Problems of Merchant Ship Nuclear Propulsion

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The paper offers no new reactor concept but discusses the fact that all marine reactor installations proposed to date are totally uneconomic. In addition, the apparent savings in relation to new reactor designs disappear when a project is required to conform to the accepted conservative design criteria and contruction codes for marine nuclear work. Accordingly the major engineering and ship items are examined which are amenable to modification and cost reduction without impairment to the reliability required of a marine installation.

Suitable reactor types already proven on land, together with those being developed, or capable of development, as marine reactors within the present decade, are briefly examined in relation to the proposed design variations and the potential of each reactor in a marine installation is discussed.

The paper concludes that parity with conventional marine engines will ultimately be achieved, but for any chosen reactor type considerable financial outlay on development and proving a land based prototype installation, will be necessary.

INTRODUCTION

It is necessary to examine the feasibility of any equipment designed for the production of power in terms of engineering and cost. The safety of a plant both in respect of itself and its operators is an inherent factor in these items.

Nuclear propulsion combines nuclear reactors, which to date have a remarkably high safety record, with well found conventional ships, which are seldom in hazard unless in consequence of human error. Accordingly it is reasonable to concede that almost any reactor could be installed in a hull form and the ship operated under internationally acceptable safe conditions. Unfortunately, whilst such a project is feasible in terms of engineering there remains one basic problem. It is not feasible in terms of cost.

From this one problem a number of subsidiary problems evolve, all associated with determining the least costly reactor, due regard being paid to the safety requirements of each reactor type. It is often claimed that too stringent safety requirements are the cause of high cost, but this is not wholly true.

Marine nuclear reactors occupy a volume considerably larger than the boilers they replace and thus the cargo capacity is reduced. Economic viability will be apparent in ships where high utilization factors are possible and where the beam of the ship is large enough to maintain a machinery space length comparable with or below that of conventional plant. This implies a large ship and demand for such ships in any trade is limited.

The ultimate aim of nuclear plant must be economic parity with dry cargo vessels of 10,000-15,000 d.w.t. and such a ship carrying a high non-propulsive load, e.g. a refrigerated meat ship trading through the tropics, might offer the best prospect in this field. If the cost of a nuclear plant plus 20 years fuel and maintenance exceeds the cost of boilers and associated oil fuel and maintenance for the same period, the reactor installation must offer other advantages, such as higher speeds, greater reliability or larger utilization factors.

It is of course possible that the size of a dry cargo ship may change in the manner that an oil tanker has changed over the past decade. As an example the introduction of cargo containers may lead to larger ships trading to a few large well equipped and highly mechanized ports linked to their hinterland by priority road and rail transport. However, it is more realistic to relate nuclear propulsion to contemporary ships and endeavour to illustrate as simply as possible its cost and to discuss acceptable design modifications which could effect a reduction in price.

ECONOMICS

There are three types of ship which can have a high utilization factor, the passenger ship, the tanker and the ore carrier. Present trends suggest a preference for 50,000-g.r.t. passenger ships with 30,000 s.h.p. and 65,000-d.w.t. tankers and ore carriers with 20,000 s.h.p. machinery installations.

The cost of the hull for such ships would be of the order of £15 million for the passenger ship and £3·5 million for the tanker and ore carrier.

The cost of the main conventional machinery would be £2 million for the passenger ship and £1 million for the tanker and ore carrier.

The large tanker, while not numerous, is built in greater numbers than the other two types.

Large ore carriers in general have a relatively short voyage length. In addition, the ports used by ore carriers are often smaller and less developed than those used by tankers.

Passenger ships are tending to be smaller as air transport increases, but as an example, a high utilization factor should be achieved by a passenger ship on the London-Australia run, and providing passengers would be prepared to accept nuclear power, such a ship might offer the best prospect in this field.

The capital cost of nuclear plant is dependent upon the type of reactor, but in general terms can be roughly estimated as £1,000/ton weight.

Excessive weight is not a major problem except that, according to the above criteria, it is expensive. The major ship problem consequent on the use of nuclear power is to reduce overall length of machinery space. Not only does this permit higher earning power but in the context of the tanker

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and ore carrier it will greatly simplify the trim and hull bending moment problems. In a passenger ship the effect of long machinery spaces in association with the elimination of bunkers introduces a stability problem. Thus a nuclear plant must be capable of integration into the hull in order to meet requirements of safety and must permit access for maintenance. As for conventional plant the installation must occupy the smallest possible space. A reactor installation could be readily installed in these three types of ship, but in the United Kingdom most reactor studies have been related to a tanker installation.

Early studies naturally centred round the feasibility of a gas cooled graphite moderated reactor. Such installations weighed 5,000 tons and thus cost about £5 million. After further optimization the weight of a 20,000 s.h.p. reactor installation was reduced to 2,000 tons which was comparable with proven water and organic moderated reactors developed in the U.S.A. The capital cost of the nuclear plant was about £2 million.

Other reactors are being developed, some specifically for marine use, and an installation weight of 1,500 tons is now estimated for those reactor types sufficiently developed for immediate installation. It is probable that the capital cost of the nuclear plant would be about £1·5 million.

In addition to the nuclear plant, fuel must be provided throughout the operating life of the ship. The fuel cost depends upon the assumptions made in relation to a large number of variables. A few of these variables are, market cost of uranium, cost of element manufacture, choice of fuel enrichment, average burn-up (degree of axial and radial flux flattening), refuelling cycle, i.e. complete core or continuous, the xenon override requirement, the quantity of fuel throughput per year and the value of irradiated fuel. There are many other factors and depending on whether immediate reality or forward looking is employed, fuel costs range from 1·0d./s.h.p. hr. to 0·15d./s.h.p. hr. Without going into a detailed judgement of these figures it is sufficient to state that a fair assessment for an immediate installation would be 0·5d./s.h.p. hr.

As a reactor installation replaces the boilers in a conventional plant it is only necessary to compare the capital cost and running cost of boiler equipment with the above figures in order to determine the economic promise of nuclear propulsion.

A boiler installation for a 65,000-ton 20,000 s.h.p. tanker would cost £150,000 and the associated oil fuel cost would be 0·3d./s.h.p. hr.

It is evident that the comparable nuclear installation figure of £1·5 million capital cost and 0·5d./s.h.p. hr. fuel cost is totally unacceptable.

The figures quoted for the boiler installation are deliberately high and the figures for the nuclear reactor are possibly optimistic and are related to production units and not prototypes.

Although a shipowner will require the cost of any new equipment to more than break even with his present plant cost it is worthwhile determining a "break even" point in order to indicate the size of the problem.

If the capital cost of the reactor installation was reduced by £1 million the extra capital required for the reactor plant would still be £350,000. Marine machinery is written off over a 20-year ship life and insurance charges and dividends must be paid over this period. Capital investment must necessarily earn 15 per cent gross profit to meet these requirements. Accordingly, investment in the extra capital cost of the nuclear boiler represents a requirement to earn an extra £52,000 per year or alternatively to save an extra £52,000 per year.

If the ship operates for the equivalent of 320 full power days a year the nuclear fuel cost at 0·5d./s.h.p. hr. will be of the order of £320,000 per year and the oil fuel cost at 0·3d./s.h.p. hr. will be about £192,000 per year. If the nuclear fuel cost could be reduced from 0·5d./s.h.p. hr. to 0·22d./s.h.p. hr. the annual fuel cost becomes £140,000 per year and saving of £52,000 per year in fuel would be effected.

These sums simplify the problem excessively but they are adequate enough to indicate that the "break even" point for nuclear propulsion will be in sight when a plant capital cost of £500,000 and a fuel cost of 0·22d./s.h.p. hr. is reached.

The costs quoted relate of course to the production of a trading ship. No portion of the costs incurred during research and development through the prototype stage of the plant are contained in this approximate estimate. Depending upon reactor choice, the cost of research and development will vary, and will be of the order of £10 million but for the purpose of this paper such costs are not regarded as a charge on the prospective buyer.

Another factor which has not been considered is the ultimate scrap value of the ship. On completion of the working life of the hull considerable expense might be incurred in disposing of the reactor plant. Thus the owner may require a greater return on his capital over a longer working life to offset this ultimate commitment.

Essentially the cost of a nuclear installation is dependent upon engineering design, construction and integration into the hull. Nuclear safety problems, associated with the chosen reactor, and safety problems, consequent upon operating a nuclear plant in a ship, also contribute to a lesser degree.

ENGINEERING DESIGN AND CONSTRUCTION OF NUCLEAR PLANT

The following list of items is covered in the proposed capital cost figure of £1·5 million. An approximate percentage cost of each item is indicated:

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

Naturally the itemized cost will vary greatly between reactor types and these figures are only intended to give a feel of the cost distribution.

In general the nuclear parameters, upon which the reactor design is based, are fixed and it is on the engineering of the above items together with the fuel element manufacture and reprocessing procedure that savings must be made.

Containment

The containment structure surrounding the nuclear plant is designed to prevent escape of fission products to atmosphere or to other habitable ship compartments after a nuclear incident. The design of the containment is dependent upon the major accident which can occur in it and an accurate assessment of this accident is essential. The arbitrarily imagined accident ranges from the highly improbable to the nearly impossible. The general accident considered is complete failure of a main primary coolant pipe at working pressure, with consequent free discharge of primary coolant into the containment through two maximum diameter primary circuit pipe nozzles. It is also assumed that the membrane separating primary and secondary fluid fails and the contents of the secondary side of at least one heat exchanger discharges into the containment. In addition exothermic chemical reaction, consequent upon core melt-down, must be considered.

Failure of high quality welded pipework is so rare that information of its mode of failure is not amenable to analysis and no record can be found of large diameter pipe failures of the type outlined above. As the assumption of such a failure produces a rapid peak pressure in the containment vessel this often constitutes the design criteria fixing the containment scantlings.

Tube failures in modern watertube boilers are very limited and can generally be attributed to an inherent tube defect or to mal-operation. A large failure of the primary/secondary interface is extremely unlikely. It is difficult to imagine under what circumstances such a failure could arise in a heat exchanger of any approved design, built to approved standards of construction and operating over limited temperature gradients.

A basic assumption which has not been stated in any marine nuclear requirements, is that the major internal accident of a primary circuit failure and the major external accident, a collision at sea can never occur simultaneously or be contingent upon each other. Thus, it is intended that in the event of a collision at sea, collision protection integrated into the hull structure abreast the reactor must be reasonably adequate to prevent breaching of the containment structure, or at least be adequate to prevent breaching of the reactor primary circuit. A flooded containment space would be the equivalent of a flooded boiler room in a conventional ship and it is suggested that this is an acceptable assessment of such an accident.

If a ship sinks beyond salvable depth it is assumed the containment space will flood and the nuclear plant will be permanently surrounded by water. If a ship sinks in less than 100ft. (30 m.) of water it is reasonable to hope that it can be salvaged and, whilst it is desirable that as little water as possible enters the hull, it is not very important whether the containment space is flooded or not, though it might be advantageous in the event of serious hull damage to permit flooding and thus provide extra shielding during the salvage operation. Complete submersion for a long period would do little damage to the primary circuit integrity of any reactor installation if orthodox materials were employed. The present requirement, to maintain a dry containment if salvage is possible, is not tenable as design data will never be available to guarantee an adequate balance valve design. In addition as the size of the containment decreases, the space available for mounting such valves in the pressure membrane will be limited.

Information released on nuclear submarines shows that the hull structure is used as the containment vessel and as these vessels are essential to a country's defence no great outcry has occurred at this stage. The submarine hull form is, of course, totally submerged and suited for use as a pressure part, being cylindrical and possessing scantlings to withstand the external pressure, consequent upon diving requirements. The internal bulkheads too, can be designed to withstand the pressure which would occur if a compartment was open to the sea during submersion and can equally be made to withstand the major nuclear accident pressure.

The Inter-governmental Maritime Consultative Organization requirements for nuclear merchant ships promulgated at the London Safety of Life at Sea Conference in 1960(1) are worded to permit containment in the hull structure stating as they do that "the reactor installation should be provided with enclosures, systems, or arrangements which will prevent the release of hazardous amounts of radio-active or toxic materials into service and accommodation spaces and the ship's environment".

Elimination of a separate containment vessel is possible if containment in the hull structure is feasible. Obviously, in such circumstances, the cost of strengthening the hull structure must not be excessive and care will be necessary to ensure that the hull stiffness is not greatly affected, thus ensuring freedom from stress concentrations.

An outside figure, to which a hull compartment might be constructed as a containment vessel without introducing major ship design problems, is about 30lb./sq. in. (2 kg./sq. cm.) and obviously the lower this pressure, in relation to any particular reactor installation, the easier and cheaper hull containment becomes.

Reactor designs which permit low containment pressure are obviously at an advantage in this context. The advantages which will accrue with a change to hull containment are:

1) A better distribution of nuclear plant in the hull.
2) A larger volume to act as the container, with consequent reduction in peak pressure.
3) A smaller volume used as machinery space, with consequent improvement in operational economy.

If the reactor containment pressure is estimated to be higher than the figure quoted above, the provision of some form of pressure suppression device might still permit of hull containment. The design of pressure suppression devices does not appear to have been given any great attention although the United States Atomic Energy Commission have accepted a liquid baffle device for the Humboldt Bay project. Reactors of the pressurized water reactor and boiling water reactor *genre* will be able to take advantage of the reduction in costs consequent upon containment in the hull structure by utilizing such a technique.

The alternative to containment in the hull structure might be to move in the opposite direction and reduce the containment vessel size. This would be achieved by reducing loop dimensions and installing the heat exchangers adjacent to, or alternatively in the reactor vessel. Such a design demands high operational reliability, as maintenance will be limited. Any increase in containment pressure will be more than offset by the reduction in size and thus the containment plate scantlings will not increase and might reduce. Economy dictates that a containment structure should be of an orthodox steel below 1½in. thick in order to avoid *in situ* stress relief.

Reactor Vessel and Primary Circuits

It is essential that the high standards of design and quality control, accepted in the land reactor field and outlined in relevant pressure codes,(2) be maintained in marine installations.

The capital cost of the reactor vessel and associated piping proposed for marine nuclear installations varies considerably. The reactor pressure vessel, designed to operate at a pressure of 1,500-2,500lb./sq. in. (105-175 kg./sq. cm.) with a 6in. (150 mm.) wall thickness, is a costly item, whereas the materials of a low pressure reactor circuit or of a pressure tube assembly are much cheaper. Not only in themselves are such pressure containers cheaper, but penetrations into the vessel for instrumentation or control are easier to engineer and the facilities for defuelling are simplified.

It is the practice in the U.S.A. to use clad steel pressure vessels and stainless steel piping for water reactors and, in the process of buying information, all countries interested in these reactor types have to accept this practice both in the commercial field and in the naval reactor field.

The cost to the British Admiralty, to maintain the low alloy circuit of the British prototype submarine machinery free from corrosion during construction, must have been high, but techniques have had to be developed to control this problem. A recent paper by Ridley *et al*(3) indicated that a positive breakthrough on the problem had been achieved, by inducing a magnetite film on the internal wetted surfaces of the circuit, by steam processing. The capital cost of commercial marine nuclear plant must be reduced by a factor of three and therefore it is essential that the reactor circuit material should be a plain carbon steel or some other orthodox cheap material. Any designer who refuses to concede this requirement is wasting his time. In the long term it may be worthwhile examining the feasibility of a pre-stressed concrete reactor vessel.

Heat Exchangers and Pumps

Consequent upon the nuclear reactors under construction in the world, an ever widening field of reliable pumps and valves is available. It is possible to buy ready designed units which fulfil normal reactor loop requirements, particularly for water reactors. Such pumps use exotic materials and ultimately a glanded pump in plain carbon steel must be developed. A low primary coolant pressure is also of considerable advantage when pump and piping costs are being considered.

Provision to remove a defective pump and replace it, without major hold-up to a ship, is essential. This requirement produces two basic solutions. The first, to build a very reliable pump. This can be done either by utilizing high engineering manufacturing skills or by reducing the number of moving parts. The second solution is to eliminate the pump completely and to rely on natural circulation. This latter solution would be preferred, if it could be shown that natural circulation would be maintained under all operational and accident conditions. However, such proof is difficult to establish at the design stage.

