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REVIEW OF DEVELOPMENT STATUS OF
SMALL TURBINE-GENERATOR UNITS SUITABLE
FOR THE NAVY UNDERSEA POWER PLANT

A. P. Fraas

MASTER

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UNITS SUITABLE FOR THE NAVY UNDERSEA POWER PLANT

A. P. Fraas

SEPTEMBER 1972

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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REVIEW OF DEVELOPMENT STATUS OF SMALL TURBINE-GENERATOR UNITS SUITABLE FOR THE NAVY UNDERSEA POWER PLANT

A. P. Fraas

ABSTRACT

This report reviews the development status of small turbine and engine generator units that might be used in isotope power sources for undersea applications requiring from 2 to 10 kW(e). The review includes units designed and built by NASA-AiResearch, Aerojet, G.E., Solar, Stratos, Sundstrand, Swenson, Thermo-electron, and Westinghouse. Where available and pertinent, drawings, performance data, and operational problems are included.

INTRODUCTION

The development status of small turbine-generator units was reviewed in the spring of 1969 from the standpoint of the Navy requirements for small isotope power plants.¹ A substantial amount of work has been accomplished in the interim; this report reviews the status of these various power plants as of mid-1971. As in the earlier review, the work of each vendor is discussed under a separate heading. It is assumed that the reader has a copy of Ref. 1 at hand, hence information such as drawings and tables presented in Ref. 1 are not included in this report.

TURBINE-GENERATOR UNITS FOR ORGANIC RANKINE CYCLES

Aerojet

Development of the 6 kW(e) Aerojet organic Rankine cycle system was continued to satisfactory completion of a 1000 hr endurance test on the turbine-generator unit.² The program was subsequently discontinued and the staff was dispersed upon closing-out of the Snap 8 mercury Rankine cycle effort. No new information important to the Isotope Kilowatt Program was developed beyond the fact that 1000 hr of operation was completed satisfactorily.

Sundstrand

The Sundstrand 6 kW(e) turbine-generator-pump unit was operated for a total of 3000 hr with a nominal turbine inlet temperature and pressure of 700°F and 100 psia.³ The condenser pressure was 0.4 psia. After the initial shakedown, no difficulty was experienced with the turbine-generator-pump unit itself, but there were frequent shutdowns as a consequence of difficulties with other components in the system and test equipment.

It would be desirable for the NAVFAC applications to be able to "bootstrap start" the unit, i.e., start the rotor with the boiler pressure available from the static head between the condenser hot well and the header drum of the projected recirculating boiler. Start-up tests at Sundstrand disclosed that it was necessary to increase the turbine inlet pressure to 12 psia to start the unit. ORNL calculations indicate that, if the nozzle pressure ratio can be maintained by dropping the condenser pressure when the turbine inlet pressure is low, the turbine should start with a boiler pressure of only 2.0 psia.

R. E. Niggeman suggested that the reason that it did not in the Sundstrand tests was that they were not able to get their condenser pressure below 0.2 psia, hence the operating pressure ratio was much less than the design value. This would produce a normal shock in the divergent section of the nozzle so that the portion of the nozzle downstream of the shock would function as a pressure recovery diffuser, and the velocity of the jet leaving the nozzle would be far below the design value. In the hermetically sealed system projected by ORNL it should be possible to maintain the design pressure ratio down to turbine inlet pressures even less than 2 psia, hence it should be possible to design the system for a bootstrap start.

The turbine-generator-pump unit was designed with flanged joints between the various sections of the housing, hence it cannot be hermetically sealed. To obtain a hermetically sealed system, the entire turbine-generator-pump unit will have to be enclosed in an outer shell that can be seal-welded.

The centrifugal pump gives a nominal discharge head of about 116 psia at the design speed of 24,000 rpm. Although no tests have been run to determine its characteristics under cavitating conditions, a similar pump

built by Sundstrand has a cavitation specific speed of about 9000. The peripheral velocity of the impeller blades at the outer perimeter of the inlet eye is about 60 ft/sec, the upper limit for operation without cavitation damage in well designed water pumps.⁴ Inasmuch as the compressibility of Dowtherm A should be substantially greater than that of water, the velocity at the impeller eye for incipient cavitation damage should be somewhat higher than 60 ft/sec. As a consequence, it appears practicable to employ the simple liquid inventory control scheme employed by ORNL in the boiling potassium reactor system.

The high speed of the pump impeller makes it necessary to employ a cavitation suppression head of about 7 ft. This in turn means that, for a fairly compact installation, a jet pump will be required between the condenser hot well and the pump inlet. In addition, the tilting pad bearing cavities must drain well, and this requires that another jet pump be employed to scavenge the bearing lubricant flow and return it to the condenser hot well. The centrifugal pump has adequate capacity to drive both jet pumps in addition to supplying the boiler feed flow.

