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ABSTRACT

An extensive study was conducted at the Lewis Research Center to evaluate an isotope Brayton electric power system for use in the 500 to 2500 W power range. The study emphasized overall system simplicity in order to reduce parasitic power losses and improve system reliability. The study included detailed parametric cycle analysis, conceptual component designs, and evaluation of system packaging. The study has resulted in the selection of a single-loop system (gas) with six major components including one rotating unit. Calculated net system efficiency varies from 23 to 28 percent over the power range. The use of the Pu-238 heat source being developed for the Multi-Hundred-Watt Radioisotope Thermoelectric Generator program was assumed. This heat source is currently under development by the Atomic Energy Commission and is scheduled to fly on a Department of Defense mission in 1974.

THE NASA-LEWIS RESEARCH CENTER has been actively engaged in Brayton cycle power system technology since 1963. To date this technology program has focused on a 2 to 15 kilowatt-electric Brayton system using an isotope heat source (1)*. The goals of this program have been high system efficiency, the demonstration of long-life potential (5 to 10 yr), and the establishment of user confidence in Brayton cycle power systems.

Because of the good performance achieved in this program (1), a study of the applicability of Brayton technology to even lower power levels (500 to 2500 W) has recently been conducted at Lewis. Use of the Pu-238 heat source being developed for the Multi-Hundred Watt Radioisotope Thermoelectric Generator (MHW-RTG) program was assumed (2)**. The study used the 2 to 15 kilowatt-electric Brayton system as a point of departure and strove for system simplicity, high efficiency, and low parasitic losses as design goals.

As a result of this study, a power system was selected that has six major components including one dynamic component (a turboalternator compressor). The system consists of a single loop, no valves, and a simple control and electrical subsystem. The study was approximately a two-man year effort and included a system parametric analysis, a conceptual design of all system components, an evaluation of a simplified control system and rotating unit speed control, an evaluation of system packaging concepts, and estimates of Brayton system cost in the 500 to 2500 watt power range.

SYSTEM PARAMETRIC ANALYSIS

The Brayton system selected for study is shown schematically in figure 1. This system differs from the 2 to 15 kilowatt-electric Brayton system (B engine) in that the alternator is either gas or radiantly cooled and cycle waste heat is rejected directly to space through a gas radiator. In the B engine concept, an oil system was used to accomplish the same tasks. Three alternator cooling schemes were employed over

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*Numbers in parentheses designate References at end of paper.

**The MHW-RTG is committed for use on a Department of Defense mission scheduled to fly in 1974. The MHW heat source is currently under development by the Atomic Energy Commission.

the power range studied. At low power, alternator heat was radiated directly to space by means of conducting fins attached to the alternator. Compressor discharge gas was used for cooling at middle power levels, and radiator outlet gas was used at the high power levels.

A parametric analysis of the power system was conducted for a thermal input power range of 2400 to 9600 watts. The ranges of the major system parameters investigated are presented in table 1. The thermal input levels studied were based on the use of from 1 to 4 multi-hundred-watt (MHW) isotope heat sources. Conceptual component designs were obtained so that component weights, pressure drop, and performance could be factored into the systems analysis. The same rotating unit design was used over the entire power range with the simple exception of the method of cooling the alternator. Other component designs varied with the power range.

The parametric analysis resulted in the selection of the system design conditions presented in table 2. The 1600° F turbine inlet temperature was selected early in the study to ensure hardware similar to that which has been successfully operated in the B engine program. The compressor inlet temperature, system loss pressure ratio, and recuperator effectiveness were selected on the basis of near-minimum system specific weight. Turbine and compressor efficiencies were based on results from testing of small radial-flow turbomachinery at low Reynolds numbers (3). The base efficiencies of 0.75 and 0.85 for the compressor and turbine were adjusted slightly to take into account the change in Reynolds number with power level. Compressor pressure ratio, working-fluid molecular weight, and turbomachinery rotational speed were selected to achieve good efficiency, reasonably sized turbomachinery, and high system pressure level. A high system pressure level was important to ensure good gas-bearing performance and to minimize heat-exchanger size and weight. The lower rotational speed of 48,000 rpm was favored as a conservative selection. A system heat loss of 10 percent was estimated for a multifoil vacuum type of insulation system, similar to that discussed in reference (4).

Radiators were designed with a 0.98 probability of no puncture in 10 years. Heat-sink temperature for the radiator was -10° F, which is representative of near-Earth orbit. For high Earth orbit or deep space missions, the radiator sink temperature would be lower, resulting in lower radiator sizes and weights.

