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NUCLEAR POWER FOR SHIP PROPULSION.

by

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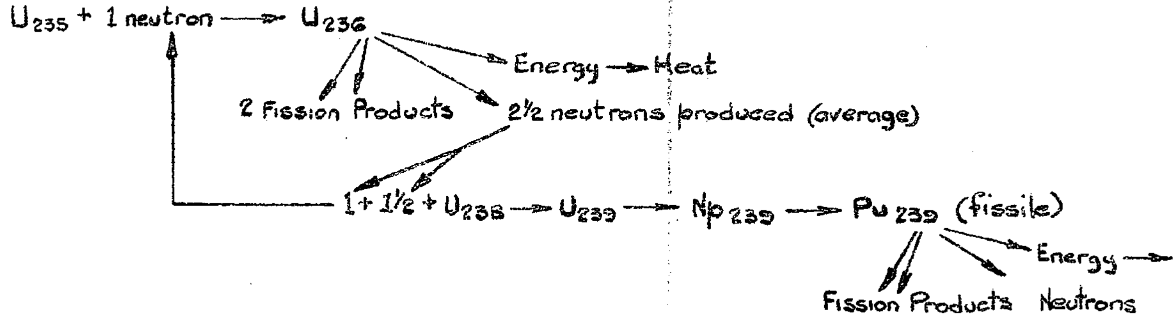
The practicability of the use of nuclear power for ship propulsion is demonstrated by the fact that ships are now at sea employing this means of propulsion. The purpose of this Paper is to describe the means at present employed in producing this power, to suggest future lines of possible development, and to describe the advantages and difficulties which may accrue from the use of this form of power for ships.

The basis of the rroduction of power by this system is the phenomenon known as fission, and materials capable of producing this phenomenon are called fissile materials. Three such fuels are of present interest, Uranium, Plutonium, and Thorium. These elements are denoted by the chemical symbols U_{238}, Pu_{229} and Th_{232}, respectively, the subscript denoting the atmic weight of the atoms. For ease of reproduction in this Paper the numerals will be placed on the same line as the chemical symbol, thus U238, etc.

It is of interest to note that one of the features of the atomic reactor in which the fission process takes place is that it procuces new fissile materials from the fuel with which it is charged, Such a reactor is said to be a "breeder plant" since it produces more useable fuel than it consumes. This, however, must not be confused with the dream of perpetual motion, for, ultimately, the fuel is all consumed and the process will cease until new fuel is supplied.

Suppose a reactor to be charged with natural uranuum, U235, and that the fission process is in operation. For every atom of U238 consumed about 0.7 to 0.8 atoms of U238 will be released from the supply of U235. U238 is the fissile material which exists as 1 part in 140 in the natural uranium U235. There are other fuels available which will produce 1.1 to 1,2 atoms of fissile material for every atom consumed in the fission process. This material which is produced is a fuel concentrate and is the probable fuel of the small reactors required for the ships of the future.

The fission process, based upon a fuel supply of U235 is as indicated below.



Note in the above process that one neutron added to U235 produces U236, the atomic weight increasing by unity, this being the weight of the neutron. This unattached neutron is necessary to start the reaction.

Free neutrons move with very high velocities, and it has been found necessary to slow them down, otherwise the process ceases. This slowing down is acheived by the use of materials known as moderators of which there are several, notably Hydrogen, Heavy Hydrogen, Carbon, or Beryllium, all of which have fairly light atoms which do not capture the energy producing neutron but, by impeding its free path and causing more frequent collisions they markedly reduce its velocity.

The fission process produces great quantities of heat which must be removed and used in some form to drive the prime movers. This necessitates the use of a coolant.

We now have the first three major requirements of a reactor, these are:-

(1) The fuel, Uranium (U235), Plutonium (Pu229), Thorium(th232)

(2) The moderator, HYdrogen (H) used as H20, Duterium or heavy hydrogen (D) used as D20, Carbon (C), or Beryllium (Be), and

(3) The coolant, Water (H20), heavy water (D20), a gas, molten metal, organic liquid or molten salt.

