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LARGE NUCLEAR-POWERED SUBSONIC AIRCRAFT FOR TRANSOCEANIC COMMERCE

by Frank E. Rom and Charles C. Masser

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

Large subsonic aircraft, greater than 905 metric tons (1000 tons) gross weight, have the potential for hauling transoceanic cargo at rates in the range of $0.006 to $0.036 per metric ton-kilometer ($0.01 to $0.06/ton-n mi) at speeds of 740 to 925 kilometers per hour (400 to 500 knots). It theoretically would take a fleet of 500 such aircraft to handle 1 percent of the forecast world ocean trade in 1980. For gross weights of 3620 metric tons (4000 tons) the cargo rate would be reduced to less than $0.012 per metric ton-kilometer ($0.02/ton-n mi). It theoretically would take a fleet of over 1000 such aircraft to carry 8 percent of the world transoceanic trade projected for 1980 or 4 percent of the projected trade in 1995. Aircraft with a gross weight of 3620 metric tons (4000 tons) using compact lightweight nuclear reactors show better performance than chemical aircraft for ranges greater than 5565 kilometers (3000 n mi). Nuclear aircraft performance is less sensitive than that of chemical aircraft to the operating and cost assumptions used. Relatively large variations in any of the important assumptions have a relatively small effect on nuclear aircraft performance.

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SUMMARY

Large subsonic aircraft, greater than 905 metric tons (1000 tons) gross weight, have the potential for hauling transoceanic cargo at rates in the range of $0.006 to $0.036 per metric ton-kilometer ($0.01 to $0.06/ton-n mi) at speeds of 740 to 925 kilometers per hour (400 to 500 knots). It theoretically would take a fleet of 500 such aircraft to handle 1 percent of the forecast world ocean trade in 1980. For gross weights of 3620 metric tons (4000 tons) the cargo rate would be reduced to less than $0.012 per metric ton-kilometer ($0.02/ton-n mi). It theoretically would take a fleet of over 1000 such aircraft to carry 8 percent of the world transoceanic trade projected for 1980 or 4 percent of the projected trade in 1995. Aircraft with a gross weight of 3620 metric tons (4000 tons) using compact lightweight nuclear reactors show better performance than chemical aircraft for ranges greater than 5565 kilometers (3000 n mi). Nuclear aircraft performance is less sensitive than that of chemical aircraft to the operating and cost assumptions used. Relatively large variations in any of the important assumptions have a relatively small effect on nuclear aircraft performance.

INTRODUCTION

The world is currently experiencing a major expansion in transoceanic trade. The Department of Transportation predicts that world ocean trade will almost double by 1980 (ref. 1); see figure 1. In 1980, world ocean trade is forecast to be about 4 billion metric tons. This represents about 12 trillion metric ton-kilometers (20 trillion ton-n mi) of ocean commerce per year.

In 1968, about 11.5 percent of all U.S. foreign trade was liner tonnage that had an average value of $0.626 per kilogram or $0.284 per pound (ref. 2). Assume that 10 to 15 percent of the cargo value is a reasonable cost for its transportation and that 7420 to 11 130 kilometers (4000 to 6000 n mi) is an average transoceanic range. This yields an allowable charge of $0.006 to $0.012 per metric ton-kilometer ($0.01 to $0.02/ton-n mi)

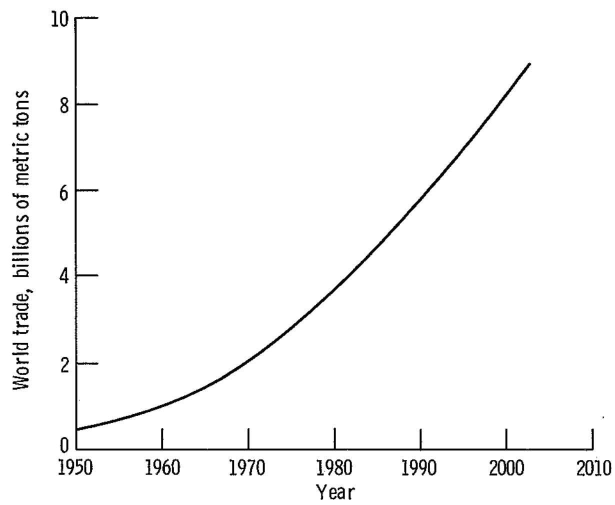


Figure 1. - Department of transportation world oceanborne trade forecast.

for cargo whose value is \$0.55 to \$0.66 per kilogram (\$0.25 to \$0.30/lbm). In other words, there may be more than 1.2 trillion metric ton-kilometers (2 trillion ton-n mi) of cargo traffic suitable for hauling at \$0.006 to \$0.012 per metric ton-kilometer (\$0.01 to \$0.02/ton-n mi) in 1980. This cost for transoceanic commerce is comparable to railroad cost for overland movement of cargo.

If aircraft could be developed to carry cargo at this cost at a speed of 740 to 925 kilometers per hour (400 to 500 knots), it theoretically would take a fleet of more than 2000 such aircraft with cargo capacity of 1360 metric tons (1500 tons) each to handle the 1980 traffic at a utilization rate of 0.6. These figures do not take into account the additional traffic that would be attracted by the large reduction in transit time resulting from the 740- to 925-kilometer-per-hour (400- to 500-knot) speed. There is, therefore, clearly an incentive to determine whether aircraft can be developed to carry cargo at a rate of \$0.006 to \$0.012 per metric ton-kilometer (\$0.01 to \$0.02/ton-n mi).

NASA has been conducting a low-level study to determine the feasibility of large nuclear-powered-air-cushion vehicles and aircraft (refs. 3 and 4). The objectives of the study are (1) to determine the feasibility of practical, safe, and economical nuclear powerplants for air-cushion vehicles and aircraft; (2) to define the key problems requiring research and development; and (3) to demonstrate or develop key technology that is required for feasibility assessment.

This report presents the results of a simplified preliminary study to determine the potential of large subsonic aircraft for achieving cargo rates of \$0.006 to \$0.012 per metric ton-kilometer (\$0.01 to \$0.02/ton-n mi). Both chemical and nuclear power are considered. The nuclear-powered aircraft use the propulsion technology that is described in reference 5. Chemical aircraft use gas turbine technology forecast for 1980.

Assumptions must be made for a large number of performance and cost variables. The results must be carefully considered in light of these assumptions. To evaluate the sensitivity of the results to the assumptions, each major assumption is independently varied and the effect on operating cost presented.

VEHICLE DESCRIPTION

The aircraft considered in this study are characterized by their lift-drag ratios and weight breakdowns. The propulsion system studied is the turbofan system. The energy sources considered are chemical (jet fuel) and nuclear.

Vehicle Characteristics

The fact that 320- to 360-metric ton (350- to 400-ton) aircraft are now in operation is used as a basis for extrapolation to the large subsonic aircraft studied in this report. The Lockheed C-5A (fig. 2) is now in active military service for hauling large equipment and cargo. The Boeing 747 (fig. 3) is in commercial passenger service. Aircraft of much larger size (two to three times the gross weight of the 747 and C-5A) are now on the drawing boards of the major aircraft companies. One company has even made a preliminary conceptual study of an aircraft 15 times the gross weight of the 747 and C-5A (ref. 6). A three-view drawing of this aircraft is shown in figure 4. It has a wing span of over 335 meters (1100 ft) and can carry a cargo of about 40 percent of its gross weight. It is powered by turbofan engines that utilize heat energy from a nuclear reactor. In addition, chemical lift engines can be installed in the wings and near the fuselage nose to provide a V/STOL capability. Although a wheeled landing gear is shown in the drawing, an air-cushion landing gear would probably be lighter and provide better operational flexibility. The aircraft could then land on and take off from land or water. Land surfaces could be relatively unprepared surfaces, such as sod or earth, if air-cushion landing gear is used. The structure weight fraction of this large aircraft is in the same range as all other transport aircraft (about 25 to 30 percent of the gross weight). This low structure weight fraction for such a large aircraft has been achieved (even though conventional aircraft materials are used) by more efficient utilization of structure materials made possible by the large dimensions of the aircraft.

Figure 2. - Lockheed C-5A aircraft. Gross weight, 361 metric tons (399 tons); cruise speed, 780 kilometers per hour (420 knots).

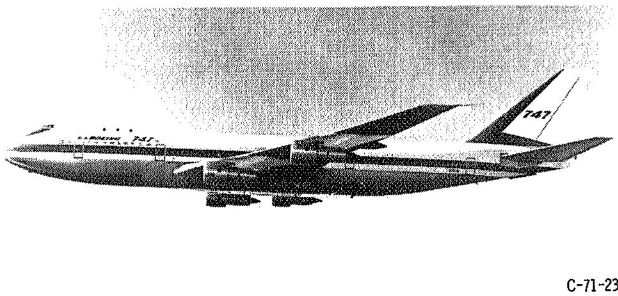
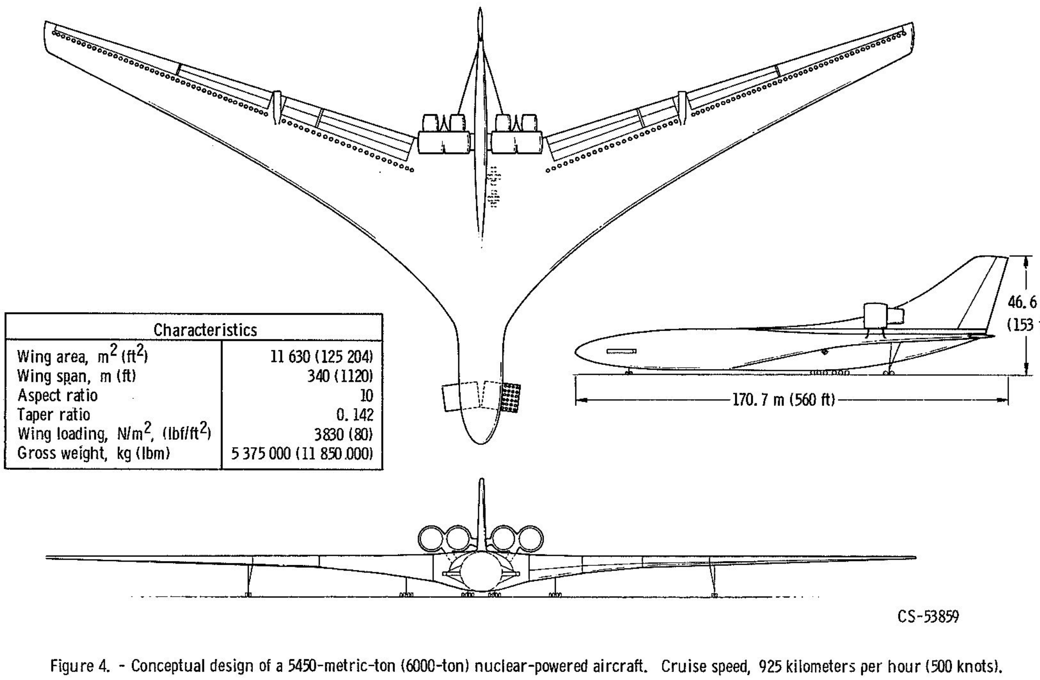


Figure 3. - Boeing 747 aircraft. Gross weight, 322 metric tons (355 tons); cruise speed, 1010 kilometers per hour (545 knots).



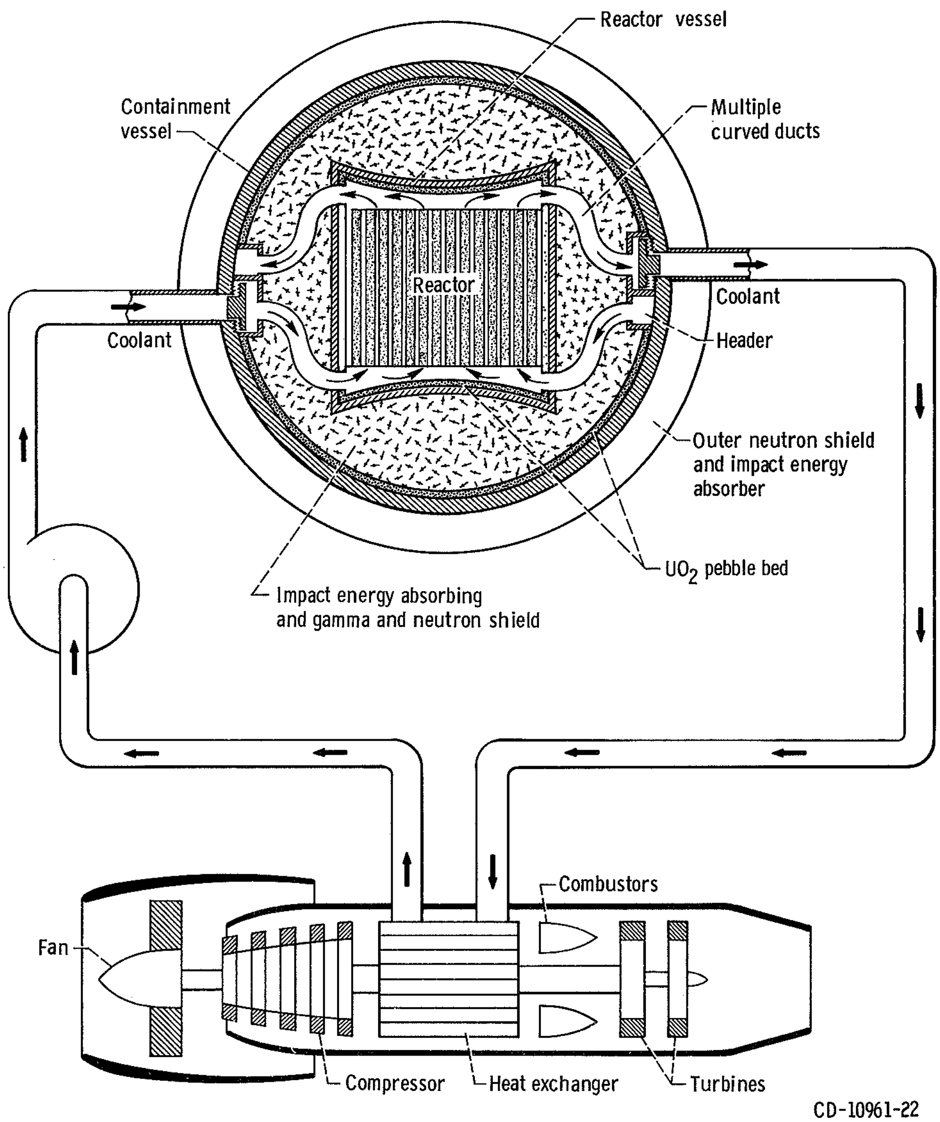
Characteristics	
Wing area, m^2 (ft^2)	11 630 (125 204)
Wing span, m (ft)	340 (1120)
Aspect ratio	10
Taper ratio	0.142
Wing loading, N/m^2, (lbf/ft^2)	3830 (80)
Gross weight, kg (lbm)	5 375 000 (11 850 000)

Figure 4. - Conceptual design of a 5450-metric-ton (6000-ton) nuclear-powered aircraft. Cruise speed, 925 kilometers per hour (500 knots).

Propulsion System Characteristics

Turbofan engines were used for propulsion. Greatly simplified performance data are used in this study to facilitate parametric analysis.

In the case of nuclear power, it was assumed that the reactor was of the high-pressure helium type shown in figure 5. The helium is heated as it flows between the hot reactor fuel elements. The hot helium is then ducted to a heat exchanger that is located between the compressor and combustor of a turbofan engine. The air flowing from the compressor is heated by the heat exchanger before it enters the combustor.



