**NASA TECHNICAL MEMORANDUM**

NASA TM X-52524

NASA TM X-52524

FACILITY FORM 602

N69-14092
(ACCESSION NUMBER)
(THRU)
34
(PAGES)
1
(CODE)
TMX-52524
(NASA CR OR TMX OR AD NUMBER)
02
(CATEGORY)

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Lewis Research Center
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

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E-4834

## SUMMARY

A preliminary design-point study was made of the applicability of nuclear propulsion to very large VTOL aircraft. Fan-in-wing lift engine configurations were analyzed using three different thermodynamic cycles: a helium Brayton cycle, a liquid metal Rankine cycle with duct heating by the condenser, and a liquid metal Rankine cycle with the condenser in the wing.

A gross weight of one million pounds and a design cruise Mach number of 0.8 at an altitude of 36 089 feet were assumed. Variation of gross weight was also considered. Areas of interest in terms of hover time and range requirements were determined that show where nuclear VTOL's appear to be superior to conventional VTOL's.

It was found that gross weight is the most significant design parameter affecting the performance of nuclear VTOL aircraft and that the Brayton cycle outperforms the Rankine cycles.

## INTRODUCTION

Air traffic congestion over major city airports is a serious and growing problem. For instance, reference 1 suggests that air traffic may triple in the next ten years. A further measure of delay and inconvenience is often added by ground transportation systems because of the remoteness of major airports from downtown business districts.

These problems markedly reduce the convenience and desirability of air travel, especially for business trips between closely spaced large cities. They could be alleviated simultaneously, however, by operating large high-speed inter-city VTOL aircraft between downtown verti-ports.

Unfortunately, routes involving numerous and/or widely separated stops may demand performance (e.g., a combination of cruising speed, unrefueled range, and hover time) beyond the capability of conventional (chemically fueled) aircraft. Relief from this situation might be provided by using a nuclear-powered VTOL aircraft for the most demanding inter-city routes.

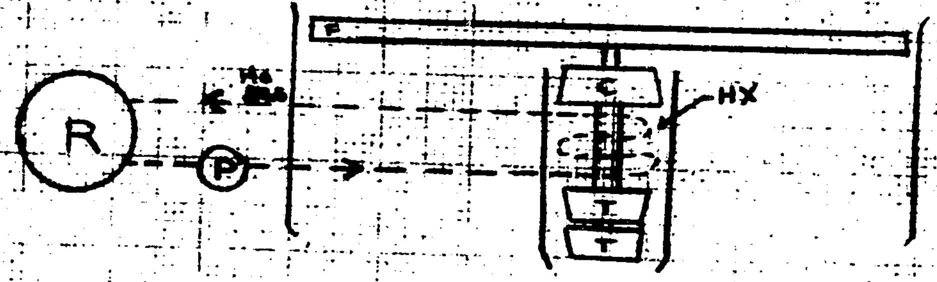
To the best of the authors' knowledge, no previous study of this alternative has been reported. This paper, therefore, presents a preliminary analysis of the performance characteristics of large nuclear VTOL aircraft. Potential areas of application are derived in an approximate manner by comparing the nuclear component weights with the chemical fuel weight of conventional VTOL's.

There are also several military mission requirements that a nuclear VTOL might fulfill. Many surveillance and search-and-rescue missions call for long range coupled with large hover endurance. This is especially true for search-and-rescue missions over desolate and hostile areas such as the frozen wastelands of the Arctic.

Three thermodynamic cycles for the lift engines are considered: (1) A helium Brayton turbofan cycle (Sketch a) - Air is compressed by a fan and then split into two streams. One stream is simply expanded in a nozzle to generate thrust while the other is further compressed, heated by an air-helium heat exchanger, expanded through fan and compressor drive turbines, and finally exhausted through a nozzle to generate additional thrust. Helium is pumped from the reactor to the heat exchanger and back to the reactor. (2) A liquid metal Rankine cycle with duct heating by the condenser (Sketch b) - Air is compressed by a fan, heated by a liquid metal-air heat exchanger, and expanded through a nozzle to produce thrust. Liquid metal (potassium) is vaporized in the reactor, expanded through a turbine that drives the fan, condensed in the heat exchanger and returned to the reactor. (3) A liquid metal Rankine cycle with the condenser in the wing (Sketch c) - This cycle is the same as the previous cycle except that the liquid metal condenser is placed in the aircraft wing instead of the fan duct. The condenser operates mainly by radiation rather than by convection.

Other assumptions include: (1) A gross weight of 1 000 000 pounds for most calculations. (2) A design Mach number of 0.8 at an altitude of 36 089 feet. (3) A fan-in-wing lift engine configuration. (4) A crew radiation dose rate of .0025 rem/hour at 130 feet separation. For passenger applications, the passenger areas are closer to the reactor than the crew, so their dose rate would be higher than this. But it is assumed that passengers would be exposed for shorter times (less flights) so that their total accumulated dose would be below recommended standards. (5) Cruise engines are turbofan Brayton types.

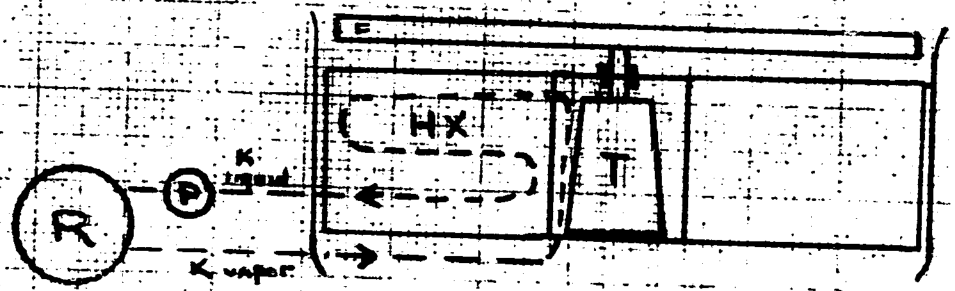
The conceptual design of the aircraft is shown in figure 1. This conventional, high L/D configuration is not necessarily optimum for the present application, but was chosen for simplicity and to facilitate comparisons with previous work. For one million pounds gross weight, the overall dimensions of this aircraft approximate those of the C5-A.



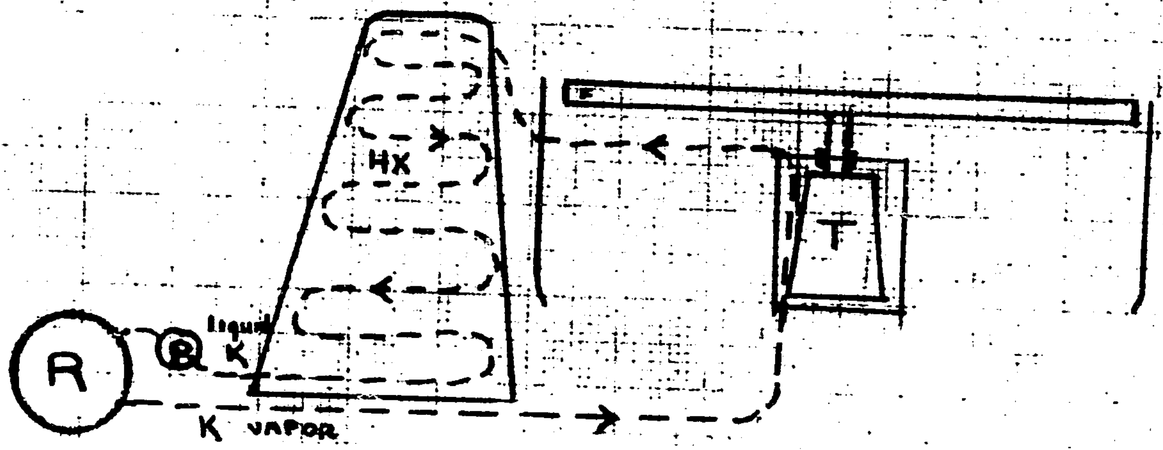
SKETCH a: BRAYTON CYCLE

**LEGEND**

C - compressor
F - fan
HX - heat exchanger
P - pump
R - reactor
T - turbine



SKETCH b: RANKINE CYCLE - DUCT HEATED



SKETCH c: RANKINE CYCLE - CONDENSER IN WING

# SYMBOLS

| | |
|---|---|
| $A$ | area, $ft^2$ |
| BPR | bypass ratio |
| $C$ | wing mean aerodynamic chord |
| $C_p$ | specific heat at constant pressure, BTU/(lb°F) |
| $F$ | thrust, lb |
| $F/P$ | thrust to power ratio, lb/MW |
| HX | heat exchanger |
| $h$ | convective heat transfer coefficient, BTU/(hr $ft^2$°F) |
| $k$ | thermal conductivity, BTU/(hr $ft^2$ °F/ft) |
| $N_{Pr}$ | Prandtl number, $\frac{C_p \ \mu}{k}$ |
| $N_{Re}$ | Reynolds number, $\frac{\rho C U}{\mu}$ |
| $(P/P)_{turb}$ | turbine pressure ratio |
| $P_2/P_1$ | fan pressure ratio |
| $P_3/P_2$ | compressor pressure ratio |
| $P_t$ | heat transferred by condenser, MW |
| $T$ | heat transfer area surface temperature, °R |
| $T_o$ | ambient temperature, °R |
| TIP | turbine inlet pressure |
| TIT | turbine inlet temperature, °R |
| $U$ | velocity of air over wing, ft/sec |
| $W$ | weight, lbs |
| $\mu$ | viscosity, lb/(hr ft) |
| $\rho$ | air density, $lb/ft^3$ |

| | |
|---|---|
| $\eta_F$ | adiabatic fan efficiency |
| $\eta_T$ | adiabatic turbine efficiency |
| $\sigma$ | Stefan-Boltzmann constant, $1.713\text{x}10^{-9}$ BTU/(ft$^2$hr°R$^4$) |

## Subscripts

| | |
|---|---|
| c | cruise |
| eng | engine |
| g | gross |
| HX | heat exchanger |
| L | payload |
| $r+s$ | reactor plus shield |
| str | structure |
| VTOL | vertical takeoff and landing |

## ANALYSIS

Payload equations may be written for each of the three engine cycle types by attributing the aircraft's non-payload weight to appropriate subsystems. The subsystem weight discussion that follows is broken down into three separate sections--each dealing with a particular engine cycle type.

### Rankine Cycle With Condenser-in-Wing Design

In this design, all the condensers are assumed to be an integral part of the wing structure. Heat removal takes place by both radiation and convection processes. The highest heat load occurs during liftoff and letdown when the reactor is operating at or near peak power. Unfortunately, the convective heat transfer coefficient is at a minimum during these phases since the flight velocity is near zero. This mismatch results in a heat transfer area requirement substantially in excess of the aerodynamic wing area requirement. Thus, the wing area is "oversized" to accommodate the condenser-in-wing concept.

