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A STEAM CYCLE FOR AIRCRAFT NUCLEAR PROPULSION

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Cleveland, Ohio

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16. Abstract

A preliminary cycle analysis of a steam-driven, nuclear-powered turbofan engine is presented. It is found that maximum efficiency and minimum thrust per unit airflow both occur for a bypass ratio of zero. (This corresponds to minimum heat-exchanger-outlet air temperature.) Parametric numerical results are presented which can be used for selecting the proper engine operating conditions for a given airplane.

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SUMMARY

A thermodynamic cycle study is made for a nuclear-powered turbofan engine where steam is the working fluid. The engine consists of an air fan driven by a steam turbine. The steam is heated in a nuclear reactor. The compressed airflow is divided; part is directed through the core of the engine where it passes through the steam condenser, and the rest is bypassed. Maximum overall efficiency η_{oa} occurs at or near a bypass ratio of zero, which corresponds to minimum possible heat-exchanger-outlet air temperature. Minimum thrust per unit airflow $F/\dot{W}_a$ also occurs at this point. An aircraft optimization would have to trade off the decrease in power requirements at bypass ratio of zero against the increase in engine size and weight caused by the low thrust per unit airflow.

It is shown that as heat-exchanger-outlet air temperature increases, η_{oa} decreases while $F/\dot{W}_a$ increases; as fan pressure ratio increases, η_{oa} increases and $F/\dot{W}_a$ increases; as steam temperature increases, η_{oa} increases while $F/\dot{W}_a$ decreases; as steam pressure increases, η_{oa} increases while $F/\dot{W}_a$ decreases; as fan or turbine efficiency increases, η_{oa} increases while $F/\dot{W}_a$ decreases; and as hot-steam to hot-air temperature difference increases, η_{oa} decreases while $F/\dot{W}_a$ increases.

INTRODUCTION

The nuclear-powered airplane has always promised almost unlimited endurance and range. Recent studies (refs. 1 to 3) have reexamined the performance potential of helium-cooled thermal-reactor nuclear airplanes in the light of new technology. These studies have shown the effect of aircraft gross weight and nuclear component lifetimes on the payload of the airplane. Reference 3 showed the off-design point flight capability of such aircraft as a function of design point.

The purpose of this study is to investigate another working fluid for aircraft nuclear propulsion, steam. Steam is attractive as a working fluid as a result of lower temperatures of the cycle. In addition, steam is less corrosive than liquid metals and is of some use as a reactor moderator.

A first analysis of a supercritical-water cycle for nuclear aircraft turbojet propulsion is given in reference 4. There, steam was expanded through a turbine, condensed in a heat exchanger, and then pumped back up to reactor inlet conditions. The steam turbine, in turn, drove a compressor which raised the air pressure entering the engine. The air then passed through the condenser, increasing in temperature, and then was expanded through a nozzle to produce thrust.

In this report, a turbofan cycle is examined. The distinction is, of course, that not all of the compressed air will pass through the engine core (i.e., some will be bypassed). The object of the report is to present numerical engine-system results that could serve as inputs to an aircraft/mission study.

The effects of steam pressure, temperature, steam turbine and air fan efficiencies, compression ratio, air-to-steam approach temperature, and bypass ratio on cycle efficiency are shown parametrically and major trends identified. No attempt at weight estimation has been made; however, a discussion of the trend of system weight as a function of cycle parameters is presented.

SYMBOLS

C_{f_j}	nozzle thrust coefficient
C_p	specific heat at constant pressure, Btu/(lb)(^oR); J/(kg)(K)
F	thrust, lbf; N
g	gravitational constant, ft/sec^2; m/sec^2
h	enthalpy per pound, Btu/lb; J/kg
J	mechanical equivalent of heat, ft-lb/Btu; dimensionless
M	Mach number
P	total pressure, psi; N/m^2
p	ambient pressure, psi; N/m^2
S	entropy per pound, Btu(lb)(^oR); J/(kg)(K)
T	temperature, ^oR; K
V_{j_c}	jet velocity out of engine core, ft/sec; m/sec
V_{j_f}	jet velocity of bypass air, ft/sec; m/sec

V_0 flight velocity, ft/sec; m/sec

$\dot{W}$ weight flow, lb/sec; kg/sec

γ specific-heat ratio

Δ change between two points

η efficiency

Subscripts:

a air

a_1 air at entrance to fan

a_2 air at outlet of fan

a_3 air at outlet of heat exchanger

oa overall

s steam

s_1 steam at reactor outlet

s_2 steam at heat-exchanger entrance

s_3 steam at heat-exchanger outlet

s_4 steam at reactor entrance

0 free stream (ambient)

ANALYSIS

Figure 1 shows the cycle that was analyzed. The steam is heated in the reactor to a temperature T_{s_1} and a pressure P_{s_1}, expanded through the turbine to temperature T_{s_2} and pressure P_{s_2}; condensed to temperature T_{s_3} and pressure P_{s_3}; and pumped as liquid water up a pressure P_{s_4} and a temperature T_{s_4}. The air at temperature T_{a_1} and pressure P_{a_1} is compressed to T_{a_2} and P_{a_2}; some of the air is bypassed and the rest is heated in the condenser to P_{a_3} and T_{a_3}. In the following analysis, h_s, S_s, and h_a, S_a will be the enthalpy and entropy per pound of steam and of air, respectively.

