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THE POTENTIAL OF NUCLEAR POWER FOR HIGH-SPEED OCEAN-GOING AIR-CUSHION VEHICLES

by Frank E. Rom and Albert F. Kascak

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ABSTRACT

The use of nuclear powerplants based on nuclear aircraft technology to power ocean-going air-cushion vehicles has been investigated. Because aircraft nuclear powerplants might be an order of magnitude lighter than current nuclear marine plants, the performance of nuclear air-cushion vehicles is dramatically altered. Instead of vehicles limited to short ranges and speeds of about 80 knots, they become vehicles with virtually unlimited range and speeds in the range of 100 to 200 knots. The study considers vehicles with gross weights of 1000 to 10 000 tons and clearance heights from 10 to 40 feet, which are sufficient to clear ocean waves 80 to over 90 percent of the time. The cargo capacity ranges from 20 to 50 percent of the gross weight. Direct operating costs are 2 to 5 cents per ton-mile and are independent of the distance travelled.

THE POTENTIAL OF NUCLEAR POWER FOR HIGH-SPEED OCEAN-GOING AIR-CUSHION VEHICLES*

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SUMMARY

The performance potential of air-cushion vehicles powered with nuclear powerplants based on nuclear aircraft technology has been investigated. Aircraft nuclear powerplants might be an order of magnitude lighter than current nuclear marine powerplants. The performance of nuclear air-cushion vehicles is therefore dramatically altered when compared to previous studies using conventional nuclear marine powerplants.

Nuclear air-cushion vehicles with gross weights of 2000 to 10 000 tons can cruise at speeds of 100 to 200 knots with payload fractions that vary from 20 to 50 percent of the gross weight while operating at clearance heights of 10 to 20 feet. Based on a simplified cost analysis, the nuclear air-cushion vehicle can carry payload at the rate of 2 to 5 cents per ton-mile. The cargo carrying capacity and the cost of hauling cargo in terms of cents per ton-mile is independent of the range. The unrefueled range for these vehicles is expected to be of the order of 1 to 2 million miles.

The use of aircraft technology for nuclear air-cushion vehicles completely changes the image of air-cushion vehicles. Instead of short haul 50- to 80-knot vehicles, they become vehicles that can travel at speeds in the range of 100 to 200 knots for unlimited distances. They can operate with sufficient clearance heights so that no contact is made with ocean waves 80 to over 90 percent of the time. The study indicates the need to more seriously consider such a vehicle as a contender for high-speed transoceanic commerce.

INTRODUCTION

There are three important revolutionary advances that have been or might be made that could dramatically affect transoceanic commerce. They are as follows:

(1) The speed potential of marine vehicles has been increased by almost an order of

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magnitude through the use of the air-cushion principle as pioneered and demonstrated by Great Britain.

(2) The unrefueled range of displacement type ships has been increased by two orders of magnitude through the use of nuclear propulsion systems.

(3) The use of advanced nuclear propulsion technology might reduce the weight of nuclear marine powerplants by an order of magnitude.

The purpose of this study is to determine the performance potential of a vehicle that combines these three advances. The use of a lightweight nuclear power system would free the chemically powered air-cushion vehicle from the restraints that arise because of the limited energy that is available from chemical fuel. In order to be economically competitive, the conventional hovercraft must operate with as small a clearance height above the surface as possible to minimize the large power required to maintain the air cushion. Low clearance height means that in rough seas the vehicle or its skirts must be in contact with the water. This in turn limits the speed of the hovercraft because of (1) the extra drag produced by the water contact, (2) the wear and tear on the skirts, and (3) the excessive impact loads on the structure.

Inasmuch as the basic cost of thermal energy from nuclear fission is potentially about one-fifth the cost of chemical fuel, it is reasonable to consider the use of the extra energy available to increase the clearance height. This height could be increased sufficiently so that the vehicle and its skirts would clear the waves entirely. In the North Atlantic peak wave heights of 10 feet are not exceeded about 80 percent of the time. Peak wave heights of 20 feet are not exceeded about 90 percent of the time. This should permit operation at considerably higher speeds because the problems arising with water contact would be eliminated.

The use of nuclear fuel also eliminates the range constraint which is characteristic of chemically powered vehicles because they use chemical fuel with its limited energy content. The major feature of nuclear-powered vehicles is that the range is virtually unlimited because of the very high energy content of nuclear fuel. The cost of operation per mile travelled is therefore independent of the range.

Past studies using nuclear power for air-cushion vehicles have not been too encouraging. The weight assumed for the nuclear powerplants in these studies (e.g., ref. 1) have generally been consistent with conventional maritime or stationary powerplant practice. These assumptions resulted in hovercraft performance that is no better than that for chemically powered systems except for very large ranges and very large hovercraft.

During the course of recent nuclear aircraft studies at Lewis (ref. 2), it became apparent that nuclear powerplant weight might be reduced by an order of magnitude when compared to conventional practice. It appears that the reduction can be obtained while maintaining safe radiation dose limits all around the reactor and while providing a reactor design that would have a life of 10 000 hours between refueling. Provisions that would prevent the release of fission products even during major aircraft accidents are being investigated. The containment of fission proaucts during major aircraft accidents seems possible in these studies at least from the point of view of not violating any basic laws of nature. This is, however, understandably a very difficult problem.

In the case of an overwater hovercraft the problem of containment is much less severe. The speed of any potential impact is much reduced thus simplifying the problem of maintaining a leak tight containment system during impacts. The decelerations that the reactor containment vessel would experience in a crash would be much less because the speed is lower. In addition, there would probably be more structure to absorb the energy of any impact. The ready availability of water for keeping the containment vessel cool in the event of a major accident is also a great advantage. It appears possible to design with confidence, a system that would prevent the rupture and/or melt-through of the containment vessel that could occur as the result of a reactor meltdown following the loss of all normal cooling systems in a major accident. It seems that the kind of safe aircraft reactor design philosophy outlined in reference 2 would be easier to achieve in an overwater hovercraft when compared to overland aircraft.

The analysis presented herein is intended to determine whether sufficient potential exists for transoceanic nuclear powered hovercraft to warrant further study in more detail. Accordingly, the analysis uses many simplifying assumptions in determining weight breakdowns, initial cost, and operating costs. Although the assumptions are believed to be reasonable and based on previous investigations where possible so as to give correct trends and reasonable conclusions, they are a subject for a much more thorough study. The analysis is not intended to give the last word in air-cushion vehicle or nuclear powerplant design. Especially it is not to be construed as an exhaustive cost analysis. The main purpose of this study is to alert the reader to the possibilities which nuclear-powered air-cushion vehicles may possess. Hopefully further thought and more careful consideration will be stimulated.

The power system discussed in the report consists of a reactor that heats high pressure helium. The helium in turn is used to produce steam to power the steam turbine fan drive systems. Other systems could be used without significantly affecting the results. For example, the hot helium could be used to heat air for gas turbine drive systems, or the helium could be used directly in helium turbine drive units. The weight and efficiencies of all such systems fall in the same range. Therefore, the major conclusions are not affected.

The performance potential of the nuclear-powered air-cushion vehicles studied in this report is measured and presented in terms of payload fraction and cost of delivering payload. The gross weight is varied from 1000 to 10 000 tons. Vehicle speeds up to 200 knots are considered. The clearance height is varied from 10 to 40 feet. The clearance height is the vertical "see-through" distance between the lower edge of the skirts or annular jet nozzles. A general vehicle concept and powerplant description is given. All key assumptions and analyses are presented in sufficient detail to permit the reader to vary assumptions or input as he wishes.

SYMBOLS

A_L	total frontal area of all lift fans, ft^2
a	exponent in wave drag expression
B	vehicle beam, ft
C_D	drag coefficient, D/q
D_A	aerodynamic drag, lb
D_M	momentum drag, lb
D_W	wave drag, lb
d_F	diameter of thrust fan engine, ft
d_L	diameter of lift fan engines, ft
F	thrust, lb
F_R	Froude number, $V_o/\sqrt{Lg}$
g	acceleration due to gravity, ft/sec^2
h	vehicle clearance height above surface, ft
L	vehicle length, ft
MW	megawatts
MWt	thermal megawatts
N_F	number of thrust fan engines
N_L	number of lift fans
P_B	base pressure, lb/ft^2
P_D	drag power, hp
P_F	shaft power of the thrust fans, hp
P_L	shaft power of the lift fans, hp
P_M	momentum drag power, hp