Primary circuit loops, with associated pumps and heat exchangers are required to be duplicated although the conditions of operation of a heat exchanger are not as onerous as that of an oil fired boiler, owing to the lower temperature gradients. The reason for insisting on duplication is associated with maintaining some degree of operation other than the basic "get you home" orthodox emergency plant.

Failure of a heat exchanger could mean a long delay to a ship, as a major replacement part, to the standard of workmanship required, could take some time to construct. In such circumstances, assuming the failure was not an inherent design defect, the ship could remain operational on one heat exchanger with only limited speed reduction.

Re-tubing of an orthodox marine boiler is seldom required and there is no doubt that the level of deterioration of heat exchangers in reactor plants is proving so low, that a single heat exchanger unit, proved by operational experience, will ultimately be accepted in any marine project. Easy access for inspection and replacement of heat exchanger tube nests is essential. The alternative approach, which is preferred if steam generators are located adjacent to or in the reactor vessel, is the provision of a number of heat exchanger units which can in the event of failure be individually isolated and renewed.

A reduction of the heat transfer coefficient, across a heat exchanger tube nest, must be caused by fouling which in turn is consequent upon deterioration of coolant, or salt water leakage into the feed system. Ships float on a salt solution and the necessity of preventing small amounts of salt from entering feed water will require very high water chemistry control.

The use of stainless steel heat exchanger tubes, as in the *Savannah,* is undesirable as they are liable to chloride attack. For a ship reactor it is undoubtedly preferable that the primary/secondary heat exchanger membrane be in a plain carbon steel or a corrosion resistant alloy. As such a unit usually consists of a tube plate and associated tubes, both items should be of compatible material. The use of a corrosion resistant alloy such as Monel is more expensive than stainless steel and accordingly low alloy or plain carbon steels are to be preferred. Evidence offered by Ridley *et al*(3), consequent upon work carried out in relation to the British submarine prototype machinery indicates that first costs in establishing techniques are high, but the ultimate corrosion level of low alloy steel is of the same order as stainless steel. This evidence is a clear pointer to the marine reactor designer. A considerable price saving must evolve from a decision to build in more orthodox and cheaper materials.

Shielding

Shielding of a marine reactor is usually in the form of a primary and a secondary installation.

The functions of the primary shield are to provide adequate protection, under shut-down conditions, in order that maintenance can be effected in the reactor compartment and to attenuate neutron flux at power, thus ensuring negligible activation of components outside the shield. Proposals to date have generally contained variable quantities of lead, concrete, steel and water. Lead is an expensive material and it is more usual for a designer to provide concrete or a steel and water shield. There is no major problem associated with the provision of a concrete primary shield, except that access must be possible around its base to permit inspection of the support members in the ship's structure. Local design of a ship's structure is only amenable to some small degree of modification and care must be taken that no stress concentration results from installing such a rigid mass in the hull.

The use of steel in association with water as a primary shield is also frequently proposed and is usually formed into an annular tank. Corrosion control of the tank is necessary, as no protective coating will stand an indefinite immersion in water and maintenance work in the tank is not possible. The shield water requires to be cooled and the coolers must be capable of inspection and repair.

Lead, as a primary shield material, should be located in a position where limited cooling only is required, as maintenance of cooling coils will not be easily effected.

The choice of secondary shield materials is limited. The use of large quantities of concrete is undesirable in the flexible structure of a ship and alternative materials are more expensive.

Secondary shielding is designed to give protection to crew members during normal ship operation and, in addition, to provide a degree of shielding sufficient to permit emergency action to be taken in the event of the maximum accident considered feasible. This requirement could be summarized as:

1) Adequate shielding to permit operation for ten minutes in habitable spaces or machinery spaces adjacent to the reactor compartment or containment structure.
2) Adequate shielding to permit continuous watchkeeping in parts of the engine room.
3) Adequate shielding to permit permanent manning of the control room.

Any material used as shielding must contribute only limited stiffness to the hull structure. The support of shielding by hanging it in or on the containment vessel has been the method usually proposed. Such shielding can prove difficult to distribute effectively, and can influence the scantlings of the containment vessel. If containment in the hull structure is contemplated shielding of such a structure might prove to be economically unacceptable. A consequence of this will be that designers must re-distribute their primary and secondary shielding proportions.

Essentially what is desirable is a reduction in primary loop dimensions. Heat exchangers must be accessible for inspection or be capable of rapid replacement. Alternatively, they must be built to the same standards as the reactor vessel and such a development would greatly increase first cost owing to the complexity of heat exchanger internal equipment. Banks of small heat exchangers, sited adjacent to the reactor vessel, or in the primary shield assembly, would appear feasible. The use of such a technique would permit a reduction and a possible re-siting of the secondary shielding which is required to limit the radiation from the short lived primary loop activity, particularly in water reactors on load.

Assuming the reactor compartment is adjacent to the main engine room, it would still be necessary to provide shielding on the separating bulkhead and it might still be necessary to provide limited shielding on the deckhead of the reactor compartment and on the ship side area in order to limit the radiation hazard in consequence of a major nuclear plant failure.

The shielding required over the ship side area should, however, be re-assessed in relation to the major accident. The consequences should be determined of relaxing the present industrial tolerances used as design criteria.

In such circumstances, access through the ship, if necessary for crew members, would be effected by a shielded walkway abreast of the reactor compartment.

The major accident concept has already been referred to and it is essential, in the event of such an accident, to have accurate knowledge of the degree of core melt-out and of maximum possible gaseous fission product release into the containment structure. A fuel element which inherently limits fission product release must be given credit for this fact, rather than be allocated an arbitrary percentage release, thus requiring excessive secondary shielding. Optimization will occur in a design requirement which limits the fission product release, at melt-out, to the same order as the aggregate loop fission product activity prior to the accident.

Collision protection will only contribute in some small degree to shielding, and the provision of additional steel or lead as shielding material is desirable. The nuclear requirements of Lloyd's Register of Shipping(4) specifically bar the use of water in wing tanks abreast the reactor space, because the impact of a collision may be transmitted through the water of a full tank and breach the inboard longitudinal bulkhead and because it is certain that, someday, the tank would accidentally be pumped out. Consideration would be given to water in a longitudinal cofferdam as an alternative to lead or concrete on a longitudinal bulkhead. It is possible that the ship construction costs might be increased by adopting this proposal and an examination of the consequences of losing the shielding medium would be necessary.

Control

The basic engineering problem associated with control of any reactor is the necessity to provide a complex control mechanism capable of intermittent and continuous operation, which is both reliable and simple. There are many ways in which control can be effected and simple requirements applicable to all installations are not easily summarized.

Considerable industrial effort is required to produce a reactor vessel head with acceptable penetrations. Accordingly, as control mechanisms are often in positions of limited access for maintenance and repair, the designer will ultimately eliminate moving mechanical linkages and seals.

A reliable control system which has limited moving parts and few or no penetrations into a pressure vessel is a great economic attraction as it reduces the number of seals and limits the amount of local reinforcement. The recent development of "spectral shift" as a method of controlling water reactors may provide a simple control system to meet the wide operational requirements.

A control system performs several different functions and the present practice is to perform all functions with one complex system. This is typified in the *Savannah* control system. Reliability in such systems is an expensive requirement.

It is possible that separation of functions such as controlled start-up, variation in output, poison overrides, flux pattern maintenance, etc., could lead to economy.

Reconsideration could be given to the basic measurements utilized to effect control. Control rods are generally governed by neutron measurement and it is possible that simplification might be effected by using temperature as the basic parameter with only limited nuclear instrumentation to indicate the gross malfunction.

Instrumentation

A paper on "Ship Reactor Instrumentation" by Anscomb and Hutber(5) gave an outline of possible requirements and there is no doubt that considerable thought must be devoted to eliminating what is desirable and retaining only that which is essential. Nuclear instrumentation requires extensive duplication, both of power supply and instruments, and early nuclear ships are bound to be over-instrumented. It will require considerable operational experience before a basic simple installation is acceptable.

Refuelling

There is a strong incentive to defuel and refuel reactors in accessible ports and this will entail special port facilities.

To permit reasonable ship economics, defuelling must occur very infrequently (1 year minimum with 2-4 years preferred) and be relatively easy to effect. Rapid access to the reactor head, rapid fuel transfer and rapid re-installation of equipment is essential. Refuelling on load in a ship is a doubtful asset. The reactor core assembly is a precision built structure and the certain safe withdrawal of fuel elements in a seaway is difficult to envisage.

Large groups of the general public could live near the area of the defuelling operation and the design of defuelling equipment must ensure that all fission products are contained.

As defuelling is a closely controlled operation it may not be possible to carry out major maintenance work during the period of defuelling and particularly will this apply in relation to reactor installation maintenance. Present marine reactor defuelling times proposed vary from three days to three months. The actual act of defuelling seldom takes more than one or two days at the outside, the remainder of the time being devoted to dismantling, re-assembling and proving control gear, and opening up and closing the reactor vessel. A subsidiary advantage of freeing the lid of control rod penetrations is apparent. The advantage of a low pressure primary circuit with the consequent light scantling is also obvious. A time available for defuelling, which would be acceptable from consideration of the operational requirements of a merchant ship would be 14 consecutive days in any one year and the shorter the time the more economic the prospect.

There would seem to be little to be gained in delaying a ship to permit shuffling of fuel assemblies. Any financial gain on this score could not adequately be determined until more experience has been gained in nuclear ship operation. Shuffling of fuel will become economically acceptable when rapid access to the fuel and rapid re-assembly of the plant is possible.

Another factor in defuelling, which is relevant, is the number of flasks used during the transfer of irradiated fuel. Such flasks are expensive and the defuelling procedure must be achieved safely and expeditiously with the smallest number of flasks possible. The potential hazard of transporting a complete core may be unacceptable but the possibility of removing large subcritical sections of core as units might show to advantage.

Collision Protection

The area of ships side abreast the reactor incorporates material for collision protection.

Collision protection has been proposed in many forms, such as multiple deck and wood/steel laminate crash barriers, as in the *Savannah,* to a ships side honeycomb structure. Some solutions are very expensive both in materials and labour and produce problems of high stress concentration when blending the protective structure into the hull. Too little is known about the modes of failure experienced in ship collision to permit of a proved design, but the basic principle requiring application is widely known in the engineering sciences and particularly the armaments industry. The principle is that the best way of absorbing kinetic energy is by so positioning material that as large a volume of it as possible is yielded, i.e. is stretched through and beyond its elastic limit. If all the material present in the normal ship side structure could be so loaded, very little penetration into the hull would be possible. Naturally from other essential considerations, some of the material is so sited as to be incapable of such a contribution. It is noteworthy that Murray and Pemberton in a recent paper(6) gave this matter considerable thought and outlined an economical ship structure designed to meet major collision requirements. It is also relevant that they state that development on this subject is being undertaken by them. There is little doubt that the proper approach to this problem is outlined in the above paper and effort must be made to determine the limit of penetration damage for any proposed design. It is probable that such work can be most economically progressed by utilizing scale models supported in a resilient media and subjected to rapidly increasing loading by a simulated ship bow structure, and in Japan such work has commenced(7).

NUCLEAR FUEL

In considering this item, we move from the capital cost to the fuel cost. It was stated earlier that the present fuel cost would be 0·5d./s.h.p. hr. and a target of 0·22d./s.h.p. hr. or less was proposed.

The cost of nuclear fuel is a major barrier to the marine reactor. The engineering cost of any reactor type can now be estimated comparatively accurately, but the fuel cost is fixed by governments and price reductions to date have only been marginal.

It is probable that in early nuclear ships, reprocessing immediately on discharge of a core will not be possible as a facility capable of processing the particular fuel element in such small quantities will not be worth constructing. In such a case an additional interest charge on fuel awaiting reprocessing will be incurred. There is, accordingly, an incentive to utilize a fuel element design similar to units already operating in order to reduce manufacture and reprocessing costs, although such a design may not be the most efficient heat source.

The assessment of the major plant accident should be based on the behaviour of the fuel element in normal and abnormal conditions. A high integrity element is preferred and a number of desirable features can readily be listed:

a) No centre melt-out during normal plant operation.
b) Limited melt-out under the major accident condition.
c) No chemical reaction with coolant.
d) Geometric stability and freedom from ratcheting.
e) Negative temperature coefficient.
f) Xenon override.

These requirements indicate that what might be termed a "rugged" fuel element is desirable. Such a design can add considerably to first costs and could result in poor neutron economy. However, it is considered that reliability of the fuel element is the most important requirement for the marine reactor.

Some cost reduction on capital equipment may be possible if fuel element integrity is assured. An example of this would be where limited melt-out reduced fission product release and thus reduced secondary shielding requirements.

A relatively strong Doppler coefficient is also desirable, as the control disadvantage during power changes is probably offset when weighed against the protection from high peak excursions, and such protection permits simple and relatively slow scram circuitry.

Possible reductions in cost could come from simplifying the fuel element assembly design and manufacture. Such simplification must not detract from the high integrity required of the element, although neutron economy must not be sacrificed in order to attain unnecessary long reliability. Claims of 25,000 MWD/tonne burn-up can only show to advantage if the core is highly rated so that the burn-up is reached in a reasonable period of time.

Based on current proposals for core rating with a peak/average ratio of 2, it is unlikely that anything above 15,000 MWD/tonne could be fitted into the schedule of maintenance of a marine reactor.

There are a number of untried fuels, which show promise at laboratory level, but at the moment the only proven fuel material is uranium, either pure or alloyed, and, to a lesser extent, uranium dioxide. Uranium dioxide is a fuel which has been subjected to considerable study recently, and there is no doubt that its many advantages are often particularly suited to the high reliability demanded from equipment at sea. Even the major disadvantage of low thermal conductivity has the attraction of limiting can temperature fluctuations in low enrichment reactors and thus contributes to ensuring can integrity.

In order to reduce the physical dimensions of the reactor to acceptable proportions for installation in a ship, it is necessary to use enriched fuel. Enrichment costs money as it represents potted electricity. A major break-through in the form of a cheap low enrichment process is a possible development, but it is not proposed to base an estimate on an unproven technique.

The alternative to a high integrity fuel element is the unclad element operating in an active primary circuit. This concept eliminates one of the containment boundaries for fission products and thus in the event of only minor accidents or spillages, involving primary circuit fluid, fission products will be released into the containment structure. An active primary circuit will also increase shielding costs and possibly limit access time for maintenance. As the number of trained crew in a ship is limited, reduced maintenance times are not acceptable. The limitations imposed when operating a contaminated circuit with its appropriate clean up loop, must be demonstrated prior to installation in a ship and, until considerable power reactor experience has been achieved it is unacceptable.

Thus, a reliable, processable, stable fuel element for the ship concept would be slightly enriched UO_2 rod canned in a proven material such as stainless steel or zirconium.

It is probable that if such an element could be associated with an existing processing plant, the fuel element cost would approach the target quoted in this paper. In the context of marine reactors, once this fact is considered to be established, fuel element design should be related only to reliability until operating experience permits acceptable design economies.

CONSTRUCTION STANDARDS

Pressure membranes in nuclear plants are not wholly constructed to recognized pressure vessel codes. In America the A.S.M.E. Unfired Pressure Vessel code is used as a basis for design in association with "Interpretations", these latter being statements relating the A.S.M.E. code to specific points of nuclear design requirements. In the United Kingdom it has been the practice to use B.S. 1500 and some A.S.M.E. interpretations as a basis for a design, and additional requirements based on the quality of article required are superimposed by the relevant inspection authority. The high quality demanded for such work has resulted in a great increase in the use of non-destructive testing techniques. As an example, there is a considerable demand by industry to use ultrasonic examination as a basis for acceptance or rejection. In America and the United Kingdom, where possible, 100 per cent radiography of all welds is required and particular attention is paid at the design stage to ensure this requirement can be met. The standard adopted in the United Kingdom is summarized in the Requirements for Land Based Reactors(2) and more particularly for ships in the Provisional Rules for Nuclear Ships issued by Lloyd's Register of Shipping.(4)

The cost of nuclear work is related to excessively high construction standards when labour troubles or accidental errors delay a project, or when the standard required is misinterpreted. There is no doubt that some increase in cost does occur, but experience shows that this is offset by added plant reliability. American submarine experience indicates that the reliability of conventional plant is lower than that achieved by present nuclear plant.

