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TECHNOLOGY OF NUCLEAR-BRAYTON SPACE POWER SYSTEMS

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ABSTRACT

The present technology of Brayton power systems is reviewed. The potential for even higher system efficiency at the 10 kWe level is assessed as well as the potential for comparable efficiency with an output of 1 or 2 kWe. System accommodation of isotope decay is briefly discussed.

The salient features are described for a Brayton power system based on this technology and employing the ZrH reactor. Reactor lives for this and competitive systems are compared. Growth capability with an advanced reactor is assessed. A concept for application of this technology to driving a gas-dynamic laser is described.

INTRODUCTION

The NASA Lewis Research Center has been conducting a Brayton-cycle power system technology program since 1963. At present, this program concentrates on two nuclear-Brayton space-power-system concepts; a 2-15 kWe Brayton system utilizing an isotope heat source and a 15-80 kWe Brayton system utilizing a reactor heat source. The 2-15 kWe system technology program which started in 1966 and the 15-80 kWe system technology program which started in 1971 have identical program goals of achieving high system efficiency over a range of powers, demonstrating the potential for long life (i.e., 5 to 10 years), and in general establishing "user" confidence in Brayton-cycle power systems. It is important to recognize that the Brayton-cycle technology derived from the NASA program is broadly applicable to undersea and terrestrial applications as well as space missions.

In concept, Brayton-cycle power conversion systems can provide NASA and the nation with a wide range of capabilities in space if coupled with nuclear heat sources. Brayton systems are suitable for use with either isotope or reactor heat sources. The high conversion efficiency of the Brayton systems results in both high power and low unit cost. In general, Brayton-system efficiency at its design point ranges from 20 to 30 percent, the particular value depending on the design conditions selected. These efficiencies are higher than for any competitive power conversion system and provide the following advantages.

First, of course, the high efficiency will result in more useful power for any given heat source. Alternatively, the quantity of heat required can be decreased, a factor of substantial importance in any cost competition of isotope power systems with solar power. Reactors for Brayton power systems can be both simple and compact. In contrast to a thermionic reactor, the fuel elements are simple in design and construction, a factor reducing not only reactor cost but also the risks associated with any technology or development program. A reactor for a Brayton power system can have a high ratio of fuel volume to core volume, a characteristic permitting the reactor to be compact and so to have a reactor shield of low weight. Alternatively for a reactor of a given size, the high fuel-volume fraction would provide a long reactor life within any given fuel-burnup limit, and particularly so if the low thermal input required by the Brayton system is taken into account.

The Brayton power conversion system itself has the potential for very long life, for one of our goals is to eliminate wearout processes within the system. In addition, the technology presently appears capable of spanning a very wide power range from perhaps 500-1000 watts of useful output up to 500-1000 kilowatts.

These goals, although ambitious, are very valuable ones if we can in fact achieve them. The principal purpose of the discussion that follows is to assess progress toward these goals. The status of Brayton technology and the performance achieved to this time will be reviewed; emphasis will be placed on the 2-15 kWe isotope-Brayton system. Extension of this technology to lower powers will be discussed. Predicted performance of the 15-80 kWe Brayton system for use with the ZrH reactor will be described. The potential for growth in performance of this system in combination with more advanced reactors will be briefly discussed, and a concept for adapting this technology to driving a gas-dynamic laser will be presented. Successful completion of this Brayton technology should substantially advance nuclear space power systems in their competition with solar power, not only in providing higher powers and independence of the space environment but also lower costs and longer lives.

2-15 kWe BRAYTON SYSTEM

Description

A schematic diagram of the system is shown in figure 1. A salient characteristic of the system is use of a recuperating heat exchanger having, in this case, an effectiveness of 0.94. Design temperatures are 1600°F at the turbine inlet and 80°F at the compressor inlet. For rejecting heat to space, two liquid-coolant loops are provided, one being redundant; in each loop, an electric motor drives a centrifugal pump for circulating the coolant through not only the waste-heat exchanger and the radiator but also through the alternator and cold plates on which electrical components are mounted.

The compressor, turbine, and alternator are all on a common shaft (figs. 2 and 3). For long life, there are no windings on the alternator's rotor, and the common rotor is supported by gas bearings. With this approach to design, no stationary element touches the rotor while it is running; no brushes, no seals, no bearings, or anything other than inert gas comes in contact with the rotor.

During operation at the design rotational speed of 36,000 rpm, the compressor and turbine each pass a constant volume flow of gas per unit time. For this reason, power output of the system can be readily changed merely by changing the gas pressure level. Both power output and the required heat input vary in nearly direct proportion to the gas pressure. In general, such variation in gas pressure in order to adjust power output is used either to adjust the maximum power output of the system as appropriate to a given application or perhaps to accommodate a variation in isotope heat output, a topic to be discussed later. Momentary variations in power demanded by the user are compensated for by deflection of power in excess of demand to a parasitic load; for the complete power conversion system shown in figure 4, the parasitic load is the flat panel at the top of the power conversion system. Power dissipated in the parasitic load is controlled by a multichannel, redundant speed control and multiple solid-state switches (SCRs).

