Nuclear-Powered Surface Effect Ships Design Problems

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Preliminary study of a transoceanic surface effect ship (SES) (GEM) is made to evaluate its commercial feasibility. Ship specifications of operating height and speed are determined for the ocean environment, and a range of sizes is considered to define the power requirements. Powerplant weight is a critical factor and state-of-the-art research is performed for suitable nuclear powerplants, and different cycles are analyzed. Optimum ship size is determined through parametric studies, for a range of powerplant specific weights. Vehicle characteristics are then determined and general arrangements are made for optimum sizes considering payload and operating cost factors, identifying a 6000-ton ship as a practical size. Structural design criteria are developed for the 6000-ton ship. Truss-type structure is found most suitable for minimum weight. Machinery weight estimates are made for the complete installation and development needs are identified. Commercial feasibility is evaluated over North Atlantic routes. The study concludes that construction of a nuclear-powered SES is feasible using present technology, but its cost characteristics would be commercially marginal. Further development of the nuclear powerplant is practical and would result in a competitive ship.

Nomenclature

D_e = equivalent diameter = $(4S_b/\pi)^{1/2}$
h = operating height
S_b = cushion area = $L \times B = L^2/2$ (for 2:1 ratio)
W_G = gross weight
W_S = structural weight
w_m = machinery specific weight
W_M = machinery weight = $W_{PP} + W_{LP}$
W_{PP} = propulsion machinery weight
W_{LP} = lift machinery weight
W_{DL} = disposable load = $W_F + W_{PL}$
W_F = fuel weight
W_{PL} = payload
W_e = equipment weight
W_E = empty weight = $W_S + W_M + W_e$
P_c = cushion pressure = W_G/S_b, psf
V = speed

Units in all mathematical equations are: weight, short tons; speed, mph; specific weight, short tons/hp; weight to area ratios, psf.

General Design Considerations

THE SES is a low-density craft compared with displacement ships and is best suited for carriage of either low-density cargo or passengers. It is characteristically of large planform area and will approach ship size in order to have good sea-keeping ability in the open ocean.

The size of a nuclear-powered SES is dictated mainly by the weight of the powerplant, which will require a large planform area for low power. However, vehicle power requirements are a function of the gross weight, operating height, and cruise speed. On the other hand, vehicle gross weight is a function of size and power.

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Design specifications for a passenger ship operation in North Atlantic service form the basis of the study so that environmental factors and employment are also considered in selecting ship size.

The natural environmental factors that influence SES performance are 1) ocean distance, 2) wave height, 3) wind, 4) temperature, 5) visibility, 6) salt water ingestion, and 7) sea ice.

Average climatological conditions[1, 2] are used as the basis of performance specification. Of these factors, wave height is significant in establishing installed lift power, and wind is likewise considered in establishing installed propulsion power. Although other factors may also influence performance, they will exert only a weak influence on the design.

Other operational factors are also to be considered in the design of the SES as follows: 1) international policy, 2) routes, 3) employment, 4) nature of the waterway, 5) navigation, 6) terminal location, 7) terminal operations, and 8) terminal facilities.

In this analysis, only employment has been considered. However, these other considerations may limit the employment of the nuclear-powered SES and are included to illustrate areas requiring further appraisal. It is the opinion of the authors that a satisfactory resolution of most of these factors is a prerequisite to further consideration of the development of these ships for commercial service. Even so, if it is assumed only that size will not be limited by operating considerations, the validity of the approach will not be in-

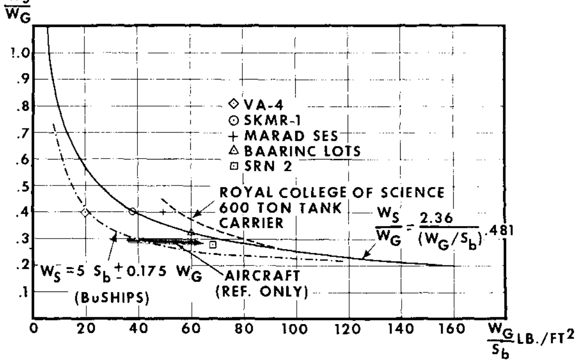

Fig. 1 Structural weight W_S/W_G vs W_G/S_b.

fluenced by omitting this consideration and the results should be helpful in evaluating potential operating problems.

In summary, the following independent variables are established as the basis for preliminary design studies: 1) operating height, 2) cruise speed, and 3) passenger service.

Preliminary design study of the nuclear-powered SES is undertaken from two distinct points of view as follows: 1) ship size and dimensions are optimized for a range of nuclear powerplant weights; and 2) preliminary structural and machinery design studies are made for a ship of selected size in order to develop better weight estimates for these components, thus allowing a preliminary evaluation of these ships from a practical and economic standpoint.

Optimum Sizes of Nuclear Surface Effect Ships

The feasibility of designing surface effect ships utilizing a range of nuclear powerplants specific weights is considered now, as well as finding the optimum size for a transoceanic surface effect ship so powered.

Generalized Parametric Study

In optimizing an SES, it is necessary to define the pertinent parameters and to examine their effect on the design and their comparative relationship.