After the system design conditions were chosen, components were configured and packaged for each of the four gross thermal input powers listed in table 1.

SYSTEM PERFORMANCE

Table 3 is a summary of the overall system performance using 1, 2, 3, and 4 MHW heat sources as the system's energy source. The system losses used to obtain the results given in table 3 include a 10 percent heat loss and a 5 percent reduction in thermodynamic cycle efficiency to account for compressor-discharge bleed flow into the bearing cavities. Bearing losses were estimated to be approximately 60 watts for all power levels; for conservatism, a value of 100 watts was used in the study. The same alternator was used over the entire power range. The alternator peak efficiency was 0.916 at a gross alternator output of approximately 1.5 kilowatts-electric. Calculated power losses for windage and electronics were included in calculating the system performance.

Ouput power was conditioned to 120 volts dc as listed in table 3. The resulting conditioned power to the user ranged from approximately 550 to 2670 watts with corresponding bus-bar efficiencies (Conditioned power/Gross thermal input) ranging from 0.23 to 0.28. The system weights and specific power (Conditioned power/System weight) ranged from 570 to 1160 pounds and 1.0 to 2.3 watts per pound, respectively. Radiator area requirements were approximately 60, 90, 160, and 210 square feet for systems using 1, 2, 3, and 4 MHW isotope heat sources, respectively.

A weight breakdown for the systems using 1 and 2 MHW isotope heat sources is given in table 4. The heat-source weight included the Pu-238 isotope fuel. The heat-source heat exchanger, recuperator, and radiator weights were calculated using computer design programs. The other weights were estimated in a first-order manner or scaled from similar Brayton B engine hardware.

SYSTEM COMPONENTS

ROTATING UNIT - The design concept selected for the compressor-alternator-turbine package is shown in figure 2. This unit includes a 3.5-inch-diameter turbine, a 3.0-inch-diameter compressor, and 1.55-inch-diameter alternator rotor, all mounted on a common shaft. The shaft is supported by foil-type gas journal and thrust bearings. The journal bearings are placed in the gap between the alternator end bells and the shaft. This minimizes the length of the rotating group and improves rotor dynamic performance. The use of foil bearings results in a simplification of this machine over the B engine rotating unit (5). Foil bearings do not require jacking gas during startup nor the installation complexity associated with pivoting-pad journal bearings and step-faced thrust bearings such as gimbaling, pivots, and preload devices. Potential pivot wear is also eliminated. Foil-bearing systems of this type have been demonstrated in rotating machinery of similar size, weight, and rotational speed.

The solid-rotor Lundell alternator (6) employed in the rotating unit concept is cooled by the system working fluid (He-Xe gas). Compressor-discharge gas is ducted through a finned heat exchanger attached directly to the stator back iron; this method of cooling is suitable for alternator output powers up to approximately 1.5 kilowatts-electric with a 400° F limitation on alternator hot-spot temperature. The performance summary (table 3) reflects the use of a radiantly cooled alternator for the 1 MHW heat-source system. Compressor-discharge gas cooling can also be used at the low power level with minor effect on system performance. Above 1.5 kilowatts-electric, radiator-discharage gas cooling was employed. With the exception of changing alternator cooling method, the rotating unit design remains the same over the 500 to 2500 watt power range.

HEAT SOURCE HEAT EXCHANGER (HSHX) - The Pu-238 MHW isotope heat source used for the study is in the form of a cylinder (6.5-in. diam by 17-in. length) and produces 2400 watts of thermal power. As discussed earlier, system power levels studied were based on multiples of this heat source. Various heat-source heat-exchanger concepts were considered and evaluated for such characteristics as weight, pressure drop, and design simplicity. The concept shown in figure 3 was selected as the most desirable of those considered.

The heat source is surrounded by two concentric axial-flow finned heat exchangers. The primary heat exchanger sees the He-Xe system gas and is used during normal system operation in space. Heat is transferred by radiation from the MHW heat source to the inner wall of the primary heat exchanger. The auxiliary heat exchanger is used for cooling the heat source when the Brayton system is not operating, such as during launch countdown after the heat source has been inserted into the HSHX. An external source of nitrogen gas would be suitable for this purpose. The system power level is increased by manifolding several primary heat exchangers and heat sources in parallel without changing the heat-exchanger design.