Experience

The operating times accumulated on the complete power conversion system and its various components are summarized in Table I. The crucial Brayton rotating units now have accumulated a total operating time in excess of one year and one unit has run for over 8 months. We plan to continue these tests. More complete descriptions of this operating experience are presented in references 1 and 2.

The measured performance of this power conversion system is summarized in figure 5 (the data points) along with an analytical computation of the system performance (the solid line). For each operating point, compressor inlet temperature and turbine inlet temperature were maintained at their design values of 80 and 1600°F, respectively. Overall system efficiency (including an allowance for heat loss from an isotope heat source) varies from 0.15 at 2 kWe to 0.26 at 10.5 kWe; the corresponding ratiator areas in low orbit about the Earth are 200 and 75 ft^2/kWe, respectively.

Future Improvements

During the time that the power conversion system was being investigated, a number of the individual components were also investigated in some detail. As a consequence of these investigations, several improvements in these components have been demonstrated. For example, addition of a turning vane in the duct elbow at the compressor inlet was found to raise compressor efficiency by 0.01. Also, resetting the compressor-diffuser vanes by 3° raised compressor efficiency by 0.04. Because these two changes in the compressor have not yet been tested in combination, the improved system performance to be calculated below will assume only 0.04 increase from the reset stator vanes. A new duct shape at the turbine exit was found to improve flow diffusion there and to raise turbine efficiency by 0.01. The turbine investigations are described in more detail in reference 3, but the compressor tests are not yet reported.

A new stator is being built for the alternator in order to improve alternator cooling and to raise system output to 15 kWe. A larger core for the recuperator has been designed in order to raise its effectiveness from 0.94 to 0.95. In addition, changes in the engine's internal electrical system are being investigated and presently appear to provide a reduction of 400 watts in housekeeping power (ref. 1).

The combination of these changes would result in the performance shown in figure 6. At 3 kWe, overall efficiency would be 0.20. For powers of 10-15 kWe, overall efficiency would be 0.29, including an estimated heat loss from the isotope heat source; in this power range, radiator area would be reduced to 62 ft^2/kWe.

Increasing turbine inlet temperature would, of course, further improve system performance. Under the Multi-Hundred Watt (MHW) Radioisotope Thermoelectric Generator (RTG) program, isotope capsules are being developed for operation with capsule-surface temperature of 2000°F and to provide thermoelectric hot-junction temperature of 1800°F. So evaluation of comparable Brayton system performance at this temperature seems appropriate. The calculated performance for the turbine inlet temperature of 1800°F is shown in figure 7 for the improved system discussed above. At 4 kWe, overall efficiency would be 0.24. For powers of 10-15 kWe, overall efficiency would be 0.31-0.32 and radiator area 58 ft^2/kWe.

VERY LOW POWERS

The excellent performance and successful attainment of our design goals for the 2-15 kWe Brayton system have led us to investigate the applicability of this technology to even lower power levels. Inasmuch as the 2-15 kWe Brayton system is basically a 15 kWe system operated far off its design point at very low powers, its performance necessarily deteriorates at the 2 kWe level. For this reason, our study to this time for these low powers has focused on Brayton systems specifically designed for outputs in the range of 500-2000 We. Although these design studies are not yet complete, enough has been done to reveal some of the system's potential in this power range.

One of the chief questions for these very low powers concerns the efficiencies of the very small compressors and turbines required. Figures 8 and 9 show, respectively, compressors and turbines tested in order to answer this question; the measured efficiencies are shown in figure 10 (refs. 4 and 5). Although, as we expected, some performance penalty is associated with such small components, the drop in efficiency is not really serious. On the basis of these data, compressor and turbine efficiencies of 0.75 and 0.85, respectively, were selected as appropriate to the power range of 500-2000 We.

The isotope heat source was based on MHW technology; accordingly, turbine inlet temperature was specified to be 1800°F. Recuperator effectiveness was taken to be 0.925, and loss pressure ratio 0.92 for all the heat exchangers. For the selected compressor inlet temperature of 80°F, the resulting cycle efficiency (ratio of compressor and turbine net shaft power to heat input to the gas) is then 0.37. A computer program (ref. 6) estimated the design and off-design characteristics of a 2.4-kW generator. Windage losses of the generator were taken from reference 7, and the power loss from flow through shaft seals was assumed to be 5 percent. Because of the importance of internally consumed parasitic power in such a small system, the working fluid rather than a pumped liquid coolant was passed through the waste-heat radiator. The parasitic powers required by the gas bearings and the control system are not yet well defined, but their sum was estimated to range from 200-400 watts.

The resulting efficiencies for such a low-power Brayton power conversion system are presented in figure 11, the shaded band corresponding to the range of parasitic power discussed above. The performance is summarized below.

Heat input, kWt	4	8
Efficiency	.20-.25	.25-.28
Power output We	800 - 1000	2000 - 2200

Advances in technology such as this can markedly affect the competitive position of isotope power supplies relative to solar power systems. In particular, if the cost of Cm-244 can be reduced to $200 a thermal watt, then isotope costs from such a highly efficient Brayton system would be only $700,000 to $1,000,000 a kWe, a value well below the cost of solar systems. Substantial incentive thus exists to evolve the technology of both Cm-244 and small Brayton systems such as this.