P_V	total shaft power of the vehicle, hp
P_W	wave drag power, hp
Q_R	reactor power, MW
q	dynamic head, lb/ft^2
q_c	dynamic head at the entrance of the condenser, lb/ft^2
q_d	dynamic head at the entrance of the fan inlets, lb/ft^2
q_i	air inlet diffuser dynamic head, lb/ft^2
q_o	dynamic head at the vehicle forward velocity, lb/ft^2
S	plan area of the vehicle, ft^2
SHP	shaft horsepower, hp
V_c	velocity at the entrance of the condenser, ft/sec
V_d	velocity at the entrance of the fan inlets, ft/sec
V_j	jet velocity of thrust producing flow, ft/sec
V_o	vehicle velocity, ft/sec
W_G	gross weight, lb
W_P	payload weight, lb
W_{PP}	powerplant weight, lb
W_R	reactor weight, lb
W_S	structure weight, lb
W_{SH}	shield weight, lb
w_F	air mass flow of thrust fans, lb/sec
w_L	air mass flow of lift fans, lb/sec
η_f	fan compression efficiency
η_L	overall efficiency of thrust system
η_p	propulsive efficiency, $2/(V_j/V_o - 1)$
η_t	overall powerplant thermal efficiency
ρ	air density, lb/ft^3
ρ_w	density of water, lb/ft^3

DESCRIPTION OF NUCLEAR-POWERED HOVERCRAFT

A schematic drawing of a nuclear-powered hovercraft is shown in figure 1. The gross weight of this vehicle is 2000 tons. It has a base pressure of 60 pounds per square foot, a length of 350 feet, and the beam is 250 feet. It is designed to fly at a mean clearance height of 10 feet above the water. This altitude is maintained by means of annular jets that direct the jet flow 30° in toward the centerline of the vehicle. The thrust required to overcome the drag of this vehicle as it moves over the water and through the air is provided by jets that are located along the stern end of the vehicle. The air for the air cushion under the vehicle is supplied by means of fourteen 16-foot diameter fans that are located in two galleries, one on each side of the centerline of the craft. Each set of seven fans draws its air supply from an inlet plenum in the gallery. The inlet plenum for each fan is supplied with air from the outside through louvered openings. These openings consist of curved guide vanes that decelerate the air from the free-stream velocity to the vehicle velocity with a minimum of loss. The louvered openings allows each engine to be shut down.

Each lift fan is driven by a 6500 horsepower steam turbine. The heat source for the steam is hot helium which is supplied by the nuclear reactor that is located approximately at the center of gravity of the vehicle. The pressurized air leaving the fan is

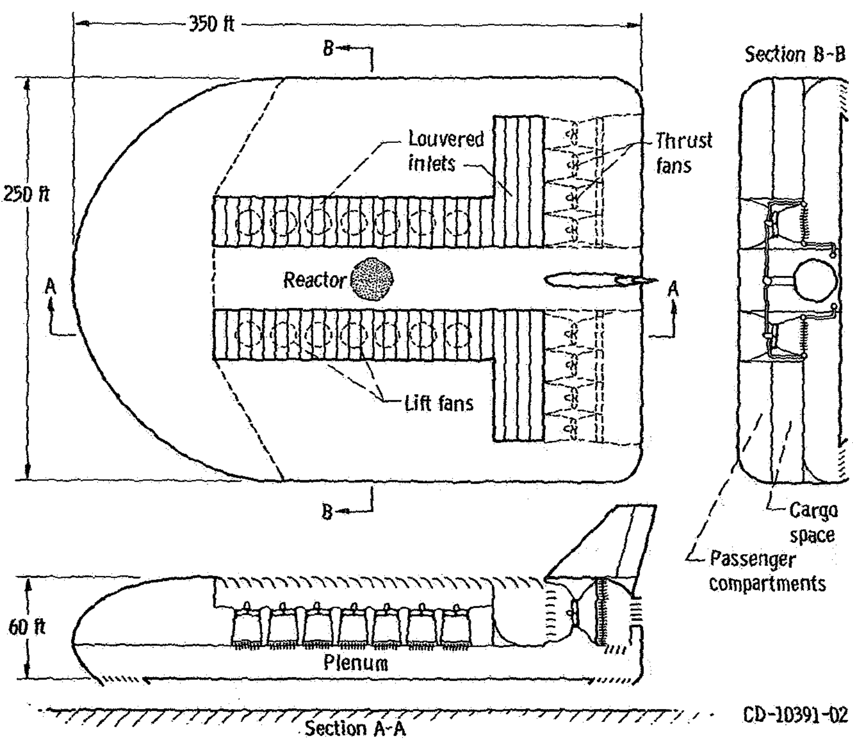


Figure 1. - Schematic drawing of 2000-ton nuclear-powered hovercraft.

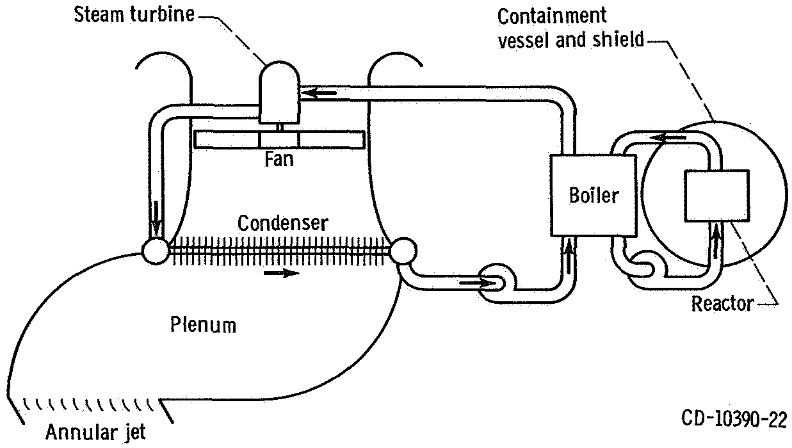


Figure 2. - Schematic drawing of power system for nuclear hovercraft.

passed over a condenser which is used to condense the turbine exhaust steam prior to its return to the boiler (fig. 2). The air from the lift fans passes into a plenum region which distributes the air to the annular jets. The jets completely surround the underside perimeter of the vehicle.

The fans for providing thrust are 35 000 horsepower each. There are eight of these. They are also driven by steam turbines. The louvered inlet plenum is similar to the inlet plenum for the lift fans. The steam condensers are located downstream of the thrust fans just as in the case of the lift fans. The air is then ducted through outlet ports in the rear of the vehicle to provide thrust. To provide extra hover capability at lower speeds, the air leaving the thrust fans can be diverted into the plenum that supplies the annular jets. This is accomplished by closing the jet port vanes and opening the vanes that divert the flow down into the air-cushion plenum.

The fans are buried deep within the vehicle and all the engines have the louvered arrangement for the inlets. One purpose of this type of installation is to minimize noise, and to maximize the possibility of providing acoustic sound absorption materials both around the engine compartments and in the inlet plenum guide vanes. The noise that does escape will be directed upward since all inlets are located on the top side of the vehicle.

To provide stability the annular jet plenum can be subdivided into several individual plenums that can be supplied by two or three engines each. This not only provides stability but also redundancy in the event of single engine failures.

The cargo space and passenger quarters are approximately 75 feet across and about 150 feet long. The combined height of the cargo and passenger space is about 40 feet. This amounts to about 900 000 cubic feet of space. Inasmuch as the payload is about 700 tons for this vehicle, the cargo density is of the order of 1.5 pound per cubic foot.

This is considerably lower than most other transportation vehicles. A characteristic of this type of vehicle is its roominess.

A schematic drawing of the propulsion system is shown in figure 2. The source of thermal energy is a nuclear reactor that is completely shielded in all directions so that a person can approach to within 20 feet of the reactor and not exceed the allowable radiation limits for the general population. The reactor is used to heat helium to a temperature of the order of 1400° F (760° C). The hot helium is then used to produce steam at a temperature of about 1000° F in a boiler. The steam is piped to the turbines which drive the fans. The turbine exhaust passes through a condenser. The condensate from the condenser is pumped back to the boiler. The condenser is air cooled and is composed of a number of finned tubes through which the steam passes as it is condensed. The fan exhaust air is increased in temperature by about 20° F as it passes across the condenser. The air from each of the fans is collected in a plenum which distributes the air to the annular jets which are used to provide the air cushion.

The main reason why the nuclear-powered hovercraft is expected to appear quite attractive is that the reactor and shield assembly is an order of magnitude lighter than that used in conventional nuclear-powered ships. This results from the application of aircraft nuclear reactor technology (see ref. 2) instead of conventional marine reactor practice. Figure 3 shows a schematic drawing of a conceptual aircraft reactor system that incorporates features designed to minimize the possibility of fission product release during major aircraft accidents.

The reactor core is located within an outer high pressure containment vessel. The containment vessel is designed to withstand any internal pressures that can result from a reactor meltdown due to a major accident. It is also designed to be automatically sealed in the event of a major accident. Quick acting sealing valves are used for all containment vessel penetrations and cooling lines. In addition, the containment vessel

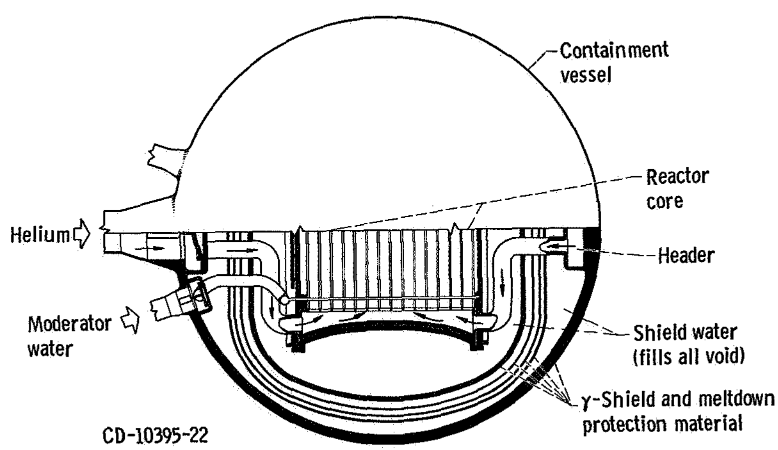


Figure 3. - Helium-cooled reactor assembly.

is made large enough so that it has sufficiently large surface area so that all afterheat generation can be safely removed by free convection and radiation to air or by submersion in water.