Nuclear aircraft powerplant

Figure 5. - Schematic drawing of a compact helium-cooled reactor for aircraft applications.

The engine can, therefore, operate on either nuclear or chemical power. Shielding and a containment vessel are shown surrounding the reactor. The shielding is complete (unit or 4π shielding) so that dose levels are the same in all directions from the reactor shield. The design dose levels used are such that a dose level of 0.25 millirem per hour at 9.15 meters (30 ft) from the reactor centerline is less than the dose due to cosmic radiation at 10.7 kilometers (35 000 ft) altitude (about 0.35 millirem/hr). Beyond 9.15 meters (30 ft) from the reactor centerline the dose decreases approximately as the square of the distance. At 30.5 meters (100 ft), for example, the dose rate is 0.025 millirem per hour. In actual practice the dose levels will be even less than the values used here because other materials such as structure, cargo, and equipment, that may be located between the shield and the dose-measuring point, provide shielding but are not included in the calculation.

An important feature of the reactor design is that a containment vessel is provided. The containment vessel is designed to prevent the escape of fission products in the worst aircraft impact accident and also in the event of a reactor meltdown that follows a major accident. Descriptions and results of experiments on the principles used to achieve fission product containment are discussed in references 3 and 7 to 10. A brief description of the principles involved is included here because this represents a departure from commonly used concepts of fission product containment.

The particular system shown in figure 5 was specifically designed for subsonic aircraft where impact speeds could be as high as 305 meters (1000 ft) per second. The containment vessel and reactor vessel are designed to prevent rupture at high impact speeds. This is accomplished by several design features. First of all, the containment and reactor vessels are fabricated of a ductile high-strength material such as stainless or maraging steel. High-strength, very ductile materials are desirable so that the kinetic energy of impact is absorbed by plastic deformation without rupture. Secondly, the outer and inner shields are fabricated of shield materials such as honeycomb structure or small spheres that absorb energy by their deformation during impact. The neutron shield external to the containment vessel is fabricated of a material like plastic honeycomb. The gamma shielding required in addition to the shielding provided by the reactor and containment vessels is fabricated of small deformable pieces of depleted uranium metal. The small pieces are designed to provide the proper volume fraction required for minimum shield weight and also to provide energy absorption capability when they are deformed during impact. The void remaining when the shielding space is filled with the uranium metal pieces is filled with water for neutron shielding. The water may also serve as an aid for absorbing kinetic energy. The high water pressures that would be generated during impact could serve to expand or stretch the containment vessel so that a greater portion of the vessel is used to absorb energy. The basic feature of the reactor system design is that it utilizes as much of the system materials as possible to serve multiple functions. For example, the containment vessel and reactor vessel serve as shield, structure, and energy absorber besides providing the basic containment functions.

To provide for retention of fission products during a reactor meltdown, two situations must be considered: meltdown without impact and meltdown after impact. To provide for the case of meltdown without impact (such as a loss-of-coolant accident), a layer of UO_2 pebbles is located just inside the reactor vessel. The UO_2 bed is a refractory insulating layer that will reduce the heat flow through the containment vessel. This causes the reactor materials and fission products to reach high temperatures without melting through to the reactor vessel. Because the reactor materials (including the wide variety of fission product compounds that are generating heat by their decay) are forced to high temperatures by the insulating effect of the UO_2 pebbles, vapors are formed. These vapors will diffuse or flow into the UO_2 pebble bed. As the vapors flow down the temperature gradient in the pebble bed, they will condense at the appropriate condensation temperature for each vapor. The net effect is that the heat-generating fission products will tend to condense in relatively uniform concentric layers at each appropriate condensing temperature. This results in a relatively uniform heat flux leaving the reactor vessel. The reactor vessel is immersed in shield water which serves to cool the vessel. The heat causes steam to form which is released to the atmosphere when the desired shield water pressure has been achieved.

In the case of reactor meltdown after impact, the shield water may or may not remain in the system. If it does, meltdown is handled as just described. For the event where no water is present in the shield, another layer of UO_2 pebbles is provided on the inside surface of the containment vessel. When the reactor melts down, the vapors that are formed flow out into the UO_2 layer and are condensed in concentric shells just as discussed previously. The insulating UO_2 provides the means for achieving as uniform a heat flux as possible around the entire containment vessel. The only means of cooling the containment vessel now, however, is thermal radiation and free convection to the air. This requirement determines the minimum containment vessel size. For a 600-megawatt reactor this corresponds to a diameter of about 6.1 meters (20 ft) if the containment vessel is not to exceed 1030 K (1400° F).

Experimental and analytical studies are underway to determine the feasibility of the principles outlined here. The results to date are given in references 4 and 8 to 10.

Inasmuch as the application studied herein is for transoceanic commerce, nuclear safety problems are eased. As indicated in references 3, 5, and 7, the design of post-impact reactor meltdown protection systems is much simpler in this case because the containment vessel would be submerged in water following an accident. The containment vessel diameter need be only about one-half the diameter of the air-cooled case. In addition, even if containment vessel rupture occurs, only the least radioactive materials, the noble (inert) fission product gases, will escape because the other fission products are dissolved or trapped in the water.

ANALYSIS

The analysis has two main subdivisions. The first deals with performance estimation in terms of weight, speed, power, and payload. The second deals with a simplified cost analysis used to estimate the operating cost as a function of the operating variables. The analysis presents only the equations and relations used. The specific values of the variables used are presented in the following section, ASSUMPTIONS. The symbols used in the analysis are defined in appendix A.

Performance Estimate

Gross weight. - The gross weight W_G of the aircraft is the sum of all the component weights:

$$W_G = W_{ST} + W_E + W_R + W_{SH} + W_F + W_{PAY} \tag{1}$$

Structure weight. - The structure weight includes the airframe, landing gear, instruments, crew, fuel tanks, furniture, and all other parts that cannot be called engine, fuel, reactor, shield, or payload. The structure weight is expressed as a fraction of the gross weight:

$$W_{ST} = \left(\frac{W_{ST}}{W_G}\right)(W_G) \tag{2}$$

Engine weight. - The engine weight is expressed as engine weight per unit thrust. It includes the turbofan engine, nacelle and, in the case of nuclear engines, the heat exchanger:

$$W_E = \left(\frac{W_E}{F}\right) F \tag{3}$$

The values for specific engine weight W_E/F that are used in the analysis are shown in figure 6. If W_G is in metric tons, F in newtons is determined as follows:

$$F = \frac{9800\ W_G}{\frac{L}{D}} \tag{4a}$$

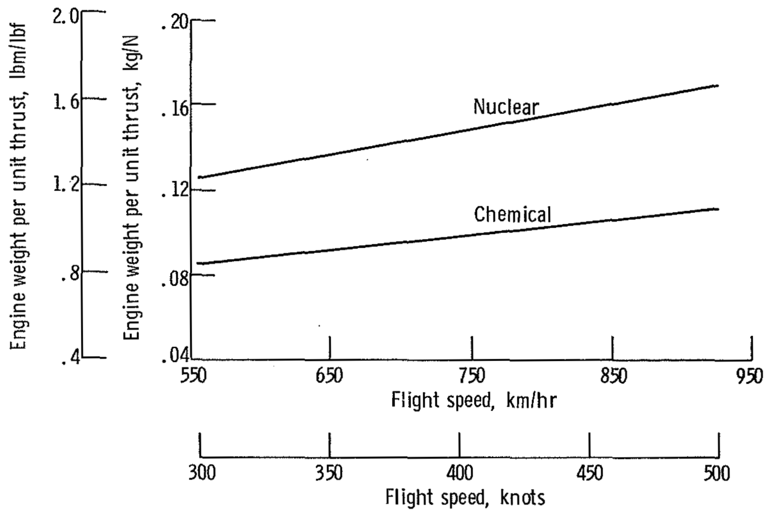


Figure 6. - Engine weight per unit thrust for nuclear and chemical turbofan engines assumed for the analysis. Altitude, 10.7 kilometers (35 000 ft).

If W_G is in tons, F in pounds force is determined as follows:

$$F = \frac{2000\ W_G}{\frac{L}{D}} \tag{4b}$$

Reactor weight. - The reactor weight is defined as the entire mass within the reactor shield. It includes fuel elements, core structure, reflector, control system, reactor vessel, headers, ducts, and everything else inside the inner diameter of the shield. The reactor is described simply in terms of weight density ρ_R and power density ρ_P. If ρ_R is in grams per cubic centimeter, ρ_P is in watts per cubic centimeter, and P_{th} is the reactor power in megawatts, the reactor weight in metric tons is

$$W_R = \frac{\rho_R P_{th}}{\rho_P} \tag{5a}$$

If ρ_R is in pounds per cubic foot and ρ_P is in megawatts per cubic foot, W_R in tons is

$$W_R = \frac{\rho_R P_{th}}{2000\ \rho_P} \tag{5b}$$

where

$$P_{th}(\text{megawatts}) = F \frac{P_{th}}{F} \tag{6}$$

where P_{th}/F is the thermal power of the reactor in megawatts per unit thrust and is shown in figure 7.

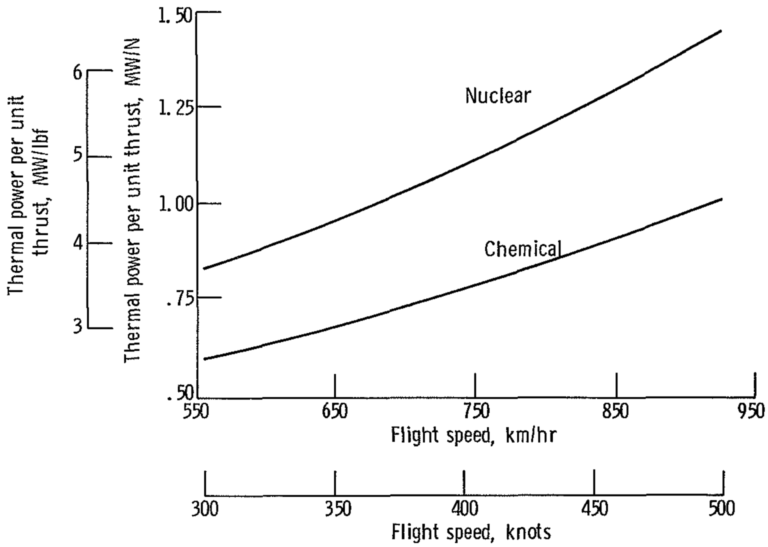


Figure 7. - Thermal power per unit thrust for nuclear and chemical turbofan engines assumed for the analysis.

Shield weight. - The shield weight has been computed assuming uniform shielding in all (4π) directions. The dose rate is 0.25 millirem per hour at 9.15 meters (30 ft) from the reactor centerline. The dose rate decreases approximately as the inverse of the square of the distance from the reactor. At 30.5 meters (100 ft), for example, the dose rate is about 0.025 millirem per hour. The shield is composed of optimum-thickness spherical layers of depleted uranium, mixtures of depleted uranium and water, and water. The reactor is assumed to be a sphere whose size is determined by reactor power density and reactor power. The calculated data points have been generalized and are expressed by the following equations (private communication with M. Wohl of Lewis):

$$W_{SH} = 20.06\, B(P_{th})^{0.281-0.0540 \ln(\rho_P)} \tag{7a}$$

where W_{SH} is in metric tons and ρ_P is in watts per cubic centimeter, or

$$W_{SH} = 22.06\ B(P_{th})^{0.473-0.0540\ \ln(\rho_P)} \tag{7b}$$

where W_{SH} is in tons and ρ_P is in megawatts per cubic foot. B is an arbitrary constant that is normally equal to unity unless a degree of pessimism is desired, in which case B can be assigned any desired value.

Fuel weight. - From the Breguet range formula, the fuel weight for chemical-powered aircraft is expressed by the following equations:

$$W_F = W_G\left[1 - \exp\left(-\frac{9.8\ RS}{\frac{L}{D}V}\right)\right] \tag{8a}$$

where R is the flight range in kilometers, S is the fuel consumption in kilograms per hour per newton, V is the speed in kilometers per hour, and L/D is the lift-to-drag ratio of the aircraft; or

$$W_F = W_G\left[1 - \exp\left(-\frac{RS}{\frac{L}{D}V}\right)\right] \tag{8b}$$

where R is the flight range in nautical miles, S is the fuel consumption in pounds per hour per pound of thrust, and V is the speed in knots.

Payload. - The payload is found from equation (1):

$$W_{PAY} = W_G - W_{ST} - W_E - W_R - W_{SH} - W_F \tag{9}$$

Or the payload fraction is

$$\frac{W_{PAY}}{W_G} = 1 - \frac{W_{ST}}{W_G} - \frac{W_E}{W_G} - \frac{W_R}{W_G} - \frac{W_{SH}}{W_G} - \frac{W_F}{W_G} \tag{10}$$

Cost Analysis

The cost analysis is a greatly simplified analysis to facilitate parametric study. It does, however, give cost estimates that are representative, even if not precise. The particular figure of merit used in the analysis is the cost of carrying cargo expressed in dollars per metric ton-kilometer (dollars/ton-n mi). It is intended that the analysis yield the total cost to the consumer for hauling cargo on the vehicle. It does not include in-port handling. It does account for vehicle utilization and load factor.

Vehicle cost. - The vehicle capital cost is composed of structure cost C_{ST}, engine cost C_E, reactor cost C_R, and shield cost C_{SH}. All costs are in dollars. Any other capital costs must be included in at least one of these four costs. The total cost is given by

$$C_{TOT} = C_{ST} + C_E + C_R + C_{SH} \tag{11}$$

The cost of the structure in dollars is given by

$$C_{ST}(\text{dollars}) = 1000\ K_{ST}(\text{dollars/kilogram})W_{ST}(\text{metric tons}) \tag{12a}$$

or,

$$C_{ST}(\text{dollars}) = 2000\ K_{ST}(\text{dollars/pound mass})W_{ST}(\text{tons}) \tag{12b}$$

where K_{ST} is the unit structure cost and W_{ST} is the structure weight.

The cost of the engine in dollars is given by

$$C_E(\text{dollars}) = K_E(\text{dollars/kilogram})W_E(\text{kilograms}) \tag{13a}$$

or,

$$C_E(\text{dollars}) = K_E(\text{dollars/pound mass})W_E(\text{pound mass}) \tag{13b}$$

where K_E is the unit engine cost and W_E is the engine weight.

The cost of the reactor in dollars is given by

$$C_R(\text{dollars}) = K_R(\text{dollars/megawatt})P_{th}(\text{megawatts}) \tag{14}$$

where K_R is the unit reactor cost and P_{th} is the required reactor thermal power.

The shield cost in dollars is given by

$$C_{SH}(\text{dollars}) = 1000\ K_{SH}(\text{dollars/kilogram})W_{SH}(\text{metric tons}) \tag{15a}$$

or,

$$C_{SH}(\text{dollars}) = 2000\ K_{SH}(\text{dollars/pound mass})W_{SH}(\text{tons}) \tag{15b}$$

where K_{SH} is the unit shield cost and W_{SH} is the shield weight.