Safe operation of the heat source implies that the isotope fuel must never be released from its containment vessel. Therefore, heat-source integrity must be maintained under all conditions of orbit, during reentry into the Earth's atmosphere, and after impact with the Earth. Reentry and impact protection have been incorporated by the AEC into the design of the MHW heat source. The maintenance of safe heat-source temperature after its installation into the Brayton system was considered in the HSHX design. The use of an insulation door at the heat-source insertion end of the HSHX was evaluated. This door would be opened by devices sensing heat-source overtemperature and thereby would expose the end of the HSHX to space. In the event that all door-opening devices failed, a low-melting-point multifoil insulation door was included as a backup. Figure 4 graphically depicts the effect of various operating modes on the MHW heat-source surface temperature.

With the auxiliary heat exchanger operating (i.e., prelaunch) the heat source surface temperature is less than 1000° F. During normal system operation in space, the calculated surface temperature is approximately 1750° F, which is well below the 2000° F allowable continuous MHW heat-source surface temperature (2). With the Brayton system shut down and the insulation door open as in an emergency situation, the surface temperature would drop to 1600° F. In the event that the insulation door should fail to open, the MHW heat-source surface temperature would increase to 2900° F until the insulation door has melted and would then decrease to 1600° F. The 2900° F is well below the 4100° F melting point of the iridium eutectic used in the MHW heat-source container design.

RADIATOR - A gas radiator was selected for the low-power Brayton system mainly to avoid pumping power and thereby to reduce parasitic losses. A further advantage is fewer components and reduced complexity, compared with an oil-cooled radiator loop.

Radiator-tube, fin, and meteoroid-armor geometry for the bumper-fin concept used are presented in figure 5. Stainless-steel tubes and headers were used in conjunction with aluminum armor and fins. The radiator tubes varied from approximately 0.65 to 0.80-inch inside diameter for the power levels studied.

A cylindrical radiator concept was selected since this appeared to be more adaptable to varying spacecraft configurations and allowed for easy stacking of the power systems. Weights of flat double-bumper-fin radiators were also calculated for the same effective heat-sink temperature and were found to be approximately one-half the weight of the cylindrical radiators. For certain applications, use of a flat (or nearly flat) radiator might be attractive.

CONTROL AND ELECTRICAL SYSTEM - The simplicity of the low-power Brayton system results, in part, from a very simple control and electrical system. Also important at low-power levels, the power consumption of the control system must be minimized to achieve high system efficiency. Numerous system control schemes were evaluated during this study. Table 5 lists the functions and hardware requirements of one of the most promising of these systems. This concept provides for a one-button system startup, ac/dc conversion, voltage regulation, and continuous speed control regardless of user load-profile. Weight estimates were made and are also presented in table 5. Results presented are for a system with 100-percent redundancy. Power consumption of this control and electrical system is estimated to be 40 watts at the 550-watt system output level and 110 watts at the 2.6-kilowatt level.

During manufacture, the power system is filled with the gas inventory required for the desired power level. Startup of the Brayton system is accomplished by allowing the HSHX to warm up to 1700° F and then applying 400-hertz motoring power to the rotating unit alternator. Motoring power is applied for a short time (10 to 15 sec) to accelerate the rotating unit to its self-sustaining speed (approximately 24,000 rpm). After motoring power cutoff, the rotating unit accelerates (by bootstrapping) to 48,000 rpm and is held at this level by a parasitic speed control.

In the event that the spacecraft and associated Brayton power system are shuttle launched, the 400-hertz power for the Brayton startup would be provided by the shuttle. For a remote startup in space, a battery and 400-hertz square-wave inverter would be provided as part of the Brayton system.

SYSTEM PACKAGING

The packaging arrangements evaluated during this study were based on the use of 5-foot-diameter cylindrical radiators as discussed previously. The 5-foot diameter was selected as being compatible with most launch vehicles. It also results in reasonable ratios of length to diameter for the radiator areas required in the 500 to 2500 watt power range.

The rotating unit, HSHX, and recuperator were oriented to reduce piping bends and to minimize piping length. Minimizing high-temperature duct length was an important constraint from the standpoint of heat loss. An additional constraint was that the HSHX (isotope insertion end) must look through a slot in the radiator for isotope insertion, for isotope auxiliary-cooling access, and for shutdown and emergency cooling while in orbit.

Figure 6 is a packaging concept that satisfied the previous requirements at the 550-watt power level. Support structure was not designed in this study and only estimates for structure weight are quoted in table 4. The radiator manifolds, however, are considered to be good structural members and would probably be used as main support members.