The equations for the cycle for steam side and air side can be written as follows:
Steam:

(1) Enthalpy changes through the steam cycle:

$$h_{s_1} - h_{s_2} = \Delta h_{s_{12}} \tag{1}$$

$$h_{s_2} - h_{s_3} = \Delta h_{s_{23}} \tag{2}$$

$$h_{s_3} - h_{s_4} = \Delta h_{s_{34}} \tag{3}$$

$$h_{s_1} - h_{s_4} = \Delta h_{s_{14}} \tag{4}$$

(2) Turbine expansion efficiency:

$$\eta_{s_{12}} = \frac{h_{s_1} - h_{s_2}}{h_{s_1} - \left(h_{s_2}\right)_{\text{isentropic}}} \tag{5}$$

(3) Determination of isentropic expansion temperature:

$$\text{From } \left(h_{s_2}\right)_{\text{isentropic}} \text{ and } S_{s_1} \text{ obtain } \left(T_{s_2}\right)_{\text{isentropic}} \tag{6}$$

Air:

(1) Temperature rise across fan:

$$T_{a_2} = T_{a_1}\left\{1 + \frac{\left[\left(\frac{P_{a_2}}{P_{a_1}}\right)^{(\gamma-1)/\gamma} - 1\right]}{\eta_{a_{12}}}\right\} \tag{7}$$

(2) Enthalpy changes through air cycles:

$$\Delta h_{a_{21}} = C_{p_a}\left[T_{a_2} - T_{a_1}\right] \tag{8}$$

$$\Delta h_{a_{32}} = C_{p_a}\left[T_{a_3} - T_{a_2}\right] \tag{9}$$

(3) Total pressure to ambient pressure ratio:

$$\frac{P_{a_2}}{p_{a_o}} = \left(\frac{P_{a_2}}{P_{a_1}}\right)\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)} \tag{10}$$

$$\frac{P_{a_3}}{p_{a_o}} = \left(\frac{P_{a_3}}{P_{a_2}}\right)\left(\frac{P_{a_2}}{p_{a_o}}\right) \tag{11}$$

(4) Jet velocity of fan air:

$$V_{j_f} = C_{f_j}\sqrt{2gJC_pT_{a_2}\left[1 - \left(\frac{P_{a_2}}{p_{a_o}}\right)^{(1-\gamma)/\gamma}\right]} \tag{12}$$

(5) Jet velocity of core air:

$$V_{j_c} = C_{f_j}\sqrt{2gJC_pT_{a_3}\left[1 - \left(\frac{P_{a_3}}{p_{a_o}}\right)^{(1-\gamma)/\gamma}\right]} \tag{13}$$

(6) Bypass ratio:

$$BPR = \frac{\left(\dot{W}_a\right)_{bypass}}{\left(\dot{W}_a\right)_{condenser}} \tag{14}$$

(7) Thrust per unit airflow:

$$\frac{F}{\dot{W}_a} = \frac{V_{j_c} + BPR\left(V_{j_f}\right)}{(1 + BPR)g} - \frac{V_o}{g} \tag{15}$$

(8) Cycle efficiency:

$$\eta_{oa} = \frac{\frac{F}{\dot{W}_a}(V_o)}{\left(\Delta h_{s_{14}}\right)(J)} \tag{16}$$

The steam and air sides of the cycle are related by

(1) Work of turbine = Work of fan, or

$$\dot{W}_s \Delta h_{s_{12}} = \dot{W}_a \Delta h_{a_{21}} \tag{17}$$

and ratioing with respect to $\dot{W}_a$

$$\frac{\dot{W}_s}{\dot{W}_a} = \frac{\Delta h_{a_{21}}}{\Delta h_{s_{12}}} \tag{18}$$

(2) Heat lost by condensing steam = Heat gained by air, or

$$\frac{\dot{W}_s \Delta h_{s_{23}}}{\dot{W}_a} = \frac{\Delta h_{a_{32}}}{1 + BPR} \tag{19}$$

From equations (18) and (19),

$$BPR = \frac{\Delta h_{a_{32}}}{\Delta h_{s_{23}}}\left(\frac{\Delta h_{s_{12}}}{\Delta h_{a_{21}}}\right) - 1 \tag{20}$$

In addition, it was assumed that no work was required to bring the steam from conditions at the heat-exchanger exit to those at the reactor entrance, or

$$h_{s_4} = h_{s_3} \tag{21}$$

$$P_{s_4} = P_{s_1} \tag{22}$$

$$T_{s_4} = T_{s_3} \tag{23}$$

For given fan efficiency, turbine efficiency, C_{p_a}, γ_a, Mach number, altitude, steam reactor outlet temperature and pressure, nozzle thrust coefficient, air to steam approach temperature, fan pressure ratio, air and steam side pressure drops through the condenser, and air outlet temperature from the condenser, it is possible to calculate cycle efficiency. Unless otherwise stated, the following values will apply to each variable:

$$\eta_{a_{12}} = 0.88$$

$$\eta_{s_{12}} = 0.88$$

$$C_{p_a} = 0.24\ \mathrm{Btu/(lb)(^oR)} = 1.005\ \mathrm{J/(kg)(K)}$$

$$\gamma_a = 1.4$$

$$\left.\begin{array}{l} M = 0.8 \\ \text{Altitude} = 36\ 089\ \text{ft}\ (11.0\ \text{km}) \end{array}\right\} \left[T_{a_1} = 440^o\ R\ (245\ K),\ p_{a_o} = 472.7\ \text{psia}\ (3.259\times10^6\ N/m^2)\right]$$

