Closed Cycle Gas Turbine as a Proposed Undersea Power Source

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Undersea application of compact and lightweight closed Brayton cycle power systems currently being developed for space is discussed. Design details of a 50 kw$_e$ hydrogen-oxygen fueled system for a short-duration undersea mission of 1000 kw-hr are presented. For this same mission, a new hydrogen-oxygen injection gas turbine cycle is described. Performance characteristics of undersea long-duration 10 to 150 kw$_e$ power systems, using radioisotope and nuclear reactor heat sources, are also presented. Development status of closed Brayton cycle power conversion systems is presented.

I. Introduction

UNDERSEA power requirements can be satisfied by minor modifications of closed cycle gas turbine systems that are now at a high level of development for use in space.[1,2] These systems use current gas turbine technology and offer advantages of low over-all system weight, long life, and low cost. Because the gas turbine cycle is sensitive to compressor inlet temperature, the ocean environment, which provides a more favorable heat sink than space, offers advantages. The closed cycle gas turbine, or closed Brayton cycle, can utilize chemical, radioisotope, or nuclear reactor heat sources at high over-all efficiency. The same power conversion equipment can be employed for short-duration chemically-fueled missions, or for long-duration isotope and reactor-fueled missions.

II. The Closed Brayton Cycle

In the conventional open cycle gas turbine, shown schematically in Fig. 1A, atmospheric air is compressed and is heated by burning fuel in the combustor. The hot gases expand through the turbine and exhaust to the atmosphere. Part of the turbine work output drives the compressor and the remainder is available for driving a generator or providing jet thrust. The atmosphere provides cycle working fluid and a heat sink for cycle waste heat within the turbine exhaust.

To be independent of the atmosphere, the system can be closed as shown in Fig. 1B. The system is charged with an optimum working fluid and the turbine discharge is cooled and ducted to the compressor inlet. Heat addition is accomplished with a heat exchanger and waste heat is rejected through the cooler. A recuperator raises efficiency by reclaiming heat otherwise lost.

Output power level is controlled by varying the pressure of the closed loop working fluid by withdrawing or adding working fluid by a compressor and accumulator. This maintains high efficiency over a wide load range because cycle temperature ratio and aerodynamic efficiencies are constant.

For minimum size and weight, space power conversion systems utilize small hermetically-sealed turbomachinery operating at optimum speeds. The rotor consists of turbine, compressor, and alternator on a common shaft supported by gas bearings lubricated by the cycle working fluid, as shown in Fig. 2. The alternator shown is of the Rice inductor type and produces 400 to 3200 Hz a.c. which can easily be converted to d.c. by static rectifiers. Static inverters can also provide a choice of a.c. frequencies.

Starting of the power plant is accomplished by gas injection, or by motoring the alternator using electrical energy from a battery.

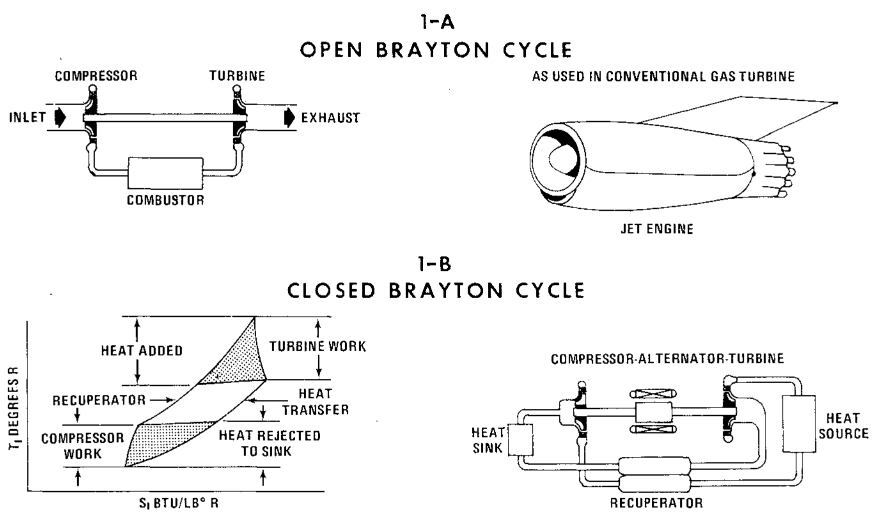

Fig. 1 The Brayton cycle.

