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PRELIMINARY ANALYSIS OF SUPERCHARGED NUCLEAR
RAMJET PROPULSION SYSTEM

Summary

A preliminary analysis has been made to compare the performance of a ceramic ramjet reactor powerplant, such as described in General Electric Report No. XDC-56-5-81, with that of such a powerplant supercharged by a metallic-vapor-cycle compressor jet. Performance at sea level, Mach 2.5 is reported for the vapor-cycle compressor jet alone, for the ramjet-alone, and for the compressor jet - ramjet combination. Results indicate that adding the compressor-jet as a supercharger for the ramjet provides an increase in specific thrust of about 20 percent over that of the ramjet alone, with an attendant increase in thermal efficiency of about 20 percent over that of the ramjet alone.

* * * * *

Introduction

This report represents the results of a preliminary analysis which has been made to compare the performance of a ceramic ramjet reactor powerplant with that of such a powerplant supercharged by a metallic-vapor-cycle compressor-jet system. This study was conducted to provide comparison with similar studies conducted by North American Aviation, Inc., Missile Development Division, under the direction of Mr. Burt L. Taylor. Mr. Taylor advised Oak Ridge National Laboratory on a visit on March 12, 1957 that the North American study had as design parameter flight at sea level, Mach 2.5, with an air exit temperature from the reactor of 2900°R. These values have been used in the present study.

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Powerplant Description

A. Ceramic-Ramjet Reactor

The reactor is similar to that described in General Electric Report No. XDC 56-5-81, consisting in general of a cylindrical reactor with tubular air passages. For the ramjet application, air is inducted through a diffuser, heated in passing through the reactor, and discharged through a nozzle to provide thrust. This powerplant is illustrated in Figure 1a.

B. Vapor-Cycle Compressor-Jet

This powerplant consists in general of a vapor turbine, an air compressor, a vapor condenser, a reactor heat source, and a pump.

The metallic working fluid, rubidium in the present case, is vaporized at high pressure by heat from the reactor. It is then expanded through the turbine, providing power to drive the air compressor. The vapor is then condensed in the condenser by the transfer of heat to air. The liquid rubidium from the condenser is then pumped back to the reactor heat source to complete the cycle. Air is inducted through a diffuser, compressed in the air compressor, and heated by the condensing rubidium. The air is then discharged through a nozzle providing thrust. This powerplant is illustrated in Figure 1b.

C. Vapor-Cycle Compressor-Jet - Ramjet Combination

In the combination of the two powerplants, the compressor jet and ramjet are in series, with the air from the vapor cycle condenser passing through the reactor before being discharged overboard. This arrangement provides air to the ramjet reactor at a higher pressure than that obtained by ram alone. This, in effect, supercharges the ramjet, providing an increase in performance due to the increased air pressure. In this case the ceramic ramjet reactor provides heat to boil the rubidium as well as heat to be transferred directly to the air. This powerplant is illustrated in Figure 1c.

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Powerplant Analysis

A. Ramjet Reactor

This report is concerned only with thermodynamic performance; thus, having specified the reactor air outlet temperature to be 2900°R , the only parameter of interest is the air pressure drop in the reactor associated with attaining this air temperature.

In General Electric Report No. XDC 56-5-81, the ramjet reactors were designed for operation at Mach 4.25 at 90,000 to 100,000 ft with air pressures on the order of 1.5 atm at the reactor inlet, air pressure drops in the reactor were estimated to be on the order of 0.5 atm. The air weight flow per unit reactor frontal area was approximately $15 \text{ lb/ft}^2\text{sec}$. It is believed that the ramjet reactor of the present study would be designed for similar or only slightly higher values of air weight flow per unit reactor frontal area. The air density at the reactor inlet in the sea level, Mach 2.5 case would be about 15 times that for the 90,000 ft altitude, Mach 4.25 case. Thus, the air velocity in the present reactor would be approximately $1/15$ that in the reactor of the General Electric report, and the ratio of reactor air pressure drop to reactor air density would be approximately $1/200$ that of the General Electric reactor, or on the order of $1/600$. This is regarded as totally negligible, and is ignored.

A calculation of the ramjet reactor powerplant performance is presented in Appendix A.

B. Vapor-Cycle Compressor-Jet

The vapor cycle compressor-jet analysis is based on the data of ORNL CF 56-8-205. For the present study the rubidium boiling temperature was set at 2000°F (2460°R). This was felt to be the maximum temperature usable with presently envisioned pipe and other structural materials.