For payload computational purposes, the aircraft is assumed to be composed of structure, reactor and shield, VTOL engines, cruise engines, and payload. Thus, the payload equation for this system is:

$$W_L = W_g - W_{str} - W_{r+s} - W_{eng,VTOL} - W_{eng,c} \tag{1}$$

The relationship used to predict the total aircraft structure weight is:

$$W_{str} = 0.24\ W_g + 0.11\ W_g \left(\frac{A_{wing}}{11750}\right)^{0.54} \tag{2}$$

This equation reflects the results of reference 2 that showed that about 11 percent of the aircraft weight was attributable to the wing structure and that wing weight varied as the 0.54 power of the area for very large wings. The constant 11 750 is a reference wing area that causes $W_{str}$ to have a value of 0.35 $W_g$ at the selected design point of 0.8 Mach number, 36 089 feet altitude, and a gross weight of one million pounds. (The same value will be used for the other two cycles.) Structure weight includes equipment and many subsystems such as instrumentation, control system, galleys, wiring, etc. The value of 0.35 $W_g$ was obtained from reference 2 which includes allowances for special features not required for VTOL operation. However, the allowances are considered to be an even trade with the more demanding control system requirements associated with VTOL flight. No weight penalty is included here to account for the lift fan holes in the wing. This could add 12-30 percent to the wing weight. Equation (2) also implies the further, and perhaps debatable, assumptions that a hybrid condenser-in-wing structure would weigh the same as a conventional wing structure, and that the condenser/wing surfaces do not interfere with the lift fans in the wing.

The heat transfer area, $A_{wing}$, was calculated with simplified relationships as follows. Assume that the wing is a flat plate with both surfaces at temperature T and radiates as a black body, the air and ground are at ambient temperature $T_0$ and are nonradiating.

The heat transferred per unit area is:

$$\frac{P_t}{2A_{wing}} = \sigma\ T^4 + h\ (T - T_o) \tag{3}$$

where, from reference 3,

$$h = 0.036\ \frac{k}{C}\ N_{Pr}^{1/3}\ \ N_{Re}^{0.8} \qquad \text{(forced convection)} \tag{4}$$

$$h = 0.22\ (T - T_0)^{1/3} \qquad \text{(free convection)} \qquad (5)$$

The heat transferred per unit area is shown in figure 2 as a function of the surface temperature T. The dashed curve is for radiation heat transfer only (first term of equation (3)), and the solid curves represent both radiation and convective heat transfer for various flight velocities. VTOL operation corresponds to near zero flight speed. The 50 and 100 ft/s flight speed curves are displayed mainly for comparison with STOL operation. The figure shows that most of the heat is transferred by radiation; and, therefore, high condensation temperatures are required to reduce the high surface area requirements.

The weight of the reactor and shield ($W_{r+s}$) was taken to be:

$$W_{r+s} = 3.8\text{x}10^5 \left(\frac{\text{Power, MW}}{1000}\right)^{0.582} \qquad (6)$$

where the installed power was assumed to be 1.1 times the zero acceleration power plus a 6 percent power allowance for liquid metal pumps. For a helium-cooled thermal reactor, equation (6) is a curve fit to the combination heavy-metal and water shield data shown in figure 3. This figure is based on data in reference 2. The higher exponent (0.582) than that used in reference 2 (0.4) is a result of the very high power levels involved. At high power levels, the reactor core weight becomes a significant part of the entire system weight since it varies as $(\text{Power})^{1.0}$ while shield weight varies as $(\text{Power})^{0.4}$. Liquid metal reactors would probably not differ significantly in size or weight from helium systems according to reference 4.

The VTOL engine weight ($W_{eng,\ VTOL}$) was calculated by assuming that the engine thrust-weight ratio was either 15 or 20. Lift engines with thrust-weight ratios of 15 have already been run while 20 to 1 engines are currently being developed. Although these numbers really represent Brayton cycle engines, they were taken to represent the Rankine cycle engines as well because similar data for the Rankine engines is lacking. This assumption is judged to be not critical since the VTOL engines account for only about 6 percent of the gross weight.

The cruise engine weight $W_{eng,c}$ was taken from reference 2 (which used cruise sizing of the engines) at the prescribed design point and is 0.075 $W_g$. This implies that the cruise engines are of the Brayton type or, alternatively, that the Rankine and Brayton engine weights are comparable. Furthermore, it is optimistic for this case if the wing area is substantially larger than the reference area of 11 750 square feet. This is because the airplane drag will increase as $A_{wing}$ increases; and, hence, more thrust and engine weight will be required than that used to obtain the above number. As will be seen later, the condenser-in-wing design has rather poor performance; and, therefore, the above optimism strengthens this conclusion.

## Rankine Cycle With Duct Heating

Instead of placing the condenser within the wing, this system employs condensers within the engine ducts downstream of the fans. This scheme allows for less heat exchanger surface area due to the forced convection of the fans and also increases the thrust of the engines provided the air-side pressure drop is not too great.

The aircraft is assumed to be composed of structure, reactor and shield, VTOL engines, cruise engines, VTOL heat exchangers, cruise heat exchangers, and payload.

Thus, the payload equation for this system is:

$$W_L = W_g - W_{str} - W_{r+s} - W_{eng,VTOL} - W_{eng,c} - W_{HX,VTOL} - W_{HX,c} \quad (7)$$

The structure weight is assumed to be 35 percent of the vehicle gross weight which is consistent with the preceding case. The reactor-shield and engine weights are calculated as before for the condenser-in-wing design. The cruise engine heat exchanger weight $W_{HX,c}$ was taken to be 5 percent of the gross weight (ref. 2). The lift engine heat exchanger (condenser) weight $W_{HX,VTOL}$ was calculated with a Lewis Research Center computer code. Essentially, the heat exchanger weight was taken to be the computed tube bundle weight plus a 20 percent support structure allowance.

## Brayton-Turbofan Cycle

The payload equation for this system is:

$$W_L = W_g - W_{str} - W_{r+s} - W_{eng,VTOL} - W_{eng,c} - W_{HX,VTOL} - W_{HX,c} - W_{ducts} \quad (8)$$

The subsystem weight assumptions for this system are identical to those for the duct-heated Rankine system with the exception of the lift engine heat exchanger weight. The latter was calculated by an approximation for the heat exchanger weights determined in reference 2; namely,

$$W_{HX,VTOL} = 57\ (\text{Power, MW}) + 300 \qquad (9)$$

Although one might expect $W_{HX,VTOL}$ to be a function of bypass ratio, turbine inlet temperatures and total pressure ratio, tradeoff studies revealed that if these variables are optimized, equation (9) holds fairly well. A weight allowance was also made for the high pressure ducts that conduct helium from the reactor to the cruise engines. This allowance $W_{ducts}$ is taken from reference 2 and is 2 percent of the gross weight.

With the above assumptions, all that is necessary to calculate payload numbers is a reactor power level computation. Power was minimized in the Brayton turbofan cycle calculations by optimizing the fan pressure ratio and overall pressure ratio for specified values of bypass ratio and turbine inlet temperature. The reactor average wall temperature was 2160° F. The Rankine thermodynamic calculations were done mostly for potassium with an 1800° F turbine inlet temperature (TIT) and represent equivalent technology level as the Brayton cycle. The turbine efficiency and expansion ratio were varied parametrically.

## RESULTS

### Brayton Cycle

Figure 4 shows how payload varies with BPR for the helium turbofan cycle. Turbine inlet temperature and $F/W_{eng,VTOL}$ are also parameters. While these parameters seem to affect payload strongly on the plot for one million pound aircraft, they are really much more insensitive parameters when larger gross weights are considered. The important point is that even at high values of turbine inlet temperature and extremely high bypass ratios, the payload ratio is quite small--less than 5 percent for a one million pound aircraft.

The optimum fan pressure ratios, overall pressure ratios, and power levels are displayed on figures 5 and 6 as functions of bypass ratio. In particular, it is evident that quite high bypass ratios are desired in order to reduce the very high power requirement (~1000 MW)--provided there is no significant decrease in $F/W_{eng,VTOL}$.

### Rankine Cycles

Under the present assumptions (which are already optimistic for the Rankine cycles (see comments on pages 4, 5, and 6), neither of the Rankine cycles yielded a positive payload at a gross weight of one million pounds. The calculations and tradeoffs involved in reaching this conclusion are discussed in appendix A. In essence, extremely low lift fan pressure ratios and, hence, very large diameter fans are required in either case. Thus, there is an enormous VTOL heat exchanger weight penalty for the duct-heated version. For the condenser-in-wing approach, heat transfer area requirements dictate a wing that is oversized by nearly an order of magnitude. This brings about a large structural weight penalty also. In either case, the weight penalties exceeded the payload capacity of the airplane even without considering the lower aerodynamic efficiency inherent in these configurations.

## Effect of Gross Weight

Figure 7 shows the variation of payload with aircraft gross weight for three different nuclear propulsion systems. The solid curve represents an advanced turbofan cycle of bypass ratio equal to 30 and a 1740° F turbine inlet temperature. The broken lines represent duct-heated Rankine cycles with assumed values of temperature and pressure. The top broken line is for a 1 percent air-side pressure drop across the duct heat exchanger (condenser), while the bottom line is for a 2 percent pressure drop. The optimum fan pressure ratios associated with these curves are quite low (e.g., 1.02 to 1.06). It is immediately apparent that the ground rule value of one million pounds gross weight is not an attractive one. The payload ratio is only 2 1/2 percent for the Brayton cycle aircraft and is negative for a Rankine cycle. The payload ratio for the Brayton cycle VTOL rises to 10 percent for a two million pound aircraft, to 16 percent for a five million pound aircraft, and to 28 percent for a ten million pound aircraft. Figure 7 also indicates that the Rankine cycle is not the best suited for this application. Besides delivering less payload than the turbofan cycles, it may be difficult to design duct condensers having such low air-side pressure drops as 1-2 percent.

The bar chart of component weights on figure 8 indicates why the Brayton cycle turbofan shows better performance than either of the Rankine cycles in figure 7. It is the relatively large VTOL heat exchanger weight caused by low cycle pressure of the Rankine system. (Raising the cycle pressure lowers the heat exchanger weight but increases the reactor-shield weight even more.) The condenser-in-wing system is also represented on figure 8. Its high structure weight, caused by oversizing the wing to accommodate condenser area requirements, eliminated any payload for the one million pound size aircraft.

The better performance potential of large sized VTOL nuclear aircraft is also seen in figure 9 which shows that the reason for increased payload ratio is a result of decreased reactor and shield ratios (recall that $W_{r+s} \alpha (\text{Power})^{0.582}$).

## Effect of Structure Weight

Reductions in the large $W_{str}$ would help increase $W_L$. To the extent that the large $W_{str}$ is associated with the high cruise L/D, we have an unusual opportunity to better the situation by picking an unconventional airframe with low $W_{str}$ even at the expense of low L/D. No increase in the $W_{r+s}$ is thereby required since only a small part of the installed VTOL-required power is presently needed for cruise; also, of course, the nuclear airplane does not suffer an increase in fuel consumption as a result of the low L/D. Figure 10 shows the tradeoff between cruise L/D and structure weight for constant payload. If a structure can be built, whose structure ratio lies below the tradeoff curve, then a payload increase is possible at reduced L/D.

## Fans, Propellers, Rotors, and Auxiliary Systems

Since the most attractive systems for nuclear VTOL invariably turn out to have very low pressure ratio "fans," it is of some interest to determine to what class of propulsion devices these systems belong. It is recognized that such classification is somewhat academic and that there also are various criteria for separating such devices into classes. Nevertheless, figure 11 shows a rough breakdown of such classes, according to their bypass ratio. From this standpoint, the nuclear lift engines tend toward shrouded props and helicopter type rotors for maximum payloads.

## Comparison With Chemical VTOL

It is evident from figure 7 that a nuclear VTOL sacrifices substantial payload capability to gain unlimited hover time and range in relation to a chemical VTOL. This is especially true for the smaller aircraft of one million pounds where the payload is only 25 000 pounds. Considering that the two million pound VTOL has ten times this payload capability, it is probable that nuclear VTOL aircraft would not be built for less than two million pounds.