$$T_{s_1} = 1360^o\ R\ (755\ K)$$

$$P_{s_1} = 1000\ \text{psia}\ (6.895\times10^6\ N/m^2)$$

$$C_{f_j} = 0.975$$

$$T_{s_2} = T_{a_3} + 50^o\ R\ (28\ K) \tag{24}$$

$$\frac{P_{a_2}}{P_{a_1}} = 1.3$$

$$\frac{P_{a_3}}{P_{a_2}} = 0.95$$

$$\frac{P_{s_3}}{P_{s_2}} = 0.95$$

RESULTS AND DISCUSSION

Effect of Heat-Exchanger-Outlet Air Temperature

Overall efficiency. - The effect of heat-exchanger-outlet air temperature on overall efficiency is shown in figure 2. As can be seen from the figure, overall efficiency increases with fan pressure ratio P_{a_2}/P_{a_1}. Since steam conditions at the heat-exchanger entrance can be found from conditions at the reactor exit, $\eta_{s_{12}}$, and equation (24), $\dot{W}_s/\dot{W}_a$ can be found from equation (18). Equation (19) can then be used to determine the bypass ratio at each point in figure 2.

When the bypass ratio (BPR) equals zero, all of the air passes through the heat exchanger; this produces a lower limit on air exit temperature. Therefore, the curves for each P_{a_2}/P_{a_1} exist from 1000° R (555 K) down to the air exit temperature where BPR = 0. This has been indicated in figure 2.

The maximum efficiency along each curve occurs at or near BPR = 0. In fact, the loss suffered by the decrease in overall efficiency in going to BPR = 0 may be offset by the benefits of the elimination of the nozzle for the bypassed air. It is important to note that at this point the steam turbine efficiency has been assumed to be constant within the liquid-vapor region. However, the condensation of steam to water on the turbine blades might cause both erosion of the blades and a decrease in efficiency. Since more water will be formed as BPR = 0 is approached, the consequent variation in turbine efficiency will tend to increase the indicated value of BPR that yields maximum η_{oa}.

Besides a peak in overall efficiency, the curves in figure 2 have another distinctive characteristic: a discontinuity in slope at an air exit temperature of approximately 700° R (390 K) (750° R (415 K) steam temperature). At this steam temperature and a steam turbine efficiency of 0.88, the expansion process terminates at a point just above the saturation line on a Mollier diagram. Expansion to lower temperature terminates in the vapor-liquid region. The point at which this discontinuity occurs will vary with $\eta_{s_{12}}$, being about 780° R (435 K) steam temperature at a turbine efficiency of 1.0.

The corresponding air-to-steam flow rate ratios are shown in figure 3. Again the discontinuity occurs at a T_{a_3} of 700° R (390 K).

Thrust per unit airflow. - The effect of heat-exchanger-outlet air temperature on thrust per unit airflow rate $F/\dot{W}_a$ for a steam turbine efficiency of 0.88 is shown in figure 4. The parameter $F/\dot{W}_a$ is important in two respects. First, it is a measure of the airflow required to produce a given thrust and will be a decisive factor in air fan and heat-exchanger size and weight (the higher the $F/\dot{W}_a$, the better). Secondly, from equation (16) it can be seen that the power of the reactor $\Delta h_{s_{14}}$ varies directly with $F/\dot{W}_a$ and inversely as the cycle efficiency. Thus, for fixed V_0 there exists a minimum power corresponding to where the ratio $F/\dot{W}_a/\eta_{oa}$ is a minimum. However, it was shown in figure 2 that η_{oa} varied inversely with T_{a_3} and it was just shown in figure 4 that $F/\dot{W}_a$ varies directly as T_{a_3}. Thus, $F/\dot{W}_a/\eta_{oa}$, and hence the power, varies directly as T_{a_3}. It can thus be concluded that minimum T_{a_3} yields both minimum power and maximum air fan and heat-exchanger size and weight. Since minimum T_{a_3} corresponds to zero BPR, a tradeoff between power requirement (and weight) against air fan and heat-exchanger size and weight is necessary to determine whether or not the turbojet (zero BPR) cycle of reference 4 was the optimum. In addition, the possible change in turbine efficiency as steam is expanded further into the liquid-vapor region should be taken into account, since this would tend to favor higher (>0) values of BPR.

Effects of Other Cycle Parameters

The remainder of this report discusses the variation of the cycle parameter to show their effect on η_{oa} and $F/\dot{W}_a$.

Steam temperature. - The results presented so far have been for a steam temperature of 1360° R and a pressure of 1000 psia. The effect of steam temperature on efficiency is shown in figure 5 and on thrust per unit airflow in figure 6.

In figure 5 it can be seen that overall efficiency increases with steam temperature. Almost 4 points in efficiency are gained by going from 960° to 1660° R (535 to 920 K) at 600° R (335 K) heat-exchanger-outlet air temperature. Thus, power requirements will be lower. At the same time, however, reactor and heat-exchanger weights will rise as a result of the higher temperature. Thus, there is a tradeoff between decreasing shield weight and increasing component weight.

In figure 6, thrust per unit airflow rate is seen to fall with increasing steam temperature. Again, power will be decreased while air fan and heat-exchanger weight will rise.

Steam pressure. - Variation of steam pressure is shown in figures 7 and 8. Overall efficiency is seen to change by less than 1 point at a T_{a_3} of 600° R (335 K) (the saturated region). In the superheated region, there is almost no change at all in efficiency.

Thrust per unit airflow rate is also insensitive to steam pressure decreasing slightly with the increasing pressure.