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Performance was calculated for compressor pressure ratios of 1.2, 1.3, and 1.4. In each case the condensing temperature was selected to yield the minimum required heat transfer per unit log mean temperature difference in the condenser, thus minimizing condenser size and condenser air pressure drop. This consideration led to the selection of condensing temperatures of 1800°R , 1820°R , and 1836°R , respectively, for the pressure ratios of 1.2, 1.3, 1.4.

A sample calculation of the vapor cycle compressor-jet performance is given in Appendix B.

C. Vapor-Cycle Compressor-Jet - Ramjet Combination

The performance of the combination powerplant was computed by taking the condenser discharge air pressure and temperature from the vapor-cycle compressor-jet calculation as that at the ramjet reactor inlet, and computing thrust obtained when the air temperature is raised to 2900°R by the ramjet reactor.

A sample calculation of the combination powerplant performance is presented in Appendix C.

Results

The results of this analysis are presented in Figures 2 and 3 of this report.

Figure 2 presents several vapor cycle compressor jet performance parameters as functions of compressor pressure ratio:

- a. Condenser Approach Temperature - the difference between the condensing temperature and the condenser maximum bulk air temperature decreases with increasing pressure ratio for two reasons: (1) increasing compressor pressure ratio yields increased compressor air discharge temperatures (condenser air inlet temperatures), and (2) increasing compressor pressure ratio requires increasing turbine power per unit air flow, requiring increased rubidium flow per unit air flow. This in turn implies an increased heat rejection per unit air flow in the condenser.

- b. Condenser Depth in Air Flow Direction - with a constant air weight flow per unit condenser frontal area, assumed to be $20 \text{ lb/ft}^2\text{-sec}$, condenser depth increases with increasing pressure ratio, reflecting the increasingly severe heat transfer requirements indicated by curve (1a). The condenser depth required for a compressor pressure ratio of 1.4 is 3 ft; for higher compressor pressure ratios it is felt that the condenser size would be impractically large.
- c. Specific Thrust - powerplant specific thrust increases with increasing pressure ratio because the condenser air exit pressure and temperature both increase with increasing pressure ratio.
- d. Thrust per Unit Heat Input - powerplant thrust per unit heat input, a measure of powerplant thermal efficiency, increases slightly with increasing compressor pressure ratio, reflecting the increasing fraction of the air energy input supplied quasi-reversibly through the compressor.

Figure 3 presents specific thrust and thrust per unit energy input as functions of compressor pressure ratio for the vapor cycle compressor-jet and the vapor cycle compressor-jet - ramjet combination. In addition, specific thrust and thrust per unit energy are presented for the ramjet reactor.

Discussion

The results of this analysis indicate that the specific thrust and thrust per unit energy input available from the vapor-cycle compressor-jet - ramjet combination are up to 20 percent higher than those obtained from the ramjet reactor alone.

The combination cycle is attractive from the viewpoint of efficiency, and also because the combination cycle could conceivably provide takeoff capability, which would not be available in the ramjet alone. The design of a reactor to

provide heat directly to air and simultaneously to provide heat at a lower temperature to boil the rubidium for the vapor cycle has not been considered in this study, but appears to be a formidable problem. Also, no estimate has been made of the weights of the various powerplants or of their performance per unit powerplant weight, although it is obvious that the increase in performance obtained by supercharging the ramjet is obtained at the expense of an increase in weight.

Appendix A

Ramjet Reactor Powerplant Performance

Sea Level, Mach 2.5

$$P_{amb} = 2116 \text{ lb/ft}^2$$

$$T_{amb} = 519^\circ\text{R}$$

1. Ideal Ram Air Temperature and Pressure, T_{0t} and P_{0t}

$$T_{0t} = T_{amb} \left[1 + \frac{\gamma-1}{2} M^2 \right]$$

$$\text{Assume } \gamma = 1.4$$

$$T_{0t} = 519 \left[1 + 0.2 [2.5]^2 \right] = 1168^\circ\text{R}$$

$$P_{0t} = P_{amb} \left[1 + \frac{\gamma-1}{2} M^2 \right]^{\frac{\gamma}{\gamma-1}}$$