At the present time there are some twentyfive known possible ways of building an atomic power unit, and this naturally leads to some confusion of thought and effort. However, only about twelve to fourteen of these methods are at present considered likely to prove to be economically sound, and these are being investigated and used. It is estimated that a five to ten year experimental programme will be necessary in order to determine the operating economies of the various systems and to select those showing the greatest promise. Due to the large capital cost involved present concentration is focussed upon large land based power stations of up to 500,000 Kw, in an endeavour to reduce the capital cost per KwH produced.

We must consider these stations in order to gain a picture of the present situation regarding the usage of nuclear power, and to form some impression of possible future trends.

The first nuclear power station was built by the Soviet Union, but it is of a design which is not considered likely to be economical in operation.

There is a large station at Calder Hall in Britain producing 60,000Kw from two units each of 30,000 Kw. The design of this plant does not lend itself to marine use as its reactor dimensions are 40 feet in diameter and 60 feet in height. The moderator consists of a graphite block weighing about 1000 tons, so that the weight alone puts it beyond consideration for our Purposes.

However it does illustrate admirably one of the systems of power generation by the fission process and is worthy of some study. A diagramatic arrangement of the system is shown below.

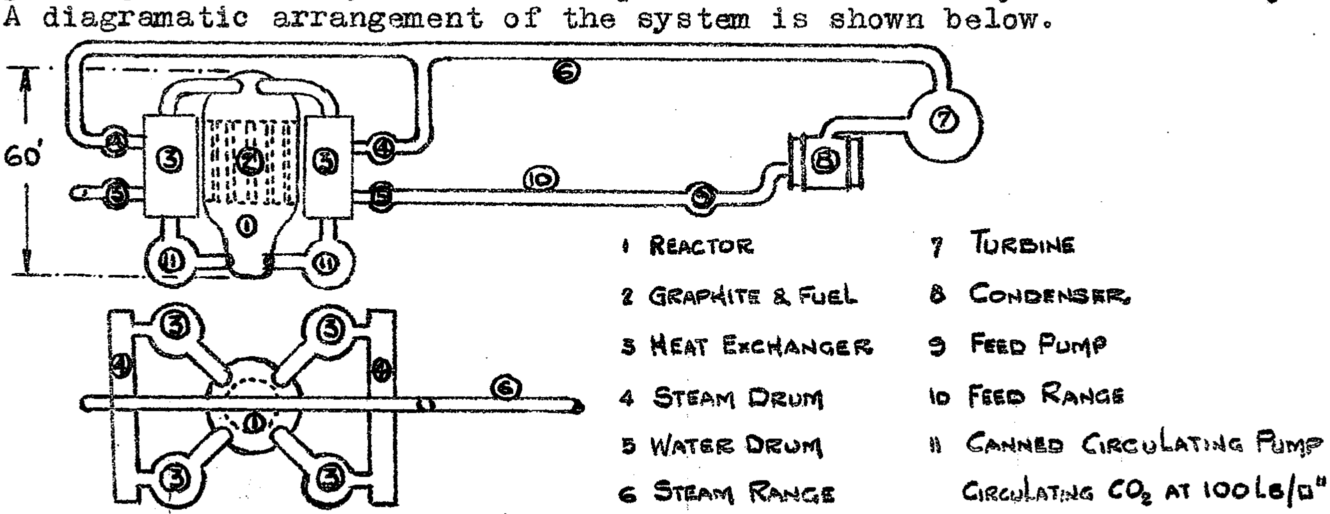


FIG 1

The medium by which heat is removed from the reactor is CO2 at a pressure of 100 p.s.i. The gas gives up its heat to water in four fairly conventional heat exchanges and is then recirculated to the reactor by a canned pump. The water in the heat exchangers boils to form saturated steam which is collected in the steam drums and passed via a pipe range to a conventional turbine house. The remainder of the process of electrical power generation is the same as in any thermal power station.

Since the gas does not come into direct contact with the water there is very little radio active leakage and the turbines do not show a very marked increase in radio activity. A dense concrete wall (which adds considerably to the overall weight of the plant) forms the radio activity shield around the reactor.