Just as for the 2-15 kWe Brayton system, a single power conversion system could very likely encompass this entire power range by properly matching the gas inventory, or pressure, to the power required. Modest variations in heat input resulting from isotope decay can also be accommodated by varying gas pressure. For example, a power conversion system designed for 2 kWe but used in an application requiring only 1 kWe could be initially filled with gas to the 2-kWe level. Accordingly, the initial loading of isotope could also be appropriate to 2 kWe. As the isotope decays to half its initial power (18 years for Cm-244), gas pressure within the system could also be reduced, thereby keeping heat demanded by the Brayton system matched to the heat produced by the isotope heat source. During the early phases of the mission, electric power would be produced in excess of the nominal demand; this excess power could either be radiated to space or, if the mission could use the power, other power needs could be supplied by this extra power.

REACTOR-BRAYTON SYSTEMS

A Brayton power conversion system is presently being designed for use with the ZrH reactor at a reactor outlet temperature of 1200°F. The design characteristics of this power system are described in reference 8 and the off-design performance in reference 9. Estimated performance for the power conversion system in figure 12 shows that efficiency and radiator area per kilowatt are practically constant over the power range from 40-80 kWe. With the increasing importance of parasitics such as pumping power at low system output, efficiency declines to 0.13 at 15 kWe. For an output of 25 kWe, about 160 kWt are required. The influence of these high efficiencies on reactor life is shown in figure 13 for the 295-element so-called Reference Reactor. For a thermal power below 200 kWt, reactor life appears to exceed 10 years for a reactor outlet temperature of 1200°F. For a less efficient system such as a thermoelectric system, the impact of the demand for thermal power has a detrimental effect on reactor life. Consider, for example, producing 25 kWe with an overall efficiency of 0.04; about 600 kWt are required. The resulting reactor life is 6 years at 1200°F and this could be extended to about 7 years by dropping reactor outlet temperature to 1100°F. This comparison displays the crucial impact that efficiency of the power conversion system can have on reactor life. Additionally, of course, the higher efficiency also extends the range of power demands that the power conversion system might satisfy. In particular, the Brayton system being designed at this time could produce 120 kWe from the 600-kWt rating of the reactor; two power conversion systems operating in parallel would be used.

This same Brayton power conversion system is being designed to operate at turbine inlet temperatures up to 1600°F just as for the 2-15 kWe system; the corresponding reactor outlet temperature is taken to be 1700°F. In addition, the present status of basic technology indicates that such Brayton systems can reasonably be used with reactor outlet temperature of 2200°F, although of course the system would require some redesign for these higher temperatures. System performance corresponding to the operating temperatures from 1200-2200°F is given in figure 14 and is further summarized in the following table.

Reactor outlet temperature, °F	1200	1700	2200
Maximum kWe	120	450	500
Unshielded weight lb/kWe	210	90	70
Radiator area, ft^2/kWe	80	25	10
No. of Power Conversion Systems for max. kWe	2	5	5

Thus, this Brayton system can provide a wide range of capabilities. In combination with a 600-kWt ZrH reactor, one or two Brayton systems can span the power range from 15-120 kWe. With a higher-temperature reactor, considerable growth is possible with a single design of the Brayton system. Consider, for example, that a 120-kWe power system using multiple Brayton systems and the ZrH reactor was installed in a long-lived space laboratory. The required radiator area for such a power system is approximately 10,000 square feet. At the time that the ZrH reactor was worn out, it could be replaced by a reactor capable of higher power, higher temperature, and longer life. By use of the same 10,000-square-foot radiator previously used for 120 kWe, 400 kWe could now be produced. The same Brayton power conversion systems previously used could continue in service; five would be needed in order to produce the full 400 kWe.

A new Brayton system at the reactor outlet temperature of 2200°F would also provide a valuable range of capabilities. In part, its specific weight would be low enough and its life long enough that it is a promising candidate for electric propulsion. The life capabilities of the Brayton system should also result in a variety of applications requiring auxiliary power. Unless reactor fuel temperature by itself is a serious barrier to achieving long life, the combination of reactor and Brayton system should also have adequate life for a variety of long-life applications for auxiliary power. Thus, the Brayton technology can span a very wide range of capabilities covering, first, powers from 15-120 kWe with the ZrH reactor and, later, a variety of applications for auxiliary purposes and electric propulsion.

POSSIBLE APPLICATION TO DRIVING LASERS

Two types of continuously operating gas lasers are the electric-discharge laser and the gas-dynamic laser. The electric-discharge laser requires a supply of electric power for the electric discharge, a compressor to circulate the gas, and a power source to drive the compressor. Very simply, the reactor-Brayton system is potentially a long-lived efficient system that can provide electric power for both the electric discharge and for driving the compressor. The compressor could be driven by an electric motor, and the rotor for both the motor and compressor could be supported on gas bearings in the same manner as the main rotating units in all the Brayton systems discussed herein.

A concept for incorporating a gas-dynamic laser into a Brayton power system is shown in figure 15. Gas from a nuclear reactor (or a heat exchanger supplied with a reactor coolant) is heated to the pressure and temperature required by the laser. After passing first through a supersonic nozzle, the laser and then a supersonic diffuser, the still-hot gas passes through a turbine and other components of a conventional Brayton power system. The Brayton power conversion system performs two functions, viz., it provides (1) the compressed gas required by the laser and (2) electric power for auxiliaries used in combination with the laser.