The potential areas of interest for nuclear VTOL aircraft are defined in figure 12 in terms of range, hover time, and gross weight. Lines of constant gross weight are plotted in terms of range and hover time such that the region above a line is favorable to nuclear VTOL and the region below the line is favorable to chemical VTOL. Here, favorable is used to mean that higher payload capability is possible. These lines were calculated by equating the nuclear powerplant weight of the nuclear VTOL to the chemical fuel weight of the chemical VTOL. This figure indicates that the nuclear VTOL is attractive for ranges greater than 4000-5000 miles regardless of hover time requirements. It also is attractive for hover time requirements exceeding one hour for short range (1000 miles) missions. However, such long hover time requirements are more characteristic of large-scale search-and-rescue or surveillance missions than commercial transportation.

A hybrid chemical-nuclear VTOL might also be considered for short hover time requirements. For instance, if nuclear power were used only for the cruise portion of flight and 20 minutes of chemical fuel hover duration is required, then the one million pound craft payload would be 125 000 pounds. This is five times the all-nuclear VTOL payload for this gross weight. For higher gross weights, the effect would not be nearly so dramatic.

Another possibility is the use of short duration reactor operation at power levels considerably above the design point. If the reactor and shield assembly were designed for cruise power levels but could safely operate at VTOL power levels for short times, then a very large increase in payload would result. This would limit the hover time, however, to relatively short periods.

## CONCLUDING REMARKS

While such a preliminary analysis as this lacks numerical preciseness, the trends indicated should be valid. For instance, uncertainty in the weight estimates for the one million pound airplane is probably as large as the calculated payloads. However, for larger gross weights the payload ratio increases rapidly. The structure ratio of 35 percent represents a fairly conservative estimate, the range of present-day jets being between 30 and 38 percent. This conservatism does not reflect the growing use of new lighter, stronger composites which could significantly reduce the weight. Moderate weight savings in structure could produce sizable increases in payload; but large payload penalties could be incurred if the design thrust-weight margin were increased from 10 to 20 percent or safety hazard weight penalties were included.

An important economic factor is the development cost of such a system. The nuclear system would involve far greater development cost unless well-developed nuclear systems become available from other requirements. Of perhaps overriding importance in this application is the safety aspect. Nuclear disaster danger--either real or imagined--could easily prevent nuclear VTOL aircraft from operating within densely populated areas. In this regard, the hybrid propulsion concept seems noteworthy. It largely eliminates serious nuclear danger by the elimination of nuclear operation in close proximity to the ground and also provides good payload capability. However, it has poor multi-stop capability for pickup and discharge purposes. The following table summarizes the mission advantages and disadvantages of these three powerplant types.

| | Advantages | Disadvantages |
|---|---|---|
| Chemical | High payload capacity for all gross weights. | Limited hover endurance and range; multi-stop capability reduces payload and/or range. |
| Nuclear | Unlimited hover endurance and range; multi-stop capability without penalty. | Serious nuclear hazards; low payload capacity unless very high gross weights are utilized. |
| Hybrid | Unlimited range, moderately high payload capacity. | Moderate nuclear hazards, limited hover endurance; multi-stop capability reduces payload. |

The following conclusions may be drawn from this study:

1. Gross weight is the most significant parameter in determining the relative performance of nuclear-powered VTOL aircraft. Payload fraction for the Brayton cycle increases from 2.5 percent at a gross weight of one million pounds to 28 percent at a gross weight of 10 million pounds.

2. The Rankine cycle does not offer as much potential in terms of payload as the helium or liquid metal turbofan cycles. This conclusion results from the much more compact air-helium (or air-liquid metal) heat exchangers inherent in the high cycle pressure turbofans. Using cesium instead of potassium in the Rankine cycle would not alter this conclusion, although turbine design problems might be somewhat alleviated.

3. Substituting a liquid metal for helium in the Brayton cycle turbofan might be beneficial, but only small improvements, if any, are expected. This is because potential weight savings are centered about the heat exchangers which are relatively small weight items. Also, it might be necessary to shield the liquid metal to liquid metal heat exchangers of the additional fluid loop involved with liquid metal systems.

4. For maximum payload, all systems considered tended toward low fan pressure ratios and, hence, large fan diameters for the lift

engines. At some point, the systems become limited by fan size. Appropriate penalties for large fan size were not considered for tradeoff in this study.

5. Specific mission requirements for VTOL aircraft dictate the choice of powerplant type. If payload capacity is of prime importance and short range and hover times are acceptable, then the chemical VTOL aircraft is best suited for the application. But many current mass transportation requirements do not fall into this category. The capability for economical and rapid inter-city transfer to several closely spaced city centers is sorely needed at present. If many takeoffs and landings are required, then hovering time could increase to the point where a nuclear VTOL becomes attractive. So the attractiveness of nuclear VTOL to commercial inter-city transport application depends critically upon the number of unrefueled stops per flight.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 17, 1968,
789-50-01-01-22.

# APPENDIX A

## RANKINE CYCLE RESULTS

Positive payloads were not obtained for either Rankine cycle at one million pounds gross weight. Cycle performance is presented on figure 13 in terms of thrust per unit reactor power (F/P) as a function of fan pressure ratio. Under the given ground rules, maximizing F/P is equivalent to maximizing the payload. The dotted curve represents the condenser-in-wing design, while the solid curves are for duct-heating at various values of air-side pressure drop across the condenser. In either case, it is clear that very low fan pressure ratios reduce the power requirement and, hence, the reactor and shield weight. There are certain practical design constraints, however, that prevent use of very low fan pressure ratios. One constraint is the fan size and another is the difficulty in achieving a very small air-side pressure drop across the condenser for the duct-heated version. Accordingly, there is some minimum fan pressure ratio below which design difficulties and/or heat exchanger support structure weight penalties offset higher F/P ratios.

### Expansion Ratio

The Rankine cycle data presented above was calculated for a turbine expansion ratio of 79 (corresponding condensate temperature is 1460° R). The effect of varying the turbine expansion ratio on F/P is shown on figure 14 for the duct-heated system. Expansion ratios greater than 100 are probably not worthwhile, especially in view of the design and weight penalties associated with such high ratios.

### Turbine Efficiency

The 0.70 turbine efficiency assumed thus far for the Rankine cycles is varied for the duct-heated case in figure 15. There is a 25 percent change in F/P over the 0.6 to 0.8 turbine efficiency range.

### Area Requirement for Condenser-in-Wing System

Condenser area as a function of fan pressure ratio is shown on figure 16 for three condenser surface temperatures. The shaded band at the bottom of this plot represents conventional aircraft wing area (both top and bottom surfaces). Clearly, huge wing surfaces (or their equivalent) are required at practical fan pressure ratios.

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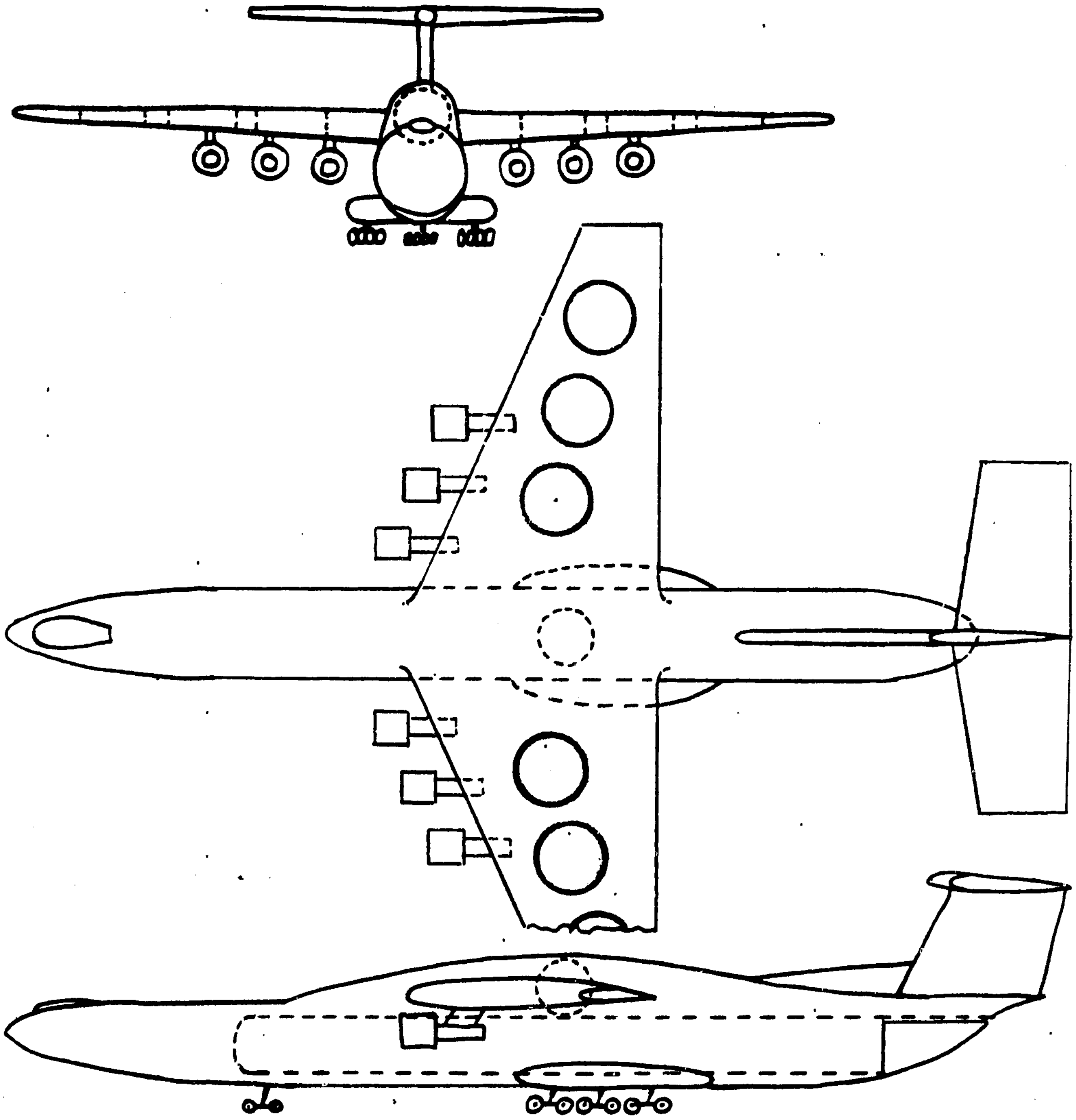