The generator has been designed with cooling passages through which the entire boiler feed flow passes enroute to the regenerative feed heater.

It should be noted that fairly close control of the turbine speed was required in the Sundstrand tests because, if the speed dropped much below the design value, the pump discharge pressure would have dropped below the boiler pressure, and the boiler feed flow would have been interrupted. However, under the lower turbine inlet pressure and temperature conditions proposed by ORNL for the isotope power unit, the pump should have an adequate delivery head to permit wide fluctuations in speed with no adverse affects on the boiler feed flow rate.

The 600°F turbine inlet temperature chosen for the NAVFAC application will require a new nozzle block if the full design output of 6 kW(e) is to be obtained. However, the existing unit could be operated to give about 3.5 kW(e) if the condenser pressure could be dropped to about 0.15 psia in order to maintain the same turbine pressure ratio. This would be possible in a hermetically sealed system.

Sundstrand has a substantial program underway currently on turbine-generator units designed to produce 40 kW(e) and 100 kW(e). This program

is being carried out as a cooperative effort with the American Gas Association. Two 40 kW systems were built. One directly drives an alternator at 12,600 rpm to generate 420 Hz. The CRU had working fluid-lubricated fluid-film bearings. The other drove a 60 Hz generator at 3600 rpm through a gearbox. The CRU had working fluid-lubricated rolling contact bearings. The gearbox was also working fluid-lubricated. The working fluid in both cases was Dowtherm A. The total test time was about 700 hr.

The current 100 kW unit will use CP-25, i.e., toluene, in a supercritical cycle. The turbine will operate at 25,200 rpm driving a 3600 rpm 60 Hz generator through an oil-lubricated gearbox. The first 100 kW(e) unit is to be completed by December 1971. Performance estimates indicate that this unit will yield a 16% thermal efficiency when rejecting the waste heat from the cycle to a 250°F hot water heater, and a 22% thermal efficiency when producing 145°F hot water. In both cases the efficiency includes losses in a natural gas-fired boiler which is only 80% efficient. Further, the units have been designed to yield good efficiency over a broad range of power outputs; as much as a 30% efficiency might be obtained at the design point if a unit were designed expressly to yield a high thermal efficiency, and if a boiler efficiency of 90% could be obtained.

The cost of the development program for the 40 and 100 kW units has been about \$5,000,000.

Stratos Unit Built for MERDC, Ft. Belvoir, Virginia

Stratos was awarded a contract with Ft. Belvoir to design, build, and shakedown test two Rankine cycle power plant units by early 1971. The working fluid chosen was FC-75, a fluorocarbon. Specifications on these units are given in Table 1. Figures 1, 2, and 3 show the system and a section through the turbine-generator.

The two units were built but the shakedown tests were plagued with many problems.⁵ These included burnout of the boiler under starting transients and faulty operation of valves.

The contract with Stratos has been closed and the Stratos group has been disbanded. The amount spent was about \$400,000. Ft. Belvoir plans tentatively to carry out further development of the unit in-house.

Table 1. Design Specifications for Stratos Fluorocarbon Rankine Cycle Power Plant

Output	1.5 kW
Voltage	28 Vdc
Weight	145 lb
Volume	8 ft ³
Sound	Inaudible at 100 m
Fuel	CITE JP4 Diesel Artic diesel Combat gas
Temperature	-65 to 125°F
Altitude	SL to 8000 ft
Reliability	.95 for 24 hr/day for 1 yr
Life	3000 hr min, 10,000 hr

Thermoelectron

The program to develop small reciprocating engines operating on a Rankine cycle has been continued. The effort includes work for several different organizations including the Ford Motor Company, a group of gas companies and gas appliance manufacturers, EPA, and their original sponsor, the U.S. Army Mobility Equipment Research and Development Center at Ft. Belvoir. The total funding in this area has exceeded \$2,000,000.

For the past two years the program has been directed toward engines operating on Rankine cycles employing fluorocarbons, with a mixture of Trifluoroethanol and water (Fluorinol 85) as the principal choice.

Their current hardware work is concentrated on small reciprocating engines.⁶ One of these is a two-cylinder engine driving a two-cylinder compressor, both using Freon 22 as the working fluid. The engine operates on vapor from a Freon boiler in the Rankine cycle system and the compressor also operates on Freon 22 in a refrigeration cycle. The 6 hp unit would be used in air conditioning equipment for medium-sized installations. The second engine is a single cylinder, 5 hp engine with a 2.25 in. bore by

TURBINE POWER:	3275 Watts Gross
FAN POWER:	94 Watts
PUMP POWER:	517 Watts
BEARING LOSSES:	295 Watts
ACCESSORY POWER:	92 Watts
ALTERNATOR LOSSES:	627 Watts
NET TO SYSTEM	1650 Watts

Fig. 1. Schematic Diagram of the Stratos Fluorocarbon Rankine Cycle Power Plant. (Courtesy of Stratos Division Fairchild Industries, Inc.)

