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By Daniel T. Bernatowicz

Prepared for the Symposium on Solar Dynamics
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NASA SOLAR BRAYTON CYCLE STUDIES

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In 1963 the Lewis Research Center undertook a program in Brayton cycle technology. It is hoped it will ultimately culminate in the development of a solar Brayton cycle system. The mission of most interest as an early application of the Brayton cycle is the manned space station, primarily, the large one in which 20 to 30 kw would be required. The modular approach appeared best with respect to packaging in the launch vehicle, as well as improved reliability by means of redundancy.

This paper describes the attractive features of the Brayton cycle and the reference cycle and discusses some of the compromises, the sensitivity of the system to some of the assumptions that were made, and the NASA program at this time.

Attractive Features of the Brayton Cycle

Table I is a list of features in which the Brayton cycle system can be expected to have an advantage over other power systems. If a very high purity, inert gas is used as the working fluid, the likelihood of material compatibility or corrosion problems is reduced. The Brayton cycle gives more freedom in selecting the cycle temperature ratio to achieve high cycle efficiency than the Rankine cycle, in which the pressure-temperature relation of the boiling fluid places some restriction on cycle temperature ratio and efficiency.

The Brayton cycle should be easier to start than the Rankine cycle because there will be no problem caused by the working fluid condensing and accumulating in undesired portions of the system. Restarting a Rankine cycle in space appears to be very difficult, whereas the restart of the Brayton cycle should not be much more difficult than the initial start.

Once undertaken, the development of a Brayton cycle system should proceed quickly and with little slippage. The absence of two-phase flow in zero-g eliminates an entire problem area and makes ground tests of the system more significant. Testing with the noncorrosive working fluid should proceed with fewer test rig problems, less down time during testing, and less expensive test equipment. Also, there is considerable experience with Brayton cycles for ground applications and turbojet engines that can be drawn upon for the space application.

An inherent potential exists for high reliability for long-term operation, primarily because there are relatively few modes of wear-out

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failures, while errosion, corrosion, and cavitation in the Rankine cycle and mechanical complexity and seal wear in the Stirling engine require considerable long-term testing for qualification. Reliability for the Brayton cycle could be established with fewer long-term tests and more concurrent short-term tests.

The Brayton cycle has a flexibility that could be important. The turbomachinery could be used without change in systems with different power outputs by adjusting the pressure level.

The Brayton cycle also possesses some obvious disadvantages. It requires a large radiator, especially when compared with the Rankine cycle, and the cycle efficiency and radiator area are very sensitive to component performance. The NASA technology program is intended to establish the level of component performance in order to determine whether these disadvantages will outweigh the advantages.

The ground rules (table II) for the Lewis Brayton cycle systems Studies were that only fixed geometry (rigid, one-piece) collectors that can fit in Saturn launch vehicles, separate turbines to drive the alternator and compressor, and only gas-filled radiators be considered. The one-piece collector was selected to avoid the uncertainties associated with erecting collapsible collectors in space. The split-turbine configuration was selected, primarily, to permit the use of a low-speed, 400 cps alternator and to separate alternator and compressor problems. A liquid-filled cooling loop to the radiator was not considered in these studies, but will be evaluated at a later date.

The studies indicate that a Brayton cycle system with a 30-ft-diameter collector (for the 33 ft Saturn V vehicle) could yield about 8 kwe in a 300-mile orbit or 12.5 kwe in a 20,000-mile orbit. A 20-ft collector (for the 21.6 ft Saturn B vehicle) could yield about 3.5 kwe in a 300-mile orbit and 5.5 kwe in a 20,000-mile orbit. The 8-kwe system with a 30-ft collector in a 300-mile orbit is of primary interest at this time.

Reference System

A schematic diagram of the reference, or target, cycle is shown in figure 1. Argon is the working fluid, lithium fluoride is the heat storage material, and the turbine inlet temperature is 1950° R. The compressor runs at about 38,000 rpm and the alternator at 12,000 rpm.

Assumed design cycle conditions and component performance are listed in table III. The loss pressure ratio of 0.85, the ratio of turbine pressure ratio to compressor pressure ratio, is equivalent to a 15 percent pressure drop through the system.

The results of the studies are summarized in table IV. A collector-absorber efficiency of 0.75 and a collector specific weight of 0.6 lb/sq ft were assumed. The system specific weight was not significantly different for the two orbits - 260 lb/kw at 300 miles and 275 lb/kw at 20,000 miles. The output powers of 8 and 5.5 are net powers after allowance for control power and bearing and other losses. The allowance was 1.4 for the 8 kw system and 0.9 kw in the 5.5 kw system.

Figure 2 shows an arrangement that might be practical for the 30-ft collector and 8-kw power system. The view at the upper left shows the stowed configuration, in which the collector is stowed inside the cylindrical radiator. Several of these systems could be stacked in the launch vehicle, then swung away from the vehicle, and the collectors deployed on telescoping struts. The overall dimensions of the 8-kw system, when stowed, can be about 31 ft in diameter and about 5 ft high.