In America there are two types of plant which are worthy of study. The first of these is somewhat similar to the Calder Hall plant, except that water is used instead of CO2 for the coolant. This water is maintained at a pressure of 2000p.s.i. in closed circuit through the reactor and heat exchangers, and, in consequence it does not boil although the temperature is raised to about 540°F. The dimensions are considerably smaller than the British plant, the reactor being about 9 feet diameter and 30 feet high, this being due in part to the usage of enrichaged fuel consisting of U235 and uranium oxide contained in zinc cans in lieu of natural uranium. Its diagram is shown below.

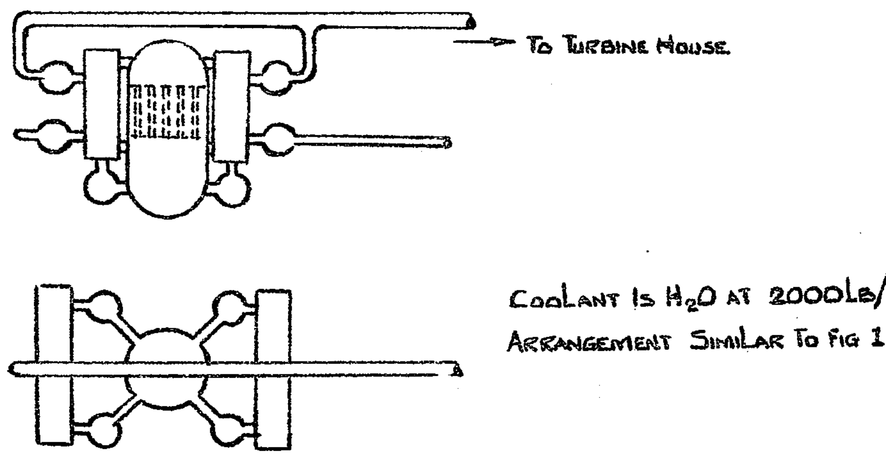


Fig. 2

The second American type is interesting from the point of view of ship propulsion and is known as a Boiling Water Reactor (BWR). The system is somewhat more simple than those shown above.

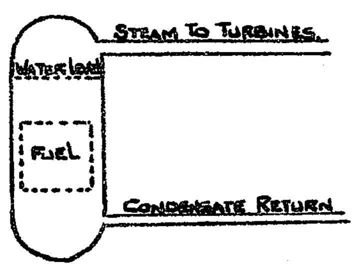


Fig 3.

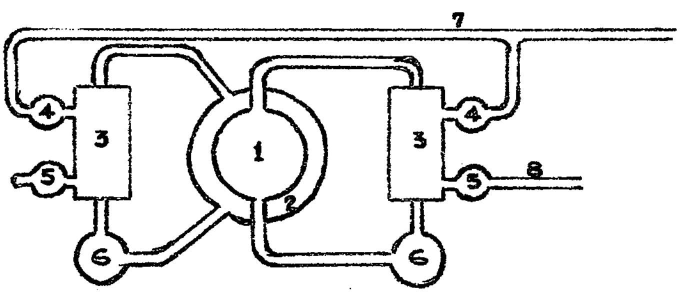
The steam from this reactor is slightly radio active, which will result in the turbines ultimately becoming slightly radio active also. It may require several weeks shut down to allow this radio activity to decay.

A full desription of this reactor will be found in the Technical Papers of the Geneva Conference of August 1955, to which reference may be made.

There are certain disadvantages connected with these reactors. Firstly, the water is slightly corrosive, secondly, neutron bombardment and gamma radiation may cause corrosion or other chemical changes in the steel reactor shell, and no one knows exactly what the long term effects of this last item will be. Thirdly, since the pressures are high, an explosion could have serious results since the atomic fuel could be scattered about.

It is known that the American prototype submarine "Nautilus" uses a pressurised water reactor, the first American type described above, and it is considered possible that the "Sea Wolf" uses molten sodium as the coolant with beryllium as the moderator, although this is not known. Security requirements forbid the giving of further information on these vessels.