Fig. 2. Cutaway View of Stratos Turbo-Alternator-Pump Unit. (Courtesy of Stratos Division Fairchild Industries, Inc.)

1.5 kW dc
Multifuel
8 cubic feet
145 lb
Inaudible 100M

Fig. 3. General Arrangement of Stratos Fluorocarbon Rankine Cycle Power Plant. (Courtesy of Stratos Division Fairchild Industries, Inc.)

1.75 in. stroke running on Fluorinol 85. Both engines are commonly operated at 1800 rpm although they are capable of operation to at least 3600 rpm. In both instances they have a few hundred hours of testing on the basic engine model. This includes some early work with Monsanto CP-34, a hydrogen-carbon-sulfur compound, as the working fluid.

The bulk of their effort initially was concerned with improving the indicator diagrams through refinements in the valve gear design. The valve gear consists of two valves - one a spring-loaded valve controlling the flow through a port about half way up the cylinder with a conceptually complex but mechanically simple balance pressure arrangement designed to yield a compression pressure close to the boiler discharge pressure. This valve vents vapor to the main exhaust system and condenser. The intake valve is located in the cylinder head and is actuated by the piston when it is close to top center. (This, of course, entails fairly high impact forces because the piston is moving with a substantial velocity at the point it starts to open the valve.)

Thermoelectron engineers are concerned about corrosion or fluid stability problems in the Freon 22 system because they wish to run at as high a peak temperature as possible. As a consequence they have carried out extensive test programs using capsules in which they have operated fluids for periods of up to 3700 hr in glass capsules with a strip of the material to be used in the system. They have also operated two boilers for periods in excess of 2000 hr. One operated on Freon 22 at 405°F and the other on Monsanto CP-34 at a boiler discharge temperature of 550°F. These boilers are of a patented double-tube design in which water is employed as a buffer fluid between the hot gas side and the working fluid to avoid hot spots. These compatibility tests have entailed, in many instances, additions of lubricants to the working fluid to determine to what extent such additions might have adverse effects. They have found several lubricants that give them a compatible system. The lubricant is carried in the crankcase of the engine and is supplied with a pressure feed pump to the connecting rod and main bearings and by splash to the piston pin and cylinder walls. Some of this lubricant does, of course, get past the piston rings and into the working fluid, but it is removed from the working fluid vapor using a

simple screen separator, and is recirculated to the lubricant sump in the engine. The condenser temperature is 210°F.

Performance tests show that they are able to get a surprisingly high efficiency in conversion of the energy ideally available in the working fluid to shaft horsepower, i.e., 72%.

All of their tests with both the single and two-cylinder engines have been carried out with a shaft seal on the engine, and they do not plan to operate an engine-generator unit in which the generator would be hermetically sealed with the engine to avoid a shaft seal. However, they have carried out tests of an electrical insulation (an amine base varnish) that appears to be satisfactory for the windings of such a generator. They estimate that it would take about \$150,000 for the development of a generator, but they do not currently have plans to develop such a unit. They feel that the leakage through their shaft seal will amount to about one pint of working fluid plus lubricant in 8000 hr. (This figure has been obtained by extrapolation from tests of around 1000 hr.)

In addition to the work cited above, they have built, tested for 100 hr, and in July 1971 delivered to Ft. Belvoir a version of their 6 hp engine coupled to a 3 kW generator. The working fluid is 85 mol% trifluoroethanol and 15 mol% water plus a fluorinated lubricant. This unit has been designed for Army service, and is a cubical package roughly 30 in. on a side with an air-cooled condenser and a diesel fuel-fired boiler. An examination of the design for this unit disclosed that neither the boiler nor the condenser is at all suited to the undersea isotope power plant application, but the engine-generator unit would be suitable.

The mechanical design of the Thermoelectron unit appears to be sound with the possible exception of the valve operating mechanism. This entails the use of a hardened steel insert inlaid in the top of the piston. The hardened steel surface serves as a tappet to open the valve which admits steam to the cylinder. The writer examined some parts that had been operated for a few hundred hours and there was no evidence of damage from pounding. However, this might prove a problem in long term endurance tests, and Thermoelectron has given some consideration to making use of a more conventionally operated valve gear actuated with a cam-tappet-pushrod arrangement. The generator is a wound-rotor unit making use of an

electrical insulation that has been found to be compatible with the fluoro-carbon working fluid in the course of extensive operation of electric motor-driven refrigeration units.

Recently an advanced prototype 3 kW generator set was delivered to MERDC for preliminary evaluation. This system used F-85 as the working fluid and Krytox as the crankcase lubricant. The overall system dimensions are 28 1/2 in. x 28 1/2 in. x 31 1/2 in. The two cylinder expander (2.25 in. bore x 1.75 in. stroke) operates at 1800 rpm and produces about 6 hp. The expander shaft is connected through a rotary shaft seal to a 3 kW, 60 cycle, 120 volt alternator designed to operate at 1800 rpm. The TECO "buffer fluid" protected boiler design was used to ensure that a thermal decomposition of the thermally sensitive working fluid did not occur. Boiler outlet temperature is 550°F and condensing temperature about 200°F. A system schematic diagram presented in Fig. 4 indicates all the system components and their relation to one another.