Shielding is provided by a combination of borated water and tungsten or depleted uranium. The shielding is designed to reduce the dose level on all sides to the dose that is permissible for general population exposure. This dose rate is 0.25 millirem per hour at a distance of 20 feet from the outer surface of the shield. The gamma shield that is provided by the tungsten or depleted uranium also serves as melt-through protection in the event of a reactor meltdown. These shielding and meltdown protection shells are designed to delay the movement of molten core materials sufficiently long to allow the heat producing fission products to vaporize from the molten mass. This would tend to redistribute the fission products more uniformly throughout the space within the containment vessel. Ideally it is desired to have the fission products uniformly distributed within the vessel after a meltdown. This would result in the lowest heat flux through the containment vessel with the resultant minimum containment vessel temperature. This technique is designed to prevent the reactor core from melting through the containment vessel. The safety design philosophy is more fully discussed in reference 2.

The reactor core is water moderated. The core is essentially a tank of water with helium flow tubes passing through it. These tubes are about 2 inches in diameter. The reactor fuel elements which contain the fissionable material are located within these tubes. There are a number of fuel pins of the order of 1/2 inch in diameter in each tube. The helium flows along these tubes in the spaces between the pins to pick up the heat that is generated in the pins by the fissioning uranium.

Helium enters the containment vessel through a quick acting emergency sealing valve. It then flows into a circumferential header around the inside of the containment vessel. From this header a number of feeder lines, with bends in three dimensions to prevent streaming of neutrons through the shield, supplies a plenum at the bottom end of the reactor. After the helium is heated as it flows upward through the reactor, it is collected in a similar header at the top end. The helium is ducted by a number of lines from this plenum to a circumferential header very similar to the inlet heater but not shown in this drawing. The hot helium passes through another quick acting sealing valve to the hot helium supply line.

ASSUMPTIONS AND ANALYSIS

The assumptions and analysis used to carry out this study are listed and discussed. The assumptions are divided into (1) thermodynamic assumptions which list all of the efficiencies, (2) the weight assumptions used to calculate weights of the major components, and (3) the cost assumptions used to evaluate the performance in terms of cost. Pertinent comments on the analysis are made in each of these sections. A summary of the major assumptions is as follows:

Thermodynamic:

Fan efficiency	0.85
Overall powerplant thermal efficiency	0.20
Thrust propulsive efficiency	0.50
Fan air flow per unit frontal area, lb/ft^2	24.3
Aerodynamic drag coefficient (based on plan area)	0.02

Weight:

Structure	$\frac{W_S}{W_G} = 0.175 + 5\left(\frac{W_G}{S}\right)^{-1}$
Powerplant, lb/shp	$\frac{W_{PP}}{SHP} = 2$
Shield, tons	$W_{SH} = 11.6\sqrt{Q_R}$

Capital costs:

Nuclear reactor system, \$/MWt	20 000
Hovercraft structure, \$/lb	20
Powerplant (average), \$/lb	35

Operating costs:

Nuclear fuel cost, \$/MW-hr	0.8
Crew costs, \$/hr-ton	0.075
Maintenance, \$/hr-ton	0.16
Interest, percent/yr	6.0
Utilization, (0.5), hr/yr	4380
Vehicle life, hr	60 000

Thermodynamic Assumptions

The thermodynamic assumptions are concerned with the efficiency of converting the reactor thermal power into vehicle velocity.

Overall powerplant thermal efficiency 0.20

This is the ratio of fan engine shaft horsepower to reactor thermal horsepower.

Lift fan compression efficiency 0.85

This is the ratio of ideal to actual fan compression work.

Inlet diffuser loss . . . . $0.1\ q_i$

It is assumed that the loss in inlet air pressure is 0.1 of the dynamic head in the inlet. The inlet air velocity is assumed to be 150 feet per second for computing this loss.

Condenser and exit ducting losses . . . . $0.3\ q_c$

It is assumed that the loss in air pressure downstream of the fan is 0.3 of the dynamic head of the air entering the condenser. The condenser inlet air velocity is assumed to be 100 feet per second for computing this loss.

Annular jet injection angle . . . . 30°

The annular jet around the entire periphery of the hovercraft is assumed to be directed 30° inward from the vertical. Analyses (e.g., ref. 11) have shown that theoretically 90° is the best; however, not much performance is gained beyond 30° compared with practical problems arising from very large angles.

Nozzle width to jet height ratio 0.5

Based on studies such as in reference 11, the ratio of nozzle width to jet height that gives the least power for a given clearance height is about 0.5 for the range of base pressures that is of interest for the present study.

Vehicle length-to-beam ratio 1.5

Propulsive efficiency 0.5

This is the ratio of jet thrust power ($FV_j/550$) to the thrust fan shaft horsepower.

Fan air flow per unit frontal area, lb/sec-ft^2 . . . . 24.3

This corresponds to an average inlet Mach number of 0.3 at standard sea level conditions (pressure, 2116 lb/ft; temperature, 59° F).

Vehicle aerodynamic drag coefficient 0.02

This is based on vehicle planform area.

With these assumptions it is possible to calculate (see ref. 3) the lift fan shaft horsepower required per foot of clearance height as a function of gross weight and base pressure loading. The results of this calculation are shown in figures 4(a) to (d). The

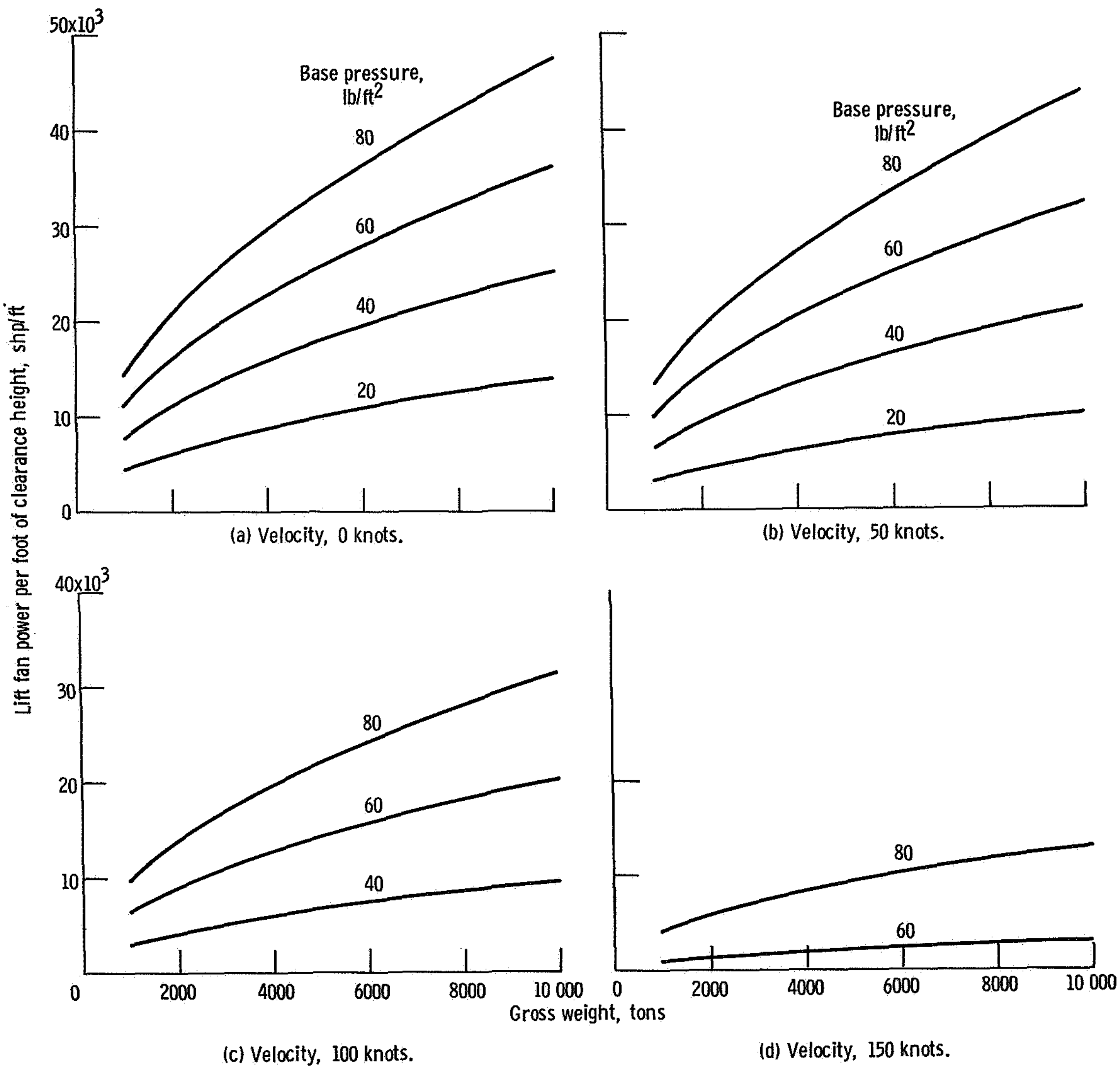


Figure 4. - Lift fan power requirement.

curves shown are computed for forward velocities of 0, 50, 100, and 150 knots. The data shown take into account the effect of the free-stream interactions with the annular jet. The net effect of the interactions are small and are therefore not discussed herein. (See refs. 3 and 4 for a more detailed explanation of this point.)