The types of reactors described above suffer from the disadvantages that the entire fuel supply cannot be used as the fission products ultimately choke the reactor and the plant must be shut down and these products removed. However, there is a reactor known as a homogenous type from which the fission products may be removed continuously while the plant is in operation. Diagramatically this reactor is shown below.



1 Reactor Containing U_{235} Sulphate in D_2O. At 2000 lb/□"
2 Jacket Containing ThO_2 in D_2O
3 Heat Exchangers
4 Steam Drums
5 Water Drums
6 Canned Circulating Pumps
7 Steam Range
8 Condensate Return

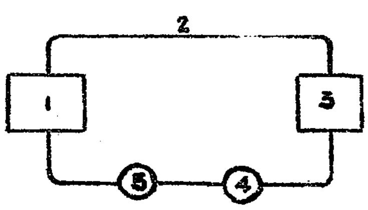
Fig 4.

The fuel here is U235 sulphate solution in either H20 or D20 contained in a sphere of zirconium jacketed by a spherical envelope of stainless steel, the jacket being filled with a slurry of ThO2 in D20. Such units produce 20 to 30,000 Kw each. The geometry of the sphere controls the speed of the reaction.

It is known that U235 sulphate is very corrosive under operating conditions and the long term effects upon the structure are yet to be determined.

To date steam has been used in order to keep the operating cycle temperatures to a reasonably low level. Higher temperatures would permit the use of the more efficient gas turbine as a prime mover the reactor in this case being gas cooled and the gas circuit being of the closed type. The problems encountered here are metalurgical and have been satisfactorily solved in the main.

In its basic features such an arrangement is as shown below.



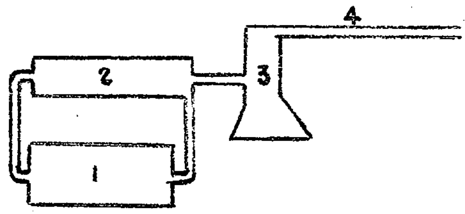
1 Reactor
2 Helium Range (800°C)
3 Gas Turbine
4 Sea Water Circulated Cooler
5 Fan.

Fig 5.

The reactor could be lined with refractory bricks containing uranium oxide which would melt at about 2000^{o}, the cooler is circulated by sea water which would not contact the fuel and hence would not become highly radio active.

This, and the following type, are both worthy of study as regards ship propulsion.

In order to simplify the system an open cycle gas turbine unit could be designed to operate very largely as indicated diagrammatically below. Here the fuel is enriched uranium 235 and the coolant is boiling sodium.



1 REACTOR CONTAINING BOILING SODIUM - FUEL IS ENRICHED URANIUM 235

2 HEAT EXCHANGER

3 AIR HEATER

4 AIR TO OPEN CYCLE GAS TURBINE.

Fig 6

There are certain advantages and disadvantages in the use of nuclear power for ship propulsion, those of prime importance are outlined below.

The fuel consumption would be very small . It appears probable that ship propulsion units will use enriched fuel in order to reduce the size of the reactor, and approximately 50 pounds of fuel would supply sufficient energy to produce 20,000 S.H.P. for a year.

The reactor itself would be very radio active and will require a complete sheilding of concrete 6 to 7 feet in thickness , or else an even thicker sheilding of water, and this of course, will be very heavy, so that the saving in weight caused by the elimination of the full bunkers may well be eliminated by the weight of the necessary sheilding. A great deal of research is required on this problem.

So far as safety is concerned, pure reactor failure does not become a problem, but extensive damage to the vessel or a foundering may cause the sea to become radio-active. In course of time as more ad moreships sink this could become serious.

At the present time there is no available design which can compare with conventional power units in prime cost. Capital costs, however, may reasonably be expected to be considerably reduced within the next five to ten years. The construction of nuclear powered ships in both the U.S.A. and the U.S.S.R. is of an experimental nature and is designed to foster research.

The conclusion to be drawn is that it is unlikely that Australian built ships will be propelled by nuclear power within the next ten to twenty years, although circumstances could arise shich would considerably modify that estimate.

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NUCLEAR POWER FOR SHIP PROPULSION

That nuclear power will be used to propel ships is clear from the attention now being given to this problem in several of the world's ship building countries.