The measured net efficiency of this system is 8.7% at the shaft. This efficiency includes all the losses associated with the boiler (78% efficient) and the auxiliary power requirements associated with the condenser fan, burner blower, and controls. (~400 watts)

One of the design goals for this system was to utilize a simple control system which would maintain the expander speed, boiler outlet temperature, and condensing pressure constant independent of load. This is accomplished by using three independent control functions taking place simultaneously as summarized below:

1. Expander Speed. Maintained constant at $1800 \pm 15\%$ by varying the throttle valve position as signaled by a speed sensor. This throttle valve is placed at the boiler outlet and varies the expander inlet pressure to match the power requirements.
2. Boiler Outlet Temperature. Remains at fixed level ($550 \pm 10^\circ\text{F}$) by varying the burner firing rate as controlled by a temperature sensor.
3. Condenser Pressure. Maintained constant (~ 30 psia) by cycling the condenser fan on and off as signaled by a pressure switch.

This relatively simple system has functioned reliably over several hundred hours of system operation. Also, this type of control system proved itself to be adaptable to a fully automatic startup procedure. System operation is initiated by turning a key — all functions required to start the system then take place automatically and power is being produced within about a minute from a cold start.

The generator has been successfully operated at temperatures as high as 125°F and as low as 0°F. Also, the multifuel capabilities of the system have been demonstrated by operating it with JP-4, No. 2 Diesel, and gasoline.

Thermoelectron has also discussed with GE at Valley Forge the possibility of developing a unit that could be used with either an isotope or a liquid fuel heat source. The Techtite group at Valley Forge is particularly interested in the application of these units to the propulsion of small research submarines — presumably for the commercial market.

Thermoelectron has designed a 110 hp V-4 power unit for installation in a motor vehicle. The details of the vehicle installation are currently being examined at the Ford Motor Company.

Thermoelectron is also designing a small turbine-generator unit to operate with the same working fluid and lubricant as employed in their engine generator units.

Westinghouse Astronuclear (Pittsburgh)

A small company-funded project was initiated in 1969 to develop a small engine-generator unit that employs a reworked Freon compressor from a 24,000 Btu/hr air conditioner. The compressor porting was modified so that it will operate as an engine on R-114 Freon at 400°F or CP-34 (Thiophene) at 500°F. The unit will operate at 3600 rpm to turn out 60 Hz current. The first unit was operated satisfactorily, but the project was dropped in part because of a shortage of funds and in part because other efforts to develop small power units were beginning to bear fruit.

Swenson Research Laboratory

Swenson has been unable to get further financial support for their 3.7 kVA steam turbine generator unit. They have done some further design

work, and would probably use a homopolar generator rather than a permanent magnet if they were to build another unit, thus avoiding the demagnetization problem they experienced under load-shorting conditions. They would also probably use a centrifugal pump on the turbine shaft with a jet pump to suppress cavitation in the centrifugal pump. There is no active development program at the time of writing, and none projected.

Navy Ship Engineering Center, Propulsion System Division

It is interesting to note that the Navy has quite a number of high speed steam turbine-generator units in service to produce 400 Hz power on aircraft carriers. These units operate at 12,000 rpm with air-to-water-cooled, wound rotors, and are rated at 600 kVA at 1000 V. The turbine inlet conditions are 1050 psia and 1000°F with a condenser pressure of 5 in. Hg and a steam flow rate of 6900 lb/hr at 600 kW(e). The units are produced by General Electric and employ 6 Rateau stages in the turbine. The first stage has a diameter of 18 in. and the subsequent stages a diameter of 16 in. The overall length is a little under 10 ft and the casing height and width are about 5 ft. The exciter is built into the unit.

The personnel responsible for this type of equipment have strongly advocated the development of hermetically sealed units with water- or steam-lubricated bearings in order to improve the reliability by reducing the number of auxiliaries. One step taken in this direction has been the design, construction, and operation of a titanium turbine to reduce corrosion and erosion problems. This unit has been operated with a corrosive steam supply with no corrosion whereas a unit built of conventional alloy steel operating in parallel with it shows corrosive attack.

Proposals from vendors indicate that a 400 Hz, 600 kVA, homopolar generator and steam turbine unit with water-lubricated bearings and a hermetically sealed casing could be procured for about \$500,000. Such a unit could be very compact — about 4 ft long and 28 in. in diameter.

Aerojet Mercury Vapor Turbine

The development program for the Snap-8 mercury vapor turbine was continued to attain the objective of 10,000 hr of operation. The program was then terminated in June 1970 and the group subsequently has been dispersed.

