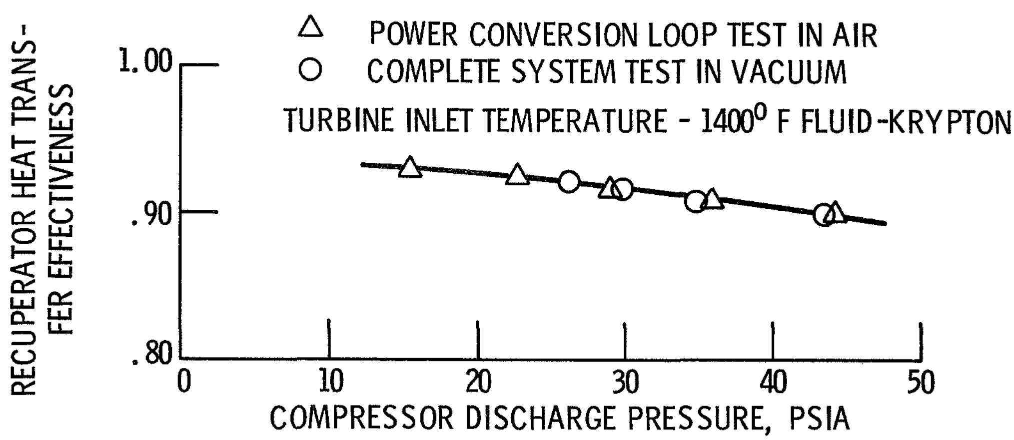


Figure 7. - Effect of pressure level on recuperator.

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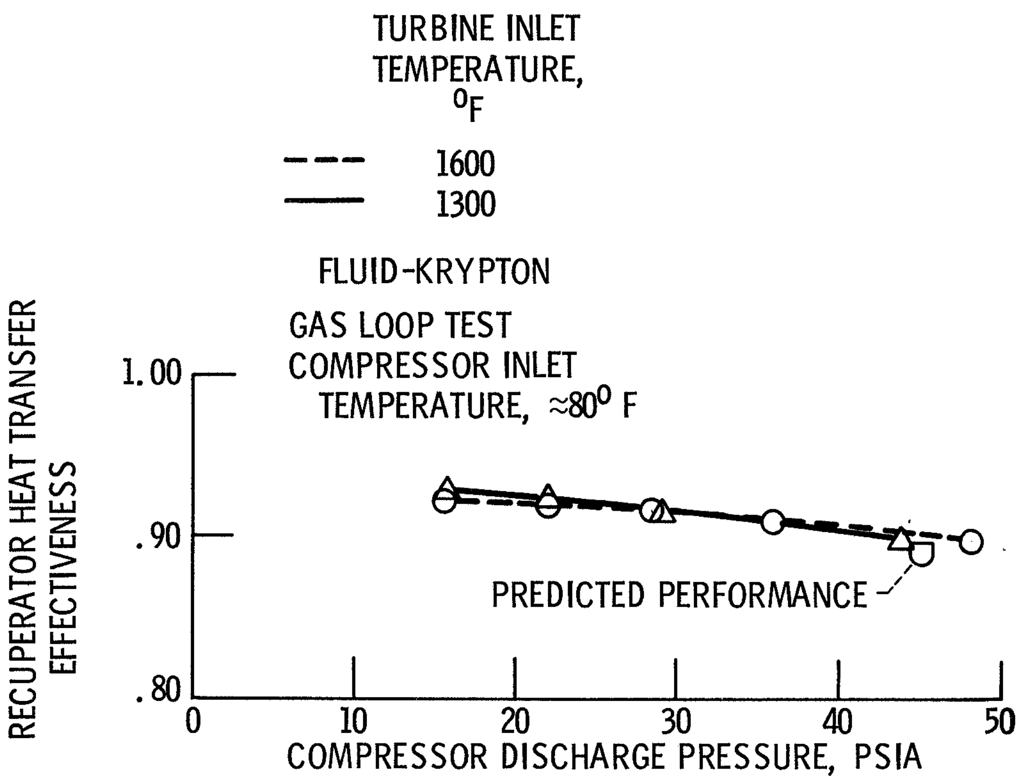

Figure 8. - Effect of turbine inlet temperature on recuperator.