The weight equation applicable to any ship size can be formulated as follows:

$$1 = W_S/W_G + W_M/W_G + W_{DL}/W_G + W_e/W_G$$

The variation of these weights as a function of the cushion pressure and their variation with the operating height and machinery specific weight can now be analyzed.

Structural weight

The structural weight may be expressed by the equation[3]

$$W_S/W_G = 2.36/(W_G/S_b)^{0.481}$$

This equation plotted in Fig. 1 applies to all ships regardless of the size. Aircraft weights have also been plotted for reference purposes.

Powerplant

The power requirements cover the power necessary for lift as well as that required for propulsion.

Lift power weight[4]

The weight equation of lift powerplant required for a craft having a length to beam ratio of 2:1 is given by the following equation:

$$W_{LP}/W_G = HP \times w_m$$
$$= 0.166\,(h/D_e)(W_G/S_b)^{1/2} \times w_m$$

Variations of h/D_e from 0.01 up to 0.05 have been considered and also values from 10 to 20 lb/hp govern the machinery specific weight.

Propulsion power weight[4]

The following equation gives the weight required for propulsion power as a function of the pertinent parameters:

$$W_{PP}/W_G = HP \times w_e/W_G = [4.3 \times 10^{-4} \times V^2(W_G/S_b)^{1/2} + 0.017 \times C_D \times V^3/(W_G/S_b)]w$$

Empty weight

Adding the structural, machinery, and equipment weights, and plotting them as a function of the cushion pressure, the

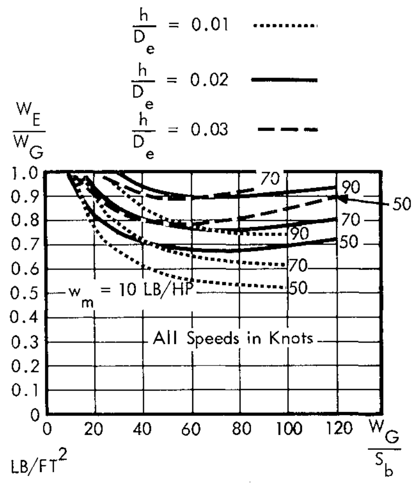

Fig. 2 Empty weight (no equipment) vs W_G/S_b.

variation of empty weight for various values of h/D_e, machinery specific weight, and speed can be ascertained. Figures 2 and 3 show these relationships.

Fuel weight

Fuel weight is constant and included in the machinery weight.

Payload

All the disposable load is payload in a nuclear-powered ship and decreases with increases in machinery specific weight, h/D_e and speed.

Specific Parametric Study

The payload may be expressed by these relationships in nondimensional form, in terms of the major design parameters and as a function of the cushion pressure, to facilitate the theoretical design. A craft of optimum design can, therefore, be defined to suit the environmental conditions.

Operating height

The New York-London route is chosen for the study because traffic in this area would support ships of large size. Operating height is based on the North Atlantic environment, which requires clearance of 16-ft waves in order to operate 90% of the time.

Experience in the United Kingdom[5] indicates that skirt-fitted craft can operate successfully at one-half the significant

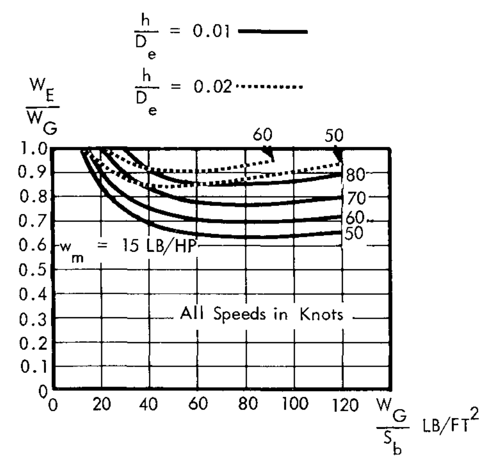

Fig. 3 Empty weight (no equipment) vs W_G/S_b.

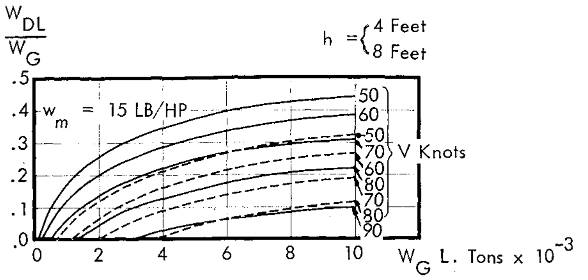

Fig. 4 Gross weight vs disposable load.

wave height. The trans-Atlantic ship must, therefore, be fitted with an 8-ft-long skirt to achieve the required clearance.

The maximum wave height is less than 8 ft 60% of the time, and so the skirt height may be reduced accordingly to give 4 ft of clearance over a hard surface.

Operating heights are therefore established consistently with climatological conditions as follows: 1) continuous high cruise speed, 4 ft; and 2) reduced cruise speed, 8 ft.

Speed

Design speed is selected to give the SES twice the speed of existing liners under normal cruise conditions and at least 20 knots under the worst conditions. The propulsion power requirements are established by the latter condition and are based on 50 knots, since head winds up to 30 knots may be encountered under these sea conditions. At lower operating heights, higher speeds can be maintained by utilization of excess lift power for propulsion.

