Nuclear Power for Commercial Vessels

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The paper presents a survey of British and American unclassified material relative to the use of nuclear power for marine propulsion.

Following a brief discussion on the principles of fission and reactor operation, five types of reactor suitable for marine use and one type suitable for fuel production are described and illustrated.

The gas cooled reactor is selected as most suitable for marine propulsion and a proposed closed cycle gas turbine plant is analysed in some detail. Various proposals for the use of nuclear power in specific ships are reviewed, and an economic analysis is made to compare a 30,000 ton d.w. tanker when operating with an oil fired steam turbine plant and when operating with a nuclear powered closed cycle helium turbine.

INTRODUCTION

Since the presentation of Sir John Cockcroft's paper (1) on the subject in 1953, much information has been released on the subject of power production using nuclear fuels and it seems pertinent that a survey should be made to define how this evolution in technology may affect the professional marine engineer.

With the world-wide increase in demand for power, which must accompany the present rise in the standard of living and the increase in population, some authorities have estimated that the limit of economical production of fossil fuels will be reached in about 100 years' time. The alternative sources of power being developed currently are nuclear and solar energy. While discussion in this paper will be confined to the former, it should be borne in mind that the present stage of development of the solar battery has produced an efficiency of the order of 10 per cent. This may well be bettered and applied to transportation within a decade, but under the present rationing system for sunshine, it seems highly unlikely that this will be available in the United Kingdom.

This paper will discuss the engineering aspects of the design, construction and operation of nuclear powered machinery. To be of interest to the marine industry, this paper must consider the economics of the nuclear plant. Authorities contend that nuclear power production ashore, providing existing development schedules are maintained, can be competitive with fossil fuelled power production in about ten years' time. It seems unlikely that a nuclear powered marine plant will show any economical advantage before that time since, in the author's opinion, one of the main factors will be the source of supply of fissionable fuel at a reasonable price and this must probably await the actual operation of a land power station using a breeder reactor. Probably one, and possibly two, nuclear powered merchant ships will be in operation within the next five years. These will not be competitive in either first cost or operational cost with vessels propelled by orthodox machinery, primarily because of the inevitable expense attached to the development of any new type of machinery. However, outside of this factor, it is hoped to show that the balance will not be as unfavourable to the nuclear powered plant as has been suggested.

The U.S. Atomic Energy Commission has recently prepared estimates of the economically recoverable reserves of both conventional and nuclear fuels, an abstract of which is given in Table I.

TABLE I.—WORLD RESERVES OF FUEL

Fuel	World reserves	Energy in B.t.u.
Coal	$3{,}482\times10^{9}$, tons	$72{\cdot}2\times10^{18}$
Oil	186×10^{9}, tons	$7{\cdot}6\times10^{18}$
Gas	560×10^{12}, cu. ft.	$0{\cdot}6\times10^{18}$
	Total conventional	$80{\cdot}4\times10^{18}$
Uranium	25×10^{6}, tons	$1{,}700\times10^{18}$
Thorium	1×10^{6}, tons	71×10^{18}
	Total nuclear	$1{,}771\times10^{18}$

The future of any leading maritime nation may well eventually depend on the availability of reactor technology and production potential. It will also depend on the location of sources of fissionable material of which uranium is the most promising. The military and political significance of this question is outside the scope of this paper, but the world-wide interest in the use of nuclear energy can be deduced from a study of the map in Fig. 1.

The details released in the recent White Paper covering Britain's ten-year plan for nuclear power development convey a note of optimism despite the capital cost involved. The White Paper states that the fuel supply prospects are now better than previously anticipated. Considerable deposits of medium and low grade uranium ores are known and thorium has distinct possibilities for conversion to a nuclear fuel. The Government is confident that the necessary supplies will be available when required. In dealing with an installed capacity of eight power stations in excess of 1,000 megawatts, this White Paper concludes, " This formidable task must be tackled with vigour and imagination. The stakes are high, but the final reward will be immeasurable ".

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By courtesy of Standard Oil (New Jersey)

FIG. 1—*World map showing location of uranium and reactors*

Uranium countries
- ● Now producing or believed capable of producing at current prices
- ○ Not fully explored but possibly capable of producing at current prices

Reactor countries
- × One or more built
- △ Active research or announced plans to build

The author suggests that the statement could well be applied to power production in the marine industry.

The main object in writing this paper is to foster interest in this new source of power, by replacing the " imagineering ", which has so far accompanied the magic words " atomic energy ", by a more rational survey of the facts. Those colleagues whose daily menu includes isotope hors d'oeuvre, potage uranyl sulphate, plutonium pie with beryllium dressing, etc., will find little sustenance in this article. They are nevertheless very welcome to partake in the feast over the author's bones, which it is hoped will follow the presentation. Security precautions will no doubt limit the range of the discussion, but the author feels that the present state of published knowledge offers ample scope for debate.

All the subject matter referred to in the presentation of this paper has been taken from unclassified sources and thus there may be an incomplete discussion on certain items.

DERIVATION OF NUCLEAR POWER

Several excellent texts (2,3,4) have been published on the principles and applications of the new technology and to include a similar complete treatment is outside the scope of this paper. However, in the interests of continuity, the following points should be borne in mind.

Fissioning is the splitting apart of the atomic nuclei of the material used as fuel. The addition of another neutron to the nucleus of a fissile material is sufficient to cause an agitated state and subsequent split up of the nucleus. The kinetic energy of the fission fragments is dissipated in the form of heat and other radiation.

Theoretically, one pound of nuclear fuel, which has a volume slightly in excess of one cubic inch, if completely fissioned, releases energy equivalent to 43 x 10^9 B.t.u. or approximately 1,000 tons of fuel oil. It is not possible to arrange complete fission of the fuel. Only a fraction can be used before chemical treatment is required, due mainly to the inevitable simultaneous production of reactor " poisons ". The transfer of such highly concentrated heat to a usable form of working fluid requires a complex system for coolant circulation. Critical control mechanisms, remote fuel handling, shielding and heat exchangers are also required. Many of these require entirely new concepts in design, due to the increased heat transfer rates and the variation in static and fluid mechanics involved. Radiation decay and corrosion and the properties of the many new materials now in use also present problems.

The heat produced by fission is, of course, on the credit side of the ledger, while the three " by-products ", alpha, beta and gamma radiation (briefly this order denotes increasing path length and decreasing ionization) are on the debit side, as they require special shielding to prevent a health hazard.

All reactors to date have been designed to use either Uranium 235, Uranium 233 or Plutonium 239 as fuel. Thorium 232, in common with other fertile material, which can be converted to a fissile material in a breeder type reactor and to a reduced extent in a non-breeder. (The numbers indicate the atomic weight or the sum of the neutrons and protons in the nucleus of the atom of that material). It is significant to remember that we are discussing the use of a metal as fuel. Uranium has a density 1·5 times that of lead, its melting point is about 2,000 deg. F., it is malleable and ductile and can be readily machined or cast. The fact that when in powdered form uranium is highly inflammable has no connexion with its use as nuclear fuel. In the homogeneous reactor, it is used in the form of a salt, uranyl sulphate, and dissolved to form a liquid fuel.

Natural uranium, U.238, contains only 0·7 per cent U.235 by weight; the other two fuels, U233 and Pu.239, must be produced artificially. The degree of enrichment of the fuel is the proportion of fissile U.235 to non-fissile U.238. The higher the enrichment, the more efficient " burn-up " of the fissionable U.235 can be expected. Of course, the production cost of the fuel is in proportion to the degree of purity required. In the present state of the art, any of the fissile fuels discussed above are costly although the prices are currently in control of government agencies, e.g. Atomic Energy Authority in Britain or Atomic Energy Commission in America. The price of fissile fuel should be considerably reduced, when in the not too distant future, the breeder type of reactor is put into service for power generation ashore. As described in a later section, these stations are expected to produce adequate quantities of fissile fuel as a by-product.

TYPES OF NUCLEAR REACTORS

Reactors are classed as either " thermal ", " intermediate " or " fast ", depending on the energy level of the neutrons. In a " thermal " reactor, the neutrons are slowed down considerably by a moderator before continuing the fission chain reaction. When the moderating action allows a higher neutron energy level to operate, the reactor is said to be of the "intermediate" type. If no moderator is provided to slow down the neutrons, then the reactor is "fast" and in some cases a fuel diluent may be necessary to spread the nuclei and so decrease the thermal flux density.

The form of the fuel, coolant and moderator create further classifications. In a homogeneous reactor, the fuel, coolant and moderator (if used) are mixed, often in liquid form. In a heterogeneous reactor, these are separated usually in solid form, which allows a definite geometric arrangement, e.g. round rods of fuel can be slipped into the moderator block in much the same way as marking pegs are placed into a cribbage scoreboard.

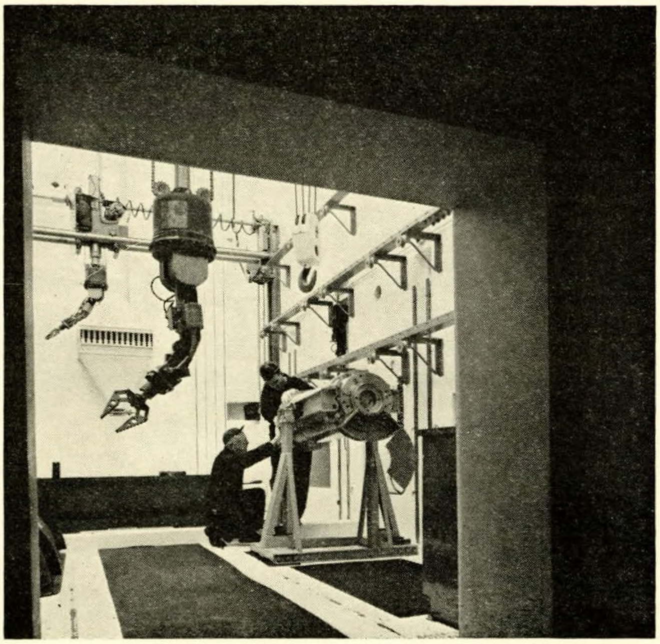
A reactor is said to be regenerative if it replaces all or part of the fissioned (burned up) fuel by creating new fuel from non-fissionable fertile material. If this replacement is equal to the amount of fuel consumed plus some excess, then the reactor is known as a breeder.

Other distinguishing characteristics are the enrichment and type of fuel, the coolant used, and, for the thermal reactor, the moderator used. A complete discussion on the recommended materials to fulfil each of these functions is given in reference 5.

OPERATION OF A NUCLEAR REACTOR

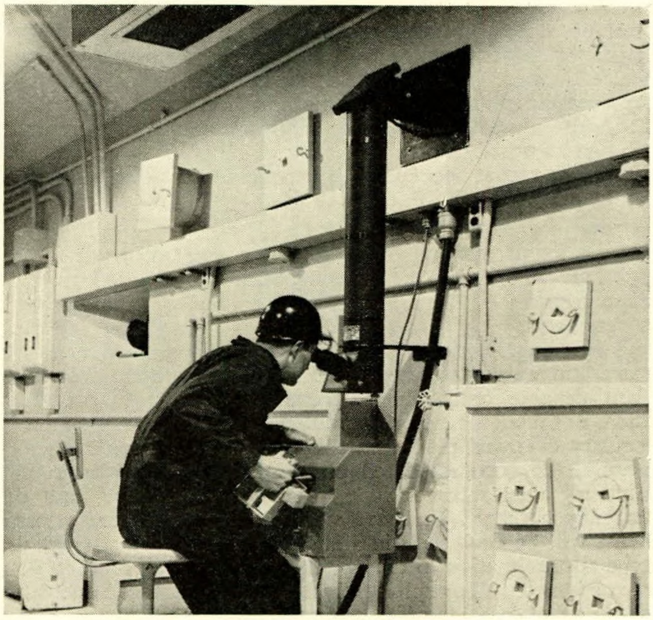
Unlike the oil fired boiler furnace where the fuel is pumped in, atomized and burnt in a continuous process, the nuclear fuel supply for a complete run between refueling ports would be carried in the core of a reactor (this excludes the homogeneous reactor). The quantity of fuel so carried would be determined not only by an allowance for "burn-up" and an excess to overcome the effects of reactor "poisons" which are simultaneously produced when the fuel fissions, but also from the concept of providing an accumulation of fuel sufficient to produce and maintain criticality.

The reactor is said to be critical if at least one of the neutrons (two or three are produced with each fission) is available to split up another nucleus and thereby maintain the chain reaction. This neutron multiplication factor (usually denoted by "k") therefore determines whether the reactor is critical or not. If the value of "k" is unity or above then the reactor is critical, but if the value falls below unity, the reactor becomes subcritical and the chain reaction ceases.