III. Short-Duration Chemically-Fueled Mission Closed Brayton Cycle

Adaptation of the closed Brayton cycle to an undersea mission requires encapsulation in a pressure vessel with

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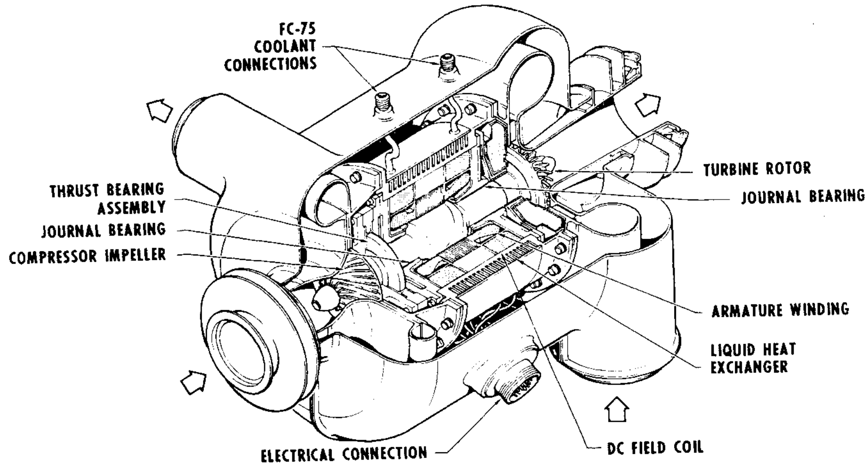


Fig. 2 Typical Brayton cycle turbomachinery.

penetration for seawater coolant. Separate vessels can be utilized to store reactants.

Figure 3 shows a schematic of a reference design 50 kw$_e$ power conversion system for a 1000 kw-hr mission. State points are shown for the full-load condition. The closed loop operates with a mixture of helium and xenon as the working fluid to provide good turbomachinery performance with good heat-transfer characteristics. Cycle waste heat is rejected to sea water pumped through the cooler.

Catalytic combustion of cryogenicly-stored hydrogen and oxygen provides heat to the cycle. This type of combustor was developed and qualified for 250 hr life on the DynaSoar Accessory Power Unit program[3,4] and employs a palladium-black catalyst impregnated into alumina substrate pellets loosely packed into the combustor assembly. Reaction can be initiated at cold temperatures without an ignitor, and takes place at all useful mixture ratios over a wide range of flow rates. An exchanger incorporated with the catalytic combustor assembly transfers heat into the closed helium-xenon loop at 1600°F at the turbine inlet.

The cryogenic reactants pass through the cooler as they leave their storage tanks, which improves turbomachinery cycle efficiency by lowering helium-xenon temperature at the compressor inlet to 30°F and also effects gasification of the reactants. Use of cryogenic reactants requires special design attention to avoid seawater freezing and to provide for boiloff.

The combustion loop is pressurized with hydrogen, and pressure is maintained by admitting makeup hydrogen as the reaction progresses. Oxygen is injected at a rate determined by the temperature of the helium-xenon leaving the heat exchanger. To sweep out the reaction product (steam) from the combustor and to condense it, the contents of the combustion loop must be circulated through the condenser by a fan.

Because circulation of hot hydrogen with the steam would result in high heat loss in the condenser, an economizer transfers a large portion of this heat into the hydrogen which, then, is circulated into the combustor. Hydrogen from the economizer is introduced downstream of the injector face, combining with the stoichiometric mixture to flow into the catalyst bed. Thus, the hydrogen-rich environment induces complete reaction, obviating precise stoichiometric ratio control.

With 29°F sea water coolant, over-all cycle efficiency is calculated to be 42.4%, as determined by the ratio of generator electrical output to heat supplied to the closed loop. Specific reactant consumption is 1.66 lb/kw-hr of useful load. High efficiency minimizes weight and volume of reactants and their pressure vessels. In this regard, pressure vessels designed for 20,000 ft depth and made of acceptable steels, such as HY-140 and HY-180, are negatively buoyant even when empty.

Figure 4 shows the sensitivity of the gas cycle efficiency to E_R (recuperator effectiveness), β (gas cycle pressure drop factor), T_6 (turbine inlet temperature), and T_1 (compressor inlet temperature). Figure 5 indicates the flat cycle efficiency characteristic as a function of load at the alternator terminals.

Weight and volume of the complete proposed 50-kw$_e$ 1000 kw-hr system are listed in Table 1. Weights of pressure vessels and flotation material are not included. The weight of cryogenic tanks includes the Dewar inner wall, controls, and expulsion heat exchangers, but assumes that a sea pressure vessel serves as the outer enclosure for the vacuum insulation space.