Optimum and Minimum Sizes

Assuming optimum values of the ratio of disposable load to gross weight from the previous analysis and plotting them vs gross weight for different speeds and operating heights will show that, as the machinery specific weight increases, the ratio W_{DL}/W_G decreases. These plots will also indicate the maximum speed that can be attained with the available horsepower at lower cruising heights.

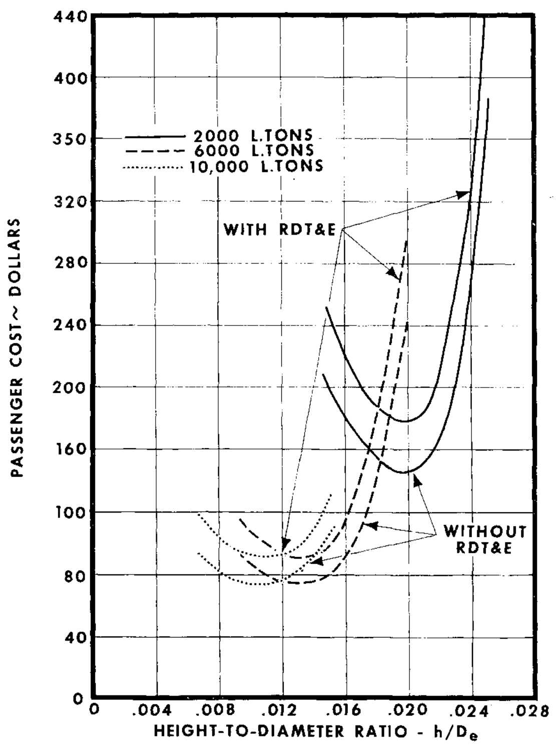

Fig. 5 Passenger cost: nuclear SES New York to London.

Such studies were made in the process of this study to establish the range of practical sizes assuming machinery specific weight of 20 lb/hp. These show that the smallest ship with no payload has a gross weight of 2000 tons, and the largest practical ship with 23% payload has a gross weight of 10,000 tons (little cost advantage results beyond this point).

The importance of reducing machinery weight to the lowest possible value is indicated by these small payload margins.

Assuming nuclear powerplants with specific weights as low as 15 lb/hp (Fig. 4), this preliminary optimization will indicate what can be obtained with this new type of craft if sufficient emphasis is placed on lowering the machinery weight.

Three sizes of nuclear powered surface effect ships examining the feasible range may be selected, the two extremes being considered the limiting conditions, either as minimum disposable load or as physical size. They are 1) 2000 long tons gross weight, 2) 6000 long tons gross weight, and 3) 10,000 long tons gross weight. For the three sizes under consideration, a preliminary cost evaluation was conducted.

The results of this preliminary analysis are plotted in Fig. 5, which shows the cost per passenger as a function of the operating height to the effective diameter ratio for the three sizes of surface effect ships under consideration.

Optimum Vehicle Characteristics

General

As discussed previously, the purpose of the nuclear-powered surface effect ship is to provide an economically competitive ship for transporting passengers over transoceanic ranges.

In keeping with these requirements, the smallest nuclear powered surface effect ship that is economically feasible appears to be close to the 6000-ton size. This size of surface effect ship will have the following characteristics:

W_G	= 6000.0 long tons
W_M	= 2963.6 long tons
W_S	= 1980.0 long tons
W_e	= 120.0 long tons
W_{DL}	= 936.4 long tons
L	= 639 ft
B	= 334.5 ft
W_G/S_b	= 60 psf
HP_T	= 360,000 (max installed)
operating height below skirt	= 8 ft (16 ft to hard structure)
max significant wave	= 16 ft
number of passengers	= 3680

The number of passengers has been determined allowing 570 lb/passenger. This includes luggage, furnishings, services, etc. As for performance, Fig. 6 shows the power requirements vs speed for various wave heights.

General Arrangement

The predominant features of the nuclear powered SES is its over-all size and the cavernous capacity of its internal envelope. Such an envelope provides for a wide variety of solutions with respect to the positions occupied by the powerplant, fans, passengers, crew, and the various passenger services.

Essentially, the 6000-ton nuclear-powered SES (Fig. 7) consists of six decks, eight centrally disposed nuclear powerplants, and thirty-two 20-ft-diam fans located around the extremities of a rectangular planform. This arrangement is conducive to a minimum structure weight comprised of two main longitudinal beams and 11 main transversal beams.

To achieve low passenger fares, the weight allowance per passenger must be kept to a minimum, accommodations cannot be lavishly furnished, and thus the available deck area must be reduced below that which is actually available, and it is estimated that a total of 50 ft²/passenger is adequate.

Providing a panoramic view for as many passengers as possible will add appeal to the nuclear SES. Since six decks with a total perimeter of 8490 ft are available, this will allow for the total number of passengers to be accommodated in rows of three seats each. The remaining deck area allowed per passenger may be used for cafeteria-type dining rooms for the passengers, sanitary services, crew accommodations, and general services. The unused deck area could supply room for playgrounds, walking areas, and other means of relaxation. With a trip duration not exceeding three days, a relatively austere approach with the consequent weight reduction is believed to be justified.