By courtesy of the Westinghouse Electric Corporation

FIG. 2—*Remote controlled handling devices for radioactive material*



By courtesy of the Westinghouse Electric Corporation

FIG. 3—*Remote controls and periscope sighting device for handling radioactive materials*

As a fissile fuel has the property of continuously emitting neutrons, some means of adjusting the "k" value is required to prevent a spontaneous build up to criticality. This is provided by control devices which have a high capacity to absorb neutrons. In the heterogeneous reactor, these devices are usually in the form of rods and shims of either cadmium, cobalt, hafnium or boron steel alloys. The movement of the rods gives a coarse control and the shims a fine control of the neutrons. In the "cold" position, both rods and shims would be full in. The power level of the reactor is selected by the withdrawal of the rods a predetermined amount. Then the gradual withdrawal of the shims further increases the "k" value of the reactor until it becomes critical and the system gets under way. The control shims are also used to compensate for fuel "burn-up" during reactor operation.

An emergency control device can be fitted so that if a shut down is required both the control rods and shims are rapidly driven into the core and the reactor immediately becomes sub-critical. This arrangement is aptly known as the "scram" control.

Since operating personnel would normally be located in a control room (6) without access to the "hot" reactor, the various operating factors such as control rod position, strength of neutron flux and coolant flow, etc., must be measured and transmitted to the control room by various instruments. These individual signals must then be used to operate automatically the reactor in a stable condition at the power level required.

Possible radiation hazards in the form of gamma rays or escaping neutrons must be detected by an elaborate system of sensing instruments located both inside and outside the reactor. The marine installation would also require these instruments on the ship's hull and on the ventilating system and sanitary system.

The removal of the spent fuel and its replacement by new fuel requires the use of remote controlled handling gear such as the mechanical tongs shown in Fig. 2 and the operating station shown in Fig. 3. These are photographs of the equipment used in the development of the full scale pilot plant, which was operated at the National Reactor Testing Station, Idaho, before a second reactor plant was installed in the U.S.S. *Nautilus*. Shipboard equipment would be essentially of the same design. The major portion of the so-called "spent" fuel is fissile after chemical processing; therefore, it has a high salvage value. It would usually be removed from the ship and dumped in a tank of water to permit the fission product heat to decay to a tolerable level. Then, encased in a " coffin " of lead, it could be transported to the re-processing plant. The disposal of the actual waste product must ensure that it does not become a health hazard. This waste will remain radioactive for a considerable period and two methods have been used for its disposal. One is to bury it in a concrete vault in as remote a location as possible. The other is to encase it in concrete and dump this out at sea. This is certainly not a commodity that can be kicked around until it is lost.

SELECTION OF REACTOR TYPE FOR MARINE USE

It will be appreciated that by various combinations of the characteristics outlined above, the number of " possibilities " is very great.

Fortunately, this range can be narrowed considerably by space and weight considerations and also from the fact that a plant capable of producing replacement fuel is precluded. Such a breeder reactor would require a far too extensive ancillary chemical plant and shielded material handling equipment to be accommodated on shipboard. The design of a suitable vessel must include provision for loading and discharging packaged fuel and waste material. These arrangements will be dealt with in a later section. At this stage, also, some approximation to the power output of the proposed plant must be made. To exploit fully the main advantage in reduction of fuel weight and to offset as far as possible the expected high first cost and fuel cost, a minimum of 15,000 s.h.p. is indicated.

The present monopoly of the steam turbine in this range of power, with the consequent accumulation of design and operating technique, has no doubt influenced the choice of steam as the working medium. It has, in fact, been stated frequently that the only difference between a nuclear fuelled steam plant and a fossil fuelled steam plant is the type of boiler used. That this is an over-simplification will be seen from the discussion of some of the possible reactor designs which follow. Also, the operational control of the fluid conditioning unit (reactor) and the turbine must be more closely integrated than is the case even with advanced steam plants using automatic combustion controls.

A list of feasible types of reactor, with no implication of the order of precedence, then becomes:—

1. Pressurized water reactor.
2. Boiling water reactor.
3. Homogeneous reactor.
4. Sodium loop reactor.
5. Gas-cooled reactor.

This list was computed from study of the U.S. Atomic Energy Commission's published five-year plan in which an investment of $200 million will be made in developing five separate types of power reactors. It is anticipated that this plan will bring within sight the objective of harnessing nuclear power on a basis economically competitive with coal and oil. The first four reactors are versions of those included in the United States A.E.C. plan. The fifth will use a closed cycle gas turbine as a power-producing unit, operating with helium as a working fluid.

The characteristics of each reactor design will now be considered. The illustrations should be read liberally. Detail design of a particular reactor depends on the type of vessel in which it is to be used. For example, the control rods and the fuel rods of the heterogeneous reactors may well be more conveniently fitted on mutually perpendicular axes. Also, the use of concrete for shielding is shown on all the reactors. Steel, lead or a composite structure could be more suitable. The probability is that lead will, in general, be found to be the most suitable shielding material for marine use.

Pressurized Water Reactor

The pressurized water reactor, as shown in Fig. 4, which is essentially as fitted in the U.S.S. *Nautilus*, has become the " pioneer " marine plant⁽⁷⁾.

The fuel rods of the reactor could be of enriched uranium or plutonium, probably clad for strength with a metal which has low neutron absorbing capacity, such as aluminium or zirconium. The control rods would be machined from a cadmium steel alloy or a boron steel alloy.

Highly purified water under pressure forms both reactor coolant and moderator to make the reactor operate at " thermal " energy level. For best heat transfer conditions in the reactor, the primary water velocity is increased by restricted passage cross-sections. By maintaining a high rate of flow through the primary circuit, the temperature rise of the pressurized water is kept to a minimum.

Heat is transferred from the primary circuit to the secondary circuit in a tubular exchanger and the steam so formed is separated in the steam drum of the steam generator. Presumably this could be arranged for either natural convection or forced convection, depending on the steaming rate required.

One obvious disadvantage of this system is the impracticability of producing superheated steam. As an example, assume the primary circuit water is pressurized to 1,000 lb. per sq. in. abs., the maximum temperature in the primary circuit must be below the equivalent saturation temperature (544 deg. F.). Allowing, say, 10 deg F. loss during transmission to the heat exchanger and a mean temperature difference between the pressurized primary water and the evaporating secondary water in the heat exchanger of, say 60 deg. F., then

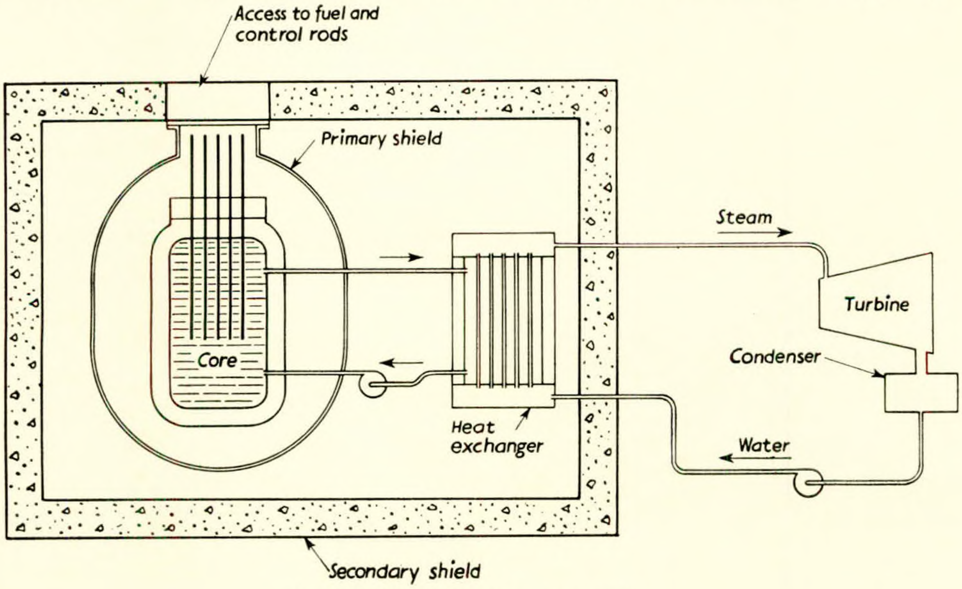


FIG. 4—*Pressurized water reactor*

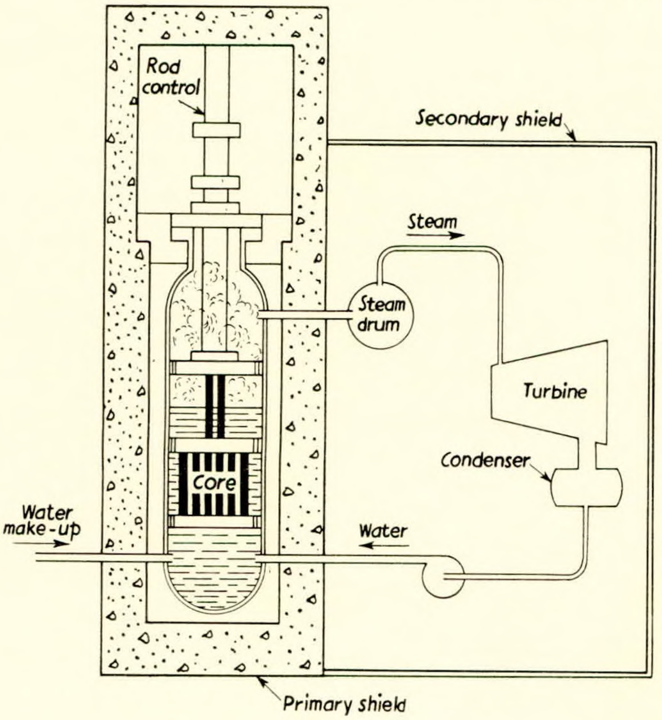


FIG. 5—*Boiling water reactor*

saturated steam at 400 lb. per sq. in. pressure will be produced.

The United States A.E.C. reactor of this type will generate approximately 200,000 kW of heat which will be transferred to the heat exchanger by circulating water at 2,000 lb. per sq. in. and 525 deg. F. Saturated steam at 600 lb. per sq. in. pressure will be generated in the heat exchanger and passed to a steam turbine generator which will have an output of some 60,000 kW. It is expected that this installation will be in operation late in 1957.

An inherent advantage of this system is that the expansion of water with temperature rise allows an increased leakage of neutrons and, hence, a system which to some degree is self-stabilized.

No claims are made that this type of reactor will produce economical power, but it is the type on which most experience is available, and, therefore, it could be claimed to be the most reliable. An improvement in neutron economy could be made by using heavy water instead of light water, and the thermal efficiency might be raised slightly by increasing the circulating water pressure. Pressure tightness of the system becomes of increasingly greater importance with either of these changes.

The principal bogey remains in the form of the efficient utilization of saturated steam. Possible modifications to the modern steam turbine designed for superheat would be interstage extraction and centrifuging of the steam, the fitting of moisture throwing rings as blading shrouds, and it would appear necessary to use blading at the l.p. end of the turbine, which has a high resistance to erosion. With present-day techniques in design and material production, designers are now in a far better position to tackle this problem than their predecessors, who faced exactly the same problem before the development of an effective superheater. Nevertheless, the principle of the acceptance of this inherent deficiency is, in the author's opinion, open to criticism.

Boiling Water Reactor

Fig. 5 shows the boiling water reactor in which steam is generated by direct contact during water circulation through the core. The arrangement is thus a simplification of the pressurized water reactor in that one of the loops is eliminated. This, however, has two additional disadvantages. First, during the boiling process of the water, which acts as moderator as well as working fluid, the variation in density allows a variation in leakage of neutrons, thus causing a fluctuation in power level of the reactor. Secondly, the steam passing off to the turbine will be radioactive, thus producing an additional shielding problem. It seems likely, therefore, that the boiling water reactor would be operated at a lower power level than the pressurized water reactor. However, it is reported that the U.S. General Electric Company has expressed a preference for this design as a long term possibility, and indeed experiments conducted at the National Reactor Testing Station in Idaho and at the Oak Ridge National Laboratory have confirmed that these reactors can give stable operation.

The materials for the fuel and control rods, which form the reactor core, could be the same as those used for the pressurized water reactor. Another feature that the two types of reactor have in common is that they can only produce saturated steam. This can be seen at a glance from the diagram in Fig. 5.

Homogeneous Reactor

The homogeneous reactor shown in Fig. 6 was designed primarily to overcome the essential limitations of the heterogeneous reactor of which the two previous reactors are examples. These limitations are:

(*a*) The separate core components of fuel, control rods, coolant and/or moderator in the limited area of intense heat, create a real heat transfer problem.
(*b*) The core structure is subject to radiation damage.
(*c*) The accumulation of fission products caused by the absorption of neutrons necessitates the periodic removal of fuel for reprocessing. This, as previously discussed, is a complex operation.