Figure 1 : Conceptual Design of Fan-in-Wing Nuclear VTOL

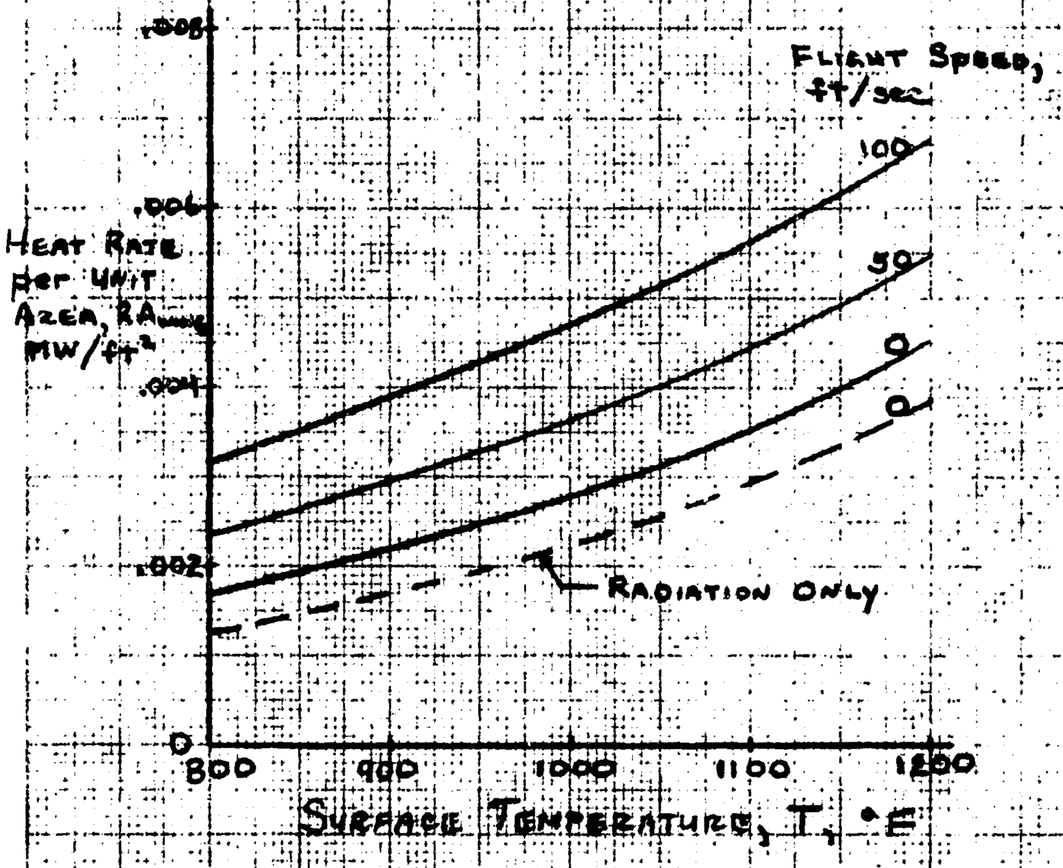

Figure 2: Heat transfer for condenser-in-wing configuration. $T_0$, 100°F.

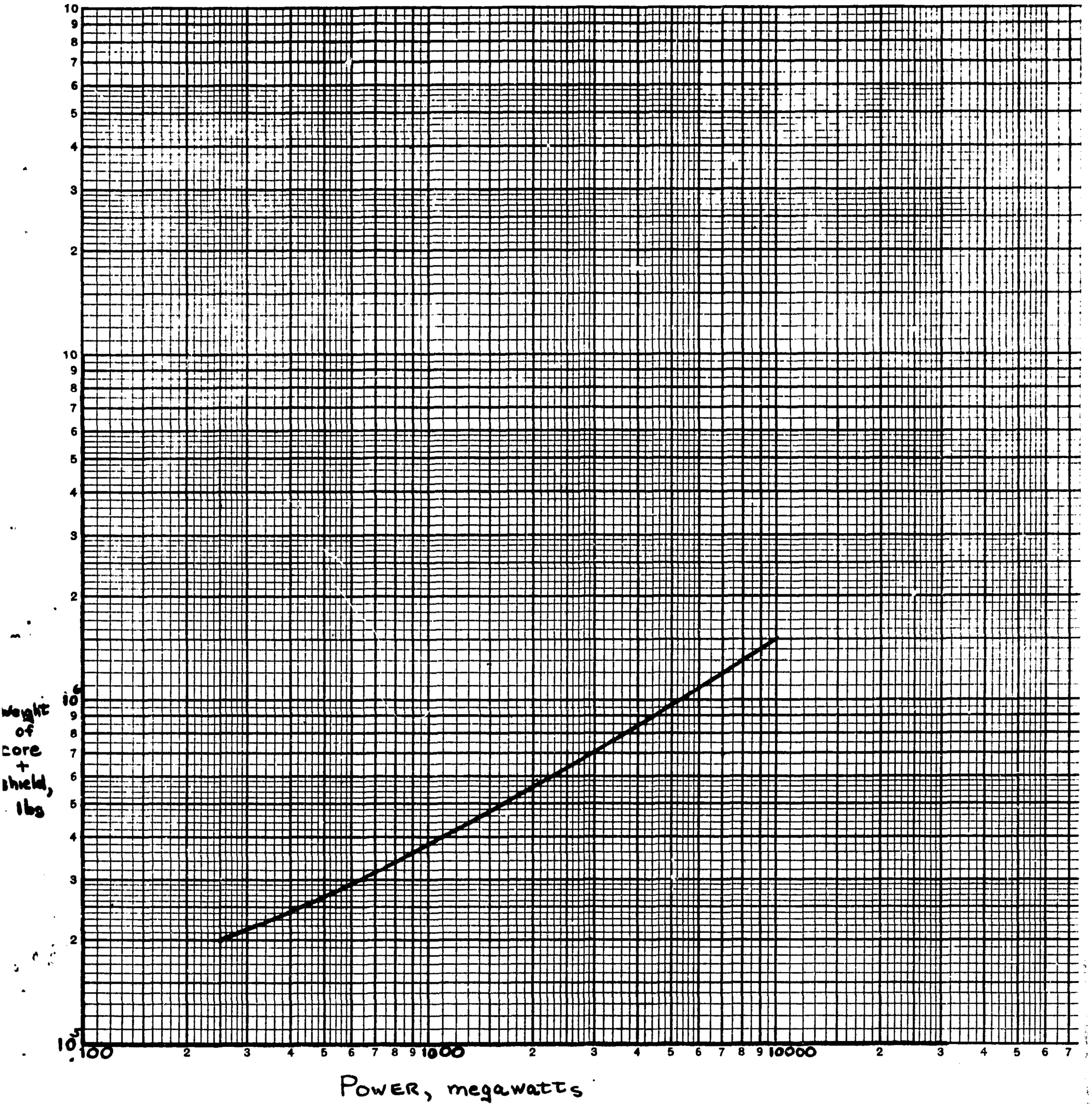

FIGURE 3: WEIGHT OF REACTOR CORE PLUS SHIELD AS A FUNCTION OF POWER

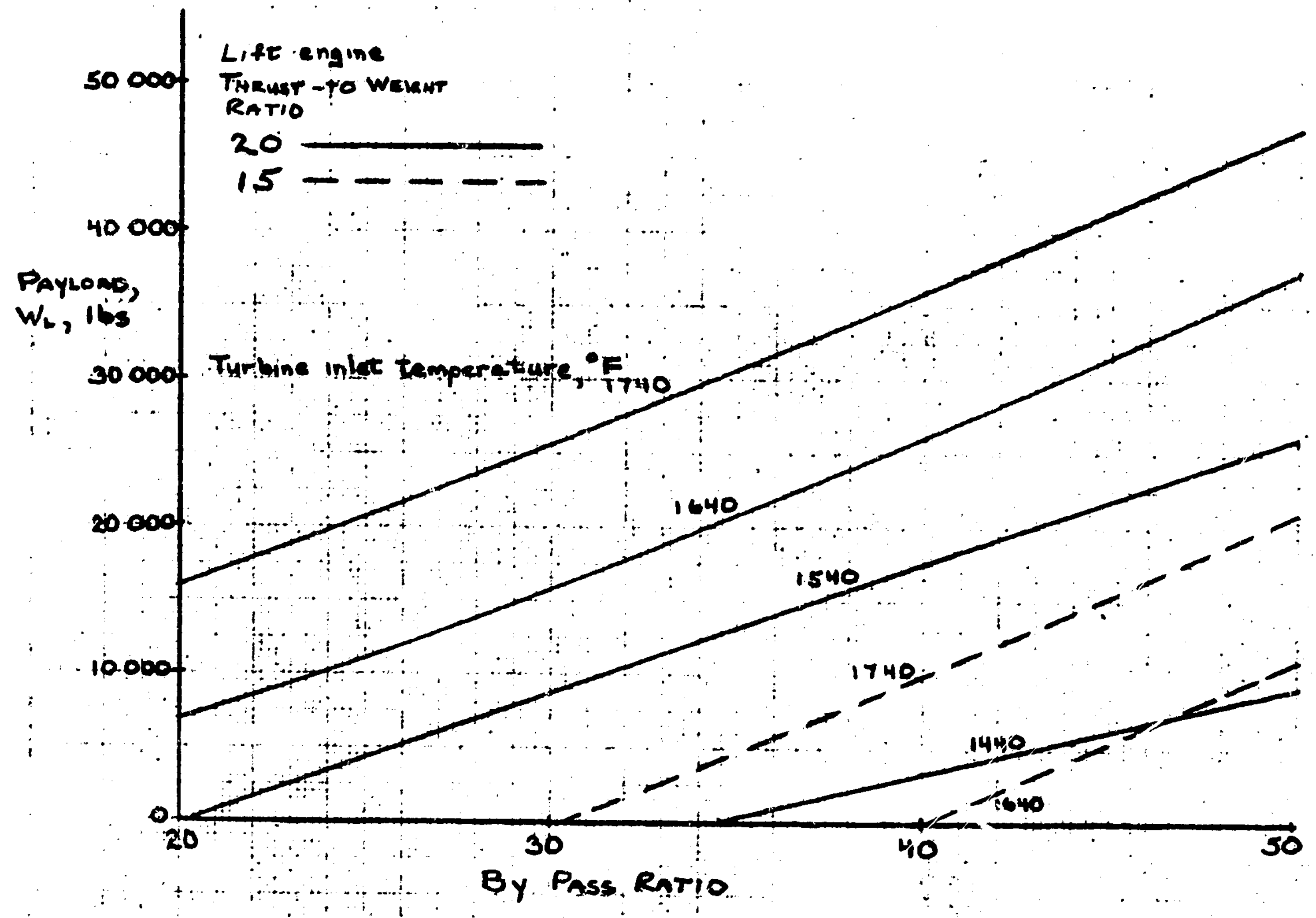

Figure 4: Effect of By Pass Ratio on Payload for Brayton Cycle; Gross weight 1 000 000 lbs.