The required lift fan airflow can also be calculated according to the techniques given in references 3 and 4 and using the previous assumptions. The airflow is needed to determine the number of fans required to supply the cushion airflow. The result of this calculation is plotted in figure 5 in terms of airflow per unit clearance height as a function of vehicle gross weight. Although the curve is plotted for a base pressure of 60 pounds per square foot, a clearance height of 10 feet and forward velocity of 100 knots, it applies within about 10 percent for the range of base pressures, heights, and velocities used in the present investigation.

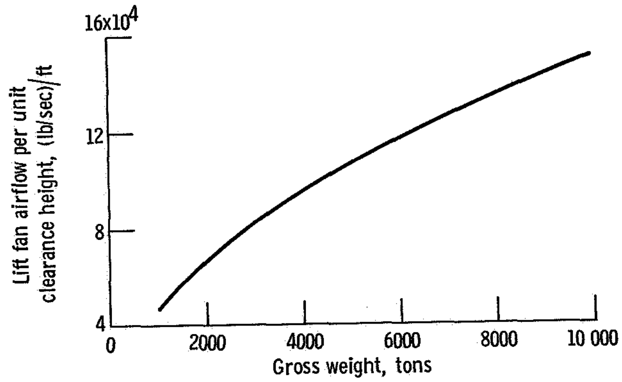


Figure 5. - Lift fan airflow. Base pressure, 60 pounds per square foot; clearance height, 10 feet; velocity, 100 knots.

The number of lift fan engines of any given size is determined by dividing the total lift fan frontal area required by the desired frontal area of any given fan. The total lift fan frontal area A_L is found by dividing the total airflow by the airflow capacity per unit frontal area:

$$A_L = \frac{w_L}{24.3} \tag{1}$$

The number of lift fan engines N_L required for any assigned lift fan diameter d_L is then

$$N_L = \frac{4A_L}{\pi d_L^2} \tag{2}$$

The drag of a hovercraft is made up of three components: the aerodynamic drag, the inlet air momentum drag due to stagnating the air required for the maintaining the air cushion, and the wave drag due to the wave making action of the air cushion traveling over water.

The aerodynamic drag D_A is computed by use of the following defining formula of drag coefficient C_D:

$$C_D = \frac{D_A}{q_o S} \tag{3}$$

where q_o is the free-stream dynamic head and S is the planform area of the vehicle. The aerodynamic drag is therefore

$$D_A = C_D q_o S \tag{4}$$

The horsepower required to overcome the aerodynamic drag is then

$$P_A = \frac{D_A V_o}{550} \tag{5}$$

The inlet air momentum drag is the power necessary to stagnate the air entering the lift fans of the vehicle. It is given by

$$D_M = \frac{w_L V_o}{g} \tag{6}$$

The inlet air momentum drag power in horsepower is then

$$P_M = \frac{D_M V_o}{550} \tag{7}$$

The wave drag due to moving the cushion pressure over the water is given by the following expression which is derived from data presented in references 5 and 6:

$$D_W = \frac{4\times 0.685\left(\frac{F_R}{0.61}\right)^a P_B^2 B}{\rho_W} \tag{8}$$

where

$$a = 1.46 \text{ for } F_R \le 0.61$$

$$a = -1.60 \text{ for } F_r \ge 0.61$$

The wave drag power is then

$$P_W = \frac{D_W V_o}{550}$$

The total drag power is the sum of the three component drags

$$P_D = P_A + P_M + P_W \tag{10}$$

and the total drag is

$$D = D_A + D_M + D_W \tag{11}$$

The thrust is equal to the drag to maintain any given speed; hence,

$$F = D = D_A + D_M + D_W \tag{12}$$

The thrust fan shaft horsepower P_F required to produce the previous thrust is found by use of η_L, the overall efficiency of the thrust system which is defined as

$$\eta_L = \frac{\text{Thrust power}}{\text{Thrust fan shaft horsepower}}$$

$$\eta_L = \frac{P_D}{P_F} = \frac{\frac{FV_o}{550}}{P_F} \tag{13}$$

$$P_F = \frac{P_D}{\eta_L} \tag{14}$$

The thrust fan power is plotted in figures 6(a) to (c) as a function of gross weight and vehicle velocity. The data shown are for a base pressure of 60 pounds per square foot for clearance heights of 10, 20, and 40 feet. The curves give the thrust fan horsepower within about 10 percent of the correct value for base pressures ranging from 20 to 80 pounds per square foot.

The total vehicle shaft horsepower is the sum of the lift fan power and thrust fan power

$$P_V = P_L + P_F \tag{15}$$

The reactor power in megawatts is given by

$$Q_R = \frac{P_V(7.46\times10^{-4})}{\eta_t} \tag{16}$$

where η_t is the overall thermal efficiency.

The thrust fan air flow for the thrust engines is found from the equation for thrust of a jet engine:

$$F = \frac{w_F(V_j - V_o)}{g} \tag{17}$$

or

$$w_F = \frac{Fg}{V_j - V_o} = \frac{Dg}{V_j - V_o} = \frac{550gP_D}{V_o(V_j - V_o)}$$

Factoring gives

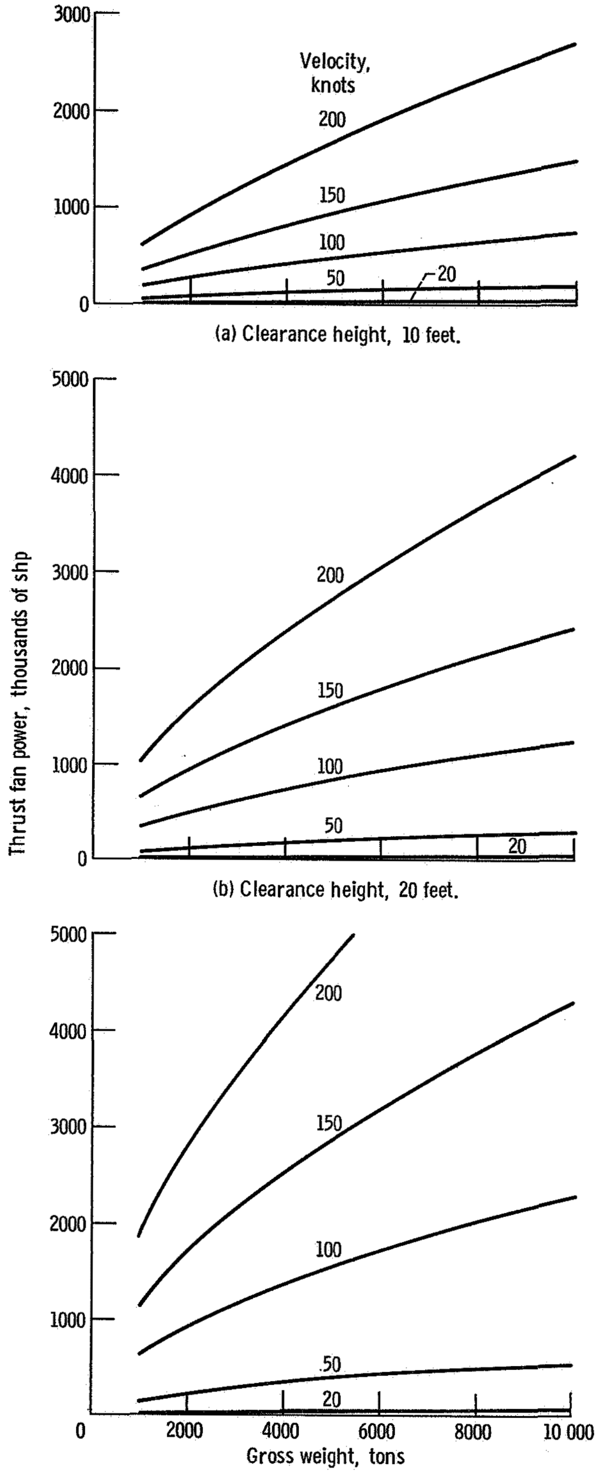


Figure 6. - Thrust fan power requirement. Base pressure, 60 pounds per square foot.

$$w_F = \frac{550P_D g}{V_o^2\left(\frac{V_j}{V_o} - 1\right)} \tag{18}$$

Thus, the airflow is determined if the jet velocity V_j can be eliminated from equation (18). This can be done by use of the definition of the propulsive efficiency:

$$\eta_P = \frac{2}{\frac{V_j}{V_o} + 1} \tag{19}$$

From this definition and the fact that $\eta_L = \eta_P \eta_F$,

$$\left(\frac{V_j}{V_o} - 1\right) = \frac{2\eta_F}{\eta_L} - 2 \tag{20}$$

Then combining equations (18) and (20) gives

$$w_F = \frac{550gP_D}{V_o^2\left(\frac{2\eta_F}{\eta_L} - 2\right)} \tag{21}$$

The number of thrust fan engines can then be found if a thrust fan engine diameter d_F is assumed:

$$N_F = \frac{4w_F}{24.3\pi\, d_F^2} \tag{22}$$

Weight Assumptions

The weight assumptions are divided into structure weight, powerplant weight, and shield weight.