As the name implies, the homogeneous reactor operates on an intimate mixture of fuel and coolant/moderator in the form of a solution of uranium salt in ordinary water. The

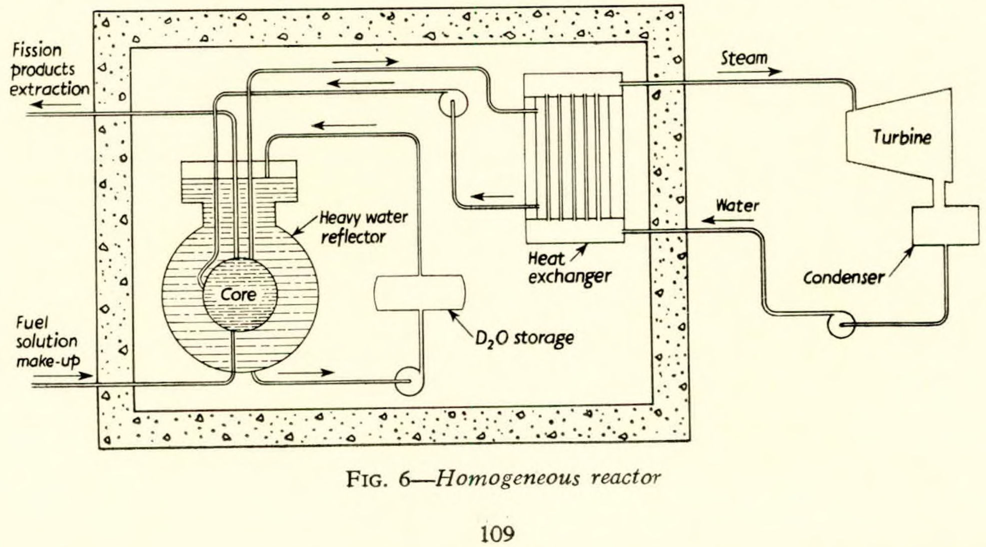


FIG. 6—*Homogeneous reactor*

primary circuit, through which this solution is circulated under high pressure, consists basically of the spherical container which forms the core and a restricted passage to the heat exchanger.

The form of the core is such that during passage through this sphere a sufficient accumulation of the solution occurs to reach criticality and, hence, the fuel will fission. Whereas, during passage through the constricted circuit to the heat exchanger, the spreading out of the solution will decrease the mass below the critical and so quench the chain reaction. Steam can be produced in the heat exchanger at reasonably high pressure but again it is saturated. In this case, however, the steam is not radioactive.

The reactor core is surrounded by a neutron reflector of heavy water and arrangements are made for addition of fuel and removal of fission products while the reactor is in operation.

One of the most striking features about this design is the absence of control rods. These are not required as the system has been proved to be self-regulating; e.g. with the main circulating pump stopped temporarily and the heat exchanger cooling down, the uranium salt solution becomes more dense. On recommencing circulation, the power output of the reactor shoots up until design level is restored. Then, by the time the solution reaches design temperature, the solution has expanded to offset the reactivity and the power output levels off.

To summarize the characteristics of this homogeneous reactor, it could, therefore, be said that the nuclear stability or safety is purchased at the expense of providing a completely leakproof system for a highly radioactive and corrosive solution subject to a pressure of at least 1,000 lb. per sq. in. The description and results of an experimental model of this type have now been published(8). It is interesting to note that although several leaks were experienced during the start-up phase, the plant finally operated for twelve months without any leakage being detected.

Sodium Loop Reactor

Fig. 7 shows the variant in heterogeneous reactor design using liquid sodium as a coolant. A version of this type of reactor is to be used on the second nuclear powered submarine U.S.S. *Sea-Wolf*. Sodium being a weak moderating material, a separate moderator will be required and this could be of graphite block construction similar to the original piles at Harwell and elsewhere. For shipboard use, the quantity of moderating medium required can be considerably reduced by designing the reactor for operating at an energy level above the " thermal ". Sodium at atmospheric pressure has a boiling point of 1,600 deg. F.; therefore, the upper reactor temperature is not controlled by system pressure and large temperature variations in coolant can be arranged. While this leads to design problems incurred in thermal stressing, it also overcomes one of the main application problems by allowing the production of moderately superheated steam (say, 600 lb. per sq. in. and 800 deg. F.). The higher level of reactor power output increases the degree of radioactivity in the sodium and this provides a more difficult shielding problem than is encountered in a thermal reactor. Also, the preparation of a sodium-cooled reactor for operation must include arrangements for external melting of the material prior to circulation in the system. In fact, an auxiliary oil fired " boiler " will be required for this purpose.

Another major potential danger is the possibility of leakage if the highly radioactive and strongly alkaline sodium were in close proximity to the steam system. Any such leakage would produce a violent reaction with water. Thus, the coolant system is separated into two stages to provide a partial solution. In the primary heat exchanger, the radioactive sodium from the core gives up heat to non-radioactive sodium which is then used to heat the secondary heat exchanger or steam generator.

Another method of safeguarding against the contact of liquid sodium and water is the use of double-wall concentric tubing in the secondary heat exchanger. The annulus of this tubing could be filled, say, with lead, giving a good heat transfer bond and a leak detecting medium.

A further line of thought has been developed (9) in the suggestion of benzine as a working fluid to replace steam. Benzine is chemically inert with sodium and, therefore, the danger of a violent reaction resulting from any leakage is eliminated. It seems probable, however, that the use of benzine would not find favour in the marine field on account of the fire hazard introduced.

Probably the major engineering problem to be faced with this type of reactor is the pumping of a liquid metal at a high temperature. Any leakage would produce both a radioactive and a fire hazard. A typical specification for leakage tolerance is one cubic centimetre in ten years and to meet this demanding service two types of pumps have been developed. One is an electro-magnetic pump which eliminates the usual rotors and, consequently, the shaft glands. This type is reliable but its efficiency is low. The other type is a centrifugal pump using fluid bearings. This has a much higher capacity, but is subject to the usual mechanical failures. A pump suitable for slightly less arduous duty is described in detail in reference 10.

Standby pumps in the system must be provided in triplicate or probably quadruplicate, as any maintenance required on a pump can only be undertaken after a waiting period of maybe days before the radioactivity has " cooled ". There is also the problem of " freezing " of some remaining coolant which could easily provide additional work and the scrapping of components.

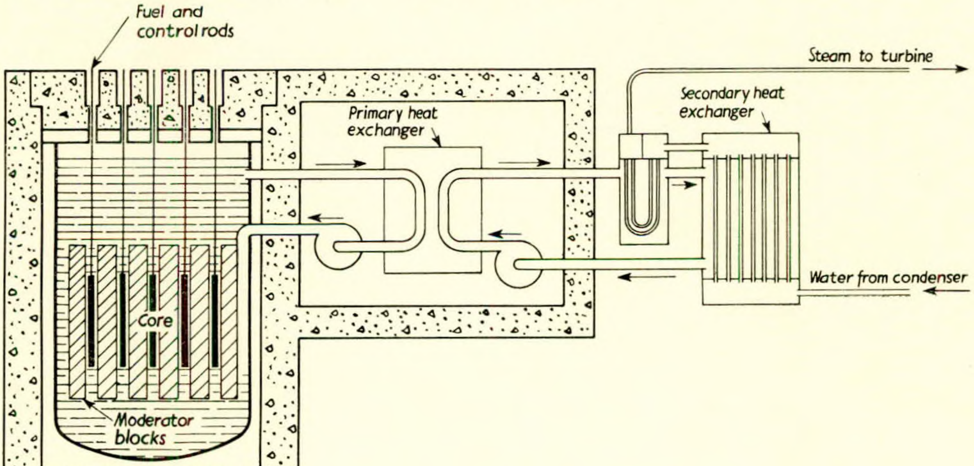


FIG. 7—*Sodium loop reactor*

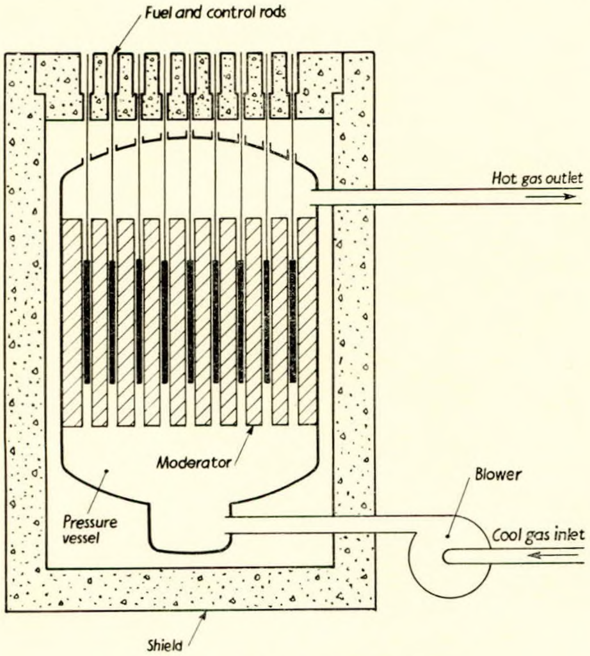


FIG. 8—*Gas-cooled reactor*

Details of suitable materials for a reactor of this type are given in reference 11.

Gas-cooled Reactor

The gas-cooled reactor, as indicated in the recent White Paper, is Britain's choice for development as a power reactor ashore. The arrangement of these land plants is presumably as envisaged in the recent Institute Section paper(12). This provides for the reactor coolant gas to circulate a steam generator in much the same manner as existing types of waste heat boilers, except, of course, that for the nuclear plant the gas would be in a closed circuit. The steam produced, again probably saturated, with its attendant complications, would be utilized in a turbo-generator set.

The gas-cooled reactor shown in Fig. 8 is of the heterogeneous thermal type. The fuel could be slightly enriched uranium, the rods of which are clad with zirconium or aluminium to minimize neutron absorption. Stainless steel could also be used for cladding but then neutron economy would be sacrificed in the interests of strength and first cost. There is also the possibility of using fuel in powdered form sealed in a metal container, thereby reducing fuel reprocessing costs, although this could introduce a danger of failure of the fuel elements during operation. The moderator is provided in the form of block graphite or beryllium oxide and the control rods could again be of boron steel or cadmium. Control of this type of reactor would be both easy and safe, consisting merely of moving the control rods in and out.

Preliminary designs and outlines of equipment have been prepared for a submarine installation (13) to compare the use of water, sodium, and helium as coolants in the nuclear power plant. The characteristics are summarized in Table II.

TABLE II.—COMPARISON OF WATER, SODIUM AND HELIUM AS COOLANTS

Reactor coolant	Water	Sodium	Helium
Shaft power output	0·90	1	1
Overall plant weight	0·97	1	0·64
Specific weight, lb. per s.h.p.	1·08	1	0·64
Space occupied, cu. ft. per s.h.p.	1·10	1	0·66
Shield weight	0·77	1	0·51

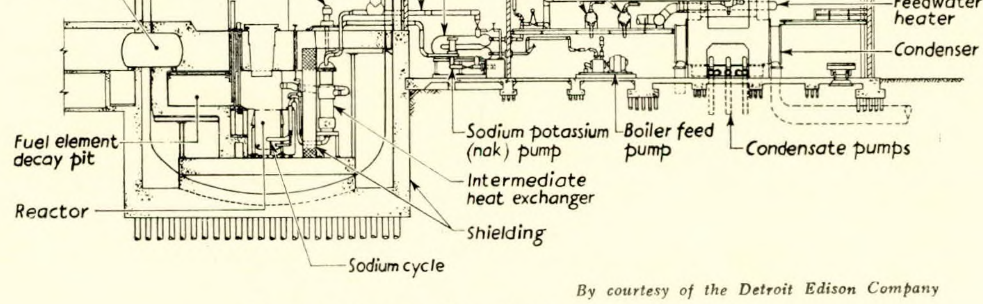
While these figures appear to favour the use of helium, their validity awaits the result of a good deal of development work to confirm a number of assumed factors.

Of the five reactor types already discussed, the marine application of the gas-cooled reactor, as outlined in a later section, offers what the author considers to be the most favourable balance between first and operating cost and simplicity and safety in operation.