Comparison with Other Systems

Table V shows the results of some studies made at Lewis, comparing several power systems for a large space station. The Rankine cycle system was an 18-kwe system with a single furlable collector supplying heat to three modified Sunflower rotating units. The modification assumed was an increase in turbine power to drive the present permanent-magnet alternator at its limit of 7 kw. This could be accomplished by increasing the arc of admission in the first two turbine stages and increasing the blade height in the third. The collector-absorber efficiency was assumed to be 0.565 and the collector specific weight to be 0.26 lb/sq ft. Allowance of 3 kw for control and pumping powers resulted in a net of 18 kw from the three units and a system specific weight of 180 lb/kw. The collector area for this Rankine cycle system is much higher than for the other dynamic systems shown because of the poorer cycle efficiency and the poorer efficiency of the furlable petal collector. A rigid collector was not used because the output of less than 5 kw for a 30-ft rigid collector and a modified Sunflower rotating unit was judged to be too low to be of interest.

The Stirling cycle system was composed of a 30-ft rigid collector and three Stirling engines of the same size that Allison has been working on. Each engine furnished 4 kw of shaft power with an efficiency of 30 percent. The net output from the three engines, after subtracting generator losses, control power, and pumping power was 8 kw. The system specific weight was 230 lb/kw. The high radiator area shown could be reduced to about that for the Brayton cycle, perhaps without a severe weight penalty, by increasing fin effectiveness.

The solar cell system weights were based on an output of 8 watts/ft^2 and an array weight of 1.4 lb/sq ft. For storage, silver-cadmium batteries with a depth of discharge of 20 percent for the low orbit and 80 percent for the high orbit were assumed.

The results of these studies indicate that the dynamic systems offer a substantial weight advantage over solar cells for the 300-mile orbit. For the 20,000-mile orbit, the advantage is not as marked. However, there is no obvious choice that can be made from among the dynamic systems. Although this Rankine cycle system is lighter, the large collector, even though it is furlable, may present a difficult stowage problem. These studies showed that the Brayton cycle radiator does not present a packaging problem if the system is stowed as shown in figure 2 and that the other systems do not possess an overriding weight advantage. These results, together with the previously discussed advantages the Brayton cycle offers, indicate that a technology program to firmly establish component performance is appropriate now.

System Compromises and Sensitivity

Figure 3 shows the effect of gas molecular weight on the ratio of heat-transfer coefficient to fractional pressure drop (in arbitrary units), which is an indicator of heat exchanger performance. Clearly, a low molecular weight is desirable to reduce the size of heat exchanger components. However, as the molecular weight is reduced, the number of compressor and turbine stages required increases. Argon was selected after consideration of the compromise between heat exchanger performance and number of turbomachinery stages.

Heat exchanger performance also improves with increasing gas pressure, as shown in figure 4. However, the compressor diameter, as seen in figure 5, decreases with pressure; and for low powers and high pressures, the compressor size may be small enough to affect its efficiency adversely. A compressor inlet pressure of 6 psia was selected for the 8-kw system.

Figure 6 shows the effect of cycle temperature ratio (ratio of compressor inlet temperature to turbine inlet temperature) on cycle efficiency and radiator area. A cycle temperature ratio of 0.275, which is lower than that for minimum radiator area, was selected because a substantial improvement in efficiency resulted with only a minor increase in radiator area.

The approach taken in studying the sensitivity of the system to component performance was to calculate the change in cycle efficiency with collector area and radiator area fixed. In this way, one could see how strongly the power output was affected by changes in component performance, while the major dimensions of the system were unchanged. It was found that with this constraint, the change in optimum cycle pressure ratio was minor over the range of variables considered. Therefore, changes in component performance could be accommodated without major changes in the turbomachinery as well as overall dimensions.

Figures 7 to 9 show the effect of compressor and turbine efficiency, recuperator effectiveness, and pressure loss ratio on cycle efficiency. A change of one point (0.01) in compressor or turbine efficiency or in pressure loss ratio results in a change of one point in cycle efficiency, or a change in power output of 4 percent. Recuperator effectiveness has a weaker influence; a change of five points in effectiveness is required to change the cycle efficiency by one point.

Figure 10 shows the effect of gas heat-transfer coefficient in the radiator on cycle efficiency when the collector and radiator areas are fixed. With heat-transfer coefficients below 5 Btu/(hr)(sq ft)(^{o}R), the value for the reference system, the efficiency drops quickly. A coefficient of 5 should be attainable with simple tubes. If the heat-transfer coefficient can be raised to about 15, perhaps by internal finning, the cycle efficiency or power output can be raised by about 10 percent.

The average sink temperature for a cylindrical radiator with its axis pointed at the sun was computed for a 300-mile orbit and is shown in figure 11. Although the maximum sink temperature calculated was only 365° R, a value of 400° R was taken for the system studies to allow for uncertainties in the albedo and the presence of the rest of the power system and vehicle. Figure 12 shows that the cycle efficiency or power changes 6 to 8 percent for a 50° R change in sink temperature near 400° R.