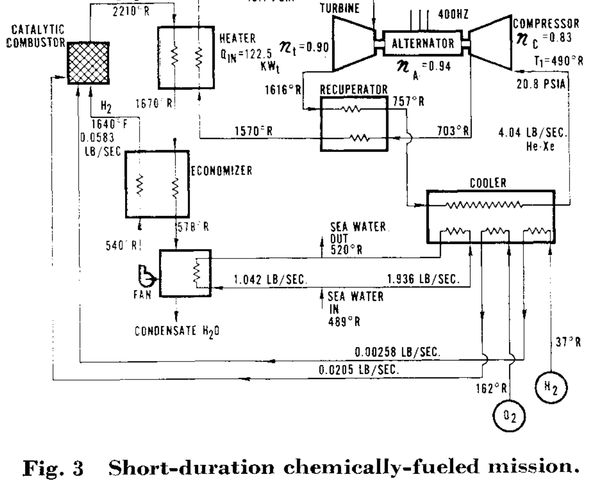


Fig. 3 Short-duration chemically-fueled mission.

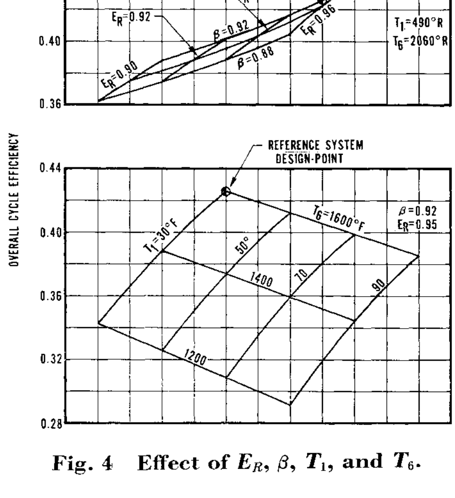


Fig. 4 Effect of E_R, β, T_1, and T_6.

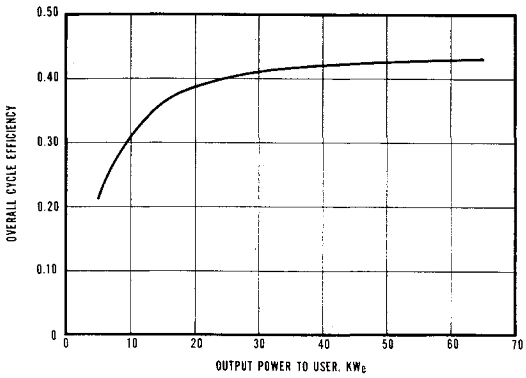


Fig. 5 Part-load performance.

Since the Brayton Rotating Unit (BRU) uses gas bearings, a brushless alternator, and has no gears, it has an inherent long life. The only wear-out mode is turbine wheel creep, but typical gas turbine wheels operating at the design temperature of 1600°F can be designed for a life in excess of 50,000 hr. The combustor may require replacement of the catalyst after 250 hr.

IV. Short-Duration Chemically-Fueled Mission, Hydrogen-Oxygen Injection Gas Turbine Cycle

Figure 6 is a schematic of a proposed H_2-O_2 injection gas turbine cycle, similar to the conventional closed Brayton cycle. Its closed loop, however, is charged with hydrogen gas that is compressed and directed through an in-line catalytic combustor. Oxygen injected into the combustor combines with part of the hydrogen to raise the hydrogen and the product of combustion (steam) to turbine inlet temperature. The hot gases expand through the turbine and pass through the recuperator and oxygen heater and then into the condenser-cooler. Cycle waste heat is rejected to sea water and the steam is condensed out of the hydrogen working fluid and directed to a storage vessel. Natural cycle circulation clears the steam from the combustor and sweeps it across the condenser surfaces.

Makeup hydrogen is injected into the hydrogen loop prior to compression. Injection as liquid lowers the compressor inlet temperature and improves cycle efficiency. Its flow rate is determined by a closed loop constant-pressure regulator. The pressure setting controls the system power output by varying the pressure of the closed loop working fluid, as in the conventional closed cycle turbine.

Oxygen gas is injected into the combustor for proper mixing, and cycle heat recuperation is accomplished during gasification in the oxygen heater. Flow rate is controlled by combustor exit temperature.

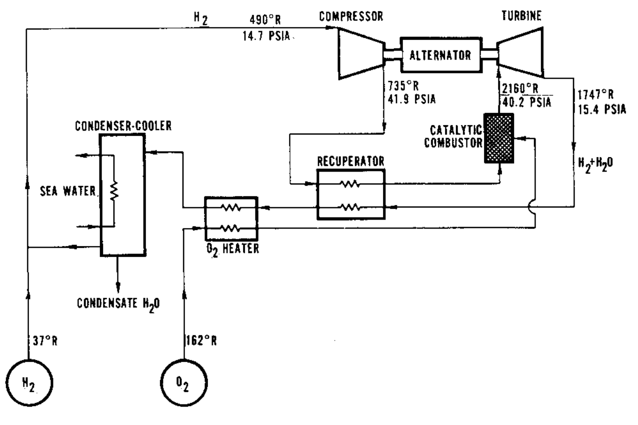


Fig. 6 Hydrogen-oxygen injection gas turbine cycle.