SYSTEM COSTS

An evaluation of the cost effectiveness of this system in the 500 to 2500 watt power range was conducted as part of this study. Per-copy costs of the power conversion system were estimated at approximately $360,000, regardless of power level. This includes the cost of the radiator, HSHX, rotating unit, recuperator, ducting, and insulation system. Heat-source costs were estimated at $580 per thermal watt with PuO_2 fuel and $140 per thermal watt with Cm_2O_3 fuel. The heat source costs include the encapsulated fuel and MHW heat-source hardware costs.

The cost effectiveness of the Brayton system when compared to competitive systems varies with the nature of the mission (i.e., orbit altitude, deep space, etc.), the power requirements, the number of missions considered, and the number of flights within a given mission. Two mission models (low Earth orbit) were evaluated that encompassed a variety of NASA unmanned satellites. Power requirements ranged from 600 to 3000 watts electric for eight different missions. For the missions investigated, Brayton system costs averaged \$3900 per watt electric using Pu-238 fuel and \$1900 per watt electric using Cm-244. These costs are about one-fourth those for radioisotope thermoelectric generators and are cost competitive with or superior to solar array/battery systems for the same missions.

CONCLUDING REMARKS

A study was conducted to determine the feasibility and performance of an isotope Brayton electric power system for the 500 to 2500 watt power range. The study has resulted in the selection of a power system with bus-bar efficiencies (conditioned power/gross thermal input) ranging from 0.23 to 0.28 over the range of power studied. System and component concepts were chosen that promise high reliability and long life. These include (1) the selection of a one-loop system incorporating a gas radiator and a gas-cooled alternator, (2) a rotating unit using foil bearings, and (3) a simple electrical and control system with low power losses. The flexibility of packaging makes the Brayton system attractive for missions using either the space shuttle or a variety of launch vehicles. Use of an isotope heat source provides added flexibility compared to a solar system since system orientation is not a requirement.

Design parameters selected allow the use of technology which has been successfully demonstrated at the component level in the ongoing Brayton program and should minimize the cost of technology and system development required to achieve a flight-qualified system. The high system efficiency minimizes the quantity of costly isotope fuel required. The high efficiency, simplicity, ease of development and low per-copy cost of the selected power system make it extremely attractive for many of the space missions planned for the next two decades.

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Table 1 - Range of Major Parameters Investigated

Parameter	Parameter range
Gross thermal power, W	2400, 4800, 7200, and 9600
Compressor inlet temperature, °F	30 to 120
Recuperator effectiveness	0.90, 0.925, 0.95, and 0.975
Loss pressure ratio	0.92, 0.94, and 0.96
Compressor pressure ratio	1.6 to 2.4
Working fluid molecular weight	39.94, 60.0, and 83.8
Rotational speed, rpm	48,000 and 60,000

Table 2 - Summary of Design Conditions

Turbine inlet temperature, °F	1600
Compressor inlet temperature, °F	[a]76
Recuperator effectiveness	0.95
Loss pressure ratio	0.94
Compressor efficiency	0.75
Turbine efficiency	0.85
Compressor pressure ratio	1.7
Rotational speed, rpm	48,000
Working fluid	He-Xe mixture
Molecular weight	83.8
Effective radiator sink temperature, °F	-10
Probability of no radiator puncture (10 yr)	0.98
System heat loss, percent	10

[a] For the 1-MHW system the compressor inlet temperature was 55° F.

Table 3 - Brayton Performance Summary

	Number of MHW heat sources			
	1	2	3	4
Gross thermal power, W	2400	4800	7200	9600
Net system efficiency, $\left(\frac{\text{Net power}}{\text{Gross thermal input}}\right)$	0.24	0.27	0.29	0.29
Bus-bar efficiency, $\left(\frac{\text{Conditioned power}}{\text{Gross thermal input}}\right)$	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

Table 4 - Brayton System Component Weights (lb)

	Number of MHW units	
	1	2
Heat source(s)	46	92
Heat source heat exchanger(s)	56	112
Recuperator	92	68
Mini-Brayton rotating unit	40	30
Radiator	170	225
Ducting	24	28
Structure	51	53
Insulation	66	72
Electronics	15	15
Parasitic load resistor	10	15
Total	570	710

Table 5 - Control System

Control function	Hardware	Weight at 550 watts electric, lb
Speed control	Control module	15
Voltage regulation ac/dc conversion	Parasitic load resistor	10
System startup	Start module	[a]32
	Battery	[a] 7
MHW heat source over temperature	[b]Heat source insulation door with: -Bourdon tube actuator -Fusable link -Explosive charge -Low melt insulation	
Intentional system shutdown	Insulation door release mechanism	

[a] Not required if shuttle power is used for startup.
[b] Any combination of these devices could be used to achieve redundancy.

