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NUCLEAR PROPULSION FOR CONTAINER SHIPS

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INTRODUCTION

The launching of Japan's *Mutsu* and the recent successful commissioning and sea trials of Germany's *Otto Hahn* once again highlight the absence of the United Kingdom from the field of nuclear merchant shipping.

Over the past ten years, well publicized statements have been offered whenever nuclear propulsion for British merchant ships has been raised. "Nuclear propulsion will never be economic"—"look at *Savannah*!" "Nuclear propulsion is dangerous"—"Nuclear propulsion is ideal for high-powered vessels but we don't want to have the first one".

In addition to this a number of serious and penetrating investigations has been carried out with the aid of a wide and authoritative cross section of shipowners, shipbuilders and others, which, to date, have reported adversely on any immediate British involvement in merchant ship application of nuclear power.

It is generally accepted that the U.K. should not follow other countries in building nuclear powered merchant ships if such ships require to be heavily subsidized in both their capital and operating costs.

The Ministry of Technology has set up a Working Party to study the probable costs and benefits to be derived from developing a British reactor for ship propulsion and the results of their study are expected in the near future. Only if there is a clear economic advantage in operating nuclear ships, will a marine nuclear reactor building programme be undertaken, for the investment involved would not be justified unless firm prospects exist for a continuing and expanding market in the sale of such reactors.

Nuclear power should give the advantage of cheap fuel for marine purposes; cheap in terms of cost per effective horsepower, cheap in terms of saving in overall weight carried, and cheap in terms of freedom from restrictions on the itinerary or delays arising from eliminating the time and complication needed for taking on conventional bunkers.

Such economic and technical advantages cannot begin to outweigh the high capital cost of nuclear power unless large powers are required, and, just as important, the type of service intended for the ship also requires that the capital investment in the ship as a means of transport will be exploited at a high rate of utilization with the minimum time spent tied up in port.

The authors' studies, over a long period of time, have tended to follow the national trend in yielding very little except experience and confirmation of opinions already held. With the advent of wide scale containerization, the studies of the application of nuclear power were directed at the purpose-built containership as these vessels do require large installed shaft horsepower and must operate at high utilization factors.

In addition to the technical and commercial factors controlling the competitive economics there are some important questions which have been raised concerning the type of organization needed in the U.K. Shipbuilding Industry to ensure the fullest exploitation of British marine nuclear expertise.

In furtherance of this desirable target, a proposal has been made to provide design and project leadership in association with other shipbuilders who may be anxious to participate in the programme of nuclear container ship construction. It is worth remembering that if nuclear powered ships are built, they will represent a new era in British Merchant shipbuilding and will have to meet all their performance guarantees first time without cost escalation or delays in delivery. It has never been suggested that Britain should build a nuclear powered ship just to keep up with the Joneses. If, as a result of studies similar to those carried out by the authors, it becomes evident that an economic nuclear powered ship can be built, then Britain must choose the right time to begin planning the overall design/development/construction programme, because even taking full advantage of existing knowledge it will take five or six years to get the ship to sea and the world is moving fast.

PREVIOUS STUDIES

Over the past decade the authors' company has completed several studies on the application of nuclear power to merchant ships, and brief summaries of these studies are given below.

In 1959 a thorough design study was made on nuclear propelled tankers, the conclusion being that, on economic grounds, no justification could be found to go ahead with the project. It is interesting to note that in the conclusions of the report the following statement was made: "It is the current feeling, in shipping and shipbuilding circles, that the largest single screw tanker should be one of about 65 000 dwt with machinery developing a power of 20 000–22 000 shp. The conclusions of the study show the optimum nuclear vessel to be one of the same size as that for the largest conventional single screw vessel with a power roughly equal to that normally specified. Thus, no reason can be seen for specifying for the nuclear tanker a ship of any size or power other than the accepted upper limit for conventional single screw vessels."

Ten years later, 200 000 dwt tankers are commonplace; 300 000 ton vessels are in service and it is understood that tenders have recently been requested for the first 475 000 dwt tanker. There is also a study group under the auspices of the Ministry of Technology looking into the feasibility of the 500 000 to 1 000 000 ton tanker. Such has been the growth of the oil tanker in the past ten years.

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In 1963 the authors' company carried out a study on a nuclear powered fast cargo liner on the Far East route, in order that a comparison of the economics of the existing vessels and that of the proposed nuclear cargo vessel could be made. The following year a pilot study was made on a nuclear powered Q3. (Q3 being the code given to the design of the original *'Queens'* replacement). These three studies provided valuable data, but showed that, on economic grounds, there was no justification in proceeding further with these designs.

Until the advent of the container ship these types of vessel were the only non-naval users of relatively high horsepowers and with a high utilization time at sea.

In 1967, the authors' company completed its first study of the application of nuclear power to container ships. The report presented the first stage results of an assessment of the potential advantages of nuclear power when applied to advanced container ship designs similar to those being developed at that time by a number of world shipping interests for high speed container services. The conclusions of this report were based on a belief that the trend towards ships of higher power and utilization would show an increasing advantage to nuclear propulsion using the designs of reactors currently being developed. A subsequent study verified this belief.

Close collaboration was maintained with the U.K. Atomic Energy Authority during this initial study which utilized the nuclear propulsion unit on which much research and development work had already been done by the Authority as part of its small power reactor programme.

The sizes of the reactor chosen for the study were 113 MW (t) and 180 MW (t) equivalent to 40 000 shp and 60 000 shp.

Four sizes of ship were selected and an economic study was made of the itineraries on the North Atlantic, South African and Australian routes:

a) 3600 containers at 24 knots with 80 000 shp;
b) 2300 containers at 24 knots with 60 000 shp;
c) 1000 containers at 24 knots with 40 000 shp;
d) 1000 containers at 27·5 knots with 80 000 shp.

The vessels chosen were criticized by several authorities who could not foresee that the shaft horsepowers would ever be as high as those proposed in the report. In 1967 the highest power being installed in a container ship was 33 500 shp and this was then thought to be the upper limit for this type of vessel in the foreseeable future. Reference is made to this prediction later in the paper.

The authors' company felt justified, however, in developing one of the above vessels further and, in 1968, a techno-economic study was made on a refrigerated container vessel (see Fig. 1) for the New Zealand trade route. This vessel was the subject of two papers(1, 2). The result of this study was most encouraging and indicated that nuclear propelled vessels could show an economic advantage over conventional vessels operating on certain routes.

Assisted by the experience gained from these earlier studies, and at the suggestion of a British shipowner, a further extensive techno-economic study was made on two larger vessels:

a) 450 000 dwt tanker;
b) 1800 20 ft I.S.O. container ship.

The results of this study have been published.(3)

GROWTH OF THE CONTAINER SHIP

Although containers had been used in transportation for many years previously, the container concept as it is known today came from America, where in 1956, the Pan Atlantic Steamship Corporation carried an experimental cargo of containers on a platform built onto an unconverted T1 tanker sailing between New York and Houston. The containers were loaded and off-loaded by a shore crane. This experiment marked the birth of today's intermodal transportation system.

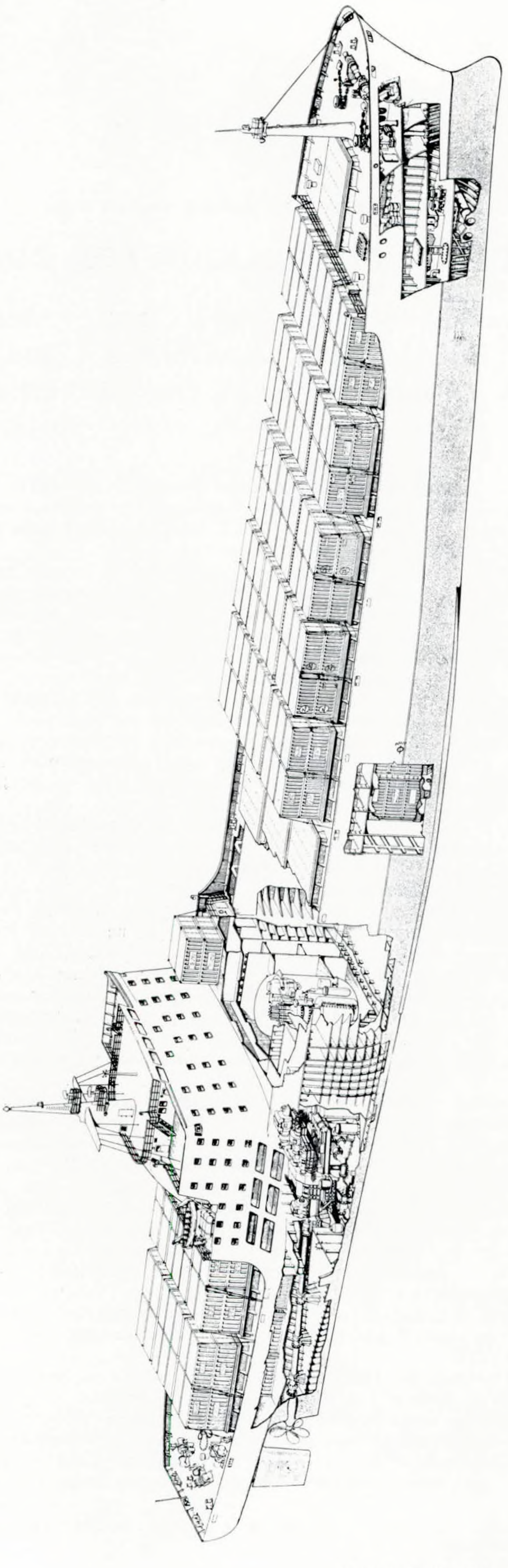


FIG. 1—*Vickers nuclear powered container ship*

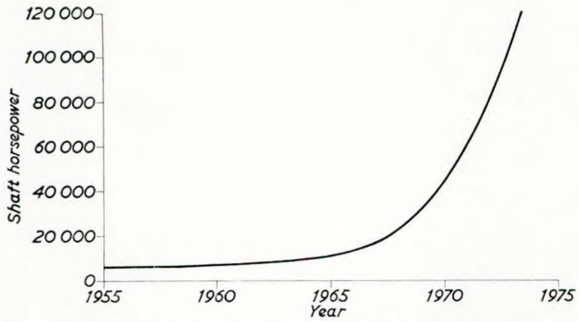


FIG 2—*Trends in container ship horsepower, ships in service or on order*

Fig. 2 shows the rate of increase in shaft horsepower, which reflects increase in size, in container ships; a gradual rise up to 1965 and then rapidly to 30 000–35 000 shp from 1965 to 1968. The OCL and ACT vessels now in service have shaft horsepower at this level. A full description of the OCL vessels is given in a previous paper.(4)

In 1968 the OCL and ACT vessels were thought to be the largest required in the foreseeable future and in the same year the Vickers 40 000 shp nuclear study was criticized by some shipowners on the grounds of its consideration of what was then thought of as an excessively high installed shaft horsepower.

Early in 1969, Sealand Service Inc. took the container ship operators by surprise by announcing their intention to build a fleet of 30 knot container ships with an installed power of 120 000 shp i.e. twice the size of the vessels at sea today.

After some speculation in various circles whether these ships would be built, Sealand confirmed their intention by placing orders with Continental yards for the vessels. This move had a far reaching effect forcing other operators to think in terms of ships of this size in order to remain competitive.

Table I shows some of the larger container vessels now on order. Three Scandinavian shipping companies have formed a consortium known as Scanservice. Their four vessels ordered in Autumn of 1969, are of particular interest as being the first large container ships to be powered by Diesel machinery. Each of these four vessels have triple screws, the power on the shafts being divided in the ratio of 9:12:9 providing a flexible arrangement for maintenance purposes.

These larger vessels set the trend for the third generation of purpose-built container ships and also represent the sizes of vessels to which the application of nuclear power is likely to show some economic advantage over conventional forms in the future.

TABLE I—TYPES OF CONTAINER VESSELS

Owner	No. of vessels	No. of containers	ISO container size	Service speed knots	S.H.P.	Machinery	Delivery date
Seatrain	2	770*	40 ft	25	60 000	Gas Turbine	1970–71
OCL	4	1800	20 ft	26	80 000	Turbine	1971–72
Hamburg Amerika	2	1800	20 ft	26	80 000	Turbine	1972
Ben Line	2	1800	20 ft	26	80 000	Turbine	1972
Scan-service	4	1700	20 ft	26	72 000	Diesel	1972
Sealand	8	1082	35–40 ft	30	120 000	Turbine	1972–73

* Approximate figure

The design of this vessel was governed by certain parameters:

1) the vessel was to carry 1800 20 ft I.S.O. containers;
2) the service speed was to be 27 knots;
3) power was to be limited to 60 000 shp on twin screws.

After applying the above limits to the vessel's physical characteristics, it was decided that suitable dimensions for the nuclear ship would be 850 ft b.p. × 105 ft × 30 ft moulded draught; a displacement of 42 700 tons on a block coefficient of 0·558. On these dimensions the cargo deadweight was limited to 20 400 tons which gave a gross weight per cent of 11·23 tons.

The results gained from the economic comparison made between the conventional and nuclear powered vessel for this particular study, were found to be most encouraging, and further reinforced the long-held belief that the application of nuclear power to certain types of vessel over specific routes could be economically justified.

LATEST DESIGN

As a result of the increase in the demand for large container ships of the size and power considered suitable for the successful application of nuclear power, it was decided to re-design the 1800 container × 27 knot container ship. The relative study has been published(3). The only limitation imposed on the new design was the fixing of the service speed to 27 knots and the number of containers to 1800 20 ft I.S.O. standard, each with a stowage rate of 17 tons gross per container. To carry the total cargo deadweight, it was necessary to increase the draught to 37 ft and the beam to 105·5 ft, these being considered as the maximum dimensions which would still allow the vessels to pass through the Panama Canal during all seasons, and under all conditions of loading. Furthermore, the itinerary was extended to enable the vessels to take full advantage of other trade routes over which it is expected there will be sufficient growth in demand for containership tonnage during the seventies to warrant their inclusion there. The modified itinerary is that shown by the chain dotted line in Fig. 3, which the authors call the Global Concept. The ports of call *en route* are Southampton, Cristobal (fuel only), Vancouver, Yokohama, Sydney, Las Palmas (fuel), and back to Southampton. This trade route would be complemented by a similar service in the opposite direction. A second itinerary was also considered as being feasible. This latter route was used as the basic itinerary for the economic comparisons which are included later in this paper. The main difference between this route and the Global Concept route is that, upon reaching Sydney the vessel returns to Southampton by way of the ports of call on its outward journey.

With the foregoing design restrictions in mind, and the selected itinerary to work from, a suitable set of design particulars for the nuclear vessel are as follows:

Length, o.a.	895·0 ft
Length, b.p.	850·0 ft
Beam, moulded	105·5 ft
Depth, moulded	80·0 ft
Draught, moulded	37·0 ft
Deadweight	31 400 tons
Displacement	59 300 tons
Service speed	27 knots
S.H.P. (MCR)	95 000/140 rev/min
Block coefficient	0·625

In order to be able to make meaningful economic comparison between nuclear and conventional vessels, a fleet of six nuclear powered container ships was assumed to be operating on the specified itinerary, capable of transporting a total of 4·9 million tons of containerized cargo per year. From this information a fleet of conventionally powered vessels was designed having sufficient size, speed, and being of sufficient number to ensure that the fleet's total transport capacity should be equal to, or greater than that of the nuclear alternative.

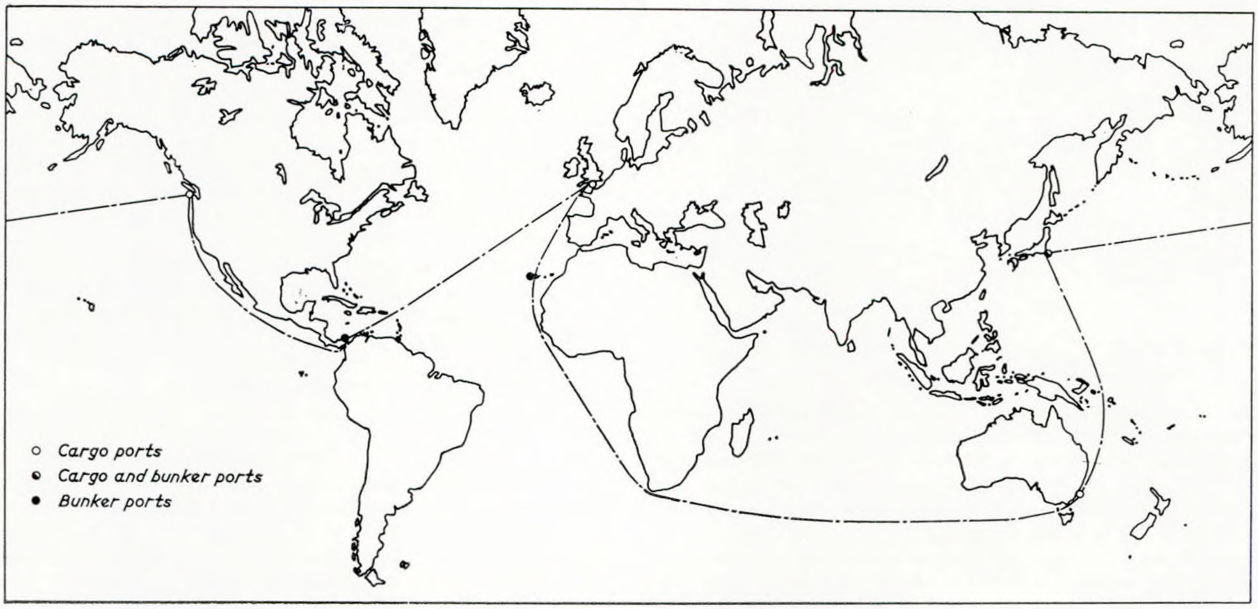


FIG. 3—*Trade route for world service*

The chosen *en-route* fuelling ports for the conventional vessels are Cristobal and Yokohama, where the present published prices per ton of oil fuel are 110/– and 116/8d, giving an average price of 113/– per ton of fuel used on the round trip journey. This latter unit fuel cost has been used in assessing the total operating cost of the conventional vessel.

In an effort to keep the number of conventional powered container ships to a minimum, and thus the total fleet capital and operating costs, it was decided to maximize the size of the individual vessels subject to the limitations imposed on them by transit through the Panama Canal. Therefore, as the dimensions of the nuclear vessel were already at the upper limits for safe transit through the canal, these were used as a starting point in the design of a 27 knot conventional vessel.

The preliminary weight build-up for the conventional vessel showed that, although its lightship weight was less than that determined for the nuclear vessel, it would be unable to carry the same cargo deadweight in the 1800 containers, even though the required volume for all these containers would obviously be available in the ship. This deficit is due to the substantial allocation of deadweight to oil fuel carried onboard. Hence, based on a gross container weight of 17 tons the conventional vessel will only be able to carry 1575 containers on the selected itinerary.

To increase the draught of the vessel thus giving the required displacement was not thought to be an acceptable solution to the deadweight problem, as the stated draught was already at the upper limit for safe transit through the Panama Canal. Also, an increase in block coefficient would have brought about an increase in the total power requirements for the service speed of 27 knots, with the results that both the vessel's capital and operating costs have been increased.

To comply with the requirements of the fleet concept and fulfil the transportation demand, it was found necessary to have a conventional fleet of seven vessels when using the 1575 container, 27 knot vessel having the same principal dimensions and displacement as the nuclear vessel.

In the present study no attempt has been made to optimize the physical characteristics of either the conventional or the nuclear vessels with respect to their individual operating economics.

It has already been stated in the paper that a figure of 4·9 million tons per annum has been taken as the total annual transport capacity available to the nuclear and conventional vessels. However, this figure is not meant to represent what is considered as the likely share of the container market which nuclear power could command in the future on the stated route, but is used merely to act as a reasonable starting point from which the authors have made their economic comparison.