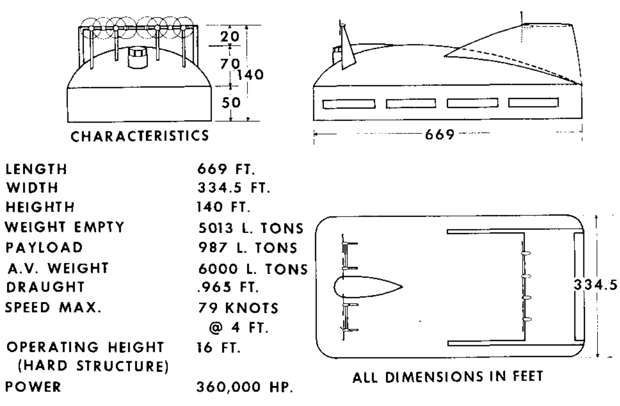

Fig. 7 General arrangement nuclear SES.

Nuclear Powerplant

General Nuclear Powerplant Technology

The prospect of transoceanic employment of SES depends entirely upon the availability of a suitable nuclear powerplant. Although this prospect results from the elimination of chemical fuel, the powerplant must also have a low weight to power ratio, and preliminary studies indicate that the specific weight must be less than 20 lb/hp for economic feasibility (Fig. 8).

A state-of-the-art review of the types of nuclear powerplants available today shows that none of them possesses suitable weight characteristics for the SES application.

The reactor types receiving predominant favor today are the pressurized water, boiling water, gas-cooled (helium), heavy water, natural uranium, sodium graphite, and fast breeder. A steam power-producing process is used in conjunction with all of these reactors. Experience in naval light combatant ships shows that steam plants using conventional fuels have a specific weight of around 30 lb/hp, which seems a fair basis for excluding the possibility of utilizing a condensing steam powerplant for an SES.

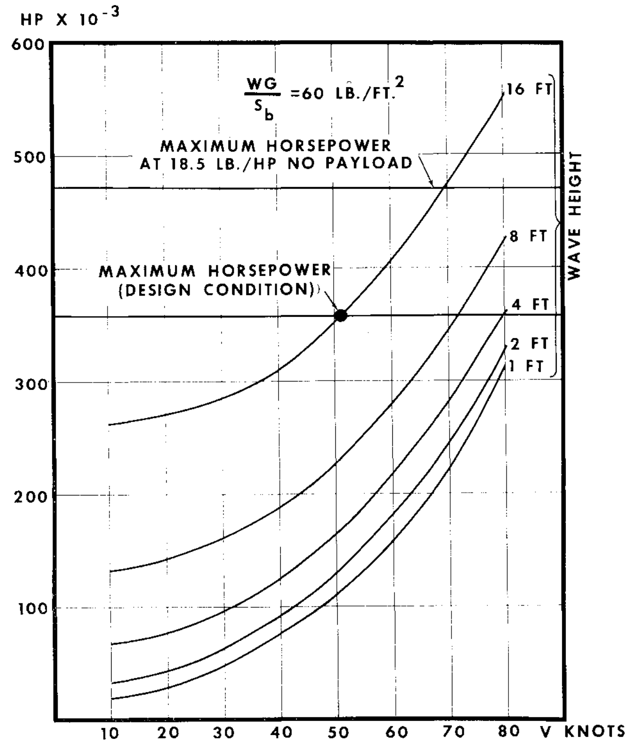

Fig. 6 Horsepower vs speed 6000 long tons nuclear SES.

Outside of the atomic submarine and commercial powerplants, the other principal development work in the nuclear power field has been directed to the development of aircraft nuclear powerplants. Both gas-cooled and sodium-coated reactors have been developed to a point for this application. These reactors were developed to be combined with open-cycle, air-breathing engines for power production. Although these engines are not directly applicable in an SES, it is believed that these nuclear reactors may be adapted to work-producing cycles, which would be suitable for the SES.

Evaluation of reactor types is beyond the scope of this paper, and the study results are based on reactor characteristics and cost information furnished by the manufacturer. Otherwise, thermodynamic and engineering principles are applied to select a suitable work-producing process as a basis for arrangement and weight studies.

Nuclear powerplant design parameters and variables

The factors to be considered in the selection of a nuclear powerplant for the surface effect ship are summarized as follows: 1) safety, 2) weight, 3) powerplant space requirements, 4) reliability and maintainability, 5) capital cost, and 6) fuel cycle cost.

The use of nuclear fuel introduces new design considerations that arise from the fact that the energy source is radioactive and that high load factors and utilization are attainable and must be realized for maximum economy.