THE BREEDER REACTOR

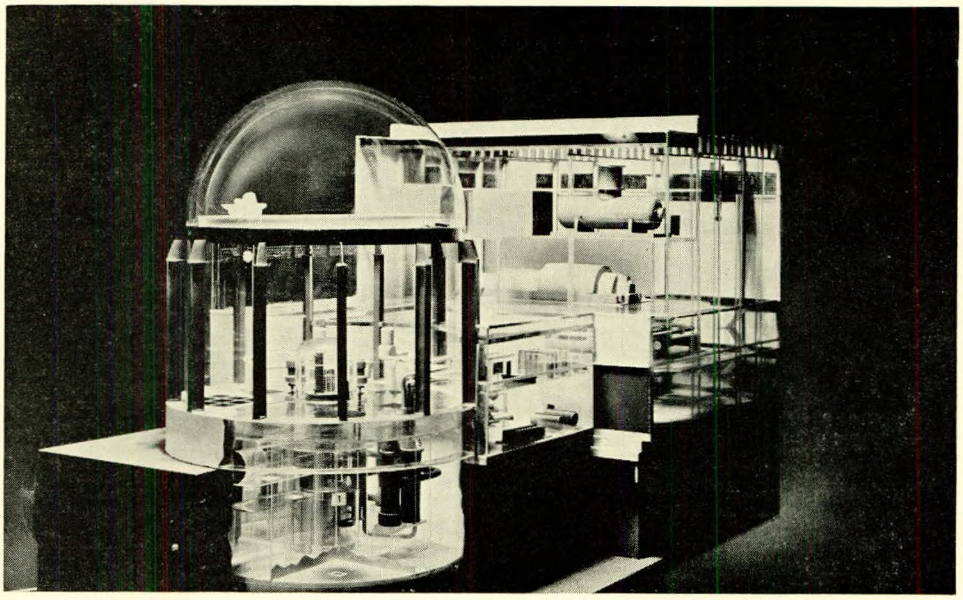
Although not likely to be used as a shipboard power producer, some mention of this type of reactor is justified in that it seems likely that it will provide a definite link in the application of nuclear power to marine propulsion. This link could well be the production of fissile fuels, available to the marine industry and others, at a price lower than that at which uranium ore could be mined, processed and marketed.

Two reactions have proved of interest in the manufacture of fissile fuel. The first is that when the natural uranium U.238 is subjected to a bombardment of neutrons, as occurs in the core of a reactor, the nucleus picks up an additional neutron and thus becomes a new element or isotope, U.239. This has a nucleus which is not stable and, therefore, it decays to plutonium 239. The second is a similar reaction commencing



By courtesy of the Detroit Edison Company

FIG. 9—*Cross section of reactor power station*



By courtesy of the Detroit Edison Company

FIG. 10—*Model of proposed power plant*

with thorium 232 which captures an additional neutron to become Th.233 and then decays to U.233.

Both Pu.239 and U.233 require chemical processing to separate them from their respective parent materials.

There are, of course, many ways of modifying the various types of reactors already discussed to take advantage of this nuclear phenomenon. The homogeneous reactor, for instance, could be made into a breeder by replacing the heavy water neutron reflector by a thorium solution " blanket ". In the heterogeneous reactor either natural or depleted U.238 could be arranged to surround the core and then be removed for processing after the transmutation occurred.

In order to achieve the highest breeding gain, the neutrons must be kept as energetic as possible. To do this, the moderating material must be eliminated to allow the energy level to rise so that the reactor can operate on the " fast " energy level. The first experimental reactor of this type was referred to in reference 1. It was built and operated at the Argonne National Laboratory and is to be followed by another of similar design, but of much larger scale, to give a heat output of 62,500 kw and an electrical output of 15,000 kW.

Encouraged by the results from Argonne and after a survey of the many possibilities, the Atomic Power Development Associates, one of several groups of American power companies and machinery manufacturers, are now working on the design and development of the power plant shown in Fig. 9. A photograph of the model of this plant is shown in Fig. 10. This represents what is probably one of the most advanced designs proposed and the reasons for its choice, despite the " pioneering" work required, merit quotation (14).

" Our reasons for selecting the breeder type of reactor were (*a*) our belief that a reactor which will produce both heat and fuel holds the greatest possibility of commercial success, and (*b*) our belief that large scale use of atomic energy for power generation can be achieved only by utilizing a large part of the total heat potential of uranium, rather than the 3 per cent to 7 per cent which seems to be the limit of most thermal reactors which use U.235 or plutonium as fuel. A breeder reactor theoretically offers a possibility of using all of the heat potential of uranium, but from a practical standpoint it likely would succeed in utilizing only about 50 per cent. At the same time it would produce more atomic fuel than it consumes."

The plant consists basically of the same design as shown in Fig. 7, except that for the larger plant both primary and secondary loops can be either duplicated or triplicated and the medium to be used in the secondary loop is a sodium-potassium

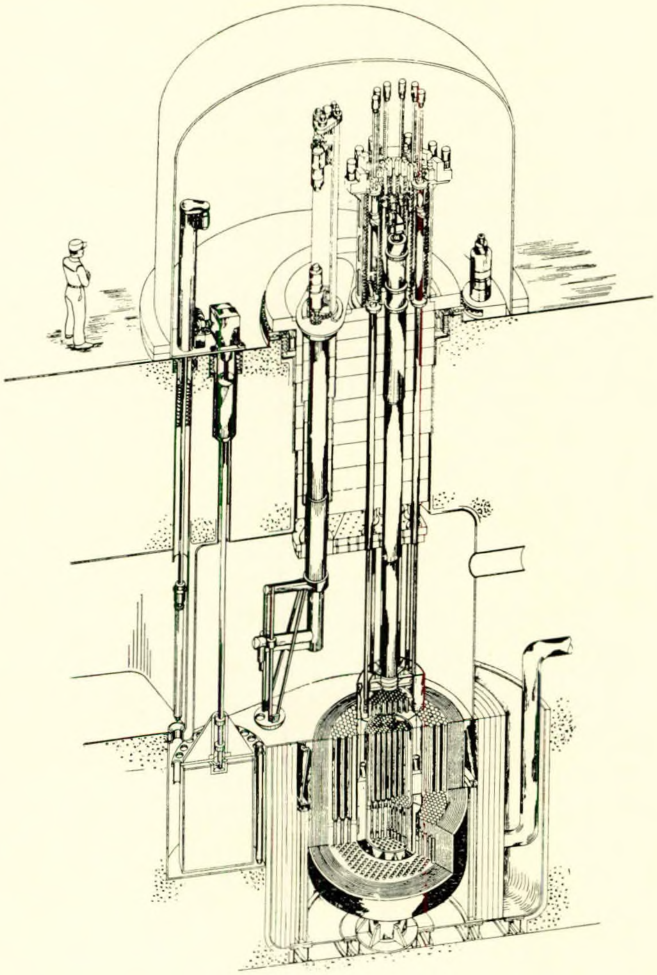


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FIG. 11—*Cross section of breeder reactor*

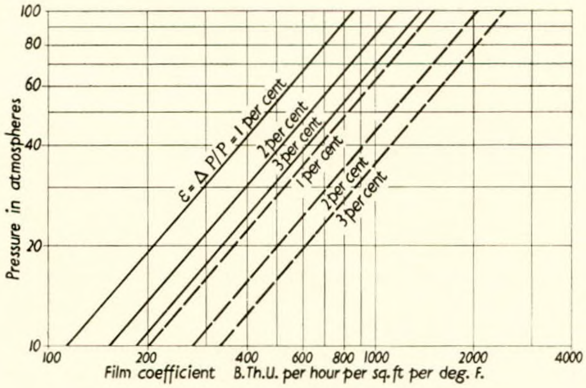


FIG. 12—*Helium-air heat transfer characteristics*

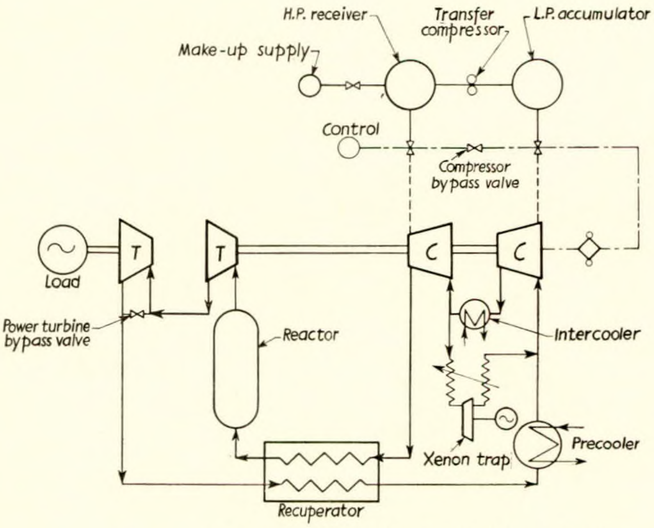
alloy in place of the straight sodium. The design as envisaged at present will produce steam at 600 lb. per sq. in. and 730 deg. F. which, while conservative by present standards, is still high enough to operate the steam plant with acceptable efficiency. The choice of these lower steam conditions allows a relaxation of the demands on the core, the design of which is of extreme importance in that it is necessary to make it as compact as possible. It is within this core that a compromise must be reached between the extremes of providing a good heat transfer bond and the effects of decay due to the high level radiation.

An illustration of the rod control and fuel handling equipment is given in Fig. 11.

Safety measures have controlled the design of the structure, as can be seen from the shielding provided. The domed casing, which completely encloses the reactor plant, is airtight to prevent the spread of radioactive contamination in the unlikely event of a failure in the system.

NUCLEAR-POWERED CLOSED-CYCLE GAS TURBINE PLANT

The heat energy in the gas from the reactor can be directly converted to mechanical work in a closed-cycle gas turbine and while the working fluid could be either air, nitrogen, carbon-dioxide or helium, the latter is preferred. The steam generating and condensing equipment are thus eliminated, as are also make-up feed, boiler water conditioning and the many other ancillary problems connected with a modern steam plant.

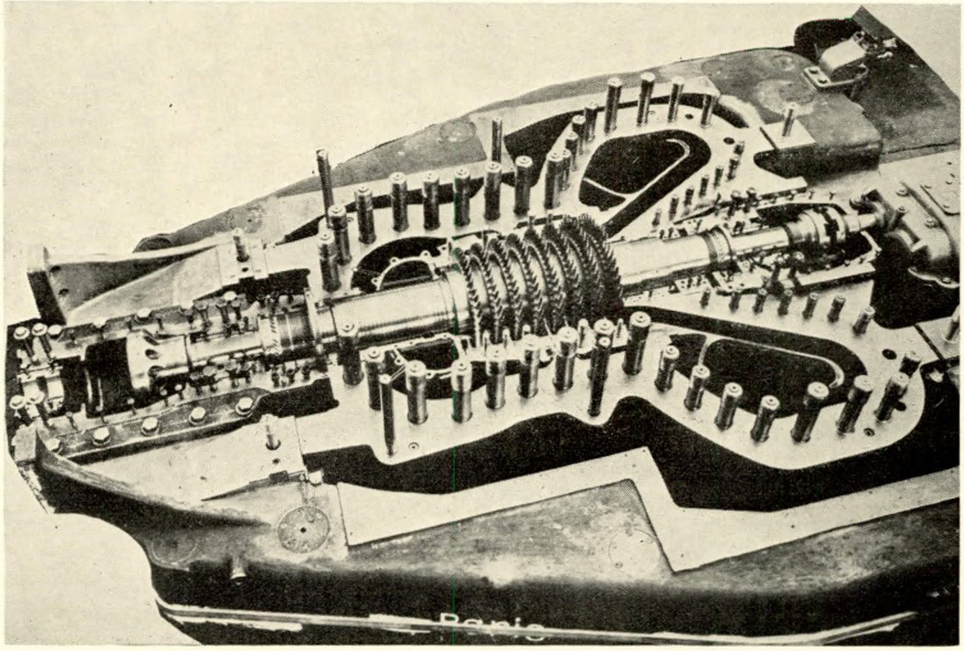


By courtesy of the American Turbine Corporation

FIG. 13—*Closed-cycle gas turbine plant*

The closed-cycle gas turbine has been under development in Switzerland for sixteen years and all the machines so far put into service have operated on air, the maximum output of any one set being 12,500 kW. Nitrogen, which comprises 77 per cent of air, has very similar characteristics. Carbon dioxide has better heat transfer properties, but all three become radioactive when heated in a nuclear reactor. Helium, however, if kept free of slight contamination during circulation, has a nucleus which is very stable under neutron flux, thus it does not become radioactive. It follows that in this type of plant, only the reactor requires shielding, allowing a far more flexible machinery arrangement and a considerable saving in weight.