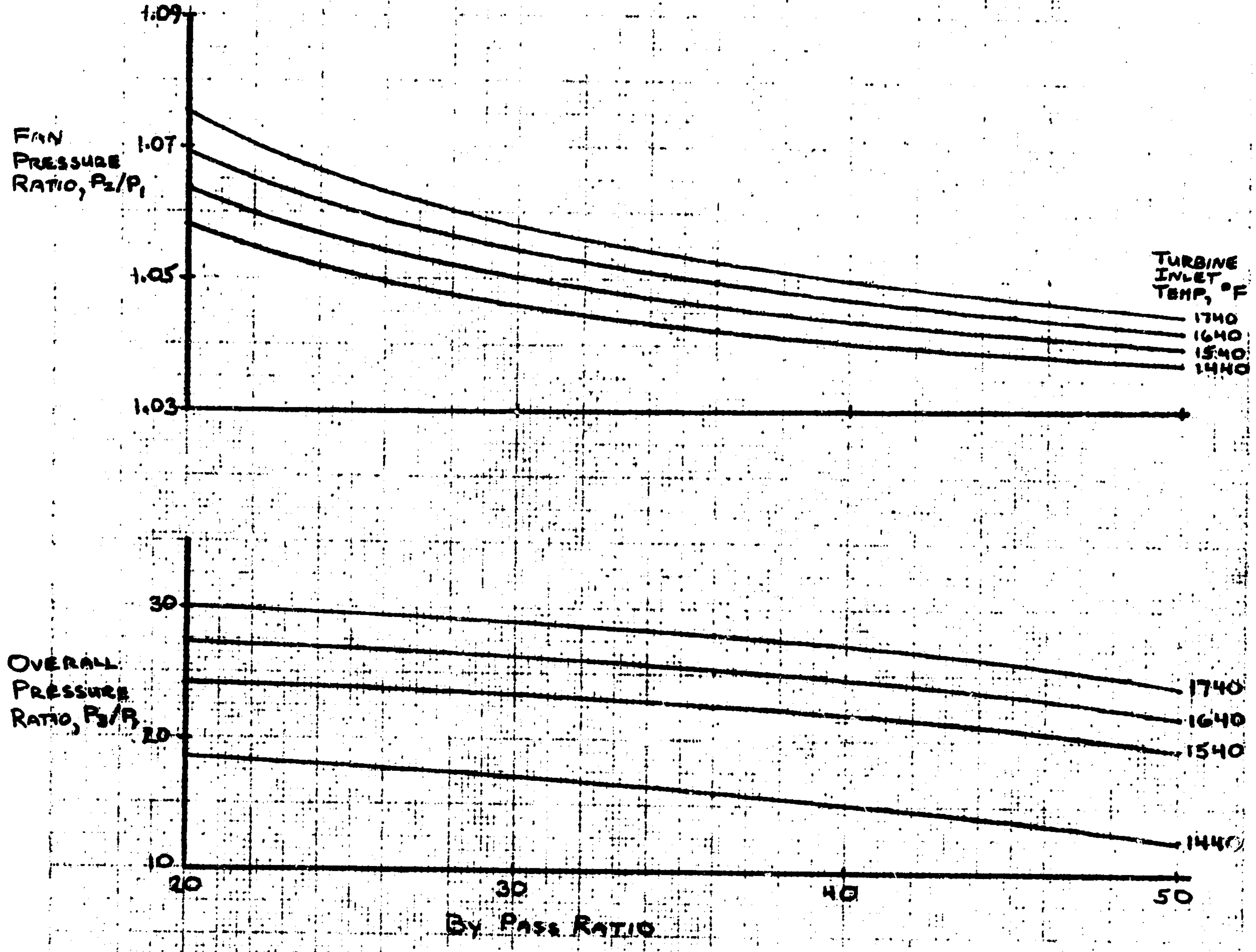

FIGURE 5: EFFECT OF BY PASS RATIO ON OPTIMUM FAN PRESSURE RATIO AND OPTIMUM OVERALL PRESSURE RATIO. BRAYTON CYCLE, GROSS WEIGHT, 1 000 000 lbs

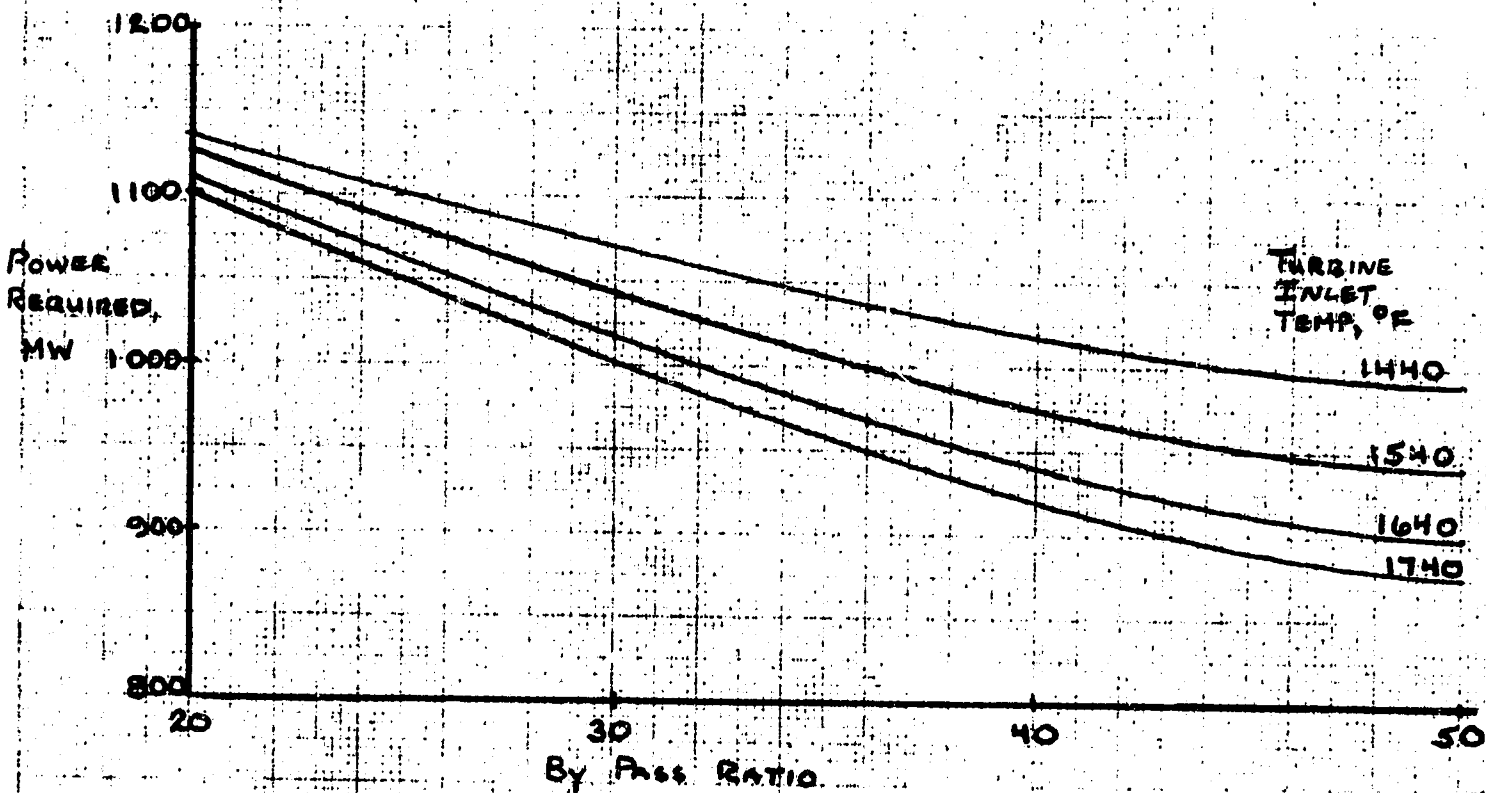

Figure 6: Effect of By Pass Ratio on Power Required.
Brayton Cycle; Gross Weight 1 000 000 lbs.

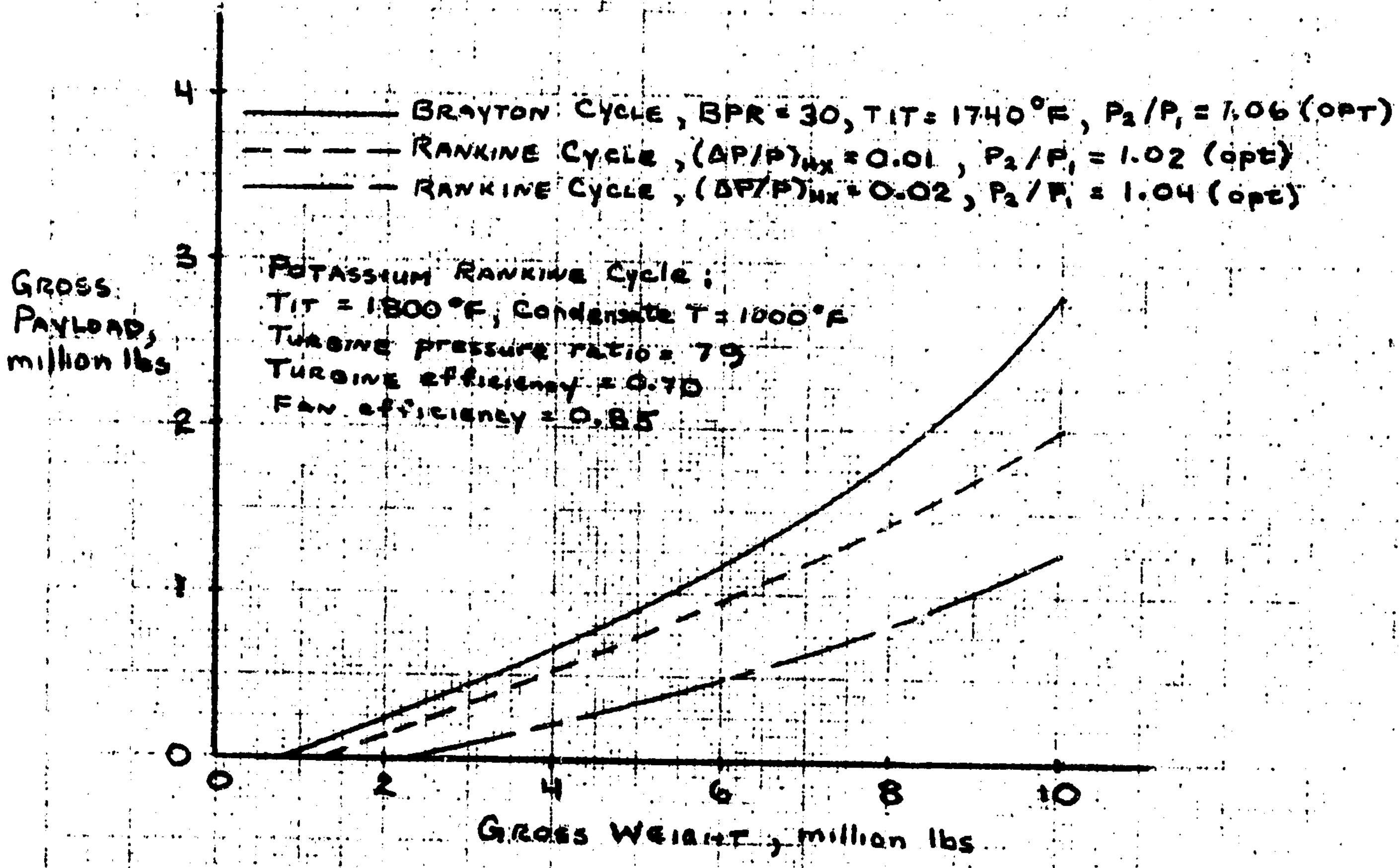

FIGURE 7: PAYLOAD AS A FUNCTION OF GROSS WEIGHT.
LIFT ENGINE THRUST TO WEIGHT RATIO, 20.