Table 1 50 kw$_e$ 1000 kw-hr system weight and volume

	Weight, lb	Volume, ft^3
Power conversion unit	1666	23.5
Hydrogen tank (dry)	281	52.0
Hydrogen reactant (including residual)	190	
Oxygen tank (dry)	183	26.0
Oxygen reactant (including residual)	1505	
Condensate storage required		26.5
	3825	128.0

The H_2-O_2 injection cycle is a considerable simplification of the conventional closed cycle gas turbine with a separate combustion loop. Many heat exchangers are eliminated, including the critical high-temperature heat exchanger, and the excellent heat-transfer characteristics of the hydrogen working fluid results in small sizes for those heat exchangers that are required. Although use of hydrogen requires many stages in the compressor and turbine, this can be mitigated by increasing molecular weight by adding another gas, such as argon, xenon, or krypton, or by allowing the steam to build up to a predetermined mixture ratio with the hydrogen. Operation of the catalytic combustor with the latter gas mixtures is considered feasible with the high inlet temperatures furnished from the recuperator and with design of the combustor to concentrate the reactants. Catalytic combustors have been operated with hydrogen and air, in which case a large percentage of inert nitrogen is present.

Efficiency levels of the mixed gas injection cycle will be comparable to those achieved by the system using the separate combustion loop. Note that condensate water lubricated bearings can be used in this system because leakage into the working fluid is not harmful.

V. Long-Duration Mission with Radioisotope Heat Source

One of the heat sources receiving major consideration for closed Brayton cycle space power systems is plutonium-238 radioisotope.[5] This alpha-emitter requires little shielding for a manned application and has a half-life of 87.4 years. Other cheaper and more readily available isotopes, such as cobalt-60 (5.2 years half-life), and strontium-90 (28 years half-life), are equally applicable; however, their radiation characteristics require greater shielding. Sea water can be utilized for a large portion of this function.

The problem of removing the heat generated in the isotope fuel, while the power conversion system is nonoperative, parallels that of "sinking" excess heat generated during the initial life of short-lived isotopes. Although the conventional closed Brayton cycle power conversion system can be utilized, this heat rejection problem suggests an alternate arrangement as shown in Fig. 7.

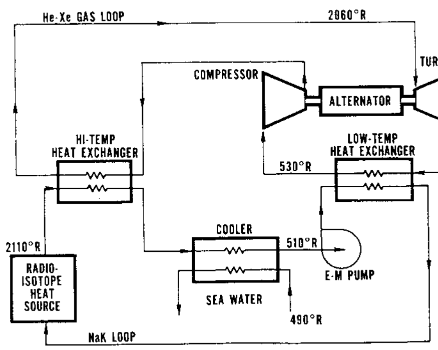


Fig. 7 Radioisotope-fueled system with liquid-metal heat-transport loop.

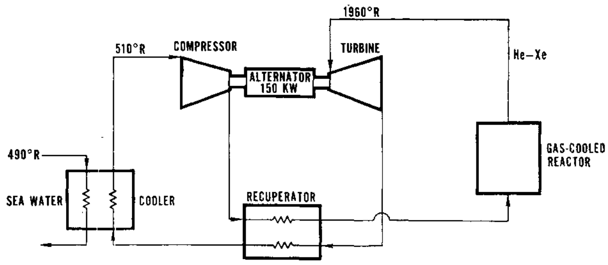


Fig. 8 Gas-cooled nuclear reactor heat source.

By using a liquid-metal heat transport loop, the isotope fuel block is directly coupled to the heat sink. When the power conversion system is not operating, all heat is transported to the sink. For systems with short-lived isotopes, excess heat can be directed to the sea water by varying the liquid metal flow rate during the exponential decay process. A NaK eutectic mixture with freezing point of 12°F is used to avoid freezing. Self-pumping of the liquid metal is achieved by electromagnetic pumps that are highly reliable,[6] with pumping power supplied by integral thermoelectric couples.

This liquid-metal heat transport loop also eliminates the recuperator, since the same function is achieved in the low-temperature heat exchanger. Over-all heat exchanger weight remains about the same, however, because the high- and low-temperature heat exchangers must be larger. Elimination of the recuperator and connecting ducts results in lower cycle gas-pressure drop and can result in higher cycle efficiency. Advancements in technology over the past ten years have removed much of the stigma attached to the first attempts to use NaK for heat transport, and successful operation of a number of hermetically-sealed systems, including SNAP 8,[7] has been achieved.