The United States Navy has one nuclear powered submarine in service, several more under construction, and several more planned.

The British Atomic Energy Authority has stated that the development of ship propulsion units is being given a high priority.

The general trend of thought in this field can be judged from the following news items, picked at random from the technical press.

Admiral Rickover of the U.S. Navy is reported to have said that by the early 1960's all major naval vessels will have nuclear propulsion.

The U.S. Maritime Commission has called tenders for two nuclear powered ships, one an oil tanker of 38,000 dead weight tons and speed 20 knots, the other a ship of different design. The specification called for operation in 1959, though this seems somewhat optimistic.

In Denmark, the shipyard of Burmeister and Wain has set aside about £200,000 for research on nuclear propulsion.

The American Senate has approved plans for a nuclear powered merchant vessel.

The Russians have announced that a nuclear powered ice breaker is being constructed.

In Norway proposals for a ship reactor have been announced.

This interest derives from the fact that the development of nuclear reactors has now reached a point where small, fairly compact units having a large output of heat can be designed. Such reactors can operate for long periods without requiring additional fuel, and this immediately makes them of interest as power units for ships.

Nuclear reactors are devices in which the fission process is carried on continuously and under control. The fissionable fuel may be either Uranium 235 (occurring naturally to the extent of 0.7% in natural Uranium), Plutonium 239 or Thorium 233, which do not occur in nature, but which are manufactured in a nuclear reactor from natural Uranium and Thorium respectively.

The energy given out in the fission process is such that, a ship reactor producing 20,000 shaft horse power, could sail continuously for a year, and only consume about 50 lbs. of one of the three fissionable fuels mentioned above.

The whole of the space normally devoted to fuel could be used for other purposes, provided the reactor was not appreciably larger than the conventional power unit.

There are two main classes of nuclear reactors, depending on the energy of the neutrons used to bring about the fission process. Neutrons are produced in the fission process, and these neutrons have high energies. Neutrons are needed to bring about the fission process, and it is in this way that a continuous operation is obtained. The characteristics of the fission process depend to some extent upon the energy of the neutron which initiates it, and the two classes of react s differ in this respect.

In the first class the energetic neutrons of fission are reduced to a low energy level by collisions with the nuclei of certain substances called moderators before they initiate other fissions. These reactors are called thermal reactors.

In the second class, fission is brought about by highly energetic neutrons, and anything which would reduce this energy level before the next fission is caused is carefully avoided in the design. These are called fast neutron reactors.

At the present time fast neutron reactors are still experimental, and are mainly of interest because they offer the possibility of "breeding", that is of manufacturing Plutonium or Uranium 233, from Uranium 238 or Thorium 232, in greater quantity than the nuclear fuel used to bring the conversion about.

They are at present of interest for very large land based power stations, and might well supply in the future the concentrated fissionable fuel which ship reactors are likely to require.

Ship propulsion units considered up to now have tended to be of the thermal or near thermal types, and use concentrated fissionable fuel made in a land based reactor or an isotope separation plant.

Thermal reactors can be built to operate on natural Uranium (0.7% fissionable content) and large power stations of this type are entirely practical.

The main British power programme consists of reactors of this type, but it is easy to see why they are not attractive as ship propulsion units, by examining their size.

The British Calder Hall station uses two reactors to produce about 60,000 K.W. Each reactor is a welded steel pressure shell, about forty feet diameter and sixty feet high, make of steel plate two inches thick. Inside the vessel is about a thousand tons of graphite and over a hundred tons of Uranium.

The whole reactor is surrounded by about six feet of concrete for shielding and outside this are four large secondary heat exchangers, in which steam is raised, followed by the turbines and alternators of a normal power station.

These reactors have been designed to use natural Uranium, and it is one of their great advantages that they can do so, but for ship propulsion the designer turns to the use of Uranium in which the fissionable content has been increased, thereby enabling him to make the whole apparatus a good deal smaller and easier to accommodate in a ship's hull.

Few details have been published of the American submarine reactors. It is known, however, that the first of these, that fitted to the Nautilus, uses enriched Uranium 235 fuel and a system of ordinary water under a high enough pressure to prevent boiling in the reactor, to provide both the moderator and the coolant. It is believed that this reactor was the forerunner of the American power station reactor, the P.W.R. or pressurised water reactor.