The system and component test times accumulated under the program are summarized in Table 2.

The total cost of the development program for the Snap-8 mercury vapor cycle system was over \$100,000,000.

Table 2. Snap-8 System* Component Test Hours - June 1970

Component	Total	Maximum for one Set of Components
Boilers	31,847	15,125
Turbine Alternators	15,717	12,442
Condensers	18,169	14,845
Mercury Pumps	30,442	12,270
NaK Pumps	56,493	10,363
Lube-Coolant Pumps	60,512	24,862
Electrical Components	37,030	20,646
Valves	100,885	
Alternators	37,573	18,094
Total Component Hours for Entire Program	415,316	

*Total test hours on the system were 15,717

Note: Above tests conducted at Aerojet-General, Azusa, California, and NASA-LRC, Cleveland, Ohio.

ORMAT Turbines, Ltd.

ORMAT has built a small turbine generator unit for a French cobalt 60 heat source. The French have assembled the system and operated it satisfactorily. No other information beyond that in Ref. 1 is available at ORNL.

BRAYTON CYCLE SYSTEMS

NASA Lewis Laboratory

A substantial effort has been under way for the past 10 years at the NASA Lewis Laboratory to develop a Brayton cycle system under their space power plant program. An extensive component test program has included

separate rigs for testing the compressor, the turbine, the generator, the gas-lubricated, tilting pad bearings, and the electrical control equipment as well as a large facility for testing the complete power plant package.

The turbine-generator-compressor units and the recuperators have been designed and built by AiResearch to NASA specifications and then installed and tested at NASA Lewis Laboratory.

A substantial amount of operating experience has been accumulated at NASA Lewis Laboratory with four different turbine-generator-compressor units. One complete power plant system has been operated for 2561 hr. Various component test systems have also been operated so that the total operating time on the four turbine-generator units that have been employed amounts to 9330 hr. Other major components have also been tested in component test rigs. The lubricating oil pump and inverter which supplies it with power has been operated for a total of 29,000 hr. The dc power supply units have been operated for a total of 25,000 hr of which 17,000 hr was accumulated with a single unit. The complete control system has been endurance tested for 4760 hr with many starts and stops and no forced outages.

NASA Lewis Laboratory initiated a program about two years ago to develop a 40 to 160 kW unit. A review of power plant requirements in spacecraft has led to a reduction in the design objective and, at the time of writing, they are planning on a 25 to 100 kW power output. Contracts have been placed with AiResearch for the design, fabrication, and delivery of turbine-generator sets and heat exchanger equipment by January 1974. The turbine-generator units are to be subjected to a set of shakedown tests at AiResearch. These units are being designed for 400 Hz rather than the 1200 Hz employed to the 15 kW unit described above.

The total cost of the program through FY 1971 has been about \$25,000,000.

AiResearch

In reviewing recent ORNL reports, AiResearch personnel noted that one might make use of a set of heat pipes similar to those employed for a thermoelectric module to drive a Brayton cycle similar to the unit they have built for NASA Lewis Laboratory.⁷ The upper ends of the heat pipes would be fitted with fins to provide ample heat transfer surface area,

and a manifold would serve to duct the air from the recuperator through these heater elements to the turbine. AiResearch estimates that this would make possible a unit that would operate with an overall thermal efficiency of 20% with a turbine inlet temperature of only 1000°F. These estimates are based on test data from the units that have been operated at NASA Lewis Laboratory under the Space Power Plant Program.

The principal characteristics of the system proposed by AiResearch are summarized in Table 3, and the effects of both turbine inlet temperature and compressor inlet temperature as estimated by AiResearch are shown in Fig. 5. It is striking to note in Fig. 5 that, in spite of its small size, the AiResearch unit would still give interesting performance with a turbine inlet temperature as low as 800°F.

A conceptual layout for a system that might be built for evaluation tests was worked out by AiResearch and is shown in Fig. 6. A major problem in the layout was provision for differential expansion between the massive heat block-shield assembly and the inlet and outlet manifolds for the heat exchangers on the heat pipes. All three would operate at different temperatures, but AiResearch feels their design would accommodate this.

The AiResearch turbine-generator-compressor contained in the Brayton Cycle demonstrator unit operating at the NASA Manned Spacecraft Center in Houston employs gas bearings built of overlapping foils. These appear to have worked out very nicely. A number of AiResearch machines in production use them. Most units are compressors driven by turbines running on air bled from the main turbojet engines in aircraft such as the Boeing 707. In one test they deliberately fed water to the foil bearings in their bearing test machine and all that happened was a drop in speed from 68,000 to 48,000 rpm.

AiResearch has not as yet built any Rankine cycle turbine-generator, although their interest in possibilities continues.