$$= 2116 \left[1 + 0.2 [2.5]^2 \right]^{3.5} = 38,184 \text{ lb/ft}^2$$

2. Actual Ram Air Temperature and Pressure, T_{1t} and P_{1t}

$$T_{1t} = T_{0t} = 1168^\circ\text{R}$$

$$P_{1t} = \eta_D P_{0t}$$

where

D = diffuser efficiency

$$\text{Assume } \eta_D = 0.814$$

$$P_{1t} = 0.814 \times 38,184 = 31,082 \text{ lb/ft}^2$$

3. Reactor Outlet Air Temperature and Pressure, T_{2t} and P_{2t}

$$T_{2t} = 2900^\circ\text{R by assumption}$$

Ignoring reactor pressure drop,

$$P_{2t} = P_{1t} = 31,082 \text{ lb/ft}^2$$

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4. Exit Nozzle Exhaust Velocity, U_3

$$U_3 = \sqrt{2 \eta_j \frac{\gamma}{\gamma-1} T_{2t} \left[1 - \frac{P_{amb}}{P_{2t}} \right]^{\frac{\gamma-1}{\gamma}}}$$

Assume η_j , nozzle efficiency = 0.95

$$g = 32.2 \text{ ft/sec}^2$$

$$\frac{R}{M} = 53.35 \text{ ft lb/lbR}$$

Assume $\gamma = 1.307$

$$U_3 = \sqrt{2 \times 0.95 \times 4.25 \times 53.35 \times 32.2 \times 2900 \times \left[1 - \left[\frac{2116}{31,082} \right]^{0.235} \right]}$$

$$= 4220 \text{ ft/sec}$$

5. Free Steam Velocity, U_0

$$U_0 = 49 M \sqrt{T_{amb}}$$

$$= 49 \times 2.5 \times \sqrt{519} = 2791 \text{ ft/sec}$$

6. Specific Impulse, I

$$I = \frac{U_3 - U_0}{g} = \frac{4220 - 2791}{32.2} = 44.4 \text{ lb thrust/lb air per sec}$$

7. Specific Energy Input, E

$$h_1 = 283 \text{ Btu/lb}$$

$$h_2 = 761 \text{ Btu/lb}$$

$$\Delta h_{1-2} = 478 \text{ Btu/lb}$$

8. Thrust per Unit Energy Input, $\frac{I}{E}$

$$\frac{I}{E} = \frac{44.4}{478} = 0.093 \text{ lb thrust/Btu per sec}$$

Appendix B

Vapor-Cycle Compressor-Jet Powerplant Performance

Steps 1 and 2 are the same as in Appendix A, yielding:

Actual Ram Air Temperature, $T_{1t} = 1168^{\circ}\text{R}$

Actual Ram Air Pressure, $P_{1t} = 31,082 \text{ lb/ft}^2$

3. Compressor Discharge Air Temperature and Pressure, T_{2t} and P_{2t}

$$P_{2t} = Z_c P_{1t}$$

where Z_c = compressor pressure ratio

Assume $Z_c = 1.4$

$$P_{2t} = 1.4 \times 31,082 = 40,514 \text{ lb/ft}^2$$

$$T_{2t} = T_{1t} + \frac{T_{1t}}{\eta_c} \left[Z_c^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

where η_c = compressor adiabatic efficiency

Assume $\eta_c = 0.85$

$$\gamma = 1.37$$

$$T_{2t} = 1168 + \frac{1168}{0.85} \left[[1.4]^{0.27} - 1 \right] = 1299^{\circ}\text{R}$$

4. Specific Energy Input to Air in Compressor, E_{1-2}

$$E_{1-2} = \Delta h_{1-2}$$

$$h_2 = 316.6 \text{ Btu/lb}$$

$$h_1 = 283.1 \text{ Btu/lb}$$

$$E_{1-2} = \Delta h_{1-2} = 33.5 \text{ Btu/lb}$$

5. Vapor Boiling (Vapor Turbine Inlet) Temperature, T_B

Specify $T_B = 2460^{\circ}\text{R}$

6. Vapor Condensing Temperature, T_c

$$\text{Assume } T_c = 1835^\circ\text{R}$$

7. Specific Energy Extraction in Vapor Turbine, E_{Turb}

$$E_{\text{Turb}} = 106.11 \text{ Btu/lb Ru for } T_B = 2460^\circ\text{R},$$

$$T_c = 1835^\circ\text{R, and entering saturated}$$

$$\text{vapor, from data of ORNL CF 56-8-205}$$

8. Rubidium - Air Weight Flow Ratio, $\frac{W_{\text{Ru}}}{W_{\text{Air}}}$

$$\frac{W_{\text{Ru}}}{W_{\text{Air}}} = \frac{E_{1-2}}{\eta_{\text{T}} E_{\text{Turb}}}$$

$$\text{Assume } \eta_{\text{T}}, \text{ turbine efficiency} = 0.80$$

$$\frac{W_{\text{Ru}}}{W_{\text{Air}}} = \frac{33.5}{0.80 \times 106.11} = 0.394$$