The good heat-transfer characteristics of the liquid metal permit a fuel block temperature of 1650°F to provide for a turbine inlet temperature of 1600°F. With a 70°F compressor inlet temperature (determined by sea water temperature and heat exchanger sizing) the over-all efficiency is 39.9% at the generator terminals. Approximately 155 lb of plutonium-238 are required for a 10-kw$_e$ system. The weight of the complete 10-kw$_e$ system, including fuel, but less any shielding and containment vessel, is approximately 810 lb.

VI. Long-Duration Mission with Gas-Cooled Nuclear Reactor

For long-duration missions at higher loads, a nuclear reactor heat source may be desirable. The simplest closed Brayton cycle system results from coupling directly to a gas-cooled reactor of a type similar to that utilized on the Army ML-1 program. That reactor operated for 2500 hr, and fuel elements were tested in-pile for 10,000 hr at fuel hot-spot temperatures equivalent to a turbine inlet temperature of 1500°F.

Figure 8 shows a schematic of a 150-kw$_e$ system that uses a working fluid mixture of xenon and helium. With the ocean heat sink providing a compressor inlet temperature of 50°F, over-all cycle efficiency at the generator terminals is 39.3%. The weight of this system is estimated to be 3000 lb without shielding and containment vessel.

VII. Long-Duration Mission with Liquid-Metal-Cooled Nuclear Reactor

The long-duration, high-power-level heat source that most closely matches the development status of the small closed cycle gas turbine is the SNAP 8 uranium-zirconium hydride compact reactor. This reactor was operated several years

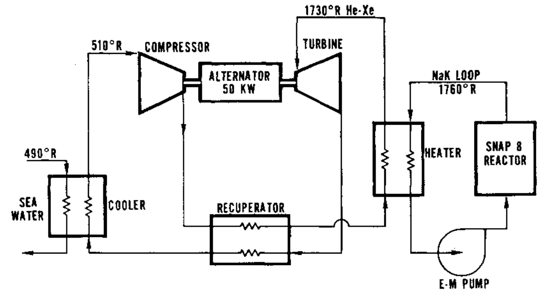


Fig. 9 Liquid-metal-cooled reactor heat source.

ago for 500 days, including one year at rated power and temperature.[7]

The SNAP 8 reactor utilizes NaK liquid metal cooling and has a rated outlet temperature of 1300°F. NaK pumping is effected by an electromagnetic pump powered by thermoelectric couples self-contained in the NaK system. The closed cycle gas turbine matches well with this reactor in spite of a comparatively low turbine inlet temperature of only 1270°F.

A schematic of a 50-kw$_e$ power output system is shown in Fig. 9. The NaK loop transfers heat to the closed gas loop through an exchanger. Cycle waste heat is rejected to sea water through a second exchanger. Reactor afterheat is transferred into the gas loop and a blower in the loop maintains gas circulation to the cooler until heat is dissipated following shutdown. The liquid-metal heat transport arrangement shown for the radioisotope system could also be used with the SNAP 8 reactor system.

Cycle efficiency of the system shown in Fig. 9 is 34.3% at the generator terminals, with a compressor inlet temperature of 50°F. The weight of the complete system is estimated at 2500 lb, less shielding and pressure vessel, and volume at 35 ft^3. Sea water can be utilized for a portion of the shielding.

A 100-kw$_e$ power conversion system would comprise two 50-kw modules in parallel with the same over-all cycle efficiency. Weight of this system is about 3500 lb, and volume 58 ft^3.

Figure 10[8] represents the operating time limits vs the thermal output power level of the latest SNAP 8 type reactor in current development. It can be seen that a 100-kw$_e$ closed Brayton cycle system requiring 292 kw$_t$ input can be operated in excess of 35,000 hr at full power before reactor life is depleted. The Brayton cycle efficiency is high enough to produce 400 kw$_e$ for 10,000 hr with the thermal output of this reactor.

VIII. Development Status

The closed cycle gas turbine is a Swiss invention for which patent applications were submitted in 1935.[9] Europeans

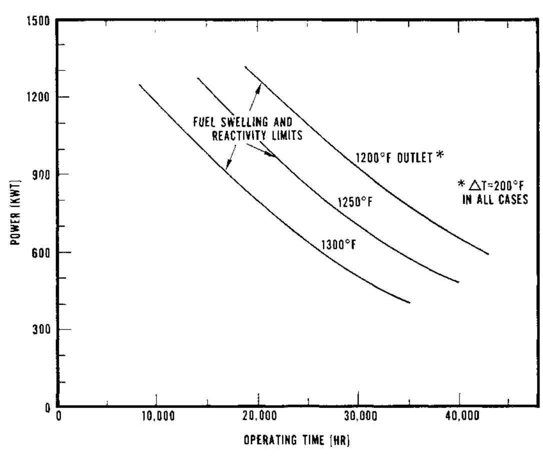
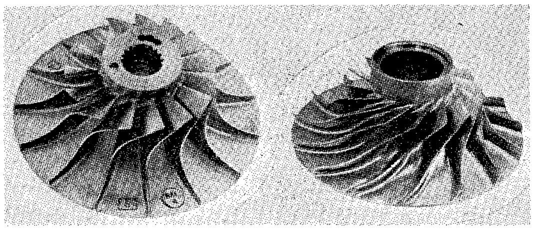


Fig. 10 Performance map-reference ZrH reactor.