NASA Brayton Cycle Technology Program

The present NASA program in Brayton cycle technology is outlined in figure 13. Small radial-flow and axial-flow compressors and turbines will be tested. AiResearch has a contract to design, fabricate, and check out radial-flow gas generator components. They will deliver next spring a research compressor and a research turbine on conventional bearings, and a few months later a combined compressor-turbine package on gas bearings. Performance testing of these units will be done at Lewis. A similar approach is planned for the axial-flow gas generator and turboalternator.

There are two contracts to design the large fixed geometry collector. Electro-Optical Systems (EOS) is considering an electro-formed nickel design, and Thompson-Ramo-Wooldridge (TRW), a stretch-formed aluminum design. The contractors are studying and evaluating analytical techniques for calculating the stresses and the response of the collector to the environment in the launch vehicle, including vibratory and varying g-loads. Presently, the studies indicate that under reversing loads there is a difficult stress problem where the collector is joined to the supporting torus.

EOS is also experimentally investigating means of improving their master by polishing. TRW, in their program to build a 5-ft collector for the Langley Research Center, will inspect the mirror after each stage of processing to determine where and how the inaccuracies arise during fabrication.

TRW also has a contract to study absorber-heat storage designs. They are also conducting compatibility tests of lithium fluoride with ten selected structural materials. These samples will be cycled from 1500° to 1850° F for about 2500 hr.

A recuperator will be designed, built, and checked out by a contractor, and its performance will be tested at Lewis.

Presently, radiator designs are being evaluated at Lewis with a consultant helping to evaluate internal finning.

During this technology phase, system studies will be conducted at Lewis in the areas of system optimization, control and start-up techniques, off design performance, and vehicle integration.

Conclusion

The system studies made to date indicate that an 8-kw Brayton cycle system using a rigid 30-ft collector would be at least competitive with other solar dynamic power systems and could be conveniently stowed in the launch vehicle if the assumed component performance is realistic. Because of the attractive features of an inert gas Brayton cycle system and because there appear to be no overriding disadvantages, NASA has undertaken a 2-year technology program in this area. At the end of the technology program, an evaluation of the system can be made with considerable confidence, and it would be decided then whether a system development is justified. If a system development is undertaken, it is felt that it should be able to move rapidly and without much slippage because of considerable past experience. It is hoped that the turbomachinery developed will find extensive application, not only as part of the 8-kw solar system, but also in systems at other power levels and with other energy sources.

TABLE I. - ADVANTAGES OF CLOSED BRAYTON CYCLE POWER GENERATION SYSTEM

(1) Inert gas working fluid
(2) Possibility of high cycle efficiencies
(3) Relative ease of start and restart
(4) Simpler development problems:
    (a) Absence of zero-g boiling and condensing problems
    (b) Noncorrosive working fluid
(5) Extensive experience in component design
(6) Inherent reliability for long term operation
(7) Flexibility in application

TABLE II. - SYSTEM ASSUMPTIONS

(1) Fixed geometry collector:
    (a) 30 ft diameter
        8 kwe net power in 300 nautical mile orbit
        12.5 kwe net power in 20,000 nautical mile orbit
    (b) 20 ft diameter
        3.5 kwe net power in 300 nautical mile orbit
        5.5 kwe net power in 20,000 nautical mile orbit
(2) Split-turbine configuration
(3) Gas-filled radiator

TABLE III. - DESIGN CONDITIONS AND ASSUMPTIONS

Turbine-inlet temperature (LiF thermal storage), ^{o}R	1950
Equivalent sink temperature, ^{o}R	400
Compressor efficiency	0.80
Compressor drive turbine efficiency	0.83
Alternator drive turbine efficiency	0.86
Alternator efficiency	0.90
Loss pressure ratio, r_t/r_c	0.85
Recuperator effectiveness	0.85
Radiator surface emissivity	0.86
Radiator gas heat-transfer coefficient, Btu/(hr)(sq ft)(^{o}R)	5
Cycle temperature ratio	0.275
Compressor pressure ratio	2.3
Compressor inlet pressure, psia	6.0
Working fluid	Argon

TABLE IV. - SOLAR BRAYTON CYCLE POWER SYSTEM STUDY

TURBINE INLET TEMPERATURE, - 1950° R;

FIXED GEOMETRY COLLECTOR, η_{c-a} = 0.75

	300-MILE ORBIT		20,000-MILE ORBIT	
	SIZE	WEIGHT, lb	SIZE	WEIGHT, lb
SOLAR COLLECTOR	30 ft diam.	420	20 ft diam.	185
POWER LEVEL	8.0 kwe	---	5.5 kwe	---
RADIATOR	485 sq ft	650	335 sq ft	425
ABSORBER	-----------	405	-----------	460
OTHER	-----------	610	-----------	450
TOTAL	-----------	2085	-----------	1520
SPECIFIC wt, lb/kwe	-----------	260	-----------	275

TABLE V. - SOLAR POWER SYSTEM COMPARISON

	Rankine	Brayton	Stirling	Solar cell
SPECIFIC WT., lb/kw (300 miles)	180	260	230	640
SPECIFIC WT., lb/kw (20,000 miles)	-----------	275	-----------	322
COLLECTOR SIZE, ft^2/kwe (300 miles)	190 (PETAL)	89 (RIGID)	89 (RIGID)	274
RADIATOR AREA, ft^2/kwe	26	61	95	---
MEAN RADIATOR TEMP., $^{\circ}$R	1000	875	590	---
MIN. RADIATOR TEMP., $^{\circ}$R	750	536	580	---