9. Specific Energy Extraction in Vapor Condenser, E_{cond}

$$E_{\text{cond}} = 320.19 \text{ Btu/lb Ru, also from ORNL CF 56-8-205}$$

10. Specific Energy Input to Air in Condenser, E_{2-3}

$$E_{2-3} = \frac{W_{\text{Ru}}}{W_{\text{Air}}} \times E_{\text{cond}} = 0.394 \times 320.19 = 126.20 \text{ Btu/lb air}$$

11. Condenser Air Exit Temperature, T_{3t}

$$T_{3t} \text{ is found from } h_3;$$

$$h_3 = h_2 + E_{2-3}$$

$$= 316.6 + 126.2 = 442.8 \text{ Btu/lb from gas tables, } T_{3t} = 1774^\circ\text{R}$$

12. Condenser Log Mean Temperature Difference, ΔT_{lm}

$$\Delta T_{\text{lm}} = \frac{\frac{[T_c - T_{2t}] - [T_c - T_{3t}]}{\ln \frac{T_c - T_{2t}}{T_c - T_{3t}}}}{\frac{T_{3t} - T_{2t}}{\ln \frac{T_c - T_{2t}}{T_c - T_{3t}}}}$$

$$\Delta T_{\text{lm}} = \frac{1774 - 1299}{\ln \frac{1835 - 1299}{1835 - 1774}} = 219^\circ\text{R}$$

13. Condenser Heat Transfer Surface Requirement Index, $\frac{E_{2-3}}{\Delta T_{1m}}$

$$\frac{E_{2-3}}{\Delta T_{1m}} = \frac{126.2}{219} = 0.5765$$

This value is a minimum for the assumed $T_c = 1835^\circ R$. This value of T_c was obtained by repeating steps 6 through 13 for several assumed values of T_c , to determine the value of T_c which minimizes $\frac{E_{2-3}}{\Delta T_{1m}}$.

14. Condenser Air Weight Flow per Unit Frontal Area, G

$$\text{Assume } G = 20 \text{ lb/ft}^2\text{sec}$$

15. Condenser Heat Transfer Coefficient, η_{0h}

$$\eta_{0h} = 9.70 G^{-.607} + 5.00 \text{ from ORNL CF 56-8-205}$$

$$\eta_{0h} = 9.70 [20]^{-.607} + 5.00 = 64.95$$

16. Condenser Depth in Air Flow Direction, D

$$D = 16.92 \frac{G \times E_{2-3}}{\eta_{0h} \times \Delta T_{1m}} \text{ from ORNL CF 56-8-205}$$

$$D = \frac{16.92 \times 20 \times 126.2}{64.95 \times 219} = 3.0 \text{ ft}$$

17. Condenser Air Flow Friction Factor, f

$$f = 0.0371 G^{-0.762} + 0.09 \text{ from ORNL CF 56-8-205}$$

$$f = 0.0371 [20]^{-0.762} + 0.09 = 0.0128$$

18. Condenser Air Discharge Pressure, P_{3t} from ORNL CF 56-8-205

$$P_{3t} = \sqrt{P_{2t}^2 - 910.94 f G^2 D [T_c - \Delta T_{1m}]}$$

18. (cont'd.)