Helium has a better heat transfer characteristic than nitrogen, which is enhanced with increase in pressure as shown in Fig. 12. This shows the variation of film coefficient with pressure for constant percentage pressure drop for gas flow in



By courtesy of the American Turbine Corporation

FIG. 14—*Typical helium turbine*

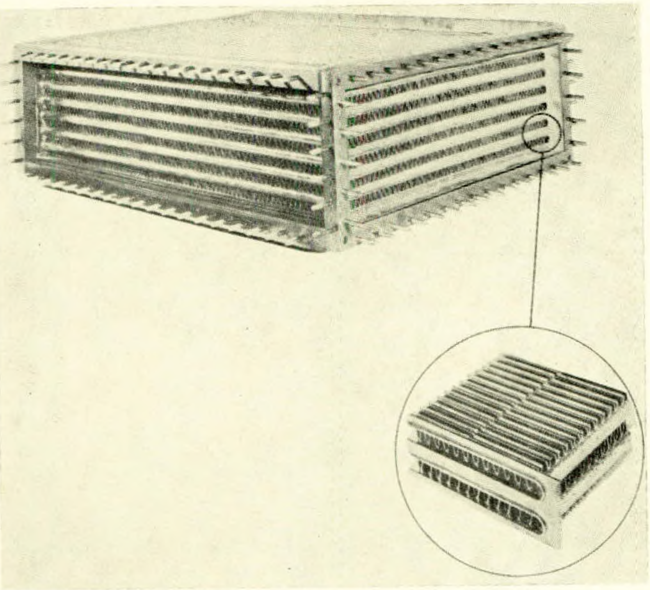


FIG. 15—*Griscom Russell plate fin heat transfer surface*

Fin material	SA-204 carbon 1/2 molybdenum
Fin thickness, inch	0·0145
Effective fin height, inch ...	0·1238
Centre line to centre line flat plate, inch	0·2655
Plate thickness, inch	0·022
Fin pitch transverse to flow, inch	0·1885
Fin pitch parallel to flow, inch	5·00
Fin surface/total surface ...	0·7974
Equivalent hydraulic diameter, inch	0·125

1-in. diameter tube 100 ft. long at 1,000 deg. F. Thus, the heat transfer surface required will be reduced compared with an air or nitrogen system, but the high specific heat of helium makes the design of turbo machinery more difficult. The number of stages required for the same temperature rise is roughly proportional to the specific heat (1·25 B.t.u. per lb. for helium compared with 0·24 B.t.u. per lb. for air). However, the cycle analysis which follows will show that the compressor temperature ratio required for maximum cycle efficiency decreases with increasing recuperator effectiveness and this fact is made use of in the design of closed-cycle helium plant by trading static heat transfer surface for stages of turbo machinery. The inert helium also removes the problem of chemical attack on the power plant components.

In common with most desirable commodities, the use of helium has one major snag—its cost. To minimize this expense, a leak-proof system will be required.

Several excellent articles and papers (15 16, 17 and 18) discuss the merits of the closed-cycle air turbine and a large amount of the subject matter applies to the helium turbine.

Fig. 13 is a diagrammatic representation of the suggested plant. Expansion is in two stages to isolate the power turbine from the compressor drive. Reversing can be accomplished either by a reversible pitched propeller (19), but the upper limit of power which could be absorbed by the propeller may not be compatible with the minimum power required for an effective nuclear plant; or the power turbine can be built as a reversible inwards flow radial machine; or a turbo-electric drive could be adopted. A typical axial flow turbine suitable for an output of about 20,000 s.h.p. is shown in Fig. 14. One of the most pressing engineering problems in producing a gastight system is the design of a suitable turbine gland. The heat transfer surface in the recuperator and precooler could be of the plate fin type as shown in Fig. 15 and the intercooler of shell and U-tube type. A typical section and general arrangement of a 60-MW turbo plant of the same type as that proposed is shown in Figs. 16 and 17, from which it can be seen that the elimination of gas ducts between components ensures a minimum pressure loss and potential source of gas leakage.

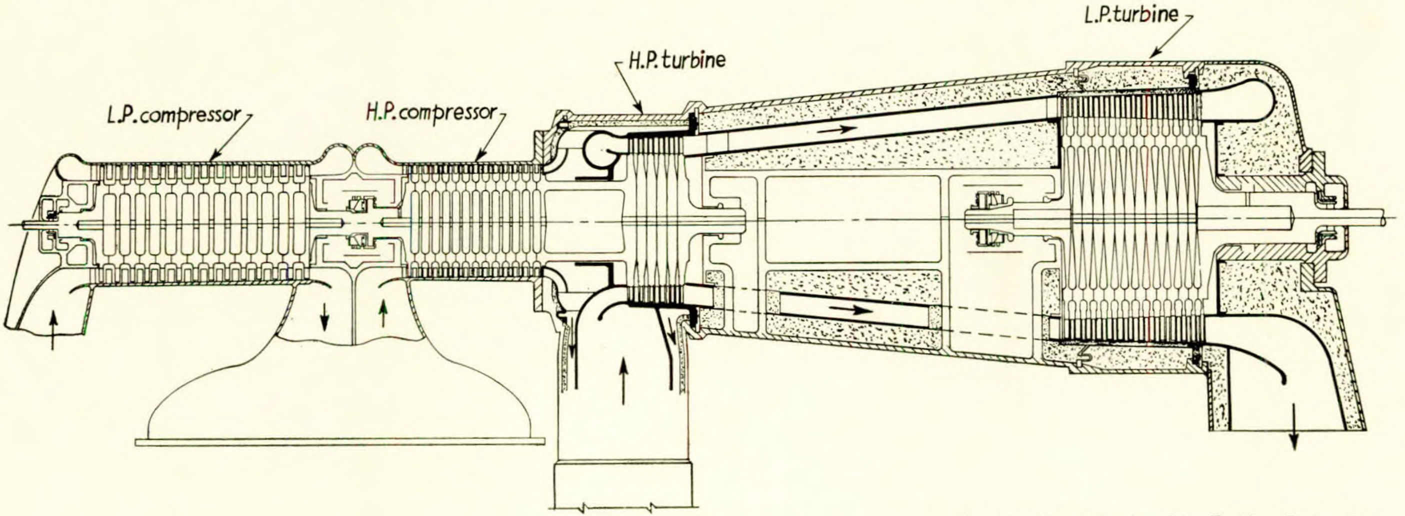
Control System

The power output of this plant varies with the system pressure. This pressure level control is effected by addition or withdrawal of working fluid from the circuit, and emergency speed control of the power turbine is effected by bypassing.

Helium that is not being circulated in the plant is stored in accumulators for subsequent use, making this a no-loss system. The accumulator system consists of two (or two groups of) storage bottles, one being the receiver and the other the accumulator interconnected by a transfer pump. In this system, the total amount of helium in the power plant and tanks is constant at all times. Any leakage loss is made good by addition of helium to the receiver from time to time as required. A simplified diagram of this sytem is shown in Fig. 13.

Manual control of valves between the sytem and the receiver and accumulator tanks allows the selection of any desired pressure level.

An overspeed governor is provided on both the high pressure compressor/turbine set and the power turbine. The governor on the compressor/turbine set is a top speed governor only, tripping a compressor bypass valve when this set exceeds a predetermined speed limit. The governor on the power turbine is designed to come into play only in the event of



By courtesy of the American Turbine Corporation

FIG. 16—*Turbine section*

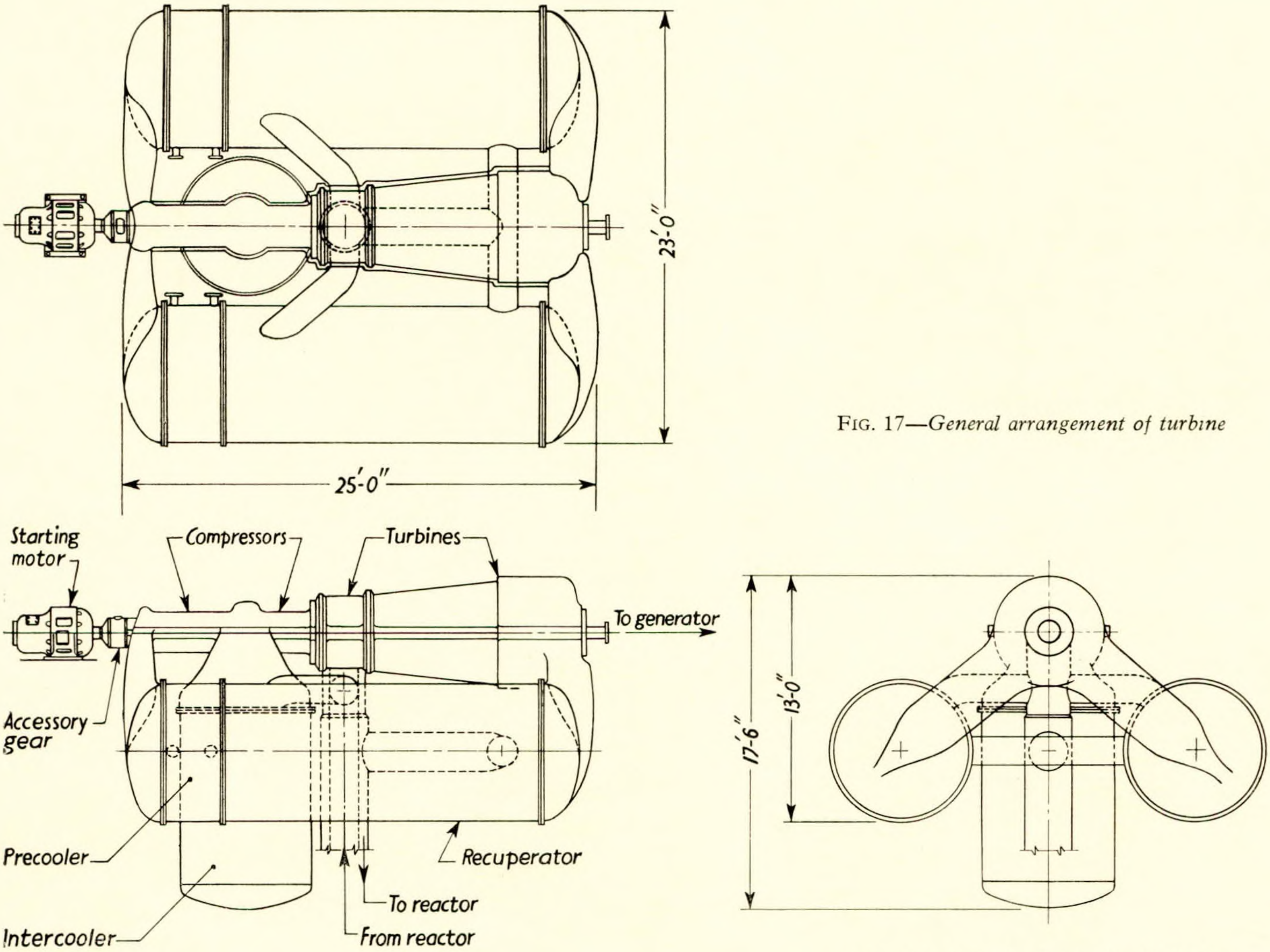


FIG. 17—*General arrangement of turbine*

By courtesy of the American Turbine Corporation

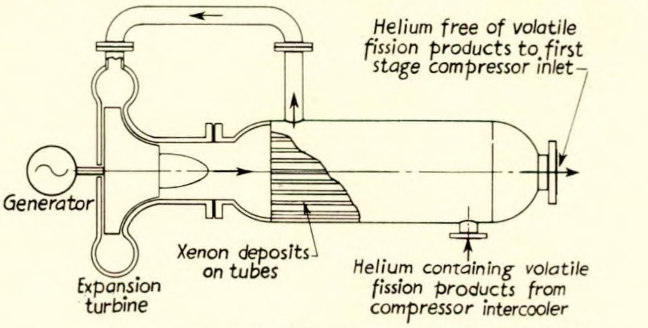
emergency, the presence of which makes it necessary to shut down the plant. In action, the power turbine governor opens the power turbine bypass valve, immediately reducing the helium flow through the power turbine. Since this reduces the back pressure on the compressor drive turbine, it tends to overspeed, thus actuating the compressor bypass valve. Further, the power turbine overspeed governor trips the system pressure regulator, resulting in the discharge of the contents of the system to the receiver. Simultaneously, the control rods are dropped into the reactor, reducing the heat input to the system.

When the power plant load is eliminated and the reactor activity level reduced, a means must be provided to cool the reactor for a period after shutdown. During both the normal procedure of shutting off the plant and the emergency condition previously discussed, the compressor/turbine set will circulate helium through the reactor until the minimum self-running speed is reached. At that time, a secondary, motor-driven circulating compressor with an auxiliary cooling loop is energized, circulating helium through the reactor until activity is reduced to a point resulting in a safe temperature level.

Xenon Removal

The helium used in this plant is available commercially at a purity of 99·99 per cent. Impurities consist of argon, carbon dioxide and nitrogen, none of which is in sufficient quantity to be of concern. There is, however, the possibility of contamination of the system by gaseous fission products escaping from the reactor fuel elements. The principal volatile radioactive impurity of the fission process is xenon and it is desirable that this be removed to prevent even a small build-up of radioactivity of the working fluid.

The xenon can be effectively removed to any degree desired by solidification in a cold trap. One procedure for accomplishing this would be to withdraw a small stream of helium from the cold end of the compressor intercooler and pass it through a heat exchanger in which it would be cooled to whatever temperature would be necessary to reduce the xenon content to a permissible level. Since the xenon is present in such small amounts, even its complete removal would leave the helium essentially undiminished in quantity. This cold helium stream would pass through a turbo expander wherein its pressure



By courtesy of the American Turbine Corporation

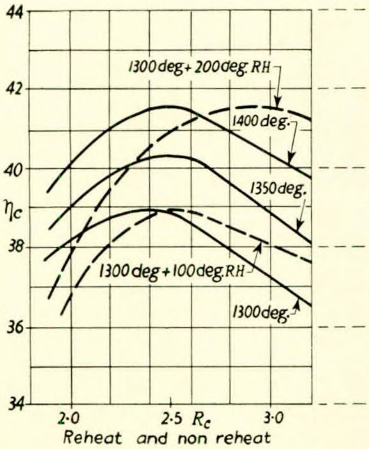
FIG. 18—*Xenon trap*

would be dropped to essentially the suction pressure of the compressor. In passing through the expander, the helium would be cooled sufficiently so that it could act as the refrigerant for cooling the xenon cold trap exchanger. A typical arrangement of this type of trap is shown in Fig. 18.