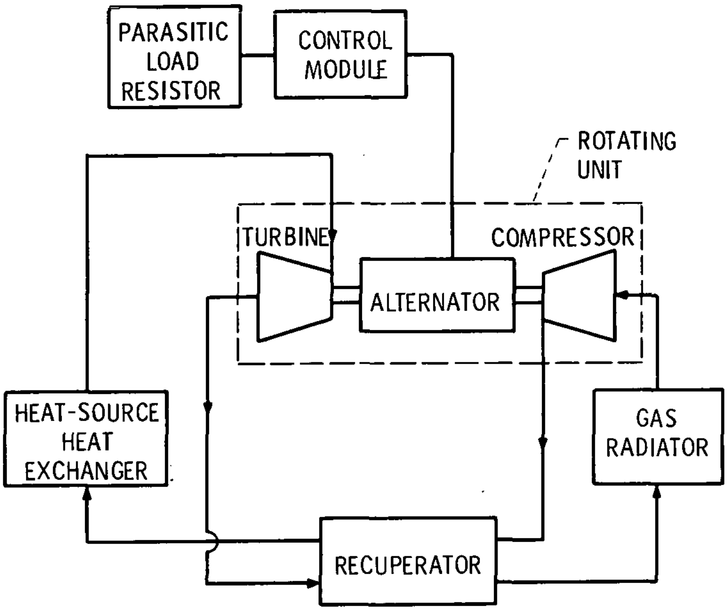

Figure 1. - System schematic.

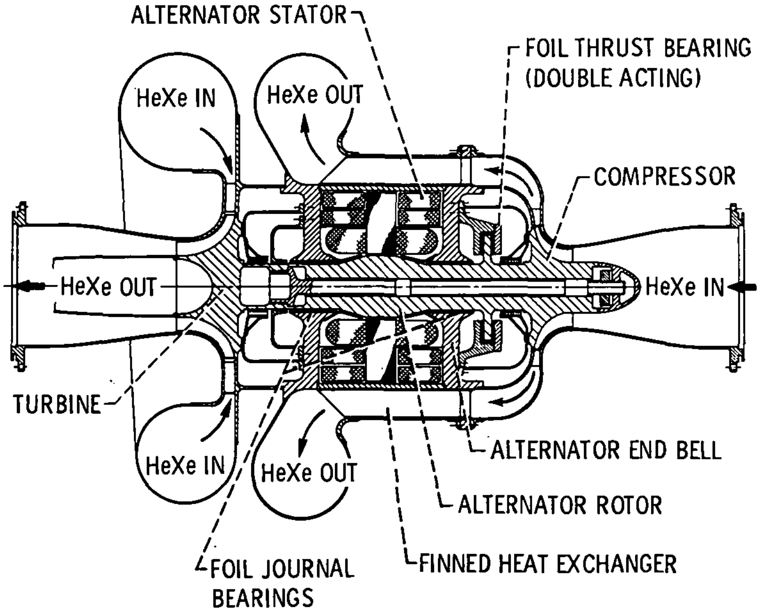

Fig. 2. - Brayton Rotating unit cooled with compressor discharge gas.