TYPE	DIA. IN.	SPEED RPM	FLUID	PRESSURE RATIO	PERFORM. %	SPONSOR
RADIAL	4.16	45,000	ARGON	2.0	82.5	AIRESEARCH
RADIAL	3.2	64,000	ARGON	2.06	80.5	USAF
RADIAL	6.0	38,500	ARGON	2.38	80.0	NASA
RADIAL β^2	6.5	38,500	ARGON	2.38	83.0	NASA
RADIAL β^2	4.25	36,000	Xe-He	1.9	83.0	NASA

Fig. 11 Compressor performance.

have applied this principle to central station generating units, and sizes up to 17.3 Mw are in service. Individual units have completed tens of thousands of hours of successful operation.[11]

American industry began studies in 1957 to apply the closed cycle principle to small conventional high-speed open cycle gas turbine as a compact lightweight space power source. However, component efficiencies were then too low, and heat exchangers too large and heavy to provide a suitable system. Over the years, improvements have produced significant advances in compressors and turbines, pushing small gas turbine cycle efficiency to high levels. Concurrent advancements in compact heat exchangers have diminished space and weight problems. Final resolution was achieved with the development and integration of process-fluid-lubricated bearings and the integral alternator. Most of these advancements have been reported.[1,2]

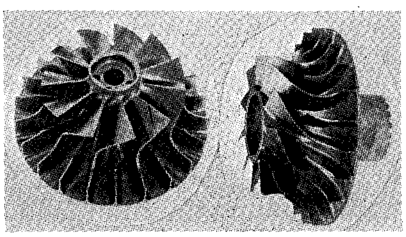
Component Development

Compressor and turbine

Demonstrated small compressor and turbine aerodynamic component efficiency levels are summarized in Figs. 11 and 12.

Alternators

The Rice-type of alternator has been integrated with the closed Brayton cycle unit because it is brushless and utilizes solid rotor construction. These factors, together with an inherently low magnetic imbalance, contribute to a long-life, low-windage component suitable for use on gas bearings. Figure 13 illustrates a two-pole machine developed for 5.4 kva, 3-phase output at 85,000 rpm. A four-pole, 14.3 kva, 1200 Hz, 36,000 rpm alternator has been developed for the NASA Brayton cycle unit. This machine has demonstrated an electromagnetic efficiency of 93.5%.[11]



TYPE	DIA. IN.	SPEED RPM	FLUID	PRESSURE RATIO	PERFORMANCE %	SPONSOR
RADIAL	3.5	53,000	ARGON	1.56	87	NASA
RADIAL	4.6	50,500	ARGON	1.56	88	NASA
RADIAL	6.0	38,500	ARGON	1.56	88	NASA
RADIAL	5.0	36,000	Xe-He	1.87	90	NASA

Fig. 12 Turbine performance.

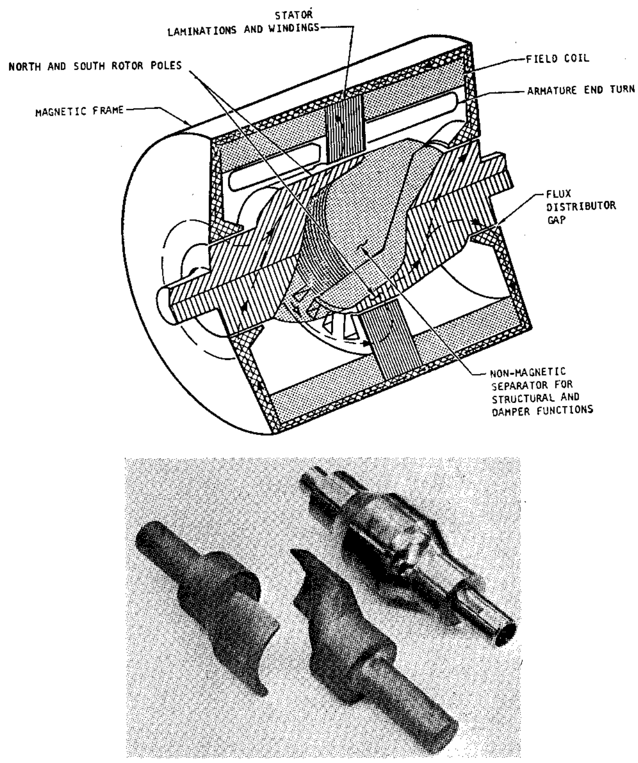


Fig. 13 Rice alternator.