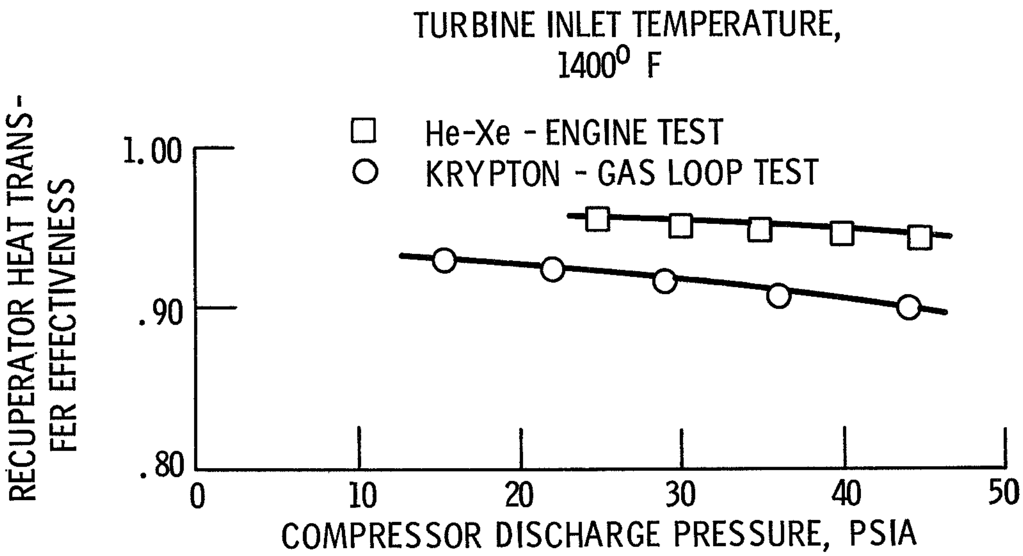

Figure 9. - Effect of working fluid on recuperator.

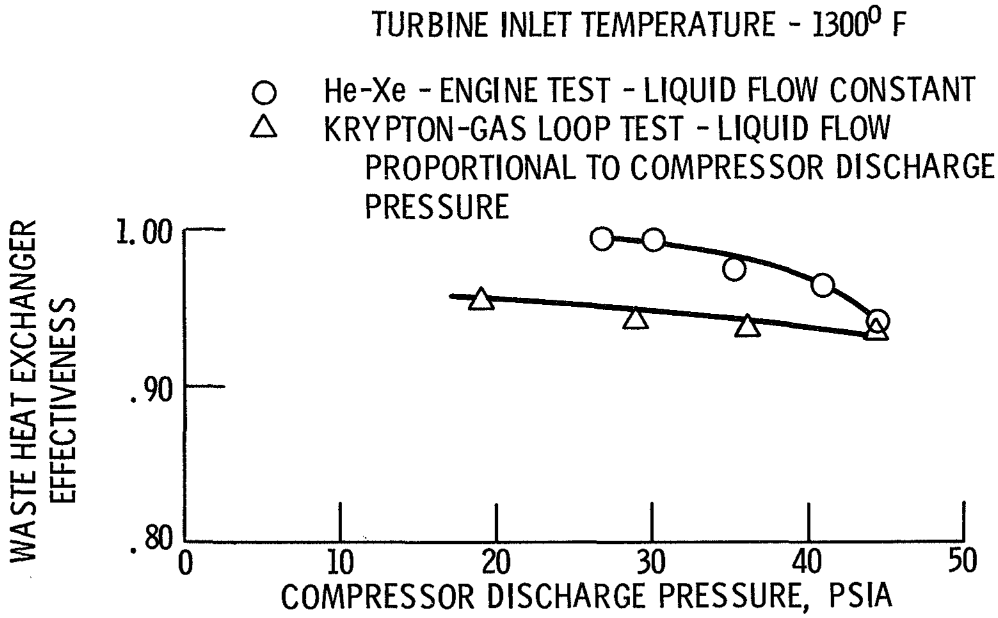

Figure 10. - Effect of pressure level on heat sink exchanger.