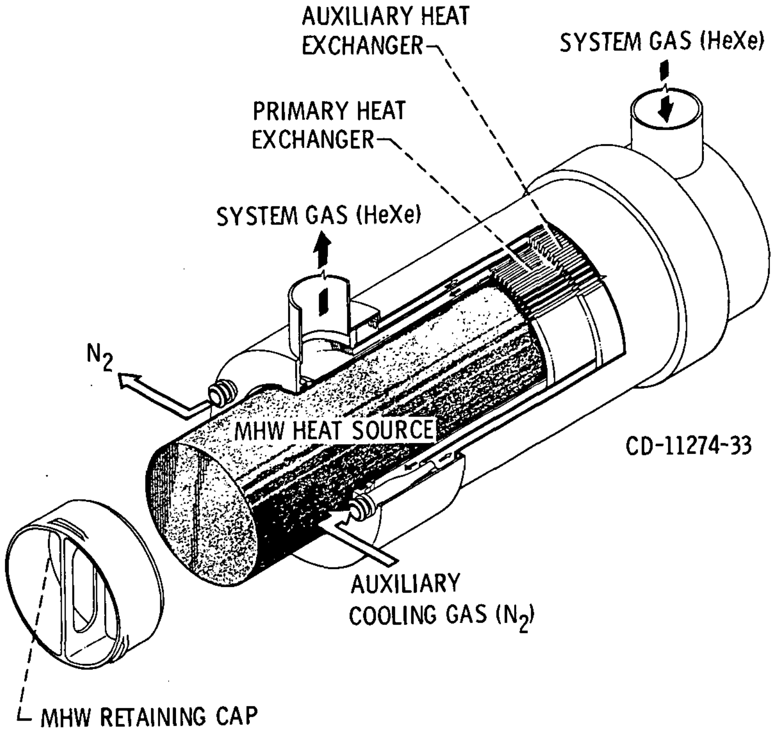

Fig. 3. - Heat-source heat exchanger.

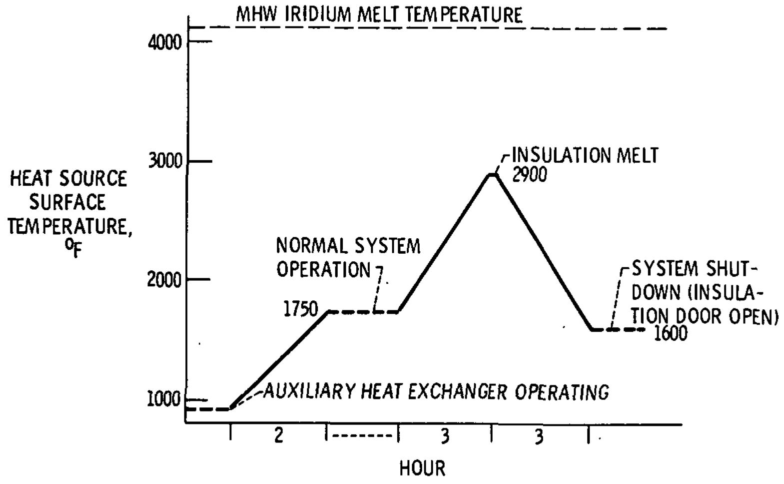

Figure 4. - HSHX operating modes

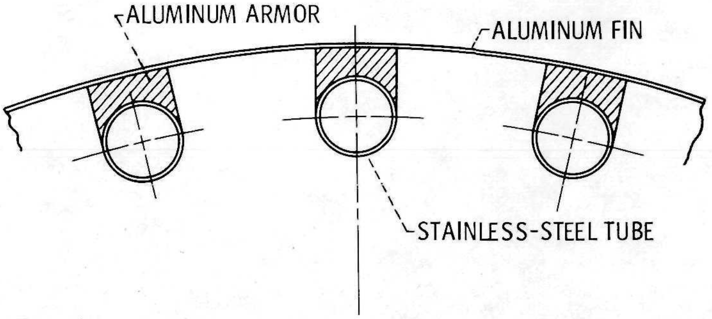

Figure 5. - Cylindrical bumper - fin radiator concept.

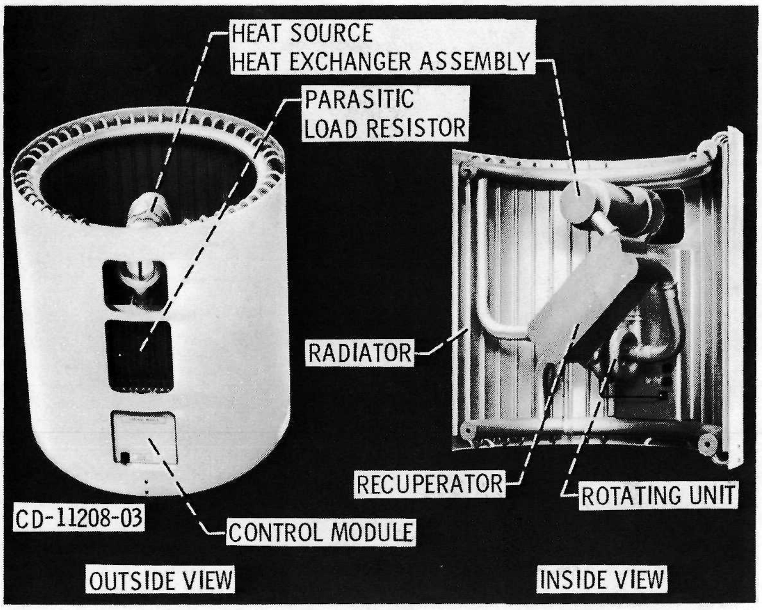

Fig. 6. - Brayton power system (550 We).

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