Operating cost. - The total operating cost C'_{TOT} is the sum of the following costs expressed in dollars per operating hour:

C'_{FC}	chemical fuel	C'_{SH}	shield depreciation
C'_{FN}	nuclear fuel	C'_{M}	maintenance
C'_{CR}	crew	C'_{INT}	interest
C'_{ST}	structure depreciation	C'_{INS}	insurance
C'_{E}	machinery depreciation	C'_{PR}	profit
C'_{R}	reactor core depreciation		

Fuel cost. - The chemical fuel cost per operating hour C'_{FC} is found from the following expression, where C_{FC} is the cost of chemical fuel:

$$C'_{FC}(\text{dollars/hour}) = C_{FC}(\text{dollars/kilogram})S((\text{kilograms/hr})/\text{newton})F(\text{newtons}) \tag{16a}$$

$$C'_{FC}(\text{dollars/hour}) = C_{FC}(\text{dollars/pound mass})S((\text{pounds mass/hr})/\text{pounds force}) \times F(\text{pounds force}) \tag{16b}$$

The nuclear fuel cost per operating hour C'_{FN} is given by

$$C'_{FN} = C_{FN}P_{th} \tag{17}$$

where C_{FN} is the cost of nuclear fuel per thermal megawatt-hour produced by fission. The nuclear fuel cost includes nuclear fuel burnup cost, fuel element manufacturing cost, fuel reprocessing and shipping costs, and interest charges on unburned nuclear fuel. It is intended that C_{FN} covers all costs associated with the nuclear fuel cycle. The reactor cost given by equation (14) therefore does not include fuel element costs because it is included in equation (17).

Crew cost. - The cost of the crew per operating hour C'_{CR} is assumed to be a constant. In other words, the number of crew members is independent of vehicle size and all other variables.

Depreciation costs. - The structure depreciation cost per operating hour C'_{ST} is the hourly depreciation of the value of the structure. The relation used to determine this cost is

$$C'_{ST} = \frac{C_{ST}}{2T_{ST}} \tag{18}$$

where C_{ST} is the structure cost in dollars and T_{ST} is the life of the structure in operating hours. This relation is a crude approximation to the rate at which funds must be set aside so that at the end of life enough funds exist to replace the item in question. It assumes that the interest accrued by the funds set aside for depreciation doubles the actual funds set aside.

Similarly, the machinery depreciation cost C'_E, the reactor depreciation cost C'_R, and the shield depreciation cost C'_{SH} are given by

$$C'_E = \frac{C_E}{2T_E} \tag{19}$$

$$C'_R = \frac{C_R}{2T_R} \tag{20}$$

$$C'_{SH} = \frac{C_{SH}}{2T_{SH}} \tag{21}$$

<u>Maintenance cost.</u> - The maintenance cost of the entire vehicle per operating hour C'_M is assumed to be proportional to the cost of the vehicle. It is given by

$$C'_M = K_M C_{TOT} \tag{22}$$

where K_M is a maintenance cost factor that depends on vehicle type and C_{TOT} is the total vehicle cost in dollars.

<u>Interest cost.</u> - The interest cost per operating hour C'_{INT} is given by

$$C'_{INT} = \frac{K_{INT} C_{TOT}}{8760\ U} \tag{23}$$

where K_{INT} is an interest cost factor which is equal to one-half the interest rate, U is the utilization factor that is the fraction of the total hours in a year that the vehicle operates, and 8760 is the total number of hours in a year.

Insurance cost. - The insurance cost per operating hour C'_{INS} is given by

$$C'_{INS} = K_{INS}C_{TOT} \tag{24}$$

where K_{INS} is an insurance cost factor and C_{TOT} is the total vehicle cost in dollars.

Profit cost. - The profit cost per operating hour C'_{PR} is given by

$$C'_{PR} = K_{PR}(C'_{FC} + C'_{FN} + C'_{CR} + C'_{ST} + C'_{E} + C'_{R} + C'_{SH} + C'_{M} + C'_{INT} + C'_{INS}) \tag{25}$$

where K_{PR} is a profit cost factor that is equal to the ratio of cost charged to the customer to the total operating cost without a profit margin. The profit, in other words, is assumed to be a fraction of the actual cost of providing the transportation service.

Total operating cost. - The total operating cost in dollars per operating hour C'_{TOT} is given by

$$C'_{TOT} = C'_{FC} + C'_{FN} + C'_{CR} + C'_{ST} + C'_{E} + C'_{R} + C'_{SH} + C'_{M} + C'_{INT} + C'_{INS} + C'_{PR} \tag{26}$$

The total operating cost (TOC) is given by

$$\text{TOC(dollars/metric ton-kilometer)} = \frac{C'_{TOT}\text{(dollars/hour)}}{pW_{PAY}\text{(metric tons)}V\text{(kilometers/hour)}} \tag{27a}$$

$$\text{TOC(dollars/ton-nautical mile)} = \frac{C'_{TOT}\text{(dollars/hour)}}{pW_{PAY}\text{(tons)}V\text{(nautical miles/hour)}} \tag{27b}$$

where p is the payload factor (ratio of average payload carried to the full payload-carrying capacity of the vehicle).

ASSUMPTIONS

The specific assumptions made and the range for which each assumption was independently investigated are given in this section. This study is preliminary in nature and is intended to indicate performance potential rather than to make precise weight-and-cost determinations. It is, therefore, useful and necessary to show sensitivity to each assumption by varying it independently over a wide range of values to lend credibility to the analysis.

Performance Assumptions

The assumptions associated with weight, speed, and power are given in this section.

Lift-drag ratio. - The lift-drag ratio L/D for 905-metric-ton (1000-ton) aircraft, both chemical and nuclear, was assumed to be 17. It was further assumed to be independent of the flight speed for the range of flight speeds considered. This is a value that is typical of today's subsonic jet transports. For 3620-metric-ton (4000-ton) aircraft the lift-drag ratio was assumed to be 20 for both chemical and nuclear aircraft. The higher L/D is assumed for two reasons: First, this aircraft is assumed to represent later technology. Secondly, the authors believe that larger aircraft will resemble flying wings, because the space within the wings will have the volumetric capacity to hold the cargo, making large fuselages unnecessary.

Structure weight. - The ratio of structure to gross weight for aircraft used in the analysis is 0.30. It is typical for large subsonic aircraft and is assumed to be independent of all vehicle and operating variables for the purpose of this analysis. The structure fraction is varied from 0.15 to 0.40 for the reference case to determine sensitivity to structure fraction.

Fuel consumption and efficiency. - The fuel consumption S for chemical turbofan engines assumed for this analysis is shown in table I. To determine sensitivity to S, it is varied at 925 kilometers per hour (500 knots) from 0.069 to 0.116 kilogram per hour per newton (0.68 to 1.14 (lbm/hr)/lbf). For nuclear turbofan engines the overall thermal efficiency is assumed to be 0.25. The corresponding value of thermal power

TABLE I. - FUEL CONSUMPTION FOR

CHEMICAL TURBOFAN ENGINES

Speed		Specific fuel consumption	
knots	km/hr	(lbm/hr)/lbf	(kg/hr)/N
300	560	0.50	0.051
350	650	.56	.057
400	740	.66	.067
450	835	.77	.079
500	925	[a].91	[a].093
500	925	[b].68 to 1.14	[b].069 to .116

[a]Base value.
[b]Varied.

per engine thrust is shown in figure 7. The efficiency is varied from 0.15 to 0.35 to determine sensitivity to this assumption.

Engine weight. - The weight per unit thrust of turbofan engines used in this analysis is given in figure 6. Sea-level, zero-flight-speed data from reference 11 were used for 10.7 kilometers (36 000 ft) altitude by applying air-density corrections. The specific engine weight in kilograms per newton and pounds mass per pound thrust is plotted as a function of flight speed. For nuclear turbofan engines the weight was assumed to be 50 percent greater than for chemical engines to account for the heat exchanger and ducting required for nuclear engines, and also to account for the lower turbine inlet temperature that is typical for nuclear engines. This assumption was varied from 0 to 250 percent.

Reactor weight. - The reactor weight density ρ_R required to calculate reactor weight (eq. (5)) is assumed to be 4.8 grams per cubic centimeter (300 lbm/ft^3). The density is the average of all materials and parts enclosed within the volume formed by the inner diameter of the shield. This density corresponds to a reactor such as shown in figure 5. The reactor power density ρ_P is assumed to be 106 watts per cubic centimeter (3.0 MWth/ft^3). As in the case of the reactor weight density, the volume used to compute power density includes the entire volume enclosed by the inner diameter of the shield.

Shield weight. - The shield weight is given by equation (7). The shield is a 4π optimized unit shield composed of optimum-thickness layers of depleted uranium metal and water. As previously mentioned, it is designed to reduce the dose level at 9.15 meters (30 ft) from the reactor center to 0.25 millirem per hour. At 30.5 meters (100 ft) from the reactor centerline, the dose level is about 0.025 millirem per hour. It actually could be less than this depending on how much structure, cargo, or other material is located between the measuring station and the reactor. The value of the constant B used in equation (7) is 1.0. To obtain a degree of pessimism in the shield weight, any desired value of the constant may be assumed. Shield weight is plotted as a function of reactor power in figure 8.

Fuel and range. - The range for chemically powered aircraft is assumed to be 3710, 7420, and 11 130 kilometers (2000, 4000, and 6000 n mi). For nuclear aircraft, enough chemical fuel is carried to give an emergency chemical range of 925 kilometers (500 n mi) for the 905-metric-ton (1000-ton) aircraft and 2790 kilometers (1500 n mi) for the 3620-metric-ton (4000-ton) gross weight aircraft at design speed. The emergency chemical range is varied from 0 to 5570 kilometers (0 to 3000 n mi) to determine sensitivity to this parameter.

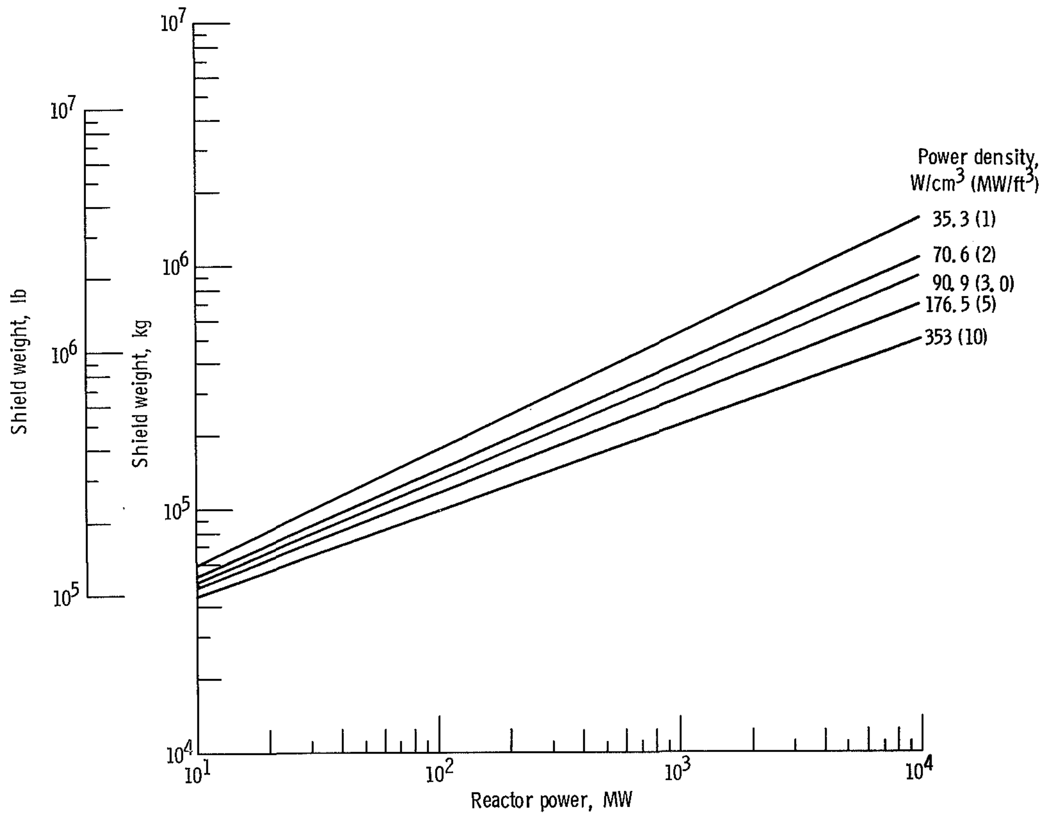


Figure 8. - Shield weight for optimized depleted uranium and water shield. Dose rate at 9.15 meters (30 ft) from reactor centerline, 0.25 millirem per hour. (Spherical shield uniform dose in all 4π directions.)

Cost Assumptions

The assumptions used to calculate specific costs are given in this section.

Initial structure cost. - The structure cost is given by equation (12). The value of K_{ST}, the structure cost in dollars per pound, assumed for 905-metric-ton (1000-ton) aircraft is \$110 per kilogram (\$50/lbm). For the 3620-metric-ton (4000-ton) aircraft, K_{ST} is \$55 per kilogram (\$25/lbm). It is assumed that the need for lower structure cost and the potential for reducing cost in larger vehicles will result in a factor-of-2 reduction in unit structure cost for the larger aircraft. This assumption is varied from \$22 to \$165 per kilogram (\$10 to \$75/lbm) to determine sensitivity.

Initial engine cost. - The engine cost is given by equation (13). The value of K_E assumed for this analysis is \$132 per kilogram (\$60/lbm) for chemical engines. For nuclear engines the cost is assumed to be 1.25 times the corresponding chemical engine cost. The nuclear engine cost does not include the cost of the reactor shield or the nuclear fuel. These costs are considered separately.

Initial reactor cost. - The reactor cost is given by equation (14). The value of the constant K_R(dollars/MWth) used for this analysis is 3500. The cost includes only the cost of the reactor vessel, the core structure, in-core control equipment, and other items within the shield. It does not include the fuel element cost. The fuel element cost is included in the nuclear fuel cost. The reactor cost is varied from $1500 to $10 000 per megawatt thermal to determine sensitivity to this parameter.

Initial shield cost. - The initial shield cost is given by equation (15). The value of K_{SH} used for this analysis is $11 per kilogram ($5/lbm). This is based on a water and depleted-uranium shield with a stainless-steel containment vessel included in the shield. The shield cost is varied from $4.4 to $55 per kilogram ($2 to $20/lbm) to determine sensitivity.

Fuel cost. - Fuel cost is given by equation (16) for chemically fueled vehicles. The unit fuel cost C_{FC} assumed is $0.0264 per kilogram ($0.012/lbm). This corresponds to a cost of about 8 cents per gallon of jet fuel. Nuclear fuel cost is found by use of equation (17). The unit nuclear fuel cost C_{FN} assumed for this analysis is $0.50 per megawatt thermal-hour. This corresponds to $12 per gram of uranium-235, or is equivalent to about 1.7 mils per kilowatt-hour of electrical energy for a nuclear electric powerplant with a thermal efficiency of 30 percent. The fuel cost includes manufacturing fuel elements, reprocessing and shipping, interest on unburned fuel, and all other charges normally credited to fuel cost. The value of fuel cost is varied from $4 to $24 per gram to indicate sensitivity of the results to fuel cost assumption.

Crew cost. - The crew cost is assumed to be $250 per operating hour for all vehicles studied in this analysis. This corresponds to the cost of crewing an aircraft like the Boeing 747 (ref. 12). This assumption is justified on the basis that an all-cargo operation does not require a large crew. It is further assumed that all vehicles are automated to the extent of a large aircraft so that only a small operating crew is required.

Depreciation cost. - The depreciation costs are calculated by equations (18) to (21). The life assumed for each depreciation cost is as follows:

Structure life, T_{ST}, operating hours	75 000
Machinery life, T_E, operating hours	50 000
Reactor structure life, T_R, operating hours	50 000
Shield life, T_{SH}, operating hours	75 000

The structure life was varied from 25 000 to 100 000 hours to determine sensitivity.

Maintenance cost. - Maintenance cost is given by equation (22). The maintenance cost factor K_M is assumed to be 15×10^{-6}. This corresponds to the maintenance cost of Boeing 747 operation (ref. 12), which is varied from 4×10^{-6} to 30×10^{-6} to determine sensitivity.