The results of cycle calculations in figure 16 show performance that might possibly be achieved. Inasmuch as so much about the laser itself is highly uncertain at this time, a range of laser efficiency (herein the ratio of beam output to inlet enthalpy) from 0.5 to 5 percent is shown. For these particular calculations, shaft power was assumed equal to laser-output power. Although actual electric power output would only be about 75 percent of shaft power, the 25 percent discrepancy is probably small in relation to the other uncertainties in such a preliminary, exploratory calculation. For a maximum gas temperature of 2500°F, theoretical radiator area varies from 15-50 ft^2/kW and overall efficiency from 5-30 percent, depending principally on laser efficiency.

CONCLUDING REMARKS

The conclusion recapitulates the beginning. Brayton nuclear power systems can provide NASA and the nation with a wide range of capabilities while using either isotope or reactor heat sources. At the 10-kWe level, a Brayton power conversion system has achieved an overall efficiency of 0.26, and over a year of operation has accumulated on its main rotating component. On the basis of already demonstrated constituent technology, an overall efficiency of 0.30 appears readily attainable at this power level. Design studies of a much smaller system indicate that with 5 kW of thermal input at 1800°F, a Brayton power conversion system can achieve efficiencies in the range of 0.22-0.26. Such systems using Cm-244 should be lower in cost than solar systems.

A reactor-Brayton system is presently being designed for use with the ZrH reactor at 1200°F, and it will be equally suitable for use with a more advanced reactor at 1700°F when the reactor becomes available. This single power-conversion-system design will span the power range from 15-450 kWe. Its high efficiency can be exploited either to extend reactor life or to increase maximum electric power output. With reactor outlet temperature of about 2200°F, the Brayton basic technology is appropriate to a variety of high-performance long-lived applications requiring either auxiliary power or electric propulsion. The principal questions concerning system life depend on the life of the reactor itself, even at 2200°F. But, in comparison with competitive power systems, the Brayton system offers the best chance for a successful reactor because of its low demand for heat, the high fuel-volume fraction that is possible, the simple reactor construction, the tolerance of fuel swelling, and even the comparatively low reactor-fuel temperature.

If gas-dynamic lasers are practical for long-time use in space, an adapted Brayton system will be suitable for providing the power and gas compression required by the laser.

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TABLE I. - BRAYTON ENDURANCE TESTS - OCTOBER 15, 1971

COMPONENT	TOTAL HOURS, ALL UNITS	MAXIMUM HOURS, SINGLE UNIT
Rotating Unit	9544	5968
Heat Exchangers	8291	5730
Pump and Inverter	27700	17010
Electric Subsystem	7951	5390
Gas Subsystem	3841	2561
Power Conversion System	2561	2561

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BRAYTON CYCLE SPACE POWER SYSTEM