A high construction standard for any article is dependent initially upon a well planned design and well planned construction procedures. In addition, a considerable amount of the work of assembly of a nuclear plant consists of welding and it takes just as long to do bad welding as good welding. The added penalty, that bad welding must be cut out and afterwards repaired, represents additional cost. Thus, a high construction standard at an acceptable price is dependent upon an adequate control of contractors' labour. Reliability means lower operating costs and lower crew costs. Thus, for the operator, high construction standards pay.

NUCLEAR SAFETY PROBLEMS

It is probable that all major nuclear safety problems are solved in the development stage and prior to any power concept receiving permission to go critical, but there are two particular aspects of fuel element design which require further consideration in relation to the mobile reactor, and these are the permissible burn-up and the approach to burn-out.

As already indicated, permissible burn-up is a problem of economic balance, but burn-out is a major irreversible event and, in the context of a mobile reactor, a conservative attitude is essential. Centre core melting of fuel, with possible consequent excessive migration of gaseous fission products to the fuel/can interface and an increase in can internal pressure, is unacceptable.

SAFETY PROBLEMS CONSEQUENT UPON OPERATING NUCLEAR PLANT IN A SHIP

The use of a direct cycle installation which passes the primary working fluid through a steam or gas turbine appears to offer economic gain as it eliminates heat exchangers, reduces the overall machinery space and increases the turbine working fluid temperature. There are, however, a number of details related to safe operation and maintenance of marine plant which will be difficult to overcome.

Accessibility to main engines and associated ship auxiliaries is essential at sea and highly trained engine room personnel should not be subjected to continuous low level background irradiation which consumes their permitted radiation allowance. It is difficult to foresee how short lived radio-active carryover, consequent upon breakdown of the working fluid, can be eliminated from the main propulsion machinery whilst the vessel is under way. In addition, due for example to a defective fuel element, long lived carry over may accumulate and a build-up of activity at air ejectors, condensers, etc., will occur. Such hazards might be acceptable if the watchkeepers were only in the engine room on a part of a watch. This implies partial or complete automation in the engine room. Total engine room automation will ultimately come, but how far away we are from such a practice, even with conventional marine plant, is well known. Semi-automation or remote control, with ability to visit the engine room to adjust auxiliary plant locally and to repair defective ancillary equipment, clear bilge strum boxes and tend to other similar common chores, is possible now, but staff still spend a major part of their working day in the engine room. Thus crew member radiation allowance could be consumed on conventional plant maintenance. The choice of automated or semi-automated engine rooms in nuclear ships is for the future, but it would seem to be an essential development, particularly for direct cycle operation.

A more immediate problem of the direct cycle is the disposition of secondary shielding to deal with a major nuclear accident releasing fission products into the reactor and main machinery space. Whether these spaces are separate or conjoined, an increase in the secondary shield quantities must occur and the cost of the shield installation will rise appreciably.

The proposal to utilize a direct cycle gas turbine as the power unit is attractive, as apart from the elimination of the heat exchanger, the high temperature would permit higher efficiency. To take advantage of high efficiency, operation must be at high temperatures—over 1,000 deg. F. (540 deg. C.)—and in such circumstances, it is necessary to prove for use, relatively exotic materials which are often difficult to fabricate and thus have high first costs and high fabrication costs. The experience associated with conventional marine gas turbine installations is noteworthy as, in general, such plants have had limited success. Such installations require proving on land over a long period prior to their application to ship propulsion.

At this stage direct cycle does not show an economic gain for ship propulsion and its application should wait until experience has been gained with closed cycle marine installations.

There are other safety problems associated with ship operation such as radio-active waste storage and disposal, standby and emergency plant operation, etc., but in general the operation of land based nuclear plant gives an adequate indication of its acceptability as a mobile reactor and, whilst the proposal that a nuclear ship is essential to obtain operational experience is a valid one, the marginal gains are very small in relation to the large financial outlay.

REVIEW OF POSSIBLE MARINE REACTORS

It is now proposed to indicate briefly, possible applications of the foregoing design modifications which might effect a cost reduction without incurring a safety penalty in relation to those proposals which are suited to the marine field and proven as land reactors in America.

Pressurized Water Reactor

This reactor type has been exploited on land and for submarine and ship application(8) but is known to be totally uneconomic.

One reason for high first cost is the production of the heavy pressure parts needed to meet the high primary circuit pressure of about 2,000lb./sq. in. (140 kg./sq. cm.) and the relatively expensive containment vessel required to contain, in the event of a major accident, a pressure of 200-300lb./sq. in. (14-21 kg./sq. cm.). A characteristic of the reactor is the low primary circuit temperature resulting in low quality steam for the main turbines. Low quality steam is only economic when it is cheap, e.g. in geothermal plant. Development lies in increasing the primary circuit temperature to permit operation at the saturated water temperature and to increase further the circuit pressure. This latter development only increases the design and construction problems and economic advantage can only be marginal.

The elimination or amalgamation of some of the subsidiary systems associated with the reactor may be possible.

The application of spectral shift—the utilization of a coolant/moderator containing a variable mixture of light and heavy water—could eliminate the problem of reactor control rods penetrating the reactor vessel with the associated problems of ligament design and sealing arrangements, although the necessity to provide an equivalent of safety rods and some shim control might still remain.

These two developments in association with an integral or a conjoined reactor/heat exchanger assembly will reduce the size of the installation and the quantity of fluid in circuit and it is conceivable that the containment vessel could get smaller and therefore cheaper or, alternatively, by utilizing a pressure suppression device, containment in the hull structure might become feasible.

It is along these lines which the P.W.R. must develop, but despite the real economic advantages which would accrue, the system is tied to heavy pressure vessels and low quality steam and it is difficult to foresee it ever proving more economic than present conventional plant.

Boiling Water Reactor

Although the boiling water reactor has wide application ashore in America, no marine version exists.(9) The fact that boiling occurs in the core ensures a higher steam temperature than for an equivalent pressure P.W.R. or, alternatively, for similar steam conditions, the design permits a lower primary circuit pressure with consequent reduction in primary circuit scantlings. A pressure suppression device would be needed to permit containment in the hull structure.

This reactor lies down under load and therefore a relatively complex control mechanism will always be required and the application of spectral shift will prove difficult.

Doubts have been expressed of the stability of this reactor under shock, impact, and seaway conditions. Theoretical studies have indicated probable stability and it is considered that this problem is not a major one. As with the P.W.R. economic parity with conventional plant is difficult to foresee.

Possible development to higher steam temperatures is feasible but the implementation of nuclear superheat requires proving on land and there is every indication that this must be classed as a long term development.

Both the P.W.R. and B.W.R. are products of American technology and use stainless steel and nickel alloys for reactor component construction. Probably the greatest contribution, which the United Kingdom will make to water reactor technology, will be the operation by the Admiralty of their prototype submarine at Dounreay, utilizing low alloy steels. This represents an ultimate cost reduction and it is foreseeable that carbon steels will be acceptable for these reactor types. Even so, it still appears doubtful that nuclear plant cost could approach parity with a conventional installation.

Organic Liquid Moderated Reactor

This reactor type has been described by Corlett and Hawthorne(10) and its application to the marine environment would appear to be relatively simple. It has many defects including low thermal efficiency, irradiation damage to coolant with the consequent necessity for a coolant purification plant, high fuel cost, poor thermal conductivity of coolant, with consequent limited steam temperature and a coolant fire risk.

Its main advantages are that the primary fluid is non-corrosive and thus the primary circuit can be constructed in mild steel. The primary circuit pressure is low and the circuit scantlings are consequently light.

In addition the primary fluid has a low vapour pressure and containment in the hull structure is possible. These advantages are such that this reactor, though lacking large operational experience in America, is particularly attractive to European countries examining its feasibility for a mobile reactor, particularly as the design and engineering is well within the experience and competence of European engineers and shipbuilders. In addition the possible reactor hazards are not as great as with water reactors and consequently the requirements to effect safety are not as stringent.

The O.L.M.R. is not readily accepted by the marine engineer as it uses an unorthodox working fluid with a high melting point. The biggest defect of the O.L.M.R. is that its development would appear to be limited, even though fuel cost reduction and an improved and cheaper coolant/moderator may be achieved. The capital cost is below that of the water reactors discussed earlier, but in the long term prospect it has no more to offer than the P.W.R. or B.W.R.

No other reactor types proved on land are immediately capable of optimization for ship installation. There are a few reactor types, however, which could be suited to the marine environment after further development.

Experience to date has shown that the paper designs of new reactors always promise great cost reductions when compared with proven reactors, as the engineering design is not fully developed. The nearer the reactor gets to reality the more expensive it becomes. It is reasonable to assume that the current assessment of the following reactors is over optimistic.

High Temperature Gas Cooled Reactor

The gas cooled reactor has been developed for power production in the United Kingdom, and American industry is seriously examining its possible further development for ship propulsion.

The high temperature gas will permit higher efficiencies, but problems with materials and coolants could occur. As an example, leakage of the helium coolant could prove economically unacceptable in Europe. Development, presupposing gas turbines and the development of cheap plutonium fuel, offers an installation which might compare favourably with conventional plant(11), but such a design is dependent upon too many assumptions to permit of a balanced assessment of its worth at this time.

Containment in the hull is possible and the size of the installation is comparable with those reactors considered above.

The high temperature gas cooled reactor, DRAGON, at Winfrith Heath will resolve some of the problems and indicate whether it is feasible as a marine reactor, in about four years time.

Steam Cooled Heavy Water Reactor

This reactor is in course of development in the United Kingdom(12) and is claimed to be designed as a marine installation. It meets many of the requirements outlined in the previous pages. It utilizes pressure tubes in lieu of a reactor vessel and thus permits light scantlings. Pumps have been replaced by thermo-compressors, a device based on the injector principle. Control is achieved by adjustment of moderator level, thus eliminating control rod mechanisms. Containment in the hull structure might be possible.

A high circuit temperature permits modern conventional plant with its associated higher efficiencies to be installed. Trouble may be experienced when the core physics is required to be defined more precisely. Some construction problems may arise as, although scantlings are light, the integration of a large number of calandria tubes into a tank structure to form the reactor vessel and into an external circuit could prove difficult.

Steam Generating Heavy Water Reactor

There is very little published data on this reactor type, but it is basically a further development of the steam cooled heavy water reactor. The reactor generates steam in the fuel element channel and thus variable two phase flow occurs through the core. In consequence there would appear to be a considerable reactor stability and control problem, requiring solution before any confident prediction of this reactor's future can be made. The engineering design could possess similar economic advantages to those outlined above for the S.C.H.W.R.

All other types of reactor could, with a little ingenuity, be installed in a hull but, essentially, all those reactors have been referred to which might be considered sufficiently developed in fact or on paper to be fitted in a commercial ship within the next decade.

THE SHIPYARD

Assuming a nuclear ship is to be built, the choice of shipyard will be limited to large shipbuilders who are prepared to undertake such a project. Modifications and retooling may well be necessary, for example a heavy lift crane up to 100 tons lift, over the berth, would be advantageous. Fundamentally the problems of the shipyard will be associated with cleanliness, and the control of materials. In addition, acceptable standards of workmanship for new types of work will require to be established and maintained.

Cleanliness requirements have already resulted in a number of semi-official specifications, but basically the subject can be summarized as a general standard, equivalent to a modern office as a working area, with firm specifications in relation to methods to be adopted during manufacture, to clean and to protect the products. It is obviously economically desirable to clean as late in the manufacturing process as possible, but the concept of cleanliness is not easily imposed, on staff or material, on a temporary or localized basis and engineering and shipbuilding organizations may find it necessary to make certain permanent alterations to their techniques, yard layout, etc.

The control of materials will prove difficult to impose as a temporary measure on a yard organization. A considerable number of materials will be new to ship and engine construction and it is possible that a large variety of steels will be employed. It is essential that an arrangement exists which ensures that the correct material of an acceptable chemical purity is available and is used in the specified way. The present method of steel testing and certification could perhaps be widened and utilized for this purpose, thus limiting the additional staffing necessary for such a task.

The control of standards of construction have already been outlined by state authorities, classification societies, and atomic energy authorities. Probably the greatest experience lies in the requirements for pressure circuits of land based reactors(2) where the techniques to be adopted, to ensure the adequacy of the chosen material for its task and the quality of the workmanship required, are outlined. The standards outlined are not commonly met in shipyards and it will require considerable capital outlay on labour and materials, together with determination and co-operation on the part of managements of engineering and shipbuilding organizations to ensure such standards can be achieved.

CONCLUSIONS

This paper is a deliberate over-simplification of the marine nuclear boiler prospect, but it endeavours to be a valid assessment of the essential problems associated with the development of nuclear ships.

It is reiterated that the cost figures used are related to an installation free of any research and development charge and it must be apparent to any reader of this paper that a considerable amount of research and development will be necessary.

When the quoted "break even" point is reached, the prospective owner must consider what additional benefit can be obtained from nuclear propulsion, to offset the additional costs consequent upon operating a unique ship in his fleet, to offset any losses incurred in disposing of the ship when it is no longer economical to operate and to increase his operating profit.

With so many variables affecting both capital cost and fuel cost, it is feasible that an economically acceptable reactor type will evolve and it will be in the interest of any maritime nation to have personnel capable of recognizing the breakthrough and exploiting it.

Operational American reactor types in their present form possess considerable areas, both in material and in design, where cost reduction should be possible. Even so it appears unlikely that something better than parity can ever be achieved with the P.W.R., B.W.R. and O.L.M.R. on the present ground rules.

If reactor types which lack operational experience are assessed, an additional set of variables must be introduced as the nuclear physics of the project will require delineation. In consequence more research and development work will be required. All the design parameters are less well defined and accordingly are assessed in a more arbitrary manner. Designs often become simplified sketches, lacking appreciation of constructional problems and not conforming to general industrial practice. Thus the cost assessment is always promising.

Three particular proposals, which are being subjected to a certain amount of optimization as packaged reactors in the United Kingdom, have been briefly examined in relation to certain broad requirements desirable in a marine installation. It is apparent that whilst all three appear to conform more easily to such requirements than developed American reactors, a considerable amount of development work to prove their adequacy is needed and a land based prototype reactor would be required to prove the design concept and to permit development of the reactor to its ultimate form.

The application of spectral shift to the P.W.R. presents a considerable change in the design and here again a prototype installation would appear essential.

A nuclear propelled ship ideally should contain only that equipment necessary to operate it as a plant. The increased costs of construction due to the higher standards of workmanship must be offset by added reliability and therefore it is logical to raise the standard of conventional plant to that of the nuclear part. Reliability is essential at the expense of first cost, and plant efficiency.

Fuel element costs are amenable to reduction in relation to choice of fuel cycle and fuel element geometry and ultimate economy may be foreseen in a particular design, but reliability is paramount and any economic advantage must await prolonged prototype testing.

Integration of the reactor into the hull and the associated requirement to limit the volume occupied by the plant are basic factors and must be implemented from the initiation of the design.

Installation in a small ship is extremely difficult to engineer and thus carries a cost penalty. Particular small ships such as ice-breakers, oceanographic survey vessels, etc., are not so dependent on commerce and trade to maintain them and thus are attractive vehicles for operating experience of nuclear plant. However, operating experience at sea is only marginally different from operating experience ashore and the capital outlay might not be considered worthwhile in terms of information gained.

Only after considerable financial outlay is a merchant ship installation feasible and only after further development will parity with conventional plant be approached.

When it is apparent that economic parity will be achieved, it is reasonable to expect shipowners to develop and exploit the nuclear boiler in competition with alternative conventional installations.

The first nuclear reactor for any merchant application should offer some prospect of ultimate economy, even if such economy will only be found in another hull. Experience with prototype design and experimental evidence of the adequacy of any plant should be found ashore, and the proper application of any national investment to determine an economic reactor for marine use lies in such work.