As a basis for illustrating the probable comparative economics, it has been assumed that the first costs of the nuclear and conventional vessels are approximately 12·8 million pounds and 9·8 million pounds. In the build-up of the nuclear vessel's capital cost the reactor price assumed is for the 15th off and would, therefore, be considerably cheaper than any unsubsidized British prototype reactor built today. Therefore, with these capital costs the total cost for the fleet of six nuclear vessels would be approximately 76 million pounds and for a fleet of seven conventional vessels 65 million pounds.

THE ECONOMIC ANALYSIS

The profitability criterion used in the following economic assessment is the required shadow freight rate per ton of cargo necessary to give zero net present value (NPV) for a specified discount rate (RD); where zero NPV is coincident with the point where the after-tax rate of return on the proposed investment is equal to the specified discount rate.

Furthermore, the shadow freight rate determined as a result of the analysis is not the sum the shipowner would charge for shipping a particular amount of goods over a fixed route, but merely represents the part of the actual freight rate which is determined by the annual operating profit on the investment and the part of the total ship operating costs which has been considered in this analysis.

Basic assumptions

In the following analysis, account is taken of these basic assumptions:

a) both the nuclear and conventional vessels operate for 350 days per year;

b) the nuclear and conventional vessels have the same itinerary;

c) utilization of the available cargo deadweight is known and is equal for both alternatives. The utilization factor (cargo deadweight used/cargo deadweight available) assumed in the analysis is taken as being equal to unity;

d) operating costs per annum for both conventional and nuclear vessels are known, and in our analysis include the following items:
  - i) wages and subsistences;
  - ii) hull and machinery maintenance and repair;
  - iii) stores and supplies;
  - iv) insurance;
  - v) overheads and miscellaneous;
  - vi) port expenses;
  - vii) canal dues;
  - viii) fuel cost;
  - ix) nuclear accident indemnity;
  - x) nuclear port handling charges;

  Items (ix) and (x) apply only to nuclear vessels and the sum included for them in this analysis is £30 000.

e) the build time for both alternatives is the same;

f) the conventional vessels consume oil fuel at a rate of 420 tons per day with an associated average cost of 113/– per ton;

g) reactor core life is equal to 4·33 years per core;

h) operating life time for both alternatives is 21·65 years (equals 5 core lives);

j) the full power operating days for the conventional and nuclear vessels are approximately 283·1 days and 286·6 days;

k) nuclear vessel has 34 crew, conventional vessel 32.

Ground rules for the analysis

The discounted cash flow method used in the analysis has been formulated to take account of the following factors:

1) equity capital ...	20 per cent
2) debt capital ...	80 per cent
3) debt repayment period	8 years
4) debt interested rate	6 per cent
5) investment grant	20 per cent
6) investment grant lag in payment ...	1 year
7) corporation tax rate	45 per cent
8) corporation tax lag in payment ...	$1\frac{1}{2}$ years
9) depreciation tax allowance ...	allowed on the capital cost of the vessel less the investment grant, and is taken in full 1 year after the vessel enters service;

10) operating life time over which discounting is taken (21·65 years)

11) scrap value (zero)

THE ANALYSIS

The economic analysis is based on the discounted cash flow technique and it is an extension of work recently carried out and published;$^{(5)}$ it includes the addition of the effects on the freight rate of obtaining a low interest government loan. No account has been taken in this analysis of the effects on the shadow freight rate of the building time and the methods of capital payments to the shipyard.

Freight rate

The required shadow freight rate necessary to give adequate after tax return on capital after allowing for the various annual cash flows have been summarized here below.

RFR = (Required annual operating profit + Annual operating costs)/Cargo deadweight × utilization factor × number of round trips per year × number of cargo carrying voyages per round trip. (1)

In (1) the net annual cash flow for the level of profit required, represents A_{min} given by Goss on page 350 of reference (5). This is derived, ignoring the scrap value of the vessel, as follows:

NPV = PV of tax allowance on depreciation + PV investment grant − capital cost + PV of loan repayment + PV of net annual cash flow. (The effect of taxation is taken when applicable) (2)

Re-writing this equation in algebraic form we have:

$$\begin{aligned}\mathrm{NPV} = {} & C_O(1-G_N)t\,(1+R_D)^{-(l_t+1)} \\ & + C_O.G_N\,(1+R_D)^{-l_i} - C_O \\ & + \frac{X.C_o}{N}\Biggl\{N-\Biggl[\frac{1-(1+R_D)^{-N}}{R_D} + (1\text{-}t)\Biggl(\frac{1-(1+R_D)^{-N}}{R_D}\Biggl[R_L(N+1) \\ & - \frac{R_L}{R_D}(1+R_D)\Biggr] + \frac{N.R_L}{R_D}(1+R_D)^{-N}\Biggr)\Biggr]\Biggr\} + A \\ & \times \Biggl[1-t(1+R_D)^{-l_t}\Biggr]\Biggl[\frac{1-(1+R_D)^{-n}}{R_D}\Biggr]\end{aligned} \tag{3}$$

Equating (3) to zero and then re-arranging terms, we are able to find the minimum value of A, ie A_{min}.

$$\begin{aligned}A_{min} = C_o\Biggl[& 1-(1-G_N)t(1+R_D)^{-(l_t+1)} + G_N\,(1+R_D)^{-l_i} \\ & + \frac{X}{N}\Biggl\{N-\Biggl[\frac{1-(1+R_D)^{-N}}{R_D} + (1\text{-}t)\Biggl(\frac{1-(1+R_D)^{-N}}{R_D}\Biggl[R_L(N+1) \\ & - \frac{R_L}{R_D}(1+R_D)\Biggr] + \frac{N.R_L}{R_D}.(1+R_D)^{-N}\Biggr)\Biggr]\Biggr\}\Biggr] \Big/ \\ & \Biggl(\Biggl[1-t(1+R_D)^{-l_t}\Biggr]\frac{1-(1+R_D)^{-n}}{R_D}\Biggr)\end{aligned} \tag{4}$$

Having found A_{min} from (4) we can now use this value in equation (1) in order to calculate the Required Shadow Freight Rate.

$$\text{i.e. RFR} = \frac{A_{min} + \text{Annual Operating Costs}}{\mathrm{Dwt} \times U_F \times \mathrm{RT/Yr} \times K}$$

Where C_o = Capital cost
G_N = Investment grant as a fraction of the capital cost
X = Loan amount as fraction of capital cost
N = Loan repayment period
R_L = Loan interest rate per annum
R_D = Discount rate
t = Tax rate (fraction)
l_t = Lag in payment of tax
l_i = Lag in payment of investment grant
n = Life of vessel
U_F = Utilisation factor
RT/Yr = Number of round trips per year
A = Net annual cash flow
Dwt = Cargo deadweight
K = Number of cargo carrying voyages per round trip

The annual operating costs, excluding the cost of fuel, for the nuclear and conventional container ships, used by the authors in their analysis, are 0·547 million pounds and 0·454 million pounds respectively. The fuel costs used for both types of vessel are shown in Fig. 4 where the effects of the discount rate on the capital intensity of nuclear fuel cost can be seen.

Fig. 5 shows the results of the economic comparisons obtained by using the analysis method given earlier. In this figure the cross-over point of the two upper lines illustrate that, only when discount rates in excess of 9 per cent are reached does the conventional vessel show any real advantage over the nuclear alternative. Furthermore, on the assumption that future advances in nuclear fuel technology and fuel cell

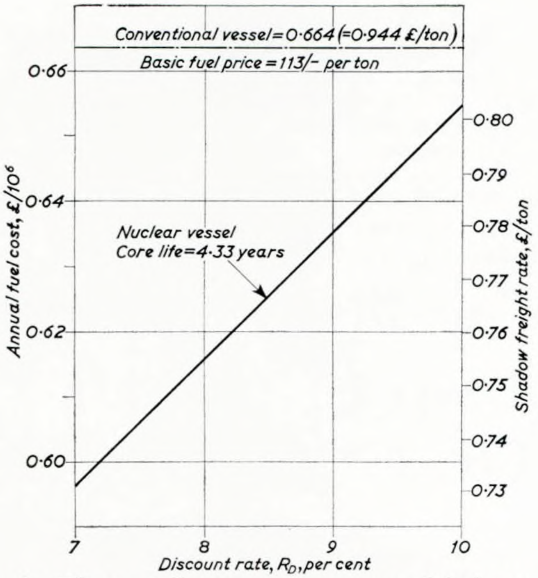


FIG. 4—*Effects of discount rates on annual fuel cost and associated part of the shadow freight rate*

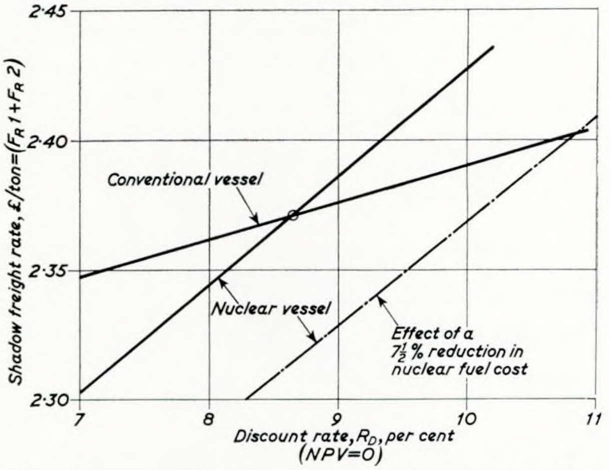


FIG. 5—*Shadow freight rate comparison between conventional and nuclear powered container ships*

manufacturing techniques will bring about a 7½ per cent reduction in the existing nuclear fuel costs, then a further reduction in the Shadow Freight Rate of the nuclear vessel is possible.

The effect of this reduction on the rate is shown by the lower chain dotted line in Fig. 5, where the cross-over point at which the conventional vessel begins to show some advantage over its nuclear alternative is at about the 11 per cent discount level, which would be considered, for most shipping ventures, to be an extremely fair return on invested capital. (These high rates of discount at the cross-over points given in Fig. 5 are liable to vary depending on the various cost assumptions made in the economic analysis.)

If it should be considered that the cross-over points shown are somewhat high, the facility has been provided in the paper whereby those who are interested in the application of nuclear power to merchant shipping can make their own assessments as to the validity of the authors' statements.

To be able to carry out this assessment for differing capital and operating costs than those used in the present study the authors have supplied Figs. 6 and 7 which show the effects of those costs on the Shadow Freight Rate over a range of discount values. Furthermore,, Fig. 8 shows the effects on this rate due to an increase or reduction in the price of fuel oil. To clarify the previous remarks an example is given: a conventional vessel—the authors have used the capital cost stated earlier in the paper, then from Fig. 6 at 7 per cent discount rate they have obtained a part shadow Freight Rate (FR1) of approximately £0·76/ton, determined by the required level of operating profit, and using the total operating cost, again already stated in the paper from Fig. 7 they have obtained the part of the Shadow Freight Rate (FR2) of approximately £1·59/ton which is determined by this cost. Adding these two part Freight Rates together (FR1 + FR2) this results in the Shadow Freight Rate of approximately

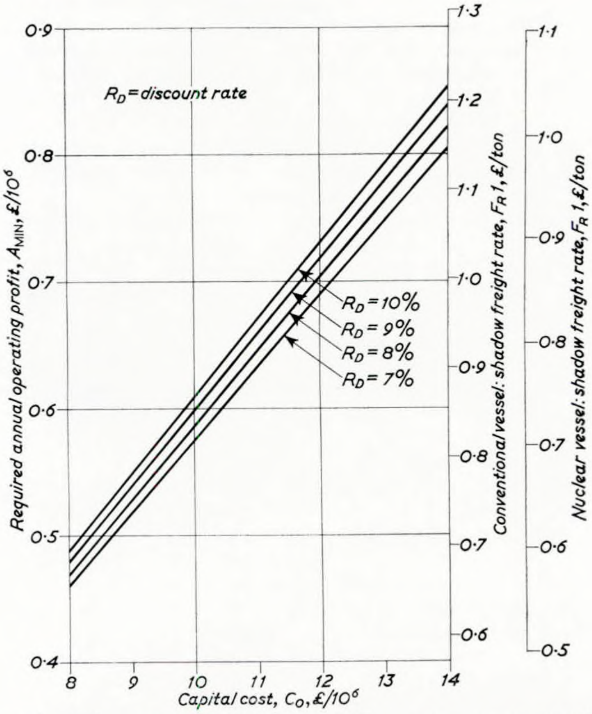


FIG. 6—*Effect of capital cost and discount rate on required annual operating profit and shadow freight rate (f_r1)*

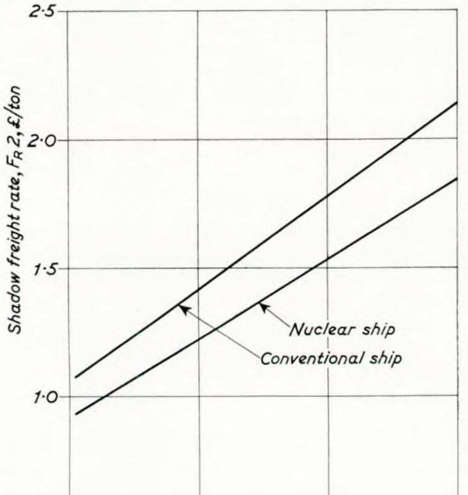


FIG. 7—*The part of the shadow freight rate affected by the total operating cost/annum for both conventional and nuclear vessels*

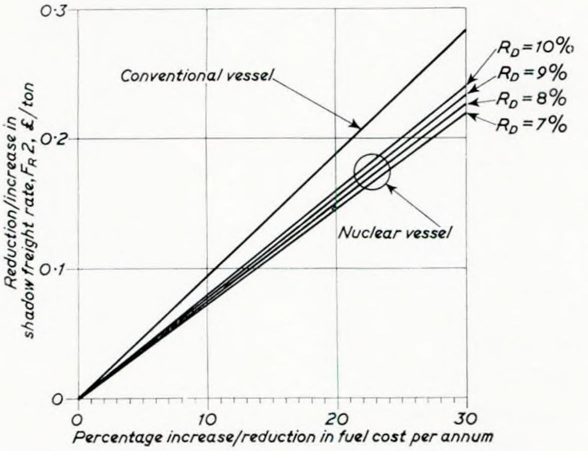


FIG. 8—*Change in shadow freight rate (f,2) due to a percentage increase or reduction to the annual fuel cost*

£2·35/ton, equivalent to that given in Fig. 5 for the conventional vessel at 7 per cent discount rate.

It has already been stated earlier in the paper that, should an improvement of 7½ per cent reduction in nuclear fuel costs come about then, there would be an associated reduction in the Shadow Freight Rate for the nuclear vessel. Then, from Fig. 8 on a 7 per cent discount rate at this reduction in fuel cost the approximate reduction in the Shadow Freight Rate can be read off, which is about £0·056 per ton of cargo. This should correspond with the Shadow Freight Rate difference between the full and chain dotted lines shown in Fig. 5 for the nuclear vessel.

THE NUCLEAR CONTAINER SHIP

The insurance companies are becoming increasingly concerned with the number of claims that they have to meet due to damage to deck containers, their contents, and, not infrequently, to the complete loss of the container, due to the vulnerability of deck containers. Although the number of claims on cargo damage has fallen, the sums involved have risen sharply with containerization, and for this reason, the insurance companies are giving consideration to a general rise in premiums for all containerized cargoes.

An innovation has been introduced into the authors' company's latest design whereby all the containers are stowed under deck. With the proposed arrangement, the shipowners could give a guarantee that all containers would be carried below deck with the possibility that the increased premium would not apply. The fact that the hatch covers are no longer load bearing units compensates in part for the increase in steelweight due to the trunk.

The basic design and construction of the vessel, except in way of the reactor compartment, is in accordance with modern container ship practice, the profile and outline section of the vessel are illustrated in Fig. 9.

Fig. 9 shows:

a) the trunk which runs the full length of the cargo holds; this trunk houses the containers normally held on deck;
b) the mooring deck aft which has been sited on the main deck;
c) the arrangement of container stowage can be seen in hold 3 on the sectional profile, the upper four containers are supported on a raft from the container guides. Forward of No. 1 hold, there is a small general cargo hold; there are no cargo handling cranes apart from two stores cranes abaft the superstructure;
d) forward and aft of the container holds there are trimming tanks; heeling and ballast tanks are fitted in the side double hull. Passive-type tank stabilizers are fitted forward and aft of hold No. 3. These extend across the beam of the ship and can be used together or singly depending on the loading of the vessel.

Accommodation is situated two-thirds aft, and, due to the high utilization of the vessel is fitted out to the highest standard. A swimming pool is sited on the main deck aft.

Fig. 10 shows the body plan and endings, which have been designed with the co-operation of the Vickers Experiment Tank at St. Albans. The salient features of the hull are the absence of sheer forward, the pronounced flair and knuckle at the forward end and a transom stern which has been adopted to provide a useful mooring deck aft and to keep the overall length of the vessel to a minimum. A single semi-balanced rudder has been adopted; from experience, this installation has been proved to be the best for this type of hull. A transverse propulsion unit has been incorporated at the fore end of the vessel to aid manoeuvrability in confined waterways.

Shaft horsepower estimates have been made from data available within the Vickers Shipbuilding Group. Fig. 11 shows a curve of service shaft horsepower. Two six bladed 21·5 ft diameter propellers have been selected in view of the high installed shaft horsepower.

The ship would be built in accordance with the highest

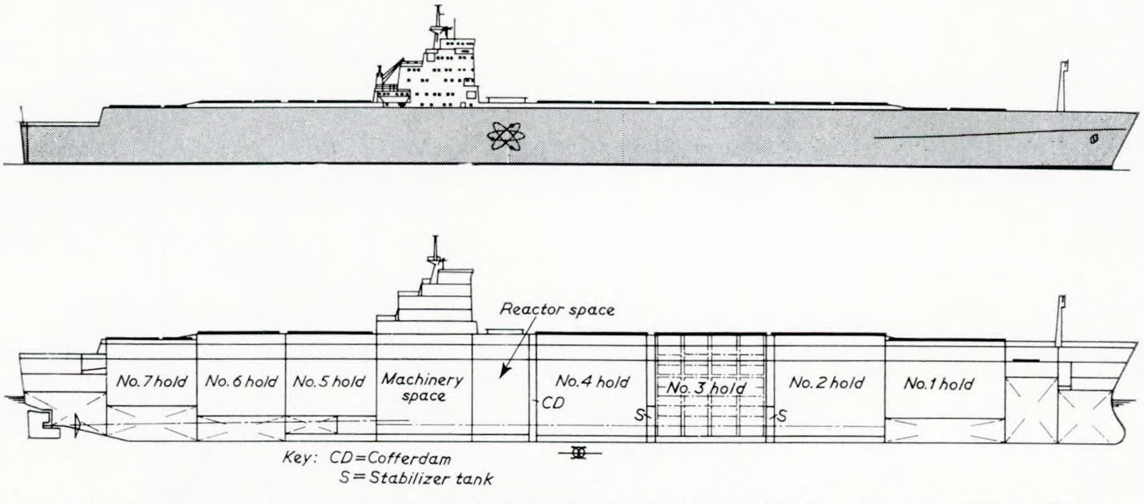


FIG. 9—*Nuclear powered container ship 1800 20 feet × 8 feet × 8 ft I.S.O. containers, 850 ft l.b.p. × 105·5 ft beam × 37 ft draught*

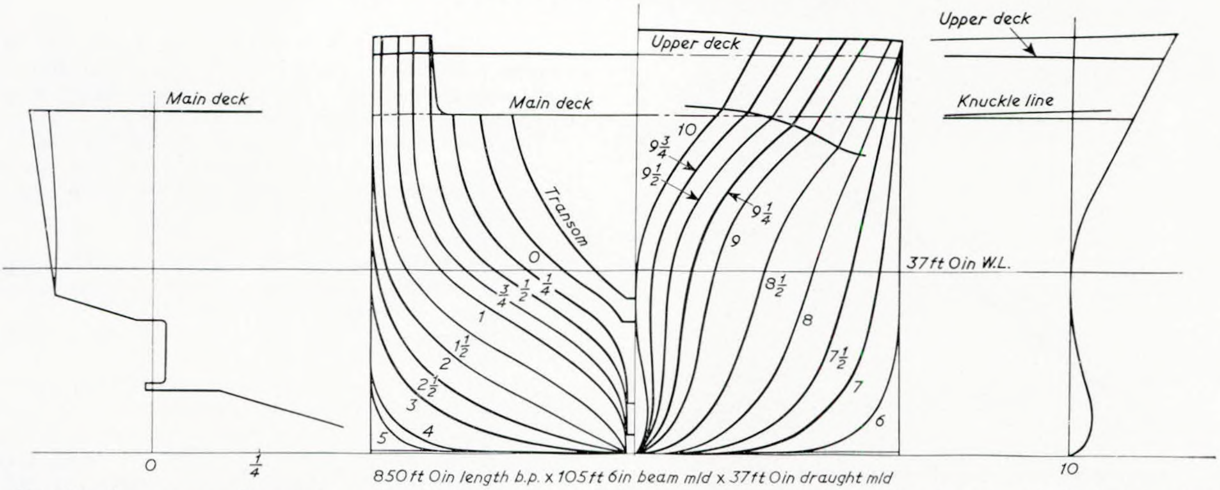


FIG. 10—*Nuclear powered container ship body plan and endings, 850 ft l.b.p., 105 ft 6 in beam mld, 37 ft draught mld*

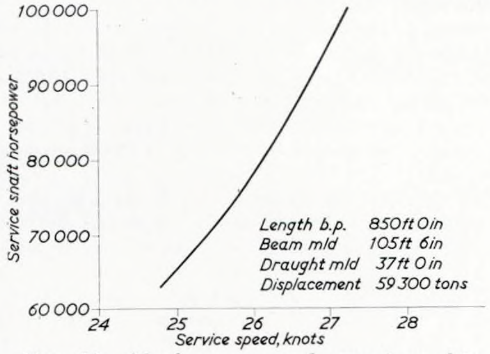


FIG. 11—*Nuclear powered container ship*

requirements of Lloyds Register, British BoT, the 1960 International Convention for Safety of Life at Sea, and the appropriate Canal and Port Authority regulations.