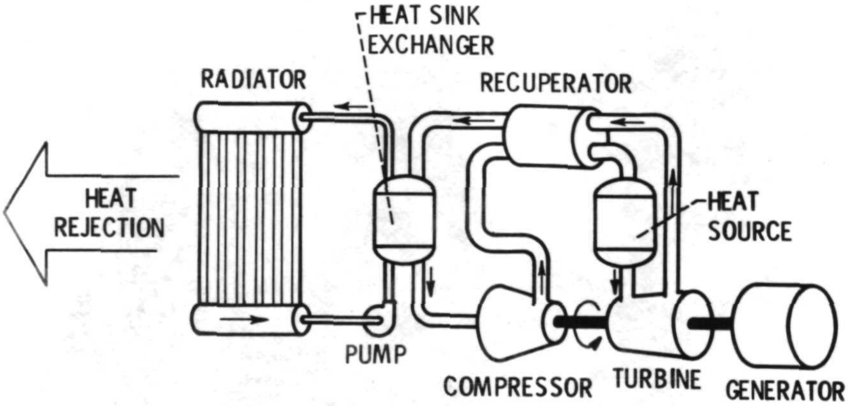

Figure 1

BRU SCHEMATIC

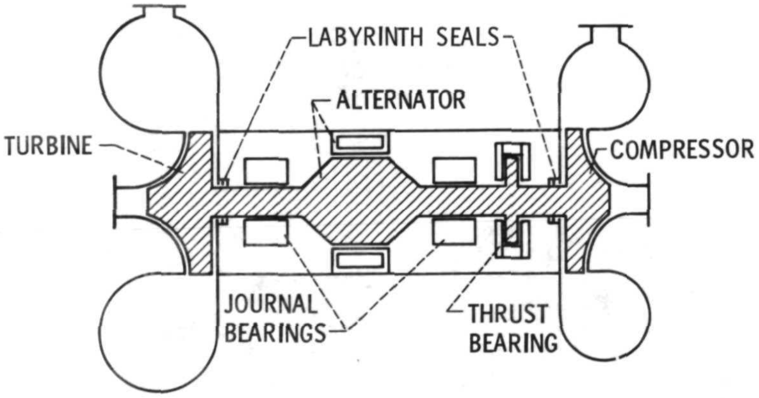

Figure 2

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BRAYTON ROTATING UNIT

CS-49701

Figure 3

BRAYTON POWER SYSTEM

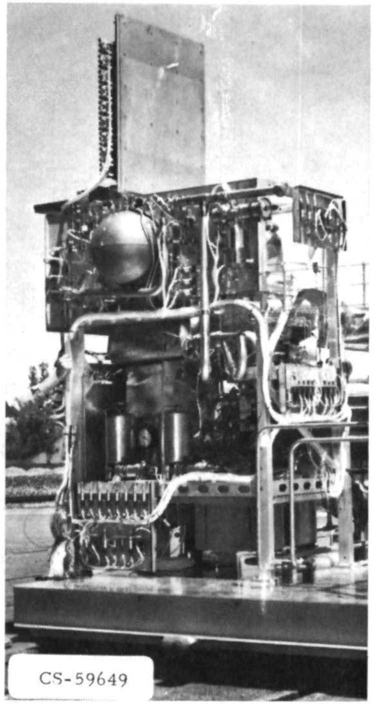

Figure 4

COMPRESSORS FOR SIZE EFFECT STUDY

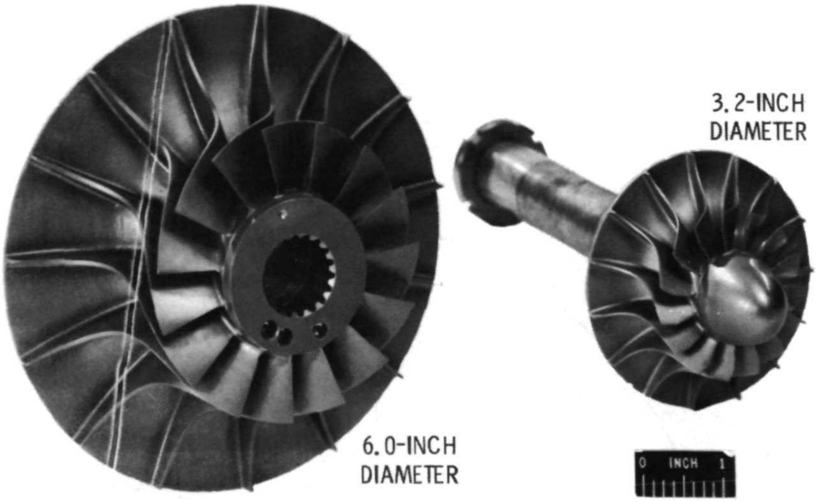

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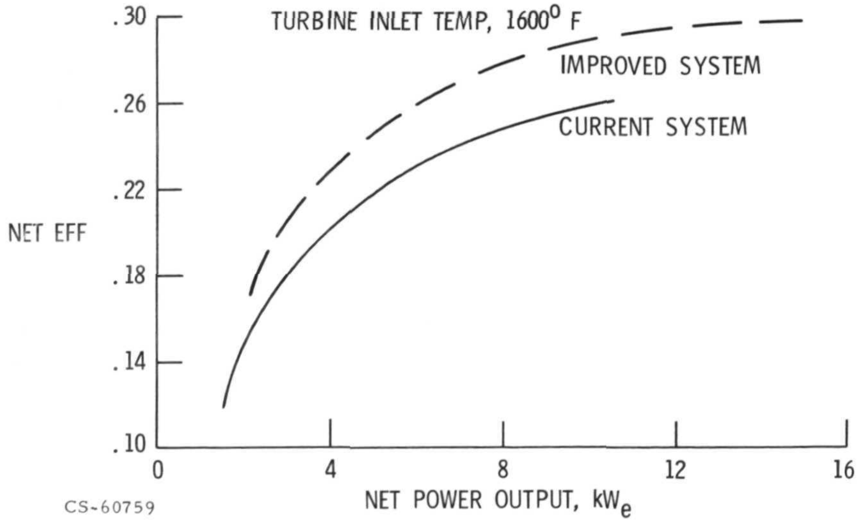
Figure 5