Solar Division, International Harvester

A 10 kW(e) Brayton cycle power unit is being developed under contract by Solar for the U.S. Army Mobility Equipment Research and Development Center at Ft. Belvoir, Virginia. Several hundred hours of successful operation were completed on the first units, and Solar was awarded a

Table 3. Characteristics of the Brayton Cycle System
Proposed by AiResearch for the NAVFAC Application

ALTERNATOR POWER OUTPUT, kW(e)	7.46
THERMAL POWER INPUT, kW(t)	30
CYCLE PERFORMANCE	
Gas Cycle Gross Overall Efficiency	0.249
Shaft Speed (N), rpm	48000
Recuperator Effectiveness, E_R	0.95
Pressure Loss Parameter, $\beta = r_t/r_c$	0.96
COMPONENT PERFORMANCE	
Compressor	
Compressor Mass Flow, lb/sec	0.930
Compressor Inlet Temperature (T_1), °F	70
Compressor Inlet Pressure (P_1), psia	47.6
Compressor Pressure Ratio (r_c)	1.64
Compressor Efficiency	0.7806
Compressor Diameter, in.	3.67
Turbine	
Turbine Inlet Temperature (T_b), °F	1000
Turbine Inlet Pressure (P_b), psia	76.9
Turbine Pressure Ratio (r_t)	1.57
Turbine Efficiency	0.89
Turbine Diameter, in.	4.18
Alternator	
Alternator Efficiency	0.92
Alternator Diameter	2.1

contract to build 22 prototype units. Seven of these have been delivered and are under test. Characteristics of these units are presented in Table 4.

Generator Development

The design and development of a high speed generator suited to the NAVFAC applications presents a more difficult task than the turbine. In view of this, developments at the generator manufacturers have also been reviewed with particular attention to suitability for high speeds with water lubricated bearings and stator windings either canned or exposed to steam.

INPUT THERMAL POWER = 30 KW,
 GAS MOLECULAR WEIGHT = 40 (XeHe)
 SHAFT SPEED, RPM = 48,000
 RECUPERATOR EFFECTIVENESS = 0.95
 COMPRESSOR SPECIFIC SPEED = 0.09
 ALTERNATOR EFFICIENCY = 0.92

Fig. 5. Effects of Turbine Inlet Temperature (TIT) and Compressor Inlet Temperature (CIT) on the Gross Electrical Output of a Brayton Cycle System Proposed by AiResearch for NAVFAC Applications. (Courtesy of AiResearch Manufacturing Company.)

Fig. 6. Brayton Cycle System Coupled to a Heat Pipe-Cooled Isotope Heat Source as Proposed by AiResearch. (Courtesy of AiResearch Manufacturing Company.)

Table 4. Characteristics of Solar Brayton Cycle Power Plant

Output Power	10 kW - sea level 125°F 10 kW - 8000 feet 95°F		
Weight	146 pounds (less Battery)		
Volume	8.1 ft ³		
Dimensions:	Length	29.75 inches	
	Width	21.00 inches	
	Height	22.38 inches	
Fuel Consumption (at rated load)	2.50 gal/hr diesel fuel (6.9 lb/gal) 2.85 gal/hr gasoline (6.1 lb/gal) 2.60 gal/hr JP-4 fuel (6.7 lb/gal)		
Fuel Types	Gasoline Aviation gasoline Jet fuel grades JP-4 and JP-5 Jet fuel - referee CITE fuel referee CITE fuel Fuel oil grade DF-1, DF-2, DF-A Marine diesel fuel		
Output Frequency	50 hertz 60 hertz 400 hertz		
Voltage Outputs	Volts	Hertz	Phase
	120	50-60	1-3
	208	50-60	3
	240	50-60	1
	120	400	1-3
	208	400	3
	240	400	1

Westinghouse

The Westinghouse development program on small, very light weight spray-oil cooled generator units for installation on gas turbine engines for Army tanks has continued. Qualification tests are nearing completion. A smaller, much higher speed unit was designed for use with an engine intended for an Air Force drone aircraft, but the program was never funded and no units have been built. The unit was designed to produce 4 kW of electricity and operate at 50,000 to 61,000 rpm. It would produce 28 V dc current and the windings would be insulated with ML varnish. The diameter of the unit

would be only 3 1/2 in. over the stator with a 4 1/2 in. length including the bearings but not including the projecting stub shaft. It was to be a 4-pole unit with a Hiperco 27 rotor and samarium cobalt permanent magnets.

The Westinghouse development effort on larger wound rotor units designed for operation at 8000 rpm with air cooling for military installations has been quite successful. Some of these units, coupled to an AiResearch gas turbine, were installed in the natural gas building in Chicago over eight years ago and have operated with essentially no trouble ever since. The characteristics of this unit are shown in Table 5, together with companion units designed for 120 and 240 kVA. All of these units have a wound rotor with a built-in exciter so that there are no brushes, and they have demonstrated a high reliability with little maintenance. A larger unit of this same general type is being designed for the Air Force to produce 4 MW at 5 kV(L-L). This unit will weigh less than 2600 lb and will be oil-cooled.