Apart from the requirements specified in Lloyds Provisional Rules for Nuclear Ships, the nuclear vessel would be of similar construction to a conventional vessel. It is necessary, however, to protect the containment compartment over its length plus a marginal length at each end.

Collision barrier

The collision barrier, which forms the containment protection, has been described in earlier papers (1, 2, 3, 4, 5). Fig. 12 shows the method of protection.

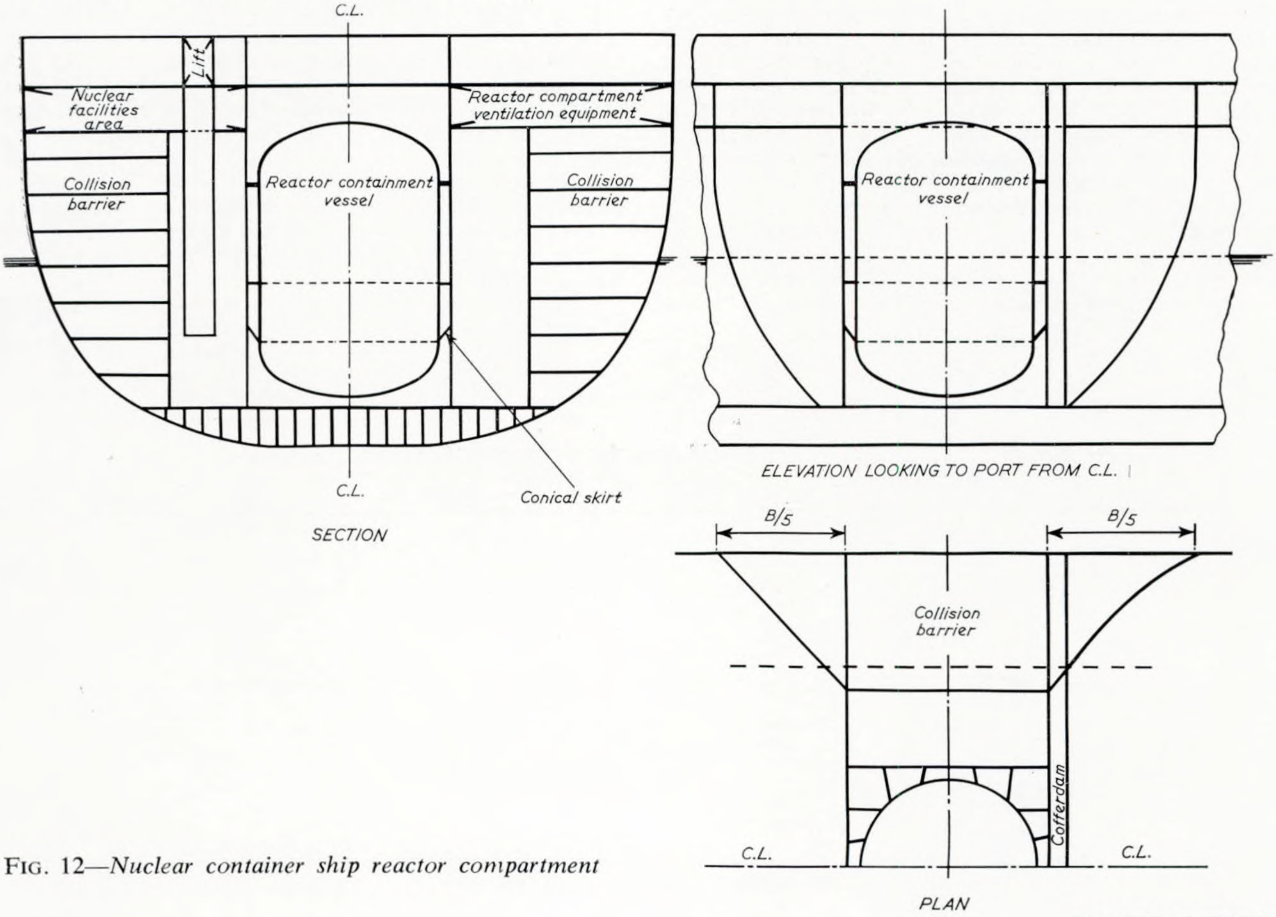


FIG. 12—*Nuclear container ship reactor compartment*

REACTOR CONTAINMENT AND SUPPORT

The containment structure is the vessel or ship compartment containing the reactor and primary circuit, and it is necessary, in the pressurized water reactor being considered in this study, to use a separate pressure vessel for this containment structure, due to the calculated maximum accident pressure being higher than could be sustained by the boundary structure of a ship's compartment, unless it was constructed with impractical scantlings.

In their calculations for the accident pressure, the authors assume a simultaneous release of the contents of the reactor pressure vessel into the containment volume, i.e. the primary circuit and some of its secondary circuit, together with any consequential exothermic chemical reaction. As an example, the containment structure of the vessels described later in this paper are to be capable of withstanding a pressure and resultant temperature in the order of 400 lb/in^2 at 450°F (240°C) without any form of pressure suppression.

As a further requirement the containment structure must not be subjected, as far as possible, to hull stresses, and it should be supported in such a way that severe local damage may be sustained by the ship's bottom, without prejudicing the support of the reactor and its relative position in the ship.

To meet these requirements it is proposed to suspend the containment vessel by means of a conical skirt, as illustrated in Fig. 12. This particular design of containment support structure has been subject to a patent by the authors' company.

The reactor will be supported within the containment vessel by means of a similar support system.

In other designs, *Savannah, Otto Hahn* and *Mutsu,* the containment is supported from the double bottom which is specially reinforced to take the load. There are two disadvantages in the double bottom means of support, i.e., firstly, it is difficult to isolate the containment support from the bending of the hull unless some form of sliding support is used and, secondly, it is necessary to mount the containment on a bridge structure above the bottom of the vessel to comply with Lloyd's Rules in respect of the vessel grounding with the bottom plating being damaged. The effect of the local hull stiffening to take the additional weight gives rise to high shear forces in way of the reactor compartment. If the ship is considered as a beam, concentrated loads are most economically introduced into the structure via transverse bulkheads and are transmitted thence to the sides of the ship as shear forces, this method has been adopted in the proposed scheme. Support by means of the conical skirt from the bulkheads not only removes the points of support of the containment vessel from the immediate vicinity of regions liable to grounding or collision damage, but also takes the load primarily by direct or membrane stresses resulting in a structure of minimum weight of a given load.

The containment leak rate must be kept below a maximum allowable limit determined by the classification society. Lloyds Provisional Rules quote a target figure of 1 per cent in 24 hours of the free volume of gaseous content in the containment vessel with all machinery installed.

NUCLEAR REACTOR AND PROPULSION MACHINERY

Nuclear reactors

There have been a number of proposals from time to time for nuclear reactors for ship propulsion. These have varied for example from the direct application of the land-based natural uranium gas-cooled graphite-moderated reactor, as used for power generation, through pressurized water, boiling water, organic and heavy water reactors (6, 7, 8, 9, 10).

The situation was summarized(11) in 1964 and, following its conclusions, the U.K.A.E.A. has developed its present proposals for the Integral Burnable Poison Pressurized Water Reactor (BPWR).

The choice of the Pressurized Water Reactor is influenced by the mass of experience available; around 70 per cent of land based reactors at present operational are either the natural uranium gas-graphite type or light water-cooled and/or water moderated. The first of these is, however, too bulky for shipboard use. There are two principal sub-divisions of the light water system, i.e., boiling and pressurized water. Pressurized water reactors are comparatively insensitive to inertia forces when compared with the boiling water type, and are inherently stable. Their reaction to temperature increase is such that the reactor tends towards a state of neutron balance similar to the initial state. This indicated probable suitability of the pressurized water reactor is corroborated by its universal choice for use in naval vessels. A recent count(12) showed 160 of these reactors to be in service, and they are used in all four of the nuclear powered non-naval vessels i.e., *Lenin, Savannah, Otto Hahn* and *Mutsu*. The Pressurized Water Reactor is compact and has a high power density. It is responsive to change in power and has a comparatively simple materials technology. The capital costs are relatively low although the absorption of neutrons by the hydrogen in the water is high, and enriched fuel is therefore required.

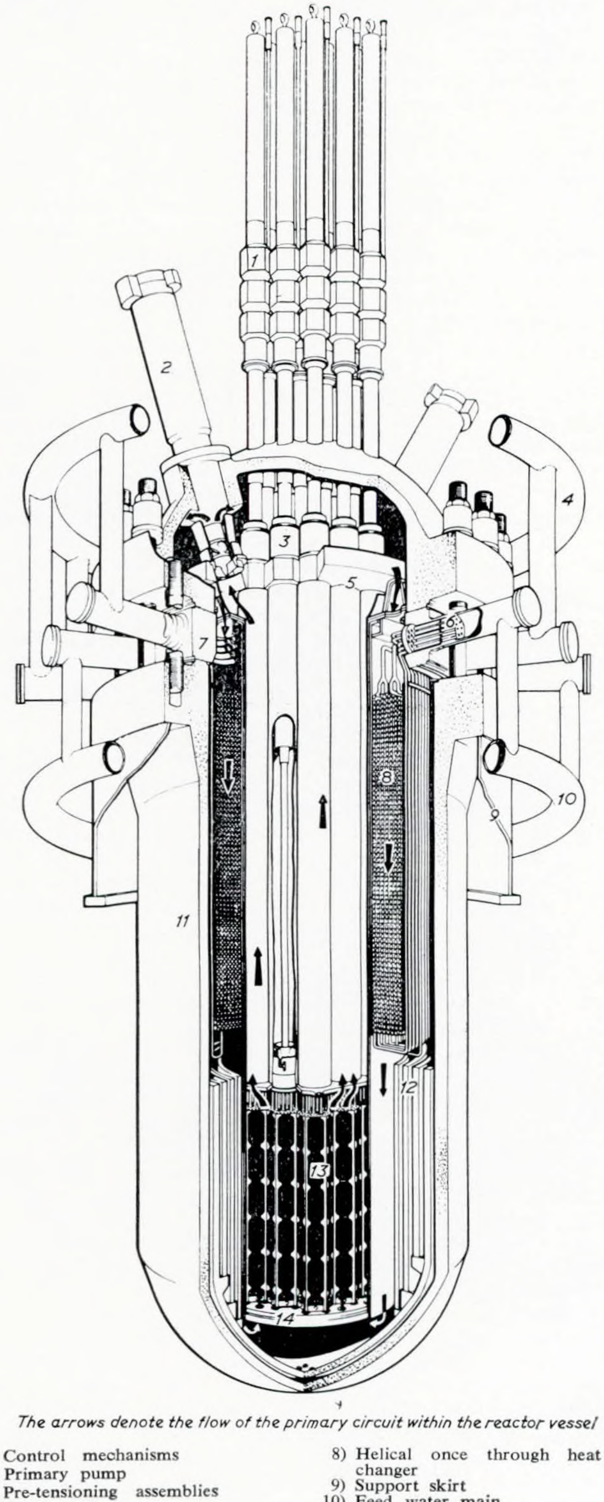
The design of integral PWR that is proposed has been developed by the U.K.A.E.A. to cover the power range up to a heat output of approximately 320 MW. The integral arrangement requires an increase in the size of pressure vessel to accommodate the additional equipment, but the elimination of separate heat exchangers and primary circuit pipework, and possibly also the separate pressurized vessel, i.e. the *Otto Hahn* reactor(13), results in the following advantages:

a) chance of loss of primary coolant by failure of large bore high pressure pipework is eliminated as there is only small bore pipework;
b) should a leak develop, there is increased time available to take corrective action before the core is uncovered because the reactor vessel contains more coolant;
c) heat removal by natural circulation is facilitated by mounting the annular boiler, or heat exchanger, higher than the core. Natural circulation will be adequate for the removal of decay heat;
d) in the U.K.A.E.A. design the risk of failure of the reactor pressure vessel is reduced since the penetrations for steam, feed and other services are taken through a collar between the head and barrel flanges of the pressure vessel, resulting in simpler design and fabrication;
e) radiation damage to the pressure vessel walls will be less as, due to the larger size of vessel, they are further from the core;
f) the whole primary circuit can be fabricated, tested and assembled under clean workshop conditions and, provided sufficient craneage is available, installed as a complete unit, requiring only auxiliary connexions.

There are, however, some disadvantages. Since the U.K.A.E.A. design of integral reactor vessel lid carries the primary pumps in addition to the usual control rod mechanisms, its design and fabrication is more complicated than for dispersed types. It is possible, however, to mount the pumps on the body of the reactor vessel. The larger size of pressure vessel results in heavier fabrications for a given pressure. Furthermore, space above the core inside the boiler ring is largely wasted and the increased height of the vessel requires longer operating shafts to the control rods with possible vibration problems. There is more stored energy to be removed in the event of loss of coolant. These disadvantages tend to limit the upper size of integral reactors to a thermal power of about 320 MW when steel reactor pressure vessels are used.

U.K.A.E.A. BURNABLE POISON PRESSURIZED WATER REACTOR

Figs 13 and 14 show the reactor pressure vessel, containing the primary circuit i.e., core, heat exchanger and pumps. It is installed within a cylindrical containment shell located within the reactor compartment. The reactor vessel is supported on a short skirt welded to the vessel barrel flange. Between the lid and barrel flanges is a collar through which pass the steam and feed pipework and other water and vent connexions. The control mechanisms are connected to the control rods in the reactor core. Long bolts passing through the flanges clamp the lid to the barrel.



The arrows denote the flow of the primary circuit within the reactor vessel

1) Control mechanisms
2) Primary pump
3) Pre-tensioning assemblies
4) Steam main
5) Core support structure
6) Tube plate
7) Heat exchanger collar
8) Helical once through heat exchanger
9) Support skirt
10) Feed water main
11) Reactor vessel
12) Thermal shields
13) Fuel assemblies
14) Core support grid

FIG. 13—*The marine b.p.w.r.*

The core consists of a number of hexagonal assemblies. Each of these contains the requisite number of fuel pins and burnable poison pins. The pins comprise sealed hollow tubes of stainless steel or zircalloy containing the uranium oxide pellets (fuel) or the boron zircalloy pellets (burnable poison). Surrounding the core are the thermal shields. The annular once-through heat exchanger is located above the core with the control mechanism extensions passing through its centre. The heat exchanger has twelve groups of coils in parallel, these are grouped to form four separate boilers which can be independently controlled.

The main reactor parameters are as follows:

1) normal primary pressure 145 b (2100 lb/in^2 abs)
2) primary design pressure 173 b (2500 lb/in^2 abs)
3) secondary steam pressure 41·4 b (600 lb/in^2 abs)
4) superheat 50°C (90°F)
5) feed water temperature 165°C (330°F)

Heat generated in the reactor core is transferred to the boilers by means of the pressurized water circulated by the primary pumps. The direction of flow is shown by the arrows. Hot water from the core rises up the centre of the boiler and is circulated downwards over the boiler tubes; the cooled water then re-enters the core at the bottom, thus completing the primary circuit.

Layout

Fig. 15 shows the integral reactor and its auxiliaries situated forward of the machinery spaces on its own compartment which extends from the double bottom through the main deck to the deckhouse above. In the top of the deckhouse there is an access hatch used during re-fuelling and during installation. A cofferdam isolates the reactor compartment from the forward cargo spaces. Collision barriers are situated between the reactor compartment and the ship's side. Aft of the reactor compartment is the engine room containing the propulsion machinery and the auxiliary machinery and services. The control room is located above and at the forward end of the machinery space.

Propulsion machinery

Turbine stop valve steam conditions are 40·4 b (585 lb/in^2 abs) 299°C (570°F). The main machinery consists of two sets of two cylinder cross-compound steam turbines. Each set drives a single fixed pitch propeller via double helical, single tandem, double reduction, articulated gearing. The steam conditions are lower than those in current use on conventional ships; however, there is ample recent experience of turbine design for these conditions already in marine and land based plant. Low stop valve steam temperature has some advantage in that it enables working to higher stresses whilst maintaining the usual safety factors. In the L.P. cylinder, there is an integral centrifugal-type water separator which maintains the steam wetness at a tolerable level in the later stages of the L.P. turbine. The steam at the exhaust end of the turbine is, however, wetter than in current conventional practice. The astern turbine is at the forward end of the L.P. turbine. Each turbine cylinder drives a single primary pinion through membrane-type flexible couplings. Slung beneath the L.P. turbine is the condenser which also accepts the discharge from the turbo alternators. Scoop circulation is employed and when the speed of the vessel falls to a predetermined value, or during manoeuvring, the auxiliary circulating pump is automatically started.

The proposed ship having only a single reactor is required to carry an emergency 'get you home' propulsion system. The possible alternatives are an auxiliary oil-fired boiler or Diesel-electrical drive. The latter is selected as it is more compact and economic. The emergency electric propulsion motor drives the H.P. pinion on the gearing.