Air fan efficiency. - The efficiency of the air fan is varied in figure 9. As shown in the figure, fan efficiency has a strong effect on overall efficiency in both the saturated and superheated regions. At a heat-exchanger-outlet air temperature of 600° R (335 K), overall efficiency increases from 0.246 to 0.270 as fan efficiency increases from 0.80 to 0.92.

In figure 10, thrust per unit airflow is seen to increase with decreasing fan efficiency. This is a result of the increase in bypass air temperature caused by the inefficiency of the fan (eq. (7)). This, in turn, leads to higher fan air jet velocity and more thrust (eqs. (12) and (15)).

Steam turbine efficiency. - The effect of steam turbine efficiency on overall efficiency and on thrust per unit airflow is shown next in figures 11 and 12. Steam turbine efficiency will likely be a function of the condition of the steam after expansion. The assumed value throughout the report of 0.88 is probably optimistic for expansions where a significant amount of water may be formed on the turbine blades. Efficiency usually decreases as the quality of the steam after expansion decreases. As previously mentioned, this situation of low-quality steam after expansion is encountered in the low BPR region that is found to yield maximum η_{oa}. Hence, the direct effect of turbine efficiency shown in figure 11 is supplemented by the effect of varying turbine efficiency on optimum BPR. A more thorough investigation of the steam cycle would have to take this variation of turbine efficiency into account. In the liquid-vapor region, $\eta_{s_{12}}$ strongly affects overall efficiency. This is a result of the rapid change of enthalpy of the water with temperature relative to the rate in the superheated region. Overall efficiency increases with turbine efficiency.

Thrust per unit airflow changes only slightly with steam turbine efficiency in both the two-phase and superheated regions.

Heat-exchanger-approach temperature difference. - The last effect to be shown is that of hot-side heat-exchanger-approach temperature difference, which is the temperature difference between the steam entering and the air exiting the heat exchanger. If this temperature difference is zero, an infinite heat-transfer area would be required. Thus, the larger this difference, the smaller the heat exchanger. Figure 13 shows that approach temperature strongly affects efficiency in both the liquid-vapor and superheated regions. The tradeoff here then is reduced power requirements with decreasing approach temperature against the rapid rise in heat-exchanger size and weight.

Thrust per unit airflow as affected by approach temperature is shown in figure 14. Increasing approach temperature increased $F/\dot{W}_a$.

An important phenomenon frequently occurs when considering two-phase flow through a heat exchanger: the so-called "pinch effect." In the cases studied herein, the majority of the heat transferred from steam to air occurs from the condensing of steam to water at essentially constant temperature. The heat transferred by the cooling of the steam prior to condensation is negligible in comparison. For example, if steam were cooled from 1050° R (583 K) and 265 psia (1.83×10^6 N/m^2) to water at 860° R (478 K) and 250 psia (1.725×10^6 N/m^2), the Δh from cooling of the steam would be approximately 100 Btu per pound (2.32×10^5 J/kg) and from condensation about 825 Btu per pound (1.91×10^6 J/kg). Figure 15 sketches a temperature profile across the heat exchanger for these conditions.

The pinch effect shows up, that is, the minimum temperature difference between air and steam temperature is not at the hot end of the heat exchanger but somewhere in the middle. In the case sketched in figure 15, air temperature exceeds steam temperature, which is a physical impossibility. This cycle would not work.

Thus, although in all the previous cases studied there was a temperature difference at the hot end of the heat exchanger, the pinch effect will frequently show up if the steam expansion through the turbine results in superheated steam conditions. Luckily, however, expansion into, or close to, the liquid-vapor region does not result in negative temperature differences. Since it has been previously shown that the areas of interest for this cycle are the cases where an expansion into the two-phase region does occur, the pinch effect has been neglected and the fact that the curves do not extend as far as indicated into the superheated region is ignored.

CONCLUDING REMARKS

The preceding analysis applies to a steam-driven nuclear-powered turbofan engine. It is found that, for constant turbine efficiency, the maximum overall engine efficiency occurs at zero bypass ratio (BPR), which is turbojet operation, and this is the most desirable operating condition from a cycle-analysis viewpoint. This may not be true, however, if there is a significant decrease in turbine efficiency as a result of expanding into the two-phase region. Erosion may also become a problem. Other cycles using reheat or regeneration might be used to avoid these effects, but were not studied herein. Zero BPR is also not necessarily the best operating condition from the aircraft viewpoint, because it also implies minimum thrust per unit airflow. Thus, there is a possible trade between power (and hence, reactor and shield weight) on one hand, and engine size, weight, and drag on the other.

Further analyses to account for component weights, component efficiencies, and aircraft configuration and flying qualities must be made to determine the optimum BPR for each mission application. The numerical results presented herein will support initial studies of that kind. The major trends appearing the present results are summarized in the following table:

Quantity which is increasing	Response of -	
	Overall efficiency	Thrust per unit airflow
Heat-exchanger-outlet air temperature	Decreases	Increases
Fan pressure ratio	Increases	Increases
Steam temperature	Increases	Decreases
Steam pressure	Increases	Decreases
Fan efficiency	Increases	Decreases
Turbine efficiency	Increases	Decreases
Approach temperature	Decreases	Increases

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 18, 1969,
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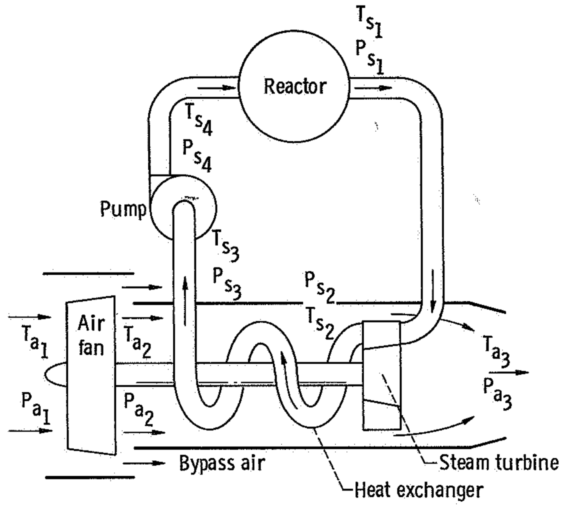

Figure 1. - Schematic of closed steam cycle.