ACKNOWLEDGEMENT

The author wishes to thank the Committee of Lloyd's Register of Shipping for permission to present this paper, particularly as it expresses a personal appreciation of marine nuclear propulsion related to acceptable classification standards for merchant ships.

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Discussion

Mr. A. R. Gatewood, S.B. (Member), opening the discussion, said that the author was to be congratulated for his very interesting survey of the present status of nuclear propulsion for merchant ships and there could be no disagreement with his basic conclusion that at the present stage of development such ships would not be commercially competitive with conventionally powered ships.

That type of survey seemed particularly timely in view of the fact that the *Savannah* had successfully completed her acceptance trials less than two weeks before and as of 2nd May 1962 was to be delivered. The trials were eminently successful and while this in itself constituted a major advancement, because many new and complex problems had to be solved, it was equally true that a careful review of the actual construction of this ship had disclosed a number of ways in which economies could be achieved in future nuclear ships and many of these, of course, had been pointed out in the paper.

The use of carbon and low alloy steels had been the subject of considerable study in the United States and the work being done in the United Kingdom was being followed with a great deal of interest. It was not believed, however, that pressures of the order of 2,000lb./sq. in. posed any particular problems, because such had been the standard pressure for central power stations for a number of years and some of the newer supercritical plants had been built for pressures in excess of 5,000lb./sq. in. In these cases there was of course an economic gain in going to the higher pressure. This was also true in the use of cladding, stainless steels and so forth because these procedures were not new with nuclear reactors and had been found to be economical in a number of the processing industries.

The goal was a nuclear ship which would show better returns on the investment than a conventional ship and an obvious example of how this might be accomplished, by an increase in the initial investment, was the present day jet plane as compared with the earlier planes. This development was not achieved overnight and he could well remember some of the learned discussions which took place after the war, when the theory was advanced that it would never be commercially feasible to get jet planes off the ground although they were of course ideally suited for military use. In this context it was gratifying to note the author's conclusion that parity with conventional marine engines would ultimately be achieved.

He would like to add just one more thought, directed particularly to the younger men present. What had impressed him most during the course of his life as an engineer was the fact that all really new ideas and concepts were true products of one individual's mind. All modern day devices, such as associations, committees, task groups and the like, could take these ideas, develop them, and bring them to fruition but always the original thought had come from the mind of an individual.

He had seen many such developments take place which were now so widespread that they were taken for granted. He had in mind the use of electricity—for lights, for motors and for the electric drive on the *Canberra;* aeroplanes, automobiles, the cinema, radio and television, rockets and space vehicles and of course the subject being discussed—nuclear energy.

About thirty years ago Professor Einstein had published his now famous equation and it was only about twenty years ago that Dr. Fermi set off the first chain reaction which proved the theory. Now in the space of about ten years or less there were ships propelled by nuclear energy and, here in England, as well as elsewhere, electricity was being generated without burning either coal or oil. To him, this was fantastic progress and he firmly believed that only the surface had been scratched.

As far as safety was concerned, it was possible and he thought probable, that they might have gone from one extreme to the other. He asked those present to stop and think for a moment what the status of these nuclear ships and power plants might have been if Dr. Fermi had had to ask for permission to set off chain reaction under a grandstand in the middle of Chicago.

Mr. M. Yamaguchi said that in view of the study of the peaceful usage of nuclear power, especially as the application to the propulsion of ships was attracting world-wide interest, the author's excellent and comprehensive survey on the matter should be appreciated by all.

In Japan, studies on nuclear propulsion had begun some four years previously. Among many researches thus conducted, he had taken part in a trial design and in experiments on a small experimental ship financed by his company. The result was discussed at the Meeting on Nuclear Power for Ship Propulsion, Hamburg, 1959 and a paper was presented to the meeting of International Atomic Energy Agency 1961, on further studies on the same ship. Now this project was taken up by his Government and a grant of some £32,000 was given to assist their study for revision and detailed calculations. Two kinds of power plant of conventional type were chosen, i.e. 36 MW P.W.R. indirect cycle and 33 MW B.W.R. direct cycle, to produce 10,000 s.h.p. because their purpose was to get experience in constructing and manœuvring nuclear ships rather than in developing a new power system.

The author referred to the pressure which a hull construction apparently could resist and that it was about 2 kg./sq. cm. Their experiment, conducted on a one-sixth scale model of a 60,000 d.w.t. tanker, showed that a centre tank compartment could resist about 4 kg./sq. cm. of internal pressure. This result opened a promising way to the use of hull construction for the containment vessel, though there remained such problems as difficulty of inspection, suppression of erupting steam from primary system and so forth.

Mr. E. Abrahamsen said that firstly he would like to thank the Institute of Marine Engineers for the valuable experience gained by him in being present at this International Conference. The present paper was a very well balanced review of the present state of the ship reactor technique and might help the most optimistic proponents to take a more realistic view of the prospects of nuclear ship propulsion. Experience to date indicated that the technical problems might be solved, but for some time to come not in a way which would put nuclear machinery in a competitive position.

The author had stated that one of the major problems consequent on the use of nuclear power was to reduce the overall length of machinery space. This was, of course, a matter of compact design. For both large tankers and ore carriers weight was as important since such ships usually had rather a lot of void space, more or less evenly distributed along the ship. Some nuclear ship designs which he had had an opportunity to check recently, showed no great difficulties in relation to large hull bending, shear forces and trim. It was possible, however, that gas cooled reactors might offer greater difficulties than the P.W.R. and the B.W.R. plants in the ships mentioned.

The author mentioned an outside figure of 2·0 kg./sq. cm. to which a hull compartment might be designed as a containment vessel, without introducing major ship design problems. Would the author hesitate to accept a figure of say 3·0 to 4·0 kg./sq. cm. as design pressure for an integrated containment structure. He felt that much of the steel weight already required for protection against collision might in some way be incorporated in an integrated containment structure and that double plated transverse bulkheads and decks as well as a reasonably high double bottom might easily take care of 30 to 40 meters of water head. This would make possible a more extensive use of pressure suppression systems. But great care should be exercised in mounting the reactor with its primary loops so that the foundations were not easily displaced as a result of collision or grounding. The best place to arrange the supports of the reactor plant would probably be in the centre of the transverse bulkheads. For tankers the risk of damage to the containment structure due to explosion in the cargo tanks should be taken care of, for instance, by arranging the deck structure outside the containment to yield before the pressure build-up was great enough to damage the containment structure.

Regarding collision protection, he wondered if some full scale tests could not be made by simulating collisions between scrapped vessels. One such simulated collision with all environmental conditions adequately described would probably provide more information about the mechanism than a dozen real collisions. He was especially doubtful about the probable pressure rise in a water-filled tank subjected to a colliding bow. Tests carried out by Kagami and associates* showed that the deformations created by hydraulic impact was rather negligible. He would like to have the author's comment on this point.

In a B.W.R. the variations in the gravity fields and of the angles of list caused by the sea environment might have an important influence on the steam volume in the boiling reactor coolant, and thus on the reactor stability. Quite a lot of work had been done in Norway on stability investigations of a B.W.R., or rather on a simplified analogue model, subjected to simulated vertical accelerations. So far the results indicated that the stability problems might be solved, but that the extent of the necessary precautions very much depended on the design value chosen for the regular cyclic acceleration. He understood that Lloyd's Register required the stability of the reactor system to be proved for regular accelerations up to 0·45*g* while a somewhat higher value had been advocated by Det Norske Veritas. Did the author feel that a reduction of the design value of 0·45*g* was justified at the present stage of development?

Dr. A. W. Davis (Member) said that there were one or two points in the paper about which he found himself in disagreement with the author. In his reference to the boiling water reactor, the author had spoken of the need for a complex control system because of the characteristic tendency of this reactor to lie down under power. A properly designed boiling water reactor did not require any special system in that regard. In fact, the inherent response to increase or reduction of steam demand was such that no movement of the control rods should be required between very small and almost maximum power output.

Towards the end of his paper, the author had said that when it was apparent that economic parity would be achieved, it was reasonable to expect shipowners to develop and exploit the nuclear boiler. Dr. Davis did not believe that that was the case. One did not buy a particular make of motor car because one was told that in another five years time the makers then would produce a vehicle superior to other makes already selling.

Nuclear marine power for merchant use had never yet been anything other than a long term project to probe the possible economic advantages of the future and he could not see where the interests of the shipowner were yet affected. It was more a national research problem.

The author had correctly drawn attention to the desirability of the reactor becoming very much smaller before its economic parity was likely in any way to be possible. That was true, but this was closely connected with the enrichment of the fuels adopted. The greater the enrichment, the smaller the reactor could be, and here one reverted to the very foundation of the economics of the problem and to the question of what was to be the cost of enrichment. This was a problem which could baffle or suppress a design in its very early stages because it reverted to the question of the control of the price of enriched uranium. In some ways, the more one kept closely in league with those who had some voice in the control of these prices, the better.

A far reaching decision had been made in 1961 when the Government decided not to go ahead with a large nuclear propelled tanker in the form then visualized, possibly on the basis of an American design. In establishing dependence on this country the real consideration for some years would have to be not the design of the ship but of the reactor and he supported the opinion of the author that such a reactor would have to be the subject of land test. The hazard of building an experimental reactor into an experimental ship was quite unrealistic and anyone disagreeing with this viewpoint would profitably study the paper* presented to this Institute a few years ago on the experimental destroyer U.S.S. *Timmerman;* the design was bound by so many features which did not function in the intended manner that no element could be proved to satisfaction within the confines of the whole project. The great warning which had been given in that paper was that there should not be too many experiments on too many things at the same time, especially when the whole was constrained within the rigid embrace of a vessel so sensitive to design as a ship.

Dr. Davis did not however wish to amplify any aspect of discouragement that might reflect from some remarks in the paper. In writing of the problems of merchant nuclear propulsion, the author had surely done a great service and while he had stressed some of the difficulties, his paper should be regarded as a source of encouragement to those who were working on the fundamental problems which had to be solved, even though that would take many years to achieve.

Mr. R. Baker, O.B.E., said that having heard Mr. Hildrew's comments on the papers of other authors, he had assumed that Mr. Hildrew knew the rules and that it would be quite possible to praise him for his paper and say nothing else. But, having read the paper, he found that impossible because Mr. Hildrew had become involved in the difficulties which he was so expert in pointing out when other authors were on trial. He did not think that Mr. Hildrew could be let off that hook.

When he had first met him, Mr. Hildrew had been responsible for safety in connexion with a certain project. He had felt rather sorry for him, for the author used to come round with a miserable look—very different from the picture in the paper. Perhaps that had been because he had been a

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* Kagami, K. *et al.* November 1960. "Research on the Collision-resisting Construction of Ships' Sides". Symposium of Nuclear Ship Propulsion, Taormina.

* Phillips, D. G. 1955. "U.S.S. *Timmerman*—An Advanced Design Destroyer". Trans.I.Mar.E., Vol. 67, p. 187.

fish out of water and nobody, except the speaker, had ever paid any attention to him. However, when he had left, there had been a team to deal with safety, eight or nine of them, and they were all as miserable as Mr. Hildrew had been.

At his home there were two squirrels. One was fat and had an enormous bushy tail and raced about from tree to tree and from twig to twig chuckling away happily. There was another, a miserable squirrel with a long scraggy tail which raced from branch to branch and tree to tree, but not exactly the same as the former squirrel because it never seemed to be enthusiastic about anything. That was what the author had done in his paper. In turn, he had said that each reactor which he had mentioned was no good. The mere fact that Mr. Baker agreed with the author did not make any difference to his argument. Surely the author could have found something somewhere which he could have praised. If he had, Mr. Baker's task would have been that much easier.

The author had said that there could be more containment, or there could be less containment; there could be more circulating pumps, or there could be fewer circulating pumps; there could be more heat exchangers, or fewer heat exchangers.

He agreed with Mr. Gatewood that there would not be any progress until some one person came along and said "We will have this; we will have one heat exchanger; we will have one circulating pump". Perhaps that state of affairs would never be achieved because very great costs were involved.

Dr. Davis had referred to the dangers of first trying a plant at sea. Those who worked at the Admiralty had spent years trying to build a shore based prototype, and they had not yet got it finished. He did not see that it would be any good when it was finished. They might find a reactor which worked, but he did not see that that would make any contribution to the solution of problems concerning a seagoing reactor. The way in which the problem would have to be tackled was by accepting the fact that the reactor took the place of the boiler; the ship being so arranged that the reactor could be taken out and a boiler put in if the reactor did not work properly. With such a method they could go straight ahead, go straight to sea and prove Dr. Davis wrong.

Mr. Gatewood and Dr. Davis both had a point when they said that in all this nuclear marine propulsion was only on the fringe of developments. When engineers listened to papers about nuclear propulsion, which Mr. Hildrew had so criticized in the past, it seemed rather like reading the correspondence between Watt's mother-in-law and maiden aunt before Watt had discovered that steam lifted the lid off the kettle. If those present did not understand the analogy, he could not help them. Was it conceivable that Watt's mother-in-law and maiden aunt could have written a letter, prior to the event, explaining in one word the point of the lifting of the kettle lid by steam? That was the present situation with marine nuclear propulsion. It would be a long time before it was possible to go ahead and in the meantime the man, with the ideas about what was to be done, was still needed. In spite of his characteristics, the author had got near to doing that in his paper.

The reactors being dealt with here could be simplified if one reactor, one heat exchanger, one circulating pump and so on were agreed on. That would go a long way towards making things simpler. If on top of that some method of control could be found, which did not involve penetrating the pressure vessel all the time, that would also help.

While the country was waiting for someone to come along and co-ordinate all the ideas, those who worked in the Admiralty knew that they were only at the beginning. They would be lucky if they could get their shore-based prototype working without any more trouble and lucky if they got their submarine working without any more trouble. It would be a long time before they could do anything other than what they were doing. In ten years they would have another conference, and someone would still be dreaming.

Dr. J. E. Richards, B.Sc. (Member) said that the author had produced an excellent and well-balanced paper on the problems of merchant ship nuclear propulsion and it was to be noted that these problems were connected with costs and not with feasibility. If a word of criticism might be offered, it was that the paper did not reflect the rapid rate of technical developments now taking place in this field. For instance, irradiation testing of fuel indicated that burn-up of 30,000 to 40,000 MW days per ton might be possible with uranium oxide fuel, whereas two or three years ago 10,000 MW days per ton had been considered optimistic. Advances were being made in the control of reactivity of pressurized water reactors by spectral shift and by the use of soluble poisons and these advances would lead to more compact and cheaper designs. There were several possibilities with steam cooling, including boiling water reactors with superheater sections. On a longer time scale, the development of fission retaining ceramic fuels could be expected, which would permit high temperature operation of gas cooled reactors.

It now seemed fairly certain that nuclear fuel costs could be reduced to half oil costs and this provided a great incentive to develop a ship reactor. Developments now in progress in reactor technology should permit advanced designs of marine reactors with capital costs considerably less than the figure of £1,500,000 quoted in the paper. It could well be that the stage would soon be reached when an energetic building programme was essential for quick success.

The vigorous programme of research and development which had been initiated by the Government was aimed at a reactor system which should be economically attractive to a wide range of shipping. The Atomic Energy Authority had the main responsibility for this programme but industry was participating and staff of the British Ship Research Association had been seconded to a team set up to investigate the special problems of nuclear ship design with the full support of the industry. It was not sufficient to restrict attention to the installation of reactors in existing ship designs. It now seemed likely that the reactor weight would be reduced to a few hundred tons so that a properly designed nuclear ship would carry more cargo that its conventional counterpart.

Mr. Lars Nordstrom said that he had read the paper with interest and thought that the author had given an excellent outline of the problems involved, however he had been a little surprised when he read the author's review of possible marine reactors. In the first paragraph of this section of the paper he had almost completely rejected the P.W.R. and in the second paragraph did the same with B.W.R. In subsequent pages it was found that other types had been treated in the same way. Mr. Nordström thought that it was much too early to do this as all the types referred to still had many possibilities.