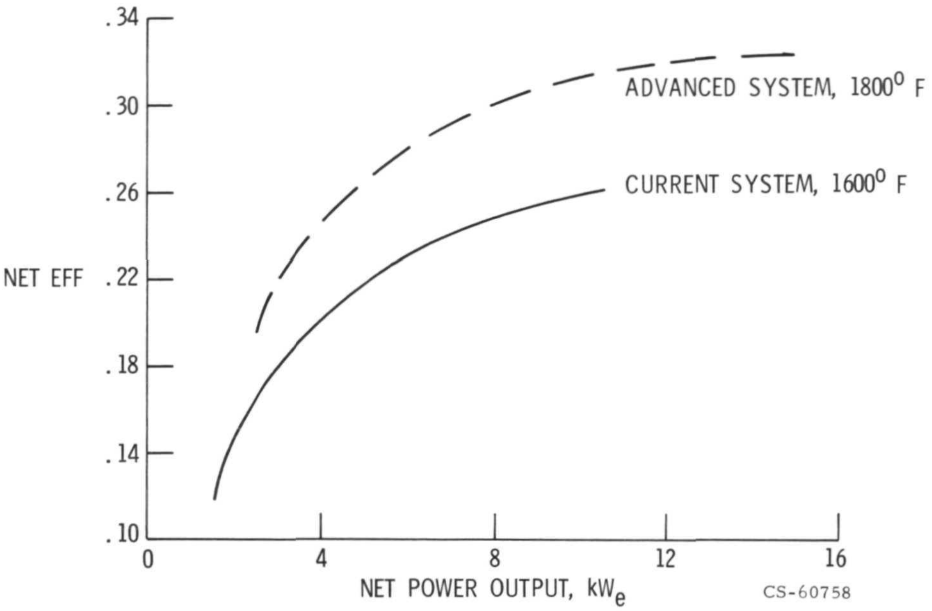
IMPROVED–SYSTEM PERFORMANCE



CS-60759

Figure 6

IMPACT OF HIGHER TEMPERATURE



CS-60758

Figure 7

EFFICIENCY OF CURRENT BRAYTON SYSTEM

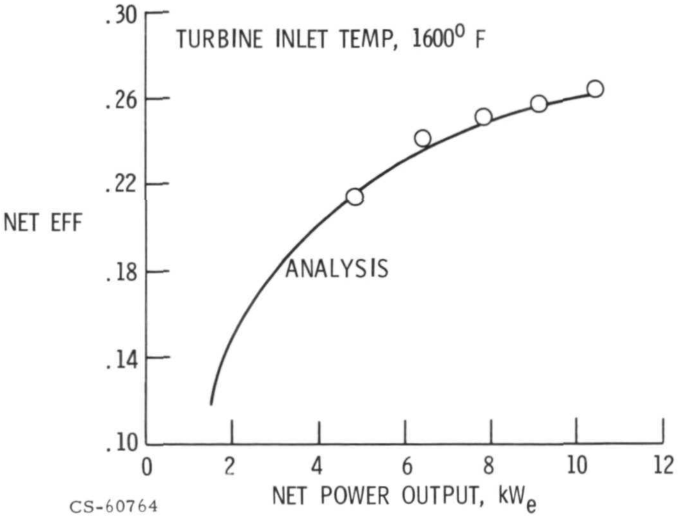


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Figure 8

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TURBINES FOR SIZE EFFECT STUDY

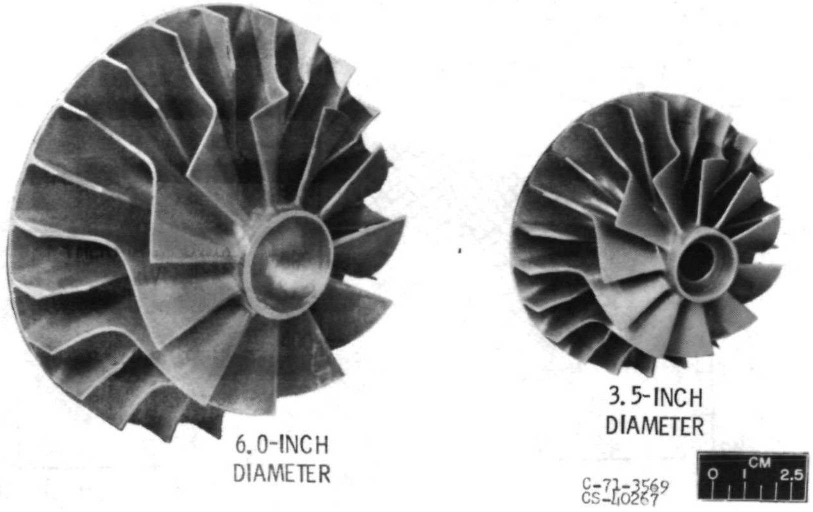


Figure 9

PERFORMANCE OF SMALL COMPRESSORS AND TURBINES

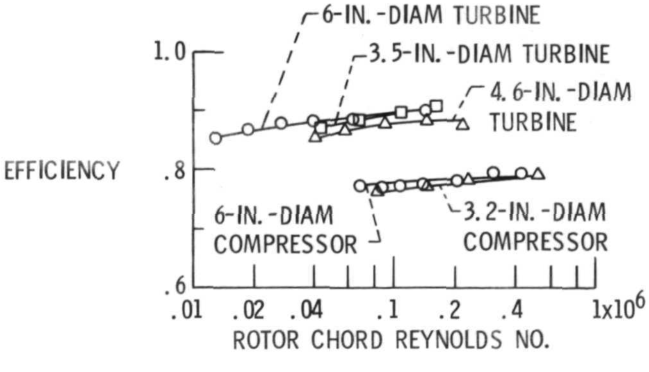
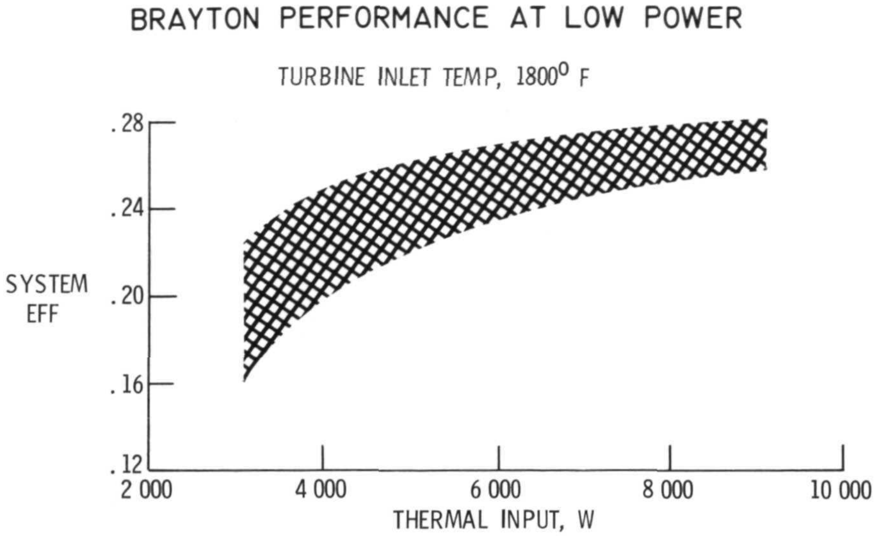