Discussions with A. E. King at Westinghouse indicate that they believe that this unit could be built to operate with the windings potted in plastic and with water-lubricated bearings so that it could be run as a hermetically sealed unit with the rotor cavity vented to the condenser. This would, of course, entail some design modifications and some development test work. However, the 4600 motor-pump units built in Britain for water feedwater and boiler circulating water installations in ships indicate that this is a reasonable course to follow. (Further information on these units is given in a later section.)

Table 5. Summary of Data for Three Typical Westinghouse Aircraft Type Generators with Air-Cooled Wound Rotors

Electrical output rating, kVA	312	240	120
Terminal Voltage	277/480	85/147	120/208
Efficiency, %	94	90	85
Length, in.	28	26	15
Diameter, in.	13.5	12	12
RPM	8400	8000	8000
Output frequency, Hz	420	400	400
Weight, lb	472	300	160

General Electric

General Electric at Erie has developed a new type of inductor-alternator in which the solid rotor has been simplified at the expense of some complication in the geometry of the stator windings.⁸ The simplified rotor makes it possible to obtain a much stronger rotor and hence much higher operating speeds. The first unit developed is designed for 10 kW at 0.8 P.F., 60/400 Hz at 93,500 rpm in a frame having an outside diameter of 6.5 in. A larger unit designed for 130 kW at 0.8 P.F., 60/400 Hz would operate at 47,000 rpm and have a frame outside diameter of only 12 in. Ten units of the 10 kW machine and converter have been built and tested. Three of these have accumulated over 1500 hr each of testing so far. Data for the two machines are presented in Table 6.

Table 6. Data for General Electric High Speed Homopolar Inductor Alternators

Electrical output rating, kVA	12.5	160
RPM	93,500	47,000
Number of poles	4	4
Frequency, Hz	3,120	1,570
Frame OD, in.	6.5	12
Length, in.	4.9	16.7

Both of these machines are designed for operation with ball bearings, but there appears to be no reason why they could not be designed with water-lubricated tilting pad or other hydrodynamic bearings, or hybrid bearings, and built in the form of sealed units.

These machines are designed for operation into a cycloconverter that converts the generator frequency to the output frequencies of 60 or 400 Hz. The output frequency is selected by use of a switch on the operator's panel. The generator is especially designed to provide the type of power necessary for the converter. For example, the output rating shown in Table 6 is the rating of the output of the converter whereas the generator has a much higher rating for proper operation with the cycloconverter.

British Central Electric Generating Board

The Central Electric Generating Board has found that major improvements can be effected in the reliability of the water pumps in their central stations by using water-lubricated bearings and allowing the stator windings and the rotor to operate flooded with water. This eliminates two major sources of trouble — the shaft seal and special provisions for the supply of lubricant for the bearings.⁹ They have over 500 of these pumps installed or on order and are extending their application from boiler recirculating duty to scavenging of condensate from high pressure feedwater heaters and other types of service. Some typical installations are given in Table 7. Individual pumps have accumulated as much as 40,000 hr of operation, and are continuing to give good service. It should be noted that this type of pump was originally developed in smaller versions for marine applications, particularly boiler feed pumps, and has established an excellent record for reliability in that service.

An obvious problem area is presented by the motor stator windings which operate in hot water. Table 8 shows permissible operating temperatures for the electrical insulation materials that they employ.

RELATIVE ADVANTAGES AND DISADVANTAGES OF BRAYTON AND RANKINE ORGANIC CYCLES

The AiResearch proposal raises anew the question as to whether a Brayton cycle ought to be employed for the Navy 2 to 10 kW(e) isotope power units. Some of the relative advantages and disadvantages of the two types of system are reviewed in this section.

Development Status

The Brayton cycle unit under development by NASA Lewis Laboratory has accumulated a total of 9300 hr of operation on the basic model with three different units having been employed in the course of the test program. The total program cost to date has been of the order of \$25,000,000. The Sundstrand total program cost has been of the order of \$6,500,000 and the total running time to date is 3000 hr. At least superficially, it would appear that the cost of the hardware for the organic Rankine cycle system inherently should be lower than that for the Brayton cycle system. A