Interest cost. - Interest cost is given by equation (23). The interest cost factor

TABLE II. - ASSUMPTIONS USED IN ANALYSIS

Assumption	905-Metric-ton (1000-ton) aircraft		3620-Metric-ton (4000-ton) aircraft	
	Baseline value	Range varied	Baseline value	Range varied
Gross weight, W_G, metric tons; tons	905; 1000	271 to 3620; 300 to 4000	3620; 4000	905 to 9050; 1000 to 10 000
Structure weight fraction, W_{ST}/W_G	0.30	0.20 to 0.40	0.30	0.20 to 0.40
Engine thermal power per unit of thrust	See fig. 7	----------	See fig. 7	----------
Engine weight per unit of thrust	See fig. 6	----------	See fig. 6	----------
Ratio of nuclear to chemical engine weight	1.5	1.0 to 2.5	1.5	1.0 to 2.5
Lift-drag ratio, L/D	17	14 to 22	20	15 to 25
Reactor weight density, ρ_R, g/cm^3; lbm/ft^3	4.8; 300	Not varied	4.8; 300	Not varied
Reactor power density, ρ_P, W/cm^3; MW/ft^3	106; 3	71 to 353; 2 to 10	106; 3	35.3 to 353; 1 to 10
Shield weight constant, B	1	Not varied	1	Not varied
Range for chemical aircraft, R, km; n mi	3710, 7420, 11 130; 2000, 4000, 6000	----------	3710, 7420, 11 130; 2000, 4000, 6000	----------
Thermal nuclear efficiency, η, percent	25	20 to 35	25	15 to 35
Fuel consumption, S, (kg/hr)/N; (lbm/hr)/lbf	See table I	----------	See table I	----------
Speed, V, km/hr; knots	925; 500	555 to 925; 300 to 500	925; 500	555 to 925; 300 to 500
Unit structure cost, K_{ST}, dollars/kg; dollars/lbm	110; 50	22 to 165; 10 to 75	55; 25	22 to 165; 10 to 75
Unit engine cost, K_E, dollars/kg; dollars/lbm:				
Chemical	132; 60	Not varied	132; 60	Not varied
Nuclear	194; 75	132 to 264; 60 to 120	194; 75	132 to 264; 60 to 120
Unit reactor cost, K_R, dollars/MW	3500	1000 to 10 000	3500	1000 to 10 000
Unit shield cost, K_{SH}, dollars/kg; dollars/lbm	11; 5	4.4 to 44; 2 to 20	11; 5	4.4 to 44; 2 to 20
Fuel cost:				
Chemical, dollars/kg; dollars/lbm	0.0204; 0.012	0.0198 to 0.0391; 0.009 to 0.018	0.0204 to 0.012	0.0198 to 0.0397; 0.009 to 0.018
Nuclear, dollars/g	12	4 to 24	12	4 to 24
Structure life,[a] T_{ST}, hr	75 000	25 000 to 100 000	75 000	25 000 to 100 000
Engine life,[a] T_E, hr	50 000	Not varied	50 000	Not varied
Reactor life, T_R, hr	50 000	Not varied	50 000	Not varied
Shield life, T_{SH}, hr	75 000	Not varied	75 000	Not varied
Maintenance cost factor,[a] K_M	15×10^{-6}	7.75×10^{-6} to 30×10^{-6}	15×10^{-6}	7.75×10^{-6} to 30×10^{-6}
Interest cost factor,[a] K_{INT}	0.075	0.060 to 0.100	0.075	0.060 to 0.100
Utilization factor, U	0.5	0.4 to 1.0	0.5	0.4 to 1.0
Insurance cost factor,[a] K_{INS}	3.5×10^{-6}	Not varied	3.5×10^{-6}	Not varied
Profit, K_{PR}	20	10 to 30	20	10 to 30
Load factor, p	0.6	0.4 to 1.0	0.6	0.4 to 1.0
Crew cost,[a] C'_{CR}, dollars/hr	250	Not varied	250	Not varied

[a]Based on Boeing 747 operating experience.

K_{INT} is assumed to be 0.0375, which corresponds to an interest rate of 7.5 percent. The interest rate is varied from 6 to 10 percent in the analysis to show sensitivity.

Insurance cost. - Insurance cost is given by equation (24). The insurance cost factor K_{INS} is assumed to be 3.5. This corresponds to the experience for the Boeing 747 (ref. 12).

Profit cost. - The profit cost is given by equation (25). The profit factor K_{PR} that is assumed for this analysis is 1.20. This assumes that the cost of the transportation service to the customer is 20 percent greater than the actual cost of providing the service. This assumption is varied from 10 to 30 percent to determine the sensitivity of the results to this assumption.

All the assumptions used in this analysis and the range over which each is varied are presented in table II.

All the results are plotted to show only the effect on total operating cost, which is used as the figure of merit. More complete tabular data of all calculated quantities are presented for only a few representative costs because of the large volume of calculations. This information is presented in appendix B.

RESULTS

Calculations of estimated total operating cost as a function of speed were made for 905- and 3620-metric-ton (1000- and 4000-ton) aircraft. The assumptions made in the analysis are intended to reflect attainable performance in the post-1980 time period. The corresponding weight breakdowns are also presented to indicate the magnitude of the important weight factors. In addition, the sensitivity of performance to most of the assumptions used is presented. The total operating cost is plotted against each varying assumption while the remaining assumptions are fixed. This is done for a speed of 925 kilometers per hour (500 knots).

The total operating cost that is used in this analysis is to be contrasted to the direct operating cost that is normally used in transportation studies. For example, the usual direct operating cost does not include profit, which is included in the total operating cost as used herein. The total operating cost is intended to be the cost charged to the consumer for transportation. It does not, however, include the cost of handling, storing, or shipping the cargo in the originating or destination port. These charges can be major items and must be considered in evaluating a total transportation system. It is also recognized that serious attention must be given to the design, operation, and geographical location of port facilities to properly evaluate a total system. A study of this type is beyond the scope of this analysis.

The 905-Metric-Ton (1000-Ton) Aircraft

The 905-metric-ton (1000-ton) aircraft is intended to be representative of the next generation of aircraft beyond the jumbo jets of today. It is assumed that the structure weight fraction is 0.30 and lift-drag ratio is 17 that is typical of today's technology. It is assumed that the cost of the aircraft structure is $110 per kilogram ($50/lbm) and that the engine cost per pound is about the same as today. Nuclear-powered aircraft are assumed to have complete 4π shielding, with dose levels from reactor radiation less than cosmic radiation doses at 10.7 kilometers (35 000 ft). The 905-metric-ton (1000-ton) nuclear aircraft has an emergency chemical fuel supply sufficient for 925 kilometers (500 n mi) flight at design conditions with the nuclear reactor shut down. A complete list of assumptions made to carry out the analysis is given in the section ASSUMPTIONS.

The total operating cost for nuclear- and chemical-powered aircraft is presented in figure 9. The chemical aircraft data are plotted for ranges of 3710, 7420, and 11 130 kilometers (2000, 4000, and 6000 n mi). For a range of about 9275 kilometers (5000 n mi) or greater, the 905-metric-ton (1000-ton) nuclear aircraft costs less to operate than chemical aircraft of equal size. The total operating cost for chemical aircraft with transoceanic ranges of 7420 and 11 130 kilometers (4000 and 6000 n mi) is about $0.024 and $0.036 per metric ton-kilometer ($0.040 and $0.060 ton-n mi), respectively, for speeds of 740 kilometers per hour (400 knots). The nuclear aircraft total operating cost is about $0.027 per metric ton-kilometer ($0.045 ton-n mi) at 740 kilometers per hour

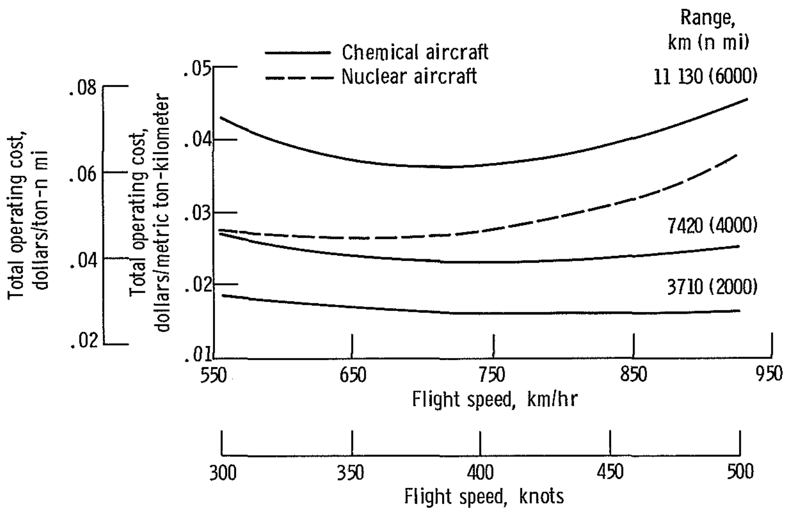


Figure 9. - Total operating cost as function of speed for chemical- and nuclear-powered aircraft. Gross weight, 905 metric tons (1000 tons); structure weight fraction, 0.30; structure cost, $110 per kilogram ($50/lbm); load factor, 0.6; utilization factor, 0.5; profit, 20 percent; flight altitude, 10.7 kilometers (35 000 ft).

(400 knots), and is, of course, independent of range. The premium the consumer is willing to pay for the speed advantage offered by cargo aircraft and the degree of cost saving due to high-speed cargo movement will determine the fraction of the total cargo market that the 905-metric-ton (1000-ton) aircraft will capture.

It is beyond the scope of the report to make a detailed analysis of the effect of flight speed. For example, careful variation of engine performance with flight speed was not attempted: the aircraft L/D was not varied with speed, structure weight was not varied with speed, etc. With the limitations imposed by these qualifications, the sensitivity to speed does not appear to be of first-order importance. There does appear to be an optimum speed in the range of 650 to 740 kilometers per hour (350 to 400 knots) for nuclear aircraft and for chemical aircraft with flight ranges of 7420 to 11 130 kilometers (4000 to 6000 n mi).

The corresponding weight breakdowns for the 905-metric-ton (1000-ton) aircraft are shown in figures 10(a) to (d). The payload fraction for the nuclear aircraft is about 0.23 for a speed of 740 kilometers per hour (400 knots). The reactor, shield, and engines constitute about 42 percent of the gross weight for this speed. The emergency chemical fuel supply for 925 kilometers (500 n mi) range at design conditions is about 4.5 percent of the gross weight.

For chemical aircraft the fuel weight is 18, 32, and 44 percent of the gross weight for ranges of 3710, 7420, and 11 130 kilometers (2000, 4000, and 6000 n mi), respectively, for a speed of 925 kilometers per hour (500 knots). The payload fraction varies from 47 to 32 to 21 percent of the gross weight for ranges of 3770, 7420, and 11 130 kilometers (2000, 4000, and 6000 n mi), respectively. The payload fraction for the 11 130-kilometer (6000-n mi) range chemical aircraft is almost the same as the payload fraction for the nuclear aircraft. The nuclear aircraft indicates a lower total operating cost, however, because of the much lower nuclear fuel cost. Even though the initial cost of the nuclear aircraft is greater than that of the chemical aircraft, the effect of the lower fuel cost dominates. Thus, the nuclear aircraft appears attractive for transoceanic commerce if the gross weight is about 905 metric tons (1000 tons). It theoretically would take a fleet of 500 of these nuclear aircraft to carry 1 percent of the transoceanic commerce predicted for 1980. Whether this fraction of the ocean commerce is of sufficient value to warrant shipment with transportation rates of about $0.027 per metric ton-kilometer ($0.045/ton-n mi) would help determine whether the large nuclear aircraft would be economically feasible. This point is certainly worth investigating further, but is beyond the scope of this report.

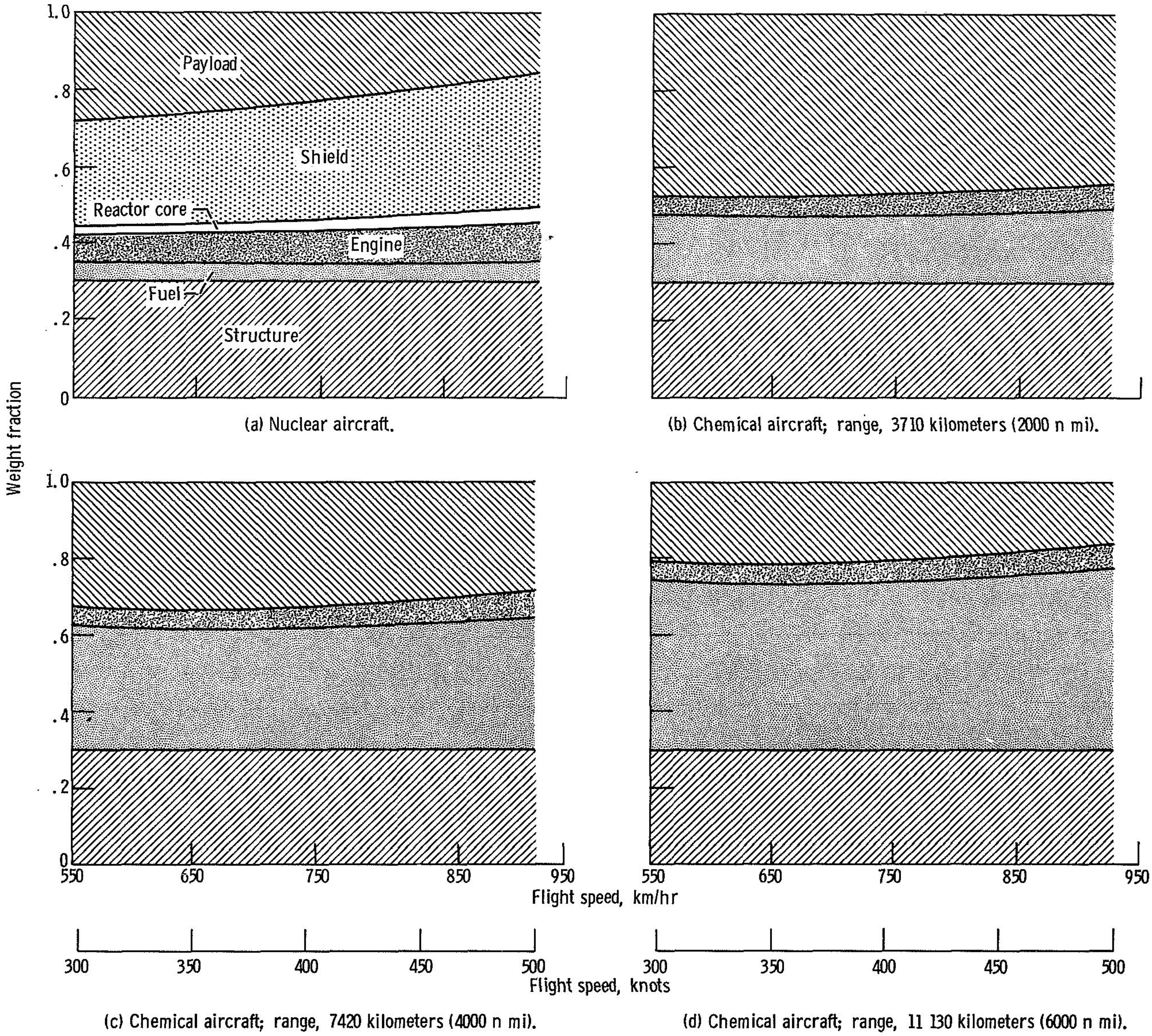


Figure 10. - Weight breakdown as function of speed for chemical- and nuclear-powered aircraft of 905 metric tons (1000 tons) gross weight. Structure weight fraction, 0.30.