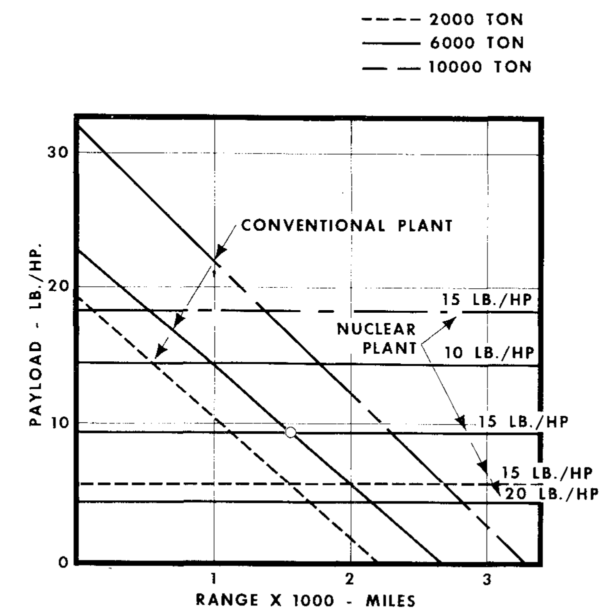

Fig. 8 Payload-range conventional and nuclear power.

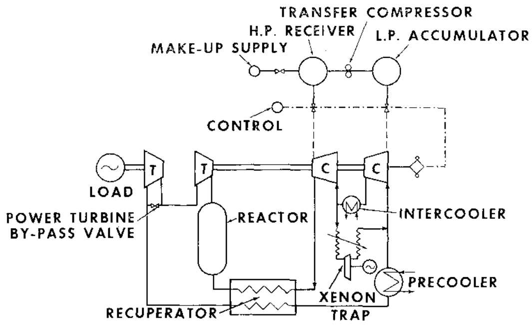

Fig. 9 Flow diagram of a high efficiency nuclear powerplant.

Radioactivity requires plant shielding and a high order of plant safety, and because it cannot be stopped at once, it requires removal of decay heat. It also renders certain plant components completely inaccessible.

The increased availability of the powerplant permits higher load factors. In the case of ship applications, it results in virtually unlimited range at high speeds. On the other hand, a more arduous duty is imposed on all plant components making good reliability essential. Similarly, the on board maintainability must be adequate.

In general, safety is a basic requirement, and because there are areas of uncertainty, the level of radiation outside of the shield is not considered a variable from the ship design viewpoint. Adequate shielding must be provided consistent with the reactor plant requirements and ship arrangements, and this must be considered as additional machinery weight. Other variables influencing shield weights are as follows.

Shield materials

Although some materials have superior shielding properties, their use usually increases powerplant costs, but results in only a small percentage saving in total plant weight.

Reactor coolant

Choice of a suitable coolant is the most important variable controlled by the designer for achieving significant improvement in nuclear powerplant physical and performance characteristics. The nuclear properties of the coolant govern the primary and secondary shielding requirements, the stored energy of the coolant system determines the containment vessel requirements, and its properties exert a strong influence on plant thermal efficiency as they establish the temperature level of which heat is added to the power cycle; hence coolant properties affect the net power output and specific weight directly.

Arrangement of components within the radiation shield

Experience in the design of the nuclear powered submarine identifies arrangement of equipment as the most important way to reduce shield weights. Compact grouping of radioactive components and keeping radioactive sources as small as possible are equally important in minimizing these weights. Direct coolant cycles, where the coolant is used as the working fluid in the power cycle, are considered mainly to obtain more compact arrangements and to reduce plant weight and cost.

These considerations of plant safety and shielding requirements are inherently related to the machinery component designs, and they imply, to a certain extent, the approach to be taken in their design so that the combined machinery weight and shield weight is minimized.

In summary, nuclear powerplant weights may be reduced, either by direct reduction of component weights or by increase in the net power output. Direct reductions in plant weight can be achieved by employment of direct coolant cycles and small lightweight components. On the other hand, net power output may be increased only by the attainment of high thermal efficiency, which will also be effective in reducing the cooling water requirements as well as the size and cost of the components. It is a conclusion of the authors that both means must be used in order to develop plants of suitable weight characteristics for the SES.

Nuclear Powerplant for the SES

A powerplant for the 6000-ton SES was chosen for evaluation of the foregoing conclusions, other installation problems, and the weight of these installations.

The gas-cooled reactor, which has been developed by the General Electric Company,[6, 7] forms the basis of the estimates for the nuclear components of the plant. This reactor is a further development of the nuclear components originally designed for aircraft installation, upon which development work has been continued, aiming at its use in combination with steam components for marine installations. The core is suitable for a wide range of power extraction, say between 20,000 and 60,000 shp. Also, the manufacturer has studied direct cycle applications for both gas and noncondensing steam cycles. Weight and cost estimates are based on information so derived.

A closed-cycle gas turbine plant is selected for this evaluation. A flow diagram of the machinery components is presented in Fig. 9. Directly coupled turbomachinery components are envisaged in which the working fluid also serves as the reactor coolant. This study is based on the use of air as the coolant, although other gaseous elements could be employed. Closed-cycle machinery is considered essential for this type of ship, but also results in other structural and operational advantages as the size of both the rotating and fixed components will be smaller.

Both a simple cycle plant and a complex cycle (one stage of intercooling and one stage of regeneration) are considered. Turbine inlet temperatures of 1400 in the simple cycle and 1300 in the complex cycle are used, with optimum pressure ratios of 6:1 and 3:1, based on minimum mass flow and maximum efficiency, to develop comparative weight and performance estimates.