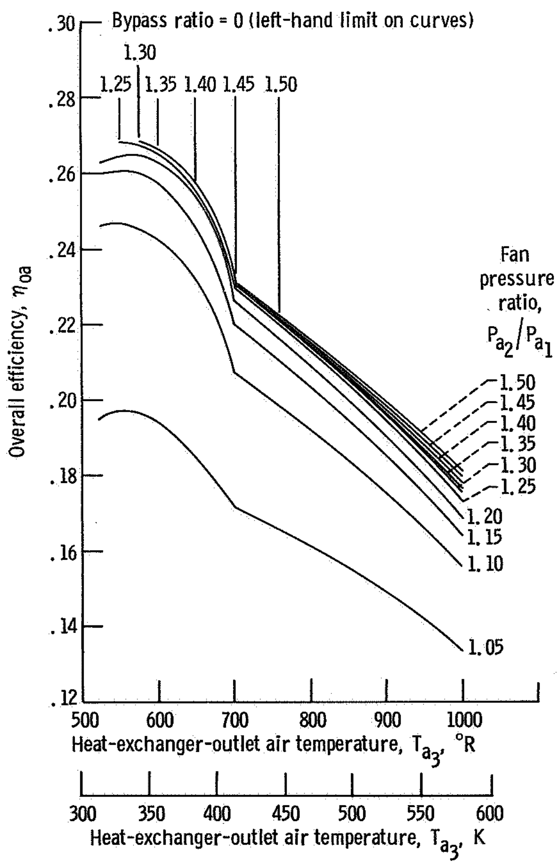

Figure 2. - Effect of fan pressure ratio on overall efficiency as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

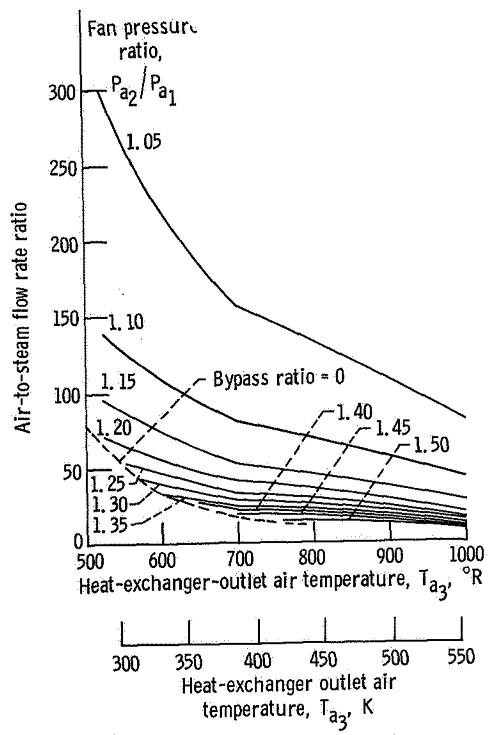

Figure 3. - Effect of fan pressure ratio on air-to-steam flow rate ratio as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895x10^{6} N/m^{2}); Mach 0.8; altitude, 36 089 feet (11 km).

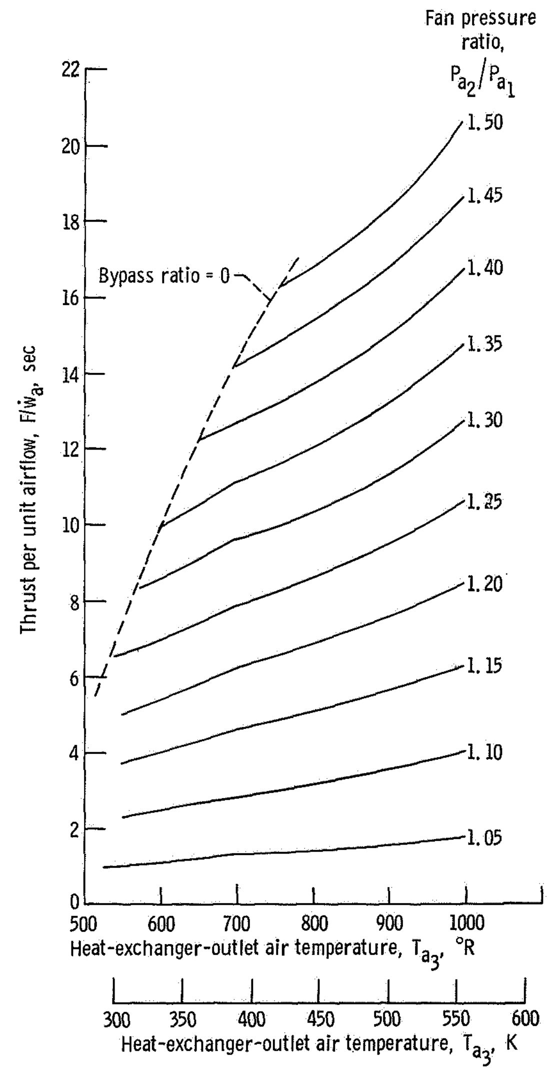

Figure 4. - Effect of fan pressure ratio on thrust per unit airflow as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895x10^{6} N/m^{2}); Mach 0.8; altitude, 36 089 feet (11 km).