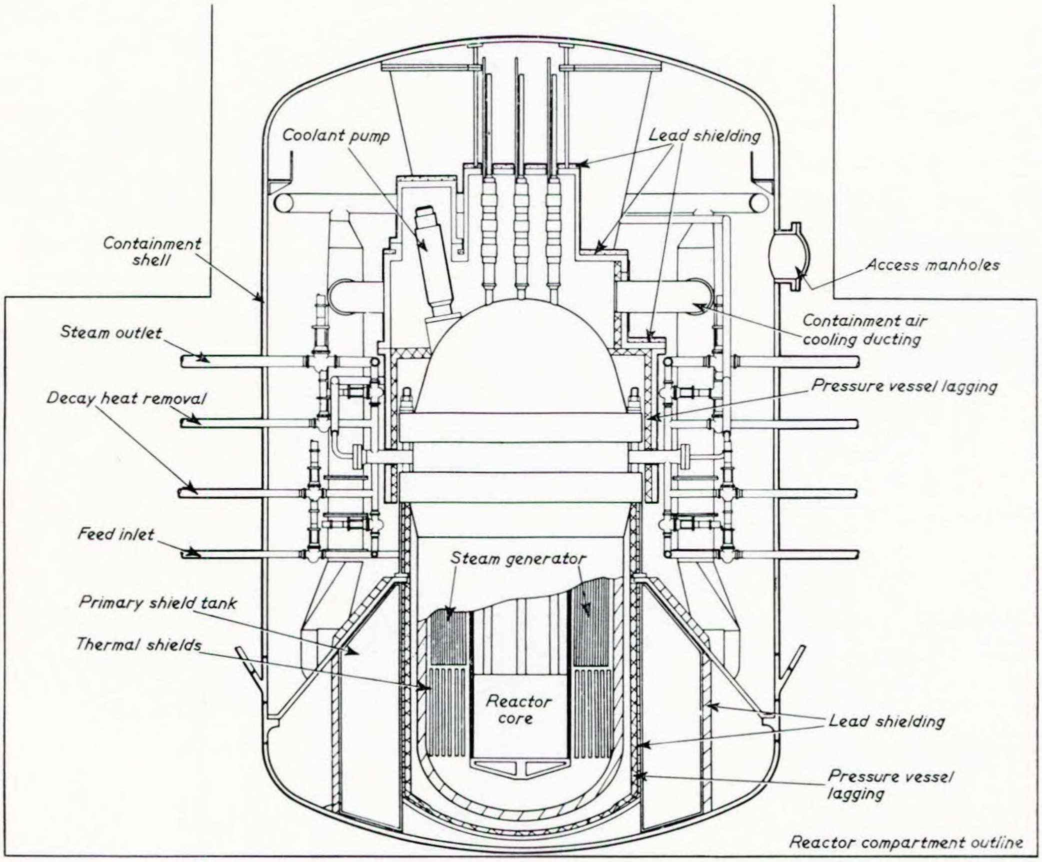


FIG. 14—*Containment arrangement*

Feed system

The once-through boiler requires very high purity feed as there are no steam drums and blow down is not possible. The feed system is therefore designed to eliminate impurities as far as possible, the principal unusual feature being the installation of a water treatment plant in the main feed line.

Fig. 16 shows a feed system including a plant of the powdered resin type. The replaceable candles or cartridges are designed to last a complete voyage; they can be replaced during cargo handling. The water treatment plant is situated immediately before the L.P. heater due to temperature limitations although recent developments with the powdered resin type of bed may permit it to be placed further downstream in regions of higher temperature. Drains are arranged as far as possible, to discharge into the feed system upstream of the resin bed. A second, smaller resin bed is situated in the make-up water line from the evaporating and distilling plant. In order to help maintain the purity of the feed and also to protect the powdered resin bed from chlorides, even a small quantity of which could saturate the bed, double tube plate condensers are fitted.

Fig. 17 illustrates a second feature of the steam and feed systems which is the combined start up circuit and dump facility.

REACTOR SERVICES

The reactor auxiliary systems are mainly located in the reactor compartment outside the containment. The principal exception to this is the pressurizing system, which is located within the containment. The auxiliaries provide essential support to the reactor to enable it to function reliably and correctly. From the operator's point of view they are probably of greater interest than the reactor itself. The principal auxiliaries are:

a) pressurizing system;
b) primary pressure relief circuit;
c) purification circuit;
d) ventilation system;
e) shield water system;
f) auxiliary cooling system;
g) emergency decay heat removal system;
h) reactor services;
i) sampling system;
j) active waste system;
k) safety injection system.

Fig. 18 shows a simplified block flow diagram of the reactor plant support systems and their interconnexion.

I) *Pressurizer*

The surge line of the pressurizer is connected to the inlet of the reactor system pumps. The spray line runs from near the coolant pump outlets. Effectively the system is an electrode boiler and has two principal functions:

i) to maintain sufficient overpressure on the primary water to prevent bulk boiling in the system;
ii) to absorb primary system volume changes during power demand changes without excessive variation in the system pressure or exceeding the plant design pressure.

II) *Primary pressure relief circuit*

Two sets of power-operated relief valves and coded safety valves are provided on the pressurizer to protect against large pressure surges and failure of the pressurizer spray system to operate. The relief valves operate automatically on reception of a pressure signal and operate at a lower setting than the coded valves. The relief valve thus reduces the operating frequency

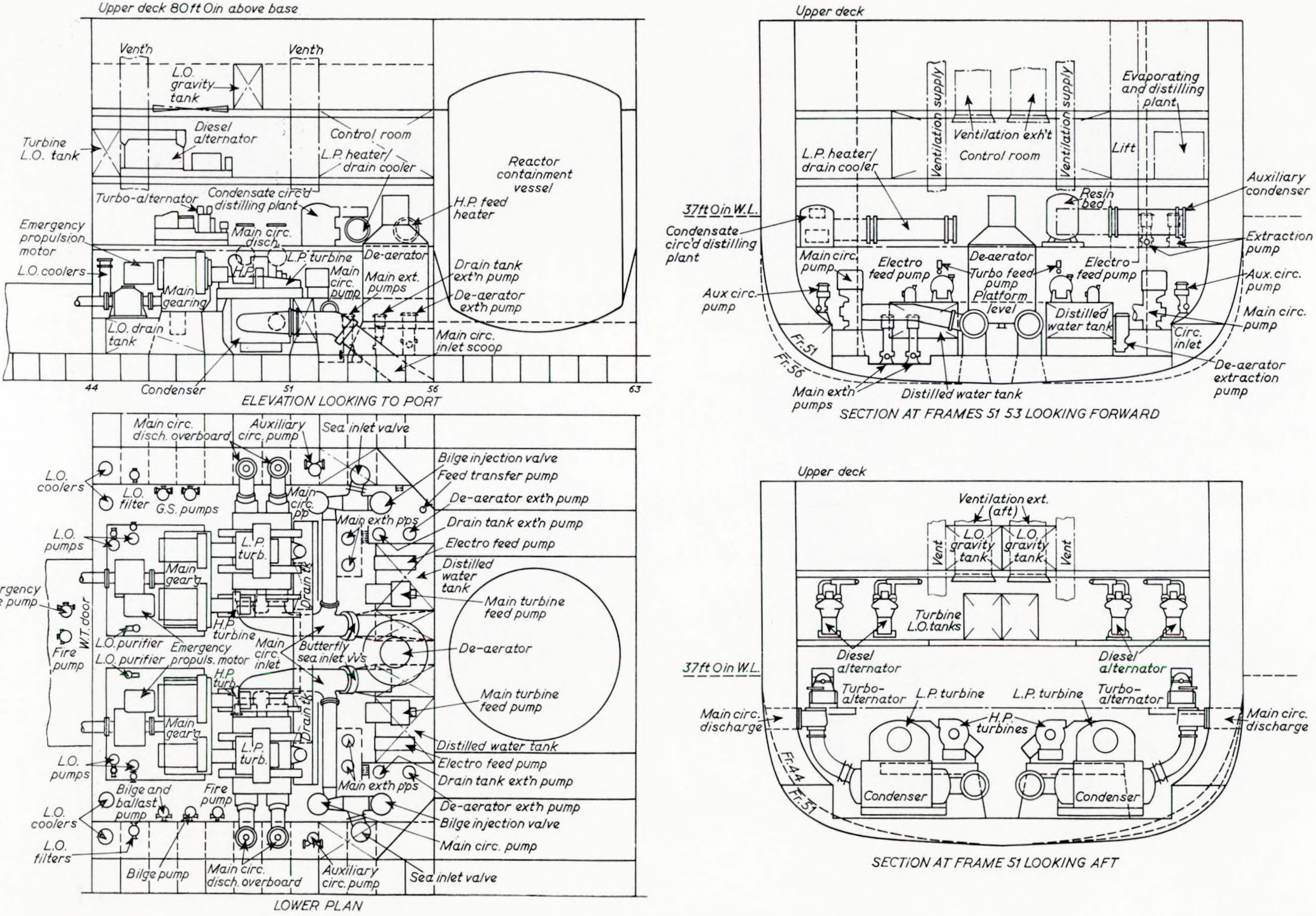
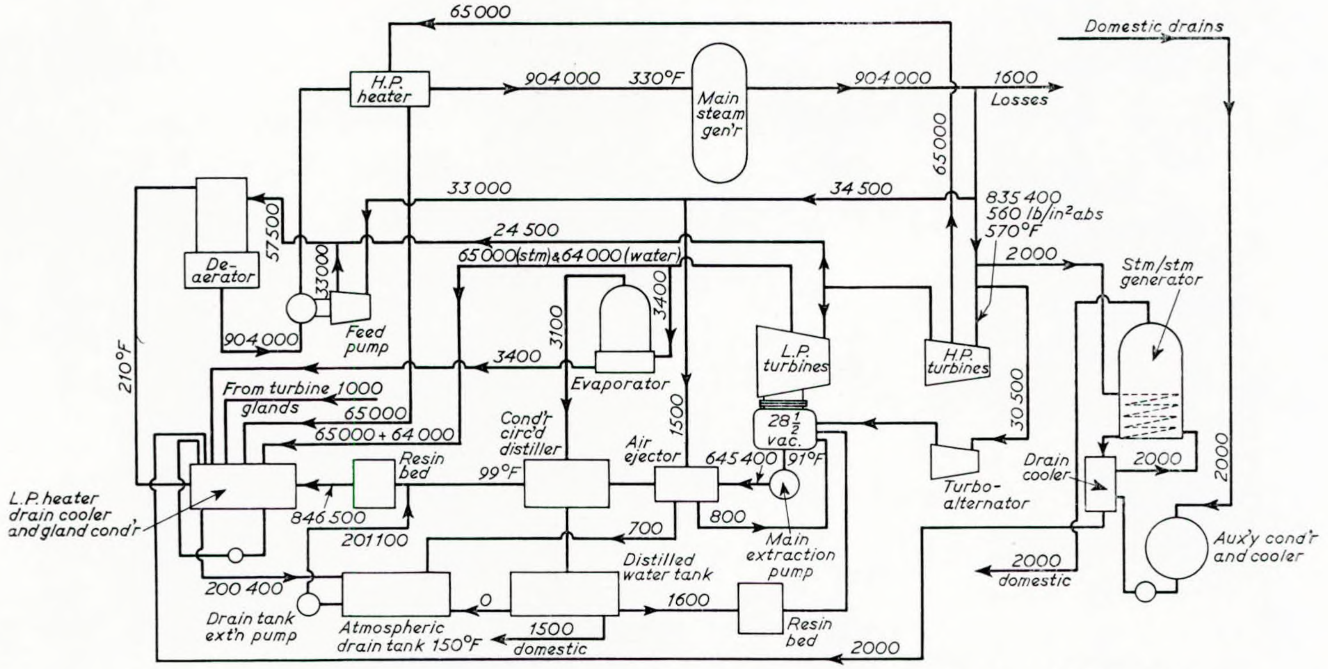


FIG. 15—*Nuclear powered container ship machinery arrangement*



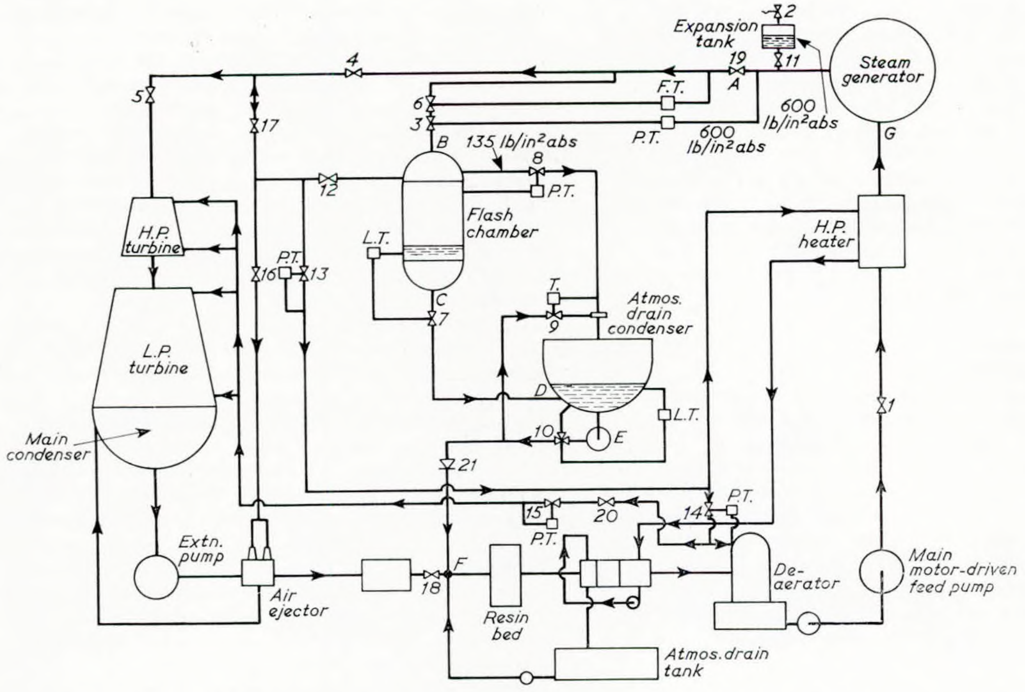
Flows are in lb/h. N.B.S.R., 7·63 lb/shp h. Alternator loading, 2600 kW. Evaporator loading, 33 tons/day

FIG. 16—*Once through b.p.w.r. nuclear powered container ship secondary plant "warm up" diagram*

of the coded valves. In operation it is most unlikely that either the relief valves or the coded valves are called upon to operate for overpressure protection. The relief valves may be actuated manually from the control station. Steam and water discharged from the pressurizer relief and safety valves pass to the pressure relief tank which is located in the containment structure.

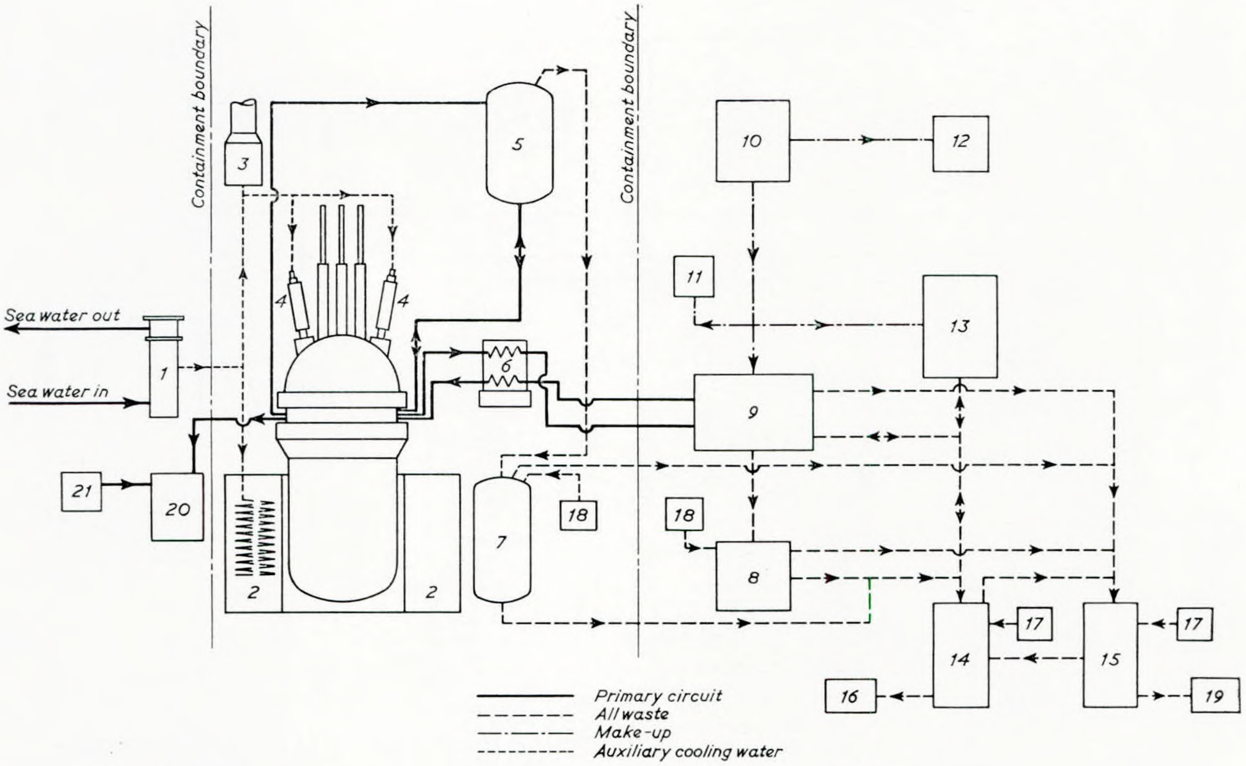
III) *Purification circuit*

The main duty of the purification system is to establish and maintain the water purity in the primary circuit by the removal of corrosion products and unwanted contaminants, the addition of corrosion inhibitors, and the addition of hydroxyl for pH control. The system also provides for the initial filling of the reactor primary circuit and for the control of the



1 Main feed valve
2 Pressure relief valve with reservoir
3 Control valve (maintains press. stm, genr, at 600 lb/in²a max.
4 Stop valve
5 Manoeuvring valve
6 Valve to maintain flow in main steam at min. of 10 per cent
7 Level control valve
8 Pressure control valve 135 lb/in²
9 Spray desuperheater valve
10 Level control valve
11 Stop valve
12 Stop valve
13 Pressure regulating valve (maintains down stream press. at 130 lb/in²
14 Pressure regulating valve
15 Pressure regulating valve
16 Air ejector stop valve
17 Stop valve
18 Stop valve
19 Stop valve
20 Stop valve
21 Non-return valve

FIG. 17—*Twin screw container vessel nuclear powered steam and feed flow diagram 95 000 s.h.p.*



1) Sea/fresh water cooling module
2) Shield tank
3) Containment air cooler
4) Primary fluid circulating pumps
5) Pressuriser
6) Regenerative heat exchanger
7) Pressure relief tank
8) Vents and drains system
9) Purification water plant
10) Demineralized water plant
11) Demineralized water requirements
12) Ships fresh water supply
13) Primary water storage tanks
14) Liquid waste system
15) Gas waste system
16) Discharge to shore facilities
17) Other active waste sources
18) Vents and drain sources
19) Discharge to atmosphere
20) Coolant sample analysis
21) Coolant samples from other sources

FIG. 18—*Diagrammatic arrangement of auxiliary circuits*

water volume in the circuit by addition or rejection of water, the need for volume changes being sensed by the pressurizer level controls. Leakages in the system indicated by a change of pressurizer level are made up by the purification system. Facilities are provided to enable decay heat to be removed by the system both on cooling down or during refuelling activities. The system also provides a means of pressure and leak testing of the primary plant and the checking of safety valves. In normal operation, purification and clean-up of the primary circuit takes place by means of feeding and bleeding the water from the reactor vessel. The system consists of a high pressure section located in the reactor containment and a low pressure section located in the reactor compartment immediately outside the containment.

IV) *Ventilation system*

The duties of the system are:

i) to cool the containment air;
ii) to supply filtered air at a specified temperature to the reactor compartment and ancillary rooms;
iii) to purge the containment volume prior to and during personnel access for maintenance, inspection and refuelling to reduce gaseous activity;
iv) to bleed the containment volume, should there be a leak in the primary circuit, through a clean-up plant to remove all particulate activity before passing to the stack;
v) to ensure that the activity level in the stack discharge is within the limits prescribed for the ship's environment.

