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GEMP-286

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MASTER

Nuclear Materials & Propulsion Operation

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By T.S. Lehman Date 10/26/71

BRAYTON CYCLE STUDY

E. L. Semple

J. D. Simpson

May 15, 1964

SPECIAL REREVIEW
FINAL
DETERMINATION

Class: U

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The studies described in this report were requested by the AEC. The purpose of the study was to provide a comparison of the characteristics of a space power system operating on the Brayton cycle with either neon or argon. The first step was the establishment of a basic cycle to be used. A straight forward gas cycle without recuperation was used as this was simpler to analyze and would demonstrate the relative characteristics of neon and argon as well as the recuperative cycle. The electric power output was established to be 1 megawatt electric. In order for the results to be comparable, pressure dependent characteristics of components had to be included. The reactor sizing calculations were performed by the use of a computer program initially developed under Air Force Contract No. AF 04 (611)-9068. Certain modifications and extensions of this program have been performed to make it applicable to closed cycle studies. An absolute weight determination for the radiator was outside the scope of the study. The results of the study are compared on the basis of heat rejection requirements as a function of the selected variables, and reactor weight comparisons are shown.

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INTRODUCTION

Initially, thermodynamic cycle conditions and gas flow rates required to produce 1 mw of electrical power were calculated for various component efficiency levels and compressor pressure ratios. Reactor discharge temperatures from 2200°F to 2300°F were selected as being within the capabilities of uncooled molybdenum turbines. A total cycle pressure drop of 15% was assumed, since earlier studies of Brayton cycle space power units indicated a minimum weight system occurs near this value. The same studies also indicated that minimum radiator area occurs at radiator discharge temperatures between 350° and 500°F, depending on reactor discharge temperature and other cycle assumptions, and that increases in area are negligible for deviations from the optimum temperature of $\pm 50^\circ\text{F}$. Other studies* have shown that minimum radiator area is obtained when compressor inlet (or radiator discharge) temperature is approximately .3 of turbine inlet temperature. Therefore, a single value of 350°F was assumed in this study for radiator discharge temperature.

In Figure 1, neon flow rate is plotted as a function of compressor pressure ratio for various combinations of compressor and turbine efficiency. The same curves are applicable to an argon cycle except that the flow rates required to produce 1 mw of power output would be approximately double those shown for neon because of the difference in specific heats

* M. G. Kofskey and A. J. Glassman, "Turbomachinery Characteristics of Brayton-Cycle Space-Power-Generation Systems," Paper No. 64-GTP-23 presented at the Gas Turbine Conference and Products Show (ASME), Houston, Texas, March 1-5, 1964.

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of the two gases (.246 vs .124). The plot indicates that required flow depends primarily on the product of the component efficiencies rather than on the relative magnitude of each. Therefore, an increase in either turbine or compressor efficiency can compensate for a deterioration in the efficiency of the other component.

Figure 1 also demonstrates that the required flow rate varies significantly with compressor pressure ratio at low component efficiencies, but is relatively invariant at high efficiencies. For this reason, a constant pressure ratio of 2.5, which is close to the optimum for minimum flow in the low efficiency range, was selected for studying variations in turbomachinery capabilities.

Personnel of GE - Advanced Engine Technology Department derived the relationship of the axial compressor and turbine efficiency for both gases to the maximum pressure level (compressor discharge) in the cycle. The compressor data are shown in Figure 2, and include compressor diameter and number of stages, as well as efficiency. At a fixed pressure level, the higher molecular weight of argon permits a higher efficiency for the argon compressor than the neon, and a substantial reduction in the number of stages required to develop the designated pressure, the diameter being only about 20 percent greater. A particular geometry and efficiency level from the curves can be maintained at flow rates other than those for which the data are given if the corresponding value of the flow function, $W \sqrt{T/P}$, is preserved by

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varying the pressure level in direct proportion to the flow rate variation. For example, an eight stage, 9.5 inch diameter neon compressor with a flow rate of 33.6 lb/sec and a discharge pressure of 350 psia will operate at about 79 percent efficiency; with a flow rate of 67.2 lb/sec, the compressor will still operate at 79 percent efficiency if the discharge pressure is increased to 700 psia.

Turbine data similar to those for the compressor are consolidated in Figure 3, with curves of diameter and centrifugal stress superimposed on the efficiency contours. In matching turbine to compressor operating conditions, a 5 percent pressure drop was imposed between compressor discharge and turbine inlet, and 2 percent of the compressor discharge gas was used to cool the turbine wheel. Each efficiency vs. compressor discharge pressure relationship is an envelope of curves for two-, three-, and four-stage turbines. As in the compressor, turbine performance for flow rates other than those specified on the curve will remain the same if pressure level is varied in direct proportion to the change in flow. Furthermore, small changes in turbine inlet temperature can be counterbalanced by varying pressure directly with the change in the square root of the temperature.

It was assumed that a material such as TZC would be used to fabricate a turbine with uncooled buckets. Extrapolation of existing data for TZC indicates that a stress level of 20,000 psi is the maximum permissible to meet a design criterion of 0.2 percent yield in 10,000 hours.

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Therefore, the curves for turbine centrifugal stress of 20,000 psi in Figure 3 represent the highest efficiencies attainable as a function of pressure level at 20,000 rpm. The higher molecular weight of argon offers no efficiency advantage in the turbine because diameter and, therefore, flow area are constrained by the centrifugal stress limitation. Slightly higher turbine efficiencies for both neon and argon can be realized by decreasing rotational speed and operating at lower pressure levels. At 15,000 rpm, compressor efficiencies can be maintained at the levels shown in Figure 2 by doubling the indicated number of compressor stages.

