NUCLEAR POWER AND SHIPS

BY

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The *Nautilus* has now been at sea for nearly a year, and nuclear power as a practical method of providing main propulsion for a ship has been proved. The measure of its success can be judged by the fact that the United States Navy has ordered a further eight submarines, a cruiser, and an aircraft carrier. It is this choice of ships which indicates the direction in which nuclear power can be most usefully employed.

Generally speaking, nuclear power can offer three major advantages to the naval designer :—

(*a*) Extended range
(*b*) No oxygen required in order to obtain the heat release
(*c*) No exhaust.

To offset these advantages, there are an equal number of disadvantages :—

(*a*) Large weight of the biological shield
(*b*) Large development charges and higher initial capital cost
(*c*) Higher running costs.

In a warship design, it is desirable that, in order to obtain the potential advantages of a new form of propulsion, the disadvantages should not seriously affect the fighting efficiency of the ship in some other direction. With nuclear power, the most likely way that the ship, as a whole, might be impaired is by the increased weight of the machinery causing a consequential reduction of hitting power or armour. Owing to the diversity of their operational roles, the problems of the surface and underwater vessel should be considered separately.

CONSIDERATIONS

The Surface Vessel

For the surface vessel, the sphere of interest can easily be outlined by comparing the weights of the appropriate nuclear power plant with the present conventional machinery. The nuclear power plant will generally consist of a reactor from which the heat is extracted by some coolant in the form of gas or liquid ; the coolant which is taken in a closed circuit to the steam generator and which, depending on the substance chosen may not, but probably will, be active. Steam from this heat exchanger will then be led to a more or less conventional steam plant. The reactor will have to be surrounded by its biological shield, as also will the steam generator, and the coolant circuit, if they are radio-active.

In order to simplify the comparison of the two types of machinery, it can be assumed, without too great a degree of error, that the weight of the steam generator and its associated shielding in the nuclear power plant is equal to the weight of the boilers, fans and uptakes, in the conventional layout. This leaves the weight of the reactor, and its biological shield to be balanced against the weight of fuel which would have been carried.

It would be possible to build one reactor capable of supplying the biggest horse-power envisaged, and this would undoubtedly give the lightest arrangement. However, this arrangement could not be tolerated from the normal damage control consideration except, perhaps, in the smallest of vessels.

Table I shows a comparison of the weight of fuel and weight of reactors for various classes of ships.

TABLE I

Ship	*Horse Power*	*Wt. of Fuel Carried (Tons)*	*No. of Reactors*	*Wt. of Reactor (Tons)*
Frigate	15,000	400	1	500
Frigate	40,000	550	2	1,000
Destroyer	40,000	620	2	1,000
Cruiser	60,000	1,100	2	1,200
Light Fleet Carrier ..	40,000	3,500	2	1,500
Fleet Carrier ..	150,000	6,200	3	2,000
Battleship	110,000	4,000	3	2,000

From this Table it can be seen that the carrier and the battleship are the only vessels which show a clear gain in weight. However, considering that the reactor weights are only rough estimates and are probably pessimistic, it is possible that the cruiser would not show too bad a weight balance. If some other great advantage could be found for the cruiser, such as a requirement for a prolonged period at sea, nuclear propulsion would then be an advantage.

In the cases where weight is saved, it is necessary to think what space would become available for extra armament, ammunition or stores. As the majority of the oil fuel in capital ships is already carried in wing tanks and double bottoms, where it acts as torpedo protection, it is only possible to replace it with armour or a bulk fluid with, probably, a high flash point. A battleship could transfer its internal fuel tanks to the wings and double bottoms, which would give rise to a certain amount of free space, but very little compared with the 2,000 tons saved weight that is available. On the other hand, an aircraft carrier could use the wing tanks and double bottoms for storing aviation kerosene. This would increase the aviation fuel stowage and the fighting endurance of the carrier would consequently be improved. A further advantage for an aircraft carrier would be the absence of a funnel and funnel gases ; the removal of funnel haze would greatly improve landing conditions, and more freedom could be given to the designer in siting the island. The absence of uptakes and boiler-room intakes would also provide much needed additional space in the ship.