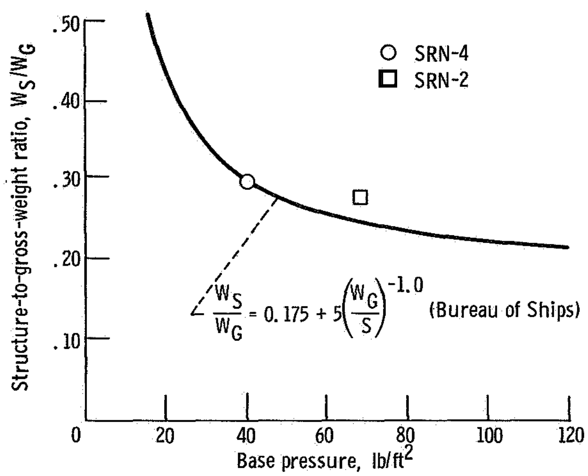
Structure weight. - The weight of the hovercraft structure exclusive of powerplant and equipment was computed using an equation given by the Bureau of Ships in reference 1. The structure-to-gross weight ratio computed from this relation is plotted in figure 7(a) as a function of the vehicle base pressure. The structure weight of the SRN-4 is representative of the largest hovercraft (~170 tons) in existence today. It falls on the Bureau of Ships curve. The SRN-2 structure is an earlier hovercraft weighing about 38 tons. It falls about 10 percent above the curve. With this support from actual practice it was decided to use the Bureau of Ships structure weight correlation.

Powerplant weight. - It was assumed that all equipment necessary to produce the airflow for hovering and thrust (aside from the reactor and shield) weighs 2 pounds per horsepower. This figure includes the weight of the reactor (less shield), piping, boiler, steam turbine, condenser, gears, fans, pumps, and all other equipment necessary to make a complete powerplant. In the studies for the Maritime Administration (refs. 1 and 7) captured air bubble vehicles and hovercraft used numbers ranging from 1 to 2 pounds per shaft horsepower. Reference 8 uses 1.65 pounds per shaft horsepower. These estimates do not include reactors. Rough estimates of the major components were made. The reactor weighs on the order of 0.25 pound per shaft horsepower, turbomachinery weighs on the order of 0.3 pound per shaft horsepower, the air condenser weighs about 0.5 pound per shaft horsepower, the boiler about 0.3 pound per shaft horsepower, gears are about 0.1 to 0.2 pound per shaft horsepower. These numbers including the reactor add up to about 1.5 pounds per shaft horsepower. A number of 2 pounds per shaft horsepower was used for the analysis.

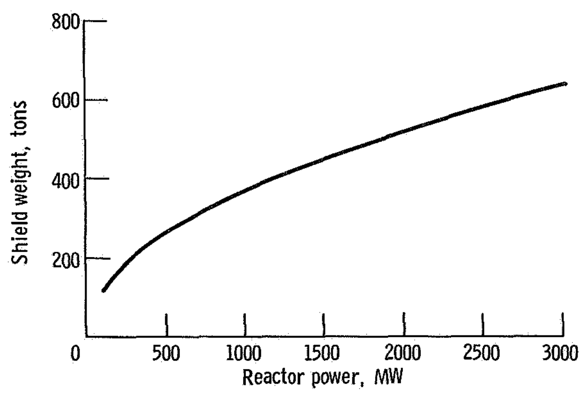
Shield weight. - Recent nuclear aircraft studies (ref. 2) have made estimates of the unit shields for compact reactors. These reactors have uniform shielding in all sides with low dose rates. For a dose rate of 2.5 millirem per hour at 130 feet, the weight of an optimized depleted uranium and water aircraft reactor shield is about 230 000 pounds for a 300-megawatt reactor with a power density of 3.5 megawatts per cubic foot. For hovercraft use, the dose level is reduced to 0.25 millirem per hour at 20 feet from the shield surface which is the allowable dose rate permitted to be received by the general public. This increases the shield weight by about 20 percent giving a weight of 275 000 pounds. Because the weight requirement is not as stringent on hovercraft as it is on aircraft, the weight of the shield is arbitrarily increased to 400 000 pounds (200 tons) to permit more flexibility in design. It can also be observed from reference 2 that the shield weight varies very nearly as the square root of the reactor power. The shield weight (tons) assumed for this analysis is then given by

$$W_{SH} = 200\sqrt{\frac{Q_R}{300}}$$

or



(a) Hovercraft structure weight.



(b) Reactor shield weight. Reactor shield materials, depleted uranium and water; dose rate, 0.25 millirem per hour at 20 feet; reactor power density, 3.5 megawatts per cubic foot.

Figure 7. - Hovercraft structure and reactor shield weights.

$$W_{SH} = 11.6\sqrt{Q_R} \tag{27}$$

The shield weight is plotted in figure 7(b). For vehicles with two reactors, the total shield weight is obtained by multiplying the shield weight of a single reactor by $\sqrt{2}$. Likewise, if it is desired to have a four reactor configuration, the total shield weight would be twice the total shield weight of a single reactor installation.

Payload. - The payload is disposable load, that is, the weight that can be used for cargo, chemical fuel, or other equipment as required for adapting the hovercraft to a particular function. It is the difference between the gross weight and the sum of the structure, powerplant, and shield weight:

$$W_P = W_G - W_S - W_{PP} - W_{SH}$$

Cost Assumptions

The following cost assumptions were made in the analysis. The assumptions should be recognized as estimates that are not based on detailed design studies. Rather they represent average numbers obtained by examining average data from similar systems that have been built or more thoroughly studied, the main purpose of the cost analysis is to show potential or trends rather than give absolute cost numbers.

Capital costs. - The three capital cost items of this study are the nuclear reactor and associated equipment for producing steam, the hovercraft structure, and the propulsive machinery.

The cost of the nuclear reactor system for producing steam is assumed to be \$20 000 per thermal megawatt of steam produced. This is based on a quotation for the price of \$30 000 000 for supplying a 2650 thermal megawatt nuclear steam system for Toledo Edison (ref. 9). This amounts to \$11 300 per thermal megawatt. This number was increased by 75 percent to allow for special problems which could be encountered in a shipboard installation.

The cost of the hovercraft structure was assumed to be \$15 per pound. This is to be compared with airplane structures which cost about \$50 per pound, automobiles which cost about \$1 per pound, and ships which cost about \$0.50 per pound. A previous analysis in reference 5 uses numbers ranging from about \$7 to \$11 per pound. The \$15 per pound used in this analysis reflects a degree of conservatism to cover detail costs that are not covered specifically in this simplified analysis.

The cost of all propulsion equipment is assumed to be \$35 per pound. In arriving at this number, the cost of marine turbine equipment is assumed to be about \$100 per pound, which is the same cost as for aircraft gas turbines. Assuming that equipment of this complex nature is about one-fifth the total weight of a complete system and assuming that the remaining powerplant equipment cost $20 per pound, the average powerplant cost is about $35 per pound. This value was used in the analysis.

Operating costs. - The operating cost items assumed for this study are nuclear fuel cost, maintenance, crew costs, interest, and depreciation.

The overall nuclear fuel cost is based on the assumption that nuclear fuel will cost $16 per gram of U-235 fissioned. This includes the U-235 basic cost, which is currently about $10 per gram. This is based on $8.8 per pound for U_3O_8 converted to UF_6 and the cost of enriching the fuel to 93-percent U-235 as given in reference 10. The additional 60-percent is added to account for reprocessing, manufacturing, shipping, interest, and all other charges for a complete fuel cycle. In terms of dollars per megawatt-hour, $16 per gram reduces to about $0.80 per megawatt-hour, which is the figure used in the analysis.