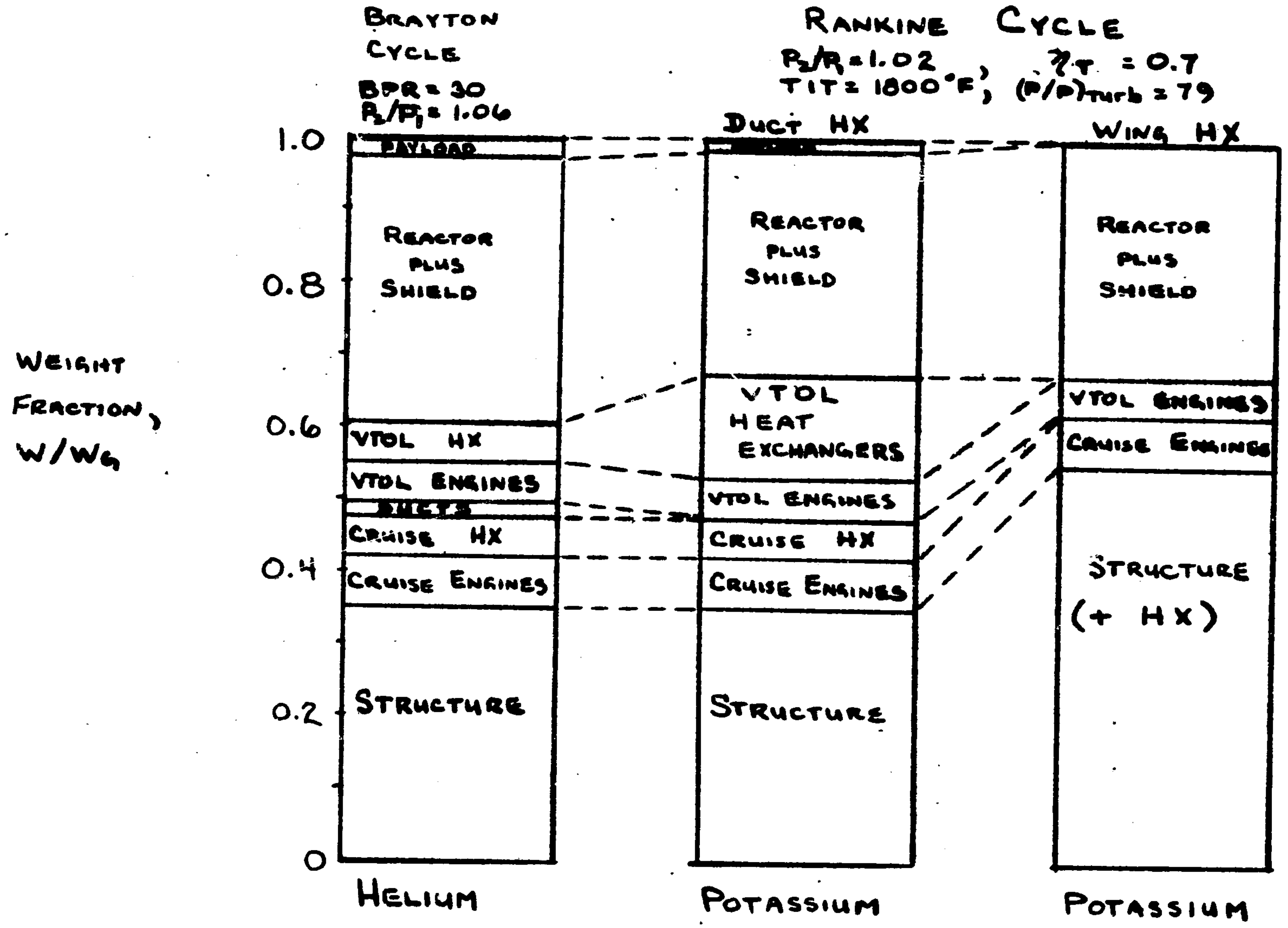

FIGURE 8 : VEHICULAR COMPONENT BREAKDOWN. GROSS WEIGHT, 1 000 000 lbs.

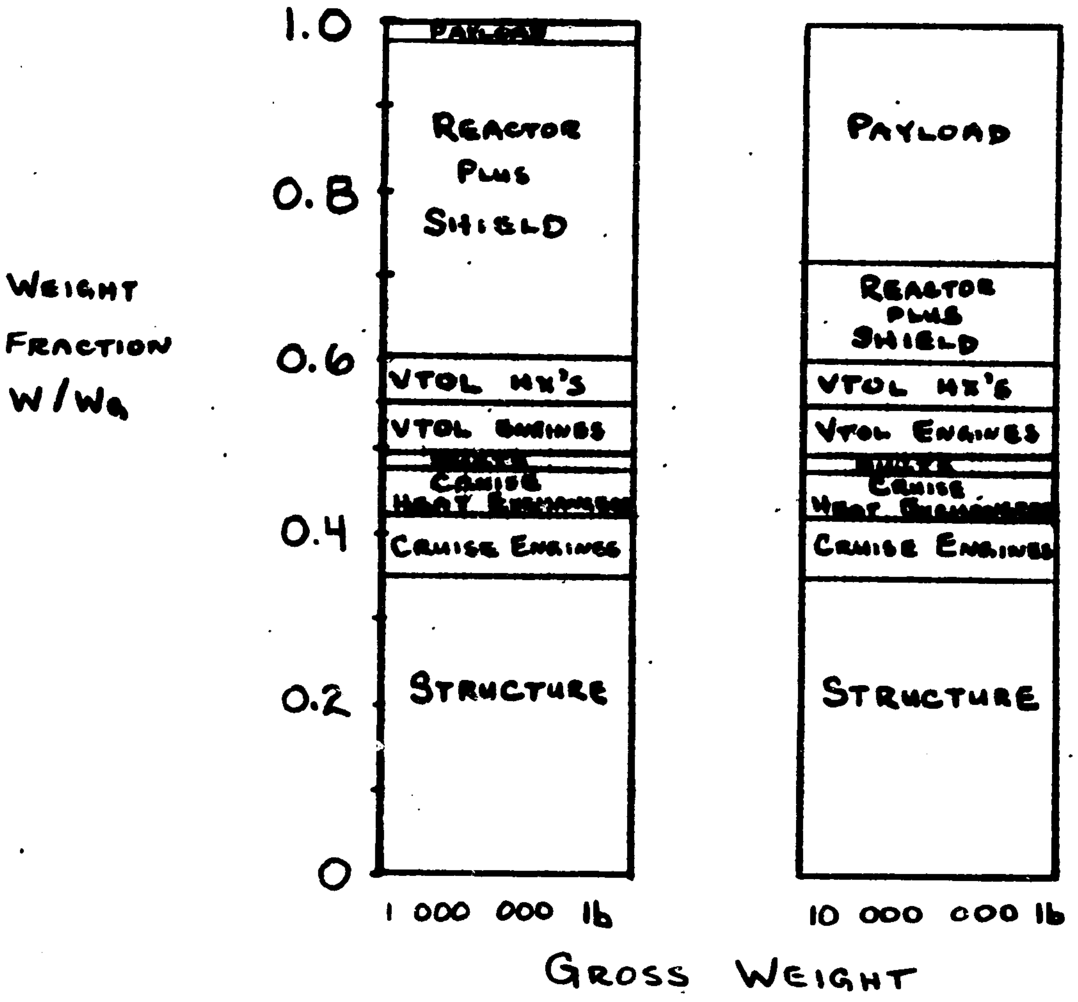

Figure 9: Vehicular Component Weight Breakdown. Brayton Cycle; By Pass Ratio, 30.

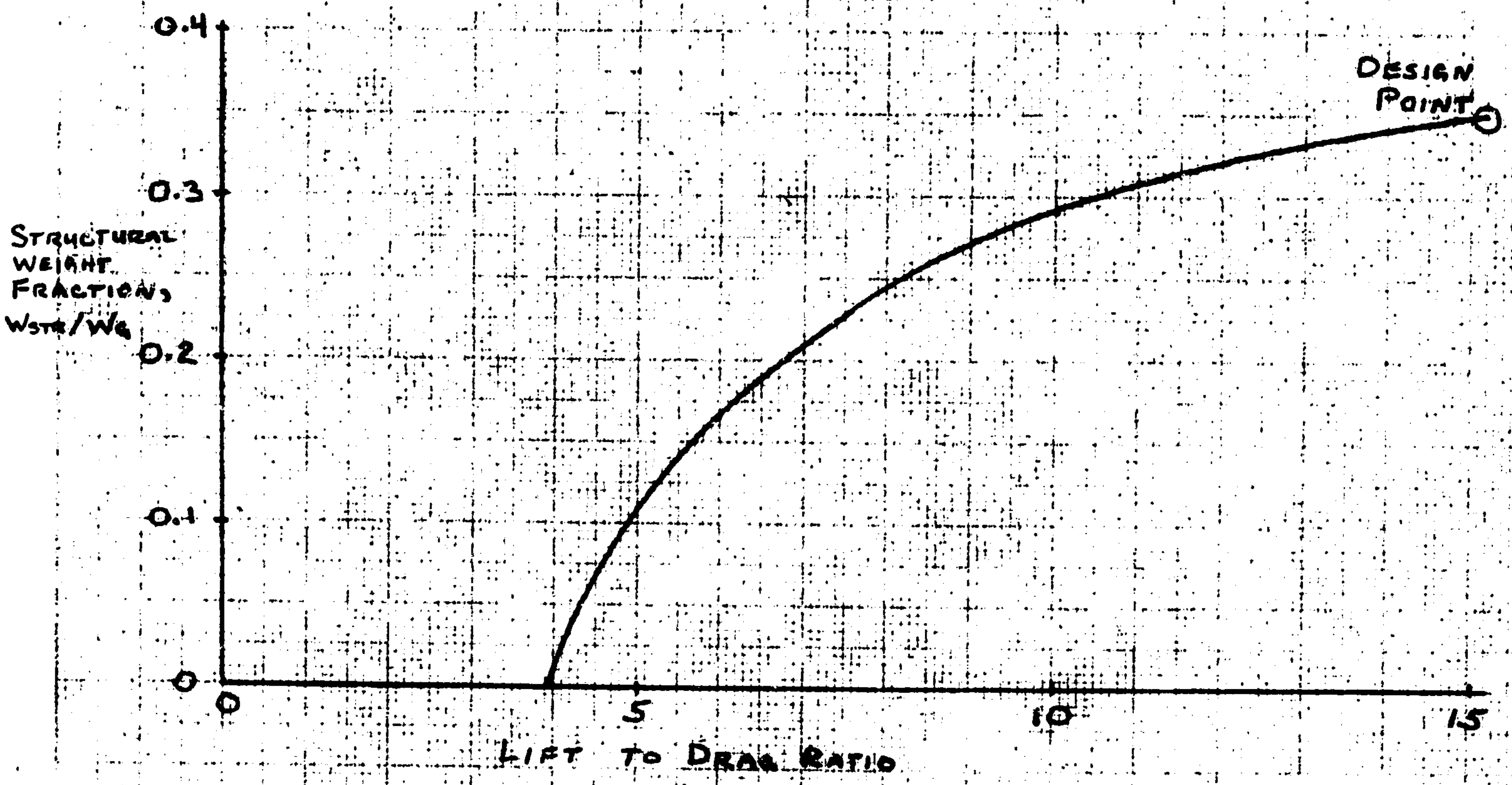

Figure 10: Allowable Structure Fraction as a Function of Lift to Drag Ratio for Constant Payload