Naturally the range and endurance of ships fitted with nuclear power would be greatly extended. Probably an endurance of sixty-thousand miles could be reasonably expected. Besides being an advantage for capital ships in a ' Pacific ' type war, it is possible that the increased range could be used in a cruiser engaged in commerce protection or raiding. The limit of endurance is then shifted from fuel supplies to other stores, such as food, ammunition, aircraft fuel, and to human endurance. The movement of the importance from fuel to other stores reflects immediately on the machinery design, in that thermal efficiency loses its greatest importance and consequently the emphasis can be even more strongly placed on minimum weight and space.

The Submarine

In order to consider the case for the submarine, it is necessary to think of the more important requirements. These can be summarized as :—

(*a*) Complete submersibility
(*b*) Small hull
(*c*) High silent speed
(*d*) High underwater passage speed.

Complete submersibility can be obtained by nuclear powered vessels as no oxygen is required in order to release the heat energy. Similarly, except for the cooling water from the cold sink of the power plant, there is no exhaust to be released. The high speed that is required is obtainable, and is only limited by the size of motive power machinery that can be fitted in a given hull. The problem of silence is one that is always with the designer, and is no worse for nuclear power than for any other form of propulsion.

The small hull is the only requirement that cannot yet be satisfied, and this is because of the large weight of the biological shield. Although no drastic decreases in weight can be envisaged through discovery of new materials, it is certain that present day conceptions of shield design will be modified in the light of experience as it is gained. It is perhaps in this field, more than in any other, that the civil power programme does least to help the ship designer. The need for economy and the freedom from space considerations has led the power station designer to bulky shields made of materials chosen more for their cheapness than for efficient shielding properties. Some idea of the size of hull required to support a reactor can be obtained from *Nautilus*, which has a hull diameter of 27 feet and a displacement of 3,500 tons.

REACTORS

Before nuclear propulsion for the Navy could be seriously considered, enriched fissile material had to be available. Although it is possible to make a reactor with natural Uranium, the twenty-foot core of BEPO, the graphite moderated Uranium pile at Harwell, gives some idea of the impossibility of fitting it into a naval vessel. With enriched fissile material, a variety of reactors become possible. The main classification of these reactors is into three types—thermal, intermediate and fast. Of these, there is little or no experience of intermediate reactors in this country, and fast reactors are only just beginning to come into service. The bulk of experience is with thermal reactors, and it is possible that only these will be fitted in ships for the next decade. The thermal reactor is one in which sufficient moderating material is present to slow down the neutrons from the high energy they have when emitted from a fissioned atom, to the thermal or low energy most suitable for causing fission in another atom.

The major problems in the design of a reactor are those of materials and heat transfer. On the material side, the reactor can be considered in five sections :—

(*a*) Fuel elements
(*b*) Coolants
(*c*) Moderators
(*d*) Containers
(*e*) Shielding.

The first three are inside the core and their nuclear properties are therefore important. The remainder are outside the core, but nevertheless can be affected by radiation. The nuclear properties of a material can be summarized as :—

(*a*) Neutron absorption
(*b*) Moderating ratio
(*c*) Radiation damage
(*d*) Induced radio-activity.

The neutron absorption of a material is important, in as much as it represents a waste of neutrons and consequently a fall-off in nuclear efficiency. Materials are chosen with a low neutron absorption in general, and where this is impossible, quantities are kept to an absolute minimum.

The moderating ratio is a method of comparing the possibility of a neutron losing energy by hitting and rebounding from a nucleus with the possibility of it being absorbed, and consequently lost, when it hits the nucleus. Obviously, the most successful moderators are those in which the chance of scattering is higher than the chance of absorption. The loss of energy due to scattering may be compared with the slowing down of billiard balls when they collide.

Radiation damage can take many forms, from the mere displacement of atoms in the metallurgical lattice, with consequent hardening of the material, to complete dissociation. Certain materals are more susceptible to damage than others, and certain types of damage are more tolerable than others.