The total crew cost is assumed to be $0.075 per hour per ton of gross weight based on numbers from references 7 and 8. The cost of maintenance including a burden of 60 percent is assumed to be $0.16 per hour per ton of gross weight. The cost of interest is assumed to be 3.0 percent per year of the total vehicle initial cost. This is an approximation to a 6-percent yearly interest rate on the depreciated value of the capital equipment. Depreciation is based on a 60 000-hour operating lifetime for all capital equipment. It is assumed that the utilization is 0.5, that is, 4380 hours of operation per year.

RESULTS AND DISCUSSION

The results of this study of nuclear-powered air-cushion vehicles is divided into three main categories: (1) power requirements, (2) weight, and (3) cost analysis.

Power Requirements

The power requirement for air-cushion vehicles consists of two parts. The first is the power required to maintain the air cushion and the second is the power required to maintain the thrust to overcome the drag as the vehicle moves.

Lift fan power requirement. - The power required to maintain the air flow for the air cushion is calculated with the assumptions discussed in the ASSUMPTIONS AND ANALYSIS section. The results of these calculations are presented in figures 4(a) to (d) for velocities 0, 50, 100, and 150 knots, respectively. The lift fan power per foot of clearance height is plotted as a function of gross weight and base pressure. The lift fan horsepower increases directly with clearance height, almost directly with base pressure, and about as the square root of the gross weight. Lift fan power decreases with increasing velocity because a part of the required increase in pressure for the air cushion is obtained by ram compression due to the forward velocity of the vehicle. The energy required for the ram compression is supplied by the thrust engines.

At a speed of 100 knots the lift fans for a 2000-ton air-cushion vehicle operating at a clearance height of 10 feet with a base pressure of 60 pounds per square foot requires 90 000 horsepower. A 10 000-ton vehicle operating at 150 knots, a clearance height of 20 feet and a base pressure of 80 pounds per square foot requires a lift fan power of 256 000 horsepower.

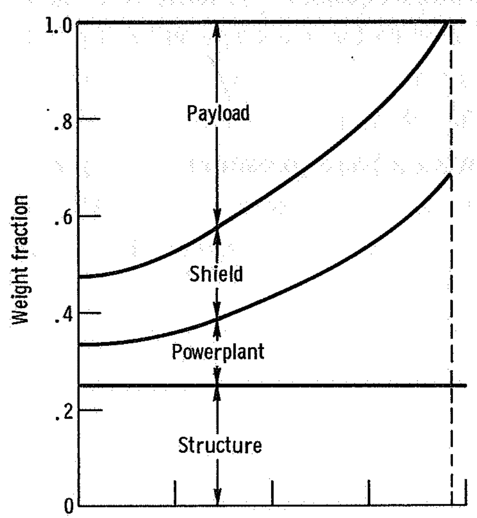
Thrust fan power requirement. - The power required to overcome the total vehicle drag as it operates at any given speed is called the thrust fan power requirement. The vehicle drag includes aerodynamic drag, wave drag, and inlet momentum drag. The inlet momentum drag is due to stagnating the air that is supplied to maintain the air cushion. The thrust fan power requirement is presented in figures 6(a) to (c) for a base pressure of 60 pounds per square foot and clearance heights of 10, 20, and 40 feet. The thrust fan power is plotted as a function of gross weight for velocities of 20, 50, 100, 150, and 200 knots.

The thrust fan power requirement for base pressure ranging from 20 to 80 pounds per square foot are within 10 percent of the values plotted for 60 pounds per square foot. Therefore, only the data for 60 pounds per square foot are shown.

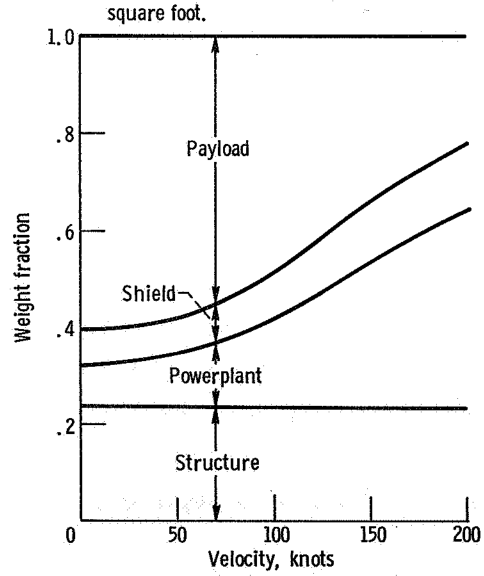
For a gross weight of 2000 tons, a clearance height of 10 feet, base pressure of 60 pounds per square foot, and a speed of 100 knots, the thrust fan power is about 270 000 horsepower. The total vehicle horsepower is then 270 000 horsepower plus the 90 000 horsepower required for the lift fan or about 360 000 horsepower. For a basic pressure of 80 pounds per square foot, a velocity of 150 knots and a clearance height of 20 feet, a 10 000-ton vehicle requires a thrust horsepower of 2 610 000. The total horsepower for a 10 000-ton vehicle is then 2 610 000 horsepower plus the lift fan power 256 000 horsepower for a total of 2 860 000 horsepower.

Weight Breakdown

The weight breakdown of two representative nuclear-powered air-cushion vehicles are shown in figures 8(a) and (b) for gross weights of 2000 and 10 000 tons, respectively. The weight breakdown expressed as a fraction of the gross weight is plotted as a function of the vehicle velocity. In figure 8(a) for a 2000-ton vehicle operating at a clearance height of 10 feet with a base pressure of 60 pounds per square foot, the structure weight



(a) Weight breakdown of 2000-ton nuclear-powered hovercraft. Clearance height, 10 feet; base pressure, 60 pounds per square foot.



(b) Weight breakdown of 10 000-ton nuclear-powered hovercraft. Clearance height, 20 feet; base pressure, 80 pounds per square foot.

Figure 8. - Effect of velocity on weight breakdown.

fraction is about 0.25 of the gross weight. The powerplant weight fraction increases rapidly with velocity reflecting the higher power requirement at higher speeds. At a speed of 100 knots the powerplant constitutes about 0.18 of the gross weight. The remaining weight is what is left over for payload which is the cargo and any special equipment required for any particular application. At 100 knots the payload fraction is 0.35 of the gross weight. At 150 knots the payload is still 0.20 of the gross weight.

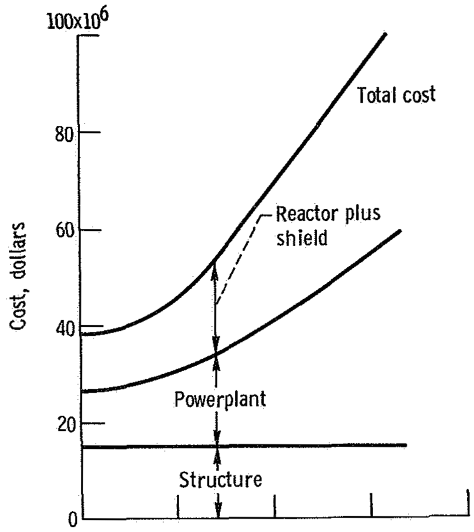
For a 10 000-ton nuclear air-cushion vehicle the powerplant and shield weight become a smaller fraction of the gross weight even when the clearance height is increased to 20 feet (fig. 8(b)). At 100 knots the payload fraction is about 0.49 of the gross weight. At 200 knots the payload is still about 0.22 of the gross weight.

The reason for this startling good performance at such high speeds when compared to the results of previous analyses is that the powerplant plus shield weight is markedly less than has been used in the earlier studies. For example, conventional nuclear marine powerplants including shielding and the reactor weigh on the order of 50 to 150 pounds per shaft horsepower. The weight per shaft horsepower of nuclear propulsion systems using aircraft type design philosophy is estimated to be of the order of 4.3 for the 2000-ton system and 1.5 for the 10 000-ton system. It is therefore clear why the performance of the nuclear air cushion vehicles shows up so well. It would be worth investigating why there is such a difference; whether the difference is real; and what needs to be done in order to achieve in practice the low powerplant weights that are predicted through the use of nuclear aircraft technology. The large payload fractions at speeds in the range of 100 to 200 knots with clearance heights in the range of 10 to 20 feet is indeed an attractive carrot to inspire more detailed study.

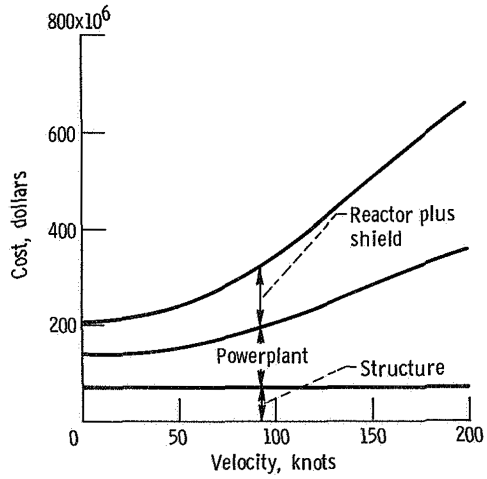
Cost Analysis

Estimates were made of the capital costs and operating cost of nuclear powered hovercraft using aircraft powerplant design philosophy. It should be emphasized that the cost analysis is rudimentary and simple. Its purpose was solely to determine whether any economic justification exists that would warrant more careful study of the nuclear air cushion vehicle for commercial application.