V) *Shield water system*

The function of the system is to maintain the shield tank always full of water by controlling the level of water in the head tank. The size of tank required is determined by the shield water expansion under normal operating conditions. The larger volume variation which takes place due to heating on the start up of the reactor is catered for by allowing the excess to drain to the reactor compartment sump through an overflow pipe. The volume reduction on reactor shut down is supplemented by make-up water on receipt of a signal from the level controller. A level indicator/alarm is fitted to give warning of a low level in the head tank. Cooling of the shield tank, to maintain the water at near ambient conditions, is by a cooling coil in the tank through which circulates water from the auxiliaries cooling system.

VI) *Auxiliary cooling system*

The duty of the system is to remove heat from primary plant components to maintain their specified working temperatures. The primary circulating pump bearings are cooled by recirculating primary water from the pump through an external cooler fixed to the pump body, the heat being rejected to the fresh water system. The pump stator is also cooled by a water jacket through which circulates the fresh water cooling flow. The containment air is cooled by the recirculation of the air through coolers, the heat being passed to the fresh water system. The primary water purification flow is cooled to the required ion-exchange working temperature by means of the fresh water system, the cooling being effected in the non-regenerative heat exchanger of the purification system.

VII) *Emergency decay heat removal system*

The duty of the system is to remove heat from the reactor core in the event of an emergency resulting from loss of all electrical supplies. Two completely independent systems are located on port and starboard sides of the ship. The system relies on natural circulation both in the loop and inside the reactor pressure vessel. The loops are connected to the feed inlet and steam outlet headers of a section of the boiler. When in use heat is transferred from the primary coolant to the water in the boiler which in turn transfers this heat through an air cooler to atmosphere.

VIII) *Reactor services*

This service supplies hydrogen, nitrogen and compressed air to the reactor plant as follows:

- i) hydrogen gas is added to the primary coolant via the surge tank in the purification system to maintain an excess of hydrogen in the primary coolant. This is necessary to control the level of oxygen in the primary water, oxygen being formed continuously by radiolytic dissociation of water in the core;
- ii) nitrogen gas is needed for the gas blanketing and purging of tanks associated with primary fluid. Gas blanketing is used in the vapour spaces of tanks in order to minimize corrosion;
- iii) compressed air. The plant includes an air compressor unit producing a supply of compressed clean, dry air. The supply is led from the receiver to a number of distribution manifolds located near to the system valves being operated. The vent side of each system valve is open to containment atmosphere.

IX) *Sampling system*

The sampling system provides for the withdrawal from inside the containment of samples from the primary circuit, the pressurizer vapour space, the pressure relief tank and the shield tank. Outside the containment, samples can be taken of the primary water before and after the purification system ion-exchange columns, and of the make-up water before it enters the purification system at the surge tank. On the secondary system, sampling of the water before and after the demineralizers and downstream of the feed pumps is provided. In addition local samples are taken at routine intervals from various points in the plant outside the containment. Gas samples may be taken and analysed automatically to check the level of the hydrogen/oxygen and fission gas level in various tanks. Water from pressure circuits can be checked by in-line instrumentation and returned to the circuit. Routine manual analysis using sample bottles will permit more detailed analysis of the samples on a shore facility. An on-line auto-analyser will survey the secondary water continuously and give an alarm if the chloride level becomes excessive due to a condenser leak. The sampling station will consist of a shielded cubicle with a hood and an extract duct connected to the gas waste system.

X) *Active waste systems*

The gas waste system provides for the collection of waste gases from the reactor primary and auxiliary system and, if necessary, active gas from the secondary system air ejectors. The potential sources of active gas are gases released from the primary water and, in the event of operation with a leaking boiler tube, gas from the secondary circuit. The gases can be stored, if necessary, or can be discharged under suitable conditions through the ventilation system filters. The liquid waste system is arranged to collect all active or potentially active liquid waste from the reactor primary system, the reactor auxiliaries, and the secondary system. Liquid waste from the primary system, the auxiliary systems handling primary water and reactor compartment drainage water is led to the high activity liquid waste tanks. Low activity waste from the secondary drains, the auxiliary cooling system drain, and from subsidiary systems and facilities such as washrooms, etc, are collected in a separate tank. Monitors are provided to determine the activity level of the wastes.

XI) *Safety injection system*

The system is designed to prevent severe damage to the core following the unlikely event of a major fracture of the primary circuit. Relatively small leaks within the maximum capacity of the purification system pumps and normal make-up and storage facilities will not hazard the core; the purification system will automatically maintain the primary circuit water-level in the pressurizer. In the event of the leakage from the system causing a rapid lowering of pressure and level, the reactor is automatically shut down. The containment is also invoked by the closing of all containment isolating valves with the exception of the safety injection line. The safety injection system is arranged for automatic operating on low pressure and level in the primary circuit, and, in case of instrumentation failure, can be started manually. At a pre-set pressure and level in the pressurizer, the standby electrically-driven feed pump is started and water is injected into the reactor vessel from the storage tanks. Should the pressure or temperature in the containment reach unacceptably high levels, the spray pumps are automatically started and these pumps deliver water to the containment sprays to condense the steam and cool the containment; the spray facility can also be started manually. Should the amount of stored water prove inadequate, water can be drawn from the ship's ballast tanks. When sufficient water has been injected into the containment to reduce the pressure and temperature to acceptable levels, the core can be cooled by recirculating the water in the containment through the pumps and coolers of the auxiliaries cooling system. This facility could protect the core indefinitely.

INSTRUMENTATION

Instruments and controls are provided for the safe and efficient operating of the reactor and auxiliary plant. Control of the plant will be accomplished primarily from a central control room but local measurement and control will also be used where practicable, mainly on auxiliaries.

The basic requirement is to monitor the start up and shut down of the reactor plant and its correct working at all power levels. Neutron flux level detectors within the primary shield water tank will measure over source, intermediate and power ranges. They are supported by measurement of primary coolant flow (inferred from pump speed and current measurements), pressure and temperature. Detectors and their respective instrumentation channels measure pressurizer water level, pressure and temperature. In order to control the whole plant as a unit these measurements are integrated with measurements of flow, temperature and pressure of the steam, and temperature of the feed water. Brought together with this instrumentation is the instrumentation required to monitor temperatures, pressures, levels and the analysis of all supporting plant and auxiliaries as appropriate.

The instrumentation is of a standard modular design making replacement of items a simple task. As far as possible transistorized equipment of proven design and manufacture is used.

A data logging system will monitor all transducer outputs and compare selected measurements with pre-set alarm levels. Routine print-outs will be available regularly from selected points as decided by experience.

The protection system consists of a 'two out of three' protection logic system. The three protection logic lines are made up of primary plant parameters that would lead to dangerous plant states if not controlled to a specific set point. The Control Room layout consists generally of desk space integral with vertical instrument panels. Instrument panel and control desk layout follow a general pattern from left to right of turbine, steam generator and reactor instruments and controls.

ELECTRICAL SYSTEMS

The configuration of the main electrical supply and distribution systems will need to fulfil the requirements of the various classification, port and safety authorities under whose jurisdiction the ship may come. The primary consideration in a vessel of the proposed type will be reactor safety and the necessary integrity of the electrical supplies required to support the reactor under all conditions of fault or failure.

Electrical generation is at 3·8 kV, 3-phase, 60 Hz, through a combination of turbine and Diesel generators, sized as follows:

a) 2 turbo-generators rated at 1875 kVA at 0·8 pf (1500 kW);

b) 4 Diesel-generators rated at 2185 kVA at 0·8 pf (1750 kW).

The maximum sea load will be supplied by the two turbo-generators.

For manoeuvring, the Diesel generators will support the turbo-generators.

Sufficient Diesel generator capacity is specified for the ship to be on emergency propulsion and at the same time perform a hot start-up of the reactor.

The foregoing points, and the selection of electrical power for emergency propulsion have the effect of requiring a high installed generator capacity with a comparatively low utilization.

The main distribution voltage of 3·3 kV is chosen because of the high prospective fault level from the large installed generator capacity. Large motors (where possible) are supplied at 3·3 kV directy from the main distribution system. Other services are supplied at 440V from distribution centres equipped with 3·3 kV/440V transformers; 440V distribution is supplied from a system of essential and non-essential busbars. This system together with the emergency generator and battery supported supplies for the reactor instrumentation ensure a high system integrity.

REACTOR START UP

Following initial fuel loading or refuelling operations, the reactor primary system, support systems and, in part, the secondary system are filled with demineralized water. The primary system is continuously vented and operated as a solid water system. By the combined operation of the purification system charge pumps and let-down valves the main circuit pressure is raised to about 20·7 b (300 lb/in^2 abs). The reactor primary pumps are operated intermittently and venting is carried out continuously round the system until visual inspection of the vent fluid shows that continuous primary pump operation can be commenced. Power is supplied from the Diesel alternators.

The pumps are now run continuously and the pressurizer heaters energized, heat-up rate is limited for mechanical reasons to about 10°C (18°F) per hour. Water is circulated between the reactor pressure vessel and the pressurizer through the surge and spray lines. The plant continues to operate as a solid water system, expansion water being removed through the purification plant let-down valves to the surge tank. A final physical venting of the system is carried out at approximately 90°C (160°F) and heat-up is not continued beyond this temperature if the oxygen level in the primary water is greater than 0·1 ppm. With the pumps stopped and heaters off, system pressure is now raised by means of the purification plant make-up pumps (to leak test pressures after refuelling or if any strength welds or seal welds have been broken during maintenance).

The heaters are re-energized and the pressurizer temperature raised to approximately 200°C (400°F). At this point water is bled from the main circuit via the pressure reducing station to the surge tank and the pressurizer pressure falls to that corresponding to saturation pressure. Water flow to the surge tank continues until the pressurizer level is reduced to normal operating level forming the steam bubble in the pressurizer.

During subsequent heat-up the operator maintains the pressurizer level and pressurizer temperature by manual operation. The pressurizer pressure is kept sufficiently high to provide the primary pumps with sufficient suction head and prevent boiling of the primary coolant. In the early stages of system heat-up the rate is readily achieved by means of the primary pumps and pressurizer heater operation. Eventually it is impossible to maintain a reasonable heat-up rate with the pumps and heaters and beyond this point nuclear heat is employed.

The plant is brought to criticality by manual operation of the reactor control system and the nuclear power level raised to a few hundred kilowatts. During the rise in temperature the operator maintains the required reactor power level by withdrawal of the control rods.

As the primary pressure is increased the pressure reaches the low pressure set points for the operation of the safety injection system and the reactor scram, which are now brought into the operational condition. When normal pressurizer conditions are achieved the pressurizer heater and spray system are switched to automatic control and similarly automatic level control is switched in once full primary temperature has been reached.

There are a number of ways of starting the secondary system, for a wet start, for example, the boiler tubes are full of feed water which rises in temperature with that of the primary circuit. When nuclear heating commences the motor-driven feed pump and de-aerator extraction pump are started. The boiler pressure is raised to 41·4 b (600 lb/in^2 abs) and maintained at that level using a small expansion tank to take the overflow as the temperature rises. A small flow is allowed to pass through the boiler to a flash chamber where steam is produced and raised to a level of about 9·3 b (135 lb/in^2 abs). The flash chamber level control discharges surplus water and steam to the atmospheric drain condenser and thence back into the feed system.

As reactor temperature is increased the feed flow rate is slowly increased to maintain the temperature of the fluid leaving the boiler at 200°C (400°F) and during this period steam from the flash chamber passes to the H.P. heater and de-aerator. Flash chamber steam is then supplied to the main turbine glands, turbo-generator glands and air ejector, drawing vacuum on the main condenser. As further steam becomes available the main turbine turning gear is engaged and warming-through commences.

When the primary circuit is up to temperature and pressure and steam at operational conditions is available from the boiler, the main steam lines are opened. To maintain the steam flow above the level of boiler instability the balance of flow not required for warming-through etc is passed to the atmospheric condenser and back to the feed line.

The turbo feed pump is then started, the turbo-generators warmed through and put on the board. Control of the reactor is then switched to automatic, and variation in load is met thereafter by the reactor inherent characteristic.

When the steam demand rises sufficiently, the flash tank and bypass systems close automatically.

CONTROL

Inherent in the reactor design are a negative fuel temperature (Doppler) coefficient and a negative moderator temperature coefficient. In the steady state, the rate of heat removal from the primary circuit is predominantly determined by the secondary mass flow. Regardless of load, the temperatures at inlet and outlet of the boiler change little. In the event of an increase in load the moderator temperature, i.e. the primary circuit temperature, is initially reduced below normal; this releases reactivity which restores the moderator temperature to its normal working level at the new load. Additionally the fuel itself has a reactivity effect. As power is increased, fuel temperature increases, in turn increasing the resonance (Doppler effect) absorption of neutrons in U-238 which reduces reactivity.

Combining the fuel reactivity effect with that of the moderator results in a fall of average moderator temperature of 12°C (22°F) as power is increased from zero to 100 per cent. This load following is entirely automatic. No movement of the control rods is required during manoeuvring and indeed no other operator action is required other than to vary the power demand on the secondary side.

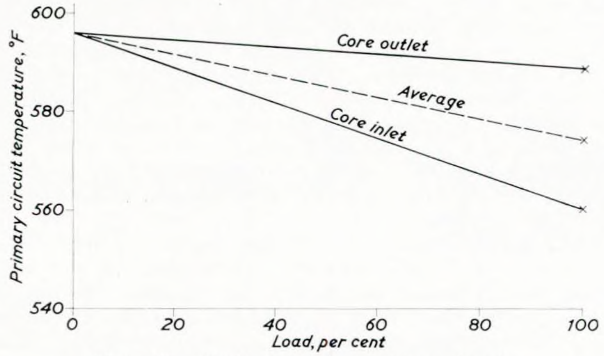


FIG. 19—*Variation of primary circuit temperature with load*

Fig. 19 shows a typical coolant temperature/power level characteristic. This characteristic is somewhat idealized since the curve assumes a constant moderator temperature coefficient/fuel temperature coefficient ratio throughout the temperature range. The change in temperature results in a primary water volume insurge or a volume outsurge from the pressurizer. The pressurizer operation is again automatic and requires no operator action.

Steady power operation changes in the average coolant temperature take place also to compensate for variations in the fission product poison build-up and decay changes, and due to burn up of the fuel and burnable poison. These long term variations in the coolant temperature are compensated for by control rod movements. The rod controller will maintain a processed signal from the coolant temperatures within a narrow band.

In the proposed BPWR the boiler steam pressure will be kept constant; as load falls from 100 per cent to zero the steam outlet temperature rises from the full load temperature of approximately 302°C (576°F) to 313°C (594°F).

As a forced circulation once-through boiler is used, two control problems result:

a) once-through boilers are inherently unstable;
b) having no drum capacity, they respond to changes in flow and heating conditions very rapidly.

In dealing with the second problem i.e., as the reactor has a comparatively large thermal inertia, the boiler control system must be very closely integrated with the reactor control system. Absence of a reserve of feed in the boiler, normally provided by the drums means that output variations require immediate input action.

Conventional water level indicators cannot be fitted; high levels of water in the boiler therefore, will be indicated by a fall in outlet temperature from the normal superheated value towards that of water at saturation temperature. The outlet pressure will be controlled directly by the feed regulator.

The inherent instability of the once-through boiler leads to special start up techniques. The instability arises from the change in flow characteristics at the onset of boiling. For a given heat input, if the mass flow is progressively reduced the stage will be reached in the individual tubes when boiling can commence. The changes in specific volume, resulting from the onset of boiling, lead to a region of negative slope in the pressure drop/mass flow characteristics of the boiler in this region. Thus in any practical boiler in which there are several flow paths in parallel between common headers, unstable flow conditions between parallel paths is possible. In practice the instability can be controlled by adding sufficient positive resistance to the tube to swamp the effect of the negative resistance resulting from the change of state. This is done by adding a throttling nozzle at the inlet to each of the tubes in the form of a short piece of relatively small bore piping up to 18 in. in length. Furthermore, the boiler will not be operated in the unstable region. Should power demands be low, i.e. in harbour, if necessary the boiler load will be maintained by means of the steam dump system.

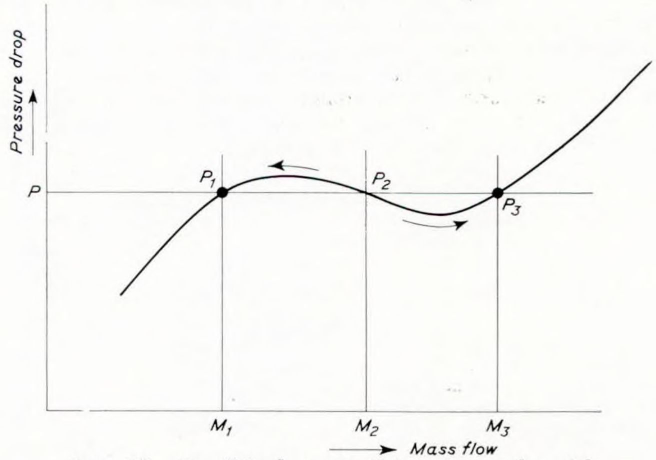


FIG. 20—*Possible flow conditions in a tube with unstable distribution*

Fig. 20 shows graphically the instability.(14) If the pressure drop across the tubes is represented by P, more than one flow is possible. The flow corresponding to P_1 is often so small that the working medium in the tube not only evaporates entirely, but is also more or less superheated. At point P_3 there is generally little or no steam formation. Both P_1 and P_3 represent steady states. The flow corresponding to P_2 is, however, unstable and the least disturbance from outside will push it to points P_1 or P_3.

An alternative system of reactor control that could be used is an absorber following control system known as "Tav". This is one in which the average moderator temperature is not permitted to vary over the range experienced with inherent load following and is kept at a constant temperature. Operational transient variations in the primary water temperature are reduced by the use of solid absorbers, i.e. control rods. Changes in the load demand are reflected to the core by the primary water as in the case of inherent control but, following the start of the transient, absorbers are used to reduce the primary temperature swings. Reactivity changes caused by changes in fuel temperature are compensated by the control rods, operating from "Tav" error signal either by manual or auto control, and the average primary temperature is returned to the controlled value. The degree to which the control system can smooth out transient variations has implications on the pressurizer size requirements, operating pressure and the secondary pressure variations.

In order to be able to maintain power and xenon override over the life of the core a large amount of excess reactivity must be present initially. The longer the life of the core and the closer one wishes to approach the maximum theoretically possible burn-up the greater this excess must be and the greater is the problem of controlling it. This excess reactivity must be then released over the life of the core to compensate as nearly as possible exactly for burn-up. The proposed reactor uses burnable poison to control the rate of release of reactivity from the core. A burnable poison is an absorber of neutrons which is progressively destroyed by irradiation during the operation of the reactor.

The excess reactivity can, however, be taken up in a number of other ways:

a) under moderation by altering the proportions of heavy water and light water as in spectral shift control;

b) soluble poisons;

c) control rods and similar removable absorbers.

Burnable poison is the only one which can be made a fixed part of the core structure, it can in fact be combined with the fuel, which is of considerable advantage in the marine reactor in that the absorber cannot either by accident or design, become separate from the core it is controlling. Ideally, a burnable poison would be designed to compensate exactly for the excess available reactivity and to maintain the core multiplication factor (k_{eff}) at unity at all stages of burn-up apart from a margin left for xenon override following load reduction or shut-down. In practice the burnable poison will not fit so exactly and thus a mismatch will occur between the ideal and the actual k_{eff}.