Bearings

Pad-type and foil-type gas bearings have demonstrated successful operation, and process-fluid-lubricated bearings, such as water, have also been successfully developed.

Figure 14 shows representative gas journal and thrust bearings that have successfully operated in Brayton machinery. The journal bearing consists of three pivoted pads, one of which is spring mounted to accommodate dimensional changes. Orifices in each pad supply pressurized gas for lift-off during starting. After the shaft has reached nominal speed, the gas supply is shut off and the bearing goes from hydrostatic to self-acting hydrodynamic operation. The thrust bearing is the Rayleigh stepped-sector

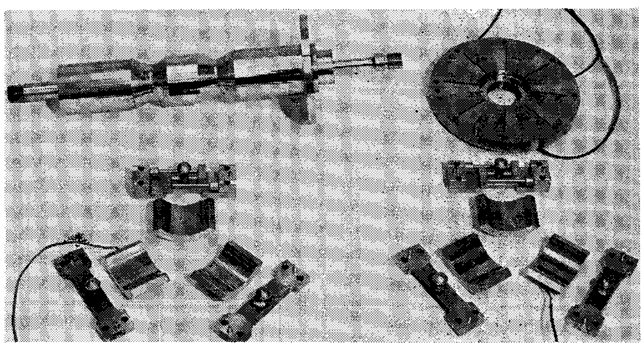


Fig. 14 Typical pad-type gas bearings.

Table 2 Design conditions

Cold inlet gas	801°R	13.8 psia
Hot inlet gas	1560°R	6.73 psia
Gas flow rate (each side)	36.69 lb/min argon	
Effectiveness, $E = (T_5 - T_2)/(T_9 - T_2)$	0.9	
Total pressure drop, $\Delta p/p$	2.0% (total both sides)	
Weight	413 lb	

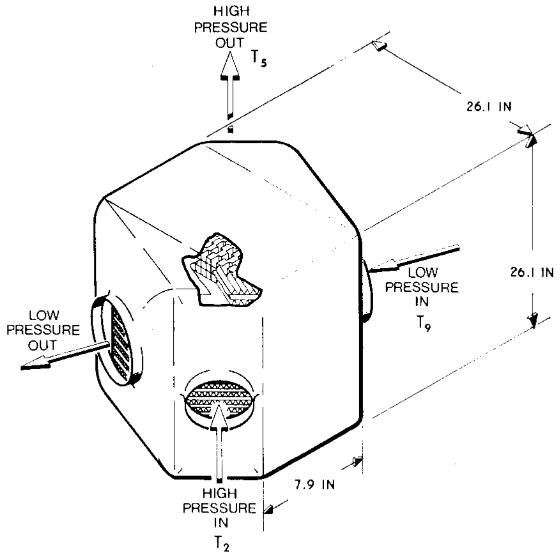


Fig. 15 Recuperator.

type with hydrostatic lift-off orifices, and is mounted in a gimbal for alignment.

Recuperators

Several high-effectiveness compact recuperators have been designed, built, and tested. An example is the plate-fin unit for a 10-kw closed Brayton cycle space power system[12] of Fig. 15 which uses solar heat at the design conditions shown in Table 2.

Closed Brayton Cycle Systems

A 3-kw Brayton cycle demonstrator (BCD), using surplus low-efficiency components, was tested in 1967 and demonstrated a cycle efficiency in excess of 20%,[13] with electrical heaters to simulate a radioisotope heat source. The 64,000 rpm rotating unit, shown in Fig. 16, consists of turbine, compressor and a two-pole Rice alternator mounted on foil gas bearings. It is equipped with automatic controls and operates on argon with a turbine inlet temperature of 1540°F. The BCD is presently at NASA Houston for evaluation.[14]