Since the gas flow required to hold down the xenon concentration in the working fluid of the power cycle is only of the order of 1 per cent of the mass flow, the dimensions of the cold trap heat exchanger would be small, as would the turbo expander required to provide the cold end drop in temperature. The passages of the cold trap would gradually become plugged with xenon and its decay products until eventually it would require replacement by a new unit. The size of this trap would be such that it could be cleaned or disposed of, depending upon which would seem to be desirable in the final design.

Choice of the Cycle Details

In order for any closed cycle nuclear power plant to be attractive economically, it must be a high temperature machine, i.e. it must operate at cycle temperatures in excess of 1,200 deg. F. All experience to date with closed-cycle power plants has been at a cycle temperature of 1,250 to 1,300 deg. F., as dictated by the limiting tube wall temperature in a fired air heater. In a nuclear plant this restriction is removed and the turbine inlet temperature is only limited, within reason, by reactor outlet temperature. However, a plant of conservative design would limit such temperature to 1,500 deg. F. In establishing a cycle for the helium plant, the values of 1,300, 1,350 and 1,400 deg. F. cycle temperature were assessed against a 1,300 deg. F. cycle temperature with 100 and 200 deg. F. reheat.



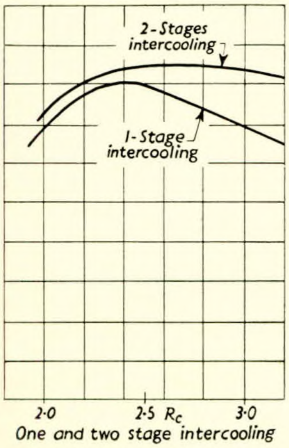


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FIG. 19 *(left)—Comparison of reheat and non-reheat cycles*
FIG. 20 *(right)—Comparison of single and two-stage intercooling*

A comparison of cycle efficiencies on the basis of pressure ratio is shown in Fig. 19. These were computed using reasonable polytropic (stage) efficiencies for the turbo machinery and taking pressure losses for the two types of system into account. There is little difference in efficiency between a 1,400 deg. F. non-reheat plant and a 1,300/200 deg. F. reheat plant. The 1,400 deg F. non-reheat cycle was chosen since it shows an optimum efficiency at a lower pressure ratio than the reheat cycle and also does not involve the use of a reheat exchanger.

Appreciable gains in efficiency in a closed-cycle power plant are effected by moderate intercooling. The value of single versus two-stage intercooling was assessed and plotted in Fig. 20. The dual stage intercooling provides only an increase in efficiency from 42 per cent to 42·5 per cent, while requiring an addition in pressure ratio to achieve this optimum from 2·4:1 to 2·8:1. Thus, the single stage intercooling was selected.

The design conditions selected are as follows:—

Total compression ratio		2·4:1
Pressure losses, per cent:—Intercooler	0·75	
H.P. recuperator	1·50	
Reactor	1·50	
L.P. recuperator	2·25	
Precooler	1·00	
Total, per cent		7·00
Expansion ratio:— 2·4 (1—0·07)		2·233:1
Compressor inlet temperature:— based on 75 deg. F. sea temperature, deg. F.		90
Turbine inlet temperature, deg. F.		1,400
Recuperator effectiveness, per cent		92·3
Mechanical and other losses, per cent		5·0

Physical Constants for Helium

Specific heat at constant pressure, B.t.u. per lb. $Cp = 1·25$
Ratio of specific heats $\gamma = 1·658$
Gas constant $R = 386·2$
$(\gamma-1)/\gamma = 0·398$

Analysis of Cycle (Fig. 21)

Compressor (equal work done in each stage):—
Absolute temperature at inlet $T_1 = 550°R.$
Compressor ratio per stage $= \sqrt{2·4} = R_c = 1·55:1$
$R_c^{(\gamma-1)/\gamma} = 1·191$
$1—R_c^{(\gamma-1/\gamma)} = 0·191$
Adiabatic temperature rise $\Delta T_{ad} = 105°F.$
Adiabatic efficiency $\eta_{com.} = 0·88$
Actual temperature rise $\Delta T = 120°F.$
Absolute temperature at outlet $T_2 = 670°R.$
$T_3 = 550°R.$
$T_4 = 670°R.$
Total temperature rise (compression work) $= 2 \times 120 = \Delta T_{com.} = 240°F.$

H.P. Turbine

Absolute temperature at inlet $T_6 = 1,860°R.$
$\Delta T_{com} = 240°F.$
$T_7 = 1,620°R.$
Adiabatic efficiency $\eta_{exp.} = 0·888$
Adiabatic temperature drop $\Delta T_{ad} = 270°F.$
$T_7{}^1 = 1,590°R.$
$\frac{T_6}{T_7{}^1} = 1·17$
$\frac{\gamma}{\gamma-1} = 2·51$
Expansion ratio $R_{e\ HP} = (1·17)^{2·51} = 1·48:1$

L.P. Turbine

Total expansion ratio $R_{e\ TOT} = 2·233$
$2·233/1·48 = R_{e\ LP} = 1·51:1$
$(R_{eLP})^{·398} = 1·178$
$T_7 = 1,620°R.$
$T_7/1·178 = T_8{}^1 = 1,374°R.$
Adiabatic temperature drop $\Delta T_{ad} = 246°F.$
Adiabatic efficiency $\eta_{exp} = 0·888$
Actual temperature drop (output work) $\Delta T_w = 218°F.$
$T_8 = 1,402°R.$

Recuperator

$T_8 = 1,402°R.$
$T_4 = 670°R.$
Available temperature range $\delta_t = 732°F.$
Effectiveness, per cent $\eta_r = 92·3$
Increase in temperature in recuperator $\Delta T = 675°F.$
Outlet temperature $670 + 676 = T_5 = 1,346°F.$

Reactor

$T_6 = 1,860°R.$
$T_5 = 1,346°R.$
Increase in temperature (heat supplied) $\Delta T_R = 514°F.$

Precooler

T_4 = 670°R.

Loss in recuperator = 732—676 = 56°F.

T_9 = 726°R.

T_1 = 550°R.

Temperature drop (to circulating water) δ_t = 176°F.

Cycle Efficiency

Output T_W = 218°F.

Input T_R = 514°F.

ηcycle = 42·4%

Work Rate

$$\frac{2{,}544}{T_W \times 1{\cdot}25} = W = 9{\cdot}35 \text{ lb. per h.p. hr.}$$

To assume a value of 7 per cent for the overall pressure loss in the cycle may be regarded as optimistic. It is believed that this value can be attained with careful design and without excessively large heat transfer surface. Referred to an air cycle plant, this is the equivalent of a total overall pressure loss of 11 per cent assigning 5·5 per cent total pressure loss to the reactor, which would be the equivalent pressure loss in a fired heater.

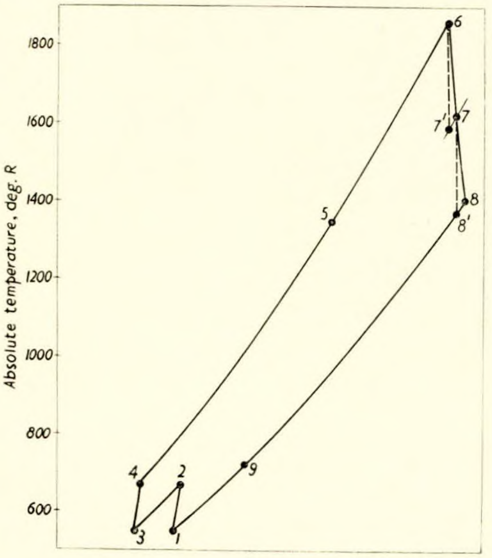


FIG. 21—*Proposed cycle for helium plant*

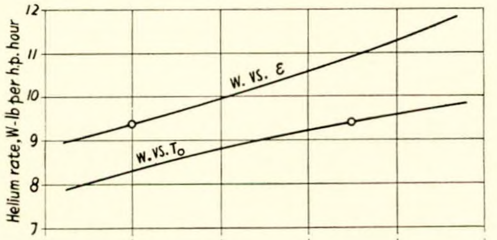


FIG. 22—*Correction for off-design conditions*

The assumption of a sea temperature of 75 deg. F. will certainly be on the high side for the majority of steaming time and, when this is so, an improvement in cycle efficiency can be expected.

The effect produced on work rate and cycle efficiency with variation of overall pressure loss and sea water temperature is plotted in Fig. 22.

ECONOMIC ASPECTS OF THE USE OF NUCLEAR FUEL

A power of 15,000 s.h.p. has been mentioned earlier as a minimum to fully exploit the advantages of the use of nuclear fuel. Crever and Trocki (13) make two significant comments on this consideration: (*a*) " As the amount of shielding is practically independent of power output, a nuclear power plant of low power will be penalized excessively with respect to its power output ". (*b*) "Power plants for propulsion of larger ocean going vessels (of the order of 10,000 h.p. and above) are of sufficiently large power output to fall within the favourable range for a nuclear power plant of current design ".

To illustrate the finance involved in powering a vessel today, estimates of propulsion machinery derived from the costs for five ships are given in Fig. 23. The vessels represent current design of cargo ship, tanker and passenger liner, but this variation does not impair the comparison of the machinery involved as they are all fitted with geared steam turbines. Costs include boilers, turbines, shaft and propeller, but do not allow for cargo handling machinery, steering gear, etc. In the power range pertinent to this discussion, the cost of the steam generators and auxiliary equipment is of the order of 20 per cent of the machinery costs indicated.

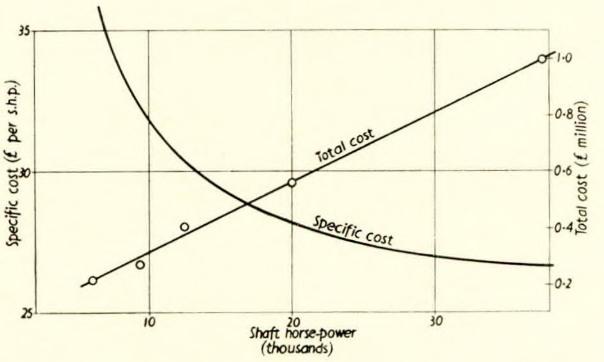


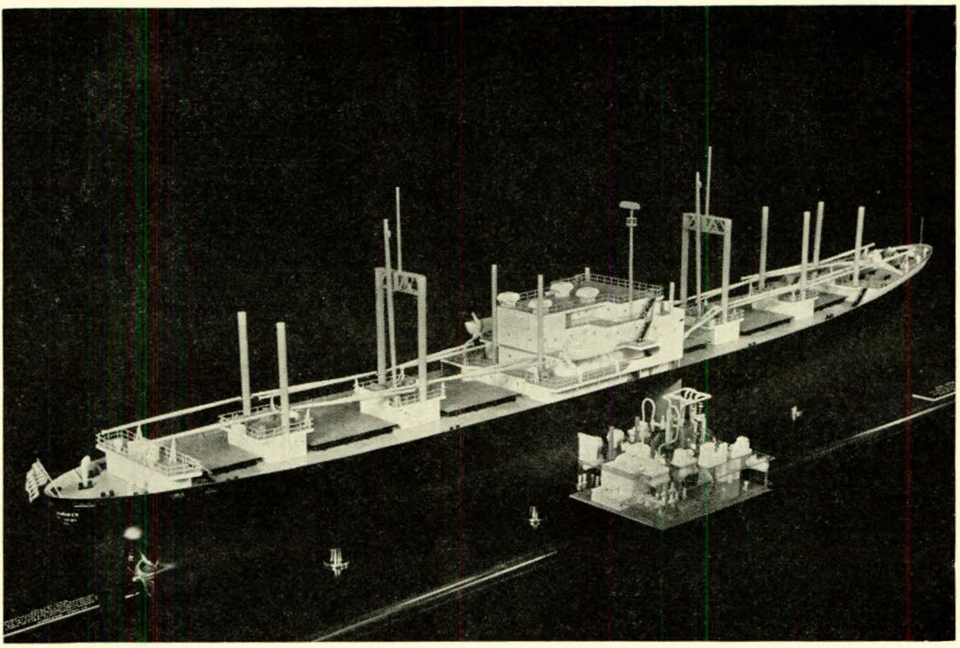
FIG. 23—*Graph of cost estimates for steam turbine machinery*

High-powered Cargo Ship

An economic analysis has been made of the application of nuclear power to the " Mariner " class ships (20). These cargo vessels have a displacement of 21,000 tons and develop 17,500 s.h.p. to give a cruising speed of 20 knots. The maximum output is 19,250 s.h.p. and is, therefore, within the range considered feasible for nuclear powering. The design and operation of these ships is described in references 21 and 22 respectively.