The 3620-Metric-Ton (4000-Ton) Aircraft

The 3620-metric-ton (4000-ton) aircraft represents anticipated performance beyond 1980. The major difference between the 905-metric-ton (1000-ton) aircraft and the 3620-metric-ton (4000-ton) aircraft is that the assumed structure cost is reduced from $110 to $55 per kilogram ($50 to $25/lbm) and the lift-drag ratio is increased from 17 to 20 due to advances in technology and effects of larger scale. The emergency chemical cruising range is increased from 925 kilometer (500 n mi) to 2775 kilometers (1500 n mi) for the 3620-metric-ton (4000-ton) nuclear aircraft.

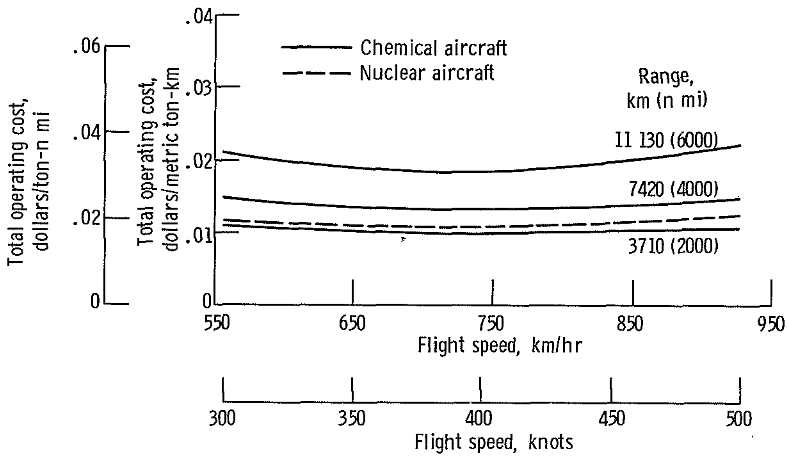


Figure 11. - Total operating cost as function of speed for chemical- and nuclear-powered aircraft. Gross weight, 3620 metric tons (4000 tons); structure weight fraction, 0.3; structure cost, \$55 per kilogram (\$25/lbm); load factor, 0.6; utilization factor, 0.5; profit, 20 percent; flight altitude, 10.7 kilometers (35 000 ft).

The total operating cost for nuclear- and chemical-powered 3620-metric-ton (4000-ton) aircraft is presented in figure 11. The chemical aircraft data are plotted for ranges of 3710, 7420, and 11 130 kilometers (2000, 4000, and 6000 n mi). For a range of 4565 kilometers (3000 n mi) or greater, the nuclear aircraft costs less to operate than do chemical aircraft. For transoceanic flights, which require ranges of the order of 7420 to 11 130 kilometers (4000 to 6000 n mi), the total operating cost for chemical aircraft varies from about \$0.014 to \$0.022 per metric ton-kilometer (\$0.024 to \$0.037/ton-n mi) at a speed of 925 kilometers per hour (500 knots). The total operating cost for nuclear aircraft is about \$0.012 per metric ton kilometer (\$0.020/ton-n mi) at 925 kilometers per hour (500 knots). The operating costs can be reduced only slightly by reducing speed. The minimum operating cost shown for nuclear aircraft occurs at speeds of about 700 to 790 kilometers per hour (375 to 425 knots) and is about \$0.0107 per metric ton-kilometer (\$0.018/ton-n mi). A feature of nuclear aircraft is that the total operating cost is independent of range.

The corresponding weight breakdowns for the nuclear- and chemical-powered 3620-metric-ton (4000-ton) aircraft are presented in figures 12(a) to (d). For the nuclear aircraft the payload varies from about 40 percent to 30 percent of the gross weight for speeds ranging from 740 to 925 kilometers per hour (300 to 500 knots), respectively. The reactor, shield, and engines constitute about 20 to 27 percent of the gross weight for this same speed range. The emergency chemical fuel supply that will give a 2775-kilometer (1500-n mi) range at design flight conditions is about 12 percent of the gross weight.

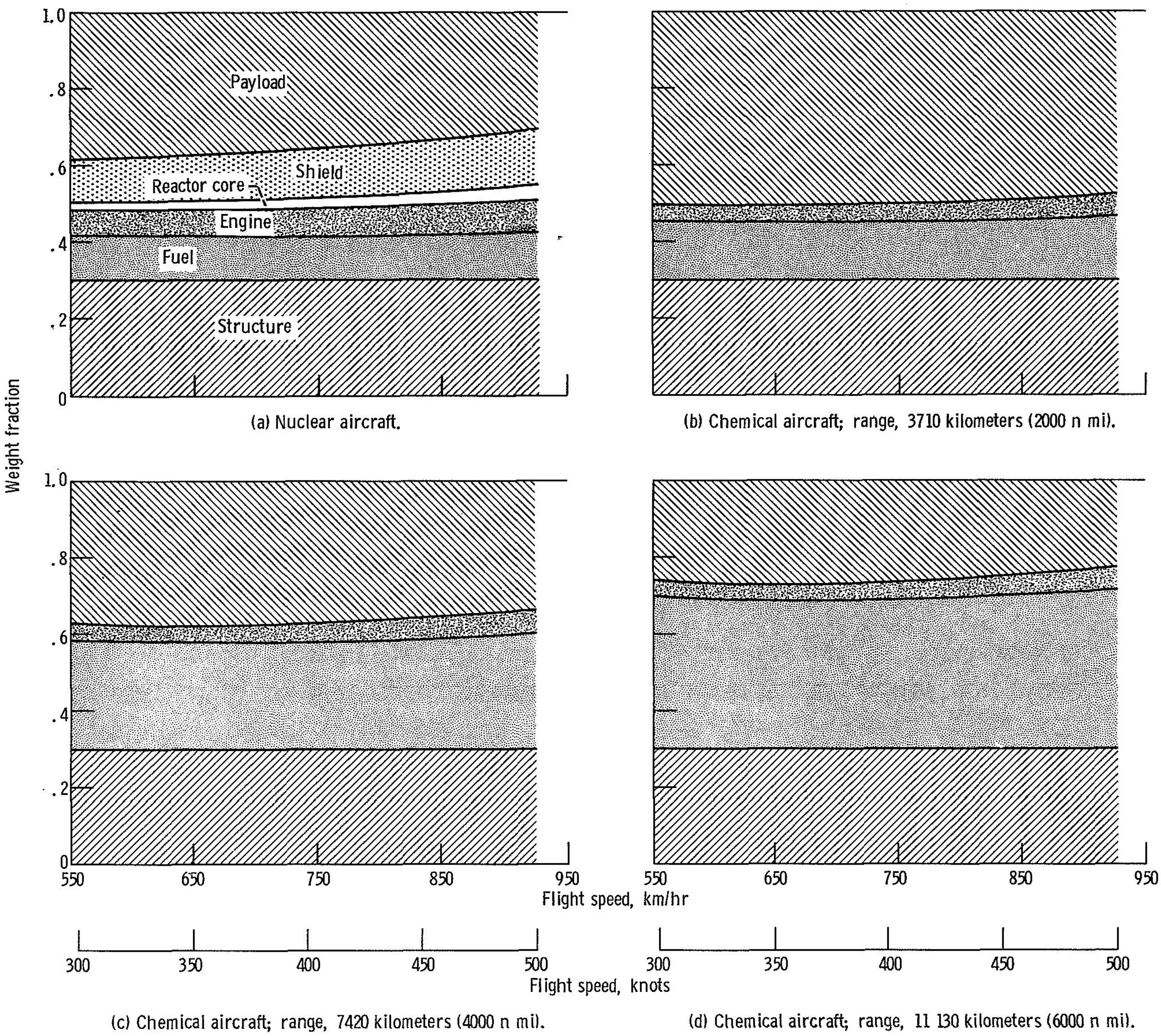


Figure 12. - Weight breakdown as function of speed for chemical- and nuclear-powered aircraft of 3620 metric tons (4000 tons) gross weight. Structure weight fraction, 0.30.

For chemical aircraft the fuel weight fraction becomes dominant as range is increased to 11 130 kilometers (6000 n mi). The fuel fractions for transoceanic ranges of 7420 and 11 130 kilometers (4000 and 6000 n mi) are about 30 and 40 percent, respectively, at speeds in the range of 550 to 925 kilometers per hour (300 to 500 knots). The chemical aircraft payload fractions for 7420- and 11 130-kilometer (4000- and 6000-n mi) ranges are about 35 and 25 percent, respectively, for the same speed range. The payload fractions are not greatly different from those for nuclear aircraft. The superior performance of the nuclear aircraft on a cost basis is chiefly due to the lower cost of nuclear fuel. The greatly reduced fuel cost more than compensate for the higher capital cost of the nuclear aircraft.

The payload delivery capability of a 3620-metric-ton (4000-ton) nuclear aircraft is about 0.95 billion metric ton-kilometers (1.6 billion ton-n mi) per year, including the assumption of a load factor of 0.6 and utilization of 0.5. A fleet of 1000 of these aircraft theoretically could haul 8 percent of the world transoceanic cargo trade predicted for 1980 or 4 percent of that predicted for 1995. These predictions do not take into account any increase in trade that would probably be attracted by the high-speed of air transportation. Lower inventory costs and the possibility of shipping perishable goods are examples of the factors that will determine the amount of additional trade attracted by the high speed.

Sensitivity to Assumptions

In a broad analysis of the kind presented in this study many assumptions must be made to arrive at specific numbers such as total operating cost. To completely justify each assumption so that no one would question any of them would be at best an impossible dream. Therefore, the authors have taken the liberty, first of all, to greatly simplify the analysis so as to minimize the number of variables that are considered and, secondly, to select reference values for each of the variables considered. It was the intent to select what are thought to be reasonable projected values for each of the variables. However, recognizing that there is a great possibility that the reference values may be questioned, almost every variable was independently varied to determine the sensitivity of the results to the particular assumed value. The effect on total operating cost caused by varying each of the major variables is plotted in the next series of figures.

Parts (a) to (t) of figures 13 and 14 show the effect of varying the following variables on the total operating cost for 905-metric-ton (1000-ton) and 3620-metric-ton (4000-ton) aircraft, respectively:

(1) Lift-drag ratio
(2) Structure weight fraction
(3) Structure cost
(4) Gross weight
(5) Load factor
(6) Utilization factor
(7) Maintenance cost factor
(8) Interest rate
(9) Profit rate
(10) Structure life
(11) Chemical fuel cost
(12) Specific fuel consumption
(13) Thermal efficiency
(14) Chemical range for nuclear aircraft
(15) Ratio of nuclear to chemical engine weight
(16) Uranium fuel cost
(17) Reactor cost
(18) Shield cost
(19) Ratio of nuclear to chemical engine cost
(20) Reactor power density

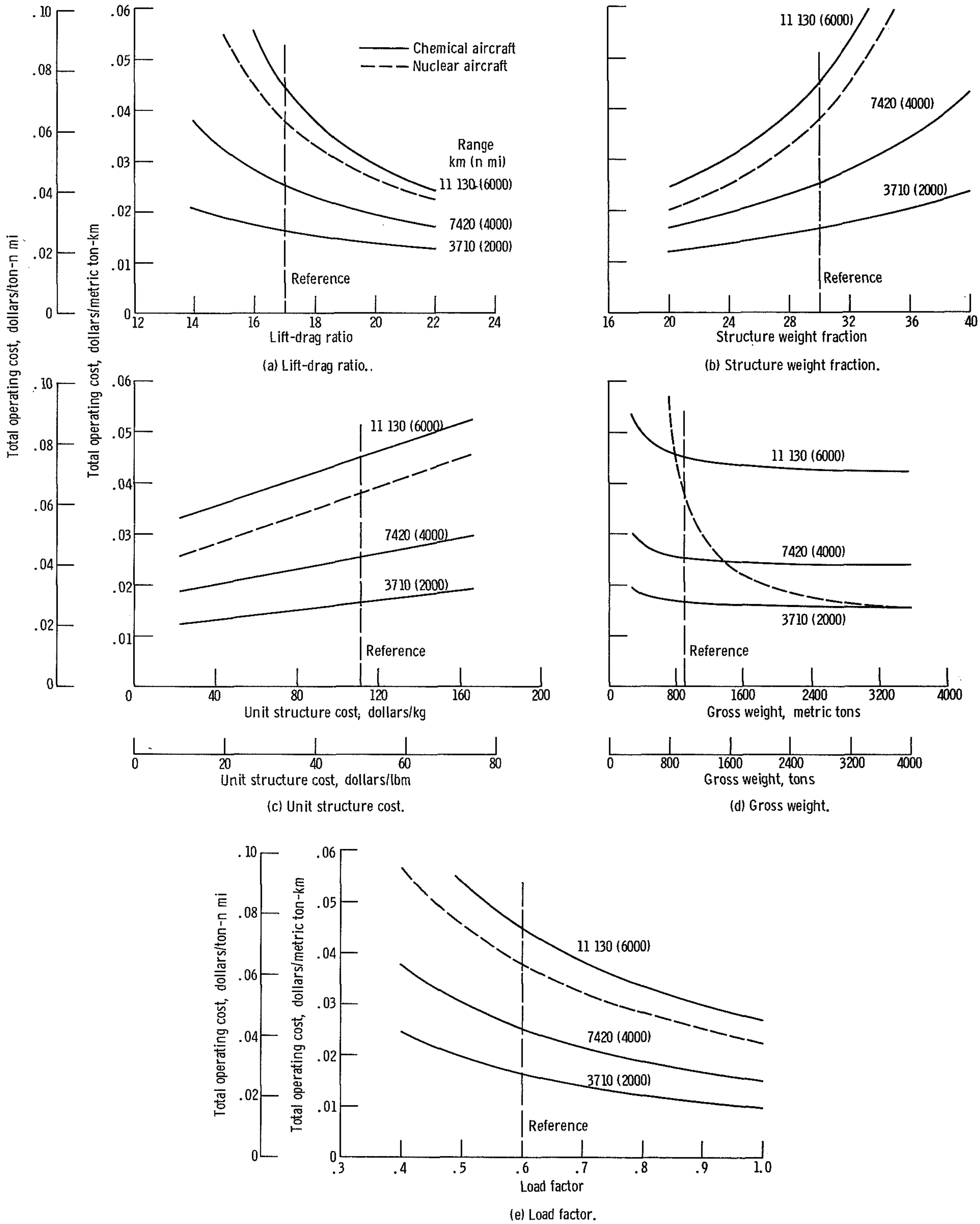
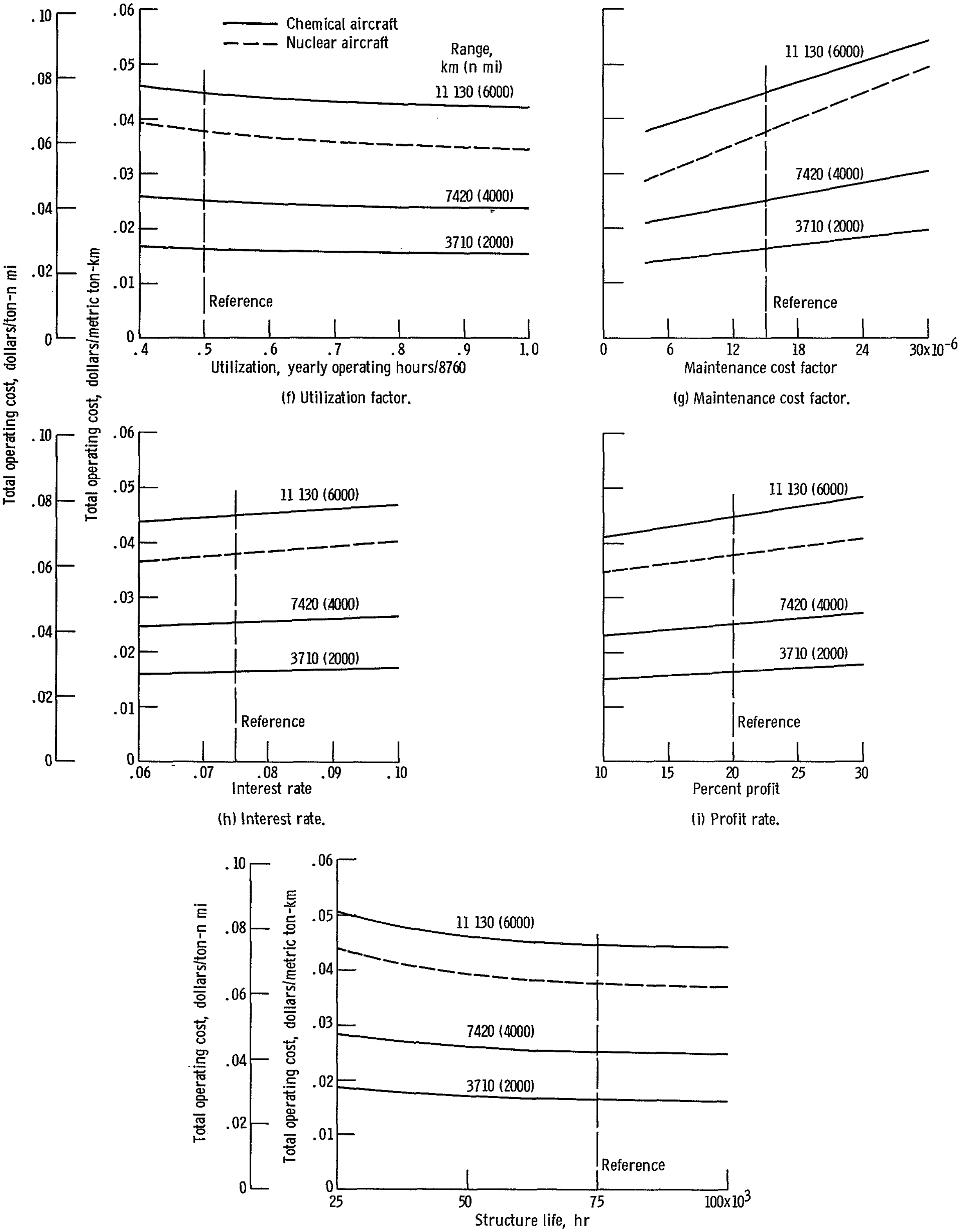