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SCHEMATIC DIAGRAM OF SOLAR BRAYTON CYCLE SYSTEM

ARGON WORKING FLUID

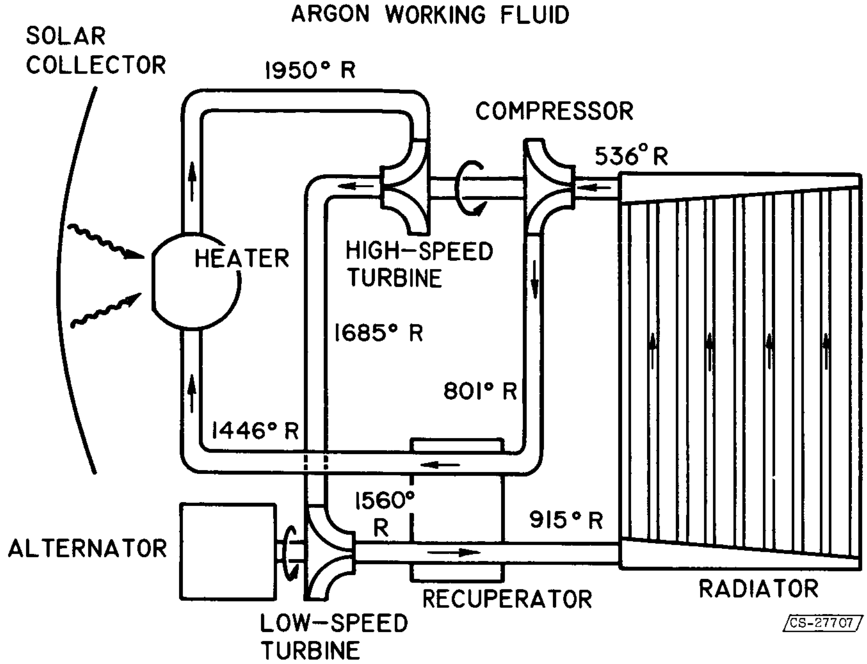

Figure 1

SOLAR BRAYTON CYCLE POWER SYSTEM

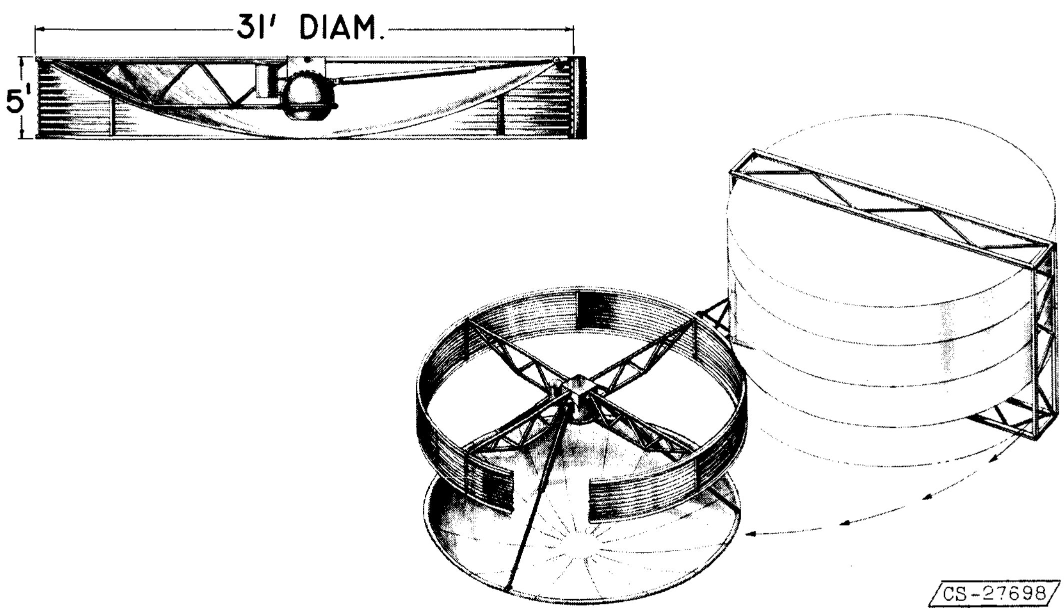