Figures 9(a) and (b) present the cost breakdown of nuclear air-cushion vehicles as a function of velocity using the assumptions listed in the ASSUMPTIONS AND ANALYSIS section. Figure 9(a) is for a 2000-ton vehicle operating at a clearance height of 10 feet and base pressure of 60 pounds per square foot. Figure 9(b) is for a 10 000-ton vehicle at a clearance height of 20 feet with a base pressure of 80 pounds per square foot. At speeds less than 75 knots the cost is about equally divided between reactor plus shield, powerplant, and structure. At higher speeds the reactor plus shield and powerplant



(a) Cost breakdown of 2000-ton nuclear-powered hovercraft. Clearance height, 10 feet; base pressure, 60 pounds per square foot.



(b) Cost breakdown of 10 000-ton nuclear-powered hovercraft. Clearance height, 20 feet; base pressure, 80 pounds per square foot.

Figure 9. - Effect of velocity on cost breakdown.

costs increases, reflecting the increasing power requirement. An estimate of capital cost was necessary to compute depreciation and interest costs for determining direct operating costs.

The direct operating cost for the simplified analysis used herein is defined as the cost in cents per ton mile of payload of the fuel, maintenance, crew, depreciation, and interest. The life of the entire vehicle was assumed to be 60 000 hours and the utilization was 0.50 or 4380 hours per year. The basis for the assumed costs is discussed in the ASSUMPTIONS AND ANALYSIS section.

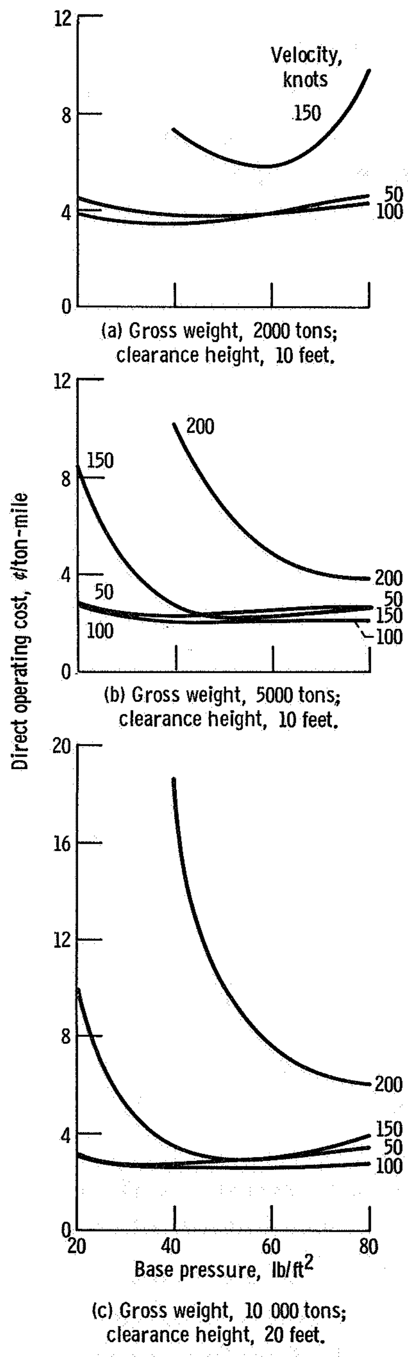
Figures 10(a) to (c) present the direct operating cost as a function of the base pressure for 2000-, 5000-, and 10 000-ton vehicles, respectively. The 2000- and 5000-ton vehicles operate at a height of 10 feet above the water, while the 10 000-ton vehicle operates at a height of 20 feet.

Figures 10(a) to (c) show that the direct operating cost is not sensitive to base pressure in the range of 50 to 150 knots for base pressures of 40 to 80 pounds per square foot. There is a tendency for the best base pressure to increase with speed. A base pressure of 60 pounds per square foot appears to be a good choice for any weight vehicle for speeds up to 150 knots. At 200 knots a base pressure of 80 pounds per square foot appears to be the best choice.

For a 2000-ton vehicle at a clearance height of 10 feet and speed of 100 knots, the direct operating cost is about 4 cents per ton-mile. For a 5000-ton vehicle at a height of 10 feet and speeds up to 150 knots, the direct operating cost is in the range of 2 to 3 cents per ton-mile. The direct operating cost for a 10 000-ton vehicle operating at 20 feet and speeds up to 150 knots is also in the range of 2 to 3 cents per ton-mile. At 200 knots the cost increases to about 6 cents per ton-mile. These costs are 100-percent load factor costs. If a load factor of 0.6 is assumed, the costs would range from 3 to 5 cents per ton-mile for speeds up to 150 knots.

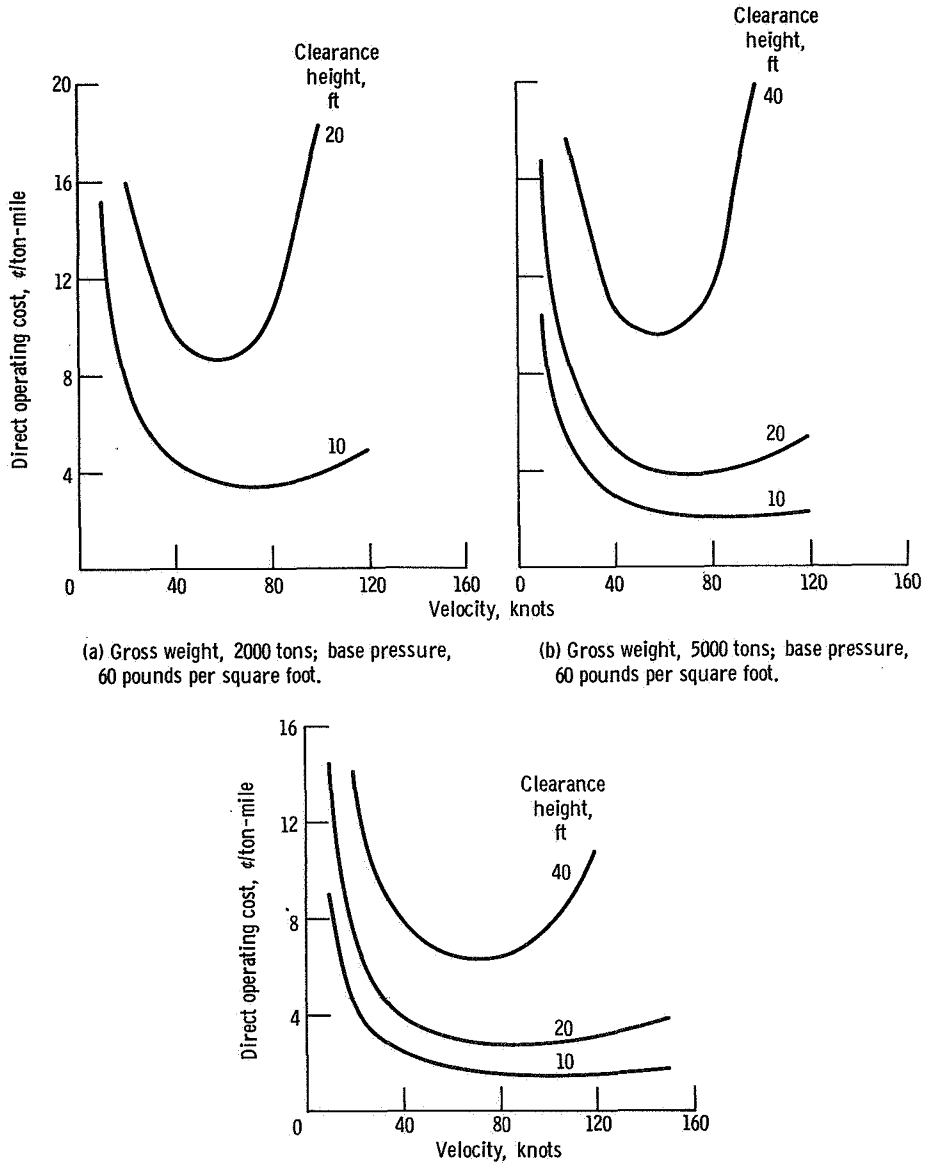
The effect of clearance height is shown in figures 11 (a) to (c). The clearance height is an important parameter for high-speed transoceanic travel. Present air-cushion vehicles as discussed in the INTRODUCTION are limited to speeds less than 80 knots because of the drag due to the contact of cushion skirts with waves, the wear on the skirts, and the impact loads on the structure. To achieve higher speeds, the vehicle or its skirts should not contact the water at all. In the North Atlantic peak wave heights of 10 feet (average wave height of about 6 ft) are not exceeded about 80 percent of the time. A clearance height of 10 feet would permit cruising at speeds over 100 knots 80 percent of the time. In order to increase this to 90 percent, the vehicle should be designed for a clearance height of 20 feet since peak wave heights do not exceed 20 feet (average wave height of about 14 ft) about 90 percent of the time. In order to achieve high transoceanic velocities (100 to 200 knots), the clearance height must be greater than 10 feet and preferably 20 feet.