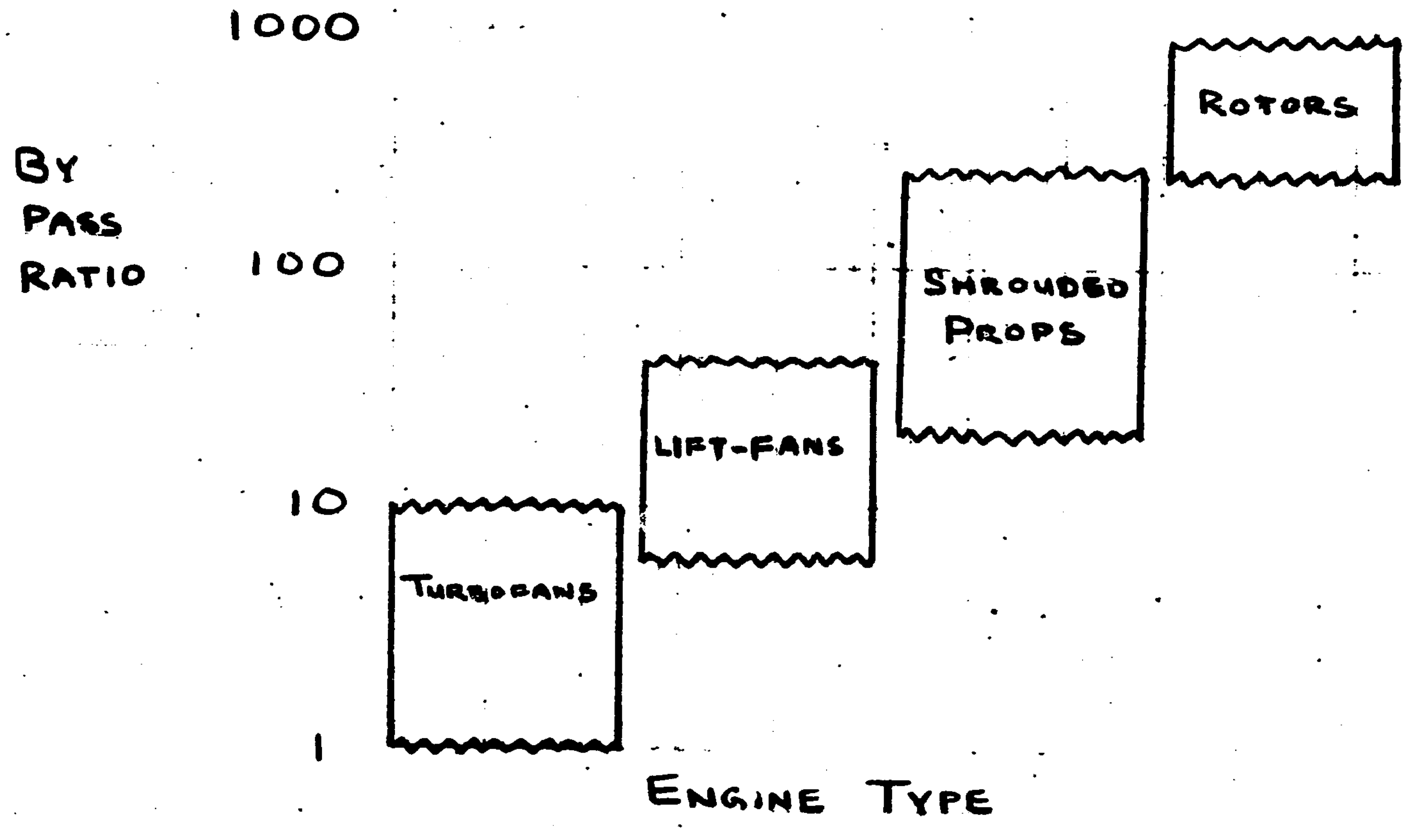

Figure 11: Type of Engine in Terms of By Pass Ratio

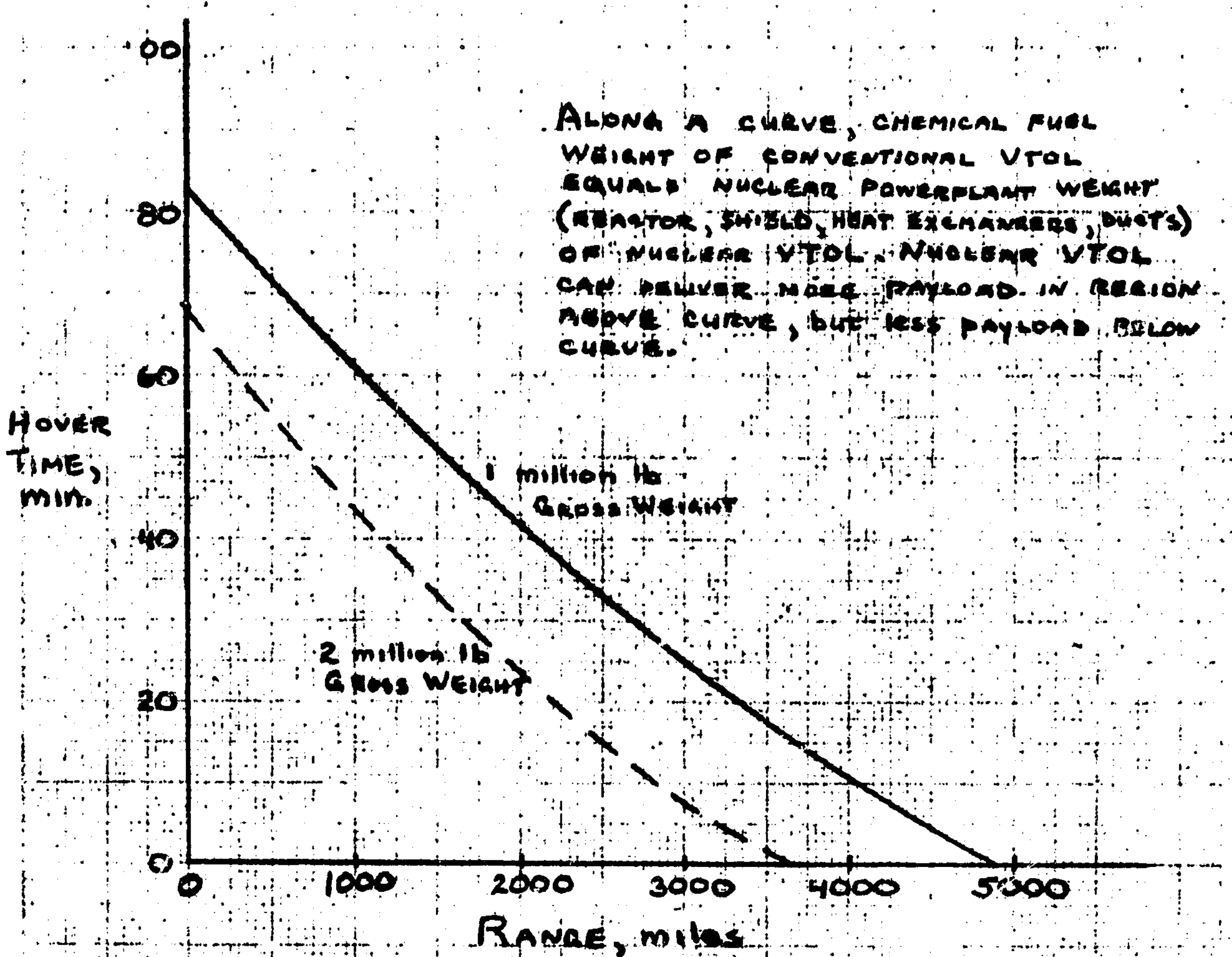

FIGURE 12: PAYLOAD ADVANTAGE OF CHEMICAL OR NUCLEAR VTOL AS A FUNCTION OF RANGE AND HOVER TIME.

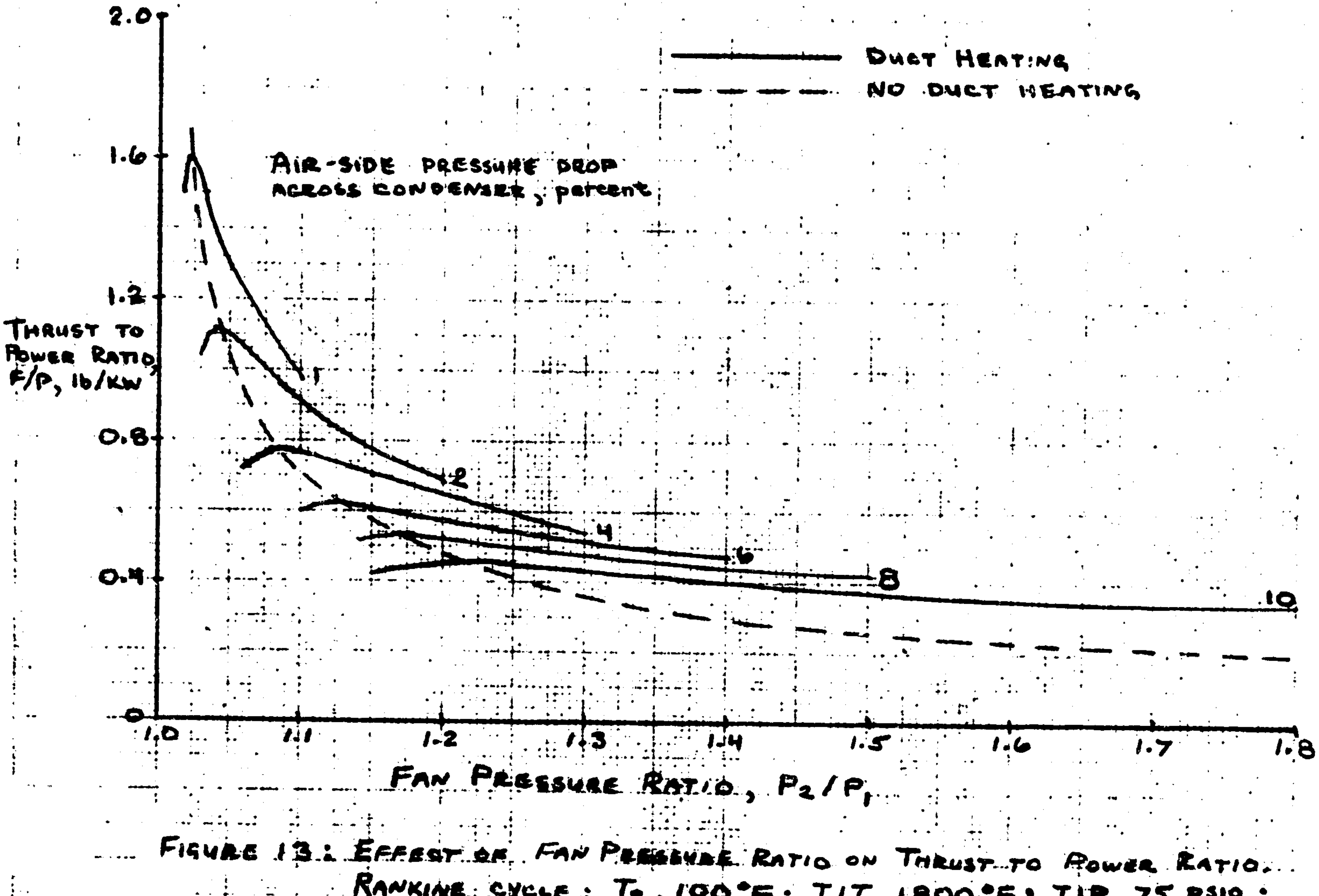

FIGURE 13: EFFECT OF FAN PRESSURE RATIO ON THRUST TO POWER RATIO.
RANKINE CYCLE; $T_0$, 100°F; TIT, 1800°F; TIP, 75 psia;
$\eta_T$, 0.70; $\eta_F$, 0.85; CONDENSATE TEMPERATURE, 1000°F;
TURBINE EXPANSION RATIO, 79.