Figure 2

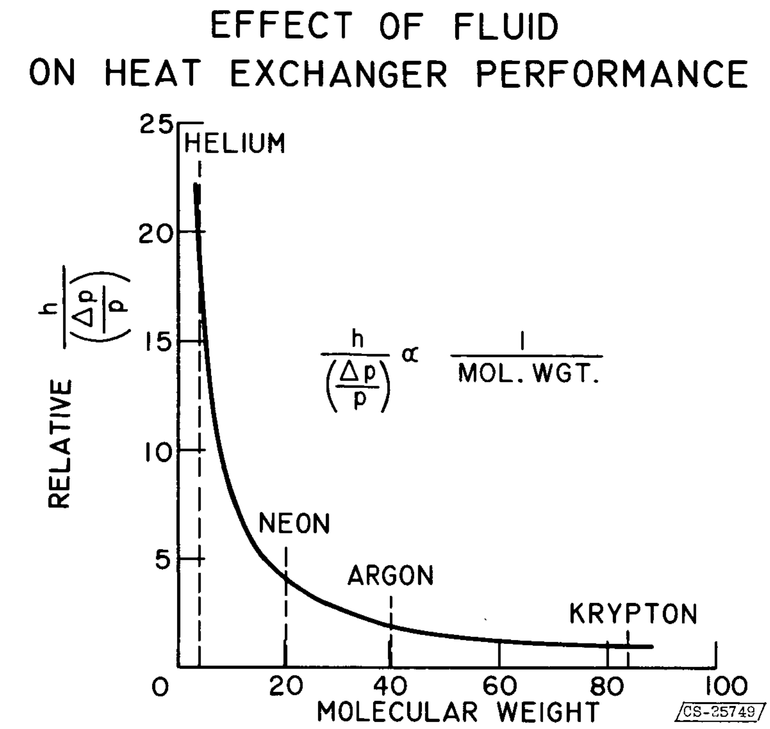

Figure 3

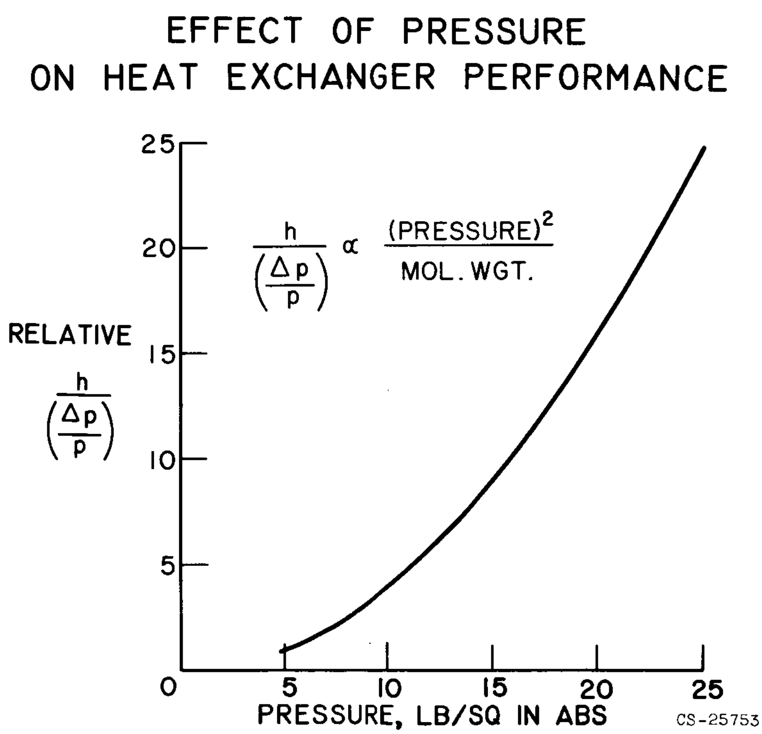

Figure 4

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EFFECT OF COMPRESSOR INLET PRESSURE ON COMPRESSOR DIAMETER

(GENERATOR OUTPUT = 9 KW)