Table 7. List of Glandless Pump Applications

Station*	Boiler Capacity, klb/h	Pumps per Boiler	Flow, Gal/min	Total Head, ft	Suction Pressure, lbf/in ² (g.)	Temp., °C	Nominal rev/min	Motor Rating, hp
Boiler circulating pumps (conventional stations): motor above pump								
High Marnham	1400	3/4	5700	161	2650	340	1470	250
Thorpe Marsh	3750	6	8100	161	2650	340	1470	550
Blythe 'B' (5&6)	1900	4	8050	142	2650	340	1470	550
Boiler circulating pumps (conventional stations): motor below pump								
Blyth 'B' (7&8)	2050	4	8800	140	2650	340	1470	475
Drakelow 'C'	2400	4	12900	136	2650	340	1470	600
West Burton	3450	4	13900	116	2650	340	1470	600
Fiddlers Ferry	3450	4	13900	116	2650	340	1470	600
Cottam	3450	4	11120	138	2650	340	1470	600
Fawley	3450	4	9650	130	2650	340	1470	500
Pembroke	3550	4	9650	130	2650	340	1470	500
Kingsnorth	3350	4	11700	167	2650	340	1470	750
Boiler circulating pumps (nuclear stations): motor above pump								
Bradwell	171	2†	1480	105	850	270	1470	70
	88	2†	680	67	250	195	2950	25
Berkeley	140	2†	750	96	400	220	2950	35
	65	2†	320	51	100	160	1470	10
Hinkley Point 'A'	310	2†	2000	178	700	255	1470	150
	173	2†	1200	85	250	195	2950	40
Boiler circulating pumps (nuclear stations): motor below pump								
Trawsfynydd	288	2†	2020	125	1000	280	2950	70
	155	2†	1230	108	350	215	2950	40
Sizewell 'A'	539	2†	2970	74	750	260	1470	120
	194	2†	1150	137	350	215	2950	90
Wylfa	1430†	2	950	75	850	270	1470	30
Boiler recirculating pumps (conventional stations): motor below pump								
Tilbury 'B'	2350	1	318	440	2650	340	2950	90
Eggborough	3350	2	318	440	2650	340	2950	90
Ironbridge	3350	2	318	440	2650	340	2950	90
Aberthaw 'B'	3350	2	397	440	2650	340	2950	100
Rugeley 'B'	3400	2	397	440	2650	340	2950	100

Some values are approximate or have been rounded-off for convenience of presentation.

*All 415 V except Kingsnorth which is 860 V.

†First listed h.p. boiler, second l.p. boiler.

†Once-through boiler, two pumps installed per start-up drum.

Table 8. Maximum Permissible Hot Spot Temperatures of Electrical Insulation Materials When Submerged in Water

Material	Temperature °C
Heat resisting p.v.c.	70
Polyethylene (high density)	60
Cross-linked polyethylene (high density)	80
Polypropylene	80

close examination of the two types of turbine-generator unit and of the heat exchanger equipment required tends to confirm this.

The estimated thermal efficiency of the AiResearch Brayton cycle system at the temperatures available with an isotope heat source is about 20% as compared to about 18% for the Sundstrand organic Rankine cycle system. It is quite evident that AiResearch has done an extremely elegant and highly refined job in order to get the remarkably high performance that they have obtained from their Brayton cycle system. Further, it seems unlikely that any appreciable improvement can be obtained over the system now under test at Lewis Laboratory. On the other hand, the organic Rankine cycle turbine-generator unit and related heat exchanger equipment is inherently much simpler and hence less costly. Further, the effort at Sundstrand has not required a highly refined design. Thus, further improvements in performance could be obtained with a modest investment in design and development work. This is a consequence of the inherent difference between the two systems; the net output and thermal efficiency of the Brayton cycle system are exceedingly sensitive to component efficiencies whereas the net output and overall thermal efficiency of the organic Rankine cycle are not.

Overspeed

The Brayton cycle unit inherently must operate at a design speed close to the upper limit permissible from the rotor dynamics standpoint, whereas the organic Rankine cycle turbine (in which the design speed is inherently much lower) can be operated at a turbine speed which is far below the limit

imposed by rotor dynamics considerations. This in turn means that the control system can be very much simplified with an organic Rankine cycle system if the generator output is rectified to yield dc power. If this approach is followed, the turbine generator speed could be allowed to float and the voltage could be controlled by regulating the field. The same sort of control system as employed in automotive alternators could be used. Thus, the control functions to be carried out for normal running conditions would be much simpler than for the Brayton cycle system. Further, if the unit is designed so that a large overspeed can be tolerated, a sudden loss in the electrical load will not endanger the unit. A loss of electrical load occurred with one of the NASA Lewis Laboratory units, and the bearings were damaged as a consequence of the run-away. As a matter of fact, in the Brayton cycle system as proposed, the combination of thermal inertia in the system and the inherent characteristics of the turbine-compressor-generator unit are such that complex control actions are required to prevent damage to the unit in the event of a sudden loss of electrical load.

Startup

The startup problems of the Brayton cycle unit appear to be more complex than those of a Rankine cycle system. A jacking gas supply must be provided to float the rotor in the bearings prior to an attempt to start, and a carefully phased sequence of operations must be employed to bring the system up to its normal operating conditions. The control functions involved in this startup procedure appear to be inherently much more complex than those required for the Rankine cycle systems of the type envisioned in ORNL-TM-2961 for isotope power units.¹⁰

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