The latter cycle naturally increases the complexity of the arrangement of all plant components, but it is believed to be highly desirable in the SES from the standpoint of attaining higher efficiency. Also, its use will reduce the cooling water requirements by an order of magnitude, which is important in a ship operating above the surface.

The study is based on the use of eight 45,000 shp plants to provide the power required by a 6000-ton SES. This selection represents a compromise taken for practical reasons in regard to complexity of transmission problems.

A powerplant arrangement is envisioned as follows. Each reactor will be directly coupled to two turbocompressor units having a separate power turbine to deliver useful work. Each power turbine will be coupled to three lift fans and a propulsion unit, through clutches and a mechanical transmission system. Either turbine will be capable of furnishing power to the propulsion unit, whereas the fans will not be cross-coupled.

The lift fan power requirements are developed analogously to flow in a ducted system in terms of vehicle design parameters. The requirements are for six 6000-hp fans, which would deliver 220,000 ft^3/sec at discharge velocity of 150 fps. Performance and weight estimates used were furnished by the Joy Manufacturing Company for axial flow units, which could be supplied by them.

Mechanical transmissions comprise a clutch, right-angle drive, and a second-stage reduction gear for each power-absorbing unit, in addition to a primary reduction gear on each power turbine. By selecting design speed of the right-angle drive to give tooth loading favorable to good reliability and taking the reduction in two stages, both gear and shaft weights may be minimized and reliability of the system can be maximized.

Cooling water requirements for precooling of the working fluid is furnished by liquid coupling of the precooler to the air intake system.

Weight estimates show that the simple cycle plant will have a specific weight of 20.20 lb/hp compared with 18.74 lb/hp for the regenerative cycle. The specific weight of the respective reactor assemblies, which includes the reactor, shielding, compressors, turbines, and precoolers, will be 16.60 and 11.90. Although part of this difference is offset by the addition of the intercooler and the regenerator, there is a net gain of 1.46 lb/hp. Weight breakdowns are given in Table 1.

The pronounced reduction in specific weight of the nuclear components of the complex plants results from increase in the thermal efficiency of the power-producing cycle, which is obtained at a lower pressure ratio yet at the same pressure level on the high side and a higher pressure level on the low side of the system. The efficiency of the simple cycle is found to be 20.8% compared with 32.0% for the complex cycle; these result in corresponding fuel cycle costs of 4.24 and 2.97 mils/shp, respectively.

The estimated cost of the complete powerplant employing the regenerative cycle is found to be 19% less than the simple counterpart and amounts to $8.32 million for each 45,000 hp unit, which is equivalent to $185/shp.

Both capital and operating costs are important from the standpoint of transportation economics. The omission of detailed discussion of the life characteristics and fuel cycle costs from the paper is deliberate. In this regard, the authors note simply that the estimates are based on extensive development work by the manufacturer. The refueling cycle of 6000 hr is satisfactory for the projected ship utilization, and the manufacturer's estimates of refueling costs and time make its accomplishment practical in conjunction with an annual lay-up and inspection routine.

The scope of the work is limited as far as the powerplant is concerned, but the projected information on plant performance and physical characteristics is considered practical and attainable.

Structural Considerations

To provide a realistic preliminary weight estimate and to show the feasibility from the structural point of view of the design of an SES of the 6000-ton size, a preliminary stress analysis of the primary structure and powerplant supports was performed.

Stressing Conditions

The stressing condition for the primary structure will be the SES simply supported at the ends and with a concentrated load at the center equal to the craft gross weight; this weight will render the same stresses as in the case of the distributed load by applying a load factor between 2 and 3, consistent with the Ryan[8] criteria.

Primary Structure

Preliminary estimates of the weight of very large light alloy skirted structures, similar to the class of surface effect ships demonstrated by the SKMR I, the SRN2, the VA-3, and many others, have indicated that, in order to maintain the same percentages of empty weight to gross weight, the depth of structure would have to increase disproportionately to the other linear dimensions. This, of course, is a direct result of the square-cube law; neglecting the advantage of building more efficient structures when sizes are increased, for equal stress levels, the depth of structure must rise by a factor of 4 when the length or the width is raised by 2.

Examination of trussed beams, smaller in depth than the tension field structures, provided a more efficient structure in keeping with the smaller structures.

It was, therefore, decided to maintain the maximum depth of the structure at a value somewhat between the depth associated with tension field beams and simple trussed beams of minimum depth. A "K" type of truss is proposed since this offers a desirable form of multiple web system, has comparatively low secondary stresses, and is particularly adapted for long riveted spans.

Powerplant Supports

It has been assumed that each powerplant is supported by 18 beams. The construction of these beams is in accordance with aircraft practice.

Structural Weight Estimate

Primary and other structural weights are indicated in Table 1.

Final Weight Estimate

After this preliminary stress analysis and structural weight estimate, a new weight estimate is conducted for the 6000 long ton SES. This weight breakdown is listed in Table 1, and these values are consistent with the preliminary estimate. They will, therefore, be used in the economic analysis.