For example, a study had been made by his company in which, taking the P.W.R. as a beginning, an advanced concept had been carried through in detail. It was found that the size of the reactor, in its containment, plus a secondary shield was about the same as a pair of boilers plus air-heaters, of equivalent output. A figure had been arrived at, for the total weight of the reactor installation (reactor system, containment and shielding), of 1,300 tons, or somewhat lower than the figure mentioned by the author. This was less than half the weight of the *Savannah* installation. The total machinery weight arrived at, in his company's study, was about equal to a Diesel installation with a few hundred tons of fuel.

Another interesting point arising from this study was that it was found that the amount of water, contained in the primary system, could be reduced to about one-third of that in the *Savannah* installation. This in turn meant a much lower pressure in the containment in the event of an accident, or alternatively meant that the containment could be made much smaller.

He was sure that other systems, such as B.W.R., H.T.G.C.R. and S.C.H.W.R. also held great potentialities.

He also thought that a little care should be taken with regard to definitions. What was to be the designation of the supercritical water reactor (the counterpart of the Benson boiler)? Was it a pressurized water, boiling water or steam cooled reactor? He mentioned supercritical pressure because he thought that a good deal could be gained from this, referring to film boiling and burn-out.

Finally, his philosophy was that those involved in this work should be grateful that nuclear propulsion was not at present economic. If it were, they would all be working under great pressure to get nuclear ships to sea and the money to do this would be showered upon them. As it was, work could be carried out in a calmer atmosphere and many mistakes could thus be avoided.

Mr. W. R. Wootton said that he was a squirrel with a scraggy tail and, unlike Dr. Davis, he would not hesitate to discourage if he felt that discouragement would be to the general benefit. In the author's excellent appraisal of the problems of merchant ship nuclear propulsion, he had suggested that it was only realistic to relate nuclear propulsion to contemporary ships. It was to be inferred from his data that the 30,000 s.h.p. nuclear passenger ship would operate at a cost some 10 to 20 per cent higher than a conventional passenger ship and the 20,000 s.h.p. tanker some 30 to 60 per cent higher than the conventional tanker. It was clear, however, that the author entertained the possibility that nuclear drive would lead to the equation being improved for advanced ships, for he had said that "it is of course possible for the size of the dry cargo ship to change in the manner that an oil tanker has changed over the past decade. As an example, the introduction of cargo containers may lead to larger ships . . . Passenger ships . . . might offer the best prospect in this field". One was inclined to ask, therefore, whether time was not being wasted in seeking a solution to the problem of reducing the capital cost of nuclear marine steam raising plant by a factor of as much as ten.

He found it difficult to support the author's arbitrary suggestion that if capital cost could be reduced by a factor of three, that might find acceptance provided that fuel costs were simultaneously reduced by about 30 per cent. The author would find himself right back to the situation currently prevailing with the big land nuclear power stations; here the fuel cost was low but the capital cost was twice that of conventional stations, together however, giving parity for the cost of generation of electricity. Yet the operator showed no anxiety to give the nuclear plant preference despite clear attractions on grounds of siting, lack of atmospheric pollution and so on, simply because the excessive capital outlay was embarrassing. The author had recognized this and had said that "a shipowner will require the cost of any new equipment to more than break even with his present plant cost . . ." but the arbitrariness of his subsequent statements was misleading. The only tenable target for the nuclear power designer was to reduce both capital cost and fuel cost at least to the same level as those of a conventional plant and this now established the magnitude of the basic problem of merchant ship nuclear propulsion, namely, that the capital cost of the steam raising plant must be brought down by a factor of ten or thereabouts and the fuel costs, on the author's own bases, by some 40 per cent. Lowering the fuel costs might be a tractable problem since uranium as a fuel *per se* was so very cheap, but a reduction of the capital cost by a factor of ten left the designer forlorn, at least within his present terms of reference. It was well known that nuclear power best befitted demands for power on the grand scale and every step taken in that direction progressively introduced rationality into the problem. Was it possible that so long as efforts in certain quarters were anchored to contemporary ships, with their traditional requirements of power, others elsewhere might be turning towards advanced ships with much greater power requirements?

In conclusion, he had noticed that the author had said that the P.W.R. had the advantage, since numbers had been built and operated in marine application, of being known to be quite uneconomic. While that might be true insofar as designs to date were concerned, he should perhaps point out that the B.W.R., the S.G.H.W.R. and the S.C.H.W.R. were all at a disadvantage since none had been built and operated in marine application and were thus not yet known to be equally uneconomic.

Mr. H. N. E. Whiteside (Member) said that many countries had faith in the nuclear propelled merchant ship and there was little doubt that new developments and experience would produce a nuclear "boiler" which would show promise of competing with conventional plant within the next five to ten years.

The mechanical and the nuclear parts of the marine reactor must be reliable, as a failure of the plant at a critical moment could endanger the ship. A serious nuclear accident to the ship in mid-ocean might result in the ship being abandoned and the persons on board taking to the life saving appliances. A serious nuclear accident in close waters could result in a hazardous situation arising on all coasts which might be affected by radio-active matter carried by wind or sea currents.

A completely safe ship could not be built, for the hazards of the sea made it impossible. In view of this, the designs of marine nuclear reactor installations must be such that there were no radiation or nuclear hazards, at sea or in port, to persons, food, or water resources, which would be unacceptable to any country which the ship might wish to visit.

Comparing the three types of ship quoted by the author, the passenger ship, the tanker and the ore carrier, it was felt that a nuclear propelled 50,000-ton passenger ship should be much nearer the "break even" point than the author implied. There were many advantages that could be applied to a nuclear propelled passenger ship that could not be applied to the tanker or ore carrier, provided that the number of passengers carried was maintained. It would be difficult to estimate how passengers would react to travelling on a nuclear propelled ship should there be a serious nuclear accident to one of these vessels.

There appeared to be some misunderstanding with regard to the requirement of certain authorities that the containment vessel or structure should be protected against collapse arising from external sea water pressure. This, in the first place, was intended to be a safety measure and was to prevent the containment collapsing and damaging the primary circuit. The economic aspect of salvaging the reactor intact was also important. If the ship should sink in very deep water, the question of collapse was not so important, but if the ship should sink near to a shore, it was prudent that collapse should be prevented in order to maintain containment as long as possible, even though the ship might not be salvable.

In many papers and discussions concerning the problems of designing marine nuclear installations, awkward problems were not always faced up to. There was a feeling that if certain difficult conditions arose within the installation during operation, the reactor could be shut down and the ship could proceed on the voyage using independent emergency propulsion plant. It was not intended that the emergency propulsion plant, or "get you home" propelling unit, as it was commonly called, should be an excuse for some slight relaxation in reactor reliability. The emergency propulsion plant was intended to enable the ship to maintain some navigational control over its movements for a few days should the reactor installation fail.

If it had been the intention that the emergency propulsion unit should be available to get the ship back to its home port in the event of a reactor failure, the amount of fuel which would have had to be carried around would have been an economic burden, which the shipowner might carry if he wished, but one which regulations should not require. This expensive independent propulsion unit would not be a requirement once marine reactors had proved their reliability.

Failure to remove the decay heat which was generated after a reactor was shut down would in most cases lead to a complete melting of the fuel which might in a short time melt through the reactor pressure vessel and even through the containment vessel so causing a possible environmental hazard.

One of the problems some designers of marine reactor systems seemed to have difficulty in solving satisfactorily was the arrangement for the safe removal of decay heat under all accident conditions.

Provided the ship was afloat and had an electric power supply, there seemed to be no difficulty. With present-day conventional merchant ships, maintenance of electric power supplies under conditions of a heavy list of much more than 20 deg. was difficult.

Should the nuclear ship have no power supply, or be ashore, or have a very heavy list which caused the ship to be abandoned, special arrangements should be provided to remove decay heat under these and other accident conditions, otherwise the ship might become a radio-active hazard.

When nuclear ships became more numerous it was suggested that future developments which might result in a considerable reduction in capital and operating costs might take the line of using multiple independent reactor units. These units could use comparatively small standard sized reactor pressure vessels, and standard fuel elements and could be adopted to cover a range of, say, 6,000 to 10,000 h.p.

Using the integral or conjoined reactor/heat exchanger assembly the author had referred to, the small primary and secondary circuits would be such that in an installation requiring, say, two units, the common reactor space within the hull could be used as a containment as the maximum credible accident pressure would not be unduly high.

The refuelling operation need only take a day or two and this could be fitted in with the ship's periodical long stay in port to cover survey requirements.

Refuelling would be simplified as the complete used units would be lifted out and reconditioned fuelled units replaced, the reconditioning and inspection of the units being carried out ashore under ideal conditions.

Used fuel element processing could be an automatic process. The capital interest charge on the fuel awaiting processing, which could be an appreciable amount, would be reduced. Instrumentation could be standardized and reduced to a safe minimum. The arrangement of the units within the reactor space could suit the requirements of the naval architect and flexibility of positioning might solve many of his problems. Where more than one unit was installed in a ship the expensive emergency propulsion unit might be dispensed with. The possible advantages of using standard units when nuclear ships became more numerous should be investigated.

Dr. S. G. Bauer said that he had read the paper with the pleasure which came from finding oneself in full agreement with the author and he had been especially gratified by the complete absence of special pleading. This was a new experience in papers on nuclear ship propulsion. He said that he would like to pursue the author's arguments about fuel costs a little further. It was worth recalling that an atom of uranium-235 when disintegrated by fission produced only about 2½ neutrons and for this simple reason neutrons were very expensive.

A practical marine reactor would need to have an endurance between refuelling of at least two years and since reactivity had to be maintained to the end there was bound to be a substantial excess reactivity at the start. In the conventional way of reactor design the excess neutrons were absorbed in control rods throughout the core life so that at the end of life there was just enough fissile material left to achieve a reaction with the control rods withdrawn. Unfortunately this was an expensive proceeding because neutrons were expensive.

Recent work had shown that it was quite possible to improve this situation by absorbing the excess neutrons usefully by resonance capture in uranium-238. In practice this could be achieved by designing reactors with variable moderator characteristics such that the proportion of neutrons captured by this resonance could be varied at will. In fact such resonance control in one form or another was essential if nuclear fuel costs were to be brought down to the range that the author had mentioned. He hoped that he was not speaking out of turn when he said that it was this concept of resonance control which was at the base of the current approach to nuclear marine propulsion in this country.

Mr. J. R. G. Braddyll felt that Mr. Hildrew had said very little about oil-fired boilers but what he had said implied that they were very cheap, very efficient and very reliable. His statement that tube failures in modern watertube boilers were very limited might be true but Mr. Braddyll suggested that in the last decade there had been a very large number of burst tubes, particularly in boilers less than 12 months old. These had been due to build-up of scale on the inside of the tubes which prevented adequate heat transfer from a furnace temperature of 2,600 deg. F. It was, however, on the gas side of the tubes that most owners complained of problems concerning soot and slag in the boiler and superheater tubes, choking or fires in the air-heaters or corrosion in the economizers. Even in Diesel engines the burning of oil fuel presented problems in the form of carbon and corrosion. With a nuclear boiler these problems did not arise—no smoke, no carbon, no corrosion, no high temperature. When they could get the price right, he believed it would be these factors which would influence shipowners to prefer nuclear propulsion in due course of time.

Mr. Hildrew referred to Captain Ridley's recent paper on the "Dounreay Submarine Prototype" and the positive breakthrough on the problem of corrosion of ferritic steels during fabrication, namely, the forming of a magnetite film on the internal surfaces by steam processing. Undoubtedly, this was a significant step forward and he thought a word of credit should go to Mr. Maurice Oldham, his company's chief chemist and metallurgist, who had been responsible for this development work. His company were inclined to believe, however, that in spite of such precautions a practical solution might be to allow some very slight relaxation of complete cleanliness standards during fabrication followed by chemical cleaning and passivating, as used in conventional power stations and indeed present marine practice. As a matter of fact the fabrication of stainless steel for primary circuits had been found to be easier than the fabrication of low alloy steels. Notwithstanding this, nor indeed the good experience of the Americans, he did not care for the use of stainless steel systems in merchant ships. The penalty for the accidental entry of salt into the feed system was too high.

In considering the direct cycle installation, the author made much of the difficulties of remote control and automation of the engine room. Mr. Braddyll believed this to be the least of the problems—in fact he thought the industry would see continuous development of automation in conventional ships. Certainly the reactor was likely to be highly automated and remotely controlled and he would have thought that the extension of this facility to the engine room was really no significant problem.

Finally, he wished to refer to the short section entitled "The Shipyard". There seemed to be something of an implication that British shipbuilding and engineering works were not really quite up to handling nuclear work. In his company's engineering works it was being done and whilst he conceded that it was not necessarily easy he did not feel that there were any problems that a well organized engineering works could not tackle. The overall facilities required for building and commissioning a nuclear ship were quite extensive and must be paid for, but the engineering problems were, in a general sense, the same as ever, but probably with a new emphasis on extreme cleanliness.

There was a very major problem in developing a reactor system which would appear attractive to shipowners and yet another attack was made on this problem under the auspices of the A.E.A. with B.S.R.A. co-operation. He wished to make it absolutely clear that when such a system was a practical proposition for installation in ships, the British marine engineering and shipbuilding industries would be fully competent to do any part of the fabrication and installation work that they might be called upon to do.

Mr. A. J. Taylor said that Mr. Hildrew's paper was the first one to his knowledge that bluntly stated the current situation on nuclear propulsion. The situation had not just become apparent, in fact, nearly three years ago one of the tenders to the Ministry of Transport also stated clearly that economic nuclear propulsion was not a current feasibility with any system. Against the background then existing with vociferous proponents of new and untried systems proclaiming their wares, such a statement required a little more time for the truth to surface. The claims for such systems had died away markedly in recent months.

The author drew attention to several methods of reducing capital cost which were currently under active study. In Great Britain, work sponsored by the Ministry of Transport was largely concerned with variants of the water reactor systems and if the methods suggested were applied to these systems, the general effect was probably to level out the capital costs of the contending types of reactor. The author was particularly pessimistic about the pressurized water reactor and was probably too unjust in his statements. The P.W.R. was unfortunate in that it had been built in several shapes and forms but the plants had largely been "first-off's" or "specials" from which the long term economics were not immediately apparent. The current status of land P.W.R. plants using the technique developed by M. C. Edlund promised attractive economics and it was for this reason that work in this country and in Europe had taken this basic idea applied to water systems as an important avenue for exploration. It was too early to see whether the economics survived in a marine environment.

The preoccupation with "quality" of the steam produced by various systems was not a valid basis for the assessment of economic worth. It was by no means certain, for instance, that nuclear superheat was a worthwhile objective. The cost of providing it could easily swamp the benefit claimed from increased efficiency. Similarly, the small differences in steam pressures likely to be obtained from contending systems were not likely to be an overriding factor in the judgement of economics for relatively small powers.

It was quite possible that the work currently being done in Great Britain would not result in a plant design giving immediate economic parity and it was a matter for judgement how far the paper studies should be pursued before prototype construction was commenced. Overseas groups (such as the E.N.E.A.) were studying less advanced concepts with a view to undertaking construction as soon as possible and there seemed little doubt that any group that constructed early in its programme would have a better foundation for more rapid progress toward the target of economic parity than one that persisted in surveying the next meadow.

One problem that was perhaps too far distant for much concern at the moment was that which had faced the designers of land based plant. From the marine standpoint, the economic target was so far away that it looked stationary. When it was approached closer, he believed that it would be found that it was receding, and the closer it was approached the greater would be the stimulus for it to recede further. The problem might not be as difficult as in the land power station situation, where the great increase in conventional plant output had given much of the cost saving, but, nevertheless, he was sure that if only a fraction of the effort spent on nuclear power became available for conventional plant development, then further difficulties for the nuclear designer could be produced.

Mr. P. Steward took up Mr. Hildrew's remarks, on page 507 of the paper, about possible marine reactors. He said that there were three general points which must influence the ultimate choice of a reactor with sufficient development potential for marine use. They were, firstly, choice and cost of nuclear fuels; secondly, irradiation or exposure limits; thirdly, elimination of a sea water flooding hazard.