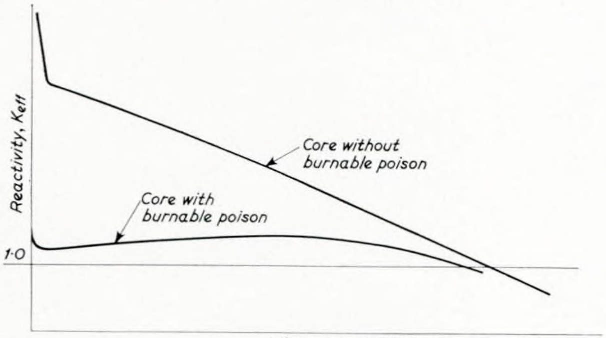


FIG. 21—*Reactivity-lifetime characteristic for a p.w.r. core*

Fig. 21 shows the change of reactivity over the lifetime of the reactor with and without the use of correctly shielded burnable poison.

NUCLEAR SAFETY

No human endeavour is entirely free from risk and the shipowner is well aware that the most common causes for ships being lost are strandings, fires, collisions, foundering and weather damage(15). Compared with these natural hazards of the sea, it is relatively straightforward to deal with the technical and predictable safety problems associated with nuclear reactors. The safety problem peculiar to a nuclear reactor is the radiation produced by the fission process.

When an atom of uranium is split, new atoms are formed and radiation given out. The new atoms, or fission products formed may be isotopes of any of about 38 elements, some of which may be radioactive. It is generally agreed that the isotopes of iodine, and particularly 1–131, carry a greater threat to health than any of the other fission products that might be released in a reactor accident. The reason for 1–131 being of particular concern is that it is volatile and if present in the atmosphere is easily taken into the body through the respiratory system and can give a dose of radiation which is greatest to the thyroid gland.

To put the hazard of radiation into perspective, it is important to remember that a reactor cannot give rise to an atom bomb type explosion and that man has always been subjected to radiation from natural sources. For example, a person living near sea level may receive a total body dose of about 100 millirad per year and someone living in a place like Denver, which is a mile above sea level, may receive twice that dose. Also in parts of India the dose level may be 40 times the sea level dose and in parts of Mexico it may be 100 times the sea level dose.

Advice on the protection required against harm from radiation is given in the recommendations of the International Commission on Radiological Protection, an organization which has been functioning since 1928 and was concerned with protection against X-rays and radium. The Commission kept its recommendations under review so that they now cover all the radiation protection advice, in terms of allowable exposure, that have to be associated with a nuclear reactor.

There are two parts to the nuclear safety argument concerned with a nuclear ship; the first is the protection of the crew and the second is the protection of the population at large while the ship is in port or sailing near centres of population. Shielding around the core attenuates to a safe level any radiation generated within the core. Therefore, during normal operation there is no hazard to the crew and so obviously there is no hazard to any population that may be near the ship. Also facilities are provided on the ship for the safe storage of any active gaseous, liquid or solid wastes generated during the operation of the reactor so there is no question that the discharge of such materials could cause a hazard to the public.

The second part of the nuclear safety argument is concerned with the probability of some failure of part of the reactor causing fission products to be released. The approach to this problem has been to recognise that there is a probability of a whole spectrum of failures associated with a reactor, as with any other engineering construction, and to design the reactor in such a way that the probability of a release is acceptably low whether the ship is at sea or in harbour. If the balance between heat production and heat removal is disturbed in a seriously adverse manner, such as could happen if the primary coolant were lost, the fuel could overheat and fission products might then be released. Before fission products can escape from the ship they have to pass through several barriers, each of which reduces the quantity that will escape. The barriers through which the fission products would have to pass after they escaped from the fuel pellet—and not all fission products will escape from the fuel pellet—are the fuel cladding, the primary coolant, the reactor pressure vessel, the reactor containment and the reactor compartment. With the quality of design and construction that will be associated with each of these barriers, it is envisaged that a nuclear powered ship of the type described will be able to satisfy national and international legislation that will be in force to deal with nuclear powered shipping.

Major world port authorities are not likely to raise objections to a nuclear powered ship using their ports if national and international legislation requirements have been satisfied. Two years ago when the question of nuclear ships was raised at the presentation of a paper(16) on port planning, the Head of Research and Planning of the Port of London Authority answered that given adequate safety from the radiation hazard, such ships would present no special problems to port authorities unless the power/weight ratios they made possible radically altered the dimensional relationship of ship form. The question of public safety was largely a matter for government. Doubtless it would be covered by national and international rules.

Clearly the hazard related to a nuclear reactor is less than that associated with many of the problem cargoes ports handle as part of their normal routine.

SECONDARY CIRCUIT ACTIVITY

Integral reactors which have the heat exchanger (once-through boiler) located in the region of the core neutron flux, produce steam containing activated nuclides arising from activated corrosion products and activated secondary coolant, principally the isotope N–16.

Because of the high purity of the secondary coolant, almost all of the radioactivity in the coolant is, however, due to short-lived oxygen decay.

The secondary circuit activity has, however, been reduced to neglible proportions by raising the boiler relative to the core and by providing additional shielding within the reactor pressure vessel between the core and the boiler. The design aim is to produce a unit which requires no special precautions against radiation in either the operation of the ship or during cargo handling.

DECAY HEAT REMOVAL AND EMERGENCY COOLING

In the context of a nuclear merchant ship the disposal of the heat generated in the core following shut down can present special problems. The decay heat generation falls exponentially, the total heat at any particular time depending on the operational history of the reactor in the period since the previous shut down.

In normal circumstances the decay heat will first be removed by the secondary circuit bypass and dump system with the Diesel alternators supplying essential and auxiliary loads. During this period with the bypass open the electrical feed pump throttle may be adjusted manually or automatically to maintain the primary water temperature in the range of normal operation. Continued operation in this condition reduces the secondary flow to intermittent operation, and primary circulation is reduced to one pump. After about a day in this condition the decay heat has fallen sufficiently to enable its final removal via the purification system.

In the unlikely event of complete loss of electrical supplies the decay heat following shut down will be removed by natural circulation to two or more air coolers situated on the upper deck. These air coolers are connected across the main boiler. In the event of the system having to be used, valves operate to form a closed loop between the reactor and the coolers. Decay heat from the reactor core is transferred by natural circulation within the reactor pressure vessel to the reactor boiler. A second natural circulation circuit transfers the decay heat to the coolers on the upper deck.

This system is designed to ensure that the decay heat will be removed even with the ship stranded and heeled and it does not rely on the supply of cooling sea water or emergency electrical supplies.

CONCLUSIONS

The studies carried out by the authors have covered many methods of obtaining economic appraisals of nuclear power, and the authors have come to the firm conclusion that the only realistic approach in comparing nuclear and conventional vessels is to adopt a fleet concept; furthermore this is the only realistic way in which the nuclear ship can be shown to be fully competitive, as the integration of a nuclear ship into a conventional fleet does not allow the nuclear ship to reach its full economic potential.

It is clear from the results given in this paper, that provided the actual cost figures for reactors and for nuclear fuel are eventually established to be within certain favourable ranges of possible values, then nuclear power is more than competitive in the type of ship described, when operating on the given itinerary.

At this point in time, uncertainty as to the values of cost for the nuclear aspects is inevitable for, until a full design programme for these items has been carried out, a large degree of variation can not be ruled out. It is not for the shipbuilders to say whether the results given from their calculation will eventually be proved to be achievable, bearing in mind this uncertainty.

The importance of the possible benefits to the shipping world of nuclear power being adopted on a wide scale would appear to justify continuing investment in research on a national basis in order to ensure that correct decisions are taken and the current uncertainties reduced to reasonable accurate probabilities.

ACKNOWLEDGEMENTS

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REFERENCES

1) Gaunt, I. A. B. and Wilkinson, G. R., 1968–69 Session, "Vickers Nuclear Power Container Ship", Manchester Assoc. of Engineers.
2) Gaunt, I. A. B. and Wilkinson, G. R., 1969, "Nuclear Propulsion for Merchant Ships". Port of London Marine Officers' Assoc.
3) Wilkinson, G. R., Rouse, J. R. and Gaunt, I. A. B., 1969, "Nuclear Propulsion for Merchant Ships", Newcastle upon Tyne Naval Architects Society.
4) Meek, M., 1969, "The First OCL Container Ships", R.I.N.A.
5) Goss, R. O., 1967, "The Economics of Automation in British Shipping." *Trans. R.I.N.A.*
6) Hinton, Sir C. and Moore, R. V., 1958, "The Nuclear Propulsion of Ships". *Jnl. Jt. Panel Nucl. Mar. Prop.,* Vol. 2, p.1.
7) Richards, J. E., 1960, "Nuclear Power for Ship Propulsion". *Jnl. Inst. Fuel,* Vol. 33, p. 271.
8) Corlett, E. C. B. and Hawthorne, E. P., 1960, "The Prospect for a Nuclear Powered Day Cargo Liner with Particular Reference to the Organic Moderated Reactor". *Jnl. Jt. Panel Nucl. Mar. Prop.,* Vol. 4, p. 1.
9) Rolls-Royce Ltd., "The Steam Cooled Heavy Water Marine Reactor", 1961. *Nuclear Engineering.*
10) "The Vulcain Project Status Report", 1967. *Nuclear Engineering,* Vol. 12, No. 128.
11) "Nuclear Power for Ship Propulsion", 1964. *HMSO Cmnd.*
12) *Jane's Fighting Ships,* 1968–69. Sampson Low, Marston and Co. Ltd.
13) *Atomwirtshaft,* 1968.
14) Profos, P., "Stabilization of Flow Distribution in Forced Flow Heating Surfaces". *Sulzer Technical Review.*
15) Report of the Committee on the Safety of Nuclear Powered Merchant Ships, 1960. *HMSO Cmnd.*
16) Ordman, N. N. B., 1968, "Some Basic Considerations". *Procs. of the Inst. of Civil Engineers,* Vol. 39, Discussion of Paper No. 7022.

Appendix

It is almost a year since this paper was written, and a number of important changes have taken place which affect the comparative economics between conventional and nuclear powered ships. The most striking example of these changes is the substantial increase in the price of fuel oil during the last few months.

This is illustrated by Fig. 22 which shows the variation in United Kingdom fuel oil prices from 1951 to 1970. One point of interest is that the peaks in the curve tend to occur at times when major military conflicts were taking place.

During the latest of these conflicts the trans-Arabian pipeline was disrupted. This and the reduction in oil supplies from Libya, increased freight rates by the Cape route, and increased demand by power stations have all helped to bring about a shortage of fuel oil resulting in the increased bunker fuel oil prices.

There is likely to be little reduction in prices in the near future. Demand for world tonnage is likely to continue its present steady growth, with land based power consumption rising annually. With the general trend in the power supply industry to convert to either nuclear or oil fired plant the present situation can only worsen.

Considering the effect fuel oil prices would have on the conventional container ship illustrated in the text: increasing the price from 113s per ton to 175s would raise the annual fuel cost of the vessel by about £0·36 m.

Another change is the increase in capital cost of both nuclear and conventional vessels plus a marginal increase in the price of nuclear fuel.

As all these factors are important in the assessment of comparative ship economics, a re-appraisal of the economic case either for or against the nuclear ship follows. For this purpose no change was made to the basic design or annual transport capacity of either vessel.

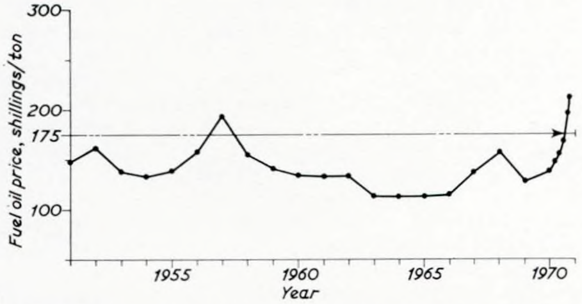


FIG. 22—*Bunker fuel oil prices at U.K. ports—yearly average contract prices 1951—Aug. 1970*

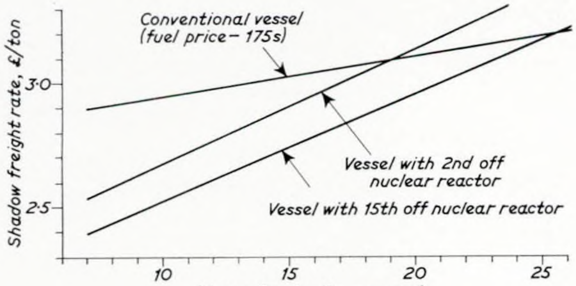
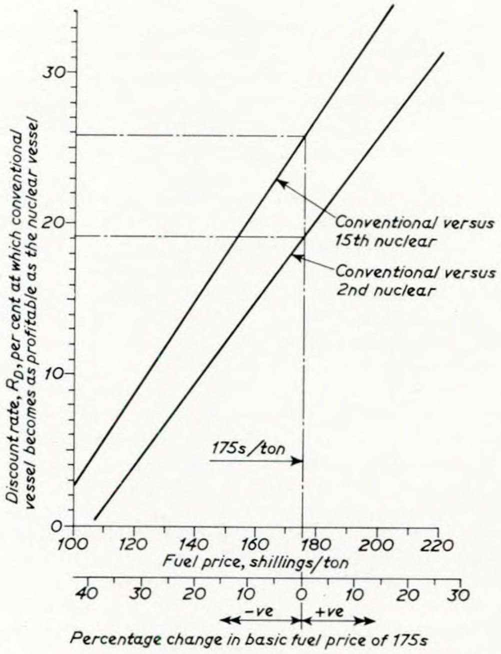


FIG. 23—*Shadow freight rate comparison of conventional and nuclear powered container ships*



FIG, 24—*Relationship between price of bunker 'c' fuel oil and the discount rate R_D at which conventional vessel becomes as profitable as nuclear vessel*

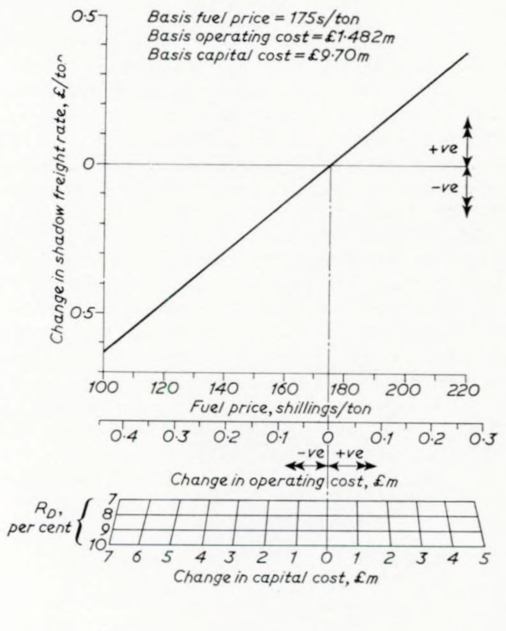


FIG. 25—*Effect on shadow freight rate of a change in basic capital, operating or fuel costs of conventional vessel*

Increases were made in the capital cost estimates for both nuclear and conventional vessels. The figure 113s ton for fuel oil was raised to 175s per ton. Finally, the price of nuclear fuel was increased by just under 5 per cent to cover normal inflation and price rises in general.

The results using these price increases are plotted on Fig. 23, which updates Fig. 5 in the text. This shows how increase in shadow freight rates (caused by increased capital

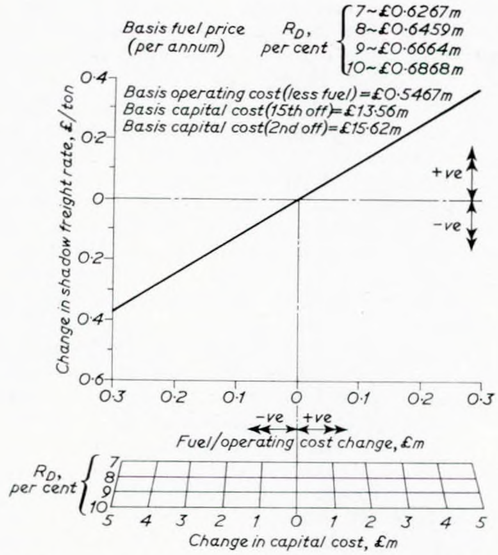


FIG. 26—*Effect on shadow freight rate of a change in basic capital, fuel or operating cost of nuclear vessel*

costs), together with a further separation of the lines due to the high differential increase between conventional and nuclear fuel prices. The effects of these two factors can also be seen on Fig. 24 which illustrates the threefold increase over the crossover discount rate of nuclear and conventional vessel economic superiority shown on Fig. 5 of the text. Fig. 24 also shows the effect which changing fuel oil prices have on the crossover discount rate. From this the discount rate at which the conventional vessel would show a better investment return than the nuclear vessel now stands at just below 26 per cent for the ship with a 15th off nuclear reactor and just above 19 per cent, a reasonable price, for one with a 2nd off nuclear reactor.

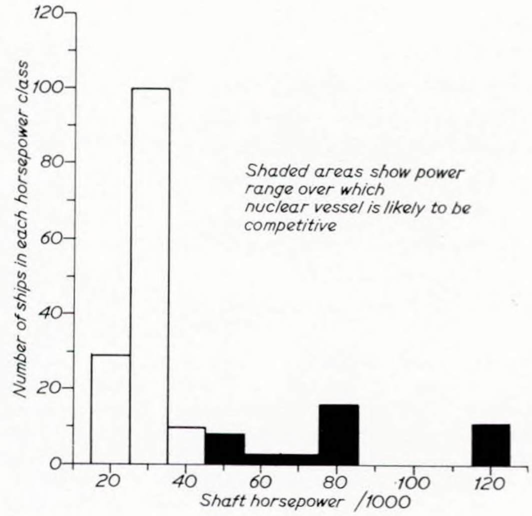


FIG. 27—*Distribution of container ships over a range of horsepowers in service and on order prior to Aug. 1079*

Figs 25 and 26 indicate capital and operating cost figures used in this re-appraisal and the effects on the shadow freight rates.

There are now about 39 container ships within the horsepower range over which nuclear power is likely to become competitive (Fig. 27). The number of large capacity container ships is almost certain to increase, thus giving a potential market for nuclear propulsion. The Government are still considering the Ministry of Technology report which suggested that the nuclear ship project would not be economically justifiable at present. The Government however may have to consider the findings of the study group's report in light of rising fuel oil prices.

Discussion

MR. B. HILDREW, M.Sc., Member of Council, I.Mar.E., said that his first criticism was that the paper covered too much ground. Moreover it analyzed material which was available eight years ago. The BPWR had changed very little since it was proposed, although, if he remembered correctly, it was devoid of control rods, but did have shut down rods. Could the authors say which areas had been redesigned?

Mr. Hildrew went on to say that in the late 50's and early 60's, it was recognized that the reactor farthest from reality always looked the safest and most attractive, and it was at that time hoped that new designs would be forthcoming. However, because the Government removed any incentive for new nuclear power designs, none had been developed. If the Government had encouraged some degree of research and development, the present paper would not have given the impression of picking up the chips where they fell seven years ago.

The speaker regretted that he had not done the sums proposed in the first part of the paper, and was not therefore in a position to challenge their graphical presentation and economic conclusions. But in the penultimate and final paragraphs, he had noted that continuing research was considered desirable, though it was not indicated what form this should take.

He agreed that with the greater demand for installed power, the proposed economic feasibility of a nuclear propelled vessel was coming closer to a reality—if it had not already done so. However, the capital cost could well be rising faster than that of a more orthodox conventional marine boiler. If the difference in capital cost between the nuclear reactor and a conventional boiler was equated to the difference in fuel cost of oil and uranium over the working life of the ship, this provided a simple crude calculation which he himself outlined to the Institute in 1962*. It was still applicable today. If detailed analysis was required, other factors might also have to be considered, not least the possible costs incurred in break-up of the vessel at the end of its working life. The capital differential between six nuclear-powered and seven conventional ships still seems to be about £1·5 m, and this represented a difference in capital costs between the two machinery installations. It was too high and must be at least halved. This should lead to an assessment of what would be the cheapest capital cost for the most primitive nuclear installation.