Nuclear Surface Effect Ships Costs

General

The procedures for determining costs for very large nuclear SES are, at the best, extremely speculative, particularly with regard to the weights and cost of the nuclear engines themselves. In general, the same procedures defined in Ref. 9 have been used for determining flyaway costs and depreciation costs. The same data for deriving structure and propulsion hardware costs found in Ref. 9 have been employed. Equipment weight, assumed to be 2% of the gross weight and costing $10/lb, has also been used. Data in Refs. 6 and 7 were used to predict nuclear engine costs, and a nominal value of $185/hp is found to be representative.

Route characteristics were examined in a manner similar to that of Ref. 9, although somewhat simplified.

The wave height distribution for each route was used to determine the average height at which the vehicle would have to travel during the year. Since engine horsepower requirements were determined from the requirement for a 50-knot capability at a 16-ft wave height, a penalty was applied when the waves were greater than 16 ft. It was assumed that the nuclear SES would go around the storm center, effectively in-

Table 1 Final weight breakdown

Item	Weight, lb
Structure	
Primary structure	2,615,357
Other structure	1,819,843
Powerplant	
Reactor assembly	5,450,400
Other machinery	1,141,200
Electric system	154,200
Passenger furnishings	552,000
Passenger services	552,000
Equipment	268,800
Crew	147,200
Passengers and luggage	846,400
	13,547,400

creasing the range by 50% whenever the waves were greater than 16 ft. Further, it was assumed that when the vehicle was traveling around this storm center, it would be moving at 50 knots with a power required to negotiate 16-ft waves. Travel distance and time were based on the average of all these characteristics throughout the year.

Total trip time was determined, using the travel time and adding turnaround time. A minimum of 24 hr was assumed for each trip to account for servicing and maintenance. In addition, it was assumed that passengers could be loaded and unloaded at a rate of 250/hr. Thus, whenever the passenger load exceeds 6000, additional turnaround time is required over and above the 24-hr minimum.

This total trip time was used to determine the number of trips made per year. A total of 350 days was used as the operational year, allowing 15 days for major overhaul and renovation. The number of trips determined in this manner was multiplied by the travel time to provide annual utilization.

Depreciation was based on the flyaway costs and the annual utilization, allowing for 15% residual value at the end of useful life. Useful life of structure and equipment was assumed to be 10 yr, the value for engines and propulsion hardware was assumed to be 7 yr.

Maintenance costs were assumed equal to the depreciation costs, primarily because of the fact that there is no way of predicting costs for nuclear powerplants from the sound basis of operational experience, although maintenance costs predicted in this manner are somewhat low when compared with current airline operations. This assumption seems reasonable because, from information currently available, the maintenance cost of nuclear engines appears to be much less than that for conventional engines.

Fuel life has been estimated at 6000 operating hours with fuel costs of $112/operating hour, plus a fuel charge of $511/day. In addition, fuel replacement costs were estimated to be $70,000 for individual power units for each recharge.

Crew costs have been determined based on ship experience. The crew in this case represents only the manpower required to operate the vehicle. The cost of stewards is added, using a yearly salary of $7200 for 2000 hr of work. Here again, one steward was assumed for every 40 passengers.

Direct operating costs were determined by adding all the depreciation, maintenance, fuel, refueling, crew, and steward costs. Indirect operating costs were estimated at 54% of the direct operating costs.

The sum of the direct and indirect operating costs determines the total operating cost, which, when divided by the travel time, produces the voyage cost. Cost to each passenger and cost per passenger mile are then determined. A mathematical model was constructed and programed for the CDC 160-A computer.

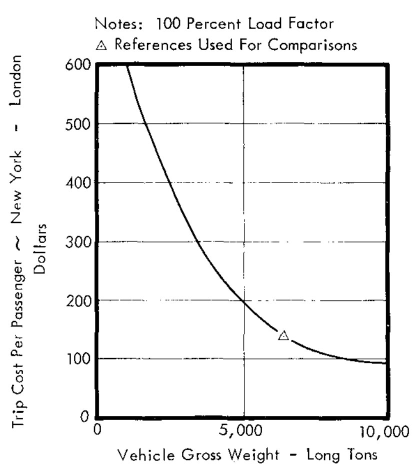

Fig. 10 Passenger trip costs for various sizes of nuclear SES.

Analysis

For the purpose of analyzing the economic characteristics of the nuclear surface effect ship, a specific operation was selected as the basis for comparison. The operation covers the carriage of passengers to and from New York to London. This operation was selected as it is the highest density route at ranges of 3000 miles or more. In addition, it also has, on the average, close to the worst sea conditions for routes in this range. The trip costs for this operation are shown by the triangle in Fig. 10.

The research, development, test, and evaluation (RDT&E) costs were not included in these costs analyses. It was assumed that the vehicle would be developed and paid for as a separate project. However, when evaluating the over-all ship cost, these RDT&E costs should be noted. For the basic configuration (6000 long tons), RDT&E costs were estimated to be $1,134,180,000, amounting to an approximate $27 (18%) increase in trip cost for the New York-London route.

Comparisons

The data provided by the computer program were used for making the following comparisons: 1) size, 2) powerplant system weight, 3) engine cost, 4) passenger weight allowances, 5) reduction of number of vehicles purchased, and 6) range and route. The results are plotted in Fig. 11.