Figure 13. - Effect of variation of major assumptions on total operating cost for chemical- and nuclear-powered aircraft of 905 metric tons (1000 tons) gross weight.



(f) Utilization factor.

(g) Maintenance cost factor.

(h) Interest rate.

(i) Profit rate.

(j) Structure life.

Figure 13. - Continued.

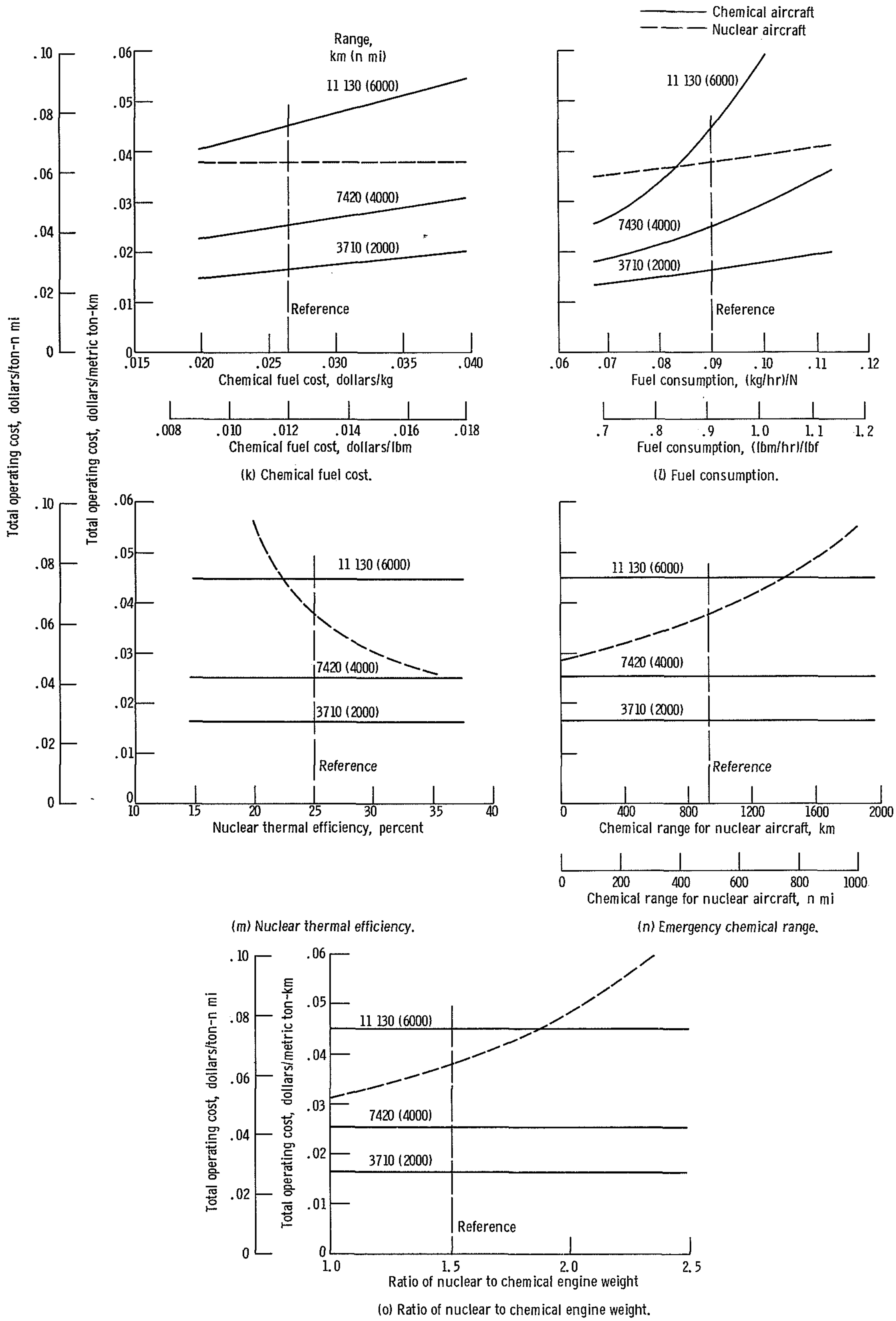


Figure 13. - Continued.

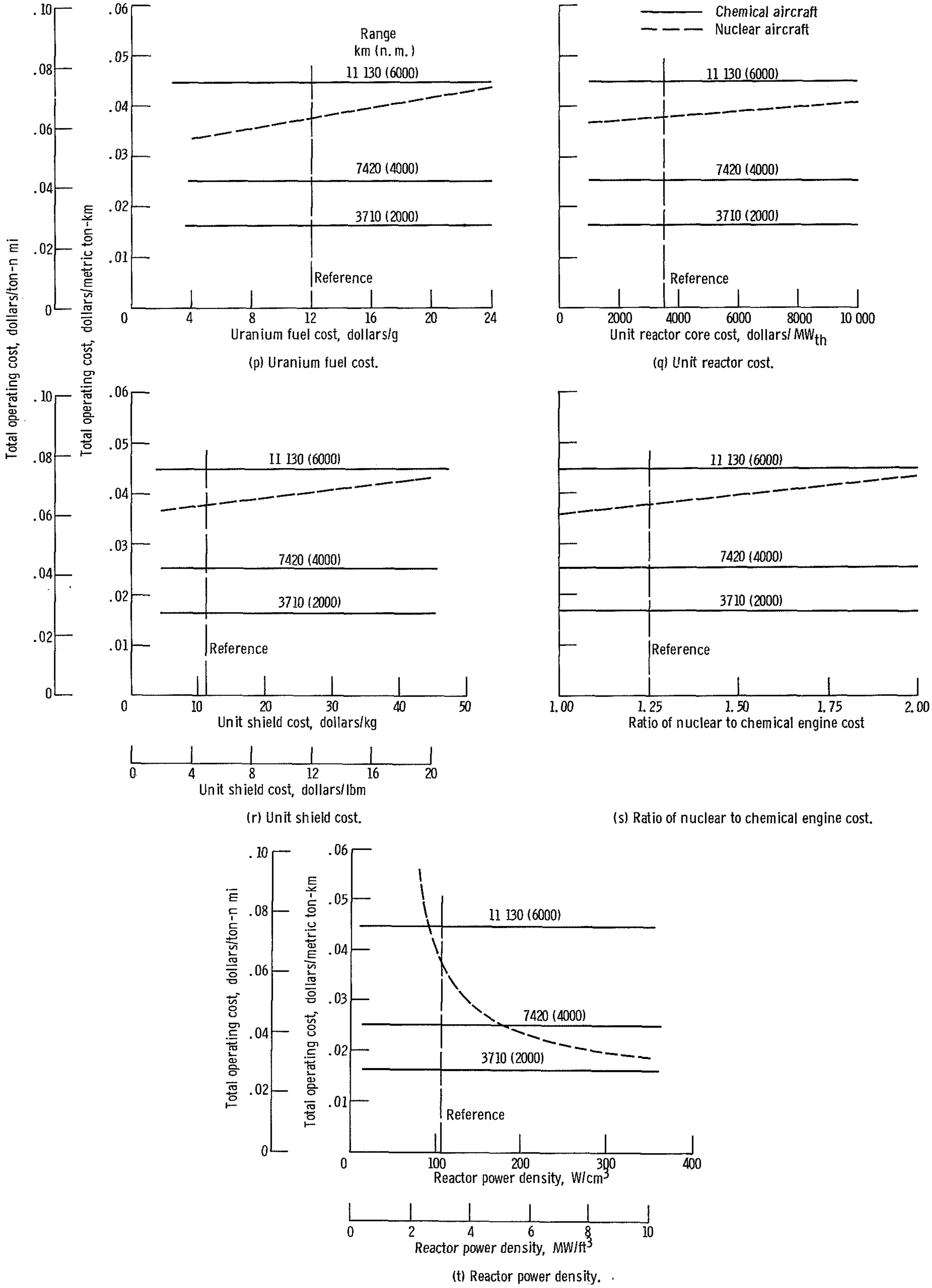


Figure 13. - Concluded.

905-Metric-ton (1000-ton) aircraft. - Figures 13(a) to (t) present the effect of varying the main assumptions used in this analysis of 905-metric-ton (1000-ton) aircraft. From a quick examination of all the figures, it is obvious that lift-drag ratio, structure weight fraction, structure cost, gross weight, and load factor (figs. 13(a) to (e)) are the variables to which the total operating cost for both chemical and nuclear aircraft is most sensitive. However, with the exception of gross weight, variations of these parameters do not affect significantly the relative merit of chemical and nuclear aircraft. For the ranges of these variables presented, the 905-metric-ton (1000-ton) nuclear aircraft gives better performance than the chemical aircraft for ranges of 9275 kilometers (5000 n mi) or greater. Significant improvement can be obtained by increasing gross weight of the nuclear aircraft.

Increasing the lift-drag ratio from 17 to 20 causes an important reduction in total operating cost of nuclear and chemical vehicles, especially for the longest ranges.

The longer range chemical aircraft are more sensitive to structure weight fraction than lower range chemical or nuclear aircraft because the payload fraction is smaller for the longer range chemical aircraft.

The structure cost is one of the more important fractions of the total cost. Variations in it, therefore, cause marked effects on the total operating cost. Increasing the structure cost to $165 per kilogram ($75/lbm) increases the total operating cost by about 20 percent for both nuclear and chemical aircraft.

The gross weight has a more important effect on nuclear aircraft performance than on chemical aircraft performance. This is because the shield weight of the nuclear aircraft does not change in direct proportion with aircraft size. The shield weight varies approximately as the 0.4 or 0.5 exponent of the reactor power (hence, gross weight). Therefore, reducing gross weight has the effect of increasing the fraction of the gross weight that is shield weight. This reduces the payload fraction. As shown in figure 13(d) for gross weights of less than 905 metric tons (1000 tons), the operating cost of the nuclear aircraft increases rapidly. Conversely, as gross weight is increased, the shield weight fraction reduces and the operating cost decreases.

The load factor affects performance strongly because it directly affects the efficiency of operation. Reducing the load factor by one-third increases the total operating cost by 50 percent for all aircraft, nuclear or chemical, regardless of range.

Of less importance to the cost performance for both nuclear and chemical aircraft is utilization factor, maintenance factor, interest rate, profit rate, and structure life (figs. 13(f) to (j)).

The chemical fuel cost and fuel consumption (figs. 13(k) and (l)) are important especially for chemical aircraft. These factors also affect somewhat the relative cost performance of chemical and nuclear aircraft.

For nuclear aircraft, thermal efficiency, emergency chemical range, and the ratio of nuclear engine weight to chemical engine weight (figs. 13 (m), (n), and (o)) are of