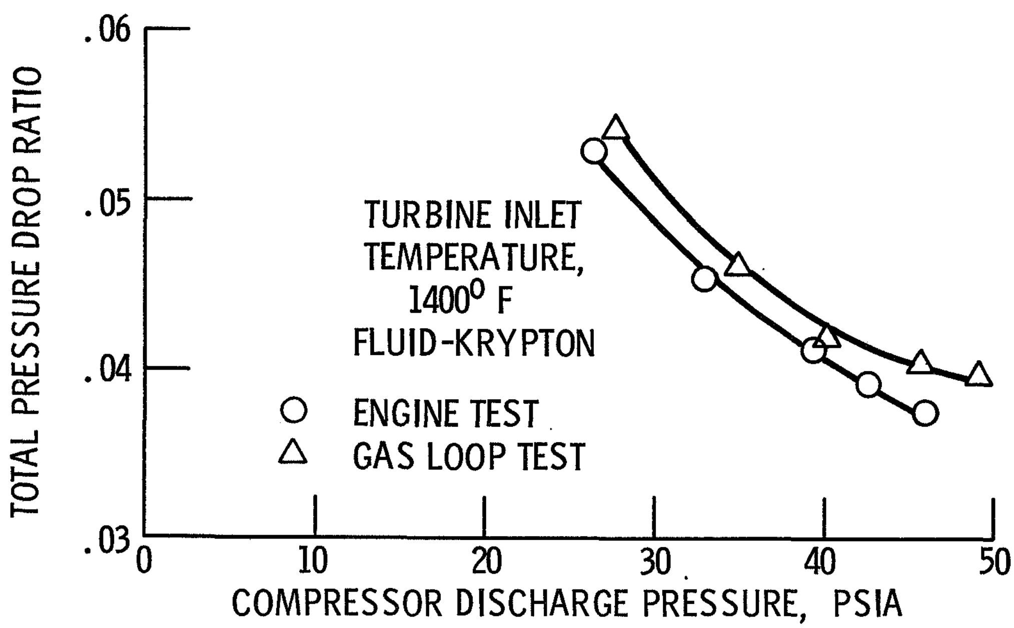

Figure 11. - Effect of pressure level on BHXU pressure drop.

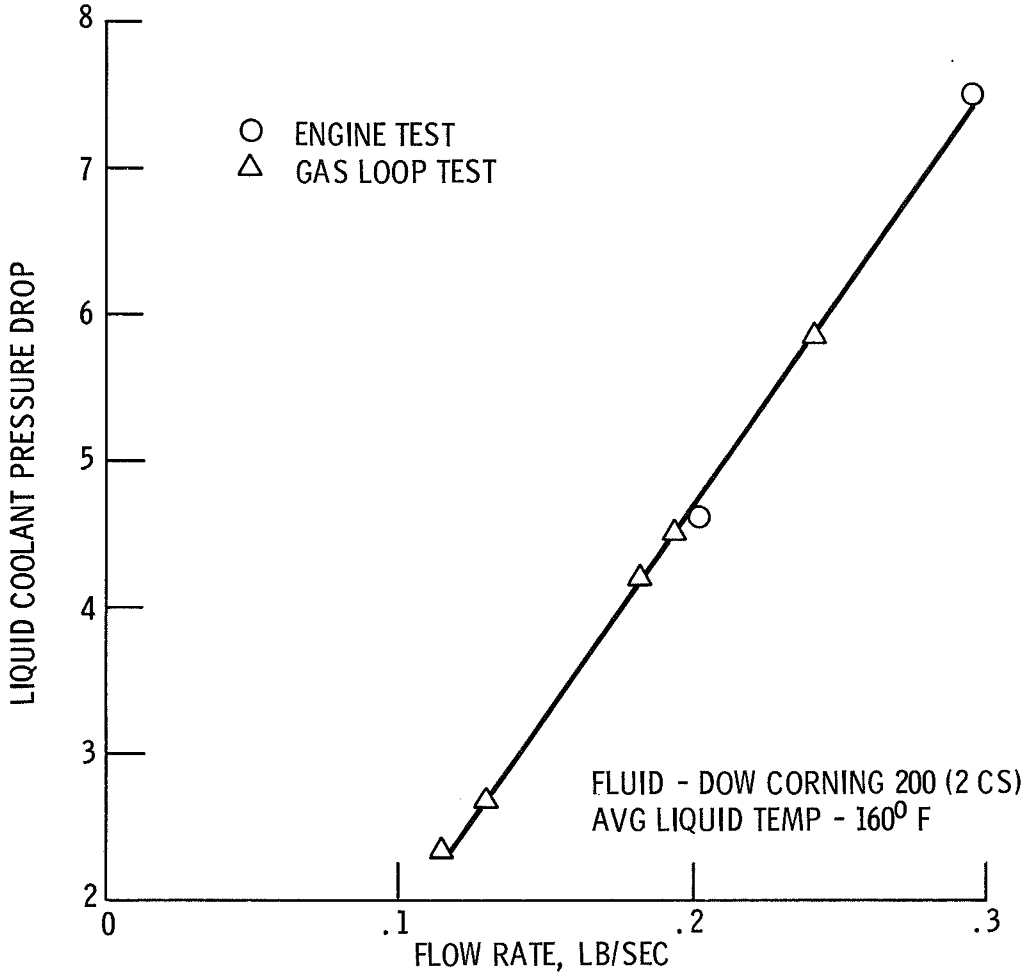

Figure 12. - Effect of liquid flow rate on heat sink exchanger pressure drop.