Turbine and compressor efficiencies were selected from Figures 2 and 3 for each gas at several pressure levels consistent with the indicated nominal flow rates. The actual flow rates required to produce 1 mw of power output were calculated for turbine inlet temperatures of 2200°F, 2250°F, and 2300°F, and the corresponding pressure levels were determined by observing the proportional relationships among flow, pressure, and the square root of temperature. The results of the cycle calculation are presented in Figure 4. For each gas, the relatively higher compressor efficiencies achievable at low pressure levels reduce the required flow rates, since turbine efficiency varies little with pressure. At any pressure level, the argon flow rate is greater than the neon flow rate. However, because compressor efficiency with argon is higher, the difference is less than the factor of two that might be expected from a consideration of just the specific heat difference. Also an equitable comparison between the two gases requires consideration

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of the film temperature drop in the turbine. For the same turbine bucket temperature, argon gas temperature may be 25° to 50° higher than neon gas temperature, thus further diminishing the difference between flow rates at a given pressure level. Although turbomachinery weight is an insignificant portion of total system weight, it is noted that argon turbomachinery would be lighter than neon turbomachinery at the same pressure level, and that these weights would increase with increasing pressure.

The reactor weight calculations shown in Figure 5 were computed by the NMPO reactor sizing program. This computer program reconciles the aerothermal, nuclear, mechanical and geometrical restraints associated with the 710 reactor. Utilizing a given mechanical arrangement for the reactor, all components can then be weighed in terms of material thicknesses required to sustain the aerodynamic and mechanical loadings applied to them. The nuclear calculations implicit within the calculation provides sufficient reactivity to compensate for the reduction in the average fuel loading required to power flatten the reactor, the negative temperature and Doppler coefficients, as well as sufficient reactivity for the expected operating life. The results of these calculations have also been correlated with critical experiment results in order to account for discrepancies between predicted critical mass and that experimentally observed.

The aerothermal calculations are based on single channel turbulent compressible flow with heat addition according to a prescribed profile.

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Although the reactor weight contributes little to the overall system weight, it can be seen from Figure 5 that there is a slight variation in reactor weight with maximum system pressure. The reactor in general will be smaller and lighter with higher system pressure as expected for a heat exchanger component.

An additional restraint which had been imposed on the choice of allowable reactor systems is that the flow at the exit of the coolant channels is in the turbulent regime. It is not believed that this is a completely restrictive requirement but additional data would have to be obtained on multiple coolant channel passages and the sensitivity of the flow distribution effects to variations in friction before operation in the transition flow regime could be considered. Laminar flow would also be a possible consideration if the pressure level were desired to be lowered to an even greater extent than that which is shown on the curve.

Radiator weight is by far the dominant item in the system. Data were not available to assess the effects of pressure level or choice of gas on this component weight. However, required radiator effective area is shown in Figure 6 to indicate possible trends. This area is defined by the following equation which considers the film temperature drop to be negligible:

$$A_{c\text{ff}} = \frac{W C_p}{\sigma \epsilon T_s^3} \left\{ 2 \tan^{-1} \frac{T_{\text{out}}}{T_s} - 2 \tan^{-1} \frac{T_{\text{in}}}{T_s} + \ell_n \left[\left(\frac{T_{\text{in}} - T_s}{T_{\text{out}} - T_s} \right) \left(\frac{T_{\text{out}} + T_s}{T_{\text{in}} + T_s} \right) \right] \right\}$$

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where

σ = Stephan Boltzmann constant

ϵ = Radiator surface emissivity

T_s = Sink temperature - $^{\circ}\text{R}$

T_{in} = Gas inlet temperature - $^{\circ}\text{R}$

T_{out} = Gas discharge temperature - $^{\circ}\text{R}$

Although at a fixed pressure level, the argon flow rate is greater than neon flow rate, the lower specific heat of argon offsets this effect to yield a lower heat rejection rate. Thus the effective area required to dissipate the heat is smaller. The ultimate comparison between neon and argon will depend upon detailed determinations of the weights associated with the effective areas and an assessment of the implications of argon activation.

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BRAYTON CYCLE
SPACE POWER UNIT

Net Power Output 1 MW
Turbine Inlet Temp - 2300°K
Radiation Discharge Temp - 350°K
Total Pressure Drop - 15%
Working Fluid - Helium

Figure 1

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Figure 2

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TURBINE

Turbine Inlet Temperature - 2300°K
 Turbine Pressure Ratio - 2.10
 Reactor Pressure Drop - 5%
 Flow Rate - 23.6 Volume for neon (compressor)
 69.2 Volume for argon " "
 Speed - 10000 rpm

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COMPRESSOR FLOW RATE

Compressor Inlet Temperature - 350°F
 Optimum Compressor Pressure Ratio
 Speed - 20000 rpm
 Turbine Stress 20000 psi

Figure 1

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REACTOR HEIGHT

Maximum Fuel Element Surface Temp - 4550°F
Reactor Inlet Temperature - 575°F ± 20°
Reactor Pressure Ratio - 1.95
Fuels - Uranium, Plutonium, Tantalum clad

Figure 5

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K-E 10X10 TO THE 1/2 INCH 359-12
KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 6

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