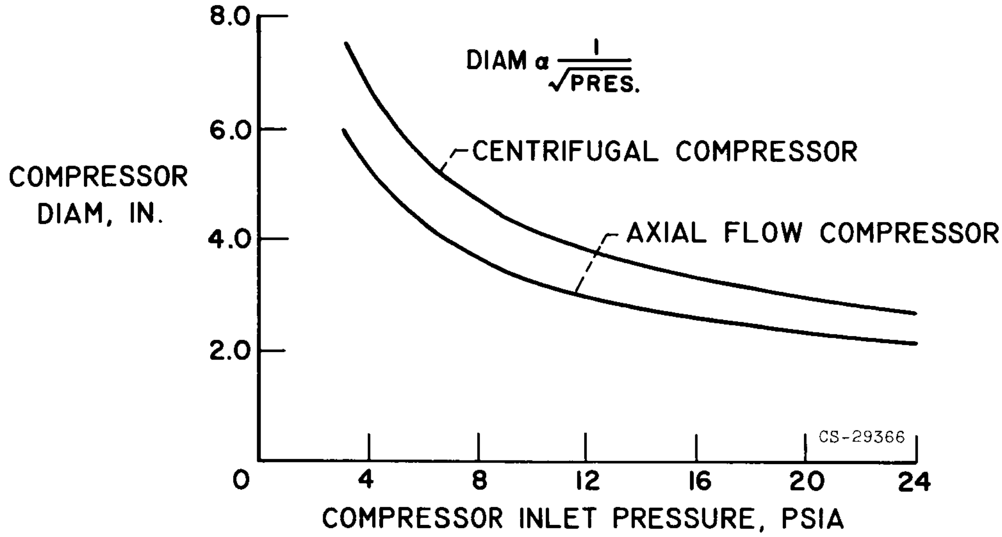

Figure 5

EFFECT OF CYCLE TEMPERATURE RATIO ON CYCLE EFFICIENCY AND PRIME RADIATOR AREA

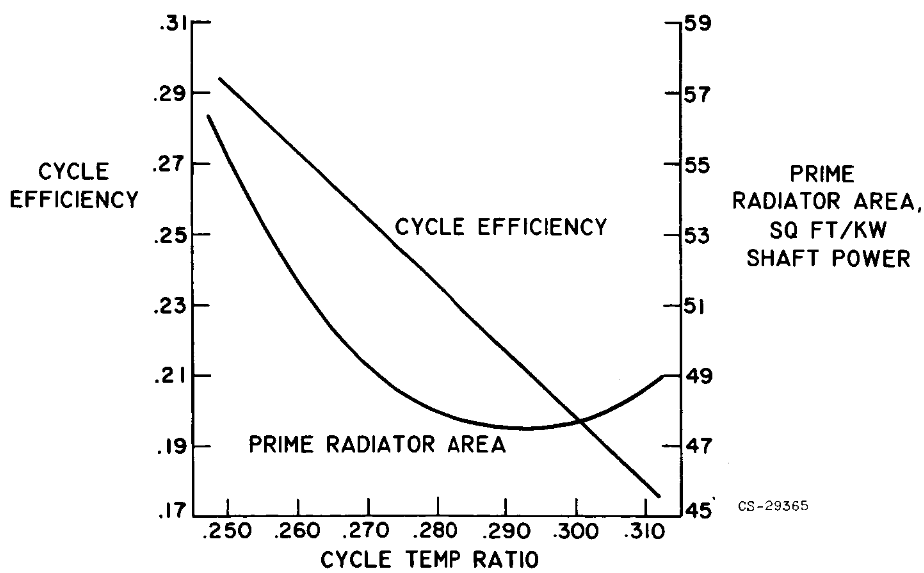

Figure 6

EFFECT OF TURBOMACHINERY EFFICIENCIES ON CYCLE EFFICIENCY WITH CONSTANT COLLECTOR AREA AND PRIME RADIATOR AREA

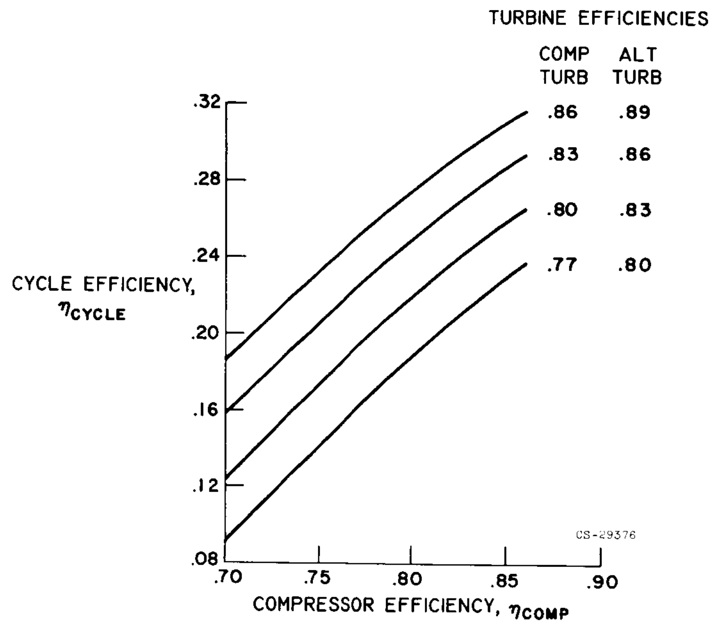

Figure 7

EFFECT OF RECUPERATOR EFFECTIVENESS ON CYCLE EFFICIENCY WITH CONSTANT COLLECTOR AREA AND PRIME RADIATOR AREA

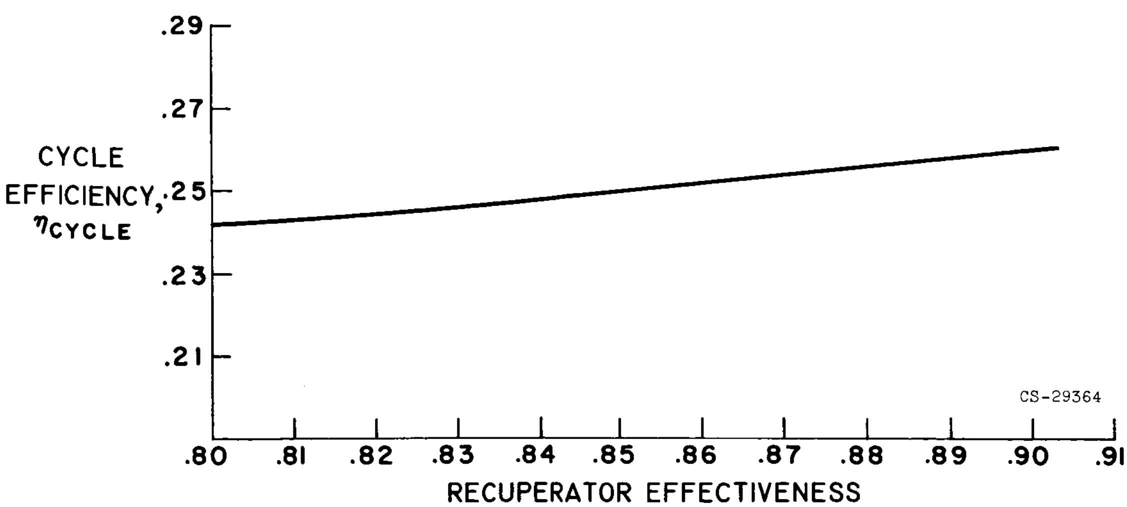

Figure 8

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EFFECT OF PRESSURE LOSS RATIO ON CYCLE EFFICIENCY WITH CONSTANT COLLECTOR AREA AND PRIME RADIATOR AREA