It has also been disclosed that a later submarine reactor, that in the Sea Wolf, uses enriched Uranium 235 but is cooled with molten sodium metal, and no doubt uses some moderator, perhaps beryllium or carbon, instead of water.

The American Pressurised Water Reactor is of a type which might well be adapted to ship propulsion. As designed for a land based power station, it is obvious that no endeavour will have been made to keep down the overall dimensions, and this must be borne in mind when examining it.

The essential features of this reactor are as follows -

The reactor produces 60 M.W. of electrical power from a pressurised, light water cooled and moderated heterogeneous thermal reactor, in which the fuel is partly a highly enriched Uranium 235 and partly natural Uranium. The cooling water, under sufficient pressure to prevent boiling, is circulated through the reactor core where it extracts heat, then through external heat exchangers where it gives up this heat to other water, which boils and produces steam. The steam drives a turbine alternator system to produce power.

The reactor vessel is 33 feet high and about nine feet in diameter. The wall thickness over the tubular section is eight and a half inches. It is built of carbon steel with a thin stainless steel cladding on the inside. It weighs about 250 tons.

Four inlet and four outlet points are provided, each of six inches diameter. The fuel assemblies are of thin flat plates assembled to give the best possible cooling system.

The highly enriched assemblies are of Zirconium-Uranium 235 alloy, clad with Zircaloy 2. The fertile elements consist of natural Uranium Oxide, which has been sintered to give high density, and is then clad with Zircaloy tubing.

The pressurised cooling water is at 2,000 p.s.i. It circulates in four independent cooling loops, each with its own canned rotor pump and heat exchanger-boiler. The water entering the reactor at full power is at 508°F and it leaves at 542°F. Steam raised in the heat exchangers is at 600 p.s.i. and is of course saturated. The coolant circulating pumps, handling 16,800 g.p.m. each are driven by a canned rotor motor, eliminating all chance of leakage. The motors are each of 1,200 K.W. capacity.

The plant arrangements for control, for water purification, effluent disposal, etc. are fairly complicated, but present no fundamental problems. The plant is being built by the Westinghouse Electric Corporation for the U.S. A.E.C. and the Duquesne Light Company at Shippingfort near Pittsburg.

The P.W.R. has primary and secondary cooling circuits to limit radio activity to the primary system and to give stable heat transfer conditions within the reactor.

The possibility of using the reactor itself as a steam boiler and eliminating the secondary circuit has always seemed attractive, but the process of steam production within the reacting core seemed likely to cause unstable operation, and this might lead to power surges of a dangerous character. That such difficulties could be controlled was shown by the American first boiling water reactor, and this is being followed by a larger experiment, E.B.W.R., which, if successful, would seem of interest as a step in the development of ship borne power units.

Some details of E.B.W.R. follow -

The reactor is contained in a pressure vessel seven feet in diameter and twenty-three feet high, built of steel and clad inside with stainless steel. The working pressure is 600 p.s.i. The core consists of box like assemblies of flat plates, some of which are of natural Uranium, while the others are of Uranium 235-Zirconium alloy. Both types have the same heat capacity and fission rate. Various core assemblies are possible, for this is an experimental reactor. One, for example, requires about five tons of natural Uranium and forty-two pounds of Uranium 235. All fuel elements are clad in Zircaloy 2.

The reactor is designed to produce 20 M.W. of heat.

The wide diameter reactor vessel provides space for the natural circulation of the boiling water and for steam disengagement. The percentage of steam voids in the cooling channels in the reactor core has a strong effect on the reactivity of the core and this in turn is affected by the rate of steam take-off and by any sudden changes, up or down, in this rate. It is considered that these problems of control have been satisfactorily solved and that no difficulties with large power surges will be met.

The steam produced at 600 p.s.i. is of course saturated. It passes through a steam dryer to remove liquid carry-over which will be slightly radio active. The turbo generator is rated at 5 M.W. It is enclosed in a completely sealed container to prevent leakage of radio active materials. The condensate from the condenser is returned to the boiling reactor. It has been estimated that the cost of power from this unit will be about 20 mills/K.W.H. but this should be considerably reduced in larger and later units.