Induced radio-activity is not important in the nuclear design of the reactor, but plays an important part in the shielding problem, and in maintenance difficulties. This has two aspects—how active does a material become ; and how long does it stay active ?

The success of a reactor design, particularly for use at sea, depends on the reliability of the fuel elements. The usual design of a fuel element consists of the fissile material surrounded by a can. The function of this can is threefold :—

(*a*) To prevent chemical interaction of the coolant with the fissile material.
(*b*) To retain the highly active fission products, and consequently avoid contamination of the rest of the coolant circuit.
(*c*) To provide structural strength to the fuel element.

The fuel may be natural or enriched Uranium by itself, or an alloy containing Uranium. Equally well, other fissile material can be used such as Plutonium or U235, usually in the form of an alloy. The fuel can may be a loose fit on the fuel with a pressurized gas filling to act as a heat transfer medium, or else a metallurgical bond can be made between the can and the fuel alloy. The latter course is preferable as, in the event of a can failure, only a small area of the fuel will be subject to corrosion from the coolant. It is, however, more difficult to achieve.

Materials for cans require the following major properties :—

(*a*) High corrosion resistance to the coolant

(*b*) Resistance to thermal cycling stresses
(*c*) Low neutron absorption
(*d*) High strength to enable thin sections to be used, while providing adequate strength to the fuel element. This implies good creep and fatigue properties
(*e*) High melting point to allow high temperatures in the coolant.

It is difficult to obtain these properties in one material, but the most suitable ones are aluminium, magnesium, zirconium and stainless steel. Stainless steel has all the properties except low neutron absorption ; consequently, if it is employed, it must be kept to a minimum.

The materials that satisfy the nuclear requirements for moderators are very limited, and are shown in Table II, which gives also their relative merits.

COOLANTS AND POWER CYCLES

To be considered in conjunction with the choice of fuel element and moderator is the coolant. The requirements here are largely dictated by normal engineering requirements and are summarized as :—

Dictated by heat transfer and pumping loss considerations :

(*a*) High specific heat
(*b*) High conductivity
(*c*) High density
(*d*) Low viscosity
(*e*) Low melting point
(*f*) High boiling point.

Dictated by nuclear requirements :

(*g*) Good chemical compatibility
(*h*) Low neutron absorption
(*i*) Freedom from dissociation under irradiation.

Liquid Coolants

The more common liquid coolants are water and liquid metals such as sodium and potassium or their alloys. Generally speaking, they may be considered as low or high temperature coolants respectively.

Water is the ideal heat transfer medium, but to get quite moderate working temperatures requires a high pressure to suppress boiling. Another advantage is that it can easily be combined with the moderator and consequently the reactor design is simplified. Although it has a fairly high neutron absorption, the activity that results is very short lived, with the result that maintenance can be quickly started on the external circuits. The corrosion and dissociation problems, though difficult, are not insurmountable.

On the other hand, liquid metals, although their heat-carrying characteristics are not so good, have good heat transfer characteristics and they will withstand very high temperatures without pressurization. There is little or no damage by irradiation, but the corrosion problem is very severe. The activity that is produced by irradiation is in general long-lived, and maintenance problems are consequently more difficult. Experience in circuit technology is rapidly being gained, and consequently handling problems are being reduced. For use at sea, there is a danger of fire if liquid metals come in contact with water. Because they do not require pressurizing, scantlings of constructional materials with high neutron absorption inside the pile are reduced.

Pumping losses with liquids are small but, in order to prevent leakage of radio-active coolant from the circuit, new glandless pumps have had to be