The table "Capital Cost Breakdown" represented what was the approximate capital cost breakdown of a nuclear

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* "Problems of Merchant Ship Nuclear Propulsion". Institute of Marine Engineers Transactions, Vol. 74 Page 501.

CAPITAL COST BREAKDOWN

1. Containment	12 per cent
2. Reactor vessel and primary circuit	25 per cent
3. Heat exchangers, pumps, etc.	10 per cent
4. Primary and secondary shield	10 per cent
5. Core structure and control	10 per cent
6. Instrumentation	10 per cent
7. Defuelling and refuelling	10 per cent
8. Collision protection	3 per cent
9. Other auxiliary plant and facilities	10 per cent

installation. It was doubtful if any progress could be made towards an economic nuclear ship until some of these items were eliminated or simplified, or labour costs reduced. Thus the suggested containment design in the paper, which was technically a most attractive one, providing the reactor support structure was adequately designed in relation to the conical containment support, could perhaps be more economically achieved by incorporating a pressure suppression system and containing within the hull structure.

With regard to the BPWR and the authors' mention of the possibility of eliminating a separate pressurization vessel if it is only referred to as a possibility, then it cannot be eliminated.

In the last two years, the gas turbine had again come to the fore, and serious attention should be given to the direct cycle gas cooled nuclear system. Such a proposal eliminated heat exchangers, as well as one of the major criticisms of main propulsion gas turbines—the requirement for high quality fossil fuel. The technology for gas-cooled systems was well developed both industrially and in the U.K.A.E.A. Such a development would enable a number of items shown in the table to be reduced. However, safety requirements were paramount, and would need careful re-assessment. Some £1000 m will be spent on *Concorde,* and apart from keeping a small number of people employed in a period of full employment, the exercise will have been of doubtful value. How much better if a country dependent on sea trade for its existence had devoted, say, £10 m to nuclear propulsion seven years ago. How much better to invest now a similar sum in the proposal outlined above, linking the marine development of two concepts already in service on land. A successful development in either or both areas would be of inestimable value to U.K. trade.

This paper was of value in that it showed how little we, as a country, had moved in this field during the last seven years. It also reflected how much shipping had changed in the same period, particularly in the interlinked areas of size, speed and power. Any economic analysis must be linked to potential engineering developments, and Mr. Hildrew suspected that the economists at the Ministry of Technology might lack this essential engineering competence, however much they might be otherwise persuaded.

The authors should have looked more critically at the nuclear reactor proposed, and the alternatives available. The cost was still well in excess of the conventional plant, and until some radical changes in design were made, this would limit the progress which was possible. If nuclear propulsion was to be a technological asset to this country it was essential that the Government provided the financial support for the development of a better concept than the present BPWR. It might also be of value if some professional marine engineers were directly associated with future developments.

In the section on reactor start-up, reference was made to the raising of pressure after leak-test pressure on refuelling. What was the leak-test pressure for this design?

Mr. Hildrew concluded by saying that he was rather interested in Mr. Rouse's final comments, arguing from historical experience. He thought that this was a dangerous thing to do with a new concept. If we were going into high powers, we had to have single reactor ships with get-you-home capabilities, just as we had conventional ships with single highpower boilers and get-you-home facilities.

Mr. H. Boos asked, in relation to the authors' claim that in the past ten years a number of studies had been carried out with the aid of a wide and authoritative cross-section of shipowners, how wide this cross-section was. He asked this because, after following technical and economic studies over a number of years, he agreed completely with the authors that these studies had only confirmed the opinion he already held—namely, that there was a definite case for nuclear propulsion applied to merchant ships. Nevertheless so far, the shipowners did not seem to believe this.

The situation was referred to by Mr. Hildrew, and during the last ten years studies at various levels of technical sophistication had been made together with economic assessments, relating to trends in shipping of five or six years ago which had now become a reality. Yet the only nuclear ships that had been built were either military or research vessels, financed by public funds, without direct participation by shipowners. Therefore Mr. Boos did not believe that this kind of study would get us much further, though he appreciated the work put in by the authors.

He then went on to ask if the authors could produce shipowners' evidence to support their argument to the effect that the total annual transport capacity available was 4·9 m tons a year? He was not in a position to evaluate this, nor were technical institutions and organizations; but the shipowner was.

Could we really rely on the vessel being available for 350 days a year throughout its lifetime? This was a basic point in the economic analysis. Was a cargo deadweight used/cargo deadweight available ratio equal to unity a reasonable assumption? He was not contradicting the assumption, but felt that as technicians, engineers were not able to evaluate these assumptions—yet everything stood or fell with these points. The authors hinted at the necessity for a full design programme in their conclusions and wrote: "It is not for the shipbuilders to say whether the results given from their calculation will eventually be proved to be achievable, bearing in mind this uncertainty." How, then, he said, could we arrive at a situation where this kind of calculation was made from the shipowner's point of view and not that of the backroom boys?

Finally, Mr. Boos believed that technical studies and economic assessments for nuclear ship applications should not be restricted to a national basis and thus to what one individual country could afford, but along the lines of conventional container transport which was showing a tendency towards the formation of international consortia.

Dr. O. O. Ejiyere said that the heat exchangers or steam generators in a nuclear ship propulsion reactor were insufficiently shielded and allowed contamination by particles interacting with the components. Heat exchanger contamination partially affected the components, causing radio-activity. The bombardment of the heat exchanger components by high energy particles mingled with the superheated coolant flow on the components, caused deformations in the metallurgical, structural and mechanical properties of the heat exchanger materials and the reactor pressure vessel itself.

Multi-particle interactions with the PWR vessel and the components of the heat exchanger produced particle multiplication. This was very possible in multi-neutron interactions which would result in the multiplication of neutrons in groups.

The neutron or gamma radiation interaction with the nucleus might affect the exchange force, non-exchange force, and multiplication productions. The interactions caused deuteron production in the nuclei of the atoms of the steam and secondary coolant water. There were probabilities that the particles emitted by the PWR not only interacted with the nuclei of the steam and secondary coolant to form radioactive deuterium steam and secondary deuterium coolant, but also escaped with the steam and coolant on non-exchange force interactions. Particles capable of escaping through the heat exchangers, air coolant ducts, etc., were particles with high energy, mostly fast neutrons, gamma rays, etc. This mostly occurred when particles interacted with the steam produced, which was condensed to form water containing deuterium compound. Dr. Ejiyere would be interested to know how engineers and physicists could contain heat exchangers or steam generators within the secondary pressure vessel, without neutrons, gamma rays, etc.—particles—interacting with the steam and secondary coolants which caused the formation of heavy water?

Secondly, how was the steam generator freed from neutron bombardment?

Mr. T. Deighton, although an engineer, confined his remarks to the authors' cost analysis. This section he said contained a number of imposing equations but it was not possible to check any of the cost curves by these equations because important items of input data were not given.

The difference between £12·8 m and £9·8 m quoted, when allowance was made for the increased cost of saturated turbines—notionally £0·2 m and allowing for the cost of a boiler in the conventional plant at say £0·4 m gave about £3·2 m for the cost of nuclear plant itself.

This appeared to be reasonable for the cost of a series nuclear plant exclusive of the core, but in order to be able to put one of these plants into a ship you had to spend a lot of money on research and development, even for something of this nature, which was, to a certain extent, already developed. It could not simply be put into a ship in its present form. Was this research and development cost to be spread across the total of six or seven ships, or would some kindly government contribute the money and write off the amount? It might be some £6–£8 m.

Secondly, the first plant of a series would cost quite a lot of extra money over the notional £3·2 m for certain items such as special tools, drawings, electrical instrumentation reliability, and proving the fabricational feasibility of the rather peculiarly shaped pressure vessels. A cost of something of the order of £0·8 m should be allowed for this.

Also no mention was made of how the cost of refuelling at say, somewhere between £0·3–£0·4 m was allowed for. Every time the plant was refuelled, you had to spend a lot of money to make it safe, open it up, de-fuel it, put in the new core and seal it up again. A notional figure for the cost of this might be about £0·3–£0·4 m. Had this been included? He couldn't, he said, see it in the paper.

Mr. Deighton's third point concerned the cost of a technical back-up organization. When you had a nuclear propelled ship at sea, you had to have an organization to monitor and assess the performance and safety of the plant and to give information and instructions to the operators. Such an organisation could be quite expensive—something in the region of £50–£100 might be appropriate here. How were all these costs included, to make up the cost assessment?

Also, how did the authors cost the core itself? He saw no mention of a detailed cost breakdown. It would be interesting to know how much had been taken for the cost of fissile material and also the cost of fabricating the core.

Finally, in connexion with the collar between the flanges of the reactor pressure vessel, Mr. Deighton said that when you had primary fluid on one side of the collar and feed inlets and steam penetrations alternatively arranged around the circumference, temperature transients were possible, leading to very awkward thermal fatigue stress conditions which would seem highly undesirable for this type of plant. It would be interesting to know whether this aspect had been examined and with what conclusion.

Mr. P. Weiss, said that he would like to make some comments and ask for clarification on some points related to the safety aspects of the ship.

Accommodation was situated two-thirds aft and this layout resulted obviously from the necessity to accommodate a suitable collision protection structure, since the shape of the aft part of the ship did not provide a sufficient beam to meet the widely accepted rule of B/5 for the side width of the barrier. Was there, in the authors' opinion, a significant economical penalty incurred in the handling of containers by dividing the storage space into two separate parts? Or was there an incentive to devise some arrangement allowing the shifting of the accommodation to the aft, for example by installing the containment vessel at an upper level in the ship in order to find a sufficient width abreast the reactor compartment?

It was said that the containment vessel leak rate had to be kept below a maximum allowable limit determined by the classification society. This was a somewhat sweeping statement. In Mr. Weiss' opinion, it was clear that, if an agreed value was useful for the design and appraisal of the effectiveness of the safety provisions to limit the consequences of a potential major accident, there was by no means a definite upper limit which could not be trespassed. In fact the containment vessel leak rate was only one factor among a great number of others which had to be incorporated in the safety analysis to assess the behaviour of the ship under assumed accident conditions and to evaluate the probable consequences to the environment.

There was no mention of the material to be used for the main heat exchanger coils. This was a rather important choice and had to take into account the more or less stringent requirements for the chloride content of secondary water, which could be very low if an austenitic stainless steel was chosen and might prove difficult to achieve during operation. What was the opinion of the authors on that point?

The purification system provided a means for the checking of safety valves. It was well known that the leaktightness of safety valves, after checking *in situ*, was not always compatible with the allowable leak rate of the primary circuit of a nuclear plant. Was there any special arrangement designed to cope with such leaky valves or to avoid this drawback?

Some more details on the clean-up plant installed downstream of the ventilation system would be appreciated, since the efficiency and reliability of the filtering equipment played a major role in the safety assessment of the nuclear installation. More particularly, it would be interesting to know the degree of redundancy introduced in the system, the type of filters used and the provisions foreseen to check the filter efficiency during service of the ship.

The emergency decay heat removal system relied on natural circulation both in the loop and inside the reactor pressure vessel. In that way, the system was completely independent of any electrical supply and this was a commendable design basis. However, in dealing with emergencies on a ship, very large values of list were not to be dismissed and could, above a certain angle, negate the operability of the system. Was there any list limit and which one?

The possible operation of the plant with a leaking boiler tube seemed to be contained in the description of the active waste systems. It appeared that, in this case, it would be more convenient to shut down the group of coils affected by the leak and to run the plant with the remaining three groups. Was there any definite procedure foreseen?

Concerning the low activity liquid waste, there was no mention of a possible release to the sea. Was there a basic design philosophy to store any waste generated by the nuclear plant on board whatever its activity level? If this was the case, it should be recalled that, according to the available operating experience, even as scant as it was, in practice this goal was rather difficult to achieve.

Mr. Weiss went on to say that the part of the paper devoted to the nuclear safety of the ship deserved some more important remarks.

In the first paragraph, it seemed that a definite borderline was set up between natural hazards of the sea and the peculiar safety problems stemming from the radioactive materials produced during the fission process. Obviously this was an oversimplification since the nuclear plant would be unavoidably involved in almost every mishap of the ship. The high safety level which was sought for in active material retention, implied the thorough analysis of the ship's behaviour, even in extreme cases such as collision or foundering, to assess the effectiveness of special structures or arrangements specifically designed to protect the reactor plant and to avoid any uncontrolled release of activity. It was probably in that field that the greatest uncertainties still existed.

Iodine isotopes were certainly of special concern in safety analyses; however, it should be kept in mind that the filtering equipment of the ventilation system was designed to remove a great amount of the iodine and iodine compounds leaking from the containment vessel and that other active products which were not readily retained by the filters would become more significant. This would particularly be the case for noble gases.

In the first part of the safety argument, it was stated that any active waste was safely stored on board ship. As already noted for liquid waste, this philosophy would prove unpracticable and it was probable that some discharge of liquid and gases would have to be performed during operation of the ship because there would be either some minor leakage in primary circuit, or purging of the containment vessel atmosphere for maintenance purposes. Therefore it would appear wise to design the storage facilities for such releases, i.e. to provide the equipment required to control the total and specific activity of the discharges.

In the second part of the safety argument, the probability of a whole spectrum of failures and of a release was mentioned. Some more details would be appreciated on that topic. Were the authors ready to use, in the marine field, the approach to safety appraisal developed in the U.K., which was based on an objective safety rating covering the whole range of conceivable accidents, the corresponding risks being judged by reference to an absolute risk criteria? This would be a very promising method based on sound theoretical grounds which could not be said of the so-called maximum credible accident approach currently used in the safety evaluation of water cooled reactors.

Unfortunately, Mr. Weiss concluded, the implementation of the "probabilistic method" was still impeded by the scarcity of reliable statistical data and also by the lack of a widely accepted risk criteria. The views of the authors on this point would be welcomed.

Mr. A. H. Syed, B.Sc., M.I.Mar.E., said the authors had endeavoured to show that as a fleet concept nuclear propulsion was very competitive, the cost of the reactor being taken as that of the 15th off, not the prototype. This would not appear to be realistic at the present time, since there was not even a prototype at sea. It would be interesting to know the amount of research and development work to be done before this could begin, and to know who would foot the bill. Also, what was the difference between the first and the fifteenth reactor, as regards the economic appraisal?

Another factor, of great interest to the shipowners, was the building time for the nuclear ship. Some indication of this would be appreciated.

The paper presents a comparison of the lightship weight, but no figures are given. Some idea of the breakdown of the weights of machinery and hull, for the two types of ship, would be of interest.

Mr. Syed went on to say that personnel were required to be of high calibre, specially trained in the nuclear plant and in protection methods. In addition, a large proportion also needed conventional certificates of competency. The services of a qualified health physicist would be necessary, at least in the initial stages. All these would add to the expense, and he wondered if this had been taken into account.

What speed would the get-you-home system for this type of ship provide? No doubt it would be prudent to keep personal surveillance, so as to gain watchkeeping experience, but looking ahead an unmanned engine room was desirable for future generations of ships. What major obstacles, if any, did the authors foresee in designing the plant for unmanned operation and what advantages would be gained?

The new generation of conventional gas turbine main propulsion machinery was now showing great potential and was gaining in popularity, particularly for containership application. Bearing this in mind and also the recent advances made in the field of high temperature helium cooled reactors, a direct cycle nuclear gas turbine offered a very compact integrated design, with such advantages as complete elimination of the secondary cycle and simplicity as compared with the boiling water type reactor concept) and as such appeared to be an attractive proposition for merchant ship application. It would appear highly desirable that research and development efforts should be directed towards evolving this type of machinery if nuclear ships were to be competitive with conventionally powered ships.

Mr. R. V. Turner said that because the need to enlist the support of shipowners had been mentioned, he thought it was important to point out that behind the work summarised in this paper, there was an earlier study on the optimization of container ships, carried out by his company in 1965.

To avoid missing the correct level of optimization it was considered necessary to go up an order of magnitude from the designs then current both in container numbers and in shaft horsepower. Thus a ship was envisaged with 10 000 ISO 20 ft containers, and with 300 000 shp (equivalent to 35 knots service speed). This was the end spot that was thought appropriate in 1965. As a result of this, it was concluded that the current ships on order were grossly undersized, and that costs per container trip could be very substantially reduced, by a substantial increase in size—to say a ship carrying 2000 containers in the speed range 25–30 knots, with a shp of 60 000. This conclusion was really to the effect that the then current generation of ships would be rapidly out-moded by larger and faster units, and the significance of nuclear power in regard to this was recognized. Therefore, despite critical comments by various people, including shipowners, the policy of putting great emphasis on nuclear power was continued.

The results at the present day, if seen in conjunction with the fact that this type of ship was being built in increasing numbers, show that one had to be very cautious about taking advice which could be based on a limited assessment of future trends and which did not include adequate knowledge of the economic forces at work throughout the world.

Professor G. N. Walton said that although the question of fire risk was mentioned in the text, no discussion was given to the relative fire risk of conventional ships as compared with that of the nuclear powered ship. In a ship using conventional power the fuel was essentially inflammable. He had no statistics on the incidence of engine room fires and boiler room explosions in conventional ships but it was possible that they were not a negligible consideration in the estimation of insurance premiums. During operations the components of the furnace should be above the ignition temperature of many materials and cargoes. There was also the possibility of the escape, or blow back of oil vapour and the explosion risk associated with it.

In nuclear powered ships there was no comparable fire risk. The fuel was not by nature inflammable. Although uranium metal had its fire risk, the metal would not be used, and uranium oxide was nearly fully oxidized and had no fire risk. Similarly the other components of a reactor such as the water coolant, the steel and other metals had no fire risk.

With zirconium there was some danger of a metal-water reaction but the risk of this was exceedingly remote. In the operating system no exposed part of the reactor or fuel operated above about 300°C which was well below the ignition temperature of most materials. The fuel associated with auxiliary power could also be eliminated in the long term. The fission products in reactor fuel certainly represented a serious hazard but it was considered this was not of a destructive and violent nature comparable to that of fires. Although insurance premiums and costs on nuclear ships were likely to be initially high because of their unfamiliarity, and the lack of statistics, in the long run it was possible that the insurance on nuclear ships would be considerably lower than that on conventionally powered vessels.

The same considerations applied to the fire risk in shore-based refuelling installations. It was possible that a fleet of nuclear propelled merchant ships which would have a low fire risk, and which could go anywhere in the world independently of shore based fuelling supplies, would be an important national asset.

MR. N. BATTLE said that he had, over a number of years, seen the proposed reactor design and he wondered if the BPWR was now as well developed as the authors suggested For instance, in the case of the once-through steam generator; had any testing been done on this type of unit? Had the self-pressurizing concept been developed, and if so, what experience had been gained of the pumping of near saturated water? Also, he suggested that neutron detectors would not be effective in the shield tank, where there was a large amount of water and steel between them and the reactor core.

Had the cooling spray systems been tested? One could install them but couldn't test them at commissioning, and they might not work in the way intended, since when there was a reactor accident, there was likely to be a complete loss of electrical supplies.

It seemed that some updating of the reactor design was needed. It had been around in the form shown for quite a long time.

Mention was made of the advantage of the high coolant inventory from the leak point of view, but would not a low one be better in the event of a containment accident? Also, what about fission products which could be released into the containment? Was there any shielding protection for the crew, in the event of such an accident?

Mr. D. F. STREETON, A.M.I.Mar.E.,, said that escalation in the fuel oil costs was mentioned in the appendix and that much of the cost information used had been available for a year. What were the ground rules used for the nuclear fuel costs? About a year ago, uranium (U_3O_8) prices were about \$8/lb, but they were at present down to between \$6·8 and \$7·5, which seems to suggest that if this study was based on present-day conditions, the case for nuclear propulsion, in terms of operating costs would be enhanced.