Firstly, on choice and cost of nuclear fuels; in this country so far only natural or low enriched uranium had been considered. Although enrichment would enhance the burn-up of a reactor, it would probably not compensate for the increase in fuel production costs. Typical average exposure figures for a conventional pressurized or boiling water reactor using 4-6 per cent enriched fuel would be about 12,000 MWD/tonne of fuel depending on the particular reactor selected. On a spectral shift P.W.R. this exposure could be increased to about 20,000 MWD/tonne for the same enrichment.

Secondly, on irradiation and exposure limits; apart from the inherent physics limitations on maximum fuel exposures, uranium dioxide, the fuel currently being proposed for most marine reactors, could not be irradiated much beyond the 40,000 MWD/tonne level. This meant that with a maximum to mean power density of two, the average exposure level was limited to 20,000 MWD/tonne. This maximum limit of 40,000 MWD/tonne was set mainly by irradiation damage leading to fission gas swelling. Exposures beyond this limit might come with the development of cermets where the fission gases tended to be accommodated within the fuel matrix. It was expected that cermets of uranium dioxide dispersed in stainless steel or beryllium metal should give maximum exposures of at least 100,000 MWD/tonne.

Thirdly, on elimination of a sea water flooding hazard; in the marine environment a reactor was likely to become flooded with sea water because a severe ship collision, with breaching of the reactor pressure vessel, could never be discounted. This meant that it was desirable to design a reactor which was safe under this particular accident condition. Unfortunately, reactors which had attractive fuel cycles usually suffered from a reactivity addition when flooded. This criterion applied to both gas cooled and spectral shift reactors. In the use of gas cooled marine reactors, the cost of providing control, to hold down the additional reactivity on flooding, severely curtailed their development potential.

Captain W. T. C. Ridley, O.B.E., R.N. (Member) said that he wanted mainly to ask what it was that everyone was looking for. Many words had been written, by the author and others, about merchant ship nuclear propulsion. Most of them seemed to be concerned with economics and the general feeling seemed to be that until they could get an economic reactor, nobody in this country would have a nuclear propelled merchant ship. Was economics the only reason why nuclear propulsion was required in merchant ships? The Admiralty had other reasons for using nuclear propulsion, such as in submarines, and the question of the economics did not arise. But was it true that the only reason the mercantile shipowners wanted nuclear propulsion was that it would be cheaper? It had almost been demonstrated by the author, who had said that he did not want to be too pessimistic, that nuclear propulsion would never be economic. He had included a few words to show that it would be eventually, but he had not proved anything.

Not even the most optimistic of its protagonists would pretend that nuclear propulsion would apply to any but a few of the largest and longest-range ships; so that even if the reactor first cost and fuel costs showed a small economic gain, would the impact be sufficient to justify the expenditure of so much time, effort and money on research and development? It had been suggested years ago that the world would soon run out of oil, but, to judge from the price of the shares of the oil companies, that seemed unlikely now. However, if that was indeed the reason, then it was not necessary to talk about economics and similarly if the reason was really to gain prestige. If the only reason was economics, then everyone was wasting their time.

Mr. E. G. Bevan, A.R.C.S.T. (Graduate) said that in his review of high temperature reactors, Mr. Hildrew had made no reference to one of the major problems influencing the design of this type of reactor, that of the flooding hazard. Apart from the difficulty of obtaining suitable materials, perhaps the most formidable problem opposing the adoption of the high temperature gas cooled reactor for marine use was the increase in reactivity which occurred when the core was flooded with light water.

The worst condition for flooding occurred when the core was at the start of life when no parasitic absorbing poisons were present. The results from calculations carried out on the

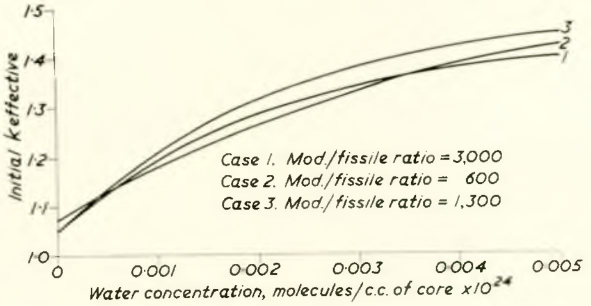

FIG. 1—*Changes in initial k effective due to flooding*

flooding of a 6ft. 6in. 55 MW, graphite-moderated, plutonium fuelled marine reactor were shown in Fig. 1.

The graphs showed the increase in reactivity due to the presence of light water in the core. The particular design considered had a total core voidage of 15 per cent and the top of the curves indicated the value of k effective when the core was flooded in the clean cold condition.

Three cases had been considered: Case 1, a dilute system, with a moderator/fissile ratio of 3,000; Case 2, a concentrated system, with a moderator/fissile ratio of 600; Case 3, a system with a moderator/fissile ratio of 1,300, which was the optimum concentration considering economics and burn-up.

The rise in reactivity due to total flooding in the cold condition might be between 35 and 39 per cent, depending on the concentration of the system, but clearly from the graphs no adequate solution to the problem could be found in varying the fuel concentration.

It was difficult to estimate the probable water concentration when the core was flooded under operating conditions, or in the case of a leaking heat exchanger tube, but if it was assumed that ten per cent of the voidage space was filled with water droplets, then the rise in reactivity would be approximately nine per cent. This figure, however, might be somewhat larger if the reactor had a large negative temperature coefficient.

Calculations on the amount of boron-10 required to bring the k effective in Case 3 down from 1·45 to a safe value of 0·95 gave a figure of 0·0000166 atoms of boron-10/c.c. of core × 10^{24}.

A similar figure was obtained in America when an investigation was carried out on the "Yankee" P.W.R. into the effectiveness of boron-10 in a light water medium.

If this boron-10 was to be pumped into the feed water in the form of boric acid as a means of overcoming the reactivity rise due to water entering the void space, the concentration of boric oxide in the feed water would be the prohibitive figure of 90,000 p.p.m.

Results were also obtained for the flooding of a 5ft. beryllia core and these gave a value of 31 per cent rise in reactivity in the clean cold condition.

The flooding hazard was not peculiar to these two types of reactors, but was common to all under-moderated systems where increased thermalization favoured absorption in fissile materials, which included those reactors based on spectral shift.

In the case of the gas cooled reactor, it would be extremely difficult to produce a mechanical design which would allow for the insertion in the core of sufficient control rods to hold down the reactivity increase with flooding, and it would appear that the only possible solution would be to decrease the voidage in present designs. This led to further problems in heat transfer, increased pumping power, and to high pressure drops through the core.

The general solution of this problem in the marine environment might be found in going to a nearly full-moderated system at the expense of short burn-up.

MR. J. R. FRANK said that he wanted to comment on the apparent change between the essential simplicity of the B.W.R. system and the final complication which appeared to be due to the multiplicity of components. He thought that many of the problems which had been raised were associated with the relatively large reactor compartment and the resulting difficulty of containment.

However, if this situation was analysed considering the ideal concept of a small highly enriched reactor system with a small fuel charge, and if in some way the system could be simplified by having fewer vessels, then this would also eliminate the rather expensive problems associated with pipe stresses due to bending moments and make it possible to obtain the small containment which was essential to marine usages. Smaller containment would impose smaller water weight and would thereby reduce the possible pressure rise.

Perhaps it was a cube law of turbine power with ship speed and weight which governed a vessel's marine economics. Reference had been made earlier to the belief that it would never be economic to use jet turbine aircraft, but the economics in that case did not work on a cube law. The carrying capacity of a ship was related to size and speed and it appeared to be the speed which could not be sufficiently altered without extreme penalty in size and cost of plant.

Correspondence

DR. T. W. F. BROWN, C.B.E., S.M. (Member) wrote that the author had adopted a very sensible attitude on the problem of developing an economic nuclear propulsion installation, which resulted in a stimulating paper. On page 502, he stated that capital costs must be reduced by two-thirds and fuel costs by a half if a nuclear plant was to break even with a conventional plant. These figures, although of a rough order, were about right for present conventional plants, but it must be remembered that conventional plants improved also during the period in which the reactors were developed to the extent given by these figures. The improvement therefore must be at a greater rate so as to break even in, say, five years. It was agreed that the areas in which development must take place if reductions of this magnitude were to be made were:

a) Containment. Reduction of containment costs by using the hull structure as containment (permitted by Inter-governmental Maritime Consultative Organization Rules) or alternatively by fitting the heat exchangers adjacent to or within the reactor vessel, so as to reduce the size of the containment vessel.

b) Primary circuit. Use of a low pressure circuit or a pressure tube design of reactor vessel. Use of a low alloy circuit (as in the British submarine design) instead of stainless steel. Typical of the author's approach is the statement, in so many words, that a designer who insists on using stainless steel is wasting his time, because his plant will be inherently too expensive (page 503).

c) Heat exchangers and pumps. Use of glanded pumps in low carbon steel. Use of a single heat exchanger and primary loop.

d) Shielding. Reduction of the difficult and expensive secondary shielding by a re-distribution of primary and secondary shielding.

e) Control. Use of a control system with few moving parts and few or no penetrations of pressure vessel, (e.g. spectral shift).

f) Instrumentation. Early nuclear ships will be over-instrumented.

g) Refuelling. It is the dismantling, re-assembly and proving the control gear which takes the time. Hence the advantage of a low pressure circuit with few control rod penetrations.

h) Collision protection. Research is needed here. Such work has already commenced in Japan.

j) Fuel element. The author favours a slightly enriched UO_2 rod canned in stainless steel or Zr, and able to use existing processing plant created for land installations.

Dr. Brown agreed with the author in demanding that in reducing costs, standards must still be maintained to give higher reliability.

Possible reactor designs were reviewed very briefly. The author was sceptical about claims for reduced costs for new reactor types, since costs always increased as the engineering design was worked out in detail. However, he was doubtful about water reactors ever achieving parity with conventional plant, so it was the new types which must be considered.

Dr. Brown was convinced that in addition to a land based prototype, operation would be required at sea before a great many of the problems of refinement and simplification could be applied to later installations.

Mr. G. H. Hodges (Member) in a written contribution, congratulated the author on his excellent paper. Nuclear power had the misfortune of having been introduced to the world in the form of a bomb. As a result it had been difficult to overcome certain reservations on the part of the general public, therefore today there were many problems to solve other than the technical design. These problems included such things as insurance, liability, port regulations and the specifications of classification societies and government agencies. Those were problems because in the past there were no requirements for such things and in consequence no ready made solutions were available.

Plans on paper did not call for action in these matters. Only a ship in being would create the necessity that would result in practical regulations.

N.s. *Savannah* was now an operational ship. Its design and construction had led through the birth and development of solutions to some of these problems. Its operation would create a demand for the solution of all the other problems. It was hoped that in the near future other countries would be added to the list of those which had opened their ports to the ship.

During the recent trials of n.s. *Savannah* he was fortunate enough to be on board for some days. The performance of the nuclear plant gave entire satisfaction.

The availability of almost instantaneous power and the extreme ease of manœuvrability of a nuclear plant were demonstrated in a very convincing manner and proved that from a technical point of view the application of nuclear power for ship propulsion was both practical and desirable.

They were however, as the author pointed out, faced with the economical problem of reaching parity with a fossilized fuel plant. He disagreed with the author as to the future of pressurized water reactors, as the development work under way indicated a more optimistic future than that indicated in the paper.

Future development and research activity would do much for the solution of the economic problem in the near future as a very large amount of work was being done on a continuing basis towards this end. Neither Rome nor the steam engine were built in a day, but they were built. With the continued effort now under way on a broad front, and with the pathfinding work of n.s. *Savannah* in connexion with the many other problems, the future for nuclear power in ships was bright and the day of its coming of age not far off.

Mr. J. McCallum, B.Sc., wrote that as the latest in the series of papers on marine nuclear propulsion which had been delivered in increasing numbers in the last few years, Mr. Hildrew's paper was probably unique in that he had no qualms about quoting figures. This applied especially to his forthright and eminently lucid remarks on the relative capital costs of conventional and nuclear boiler installations. He had not, of course, indicated the line of demarcation between boilers and auxiliary equipment. This would, perhaps, be pressing his round figures too far. This was probably the most important aspect of the paper and it was obvious that considerable effort was still required to develop a nuclear plant which was anything like competitive with conventional installations. Something more than this was required, as it was unlikely that a ship operator would take the economic risks which were inevitable without the promise of something extra to be gained from nuclear power.

The author emphasized, throughout the paper, the necessity of integrating the nuclear machinery into the ship, which meant that the nuclear plant must be specifically designed for its marine purpose. Mr. Hildrew had stated that excessive weight was not a major problem, and later remarked that early studies centred around installations weighing some 5,000 tons. Mr. McCallum was confident that the author did not intend to convey the impression that 5,000 tons would be an acceptable weight for the machinery of any type of ship. The freeboard regulations were such that any extra ton on the weight of machinery was deducted from the deadweight, and hence from the earning capacity of the ship. But from the aspect of economy of construction and operation of nuclear ships and, less critically, of conventionally powered ships, the major problem was the reduction in length of machinery spaces, both in passenger ships and in tankers and dry cargo ships.

With regard to containment, there was no doubt that the existence of a separate containment vessel was a considerable handicap in marine reactor design and also in the design of the ship structure. Containment vessels to date had been either of spherical or cylindrical form, both of which occupied a very large proportion of space within the ship, but if high pressures were to be successfully contained, these forms of containment vessel were inevitable. If containment by the ship structure was to be envisaged, the pressure would require to be relatively low and perhaps of the order indicated by the author, i.e. about 30lb./sq. in. This would represent the head at the bottom of a 70ft. deep water tank and it was certainly feasible to design a structure of this kind provided its volume was not too great and bearing in mind that vapour containment was a more onerous requirement in a flexing structure than water containment. Basically, however, the problem came back to the arbitrary assumptions made for the "worst conceivable accident condition", which, as Mr. Hildrew pointed out, were at present in the "almost impossible" range, and it would appear that a relaxation of the accident condition to permit a more realistic assessment should be under urgent consideration. It was disappointing to hear that little attention had been given to the design of pressure suppression devices—which would certainly be a step in the right direction.

Collision protection was probably more of an art than a science at this moment in time. It was well-nigh impossible at this stage to predict precisely how a complex structure would fail, particularly when the point of impact was unknown, and the only real criterion was to compare the damage caused in past accidents with the amount of kinetic energy available. The validity of information on speed at impact was very difficult to assess afterwards for obvious reasons, and it must be borne in mind that conventional ships which had suffered such an accident had not been specifically designed to resist the effects of collision. Nevertheless, a considerable degree of correlation could be deduced from an intelligent appraisal and application of available evidence on ship damage. If these conclusions could be related to model experiments—and Mr. McCallum was of the opinion that they could be—a considerable advance could be achieved. Small scale experiments which he had carried out had indicated that energy of impact could be directly related to depth of penetration on the model scale, and there appeared no reason why similar conclusions could not be derived for the full scale case. The proof of the pudding was in the full scale collision, but it was doubtful whether such a drastic check on the calculation would be willingly undertaken, any more than a practical check on the worst conceivable internal accident condition.

Mr. P. Pluys (Member) wrote that he had read Mr. Hildrew's paper with the utmost interest. The author gave indeed a very clear picture of the present position of nuclear reactors compared with conventional machinery for merchant ships. It was really noteworthy that the capital cost of plant for those reactor types, sufficiently developed for immediate installation, had to be reduced by at least 65 per cent and that a further economy of 60 per cent had to be made in the fuel bill before a marine reactor could break even with a modern steam turbine. The situation was even a little worse if the comparison was based on the Diesel engine, where considerable improvements were still being made.

The potential development of nuclear reactors was of course great; no doubt a day would come when competitive marine reactors would be available for some high powered ships. He would like to know when the author thought that that might be the case.

Another interesting point was that the author did not consider the pressurized water reactor type to be promising unless the spectral shift was applied. Some information had been published on this particular point and it would be interesting to have the author's comments on the future of that solution compared with other attractive systems.

Another interesting statement made by Mr. Hildrew was that concerning the use of the hull structure as the containment vessel. It was indeed evident that such arrangement would be of great advantage. In the case of excessive pressures however some relief device would have to be installed and more information or references with regard to the liquid baffle device would therefore be very useful.