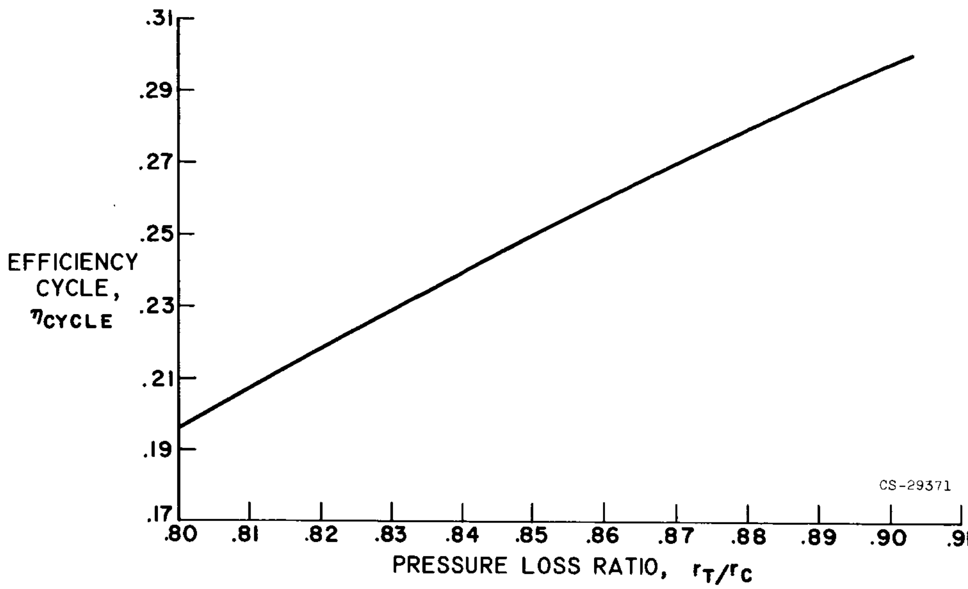

Figure 9

EFFECT OF GAS HEAT TRANSFER COEFFICIENT ON CYCLE EFFICIENCY WITH CONSTANT COLLECTOR AREA AND PRIME RADIATOR AREA

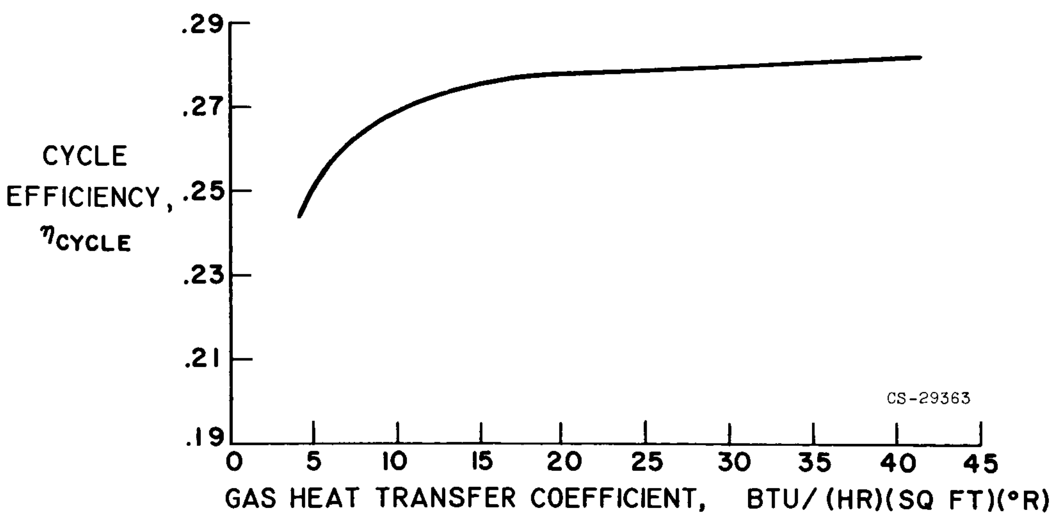

Figure 10

VARIATION OF AVERAGE EQUIVALENT SINK OF A CYLINDRICAL RADIATOR IN A 300 MILE EARTH ORBIT

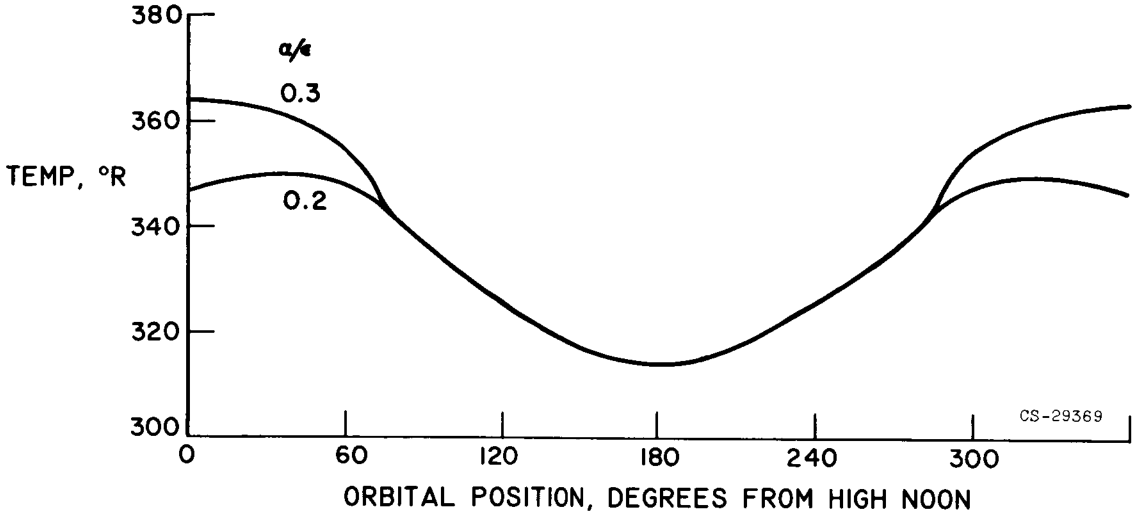

Figure 11

EFFECT OF EQUIVALENT SINK TEMPERATURE ON CYCLE EFFICIENCY WITH CONSTANT COLLECTOR AREA AND PRIME RADIATOR AREA

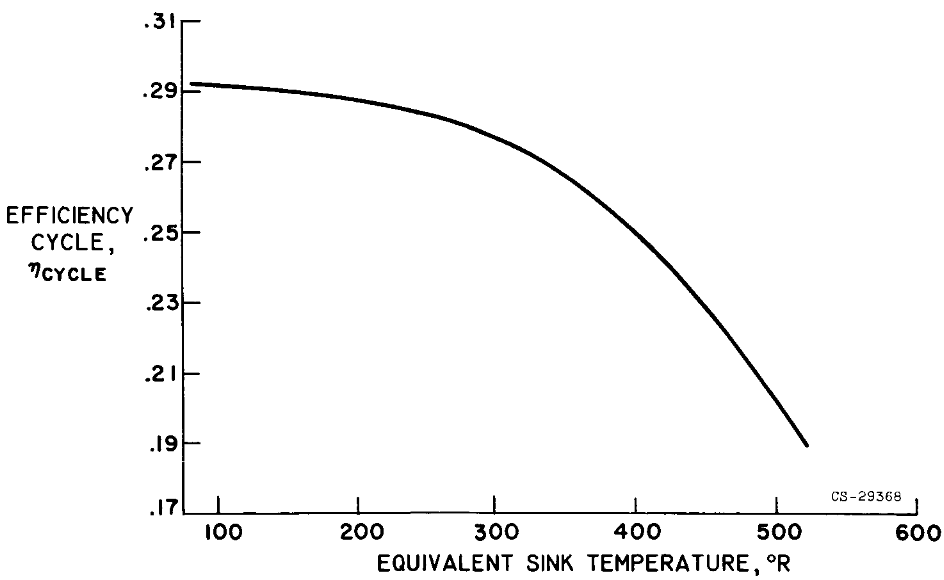

Figure 12

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SOLAR BRAYTON CYCLE TECHNOLOGY PROGRAM

I - SMALL TURBOMACHINERY PERFORMANCE	
A - RADIAL-FLOW GAS GENERATOR	- DESIGN AND FABRICATION - CONTRACT (AIRESEARCH) PERFORMANCE STUDY - NASA LEWIS
B - AXIAL-FLOW GAS GENERATOR	- DESIGN AND FABRICATION - CONTRACT PERFORMANCE STUDY - NASA LEWIS
C - TURBO-ALTERNATOR	- DESIGN AND FABRICATION - CONTRACT PERFORMANCE STUDY - NASA LEWIS
II - LARGE FIXED GEOMETRY COLLECTOR	
A - ELECTROFORMED NICKEL	- DESIGN STUDY - CONTRACT (EOS)
B - STRETCH-FORMED ALUMINUM	- DESIGN STUDY - CONTRACT (TRW)
III - ABSORBER	- DESIGN STUDY (TRW)
IV - RECUPERATOR	- DESIGN STUDY AND FABRICATION - CONTRACT PERFORMANCE TEST - NASA LEWIS
V - RADIATOR	- DESIGN STUDY - NASA LEWIS CONTRACT
VI - SYSTEM STUDIES	- SYSTEM OPTIMIZATION CONTROL AND START-UP OFF DESIGN PERFORMANCE VEHICLE INTEGRATION } NASA LEWIS

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Figure 13