The pressurised water and boiling water reactors by no means exhaust the possibilities among the present prototype land based power stations which might lead to designs for ship propulsion units. The sodium cooled graphite reactor and the homogeneous reactors using aqueous solutions of Uranium salts as fuels may lead to useful designs, but they do not look as attractive for use in ships as P.W.R. and E.B.W.R. at the present time. Sea going power units should be as simple as possible, have the maximum safety in terms of disaster to the ship, and require the least possible maintenance, particularly that involving radio active maintenance work. These conditions react adversely on the sodium cooled units, the homogeneous systems and the fast neutron breeders.

All the main programmes for land based power stations at present use the heat of the reactor to produce steam, and the steam then drives more or less conventional turbines to produce power. This is partly because steam is still the normal method of power production, and reasonably efficient and reliable plant is readily available, and also because reactor designers, faced with very difficult problems of materials have wished to keep reactor operating temperatures as low as possible, which has tied them to the steam cycle.

While this position will probably persist for some time much thought and effort is being given to the design of higher temperature reactors which might operate with a gas turbine power system.

The problems in producing such reactors, operating in the range of, say, 600°C to 1000°C are problems in engineering design and materials. They are certainly not insoluble, and real progress in the field of aircraft propulsion units, and to a lesser extent in ship propulsion units, must wait for such a solution. It is interesting to note that the development of a reactor design of this general type forms a major part of the Australian Atomic Energy Commission's research programme. Similar work is going on in several other parts of the world.

The development of medium sized, compact nuclear power units will open the door to their use in ships. Two other problems must, however, also be solved. Firstly, the reactors must be capable of installation in a ship's hull in a safe manner, so that no hazards from radio activity can occur within or without the ship, and secondly the capital and operating costs of such units must be competitive with alternate systems of propulsion.

With regard to safety, consideration must be given to safety under normal operating conditions, and also to safety under conditions of disaster - that is disaster to the whole ship or to any part of it.

Safety under normal operating conditions will be largely a matter of adequate shielding, since it may be assumed that there are no control hazards under normal operations. Shielding is bulky and heavy. Land based reactors often are surrounded by six to twelve inches of iron plate followed by six to eight feet of dense concrete.

Reduction in the weight and volume of shielding will result from making the volume of the reactor and other equipment which must be shielded as small as possible. There are obvious possibilities in using reduced shielding below a reactor where radiation would only escape into the sea, but this raises other hazards, as for example the production of radio active sea water if neutrons are allowed to escape - an effect which might be serious when the ship was in harbour.

Safety under disaster conditions requires special consideration, particularly as ships are mobile, and when in harbour are often in areas of high population density and great economic value. These are clearly problems which involve security and defence and which may be very difficult to overcome in practice.

With regard to the economic problems, there is probably no system available at the moment which would compete on either capital or operating costs with conventional ship propulsion units.

For naval vessels there are other advantages which outweigh cost considerations. The ability to steam for great distances without refuelling, eliminating the need for distant bases or frequent returns to port is something which cannot be achieved in any other way. It seems certain that progress in nuclear ship propulsion will be mainly in the naval field for some time, though some merchant ships will probably be so equipped for special reasons, such as for prestige purposes, or oil tankers for use as naval ancillaries, or the Russian ice breaker.

From the experience gained in these ways there will develop more efficient and cheaper units, which ultimately will take their place amongst the ordinary commercial fleets of the world. It is not possible to say what the time scale is likely to be.

It seems certain that ship propulsion units will always require enriched fissionable fuel. This will normally be a by-product of a land based atomic power industry, which will have all the expensive equipment required for the reprocessing of spent fuels and the preparation of the special fuels needed by the sea going power units. While such facilities could possibly be purchased in the future, it does seem that the first step towards the regular use of nuclear ship propulsion must be the development on shore of an integrated nuclear power industry. When this is established the special materials, the knowledge and the trained men will be available for nuclear power to go to sea.