TABLE II

Relative merits of the various substances		
Substance	*Advantages*	*Disadvantages*
Water	(*a*) An efficient moderator that will enable the pile to become critical with slightly enriched Uranium (*b*) Has a very low optimum moderator to Uranium ratio by volume, thereby providing a small core (*c*) Resists shock (*d*) May be used as combined coolant and moderator, thereby simplifying design (*e*) Has a very short lived activity, making maintenance of external circuits easy (*f*) The heat generated in the moderator does not require a separate cooling circuit (*g*) Is very cheap, even when used at high purity	(*a*) Requires to be pressurized in order to obtain reasonable temperatures from the core (*b*) Highly corrosive (*c*) Dissociates into its basic gases of hydrogen and oxygen
Heavy Water ..	(*a*) Highly efficient moderator that will enable the pile to become critical with natural Uranium (*b*) Resists shock (*c*) May be used as a combined moderator and coolant (*d*) Heat generated in the moderator is easily absorbed in the main coolant circuit, if the heavy water is also used as coolant	(*a*) Requires to be pressurized in order to obtain reasonable temperatures from the core (*b*) Highly corrosive (*c*) Very expensive (*d*) Dissociates (*e*) A high moderator to Uranium ratio (15 times that of water) leads to big cores
Graphite ..	(*a*) Cheap (*b*) Withstands high temperatures (*c*) If obtained with high enough purity, is highly efficient and will enable the pile to become critical with natural Uranium	(*a*) Low resistance to shock (*b*) A high moderator to Uranium ratio (35-50 times that of water) with consequent big cores (*c*) Suffers from growth under radiation (*d*) Easily oxidizes giving a mass transfer effect
Beryllium or Beryllia	(*a*) Withstands high temperatures (*b*) Withstands corrosive attack by most coolants (*c*) Of the solid moderators, it has the lowest moderator to Uranium ratio, being 3-4 times better than graphite and about ten times worse than water (*d*) May be formed by powder-metallurgy techniques into complex shapes	(*a*) Requires to be used in conjunction with enriched fuel (*b*) Highly toxic (*c*) Very expensive

developed. There is the canned rotor pump for water and electro-magnetic pumps for liquid metals, but in general, their electrical efficiencies are low, and pumping losses are intensified.

Gas Coolants

Gases are suitable for high temperature work. They have to be pressurized in order to get sufficient density but, even so, pumping losses are high. The most suitable is helium. Besides having the best heat transfer characteristics of all gases, it is nearly inert to radiation and so does not become active. It is, however, very expensive and would be difficult to provide in large quantities, particularly as it is not found in this country. With regard to heat transfer characteristics, hydrogen is the next best choice. Its disadvantages are the grave danger of an explosion should a leak occur, and the several problems that arise because of the ease with which it diffuses through many materials. As a third choice, carbon dioxide can be used. For heat transfer it is only about a third as good as hydrogen. It is cheap and suffers from no long-lived activity. At high temperatures, it tends to oxidize materials, and with graphite, can give rise to a mass transfer effect.

Of all the possible permutations and combinations of these materials, the more practical reactors that result are shown in Table III. No mention is made of the liquid fuel reactors because little development work has been done on them so far, even though they have some highly desirable properties.

TABLE III

Moderator	*Coolant*	*Fuel*	*Examples Built or Building*
Graphite	Gas (CO_2)	Natural or near-natural Uranium	Calder Hall Power Station
Beryllium or Beryllia	Liquid metal	Highly enriched Uranium	U.S.N. S/M *Sea Wolf* (Intermediate reactor)
Heavy Water	Heavy Water or Water	Natural or enriched Uranium	DIDO (United Kingdom) NRX (Canada)
Water	Water	Near natural or highly enriched Uranium	U.S.N. S/M *Nautilus* LIDO (U.K. Research Reactor)

To date, power cycles have followed conventional lines. The coolant is taken from the reactor to a heat exchanger steam generator. This is the closed primary circuit. Steam raised on the secondary side of the heat exchanger is then led to a conventional steam plant. The use of the primary circuit is two-fold. Firstly, it is used to limit the circuit that contains radio-active coolant and, consequently, has to be shielded. Secondly, it limits the field of contamination should a fuel element can fail and release its highly radio-active fission products into the coolant circuit.

Two other power circuits which short-circuit the heat exchanger are of interest. If the coolant in a water moderated and cooled reactor is allowed to boil inside the reactor, the steam generated could be led direct to a steam turbine, thereby doing away with the large and heavy heat exchanger. Steam temperatures would still be very low, but the pressure in the reactor would be considerably reduced.