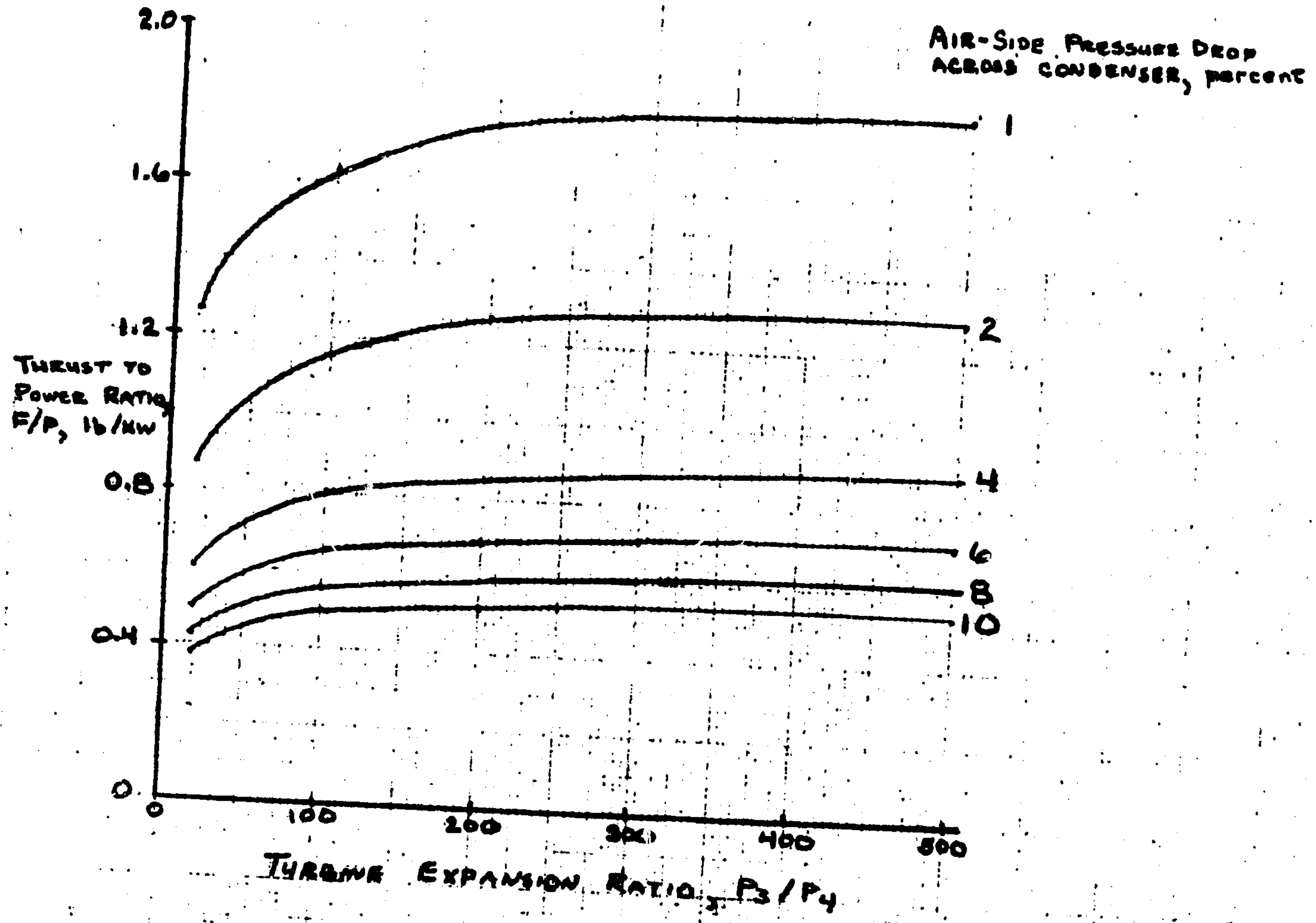

Figure 14. - Effect of Turbine Expansion Ratio on Thrust-to-power Ratio for duct-heated Rankine cycle. $T_0$, 100°F; TIT, 1800°F; TIP, 75 psia; $\eta_R$, 0.85; $\eta_T = 0.70$; optimum $P_2/P_1$.

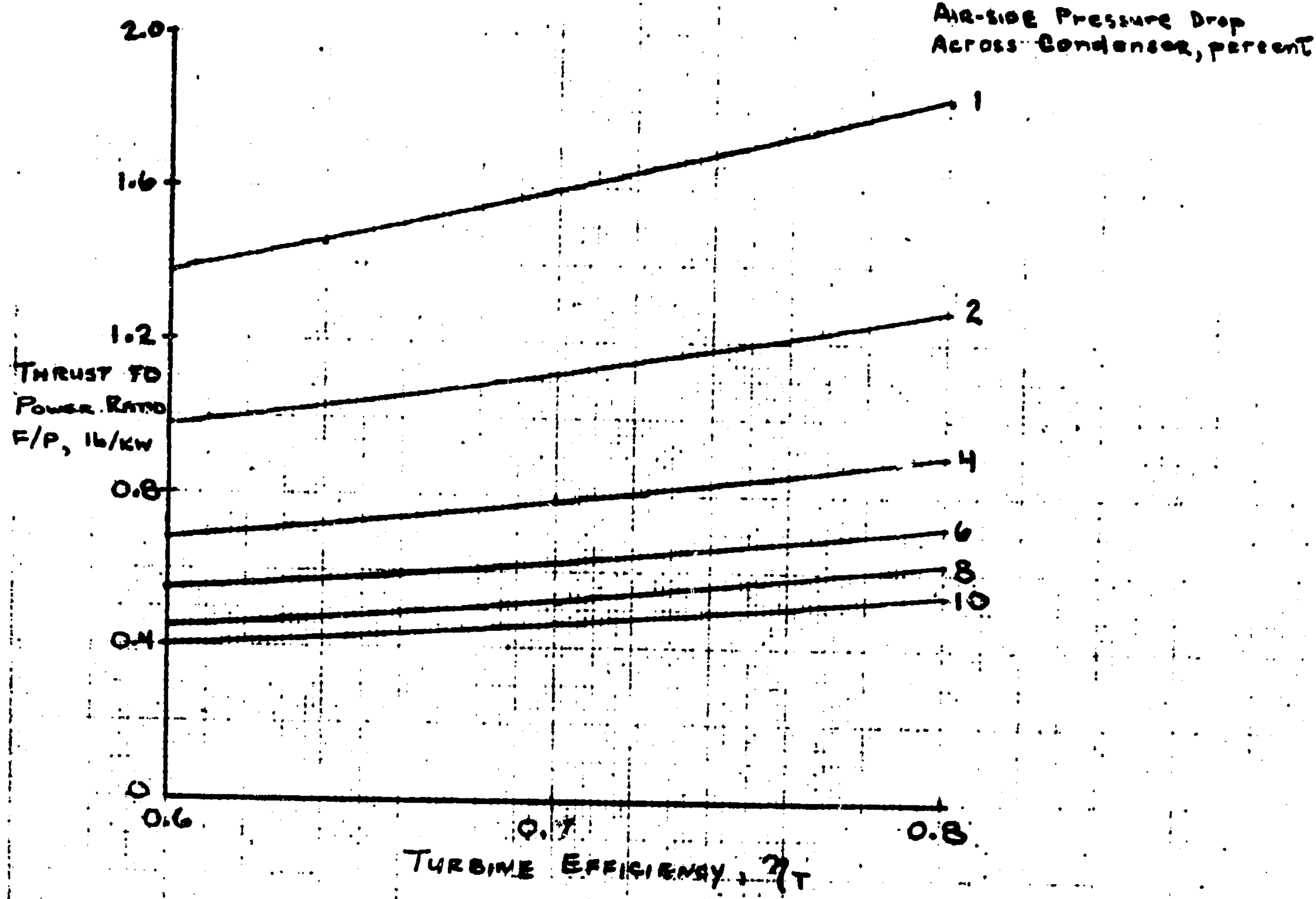

FIGURE 15: EFFECT OF TURBINE EFFICIENCY ON THRUST-TO-POWER RATIO FOR DUCT-HEATED RANKINE CYCLE. $T_0$, [illegible]°F; TIT, 1200°F; TURBINE EXPANSION RATIO, 79; $\eta_F$, 0.85; CONDENSATE TEMPERATURE, 1000°F; OPTIMUM $P_2/P_1$.

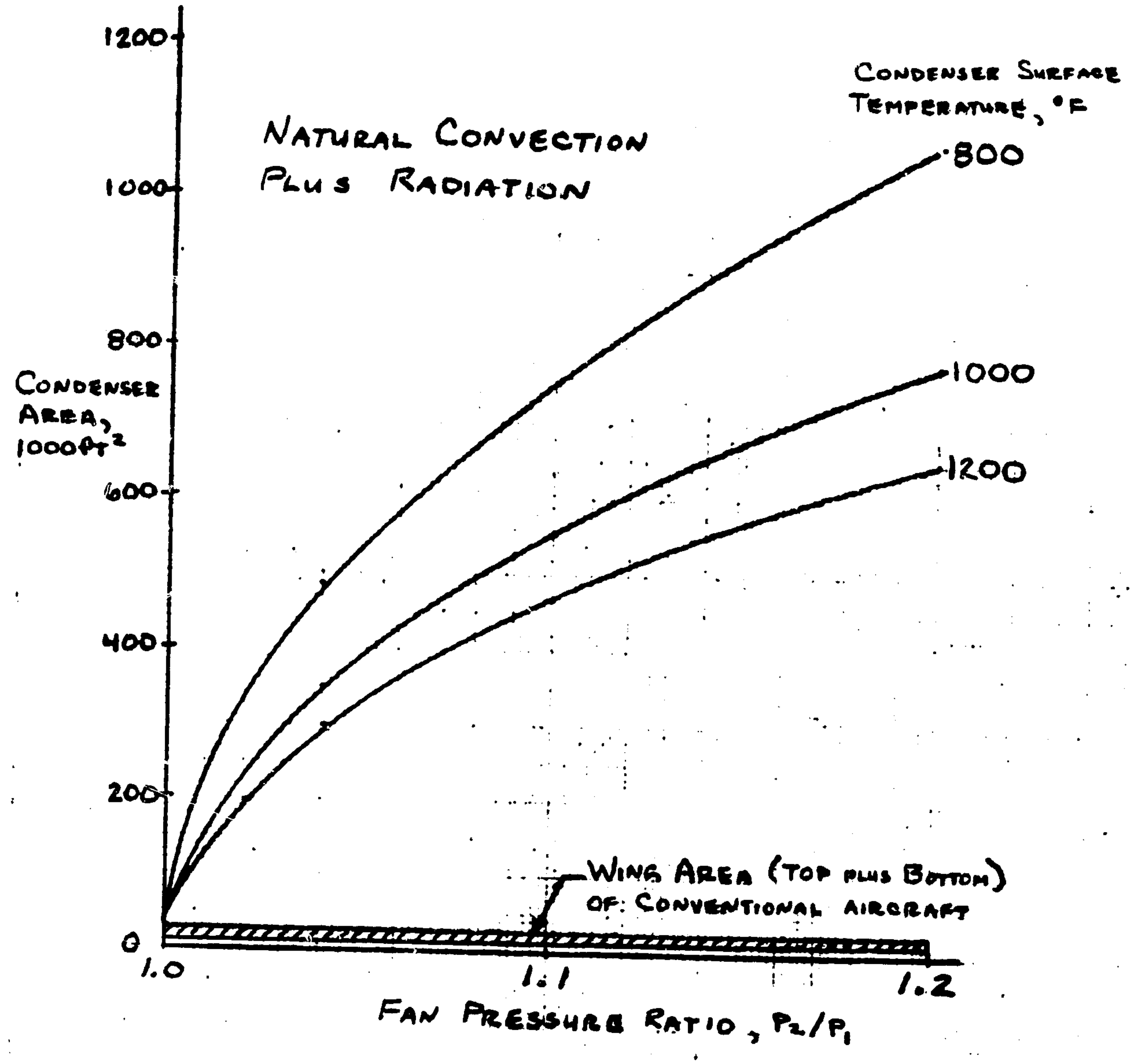

FIGURE 16: EFFECT OF FAN PRESSURE RATIO ON CONDENSER AREA FOR CONDENSER-IN-WING RANKINE CYCLE. $T_2$, 100°F; TIT, 1800°F; TIP, 75 psia; $\eta_T$, 0.7; $\eta_F$, 0.85; GROSS WEIGHT, 1 000 000 lb.