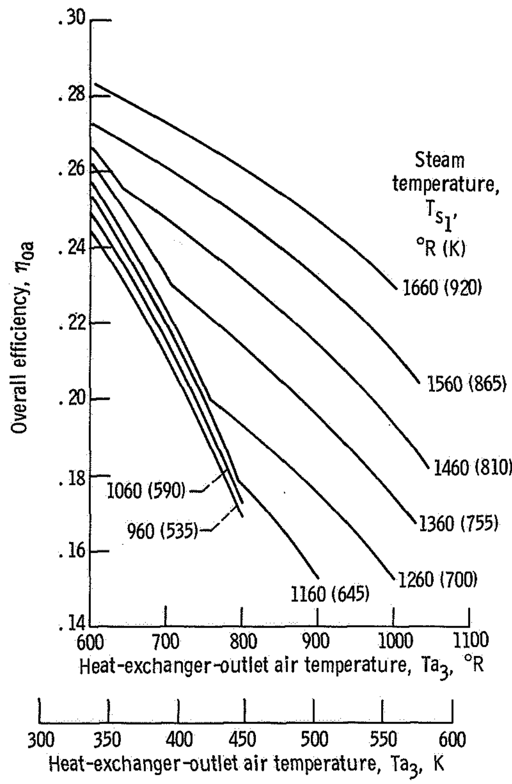

Figure 5. - Effect of steam temperature out of the reactor on overall efficiency as function of heat-exchanger-outlet air temperature. Fan pressure ratio, 1.3; steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

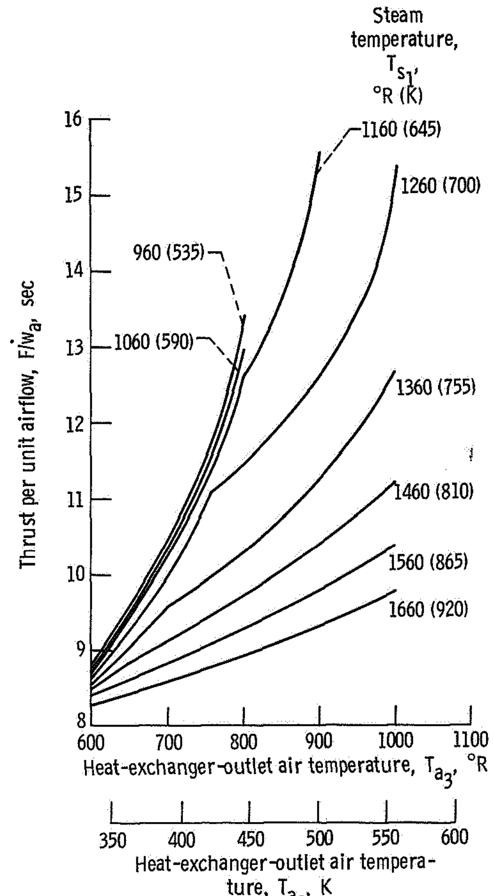

Figure 6. - Effect of steam temperature, T_{a_3}, K reactor on thrust per unit airflow rate as function of heat-exchanger-outlet air temperature. Fan pressure ratio, 1.3; steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

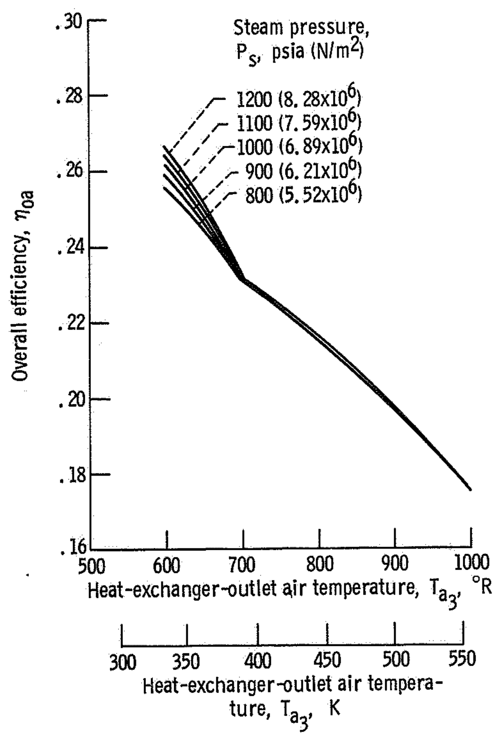

Figure 7. - Effect of steam pressure out of the reactor on overall efficiency as function of heat-exchanger-outlet air temperature. Fan pressure ratio, 1.3; steam temperature, 1360° R (755 K); Mach 0.8; altitude, 36 089 feet (11 km).