The design study made in considering the use of nuclear power in a vessel of this class has not been published. It is known, however, that a pressurized water reactor was included in the layout. Fig. 24 shows the model of this projected ship, the *Atomic Mariner*.

The conclusion reached from the economic analysis of a nuclear-powered *Mariner* was that it could not compete with the conventional power plants at present, but that the advance in reactor technology would improve the competitive position of this new power source. One factor which will adversely affect the suitability of this class of vessel for nuclear propulsion is its relatively low " load factor ", determined from the number of days at sea and the power developed. The Harvard Report



By courtesy of the Newport News Shipbuilding and Drydock Company

FIG. 24—*Model of proposed nuclear powered* Mariner

(23) assumed 170 days at sea at 10,000 s.h.p. as typical for these ships. This gives a load factor of:—

$$\frac{10,000}{17,500}\times\frac{170}{365}=26\cdot6\text{ per cent}$$

The deficiency applies in some degree to all types of general cargo carriers.

Bulk Cargo Carriers

A survey of the most desirable conditions under which to operate a nuclear-powered vessel gives a good indication of the type of vessel most likely to benefit from its adoption. As a first requirement, a high powered installation running on a long haul fully exploits the saving in oil fuel. Intermittent operation of a nuclear reactor is a wasteful procedure, as, at reduced loads, it is probable that arrangements must be made to " dump " the temporarily unused heat. Even on shutdowns, the reactor output can only be gradually reduced to prevent overheating. Thus, in both cases, a waste of valuable fissile fuel can occur. To minimize this loss, berthing and cargo handling time must be reduced. Another consideration is the special terminal facilities necessary to handle radioactive material. A shuttle service with fixed terminal ports would thus be desirable. Bulk cargoes such as ore, grain, or oil are therefore indicated and the latter appears to be preferred, particularly as the offshore loading and discharge of oil cargoes is now an accomplished fact. This is an additional advantage both in reducing manœuvring time and in providing a safety measure by isolation. The choice of an oil tanker is not a paradox as it is inconceivable that the use of nuclear energy will reduce the demand for oil within a period of time equivalent to the combined lives of several ships.

An excellent review of modern tanker and ore carrier design practice is given in references 24 and 25. The specific vessel selected as suitable for analysis in this paper is described in references 26 and 27. To meet the limitations of available dry docks and permit passage through the Suez Canal, the principal dimensions are:—

Length overall, ft.	660
Breadth, ft.	85
Loaded draught, ft.	34

The deadweight capacity loaded is 30,000 tons and the model test speed-power curve is reproduced in Fig. 25. The ballast condition curve was estimated from the model test data given, using the assumption made in reference 24 that the speed of the ship in ballast would be 4 per cent higher than the loaded service speed.

A comparison will be made between this ship and an equal sized vessel powered by a helium cooled reactor and a closed-cycle gas turbine.

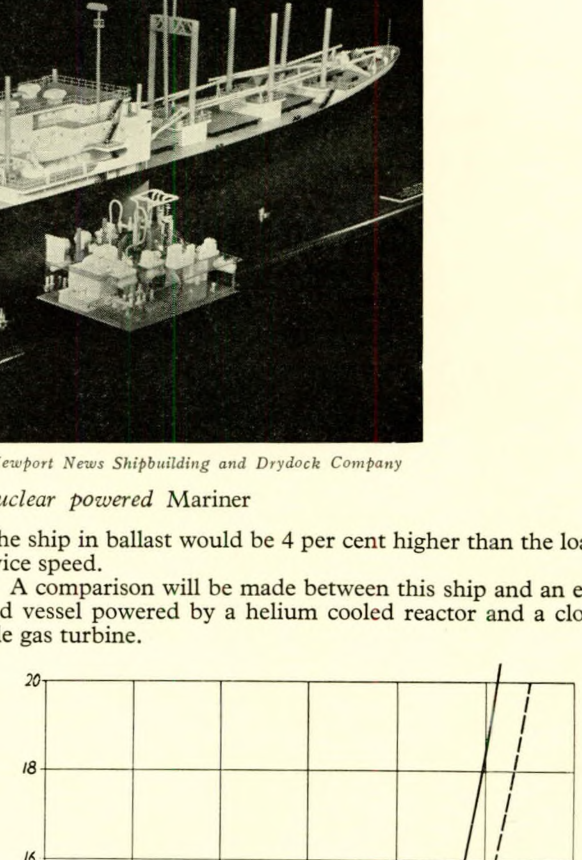


FIG. 25—*Speed/power curves, loaded and ballast condition*

For the purpose of this analysis, a typical voyage from a North European port to either the Burma or Borneo oilfields will be considered, a steaming distance of, say, 10,000 nautical miles each way.

Reduced power operation during the voyage will be assumed as follows:—

(*a*) Suez Canal passage plus berthing at both ends, equivalent to 24 hours at 50 per cent service power.

(*b*) Loading and discharging equivalent to 24 hours at 15 per cent service power. The three cargo pumps fitted are actually each powered by 500 h.p. motors and are capable of discharging the rated cargo capacity in 12 hours.

The latest published performance figures for this tanker(27) averaged over the outward and homeward passages of eight voyages, show a speed of 18·2 knots with a fuel consumption of 93·6 tons per 24-hr. day. This is higher than the predicted speed at the rated power of 16,500.

Estimate of Fuel Oil Consumption for Round Voyage

	Tons
At full speed $\frac{20,000\times 93\cdot 6}{18\cdot 2\times 24}$	4,280
At reduced speed $\frac{8,250\times 0\cdot 6\times 24}{2,240}$	54
In port $\frac{2,480\times 0\cdot 6\times 24}{2,240}$	16
TOTAL	4,350

Time for Round Voyage

	Days
At full speed $\frac{20,000}{18\cdot 2\times 24}$	46
Reduced speed and in port	2
TOTAL	48

The comparison may be simplified and still remain within the limits of accuracy allowed by other necessary assumptions, if the cost of the turbines and transmission is considered to be the same in each case. The comparison then becomes one between the “ steaming cost ” of the orthodox ship and its equivalent with nuclear powering. Fixed charges on the invested capital will be included. From Fig. 23, the cost estimate for the machinery of a 16,500 s.h.p. installation is £475,000 of which, say, £100,000 represents the cost of steam generators and ancillary equipment.

MacMillan and Ireland(28) use the following make-up for the fixed charges on this type of investment:

	Per cent per annum
Interest	2·6
Depreciation	4·9
Insurance	2·0
Maintenance	1·5
	11·0

Using these figures, the “steaming cost” for a round voyage would be:

Fixed charges $= \frac{48}{365}\times\frac{11}{100}\times$ £100,000 $=$	£1,450
Oil at 140/- per ton	£30,450
Total	£31,900

In calculating the fissile fuel consumption of the nuclear plant, the heating value of 1 gram of U.235 is taken as $65\cdot 5\times 10^6$ B.t.u. or equivalent to 25,750 horsepower hours.

The cycle developed in the foregoing section will be used and the cycle efficiency of 42·4 per cent should not vary appreciably over the whole range of powers, this being a characteristic of the closed cycle plant.

Overall Propulsion Plant Conditions and Weight Flow

Net output (at shaft), s.h.p.	16,500
Mechanical and other losses, per cent	5
Gross output, h.p.	17,350
Helium flow, lb. per hr. $17,350\times 9\cdot 35$	$=162,000$
Reactor load, B.t.u. per hr. $162,000\times 514\times 1\cdot 25$	$=104\times 10^6$
Overall propulsion plant efficiency, per cent $\frac{16,500\times 2,544}{104\times 10^6}$	$=40\cdot 4$

A 10 per cent addition to the turbine power output will be used to cover the engine room auxiliaries.

Estimate of U.235 “Burn Up” during Voyage

	Grams
At full speed $\frac{16,500\times 1\cdot 1\times 46\times 24}{0\cdot 404\times 25,750}$	$=1,927$
At reduced speed $\frac{8,250\times 1\cdot 1\times 24}{0\cdot 404\times 25,750}$	$=21$
In port $\frac{2,480\times 24}{0\cdot 404\times 25,750}$	$=6$
Total	1,954

This is the weight of fuel which is actually destroyed in producing the power for the voyage, but it only represents a fraction of the total fuel with which the reactor must be charged. A reasonable “ burn up ” percentage for the fuel for the heterogeneous gas cooled reactor, would be 25 per cent. Following this burn-up the fuel elements would require chemical processing, as described previously. The capital outlay for the plant, therefore, must include the cost of some 5,862 grams of U.235 carried as dormant fuel per voyage.

A detailed estimate of the first cost of the gas-cooled reactor is outside the scope of this paper, but, using the limited information available, a figure of £1 million, or ten times the equivalent steam generating plant, agrees with majority opinion.

If the price of U.235 is £X per gram and using the same fixed charges on investment the “steaming cost” for the voyage then becomes:

$$\text{Fixed charges} = \frac{48\times 11}{365\times 100}\left(1,000,000+5,862X\right) = 14,480+85X \quad (\text{£})$$

$$\text{Fuel at £X per gram} = 1,954X$$

$$14,480+2,039X$$

To “break even” with the equivalent orthodox steam plant, the cost of U.235 must then be:

$$X=\frac{31,900-14,480}{2,039},\ \text{say, £8 10s. 0d. per gram.}$$

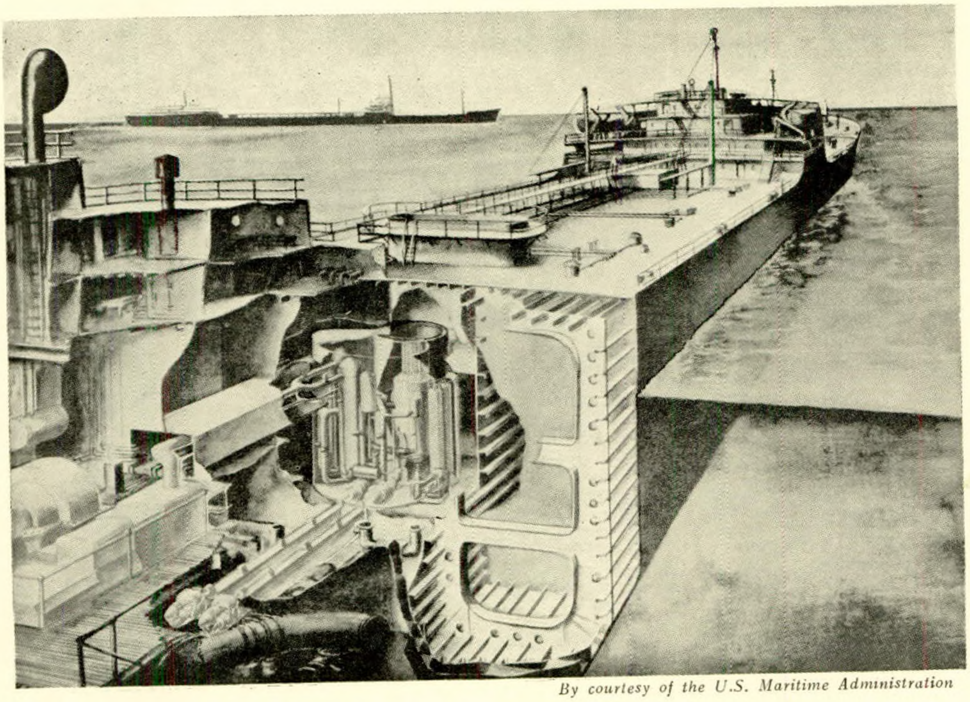
At the international conference on the peaceful uses of atomic energy held in Geneva in August 1955, the price of uranium was quoted at $25.00 per gram of U.235. It was not stated whether or not this figure included an allowance for fuel element fabrication. Even allowing for some error in this figure, with the present rate of exchange at $2.80 = £1, then it would appear that a balance in “steaming costs” for the two plants could very nearly be made.

Additional Considerations in the Comparison

The bunker fuel capacity of this 30,000-ton d.w. tanker is 4,500 tons and would be filled at the port of loading. Using a nuclear-powered plant would increase the machinery weight by some 500 tons, giving a net increase in cargo capacity of 4,000 tons.

The crew wages of all classes of vessels are now a major item in operational expense(22). On completion of the initial voyage, it appears unlikely that any additional operating personnel will be required. For instance, the advances in reactor control technology have proved that such reactor controls are complex in design, but simple in operation.