Figure 10

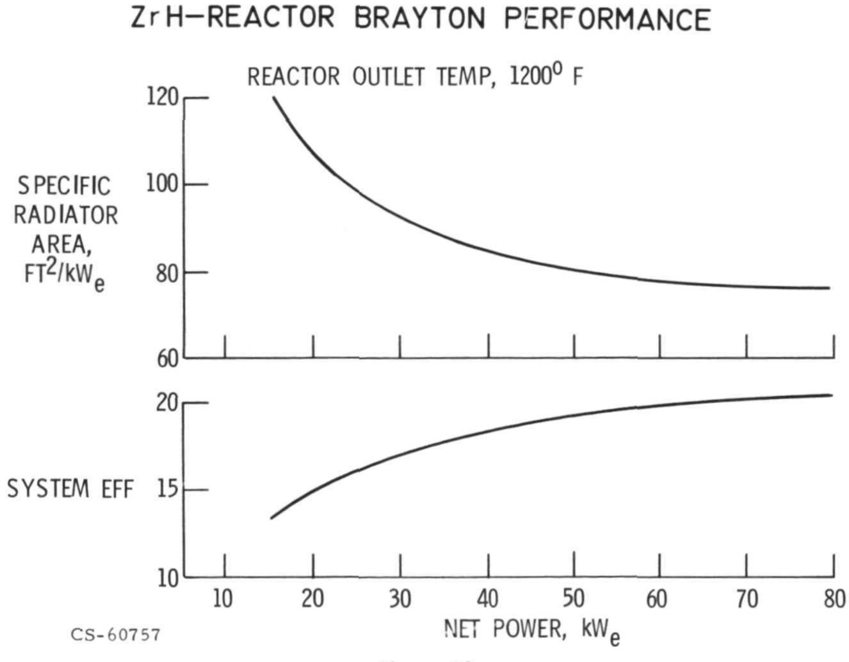
CS-60762


BRAYTON PERFORMANCE AT LOW POWER

TURBINE INLET TEMP, 1800° F

CS-60756

Figure 11


ZrH–REACTOR BRAYTON PERFORMANCE

REACTOR OUTLET TEMP, 1200° F

CS-60757

Figure 12

LIFE AND POWER OF 295 ZrH REACTOR

SOURCE: ATOMICS INTERNATIONAL

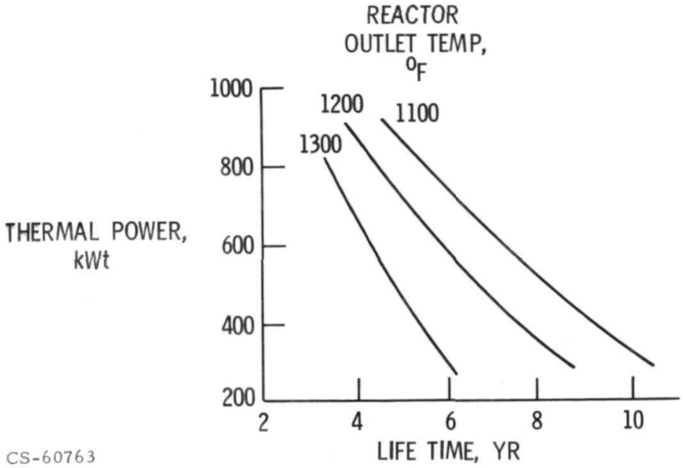


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Figure 13