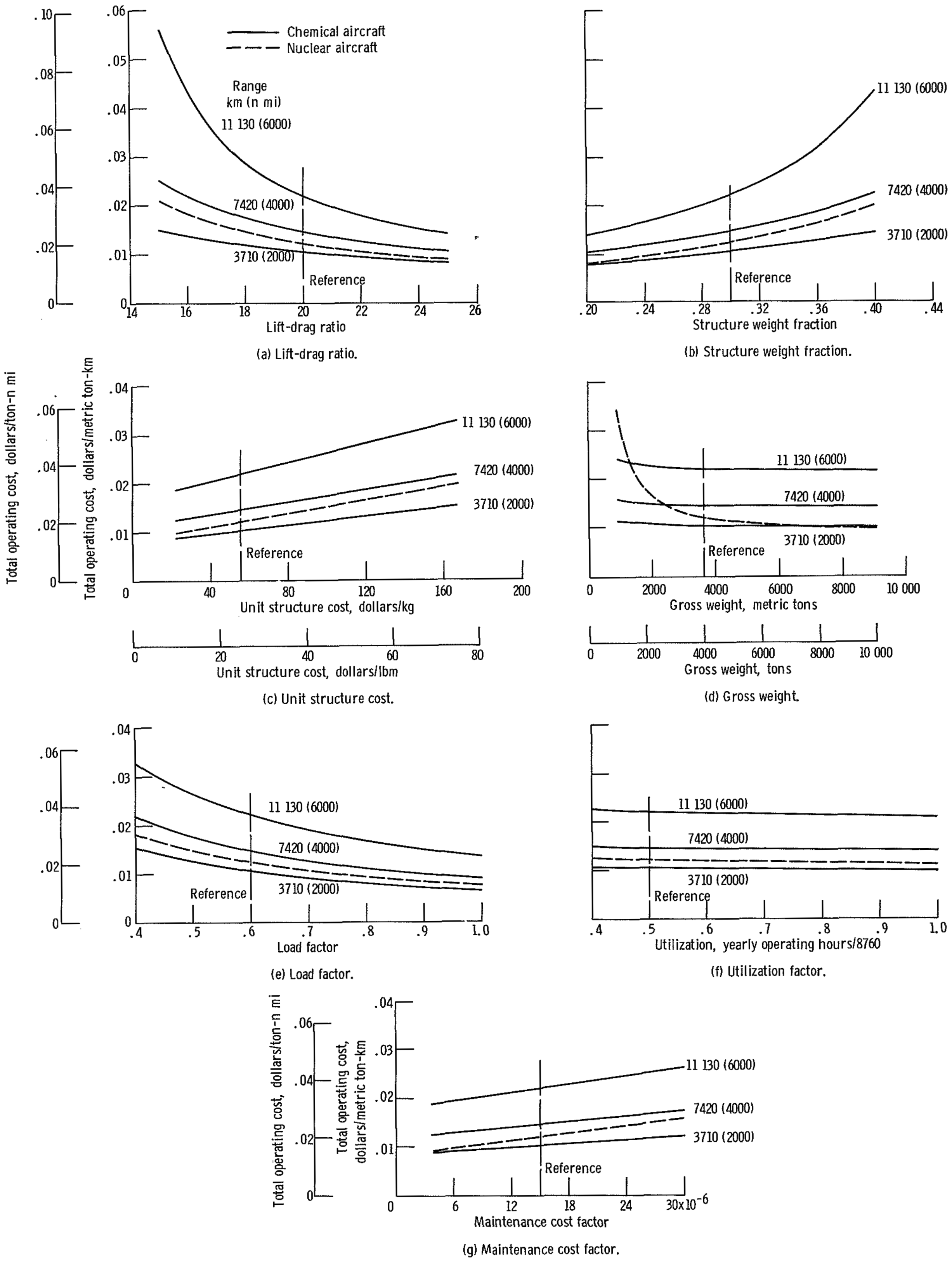
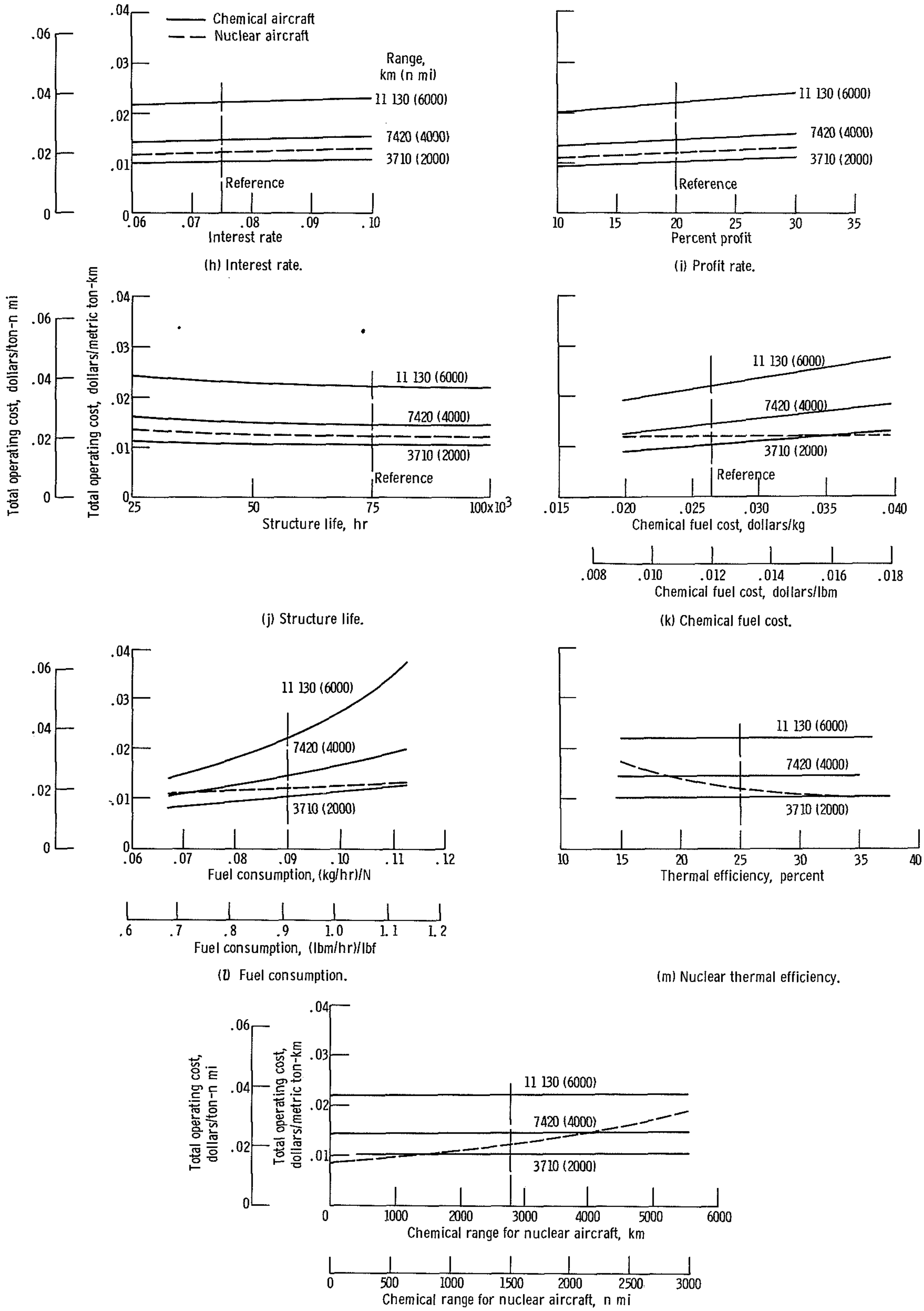


Figure 14. - Effect of variation of major assumptions on total operating cost for chemical- and nuclear-powered aircraft of 3620 metric tons (4000 tons) gross weight.



(h) Interest rate.

(i) Profit rate.

(j) Structure life.

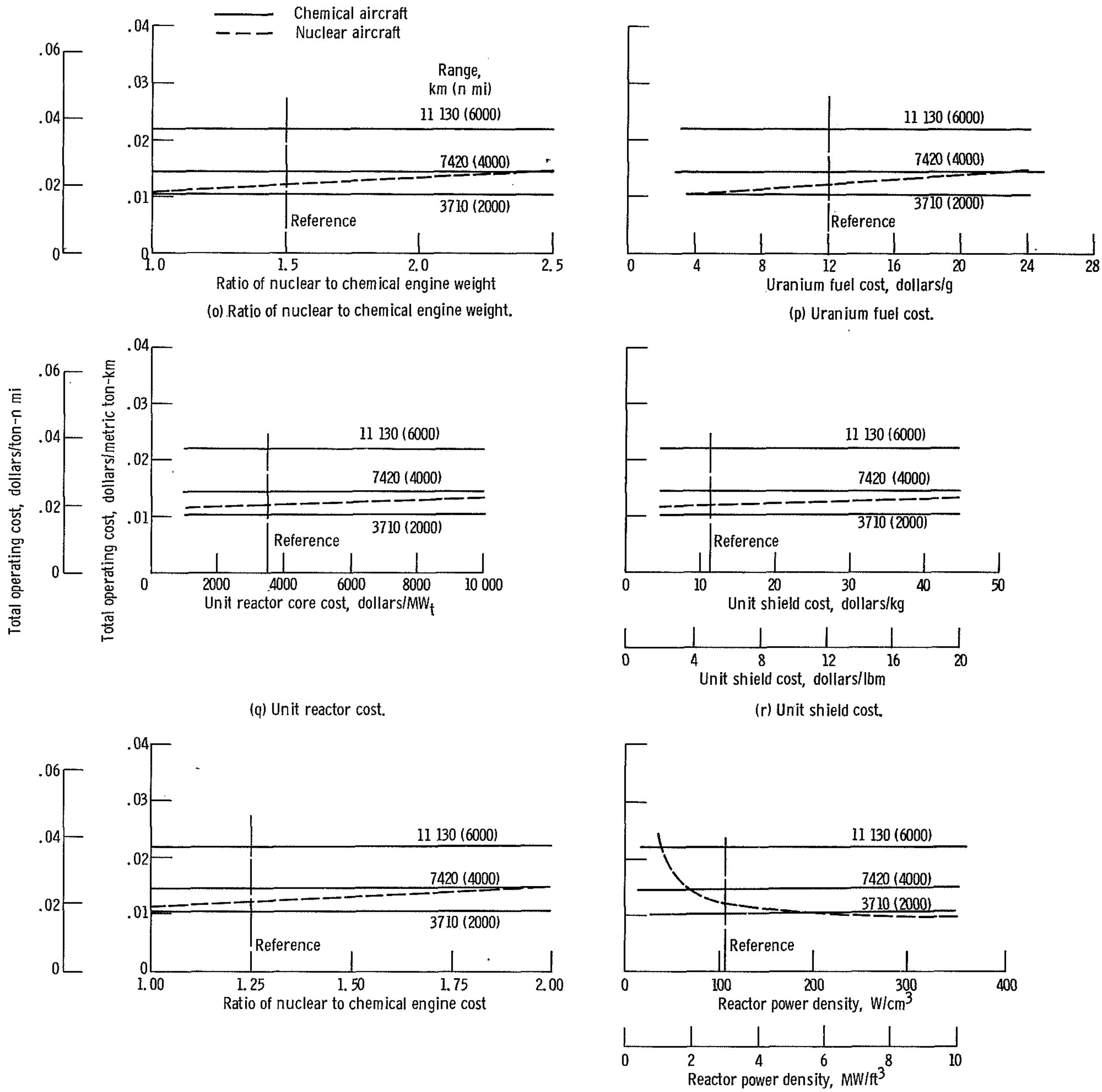
(k) Chemical fuel cost.

(l) Fuel consumption.

(m) Nuclear thermal efficiency.

(n) Emergency chemical range.

Figure 14. - Continued.



(o) Ratio of nuclear to chemical engine weight.

(p) Uranium fuel cost.

(q) Unit reactor cost.

(r) Unit shield cost.

(s) Ratio of nuclear to chemical engine cost.

(t) Reactor power density.

Figure 14. - Concluded.

importance. Reducing thermal efficiency from 25 percent to 20 percent could cause an increase in operating cost of 50 percent. Increasing emergency chemical range from 925 to 1850 kilometers (500 to 1000 n mi) would cause an increase of 50 percent in operating cost.

Uranium fuel cost, reactor cost, shield cost, and the ratio of nuclear engine cost to chemical engine cost (figs. 13(p) to (s)) appear to have little effect on operating cost because they are not large items in the overall cost. Reactor power density (fig. 13(t)) is an important parameter for the 905-metric-ton (1000-ton) nuclear aircraft. Values less than 106 watts per cubic centimeter (3 MW/ft^3) lead to large increases in operating cost. An increase to 247 or 283 watts per cubic centimeter (7 or 8 MW/ft^3) could reduce operational cost by a factor of 2.

3620-Metric-ton (4000-ton) aircraft. - Examination of figures 14(a) to (t) shows that the variables that could affect the total operating cost most are lift-drag ratio, structure weight fraction, unit structure cost, load factor (figs. 14(a) to (c) and (e)) for both chemical and nuclear aircraft and reactor power density. Variations of these parameters, however, do not affect relative performance between nuclear and chemical aircraft, except in the case of gross weight. As previously explained, the nondirect variation of shield weight with reactor power causes a rapid increase in operating cost at low gross weights. For the ranges shown for each of these variables, the nuclear aircraft shows superior performance for flight ranges above 4565 kilometers (3000 n mi). For a range of 11 130 kilometers (6000 n mi) the nuclear aircraft should weigh 1500 tons or more to economically outperform the chemical aircraft for the set of assumptions made for the more advanced and larger aircraft.

Of less importance are utilization factor, maintenance cost factor, interest rate, profit rate, and structure life (figs. 14(f) to (j)).

For chemical aircraft the chemical fuel cost and fuel consumption (figs. 14(k) and (l)) are important and affect the relative standing of nuclear and chemical aircraft performance somewhat. For example, if the fuel consumption could be reduced from 0.093 kilogram per hour per newton to 0.073 kilogram per hour per newton (0.91 (lbm/hr)/lbf to 0.73 (lbm/hr)/lbf), the break-even range would be about 7420 kilometers (4000 n mi) instead of about 4565 kilometers (3000 n mi).

For nuclear aircraft, thermal efficiency, emergency chemical range, and reactor power density (figs. 14(m), (n), and (o)) are of importance. Decreasing the thermal efficiency from 25 percent to 15 percent increases total operating cost from about $0.012 to $0.018 per metric ton-kilometer ($0.020 to $0.030/ton-n mi). The reactor power density is not important as long as it is 106 watts per cubic centimeter (3 MW/ft^3) or greater. Reducing the power density to 35 watts per cubic centimeter from 106 watts per cubic centimeter (to 1 MW/ft^3 from 3 MW/ft^3) increases the total operating cost to about $0.024 per metric ton-kilometer from $0.012 per metric ton-kilometer (to $0.040/ton-n mi from $0.020/ton-n mi).

Increasing emergency chemical range from 2780 kilometers to 5560 kilometers (1500 n mi to 3000 n mi) has a similar effect on operating cost. Uranium fuel cost, reactor cost, shield cost, ratio of nuclear to chemical engine weight, and ratio of nuclear to chemical engine cost (figs. 14(p) to (t)), have little effect on the 3620-metric-ton (4000-ton) nuclear aircraft performance.

SUMMARY OF RESULTS

A simplified performance and cost study of large subsonic chemical- and nuclear-powered aircraft has been carried out to determine the potential for transoceanic commerce. The study indicates that aircraft with a gross weight of 905 metric tons (1000 tons) yield a total operating cost of about \$0.024 to \$0.036 per metric ton-kilometer (\$0.040 to \$0.060/ton-n mi), including a load factor of 0.6 and utilization of 0.5. For ranges above 9275 kilometers (5000 n mi) the 905-metric-ton (1000-ton) nuclear aircraft shows better performance than 905-metric-ton (1000-ton) chemical aircraft. At a speed of 740 kilometers per hour (400 knots) the 905-metric-ton (1000-ton) nuclear aircraft shows a total operating cost of \$0.027 per metric ton-kilometer (\$0.045/ton-n mi). The payload is 23 percent of the gross weight. A fleet of 500 such aircraft would theoretically be capable of handling 1 percent of the forecast world ocean trade in 1980. What fraction of the total ocean trade and what further increase in trade would be stimulated by high-speed air transportation is worthy of further study, but is beyond the scope of this report.

Operating cost can be substantially reduced by increasing the gross weight from 905 metric tons to 3620 metric tons (1000 tons to 4000 tons). The total operating cost for 3620-metric-ton (4000-ton) nuclear aircraft is less than \$0.012 per metric ton-kilometer (\$0.02/ton-n mi) at speeds of 925 kilometers per hour (500 knots). This low cost comes about for two reasons. The first is that it is assumed that the unit cost of aircraft structure is reduced from \$110 per kilogram to \$55 per kilogram (\$50/lbm to \$25/lbm) because of an assumed favorable effect of vehicle size and advanced technology on construction cost. Secondly, the lift-drag ratio is increased from 17 to 20 to reflect aerodynamic improvements. In the case of the nuclear aircraft, increasing size has an additional benefit. The shield becomes a smaller fraction of the gross weight, which results in a direct increase in payload fraction. The payload fraction of 3620-metric-ton (4000-ton) nuclear aircraft is about 30 to 40 percent of the gross weight, more than 50 percent greater than for the 905-metric-ton (1000-ton) nuclear aircraft. The reduction in nuclear powerplant weight yields a further gain relative to chemical aircraft. The break-even range between chemical and nuclear aircraft is less than 4565 kilometers (3000 n mi) for the 3620-metric-ton (4000-ton) aircraft. A fleet of 1000

3620-metric-ton (4000-ton) nuclear aircraft would theoretically handle 8 percent of the forecast world trade in 1980 and only 4 percent of the trade in 1995.