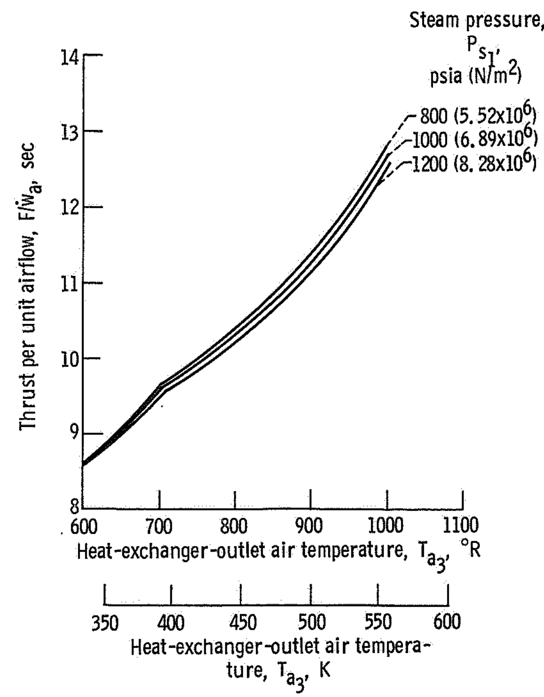

Figure 8. - Effect of steam pressure out of the reactor on thrust per unit airflow as function of heat-exchanger-outlet air temperature. Fan pressure ratio, 1.3; steam temperature, 1360° R (755 K); Mach 0.8; altitude, 36 089 feet (11 km).

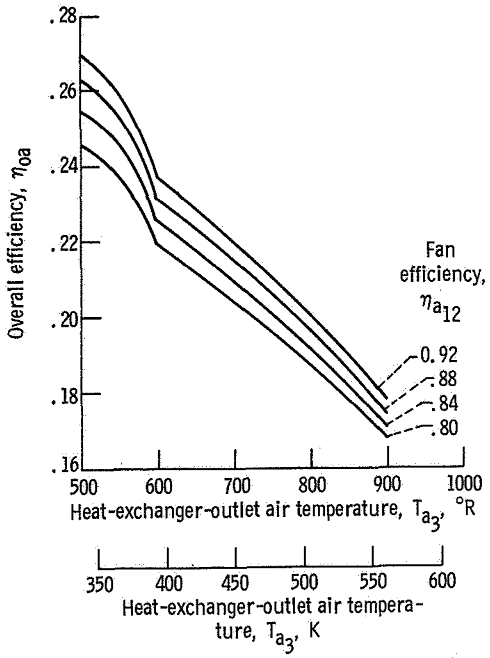

Figure 9. - Effect of fan efficiency on overall outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

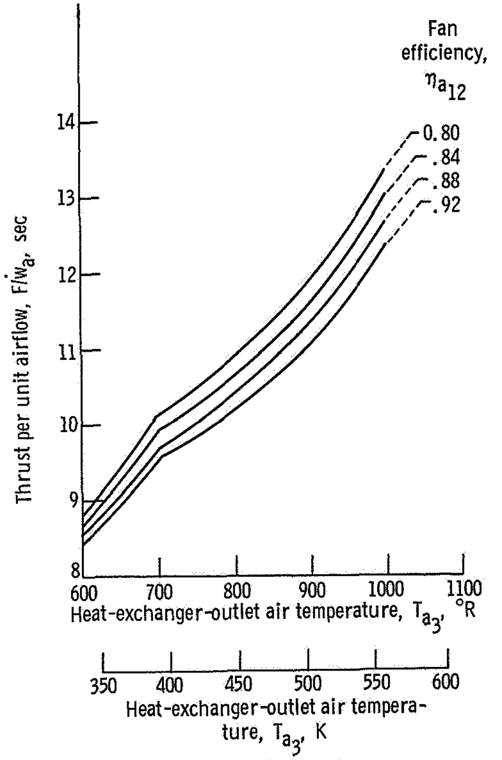

Figure 10. - Effect of fan efficiency on thrust per unit airflow as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

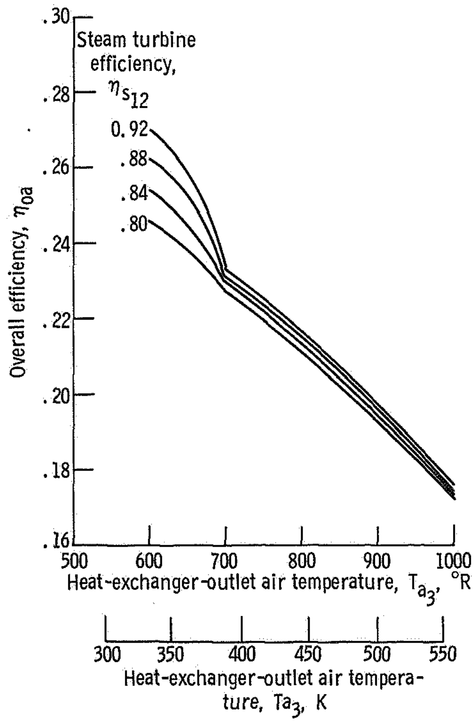

Figure 11. - Effect of steam turbine efficiency on overall efficiency as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

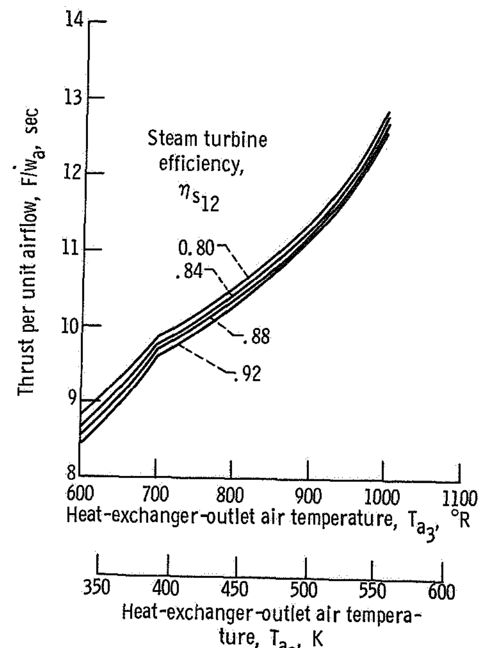

Figure 12. - Effect of steam turbine efficiency on thrust per unit airflow as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