Author's Reply

Over the past three years in contributing to the discussions on a number of technical papers relating to nuclear ships the author had consistently criticized such papers on the broad issue that whilst the information in such papers was factual no attempt was ever made to express a considered judgement on the significance of such facts.

Accordingly when invited to read the paper under discussion, it appeared reasonable to avoid similar criticism and to concentrate on opinion but to support the arguments with one simple basic fact. The fact chosen was non-technical and was £1 million—the difference between the capital cost of a nuclear boiler and conventional boiler installation.

After listening to and reading the discussion there was no doubt in the author's mind that the considerable buffeting expected and hoped for when writing the paper had not transpired. The contributors did however greatly reinforce any value the paper might have had as they covered a wide field of experience and the author was extremely grateful for the many views and opinions expressed. In this context, Mr. Gatewood's contribution was particularly attractive, based as it was on over fifty years in the extensive development of engineering and covering the rapid expansion of the sciences and their impact on the community. His particular comment on the ease of producing pressure circuits of 2,000lb./sq. in. or higher was agreed, as these did not pose excessive problems in terms of engineering, but they did represent a high production cost in Europe unless the concept of a pressure tube reactor could be developed.

The benefits of a clad circuit had never been adequately demonstrated. Undoubtedly America in the beginning weighed the unknown hazard of irradiated corrosion products and a possible permanently active circuit against the consequences of a cladding failure due to lack of adequate control during construction or due to chemical attack. After consideration that country decided to build clad vessels. Such a decision had influenced all marine reactor concepts and it was desirable that this decision, which was right at the time in the context of America and its defence, should be re-examined before implementation in the commercial field.

It was not reasonable to draw an analogy between jet planes and their piston-engined equivalents when considering the economics of nuclear ships in relation to orthodox ships, as aeroplanes did not have to obey the cube law. Some easement of the law in relation to ship form might be obtained by utilizing submarines, hydrofoils or hovercraft but such developments were yet to be proven economic.

Discussions on safety always tended to become abstract but ultimately the participants must return to square one, where it was stated that the consequences of exposing the general public to major fission product release in the event of an accident was unacceptable. The contrary judgement of a small group of scientists in Chicago in the context of a world war was probably justified, but in what, we must hope, was a long period of peace, a wider and less sophisticated opinion must prevail.

Mr. Yamaguchi's brief reference to the progress of the experimental ship study in Japan was noted with interest. It would be of value to learn if the figure quoted of 4 kg./sq. cm. was related to a structure which remained intact or represented the pressure at failure. Undoubtedly there was scope for considerable model work where proof of the adequacy of local hull design was required.

Mr. Abrahamsen's comments were noted with interest as they suggested that the major problem of trim was not so vital in certain reactor concepts on which he was peripherally associated. This was contrary to experience on large ship studies in the United Kingdom. As a design pressure for integrated containment 3 or 4 kg./sq. cm. was from safety considerations, readily acceptable, but the cost of such a structure might prove a prohibitive addition to the installation price. The figures quoted in the paper related to U.K. studies and possibly a case for higher hull containment pressures could be evolved under other economic conditions. Once it was economically feasible to build a reactor, the safety criteria now considered essential would be readily met. Reactor requirements outlined by classification societies did not prevent nuclear ships. The plain fact about such ships was that their complex plant installation cost considerably more than conventional plant and variations in permissible hull design pressures only gave a marginal price variation.

It was doubtful if any great benefit would accrue from the few full scale tests which could be carried out on old ships. The speed of a ship when scheduled for scrapping was slow in comparison with the ships examined in the context of nuclear propulsion and the construction would differ considerably over the areas which would interest the naval architect.

Transmission of damage through a liquid was not unknown in ships and adequate proof of its being eliminated from any design would be required before such a proposal could be accepted.

It was relevant to note in respect to cyclic ship accelerations that no reduction of the design value had been made. The figure of $0{\cdot}45g$ was the original figure and was determined by post-war work carried out by Lloyd's Register on conventional ships. Subsequent work carried out on the stability of a B.W.R. confirmed the adequacy of the design in relation to this figure.

Dr. Davis' remarks relative to the load characteristics of the B.W.R. were noted and accepted but to achieve such characteristics required a more complex control system than that required for a load following reactor. Load following was not achieved by a conventional boiler but shipowners bought ancillary boiler equipment to try and achieve this desirable feature. It must surely be an asset to a reactor design if load following was inherent in the core physics.

The criticism of the concept that the prospect of economic parity might be sufficient to encourage a shipowner to invest his money in a nuclear ship might be a valid one. However, philanthropy in shipowners was not unknown and a point would be reached where the prospect of an ultimate profit might prove irresistible. The figure of the cost of fuel and the necessity to enrich in order to reduce plant size were particularly relevant points but in addition there were certain areas of design where size could be reduced without enrichment. This could obviously be achieved in a spectral shift concept.

Mr. Baker's criticism cum badinage was kindly received, particularly as he concluded his contribution by totally disagreeing with his own opening cannonade. If the dubious biological and horticultural references made by him were eliminated, the basic fact emerged that contemporary designers took the middle course. The paper recommended greater circuit subdivision or less circuit subdivision—either might prove more economical. Mr. Baker opted for less, a single unit system—he was possibly right. Certainly, the half-way house of present reactor design was probably the least economic.

The concept of an interchangeable conventional boiler and reactor was probably unacceptable as shielding of present nuclear plant represented a weight penalty, which would have to be carried by a conventional installation, and this would be economically unsound. The United States of America and Russia had already built a marine nuclear plant. It was a waste of any country's resources to build another unless it could be demonstrated to show a potential at least comparable with conventional merchant ships. From the figures quoted at the commencement of the paper, some readers might reasonably assume that parity would never be achieved. This was a matter of judgement, the author being of the opinion that a considerable amount of re-thinking on current designs must occur before it was worth building a marine reactor. That such re-thinking was possible was shown by the rapid improvement achieved over the past five years.

Mr. Baker's comments on this point were adequately discussed and answered by Dr. Richards' contribution.

Mr. Nordström's criticism of the paper arose perhaps from a misunderstanding. The rejection of the P.W.R., B.W.R., etc., was based on an assessment of present published design proposals for marine installations and took account of definitive assessments by designers of the future potential of their design. It did not refer to the many new ideas which were being examined in the context of such reactors. Some such ideas might come to fruition and might make the current reactor types more economic but such development would take some years to implement.

Mr. Wootton's comments were only partially true. Nuclear land power plant had not yet given a practical demonstration of its parity with conventional plant. The brief economic survey in the paper was designed to demonstrate the size of the ship problem and was as near as it was reasonable to go at this stage. Advanced concepts of ship design for large vessels did not exist and nuclear propulsion must be related to current large merchant ships. Improved plant reliability and increased earning capacity were the main factors which could contribute to an approach to cost parity and offset higher capital cost.

A large number of nuclear ship safety requirements were surveyed by Mr. Whiteside. His remarks on the protection of the containment vessel against collapse were very relevant but it was possible to disagree with his conclusion that such vessels should be designed against collapse on sinking in shallow water. Provided orthodox materials were chosen for the reactor and piping, collapse should not damage the primary circuit. Salvage of a dry containment was a desirable requirement, but a designer would have to think a long way through such a problem before finalizing a design which was dependent upon how fast the ship would sink. Provided the primary circuit was made of conventional materials, there would be very little extra work involved in salvaging a wet containment.

The use of multiple reactor units was an attractive proposal but it was doubtful if refuelling such ships would only take the day or two usually suggested. Lifting a new reactor unit into the hull and rewelding under controlled conditions the severed steam and feed pipes would require some time and the argument that the capital charge on fuel was reduced was questionable. A ship would have a reactor in service, a reactor vessel and fuel awaiting processing and a reactor vessel refuelled and awaiting future installation.

The paper deliberately avoided direct reference to the more recent forward-looking proposals for nuclear ships primarily because they were only at the "idea" stage.

Dr. Bauer's outline of one of the more attractive methods currently being examined in the context of the control of nuclear installations was an indication of how rapidly such schemes were now developed.

Lloyd's Register records suggested that Mr. Braddyll's remarks relating to modern steam boiler defects were essentially related to modern high temperature (950 deg. F. and above) plants where a small human error in watchkeeping could rapidly induce failures. This problem underlined the necessity for more automation and a by-product of nuclear propulsion would be an acceleration to this end.

It was perhaps relevant to the section of the paper referring to shipyards that if reactor sizes could be reduced, thus permitting shop assembly, a lot of the problems associated with the construction of pressure plant in a hull would be eliminated.

Relaxation of cleanliness restrictions would obviously come with experience as would improved operating techniques and Mr. Braddyll's organization was forward-looking and as leaders of the marine industry in the nuclear field could greatly contribute to such developments. Other groups might require considerable investment to achieve the necessary facilities and experience.

One of the most significant factors to emerge from the discussion was the negative one that no contributor had challenged the economic sum improvised in the paper, and in fact a number of contributors associated with proposed nuclear marine installations had tended to take an even more pessimistic view.

Mr. Taylor adequately outlined such a viewpoint and yet argued that the experience of construction should override the lack of economic incentive. This argument could only be valid when economic parity was in sight. Until such time there would always be a strong incentive to survey the next meadow. The alternative argument in Britain must surely run that as wide experience was only available in the gas cooled reactor field, an investment in an alternative reactor type could bring other financial gains.

Mr. Steward's factual survey of the present status of nuclear fuel irradiation limits referred to a considerable body of experimental work taking place in America and Canada, most of which required proof under normal reactor conditions. Such proof was experience which must be bought by contractors who wished to use it commercially.

The sea water flooding hazard was undoubtedly overrated in paper studies, as the possibility of breaching a reactor pressure vessel by collision was virtually impossible and some degree of protection against a breach of the primary circuit was a feasible design criterion. It was interesting to note that after a long period of contemplation of a gas cooled marine nuclear reactor by British marine designers, the type was written off both by Mr. Steward and Mr. Bevan due to a hazard which was not yet properly defined.

Captain Ridley's contribution succinctly asked the basic question why nuclear propulsion was required for merchant ships. The only overriding reason was an economic one and, as indicated in the paper, such installations must be suitable to the dry cargo vessel of 10,000 to 15,000 d.w.t. The author would disagree with Captain Ridley on his assumption that economic gain could never be offered as the main advantage of nuclear propulsion. There was every indication that as the conception of mobile reactors became more simplified, the price would be competitive. The initial capital outlay on shore installations, fuel re-processing plant, etc., was not normally chargeable to the end product. Whatever capital a state was prepared to invest in the development of nuclear ships was best devoted to the development of land based prototype plant incorporating at least some of the variations discussed in the paper.

Basically, reactor installations must ultimately become smaller than conventional boiler installations and be capable of installation in an engine room. Such size reductions would force two requirements on the designer. The first was to simplify and the second was the use of high heat transfer coefficients. This latter problem would require long term proving which must be done ashore.

Mr. Bevan's remarks were particularly interesting as they represented a contribution based on factual assessments of the high temperature gas cooled reactor. His final conclusion that a fully moderated system might be acceptable providing the loss of the most cherished advantage of nuclear propulsions, long burn-up, was accepted, was worth further thought. The ground rule of long burn-up had never been closely examined. It would obviously be of advantage if refuelling was never necessary during the ship's life, but the capital outlay on a refuelling station which would only be used at infrequent intervals might not represent a sound capital investment and more frequent refuelling than the normal two or four year interval might well prove no great inconvenience.

It was interesting to note that one by one all the cherished foreseeable advantages which nuclear propulsion was judged to offer were being slowly discarded. Equally a number of newer philosophies developed from the experience of the past few years were based on such slender premises that continual re-examination and readjustment was necessary.

Mr. Frank's brief restatement of the advantages of simplification and size reduction, together with his salutary comment of the laws relating to ship propulsion, were a reminder that the fundamentals of ship and engine design did not change with the introduction of a new boiler design.

It was unfortunate that, as pointed out by Dr. Brown, the possible reactor designs were reviewed in a very brief and even scrappy manner. The purpose was to stimulate discussion rather than to give a complete definitive statement on a reactor's potential. Dr. Brown's summary admirably stated the areas on which cost reduction might be achieved and it was obvious that, with so many points of attack, a much greater cost reduction was possible on such equipment than on conventional plant. Refinement of marine plant must be developed at sea but at the present moment there was no indication that a reactor existed which was sufficiently developed and was sufficiently economic to encourage a commercial ship installation.

The advantages accruing from the mere existence of *Savannah* outlined by Mr. Hodges were true, but it could equally well be argued that the majority were already met by experience of land installations. This was apparently the view adopted to date by the British Government.

In fact all safety problems associated with any reactor plant must be solved prior to installation in a hull. Marine reactor concepts must be capable of design variations leading to improved economy and at least ultimate parity with oil fired boilers. Such parity would undoubtedly be approached by water reactors but it was difficult to see any economic potential in P.W.R. designs if the ground rules extant in Europe at the present time were maintained.

The ship problems associated with machinery weight, containment, and collision protection outlined by Mr. McCallum were those which did not appear to receive any great attention from most marine reactor consortia. This was particularly unfortunate as decisions made on these problems could greatly affect the installation layout and the installation cost. The naval architect should be a major contributor to the initial planning of a nuclear ship and not a latecomer urged to install as quickly as possible a large and often ill-conceived containment vessel into an arbitrary ship space.

The day when marine reactors would be competitive for large high-powered ships was some long time off unless as yet undiscovered developments contributed to the economy. Present new concepts being developed would, in the author's opinion, probably produce parity in a 1970 ship. The more interesting possibility of parity with conventional 15,000 d.w.t. dry cargo ships was less predictable and might never be achieved, but the impetus of nuclear space development in America and Russia could well break this barrier by about 1975. In the immediate future economic nuclear ships could be built for special marine functions and uneconomic nuclear ships might be built for experience or prestige.

The further point raised by Mr. Pluys in relation to spectral shift and its application to the pressurized water reactor was relevant. Spectral shift was a large step forward in reducing the capital costs of water reactors, but it did not reduce them enough and its application to other water reactor types might prove more effective.

It was not intended that hull structure when used as containment should be fitted with a relief device. It was the designers' hope that containment of the major accident would never be required in the ship's life. Accordingly the sum to determine the peak pressure must be a true one and the design of the hull structure to contain this pressure must be adequate.

Most of the work on liquid baffles had been carried out in America and was well documented in that country's nuclear press. An article in Nuclear Engineering* outlined present thinking on the subject.

The author thanked the contributors to the discussion. The paper endeavoured to dispel some of the rosier dreams on nuclear propulsion and at the same time maintain the feasibility of its future and it was apparent that all the contributors accepted the economic truth of the present situation but were fairly evenly divided on the possible future prospects of marine nuclear boilers.

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* Ashworth, J. P. August 1962. Pressure Suppression. Nuc. Eng. pp. 313-320.

INSTITUTE ACTIVITIES

Autumn Golf Meeting

The Autumn Golf Meeting was held at the Worplesdon Golf Club on Tuesday, 25th September 1962. Thirty-seven members attended the meeting and enjoyed a day of bright sunshine and perfect golfing conditions.

Mr. C. A. Larking (8) won the morning Stableford Competition with 39 points. Captain R. D. Fielder, U.S.N. (14) and Mr. A. Fowler (20) tied for second place with 38 points each, the prize being awarded to Captain Fielder, who had the better score over the last nine holes.

The Stableford Greensome Competition, held in the afternoon, was won by Mr. C. A. Larking (8) and Mr. J. M. Mees (19) with 38 points. There was again a tie for second place between Mr. L. E. Smith (20) with Mr. R. K. Craig, C.B.E. (22) and Mr. P. S. Rosseter (24) with Mr. D. Lyon (12), the score being 37 points. The prize was awarded to Mr. Smith and Mr. Craig who had the better score over the last nine holes.

Mr. Stewart Hogg, O.B.E., Chairman of the Social Events Committee, presented the prizes and expressed the appreciation of the members to the Committee of the Worplesdon Golf Club for the use of the course.

It was announced that the Summer Meeting in 1963 would be held at Hadley Wood Golf Club on Thursday, 23rd May and the Autumn Meeting at the Berkshire Golf Club on Thursday, 3rd October.