Correspondence

Mr. D. F. STREETON, A.M.I.Mar.E., amplified his remarks in a written contribution. There was, he wrote, an old saying that "anything can be proven on paper", and this applied both in the positive and negative sense. Like in any economic analysis the paper was based on particular 'ground rules' which could or could not be appropriate. However, even allowing for optimism in giving values to 'ground rule' parameters it was apparent that economic nuclear propulsion was becoming more feasible. Confidence in this assertion was being shown by the Germans, Italians and Japanese who had judged that there was going to be a future in nuclear merchant ships. In this country we had the "economic bug" and we seemed to forget that the first nuclear power stations were not economic, but in most countries they now were. The reason for this was that it was only the practical experience gained in building uneconomic plants which led to economic solutions. Previously a sudden brainwave often brought about economic breakthroughs, but in the field of energy conversion, these days are over. Modern technology was such that it was only by systematically pursuing defined objectives, backed by practical experience, that a new concept could become economically viable. The real question that had to be asked in this country was could there be a future for nuclear merchant ships? If the answer was yes, than serious work had to commence unless, of course, we were prepared to leave the market open to the Germans, Japanese, Italians, etc.

Due to the costs involved the main responsibility for initiating a project had to lie with the Government. However, the shipowners and shipbuilders had to be the ones to show the necessary strategical foresight. When one heard of the progressive attitudes being shown in the countries of our main competitors, it was very sad to see so relatively few people attending this Institute meeting. For this reason he said he would like to congratulate the authors not only on providing an interesting paper, but for trying to keep alive interest in this country in nuclear propulsion which many responsible persons believed had a great future. Nothing lasted for ever and although many hated to think it, the oil-fired boiler and the Diesel engine would prove no exception.

In this regard Mr. Streeton concluded by quoting from Mr. George Sulzer's address to the Institute at the annual dinner last March. Mr. Sulzer said:

"Nuclear power I believe, is not an immediate competitor for the merchant navy of the next decade, but in view of the growing acceleration in technological developments it would be dangerous to rely on any so-called expert forecast in this respect."

MR. KOSTRZEWA in a written contribution, made the following points:

1) A full pressure containment was described in the text. It is assumed that the diameter will be 10-11 m and the wall-thickness 60–70 mm. For such wall-thickness it was necessary to stress anneal the welding seams.
    a) Did the authors consider site-fabrication of the containment?
    b) Did they have under control site-fabrication techniques within acceptable cost ranges?
    c) Would it not be cheaper to provide a pressure-suppression-system, which might be part of the hull construction instead of a full pressure containment?
2) a) Why did the authors not provide an auto-pressurization of the reactor till now?
    b) It was mentioned, that there was a possibility to change to auto-pressurization later on. How would the construction be in this case?
    c) Where were the pumps located then?
3) The primary circulating pumps (obviously of the canned motor pump type) were shown in an oblique position to the axis of the pressure vessel.
    a) Had pumps, positioned in such a manner, already been tested?
4) The control rods were driven electrically.
    a) How would power transmission feed the internal parts?
    b) Did the authors test a rod drive unit under ship conditions?

5) Obviously a core was provided, that remained in the reactor during the whole lifetime without shuffling.
    a) What were the specific fuel costs obtained with this core?
    b) Why did they not provide a shuffle core as was usual in land-based reactors in order to reduce fuel cycle costs?
6) The fuel elements would be fabricated from Zircaloy or stainless steel. Certainly Zircaloy would be chosen according to the better neutron economy.
    a) Would the lattices also be made from Zircaloy.
    b) Did the authors prefer a welding or a soldering method for the fixing of lattices?
    c) Did they carry out corrosion-tests?
7) Were long time burn-up tests with burnable poisons carried out?
8) In the case of integrated reactors the neutron flux densities were relatively low according to the great water spaces between core and pressure vessel. Why did they provide thermal shields for the design?
9) The pressure vessel was supported by a cylindrical hoop which was welded to the pressure vessel. Did this design allow for the stresses resulting from radial thermal expansions being kept under control?
    a) Did this design allow for the stresses resulting from radial thermal expansions being kept under control?
10) All pipe connexions of the pressure vessel penetrated a ring between the flanges, where only the space between the screw bolts was available. Therefore, the adjunction of the steam generator had to be divided into several small pipes.
    a) Wouldn't this unnecessarily increase the break-down-danger?
    b) Did each pipe have an individual shut-off valve?
    c) Was there a chance that safeguards authorities would accept this high figure of penetrations?
    d) How did they shield the penetrations?
11) a) How did they handle refuelling procedures? Was a land-based service-station needed?
    b) Was it necessary to remove the control rod drives individually?
    c) Which were the achievable refueling times (including shut-down and restart of the reactor)?
12) a) How did they perform periodic ultrasonic tests of the pressure vessel?
    b) Did the authors consider, at least periodically, testing all welding seams?
    c) Were all welding seams achievable by ultrasonic test equipment?

MR. V. D. Y. COCHRANE said that some years ago nuclear propulsion was being considered as a viable proposition if it tended towards parity with conventional means in terms of costs; later this standard was raised to parity itself and now at the present time nuclear vessels seem to have to show a definite economic advantage.

But even though it would seem that the latest condition could be met, Britain was ill-prepared to take advantage of it.

To those people who shrugged off the efforts made in this country to prepare for the nuclear propelled merchant ship, he pointed to the success of the Japanese shipbuilding industry which over a decade ago had the foresight to prepare for the building of large oil tankers, and were now preparing for the age of the nuclear propelled large containership.

He congratulated the authors on their struggle to present a case, mostly in economic terms, to justify a nuclear building programme. To people who questioned the basic reactor type presented, on the grounds that it had remained virtually unchanged over a period of years he would remind them that many years ago pistons were connecetd to a crankshaft to propel a motor car, and it appeared that this practice would continue. It was wrong to reject a proposal simply because it basically remained unchanged.

There were four points on which he asked the authors to comment:

a) there was no mention of a prototype reactor or ship, and he would therefore question the statement of the reactor price based on the 15th off;
b) a crew of 34 was mentioned as compared to a crew of 32, when we read of the complements in other (admittedly prototypes) nuclear propelled ships;
c) what would be the results in the thermal pattern if one boiler unit was shut down, or a pump stopped in the primary circuit;
d) could the authors indicate the hydrogen consumption in the core?

Authors' Reply

Messrs. Gaunt, Rouse and Wilkinson said that the results presented in their paper and appendix were a summary of recent work carried out as a private venture by the authors' company, making use of access agreements with the U.K.A.E.A. The paper took the work only as far as it was possible for them as shipbuilders to take it. From the conclusion reached, they felt that now was the time for a further study which should incorporate the shipowning viewpoint, especially operational, and the views of port authorities, unions and all other bodies who would be affected.

Most of the contributors to the paper seemed to be somewhat pre-occupied with the various details of the reactor, its materials of construction and the radiation it emitted. Although the authors agreed that these were indeed important factors, they tried to indicate that no matter how sophisticated the machinery or technology, it was of little value if the authors were not able to show that the proposed development was economically sound and more profitable than an existing alternative. The failure to do this was the reason why nuclear power was not adopted at the time of the Padmore Report but due to the changing marine environment, nuclear power could now be shown to be a good economic proposition under particular circumstances. The authors argued they were by no means alone in this belief. Among international shipbuilding circles, the Germans and the Japanese had both recently proposed that they should join together to undertake the development of a nuclear powered container ship, the end result of which would be a fleet of such vessels.

Since shipping today was an internationally competitive business, and one on which Britain relied heavily to support its balance of payments, the dangers of leaving herself open to international competition and allowing her rivals to produce economically competitive nuclear powered ships had to be appreciated. Such ships would take three to five years to build, during which time a marginally profitable U.K. shipping industry could well become unprofitable.

There was still too much emphasis placed on the first cost of nuclear powered vessels as a basis for comparison with conventionally powered vessels; and not enough on what should be more important—that of whole-life costing and ultimately the profitability of each type of propulsion system/vessel combination.

This conservatism of U.K. shipowners regarding the price level of vessels was understandable in the past when they did not have access to large capital sums to invest in the new tonnage. Today, there were the large consortia to make large financial resources available.

Tomorrow, it could well be that the consortia would need the nuclear ship to remain viable in the face of competition and increasing operating costs.

The authors went on to say that the BPWR system had not yet been built. Most of the calculations and design were an extrapolation from existing data and some development work in parallel with the construction of the first reactor would need to be done to confirm the validity of the extrapolation. The authors had from the outset however treated the reactor like any other piece of bought out equipment.

In his interesting contribution, Mr. Hildrew suggested that the same reactor had been selected as was proposed eight years ago. There was some doubts in the authors' minds that the BPWR did date from 1962. It may be that it was being confused with Vulcain or the abandoned IBR. The design of the BPWR had been worked up to the state of firm proposals backed by the expertise of the U.K.A.E.A. It took account of existing practical experience and was a design that could be built today. Supporting data had been used from other pressurized water reactors and it was not without interest that all integral pressurized water reactors had evolved in the same direction and looked very much alike. It was the authors' opinion that the pressurized water reactor would be with us as the preferred system for a number of years yet. Mr. Hildrew's suggestion of the direct cycle gas turbine nuclear system was theoretically very attractive. It was still, however, a long way off and could not form the basis of a present day nuclear powered ship system.

The calculations and economic analysis carried out by the authors were found necessary, and the simple approach suggested by Mr. Hildrew could give a most misleading result. It had to assume that sums of money arising at different times were equally important, and none of the strategic advantages of nuclear power could be taken into account.

Referring to Mr. Hildrew's specific technical queries, Messrs. Gaunt, Rouse and Wilkinson said that the leak test pressure after refuelling and/or maintenance would be as agreed between the operator and the classification society. The elimination of a separate pressurizer vessel by an internal pressurizer using self pressurization could no longer be regarded as a possibility when practical experience had demonstrated the effect on the self pressure control system of a large reactor of the forces to which ships were subject. To date, the self pressurizing system had only been proven on a comparatively small reactor, and extrapolation to the sizes proposed in the paper would be out of context with the authors' intention to propose a system which could be safely built now. The authors had not therefore linked out economic analysis to potential engineering developments, except for the production learning curve on the reactor pricing. The oil prices used, bore no relationship to coal prices as their imaginary owner was buying the oil at as near the source of supply as possible, and certainly not in the U.K. where oil was taxed to protect the price of coal. The nuclear fuel prices were, like the oil prices, based on quotations received for the supply of fuel to the required specification.

In reply to Mr. Boos, the authors could not, for commercial reasons, divulge the names of owners with whom they had had contact, save to say that they all had a genuine interest in the possible use of nuclear power. It had nevertheless been difficult to carry out the economic study in the absence of direct owner participation which was not yet available. They admitted that many of the assumptions were, they hoped, intelligent guesses, and they would welcome any comment from people actually involved in the day to day running of a ship.

Dr. Ejiyere was worried about radiation damage. The design and shielding of the reactor were such that no precautions need be taken for radiation during the normal operation of the vessel. All liquid and gaseous wastes could be collected and discharged to shore storage facilities. It was not necessary to remove the steam generator entirely from the active zone of the core, as distance and shielding reduced the effect of radiation on the secondary system to a very small amount. The only carry-over into the secondary circuit of any consequence was the short-lived isototpe N^{16}, formed by the interaction of 0^{16} with a fast neutron. Although the gammas produced as a result of the decay of N^{16} were extremely hard, N^{16} had a half-life of only 7·16 seconds. Thus, this activity created no operational problems.

In reply to various contributors, the authors said that no account had been taken in their economic analysis of the cost of the initial research and development. If it was required to write off initial research and development over a number of units, the equivalent adjustment could be made to the economic input data in the equations.

In the appendix to the paper the costs of the second off reactor had been compared with the costs of the 15th. The second off reactor had been priced clear of the initial research and development but included a proportion of the costs of jigs and tools and production drawings, and it was also at the commencement of the learning curve.

In the calculations, a notional figure of £65 000 had been allowed as the total cost of the refuelling. Equipment write-off was over a large number of operations on a number of reactors and the authors considered that the figure suggested by Mr. Deighton was too high, unless it was based on a single reactor in a single ship.

In reply to Mr. Deighton's last point, an extensive study had been carried out by an international boiler manufacturer which confirmed the feasibility of the design.

The principle of the collar had been thoroughly tested out on BR3/Vulcain.

In reply to Mr. Weiss' suggested lifting of the reactor, the authors said that in their design studies of nuclear powered container ships and tankers they had looked into the effects of siting the reactor in other conventional boiler positions. In the container ship design they tried siting the reactor immediately forward of the machinery in the "all-aft" position, but this had been unacceptable due to the severe trim of the vessel by the stern. When siting the reactor in the conventional boiler position for this type of vessel, the stability of the nuclear vessel was insufficient unless a considerable amount of permanent ballast was carried in the double bottom. To place the reactor above the main machinery required extensive shielding beneath the reactor, quite apart from any structural difficulty in supporting such a large weight a considerable height above the keel. This bottom shielding was not necessary with the reactor in the 2/3 aft position sited on the double bottom, as the sea water then acted as adequate shielding. If divers had to go down to inspect the bottom of the vessel, the double bottom could be flooded and with the reactor in the 2/3 aft position the saving on shielding and steel structure could be given over to the carriage of extra cargo deadweight.

The safety argument and a design and built acceptable to a classification society had to be dealt with as a whole before agreement was reached on the separate parts. One of these separate parts was the containment leak rate. The authors proposed to use the methods of safety analysis being developed by the U.K.A.E.A., i.e. the criterion of accident probability rather than the maximum credible accident approach currently in use. The heat exchanger coils were of Inconel. Safety valves would be duplicated in order that a leaky valve could be isolated until the opportunity was available to deal with it. The clean-up plant installed downstream of the ventilation system consisted of two banks of filters each containing the following components:

1) a water extractor;
2) a filter unit consisting of a spark arrestor, coarse filter, fine filter and an absolute filter;
3) a carbon bed filter;
4) a filter unit consisting of a coarse filter, fine filter and an absolute filter.

The filter units and the carbon bed filter were fitted with differential pressure instrumentation to give warning that filter renewal was required.

The decay heat removal system was duplicated, having one 100 per cent leg on each side of the ship. Heat removal would be through that side which happened to be higher when the ship was listed and theoretical studies showed that a list of more than 35° would not affect the operation of the system. The heat exchanger was divided into 28 parallel paths; each path consisted of 38 coils in parallel connected to two tube plates, resulting in a total of 1064 separate coils. If a leak was detected by a rise of secondary circuit radio-activity, that boiler unit comprising a quarter part of the heat exchanger could be closed off and the load reduced accordingly. The leaking tube could be identified and plugged using relatively simple procedures. Regarding the question of safety, a comprehensive analysis would be built up from a study of every system, to give an overall understanding of the reliability and how it satisfied classification requirements.

In reply to Mr. Syed, the authors said that they had assumed, for a ship using production reactors, equal built times for nuclear and conventional systems. This could be a little optimistic but, in their view, was close enough to a correct assessment not to affect the end result.

Crew costs initially had been assumed higher on the nuclear ship because of the two extra crew, but with equal crews the same cost differential had been maintained. The 'get you home' system has been designed to maintain a ship's speed of not less than six knots.

The authors appreciated Mr. Turner's comments regarding work which was carried out by Vickers Ltd. in 1965 and they made this an opportunity to thank Vickers Ltd. for letting them use this data in the preparation of their paper.

Mr. Battle asked about the development state of the BPWR. As far as possible the design had been based on the present state of the art in order that existing experience could be utilized to the maximum. There had not been, however, any actual testing of the component mentioned. Ample Diesel generator and battery capacity was installed to ensure continuity of supplies in the event of an accident. The only disadvantage of high primary coolant inventory was a high containment pressure in the unlikely event of an accident damaging the reactor pressure vessel. This was, however, a design and fabrication problem which was preferable to the difficulties that would result from having a low primary coolant inventory, and then insufficient water or time in which to take corrective action. The containment was shielded although this was not shown on the drawings.

The authors agreed with Professor Walton's enlightened view on fire risk.

In reply to Mr. Streeton, the authors said that the reactor core was costed as another bought out item. This was quoted to them by the fuel suppliers as a capital sum and buy back value. These sums arose at different times and appropriate account was taken of this in the calculations. The authors did not involve themselves with the cost of ore, enrichment and fabrication, any more than an owner of a conventional ship, buying oil, would worry about detailed refinery costing.

Taking Mr. Kostrzewa's questions in the order he asked them, the authors said the wall thickness of the containment vessel was such that the vessel would require stress relief, which would be fabricated as part of the shipbuilder's supply with the hull, using established techniques. A pressure suppression system would possibly be cheaper but, even then, the accident pressures which could be reached were greater than the present provisional rules regulating the pressure to which a hull could be subject. There were also difficulties in the design of a hull structure to resist pressure and have an acceptable leak rate; the amount of reinforcement required could result in a greater weight of material being required than for the containment proposed, even though the accident pressure was much lower. Using the hull structure also markedly affected safety analysis as there was one less barrier between the core and the environment, and the containment boundary was extended towards possible collision areas. Furthermore, it was awkward to provide a pressure suppression system without also using a self pressurizing reactor system which had been commented upon earlier.

On a self pressurizing system the pumps had to be located in such a position that there was adequate net positive suction head over them at all times. Thus they could not be on the reactor pressure vessel lid as in the BPWR proposed.

The pumps used were of a design already in use in pressurized water reactors; they would operate in the oblique positions shown.

Ample experience of control rod drive behaviour was available from the marine reactors already at sea. All electrical supplies and mechanisms were above the reactor vessel top dome. Specific nuclear fuel costs at various discount rates could be derived from Fig. 27 of the Appendix; shuffling was not proposed for the marine application, as the economic gain would not outweigh the delay caused by taking the ship out of service between refits.

Fuel lattices or grids were of Inconel and welding would be used. Similiar fuel had already been tested.

The method of containment support permitted radial expansion with very little restraining force and was superior to other forms of support in its response to thermal movements.

The use of a large number of small pipes on the boiler ring resulted in easier control of fabrication and minimized the amount of compensation for penetrations. Damage would result in the loss of secondary fluid only. It was possible to place a valve in each pipe; however, each of the four separate boilers had been designed only to be shut off individually. Penetration shielding was not a particular problem owing to the distance of the penetrations from the active core and the amount of shielding between them and the core.

A land based service station was proposed for refuelling; this would take an estimated 22 to 25 days and could be carried out concurrently with other refitting and overhaul work. The control rods were disconnected from the drives and remained in the fuel elements during fuel discharge; the drives could, therefore, be attended to as convenient.

Detailed inspection of the pressure vessel could be arranged during refuelling.

The authors were pleased to note that Mr. Cochran's views were much in accordance with their own. They had commented earlier on the reactor pricing and maintained that there was no reason why the nuclear ship crew should eventually exceed the conventional ship crew. If a boiler was shut down the thermal pattern would be unaltered, as each set of boiler tubes extended to all areas of the total heat exchanger. If a pump stopped, the thermal pattern was similarly unaffected, as the pumps discharged into a plenum above the boiler coils. Hydrogen consumption in the core was virtually nil once equilibrium conditions had been established.

The authors' final comment was addressed to Mr. Streeton with whose opinions the authors generally agreed.

Many years ago, Britain had thrived because of her willingness to go out and seek new horizons. Then she had commanded the largest merchant and warship fleets in the world and prospered as a result. Today, we in the United Kingdom seemed to be quite willing to allow our one time great merchant fleet to slip further into relative obscurity; to accept, year by year, an increasing volume and value of our import and export trade to be carried in foreign vessels and an increasing number of our merchant vessels to be built in foreign shipyards; and to rely to an even greater extent on the technologies of other industrial nations.

Finally, during the various presentations of this paper the authors did not fail to notice the reluctance of the members of the United Kingdom shipping fraternity to express their opinions in relation to nuclear powered merchant ships, whilst on the other hand the Japanese and German owners had shown a considerable interest.

The reason for this silence was perhaps that they were all considering that it would be cheaper in the long run to buy these vessels abroad; the question was—cheaper for whom?