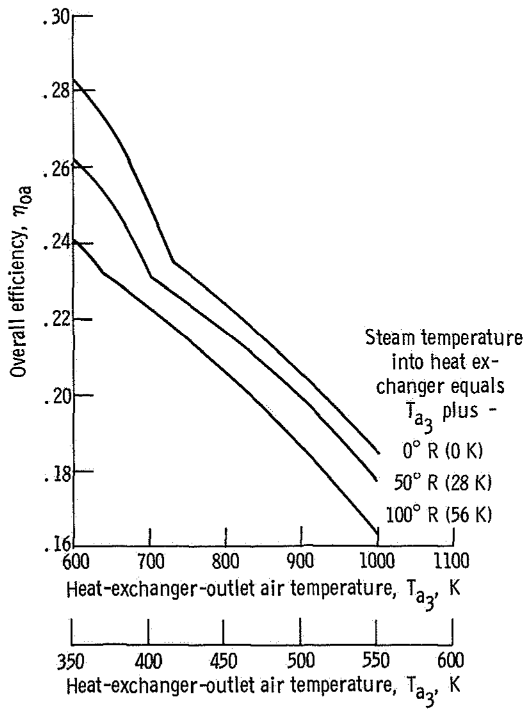

Figure 13. - Effect of hot-side heat-exchanger-approach temperature on overall efficiency as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

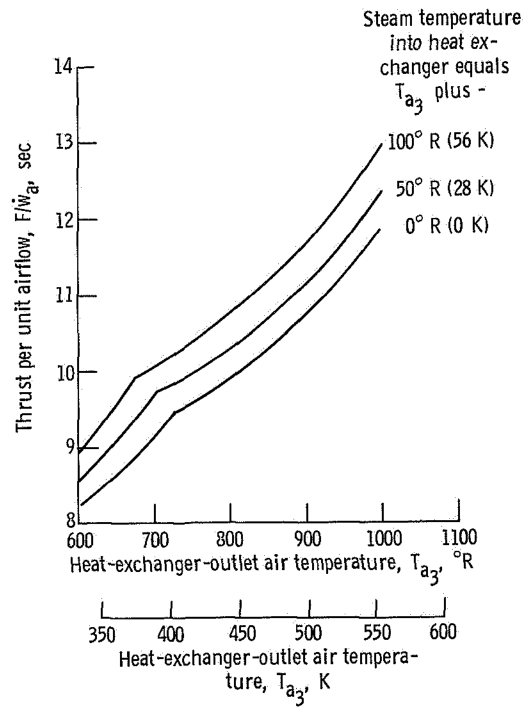

Figure 14. - Effect of hot-side heat-exchanger-approach temperature on thrust per unit airflow as function of heat-exchanger-outlet air temperature. Steam temperature, 1360° R (755 K); steam pressure, 1000 psia (6.895×10^6 N/m^2); Mach 0.8; altitude, 36 089 feet (11 km).

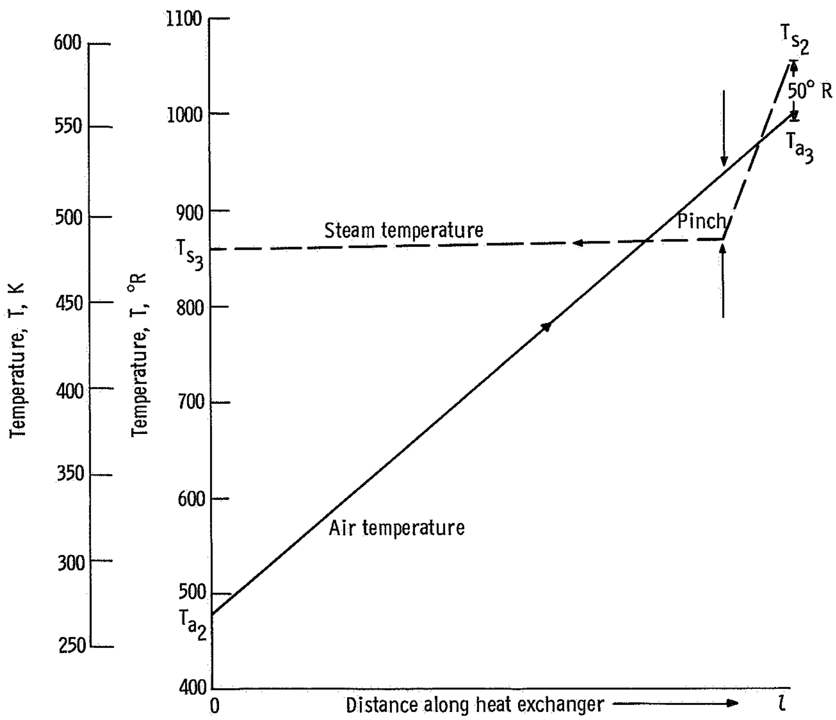

Figure 15. - Temperature profile across heat exchanger.

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