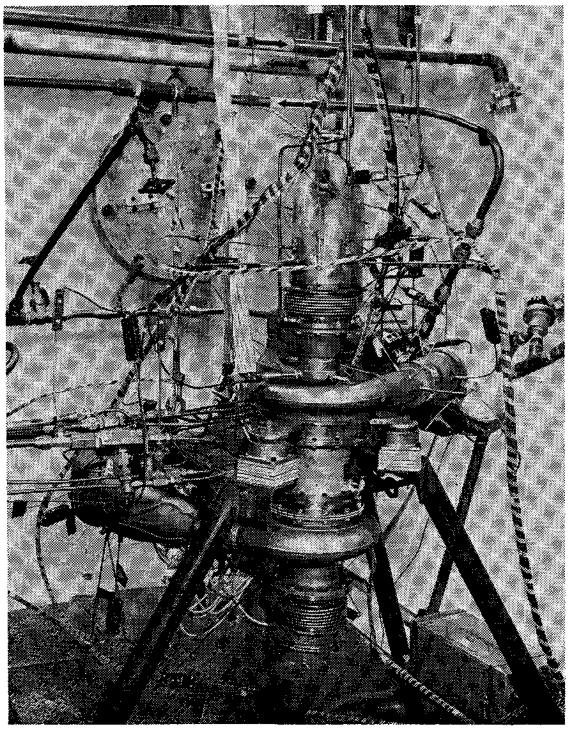


Fig. 16 BCD rotating unit.

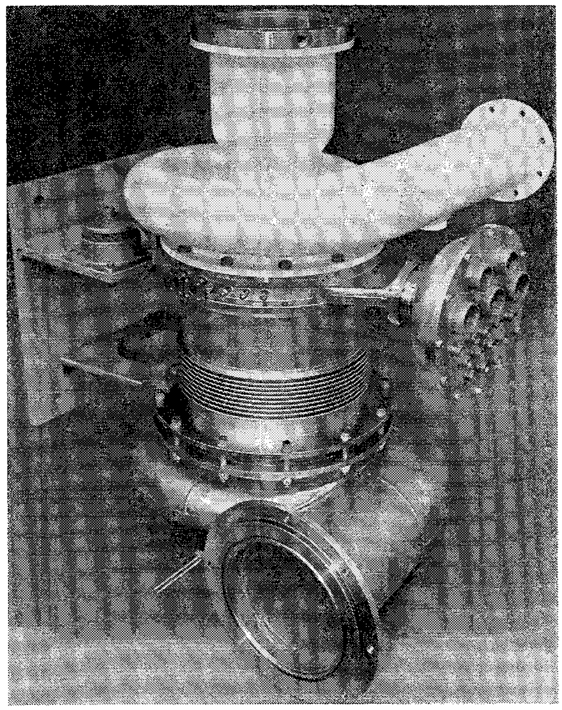


Fig. 17 Turbocompressor unit.

As part of a 10-kw, solar-powered, two-shaft, space-power system under evaluation by NASA Lewis, a turbocompressor was designed, built, and tested in 1965.[15] This unit, shown in Fig. 17, incorporated pivoted-pad gas journal bearings and a stepped-sector gas thrust bearing that operated at 38,500 rpm, using argon as the working fluid, at a turbine inlet temperature of 1500°F. The plate-fin recuperator and the cooler were also supplied for this program.

NASA Lewis is currently assembling a 10.5-kw, single-shaft, closed Brayton cycle power system.[16] It will be ground tested first with an electric heat source and ulti-

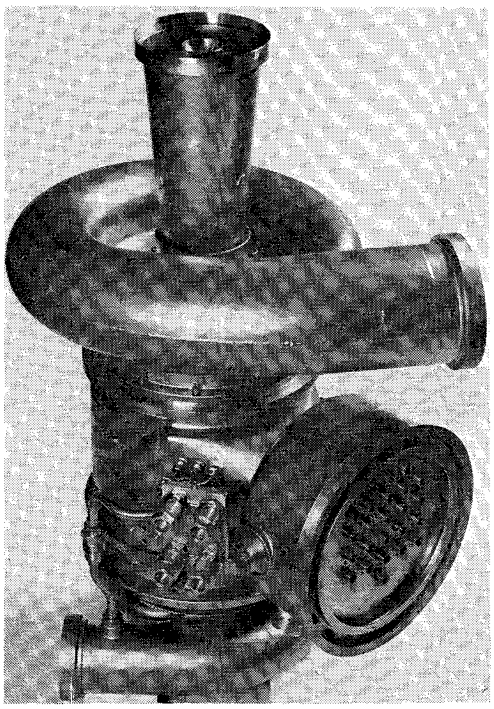


Fig. 18 Brayton rotating unit.

mately with solar and plutonium-238 heat sources. Figure 18 shows the Brayton rotating unit (BRU) for this system.[17] It is an integrated unit that operates on helium-xenon; the rotor is supported on gas bearings. Preliminary test results indicated that component design efficiencies were exceeded.[11,16] The Brayton heat exchanger unit (BHXU),[18] an assembly of the recuperator and cooler, and the engine control system (ECS)[19] components are also being furnished for NASA.

IX. Conclusion

Closed cycle gas turbine systems offer an attractive means of supplying power for short- and long-duration undersea missions. The deep ocean heat sink results in high cycle efficiency. The closed cycle gas turbine is at a high state of development as a result of many years of effort in surface and aerospace gas turbine applications.

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