For a gross weight of 2000 tons, increasing the clearance height from 10 to 20 feet increases the direct operating cost from about 4 to 9 cents per ton-mile and limits operation below 10 cents per ton-mile to speeds less than 80 knots. For a gross weight of 5000 tons, increasing the clearance height from 10 to 20 feet and 100 knots increases the direct operating cost from about 2 to 4 cents per ton-mile. Operation at a clearance height of 40 feet is possible at 100 knots, but the cost is increased to 20 cents per ton-mile. The largest vehicle considered (10 000 tons) in figure 11(c) shows operation for a clearance height of 20 feet at 150 knots to be less than 4 cents per ton-mile, compared



(c) Gross weight, 10 000 tons; clearance height, 20 feet.

Figure 10. - Effect of base pressure on direct operating cost.



(a) Gross weight, 2000 tons; base pressure, 60 pounds per square foot.

(b) Gross weight, 5000 tons; base pressure, 60 pounds per square foot.

(c) Gross weight, 10 000 tons; base pressure, 80 pounds per square foot.

Figure 11. - Effect of clearance height on direct operating cost.

to less than 2 cents per ton-mile at 10 feet. At 40 feet, the 10 000-ton vehicle operates at less than 10 cents per ton-mile up to speeds of 120 knots.

It was beyond the scope of this study to examine the case where the vehicle is operated at full power only when necessary to clear the highest waves and at part power for the remainder of the time when wave heights are less. The penalties for high clearance heights would then not be as great as presented in figure 11.

In order to better visualize the sensitivity of nuclear air-cushion vehicles to gross weight, the direct operating cost was plotted as a function of the gross weight in fig-

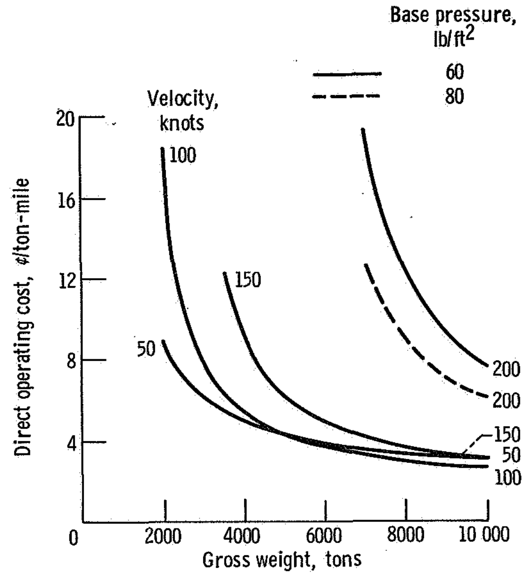


Figure 12. - Effect of gross weight on direct operating cost for clearance height of 20 feet.

ure 12. The high clearance height of 20 feet was chosen for this plot. The base pressure in all cases was 60 pounds per square foot except for the 200-knot case where both 60 and 80 pounds per square foot were plotted. Curves are shown for 50, 100, 150, and 200 knots. Below about 2000 to 4000 tons the direct operating cost increases to about 10 cents per ton mile for speeds of 50 to 150 knots. Above 6000 tons the direct operating cost is about 5 cents per ton-mile or less for speeds of 50 to 150 knots. At 8000 tons or higher the direct operating cost is about 3 cents per ton-mile. At a speed of 200 knots for a gross weight of 10 000 tons the direct operating cost is in the range of 6 to 8 cents per ton-mile.

At the higher gross weights (above about 5000 tons) there is little effect of speed in the range of 50 to 150 knots on direct operating cost. This conclusion would be altered if the following consideration is made. At higher speeds less interest charges would be accrued by the cargo in transit since it would be in transit for less time. This would be cost saving in an overall economic analysis. If the cost analysis had included such a factor, the higher speed would be favored.

Table I summarizes some of the more important results of the analysis of nuclear-powered air-cushion vehicles as carried out in this study. In the case of the 10 000-ton vehicle, the table shows the design for a base pressure of 60 pounds per square foot rather than the 80 pounds per square foot for which figures 8(b), 9(b), and 11(c) were plotted. At 60 pounds per square foot the direct operating cost is lower than for a base pressure of 80 pounds per square foot.

In table I for gross weights varying from 2000 to 10 000 tons the shaft horsepowers vary from 360 000 to 2 410 000 while reactor powers vary from 1300 to 9000 megawatts. The payloads are also large however. They vary from 700 to 4000 tons. The cargo

TABLE I. - NUCLEAR AIR-CUSHION VEHICLE SUMMARY

	Vehicle weight, tons			
	2 000	5 000		10 000
Clearance height, ft	10	10	20	20
Vehicle speed, knots	100	100	100	150
Base pressure, lb/ft^2	60	60	60	60
Total shaft hp	360×10^3	600×10^3	$1\ 909\times10^3$	$2\ 410\times10^3$
Reactor power, MW	1 320	2 220	4 070	8 970
Structure weight, tons	510	1 280	1 260	2 550
Powerplant weight, tons	350	600	1 090	2 410
Shield weight, tons	420	540	740	1 090
Payload weight, tons	720	2 580	1 910	3 960
Payload delivery rate, ton-mile/hr	82 600	297 000	220 000	688 000
Capacity, ton-mile/yr	362×10^6	$1\ 300\times10^6$	970×10^6	$2\ 990\times10^6$
Fuel cost, $/hr	1 060	1 780	3 250	7 170
Crew cost, $/hr	150	380	380	750
Maintenance cost, $/hr	320	800	800	1 600
Depreciation cost, $/hr	1 110	2 070	3 260	7 070
Interest cost, $/hr	460	850	1 340	2 910
Total operating cost, $/hr	3 090	5 880	9 040	19 500
Direct operation cost, ¢/ton-mile	3.7	2.0	4.1	2.9

carrying capacity (assuming 50-percent utilization) varies from 362 million to 2990 million ton-miles per year. These numbers rival the capacity of the largest cargo ships now sailing. The direct operating costs range from about 2 to 4 cents per ton-mile. For comparison, conventional ships operate at about 1 cent per ton-mile for general cargo; railroads and trucks at about 2 cents per ton-mile; and jumbo aircraft like the C-5 are expected to operate at about 5 cents per ton-mile.

The range of the nuclear air-cushion vehicle assuming 10 000 hours between refueling is of the order of 1 to 2 million miles.

CONCLUSIONS

A study has been made to evaluate the potential of nuclear-powered air-cushion vehicles with gross weights in the range of 1000 to 10 000 tons for speeds up to 200 knots and operating clearance heights sufficient to completely clear ocean waves. The following specific conclusions are made:

1. The use of nuclear aircraft technology for powerplants of nuclear air-cushion ve-

hicles completely changes the performance potential when compared to air-cushion vehicles powered with chemical or conventional nuclear marine powerplants.

2. Nuclear air cushion vehicles can fly at clearance heights of 10 to 20 feet and speeds over 100 knots with payload fractions in the range of 20 to 50 percent of the gross weight.

3. Based on a simplified cost analysis the nuclear air-cushion vehicle can carry payload at the rate of 2 to 5 cents per ton-mile. The low cost arises chiefly from the large payload fractions possible through the use of light-weight nuclear powerplants.

4. The power requirements for the nuclear-powered air-cushion vehicles of the size needed (2000 to 5000 tons) to give good performance are high. For a 2000-ton, 100-knot vehicle operating at a clearance height of 10 feet about 365 000 horsepower is required. Fourteen 6500-horsepower powerplants with 16-foot-diameter fans are required to supply the air-cushion flow. Eight 35 000-horsepower powerplants with 16-foot-diameter fans are required for thrust. For a 5000-ton, 100-knot vehicle with a clearance height of 20 feet, the required horsepower is 1 090 000. This would require about 28 fans about 25 feet in diameter, 14 with a rating of 20 000 horsepower each for lift and 14 with a rating of 58 000 horsepower each for thrust.

5. The range of nuclear air-cushion vehicles using nuclear aircraft technology is of the order of 1 to 2 million miles between refuelings.

6. The operating cost in terms of cents per ton-mile is independent of the distance travelled. This is to be contrasted to chemically fueled air-cushion vehicles where the cost increases as the range increases.

The study shows that the use of aircraft type technology for nuclear powered air-cushion vehicles completely changes the image of air-cushion vehicles. Instead of low range to 50- to 80-knot vehicles they become vehicles that can travel at speeds in the range of 100 to 200 knots for unlimited ranges. They can operate at sufficient clearance heights so that no contact is made with ocean wave peaks for the 80 to 90 percent of the time when ocean waves are less than 10 to 20 feet. The payload fractions are high, and the cost of delivering payload may be in the order of railroads and general merchandise freighters. An indepth evaluation of the nuclear-powered air cushion should be made to verify the conclusions of this relatively simple analysis.

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Cleveland, Ohio, May 23, 1969,
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