Sensitivity of all the major assumptions was determined by varying each one while holding the remainder constant. The most important assumptions are lift-drag ratio, structure weight fraction, unit structure cost, gross weight, and load factor. Simultaneous improvement in two or three of these factors might lead to total operating costs of less than $0.012 per metric ton-kilometer ($0.01/ton-n mi). For example, for the 3620-metric-ton (4000-ton) nuclear aircraft, if lift-drag ratio would be increased to 24, structure weight fraction reduced to 0.25, structure cost reduced to $33 per kilogram ($15/lbm), and load factor increased to 0.8, the total operating cost would be about $0.005 per metric ton-kilometer ($0.0085/ton-n mi).

For nuclear aircraft the reactor power density should be 106 watts per cubic centimeter (3 MW/ft^3) or greater to yield cost performance superior to chemical aircraft for gross weights of 905 metric tons (1000 tons). The gross weight of the nuclear aircraft should be greater than about 800 metric tons to show cost performance better than that of chemical aircraft for ranges of less than 11 130 kilometers (6000 n mi). For 3620-metric-ton (4000-ton) gross weights, the nuclear aircraft reactor power density can be as low as 71 watts per cubic centimeter (2 MW/ft^3) and show superior cost performance for ranges less than 7420 kilometers (4000 n mi).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 25, 1971,
126-15.

APPENDIX A

SYMBOLS

B	shield weight constant
C_E	engine cost, dollars
C_{FC}	chemical fuel cost, dollars/kg; dollars/lbm
C_{FN}	nuclear fuel cost, dollars/g
C_R	reactor cost, dollars
C_{SH}	shield cost, dollars
C_{ST}	structure cost, dollars
C_{TOT}	total vehicle cost, dollars
C'_{CR}	crew cost per operating hour, dollars/hr
C'_E	machinery depreciation cost per operating hour, dollars/hr
C'_{FN}	nuclear fuel cost per operating hour, dollars/hr
C'_{INS}	insurance cost per operating hour, dollars/hr
C'_{INT}	interest cost per operating hour, dollars/hr
C'_M	maintenance cost per operating hour, dollars/hr
C'_{PR}	profit cost per operating hour, dollars/hr
C'_R	reactor depreciation cost per operating hour, dollars/hr
C'_{SH}	shield depreciation cost per operating hour, dollars/hr
C'_{ST}	structure depreciation cost per operating hour, dollars/hr
F	thrust, N; lbf
K_E	specific engine cost, dollars/kg; dollars/lbm
K_{INS}	insurance cost factor
K_{INT}	interest cost factor
K_M	maintenance cost factor
K_{PR}	profit cost factor
K_R	specific reactor cost, dollars/MWth
K_{SH}	specific shield cost, dollars/kg; dollars/lbm

K_{ST}	specific structure cost, dollars/kg; dollars/lbm
L/D	lift-drag ratio
P_{th}	thermal power, MW
p	payload factor
R	range, km; n mi
S	fuel consumption, (kg/hr)/N; (lbm/hr)/lbf
T_E	machinery life, hr
T_R	reactor life, hr
T_{SH}	shield life, hr
T_{ST}	structure life, hr
U	utilization factor, yearly operating hours ÷ 8760
V	speed, km/hr; knots
W_E	engine weight, metric tons; tons
W_F	fuel weight, metric tons; tons
W_G	gross weight, metric tons; tons
W_{PAY}	payload weight, metric tons; tons
W_R	reactor weight, metric tons; tons
W_{SH}	shield weight, metric tons; tons
W_{ST}	structure weight, metric tons; tons
η	overall thermal efficient
ρ_P	power density of reactor, W/cm^3; MW/ft^3
ρ_R	reactor average weight density, g/cm^3; lbm/ft^3

APPENDIX B

WEIGHT AND COST BREAKDOWN

The complete cost breakdown is given for chemical- and nuclear-powered aircraft with gross weights of 1000 and 4000 tons. The program is written in English units. A conversion table is given below for SI units.

(knots)(1.853)	=	kilometers/hr
(n mi)(1.853)	=	kilometers
(tons)(0.907)	=	metric tons
(dollars/lb)(2.2)	=	dollars/kilogram
(dollars/ton-n mi)(0.595)	=	dollars/metric ton-kilometer

AIRCRAFT(1,000 TONS)
FAN JET
NUCLEAR POWERPLANT

SPEED	500.0	(KNOTS)
EMERGENCY CHEMICAL RANGE	500.0	(NM)
REACTOR POWER	793.4	MW(THERMAL)
LIFT/DRAG	17.0	
GROSS WEIGHT	1000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.1013	
FUEL WEIGHT FRACTION	0.0518	
REACTOR CORE WEIGHT FRACTION	0.0397	
SHIELD WEIGHT FRACTION	0.3502	
PAYLOAD CAPACITY FRACTION	0.1570	
UNIT STRUCTURE COST	50.00	(DOLLARS/LB)
UNIT REACTOR CORE COST	3500.0	(DOLLARS/MW)
UNIT SHIELD COST	5.0	(DOLLARS/LB)
URANIUM COST	0.500	(DOLLARS/MW-HR)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
REACTOR CORE LIFE	50000.	(HOURS)
SHIELD LIFE	75000.	(HOURS)
STRUCTURE COST	30.000	(MILLIONS OF DOLLARS)
PROPULSION COST	16.617	(MILLIONS OF DOLLARS)
REACTOR STRUCTURE COST	2.777	(MILLIONS OF DOLLARS)
SHIELD COST	3.502	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	52.896	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	397.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	793.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	200.	(DOLLARS/HR)
MACHINERY DEPRECIATION	166.	(DOLLARS/HR)
REACTOR CORE DEPRECIATION	28.	(DOLLARS/HR)
SHIELD DEPRECIATION	23.	(DOLLARS/HR)
TOTAL DEPRECIATION	417.	(DOLLARS/HR)
INSURANCE COST	185.	(DOLLARS/HR)
INTEREST COST	453.	(DOLLARS/HR)
PROFIT	499.	(DOLLARS/HR)
HOURLY COST	2994.	(DOLLARS/HR)
TOTAL OPERATING COST	0.063565	DOLLARS/TON-NM

AIRCRAFT(1,000 TONS)
FAN JET
CHEMICAL POWERPLANT

SPEED	500.0	(KNOTS)
RANGE	2000.0	(NM)
LIFT/DRAG	17.0	
GROSS WEIGHT	1000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.0675	
FUEL WEIGHT FRACTION	0.1916	
PAYLOAD CAPACITY FRACTION	0.4409	
UNIT STRUCTURE COST	50.00	(DOLLARS/LB)
CHEMICAL FUEL COST	0.012	(DOLLARS/LB)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
STRUCTURE COST	30.000	(MILLIONS OF DOLLARS)
PROPULSION COST	13.293	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	43.293	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	1276.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	649.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	200.	(DOLLARS/HR)
MACHINERY DEPRECIATION	133.	(DOLLARS/HR)
TOTAL DEPRECIATION	333.	(DOLLARS/HR)
INSURANCE COST	152.	(DOLLARS/HR)
INTEREST COST	371.	(DOLLARS/HR)
PROFIT	606.	(DOLLARS/HR)
HOURLY COST	3637.	(DOLLARS/HR)
TOTAL OPERATING COST	0.027497	DOLLARS/TON-NM

AIRCRAFT(1,000 TONS)
FAN JET
CHEMICAL POWERPLANT

SPEED	500.0	(KNOTS)
RANGE	4000.0	(NM)
LIFT/DRAG	17.0	
GROSS WEIGHT	1000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.0675	
FUEL WEIGHT FRACTION	0.3465	
PAYLOAD CAPACITY FRACTION	0.2860	
UNIT STRUCTURE COST	50.00	(DOLLARS/LB)
CHEMICAL FUEL COST	0.012	(DOLLARS/LB)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
STRUCTURE COST	30.000	(MILLIONS OF DOLLARS)
PROPULSION COST	13.293	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	43.293	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	1276.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	649.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	200.	(DOLLARS/HR)
MACHINERY DEPRECIATION	133.	(DOLLARS/HR)
TOTAL DEPRECIATION	333.	(DOLLARS/HR)
INSURANCE COST	152.	(DOLLARS/HR)
INTEREST COST	371.	(DOLLARS/HR)
PROFIT	606.	(DOLLARS/HR)
HOURLY COST	3637.	(DOLLARS/HR)
TOTAL OPERATING COST	0.042388	DOLLARS/TON-NM

AIRCRAFT(1,000 TONS)
FAN JET
CHEMICAL POWERPLANT

SPEED	500.0	(KNOTS)
RANGE	6000.0	(NM)
LIFT/DRAG	17.0	
GROSS WEIGHT	1000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.0675	
FUEL WEIGHT FRACTION	0.4717	
PAYLOAD CAPACITY FRACTION	0.1608	
UNIT STRUCTURE COST	50.00	(DOLLARS/LB)
CHEMICAL FUEL COST	0.012	(DOLLARS/LB)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
STRUCTURE COST	30.000	(MILLIONS OF DOLLARS)
PROPULSION COST	13.293	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	43.293	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	1276.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	649.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	200.	(DOLLARS/HR)
MACHINERY DEPRECIATION	133.	(DOLLARS/HR)
TOTAL DEPRECIATION	333.	(DOLLARS/HR)
INSURANCE COST	152.	(DOLLARS/HR)
INTEREST COST	371.	(DOLLARS/HR)
PROFIT	606.	(DOLLARS/HR)
HOURLY COST	3637.	(DOLLARS/HR)
TOTAL OPERATING COST	0.075399	DOLLARS/TON-NM

AIRCRAFT(4.000 TONS)
FAN JET
NUCLEAR POWERPLANT

SPEED	500.0	(KNOTS)
EMERGENCY CHEMICAL RANGE	1500.0	(NM)
REACTOR POWER	2697.4	MW(THERMAL)
LIFT/DRAG	20.0	
GROSS WEIGHT	4000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.0861	
FUEL WEIGHT FRACTION	0.1268	
REACTOR CORE WEIGHT FRACTION	0.0337	
SHIELD WEIGHT FRACTION	0.1453	
PAYLOAD CAPACITY FRACTION	0.3080	
UNIT STRUCTURE COST	25.00	(DOLLARS/LB)
UNIT REACTOR CORE COST	3500.0	(DOLLARS/MW)
UNIT SHIELD COST	5.0	(DOLLARS/LB)
URANIUM COST	0.500	(DOLLARS/MW-HR)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
REACTOR CORE LIFE	50000.	(HOURS)
SHIELD LIFE	75000.	(HOURS)
STRUCTURE COST	60.000	(MILLIONS OF DOLLARS)
PROPULSION COST	56.497	(MILLIONS OF DOLLARS)
REACTOR STRUCTURE COST	9.441	(MILLIONS OF DOLLARS)
SHIELD COST	5.814	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	131.752	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	1349.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	1976.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	400.	(DOLLARS/HR)
MACHINERY DEPRECIATION	565.	(DOLLARS/HR)
REACTOR CORE DEPRECIATION	94.	(DOLLARS/HR)
SHIELD DEPRECIATION	39.	(DOLLARS/HR)
TOTAL DEPRECIATION	1098.	(DOLLARS/HR)
INSURANCE COST	461.	(DOLLARS/HR)
INTEREST COST	1128.	(DOLLARS/HR)
PROFIT	1252.	(DOLLARS/HR)
HOURLY COST	7515.	(DOLLARS/HR)
TOTAL OPERATING COST	0.020329	DOLLARS/TON-NM

AIRCRAFT(4.000 TONS)
FAN JET
CHEMICAL POWERPLANT

SPEED	500.0	(KNOTS)
RANGE	2000.0	(NM)
LIFT/DRAG	20.0	
GROSS WEIGHT	4000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.0574	
FUEL WEIGHT FRACTION	0.1654	
PAYLOAD CAPACITY FRACTION	0.4772	
UNIT STRUCTURE COST	25.00	(DOLLARS/LB)
CHEMICAL FUEL COST	0.012	(DOLLARS/LB)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
STRUCTURE COST	60.000	(MILLIONS OF DOLLARS)
PROPULSION COST	45.198	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	105.198	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	4339.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	1578.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	400.	(DOLLARS/HR)
MACHINERY DEPRECIATION	452.	(DOLLARS/HR)
TOTAL DEPRECIATION	852.	(DOLLARS/HR)
INSURANCE COST	368.	(DOLLARS/HR)
INTEREST COST	901.	(DOLLARS/HR)
PROFIT	1658.	(DOLLARS/HR)
HOURLY COST	9945.	(DOLLARS/HR)
TOTAL OPERATING COST	0.017367	DOLLARS/TON-NM

AIRCRAFT(4.000 TONS)
FAN JET
CHEMICAL POWERPLANT

SPEED	500.0	(KNOTS)
RANGE	4000.0	(NM)
LIFT/DRAG	20.0	
GROSS WEIGHT	4000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.0574	
FUEL WEIGHT FRACTION	0.3034	
PAYLOAD CAPACITY FRACTION	0.3392	
UNIT STRUCTURE COST	25.00	(DOLLARS/LB)
CHEMICAL FUEL COST	0.012	(DOLLARS/LB)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
STRUCTURE COST	60.000	(MILLIONS OF DOLLARS)
PROPULSION COST	45.198	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	105.198	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	4339.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	1578.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	400.	(DOLLARS/HR)
MACHINERY DEPRECIATION	452.	(DOLLARS/HR)
TOTAL DEPRECIATION	852.	(DOLLARS/HR)
INSURANCE COST	368.	(DOLLARS/HR)
INTEREST COST	901.	(DOLLARS/HR)
PROFIT	1658.	(DOLLARS/HR)
HOURLY COST	9945.	(DOLLARS/HR)
TOTAL OPERATING COST	0.024435	DOLLARS/TON-NM

AIRCRAFT(4.000 TONS)
FAN JET
CHEMICAL POWERPLANT

SPEED	500.0	(KNOTS)
RANGE	6000.0	(NM)
LIFT/DRAG	20.0	
GROSS WEIGHT	4000.0	(TONS)
STRUCTURE WEIGHT FRACTION	0.3000	
ENGINE WEIGHT FRACTION	0.0574	
FUEL WEIGHT FRACTION	0.4186	
PAYLOAD CAPACITY FRACTION	0.2240	
UNIT STRUCTURE COST	25.00	(DOLLARS/LB)
CHEMICAL FUEL COST	0.012	(DOLLARS/LB)
PROFIT FRACTION	0.20	
STRUCTURE LIFE	75000.	(HOURS)
MACHINERY LIFE	50000.	(HOURS)
STRUCTURE COST	60.000	(MILLIONS OF DOLLARS)
PROPULSION COST	45.198	(MILLIONS OF DOLLARS)
TOTAL VEHICLE COST	105.198	(MILLIONS OF DOLLARS)
UTILIZATION OF VEHICLE	0.50	
LOAD FACTOR	0.60	
FUEL COST	4339.	(DOLLARS/HR)
CREW COST	250.	(DOLLARS/HR)
MAINTENANCE COST	1578.	(DOLLARS/HR)
STRUCTURE DEPRECIATION	400.	(DOLLARS/HR)
MACHINERY DEPRECIATION	452.	(DOLLARS/HR)
TOTAL DEPRECIATION	852.	(DOLLARS/HR)
INSURANCE COST	368.	(DOLLARS/HR)
INTEREST COST	901.	(DOLLARS/HR)
PROFIT	1658.	(DOLLARS/HR)
HOURLY COST	9945.	(DOLLARS/HR)
TOTAL OPERATING COST	0.037003	DOLLARS/TON-NM

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