REACTOR–BRAYTON PERFORMANCE AT HIGHER TEMPERATURE

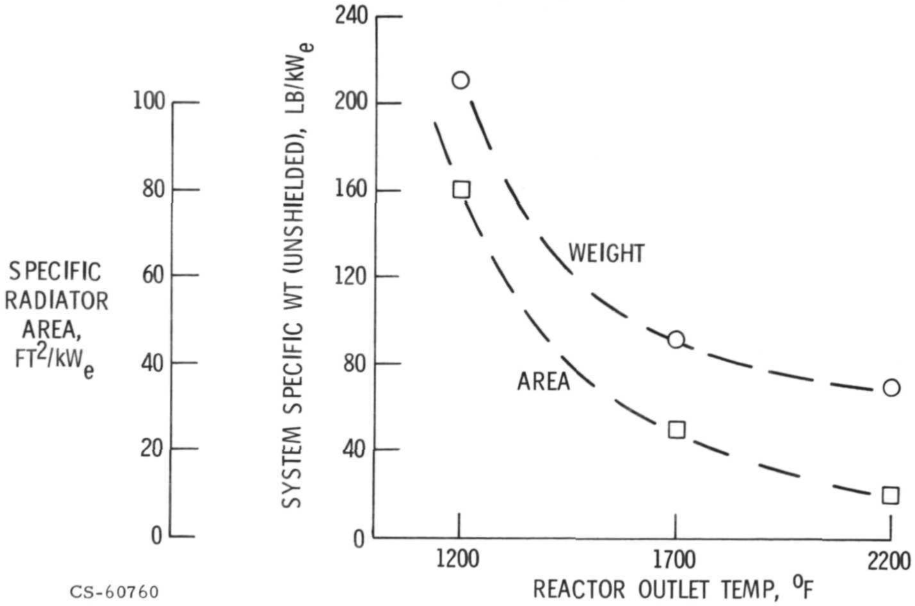

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Figure 14

CONCEPT FOR A LASER-BRAYTON POWER SYSTEM

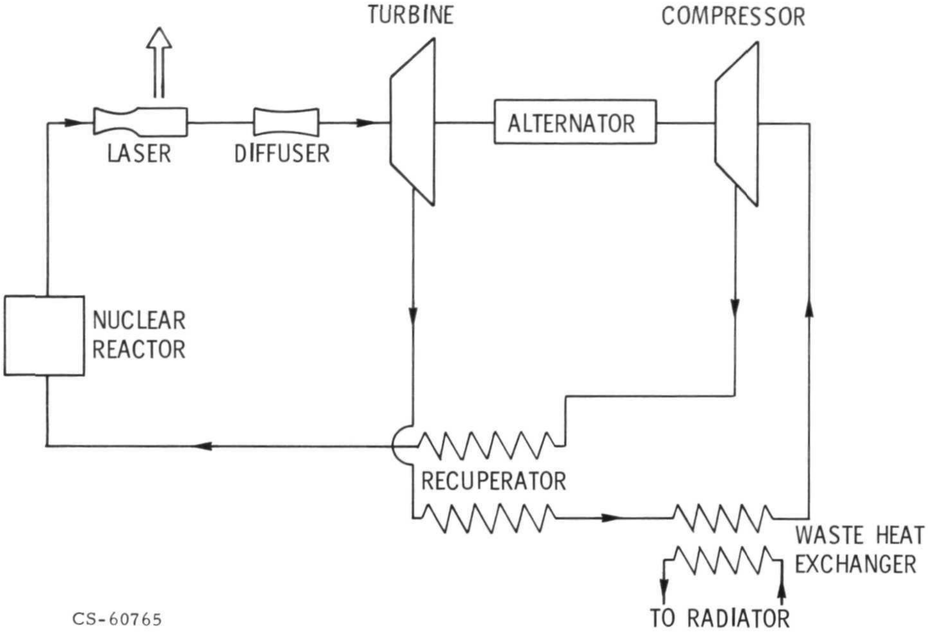

Figure 15

THEORETICAL PERFORMANCE OF A LASER-BRAYTON SYSTEM

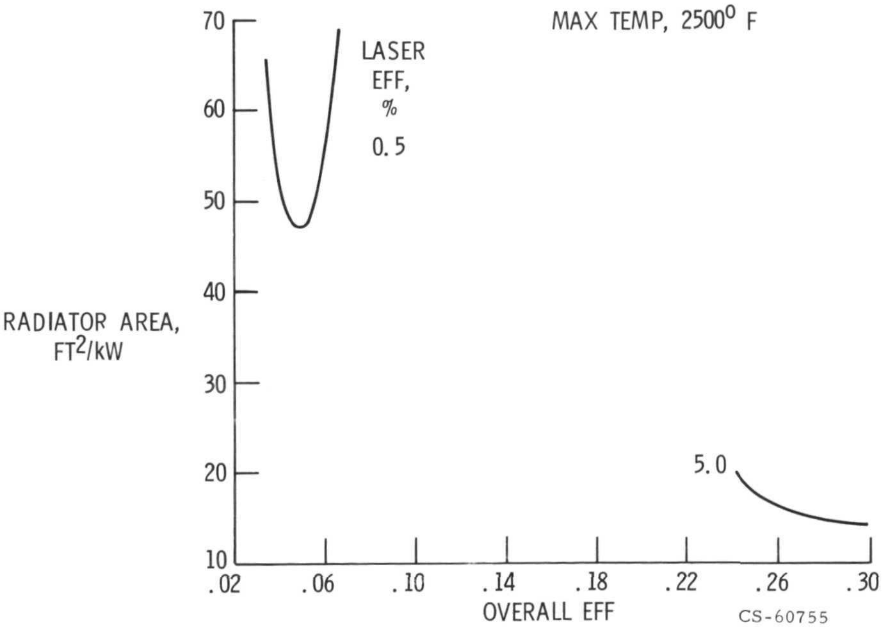

Figure 16