Conclusions

The role of the nuclear powerplant in future SES applications may not be resolved until the evolutionary process from very small to very large ships has been adequately demonstrated by practical example. One thing is clear, however, and that is that conventional annular jet SES will always be payload/range limited until such power sources become available in the right size and cost range. Examination of the Breguet range formula clearly defines the inherent problem associated with chemically powered surface effect ships of the annular jet variety.

Accordingly, this study has been devoted to checking the feasibility and performance and cost characteristics of SES powered by nuclear sources. This study finds the following results.

1) At present traffic levels, North Atlantic service is the only area having sufficient traffic volume to support operation of large SES.

2) Large tension structures are not as efficient as truss-type structures for these ship sizes. Tubular "*K*" type structures can be developed for structure to gross weight ratios of approximately 33% for very large SES.

3) Nuclear powerplants suitable for SES are not immediately available but technology exists, as a result of the aircraft nuclear power programs, which could be applied to develop plants having specific weights of 20 lb/shp or less.

4) The total machinery weight of a nuclear powered ship, having lift and propulsion performance characteristics suitable for North Atlantic passenger service, approximates 48% of the gross weight.

5) Development of suitable powerplants is a prerequisite to the development of the large, long-range SES.

Other essential powerplant components are available with some development work required; the complexity of the prospective installations, however, indicates that more thorough study of the reliability of lightweight components should be undertaken in conjunction with more detailed design study of the installations.

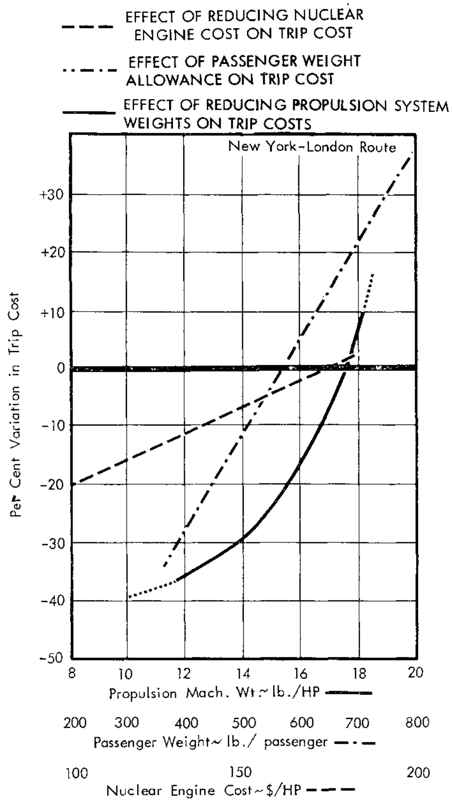

Fig. 11 Variation on trip cost.

6) The empty or light weight of a fully equipped surface effect ship, of design cushion pressure optimized for minimum structure and machinery weight, equals to 94% of the gross weight.

7) The optimum size of the SES may be determined once the gross weight is determined by tradeoff studies showing the influence of structural and machinery weight on payload.

8) The all-up weight of a nuclear-powered SES will be at least 3000 tons in order to be operationally feasible and to provide acceptable ship utilization factors.

9) Passenger costs decrease rapidly up to 6000 tons, but diminish between 6000 and 10,000 tons, and show only small advantages in ships larger than 10,000 tons.

10) A 6000-ton ship is marginally economical in comparison with either aircraft or ships in this service.

11) Reduction of the nuclear powerplant weight is more essential for economic feasibility than reduction of present costs.

12) The economics of large SES designs considered in the study are insensitive to operations heights established by sea conditions.

13) The operating costs of the nuclear SES would be 18% higher, were development costs borne by the operator.

References

[1] *U.S. Navy Climatological Atlas* (U.S. Government Printing Office, Washington, D.C.).

[2] U.S. Navy Oceanographic Office, unpublished information on sea conditions, data made available from the Sea and Swell Unit (1963).

[3] "Operational analysis of the use of air cushion vehicles in support of the Army's off-road logistic mission," Booz-Allen Applied Research Inc., U.S. Army TRECOM TR63–37 (August 1963).

[4] "The ground effect machine," Booz-Allen Applied Research Inc., Rept. BAARINC–TRO-60-6, U.S. Army Transportation Corps, Contract DA-44-177-TC-542 (TASK 6) (August 1960).

[5] "State-of-the-art report, the ground effect machine," Booz-Allen Applied Research Inc., Office of Naval Research, Contract 3695(00) (1962).

[6] "630A maritime nuclear steam generator scoping study," General Electric Co. Rept. GEMP 108, U.S. Atomic Energy Commission Contract AT(40–1-2847) (April 6, 1962).

[7] "630A maritime nuclear steam generator status report no. 1," General Electric Co. Rept. GEMP 231, U.S. Atomic Energy Commission Contract AT(40-1-2847) (September 12, 1963).

[8] "A study of GEM structures," Ryan Aeronautical Co. Progress Report (August 15, 1961).

[9] "The surface effect ship in the American Merchant Marine—Final report Part I," Booz-Allen Applied Research Inc., U.S. Maritime Administration Contract MA-3232 (February 1964).