A similar circuit can be imagined for a gas-cooled reactor, where the hot gas would be led direct to a gas turbine. Both these circuits require a high degree of gland tightness, as the coolant is radio-active, and both could lead to a difficult decontamination problem, should a fuel element fail. At the present moment, fuel element metallurgy and coolant circuit corrosion problems prohibit the use of really high temperatures, but this is only a question of development, and gas turbine plants, operating at about 500 degrees C., are probably a practical consideration now.

The choice of a water system for the submarine *Nautilus* with a theoretical maximum dry and saturated steam pressure of about 400 lb/sq in was probably governed by the practicability of a small shock-resistant core. The use of a coolant and moderator system considerably eases the design problem, which, coupled with the low moderator to Uranium ratio, enhances the chances of producing not only a small core, but a small containing vessel as well. As the weight of the shielding, which is by far the major weight in the power plant, is governed by the size of the containing vessel, this probably results in the plant of lightest weight.

Development of reliable high temperature fuel elements and gas-tight glands would enable a fast reactor, with its associated very small core, to be used for driving a gas turbine direct. This would result in a considerable saving of weight and space over the water system. Unfortunately, the reliable solution of these problems is not likely to enable a power plant of this type to be at sea for a least another decade.

PROBLEM OF THE MERCHANT NAVY

The Merchant Navy is faced with an entirely different problem. It has always been accepted that in designing warships, economics take second place, if the machinery or equipment under consideration has some very definite military advantage. In merchant ships, nuclear power must pay its way, or at least show signs of doing so in the near future. The only other alternative is that it must be able to give some highly desirable feature to a ship, that is not obtainable by any cheaper form of propulsion.

The emphasis, when considering reactors for naval use, has been on reducing size, and it has often been necessary for designers to go to the limit of heat transfer to obtain machinery with acceptable weight and space factors. This, in turn, has necessitated the use of highly enriched Uranium for the fuel. Little, if any, attention has been given to breeding, that is, the conversion of certain non-fissile materials into fissile material. Examples of this are the conversion of U238 to Plutonium 239 and Thorium to U233. Even reactors using a highly enriched fuel will have a small conversion factor as, inevitably, some of the neutrons will be captured in the non-fissile Uranium isotope 238. The object of obtaining a high conversion is obvious. Ideally, a conversion factor of unity or greater is sought, because then no other fissile material will ever need to be added to the reactor, although the fuel will need re-processing at intervals in order to restore the metallurgical properties and the distribution of fissile material. A less extreme case, but still highly advantageous is where the conversion factor is sufficiently high to allow the depletion of fuel in the reactor to be made up with natural Uranium, instead of the enriched Uranium with which it was initially fuelled.

Reactors that are suitable for merchant ships must, therefore, be a compromise between large and heavy reactors fuelled with cheap, natural or near-natural Uranium, and having a large conversion factor, and small light-weight reactors, fuelled with expensive highly enriched Uranium, with small conversion factors. With present-day technological limitations, the water moderated and cooled reactor appears to give one of the best compromises. The physics of this type of reactor is such that a reasonably small core can be built with fuel that is not very highly enriched. Consequently, a high conversion factor is obtainable. An alternative solution to this is the fast breeder reactor. This type of reactor will not, however, be considered in more detail because the fissile investment is high and the necessary technology has not advanced far enough.

Because of the high capital cost of installation, it is advisable that ships fitted with reactors should have a high utilization factor. The ideal ship to choose from this consideration is the oil tanker, with its very quick turn-round. However, little will be gained by using this type of vessel. A tanker of 25,000-tons dead-weight, with a power plant of 10,000 s.h.p. has a fuel stowage of about 1,000 tons and a cargo stowage of 24,000 tons. Replacement of the fuel with a reactor weighing about 400 tons will release a further cargo stowage of 600 tons. This represents a gain of 2½ per cent. This will make little difference in the gross takings of the shipowner and, consequently, the reactor that is fitted in a tanker will have to produce a competitive price/power ratio, i.e. in the order of 0·3d per s.h.p. hour, when compared with a Diesel propelled ship.