Section Meetings

North East Coast

The Autumn Meeting of the North East Coast Section Golfing Society was held on Wednesday, 5th September 1962, at Arcot Hall Golf Club, Northumberland.

The morning Singles Stableford was won by Mr. J. G. Loveridge (10) with a total of 40 points; Mr. C. J. Probett (3) was second with 36 points.

The afternoon Greensome Bogey was won by Mr. T. Pike (16) and Mr. L. W. Robson (16), 1 up, Mr. L. S. Colbeck (18) and Mr. E. Dimmock (8) taking second prize with a score of 3 down.

Three Hidden Prizes were also awarded.

It is pleasing to report that a member has made a generous offer of a permanent trophy for presentation to the winner of the Singles competition at the Spring Meeting, details of which will be made known later.

The Spring Meeting is to be held at the Ponteland Golf Club on Thursday, 16th May 1963.

Scottish

A general meeting of the Section was held at the Institution of Engineers and Shipbuilders in Scotland, Glasgow, on Wednesday, 10th October 1962 when the Chairman of the Section, Mr. R. Beattie, presented his paper entitled "Operational Problems of Small Diesel Ships". This was followed by a very interesting film, taken by the author, which showed shots from the International Conference, held in London from 7th-12th May 1962, the launching of different types of ships on the Clyde and at Belfast and the many varied duties which tugs carry out.

Mr. Beattie's paper evoked great interest among the 80 members and visitors present, as was evidenced by the discussion that followed which was ably dealt with by the author.

Mr. R. M. Dunshea (Member of Committee), in proposing a vote of thanks to Mr. Beattie which was carried with enthusiasm, complimented him, not only on the substance of his paper, but on the excellent film shown.

The meeting terminated at 9.25 p.m., after which light refreshments were served.

Election of Members

Elected on the 24th September 1962

MEMBERS

Edward Carlton Allen, Jr.
Jose Maria Barreiros
Bimal Chandra Basu
Jorgen Berring
Bruno R. G. Bussani, Dott. Ing.
Charles Frederick Collins
Lloyd Guy Copley, Lieut. Cdr., R.C.N.
Robert Reid Cran
John B. Davidson
George Gaffiero
Alexander Gilmore
M. J. Godiwala
Robert William Gray
Leonard Hill, Lieut. Cdr., R.N.
Arthur Gordon Hull
Alexander Hutcheon
Johann Ludwig Krauss, Squadron Eng., Lt. Cdr.(E), S. African Navy
John McKenzie Loudon
Eric John McManis
George Mawhinney
Godfrey Mortson
Maurice John O'Rourke
John Wood Aitken Paul
James Raleigh
Albert Henry Rossell
Stamatios N. Simbouras
George B. Spikas
William John Robert Thomas, Lieut. Cdr., R.N.
Philip David Vernon Weaving, Commander, R.N.
William Edward Zimmie

ASSOCIATE MEMBERS

A. A. M. Ali Khan, Lieut., P.N.
Edward Keith Anderson
John Norman Bailey
John Turner Barton
Vincent Boyle
Victor Manuel Carneiro
John Carter
Geoffrey Hugh Cheek
George Eric Clarke
Edwin Walter Cock
Richard Henry Cook
Derek Grayson Cooper
Anthony John Davies, Lieut., R.N.
Walter Henry Dawson
Hedley William Edwards, Eng. Lieut., G.M., B.E.M., R.N.
Allan Elder
Ignacy Felczak
Frederick Thomas Gay

Bryce Gemmell
Amitava Ghosh
Aidan Graham
Thomas Leopold Hanson
John Albert Hill
Neil Charles James
Harjeet Singh Jawanda
John William Jordan
Allan Marshall Kerr
Abdul Quiyum Khan
Peter Albert Knowles, Eng. Lieut., R.N.
James William Lively
John Joseph McCarthy
Frank Stewart McPherson
Derek Allan Moore
William Paul Patteson
Derek William Pope
John Porter
Bhagat Krishan Prakash
S. N. Sabnis
M. S. Sadasivan
Stephen Alexander Schollay
Nigel Wilfred Scully
Arun Sankar Sen Gupta
Edward Floyd Shepherd
Norman Henry Sherrard, B.Sc.
Gursharan Singh
Wilfred Smith
Trevor John Stenhouse
Leslie Sterling
Frank Sutcliffe
Charles Frederick Symmons
A. P. Tavadia
George Hay Taylor
Stanley Williams
Maurice William Wilmot
Peter Winkley
E. Xenitithis, Lieut.(E), R.H.N.

ASSOCIATES
Masud Ahmed Abbasi
Kenneth Roy James Bennellick
Clifford Oscar Hugh Bentley
Joseph Burn
John Anthony Clarke
Louis Henry Coussey
Max Raymond Goodacre
John Bell Harrison
S. B. Kapadia
James Henry Layn
Eric Desmond Letten
C. R. Pillay
S. K. Rajagopalan
V. C. S. Sastri

GRADUATES
S. D. Amarasinghe
John Dudley Bassett
N. S. C. Bhandary
J. L. Bhasin
Bryon John Bird, Eng. Sub. Lieut., R.N.
Robin Bourne
John William Burgess
Surajit Chakravorty
James Richard Cottam
Dennis William Crosby
Dharamvir Dewan
Baladeb Dhar
Gordon Barry Fell
Michael Edwin Findlay
Somesh Grover
Narain Tillumal Hirani
Ronald Paul Holbrook
Rama Varma Kochaniyan
Michael Stuart Lawton
Kevin Lucas
John Vincent McEvoy
Thomas John McNaught
Robert Alexander Maxwell
Robert Alex Phillips
Syed Khaja Qutubuddin
Bangalore Krishnaswamy Satyanarayana
Rajat Kumer Sen
Bishwa Nath Sinha
Kadayam Viswanathan Srinivasan
Shyam Charan Tandon
Gerrit Tomassen
Puttichanda Poovaiah Vijay
Edward Roger White
John Theodore Henry Willcox

STUDENTS
Alan Roderick Conroy
Godfrey Konwea

TRANSFERRED FROM ASSOCIATE MEMBER TO MEMBER
Kenneth James Grant
Patrick Joseph Marie Hopkins
Dennis George Maguire
John Barrie Richings
William Naismith Robertson
James Rodger
Milton Douglas Thornton
Herbert Edmund Tune
Alexander Peter Vacca, M.A. (Cantab.)

TRANSFERRED FROM ASSOCIATE TO MEMBER
Robert Findlay Campbell
William Dawson Martin
John Millar
Milton Clifford Taylor

TRANSFERRED FROM ASSOCIATE TO ASSOCIATE MEMBER
Virendra Singh Dhanda, Lieut. Cdr., I.N.

TRANSFERRED FROM GRADUATE TO ASSOCIATE MEMBER
Brian Edward Bowes
Colin Norman Brown
William Colquhoun
Ronald Edward Creathorn
Colin Robertshaw Greenough
Malcolm Dennis Hill
Ronald Albert Allen Johnson
Frederick Francis Roy Phillips
Hormis Puthenangady Varghese, Lieut., I.N.

TRANSFERRED FROM GRADUATE TO ASSOCIATE
Robert Ross
John Kenneth Brian Turk

TRANSFERRED FROM STUDENT TO GRADUATE
John Charles Beland
Kam Wing Cheung
Syed Z. Hoda, B.Sc.(Durham)
Philip Henry Inman
Michael Garbutt Kay
Peter George Swift
Kenneth Gordon Wheatley

TRANSFERRED FROM PROBATIONER STUDENT TO ASSOCIATE MEMBER
David Ronald Christie

TRANSFERRED FROM PROBATIONER STUDENT TO GRADUATE
Patrick Thomas Coleman
Roger Alan Wood

TRANSFERRED FROM PROBATIONER STUDENT TO STUDENT
Geoffrey Baxter
David Barry Melhuish

OBITUARY

G. W. Craggs (Member 12455) who was born on 15th February 1913, died on 30th August 1962, after several years of ill health. He served his apprenticeship with the North Eastern Marine Engineering Co. Ltd., from the beginning of 1929 to the middle of 1934. He also attended evening classes in engineering during this period.

He first went to sea in 1935 and served, as junior to second engineer, until the end of 1948 in motor ships owned by Adellen Shipping Co. Ltd., Hunting and Son Ltd., T. Dunlop and Sons Ltd., W. J. Tatem Ltd. and H. E. Moss and Co. Ltd. He obtained his First Class Motor Certificate in May 1949.

Mr. Craggs was serving in m.v. *Dalhousie* when she was sunk, during the second world war, and he subsequently spent some time aboard the German prison ship *Altmark*. Later he was transferred to Japan as a prisoner of war and spent 3½ years there in prisoner of war camps.

In the years following the last war, ill health compelled him to give up his seagoing career and during the last years of his life he was employed as an engineer draughtsman with C. A. Parsons and Co. Ltd. and the North Eastern Marine Engineering Co. Ltd.

Mr. Craggs was elected a Member of the Institute on 21st June 1949.

H. H. Cuttle (Member 7859), who had held a First Class Board of Trade Certificate, died on 10th August 1962 at the age of 78 years. He served an apprenticeship with Clarke, Chapman and Co. Ltd. but his early experience was gained in the small engineering shop which served the local fleet of trawlers and paddle boats in his native Scarborough. He chose a seagoing career in preference to one as a draughtsman and, in 1907, after gaining his second engineers certificate, he joined the Cunard Line.

During the first world war he served as Engineer Lieutenant, R.N.R. aboard the *Campania,* one of the Royal Navy's first aircraft carriers. This vessel, a converted liner which had been reprieved from the breaker's yard because of the war, was involved in a collision and sank in 1918.

In New York, after the war, Mr. Cuttle took over the German liner *Imperator*, renamed *Berengaria* and became second engineer of that vessel in 1925. He became chief engineer in 1933 and a few years later was appointed to supervise the installation of machinery in the new *Mauretania*.

During the second world war he served, in Australia, as assistant superintendent engineer, handling the large vessels which were using the port at Sydney. He was at Singapore in 1941, to supervise the drydocking of the *Queen Elizabeth* and *Queen Mary,* when the arrival of the Japanese forestalled these operations. However, Mr. Cuttle was able to escape.

After this he helped to organize and was engaged in the mass ferrying of American troops to Europe in the *Queen Mary* and later served as staff chief engineer in both the *Queens*.

Mr. Cuttle retired from the sea in 1945 and in 1946 settled in Southampton with his wife. In 1948 when his wife died he returned to Scarborough where he remained until his death. He was elected a Member of the Institute on 13th May 1935.

J. H. F. Edmiston (Member 9502), who died on 26th August 1962, at his home in West Wittering, was born on 6th June 1905, the eldest son of the late James Malcolm Edmiston who was for many years a Companion of the Institute. Educated at Haileybury College and Brazenose College, Oxford, he joined, in 1930, the firm of Grosvenor and Co. (London) Ltd., of which he was chairman and managing director at the time of his death. He had also since 1946 been a London manager of John Hastie and Co. Ltd. of Greenock and in 1952 founded James Edmiston and Co. Ltd. He leaves a widow and two sons, the elder of whom, James, is carrying on his business interests.

Mr. Edmiston was a well known Rugby football player, gaining his Blue at Oxford in 1926 and 1927 and for several years played regularly for Leicester and Blackheath. He was a member of the Kent County side which won the County Championship in 1927 and played for London against the unbeaten All Blacks side of 1924.

He was elected a Member of the Institute on 6th February 1956 and was also a Liveryman of the Horners Company.

D. G. Evans (Member 6184) who was born at Cardigan on 6th March 1902, died on 12th June 1962. He served his apprenticeship with the Cardiff Channel Dry Dock and Pontoon Co. Ltd. from 1917-1922. His early sea service covered the years 1923-1928 and during that time he gained his First Class Board of Trade Certificate.

In 1928 he joined the China Navigation Co. Ltd. as junior engineer, was promoted second engineer in 1929 and became chief engineer in 1937. He remained with this company for 30 years until his retirement, due to ill health, in July 1958. In the course of this long period of service Mr. Evans had a wide experience with Diesel engines, steam turbines, steam reciprocating engines, oil and coal fired watertube boilers and Scotch boilers. He had also on occasions been seconded for special duty to assist the superintendent engineer with repairs, surveys and dockings of C.N.Co. vessels.

During the evacuation of Singapore in 1942, Mr. Evans displayed great initiative under difficult circumstances when he attempted, with a hastily mustered crew, to save the m.v. *Tatung* from the enemy. He succeeded in evacuating the vessel to Batavia, but continued attacks from the air eventually made it necessary to immobilize the vessel's engines and to scuttle her. This was successfully achieved and he then led his crew to safety in a difficult trek across Sumatra.

Mr. Evans, a recipient of the Coronation Medal, was elected a Member of the Institute on 4th February 1929.

J. Hughes (Member 7121) was born on 31st October 1903. He received his education at Rutherford College, Newcastle and Wallsend Technical Institute. He also took two summer courses in marine propulsion at Wallsend and the second and first class courses in marine engineering at the Marine College, South Shields. His apprenticeship was served with Swan, Hunter and Wigham Richardson Ltd. from 1919-1925.

On completion of his apprenticeship he joined Elder Dempster Lines Ltd., sailing with that company, first as refrigeration engineer and, later, as third engineer in mail and intermediate mail steamers. In 1929 he transferred to Shaw, Savill and Albion Co. Ltd. as third engineer, remaining with that company until 1934. During his seagoing career, Mr. Hughes sailed to ports on the Continent, in Africa, Canada, the United States and New Zealand. His last voyage was to New Zealand in r.m.s. *Mataroa.*

In 1934 he left the sea and took up an appointment with the Mobil Oil Co. Ltd. as engineer and technical representative, performing his duties in the Liverpool, Manchester and Newcastle areas. He spent the remaining 28 years of his life in that employment.

In the course of his career, Mr. Evans, who was elected a Member of this Institute on 12th September 1932, earned the high esteem of all those engineering colleagues with whom he came into contact. He died on 10th August 1962.

C. S. Reed (Member 12868), who was born on 3rd July 1914, served his apprenticeship with S. G. White and Co., Sydney, Australia. He also undertook a full time course in marine engineering at the Sydney Technical College.

He saw sea service as fourth and third engineer in vessels owned by S. G. White and Co. and during the second world war served as an engineer officer in the *Queen Mary.*

From 1946-1948, as Engineer Superintendent of James Patrick and Co. Pty. Ltd., he was in charge of the reconditioning of the m.v. *Anshon,* which had been sunk by enemy action during the war. The vessel was subsequently renamed *Culcairn* and traded on the Australian coast until she was sold at the beginning of 1962.

Mr. Reed, who for a number of years had been engineer surveyor in Australia for Bureau Veritas and the American Bureau of Ships, was, at the time of his decease, marine superintendent for James Patrick and Co. Pty. Ltd., managing director of their marine engineering subsidiary, Begg and Greig Pty. Ltd. and manager of their road transport division, the Patrick Freight Line.

He was first elected an Associate of the Institute on 5th May 1950 and transferred to full membership on 4th October 1954. He died on 10th August 1962.

D. W. Urquhart (Member 6567), who died on 1st January 1962 aged 76 years, first went to sea in 1909. He served at sea throughout the first world war and in 1916 joined the Australian Commonwealth Line, with which company he remained until 1928, when his ship was taken over by the Aberdeen and Commonwealth Line. Shortly afterwards he took up an appointment with Shaw, Savill and Albion Co. Ltd. Mr. Urquhart, who held a First Class Board of Trade Certificate, achieved the grade of chief engineer, one of the ships in which he served in that grade being the t.s.s. *Raranga.*

The outbreak of the second world war found Mr. Urquhart with his ship, the *Moreton Bay,* in Australia. The vessel was taken over by the Royal Navy for war service and he remained with her as Engineer Commander, R.N.R. until 1941 when he was compelled to leave the sea for health reasons.

After his health had been restored he returned to the Shaw Savill Line as assistant superintendent engineer and so remained until his retirement in 1951.

Mr. Urquhart was elected a Member of the Institute on 2nd June 1930.