Since the pressure drop is small, total pressures are used with negligible error:

$$P_{3t} = \sqrt{P_{2t}^2 - 910.94 f G^2 D [T_c - \Delta T_{lm}]}$$

$$P_{3t} = \sqrt{[43.514]^2 - 910.94 \times 0.0128 \times 20^2 \times 3.0 \times [1835-219]}$$

19. Exit Nozzle Exhaust Velocity, U_4

$$U_4 = \sqrt{2 \eta_j \frac{1}{\gamma-1} \frac{Rg}{m} T_{3t} \left[1 - \left[\frac{P_{amb}}{P_{3t}} \right]^{\frac{\gamma-1}{\gamma}} \right]}$$

$$\text{Assume } \eta_j = 0.95$$

$$\text{Assume } \gamma = 1.338$$

$$\frac{R}{m} = 53.35 \text{ ft lb/lb R}$$

$$g = 32.2 \text{ ft/sec}^2$$

$$U_4 = \sqrt{2 \times 0.95 \times 3.96 \times 53.35 \times 32.2 \times 1774 \times \left[1 - \left[\frac{2116}{43,253} \right]^{.2526} \right]}$$

$$= 3498 \text{ ft/sec}$$

20. Free Stream Velocity, U_o

$$\text{from Appendix A, } U_o = 2791 \text{ ft/sec}$$

21. Specific Impulse, I

$$I = \frac{U_4 - U_o}{g} = \frac{3498 - 2791}{32.2} = 21.9 \text{ lb thrust/lb air per sec}$$

22. Specific Energy Input, E

$$E = E_{1-2} + E_{2-3} = 33.5 + 126.2 = 159.7 \text{ Btu/lb air}$$

23. Thrust per Unit Energy Input, $\frac{T}{E}$

$$\frac{T}{E} = \frac{21.9}{159.7} = 0.137 \text{ lb thrust/Btu per sec}$$

Appendix C

Vapor-Cycle Compressor-Jet - Ramjet CombinationPowerplant Performance

1. Condenser Discharge Air Temperature and Pressure, T_{3t} and P_{3t}

From Appendix B, for a vapor-cycle compressor pressure ratio of 1.4, the air temperature and pressure at the condenser exit are:

$$T_{3t} = 1774 \text{ R}$$

$$P_{3t} = 43.253 \text{ lb/ft}^2$$

2. Reactor Discharge Air Temperature and Pressure, T_{4t} and P_{4t}

Neglecting ramjet reactor air pressure drop, and assuming a reactor air outlet temperature of 2900°R :

$$T_{4t} = 2900^\circ\text{R}$$

$$P_{4t} = 43.253 \text{ lb/ft}^2$$

3. Exit Nozzle Exhaust Velocity, U_5

Then the exit nozzle exhaust velocity is:

$$U_5 = \sqrt{2 \eta_j \frac{1}{\gamma-1} \frac{Rg}{m} T_{4t} \left[1 - \left[\frac{P_{amb}}{P_{4t}} \right]^{\frac{\gamma-1}{\gamma}} \right]}$$

$$\text{Assume } \eta_j = 0.95$$

$$\text{Assume } \gamma = 1.307$$

$$g = 32.2 \text{ ft/sec}^2$$

$$\frac{R}{m} = 53.35 \text{ ft lb/lb R}$$

4. Free Stream Velocity, U_o

$$\text{from Appendix A, } U_o = 2791 \text{ ft/sec}$$

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5. Specific Impulse, I

$$I = \frac{U_5 - U_o}{g} = \frac{4510 - 2791}{32.2} = 53.4 \text{ lb thrust/lb air per sec}$$

6. Specific Energy Input, E

$$E = E_{1-2} + E_{2-3} + E_{\text{reactor}}$$

$$\text{from Appendix B, } E_{1-2} = 33.5 \text{ Btu/lb air}$$

$$E_{2-3} = 126.2 \text{ Btu/lb air}$$

$$h_3 = 442.8 \text{ Btu/lb air}$$

$$h_4 = 761.5 \text{ Btu/lb air}$$

$$E_{\text{reactor}} = h_4 - h_3 = 761.5 - 442.8 = 318.7 \text{ Btu/lb air}$$

$$E = 33.5 + 126.2 + 318.7 = 478.4 \text{ Btu/lb air}$$

7. Thrust per Unit Energy Input, $\frac{I}{E}$

$$\frac{I}{E} = \frac{53.4}{478.4} = 0.112 \text{ lb thrust/Btu per sec.}$$

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Fig. 1a. Ramjet Reactor Powerplant Schematic

Fig. 1b. Vapor Cycle Compressor Jet Powerplant Schematic

Fig. 1c. Vapor Cycle Compressor Jet-Ramjet Reactor Combination Powerplant Schematic

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Fig.2— Vapor Cycle Compressor Jet Powerplant Performance

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Fig. 3— Vapor Cycle Compressor Jet, Ramjet, And Compressor Jet— Ramjet Combination Powerplant Performance

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