On the other hand, the cargo liner of equal s.h.p. will have a reduced dead-weight of approximately 10,000 tons. This reduction is due to the large space used for passenger carrying and comfort. In this class of ship, the dead-weight is divided into approximately 8,000 tons of cargo, and 2,000 tons of fuel. The fitting of a 400-ton reactor now shows a release of 1,600 tons for cargo stowage, which represents a 20 per cent increase in pay load. Careful consideration needs to be given to the type of general cargo carried, in order to ensure that hold space is available for the additional cargo. In recent designs of this type of ship, emphasis has been placed on additional fuel stowage, in order to ensure that the ship can fuel at the cheapest port in its round trip. This has been carried to the extreme of doing away with a large percentage of the fresh water stowage, and fitting additional evaporators. As this represents a 10 per cent fuel consumption, it is a heavy price to pay for the additional stowage, and would be unnecessary in the nuclear powered liner. One further consideration is that fuel costs represent only about 10 per cent of the total cost of keeping a vessel at sea. Consequently, an increase in capital and running costs can more easily be borne in view of the large pay-load increase.

DESIGN RESEARCH

While fissile material is being government controlled, it is impossible for any private firm to build a reactor without the sanction and co-operation of the United Kingdom Atomic Energy Authority. At present, the U.K.A.E.A. is divided into three groups :—

(*a*) The Weapons Group centred at Aldermaston
(*b*) The Research Group, centred at Harwell
(*c*) The Industrial Group, centred at Risley.

For the Calder Hall power station reactors, a pattern of development has been evolved, but it will not necessarily apply to future projects. In the initial stages a small group at Harwell, known as the Future Studies Group, undertook the ‘ feasibility study ’ of several different reactor types. The more promising of these went through a design study, in which sketch designs were produced of all major components, and the fundamental technological and design problems solved. From the consideration of these designs, experimental programmes were drawn up to solve problems in metallurgy, chemistry, radiation technology and heat transfer. Where necessary, models were constructed in order to study coolant flow patterns. Construction of fuel elements was carried out on a small scale and such logistic problems as the supply of fuel and its processing after use were considered.

When the design study had been satisfactorily completed, the design was continued by the Industrial Group at Risley. Here detail design was undertaken. Little, if any, manufacture other than experimental rigs and a certain amount of electronic control gear, is carried out by the U.K.A.E.A., and consequently Risley was responsible for placing all construction contracts and for forwarding them. An exception to this was the manufacture of fuel elements by the U.K.A.E.A., an obvious major production job. Further experimental work, as necessary, was carried out by the Research Group, and in general, ' zero power ' experiments were their responsibility. These are small scale reactors which are allowed to become critical, but are held at the very low power level of a few watts only. This allows their design to be simplified, as no cooling circuits are required. As they work at low power, there is little build-up of fission products, and consequently little risk should an accident occur. These experiments are used in conjunction with exponential or critical approach experiments to determine accurately the nuclear constants of the core design. Control problems are also studied in these experiments. Typical of this type of reactor are Zephyr which has been associated with the fast reactor being erected at Dounreay, and Dimple, which has been used to study the problems associated with the design of heavy-water reactors.

Having designed the prototype power station reactor, and started erection, the U.K.A.E.A. began the education of industry by placing contracts for the development of similar type of reactors. For these Phase I reactors, several industrial groups are preparing designs. These groups are in general a combination of boiler, electrical and turbine firms. Initial education of their representatives is carried out at the Reactor School at Harwell, and by attached service in the U.K.A.E.A. establishments. The Reactor School runs three courses a year, each lasting three months. Since the Geneva Conference last year, a tremendous amount of information has become declassified, and the Reactor School is now open to foreign students.

A similar pattern cannot be followed for ship reactors, because a knowledge of the special problems of ship design has to be married to the design of the reactor from the earliest stages. For this purpose two teams have been set up at the Atomic Energy Research Establishment. The British Shipbuilding Research Association is studying the problem for the Merchant Navy, and a Naval Section has been established to initiate designs for the Royal Navy.