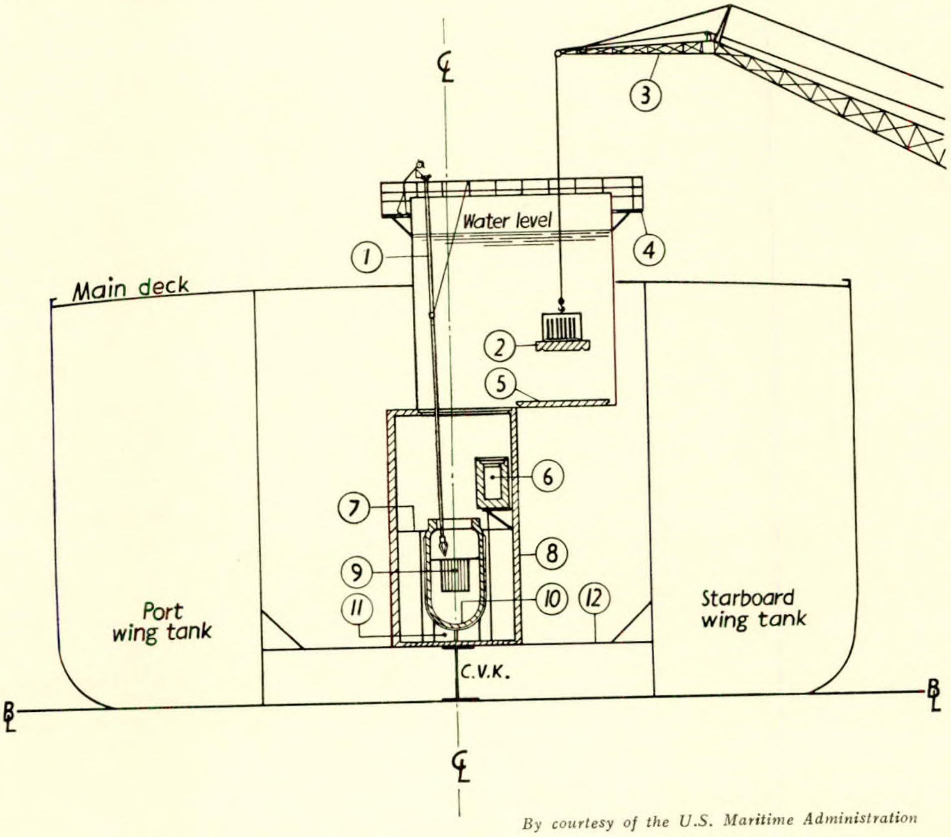
No account is taken of the additional investment to cover the charge of helium, but it is not expected that this would unduly affect the comparison.



By courtesy of the U.S. Maritime Administration

FIG. 26—*Concept of reactor installed in a tanker*

The cost of the turbo machinery has been considered equivalent to that of the orthodox steam plant and a more detailed analysis would show a definite increase in cost for the helium machinery since more stages will be required. Also, special arrangements will be required to prevent leakages not only at glands and other openings in the casings, but also due



By courtesy of the U.S. Maritime Administration

FIG. 27—*Dockside handling arrangement for radioactive material*

(1) Manipulators; (2) Reactor cover and control rods; (3) Dockside crane; (4) Catwalk; (5) Shield hatch; (6) Cask; (7) Watertight deck; (8) Shield; (9) Core; (10) Pressure vessel; (11) Reactor supports; (12) Reactor foundation

to porous castings. This latter problem is far more acute when dealing with helium under pressure than when dealing with steam.

The advantage of the nuclear power plant increases with increasing power level, therefore the decision to limit the power of the vessel selected to 16,500 s.h.p. may appear to be questionable. This was made to introduce an element of conservatism into an otherwise "pioneer" plant. The propulsive advantage of a single screw installation is thereby maintained in a well tried power range.

Alternative Proposals for Tanker Propulsion

To compare propulsion plants, Shoupp and Witzke(29) selected a tanker of 20,000 normal s.h.p. with a service speed of 18 knots. This ship would have a cargo capacity of 35,000 tons and make eight voyages of 17,000 miles per year, giving an annual total for cargo handled of 280,000 tons. Using a specific fuel consumption of 0·523lb. per s.h.p. hr. for all purposes, this gives an annual fuel consumption of 232,000 bbls., which at \$2.00 per barrel would cost \$1·65 per ton of cargo carried. Additional ship operating costs, including capital charges, overhead, port dues, maintenance and supplies, wages and subsistence, bring the total ship operating cost to \$7·15 per ton of cargo.

Details of the type of nuclear reactor proposed for this ship were not available at the time of writing, but mention is made in the paper of the use of steam as the thermodynamic fluid. Also the cost of the boiler and the boiler auxiliary equipment was estimated at \$570,000 from the "Mariner" class estimates. It was assumed that the cost of the turbines, condenser, shaft, propeller, etc., was not changed when the conventional oil fired boiler was replaced by a nuclear reactor.

Analogy with land plant data was necessary due to security restrictions on much of the information that would be more directly applicable to this field and, on the above basis, it was concluded that the cost of natural uranium was not likely to compete with conventional fuel on a straight economic basis. To compare the two types of power source in more detail:

For equal costs:
(*a*) With zero nuclear fuel cost, the maximum permissible price for the reactor plant would be \$4,800,000.
(*b*) Assuming zero investment in the plant, the nuclear fuel price cannot exceed \$27.80 per gram.

This paper agrees that a saving will be made in the combined weight of plant and fuel and suggests that every 1,000 tons of additional cargo capacity can pay for an additional plant investment of \$500,000.

Perhaps a more significant comment for immediate interest is that these figures, and the conclusion drawn from them, apply to an American-operated vessel. The equivalent European ship would have a considerably reduced ship operating cost, many items of which would be at least halved. This means that the cost of the machinery and fuel forms a larger part of the European ship operating cost. Hence the balance would be more in favour of the nuclear power plant if compared with the oil fired plant when using figures applicable to a European ship.

Another proposal is made by the Engineering Research Institute of the University of Michigan. This is included in a recently completed feasibility and preliminary design study for a nuclear power plant suitable for a large ocean-going tanker(30). An artist's impression of this installation is shown in Fig. 26.

The conclusion drawn from this study is that safe operation can be expected, but that there will be no saving in operational cost compared with an oil fired installation. This latter factor was rather to be expected since the original specification for this project called for a tried type of reactor. This, of course, considerably reduced the field of choice. A pressurized water reactor was selected and one of its inherent advantages is illustrated in Fig. 27, which shows the convenient arrangement of providing a transparent shield by flooding the access hatch above the reactor. The loading of fissile fuel and discharging of fission products is thus simplified by the direct observation afforded.

PROPOSED MACHINERY ARRANGEMENT FOR THE 30,000-TON D.W. TANKER POWERED BY A CLOSED CYCLE HELIUM TURBINE WITH A HELIUM COOLED REACTOR

The first consideration is the selection of a suitable drive and the choice is limited by the desire to keep the turbine design as simple as possible, which calls for unidirectional rotation. The transmission then must include either a reversing gear, a controllable pitch propeller or an electric drive. It should be remembered that one of the reasons for selection of this type of vessel as most suitable for nuclear powering was the minimum of manœuvring required under usual service conditions.

A reversing gear to transmit 16,500 s.h.p. appears to be too far ahead of current development to warrant serious consideration. Unfortunately, the same remark appears to be true for the controllable-pitch propeller. The author considers that this is the most promising line of development for the future. Correspondence with a leading manufacturer has ascertained that 7,000 s.h.p. is the present maximum in satisfactory service. Baker, in his contribution to the discussion on Professor Burrill's paper (reference 19) recalls an American vessel on which an attempt to transmit 14,000 s.h.p. failed. McMullen(31) records that the open cycle gas turbine plant of 6,000 s.h.p., at present being installed in the Liberty ship *John Sergeant,* will use a controllable pitched propeller. Mention is made in this paper that, if successful, gas turbines will be adopted for selected applications in the 7,500 to 15,000 s.h.p. range and it would be interesting to hear whether the same type of drive would be proposed.

The safe selection therefore must accept the additional weight, space and expense inherent in the electric drive.

All the auxiliary machinery will be electric motor driven. Power demand for port use should be of the order of 2,000 h.p., and the convenient possibility then presents itself of using the main propulsion turbine to produce this power. This scheme was used in computing the economic comparison with orthodox steam power plant. Allowing for the inefficient running of the plant at about 12 per cent of designed rating, this would not be a significant loss since the port time/sea time ratio is so small. However, the scheme demands continuous operation of the main plant and hence the placing of too many eggs in the single basket.

Until a sufficient degree of reliability has been proven, it is recommended that a separate Diesel powered plant be installed, say, of four high speed units giving a total output of 2,000 h.p. This would provide in port power only, the sea load being tapped from the propulsion power. Detailed discussion of the possible electrical systems to be used is outside the scope of this paper and can be found in reference 32. The Diesel plant would be a sound investment during the early years of the ship's operation as the carriage of some 100 tons of Diesel fuel could ensure a means of making port up to a distance of 1,500 miles in the event of a complete failure of the nuclear powered plant.

In laying out the scheme shown in Figs. 28, 29 and 30, the

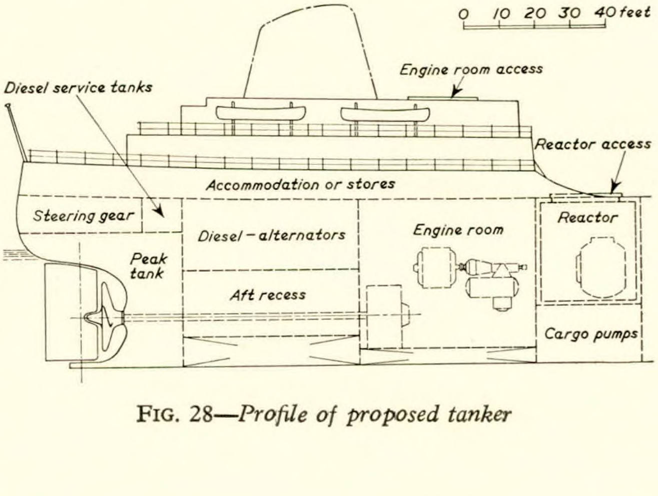


FIG. 28—*Profile of proposed tanker*

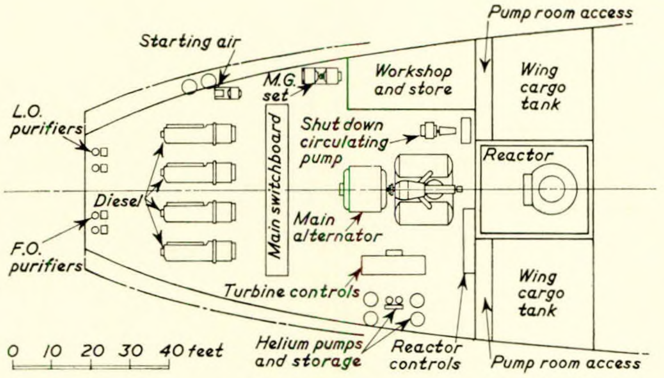


FIG. 29—*Plan at operating level*

tanker featured in reference 26 was used for guidance on the space available for the machinery. The Diesel plant is accommodated in the original boiler room, the reactor is housed in what was the aftermost centre cargo tank and the main pump room lies directly below the reactor. Direct access from deck to pump room is afforded both on the port and starboard sides by the trunk/cofferdam immediately forward of the engine room bulkhead. By eliminating the original fuel settling tanks the total machinery space is increased only slightly.

The main turbine/compressor has been shown as a single in-line unit. If conservation of engine room length is considered to be of sufficient importance, then either or both of two modifications could be effected:

(a) The main turbo alternator could be replaced by two or even three smaller units.

(b) The in-line unit could be replaced by a co-axial arrangement in which the alternator and low pressure turbine are on one shaft and the two compressors and the high pressure turbine on the other.

For future vessels in which it may be considered the Diesel alternators can be dispensed with, the space so vacated could house the reactor, thus increasing cargo space.

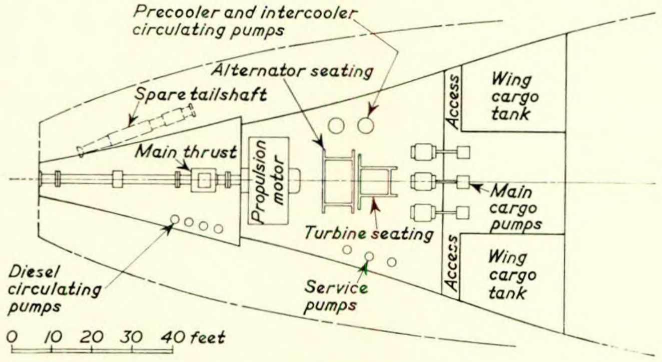


FIG. 30—*Plan at lower level*

From provisional estimates of stability, all the above arrangements would be acceptable to the naval architect.

A funnel is shown in chain dots to indicate that its inclusion depends upon factors outside direct machinery requirements. Dispersion of the Diesel engine exhaust and the display of owners' insignia are two of these which could be found alternative locations. The author suggests, however, that a ship without a funnel would resemble a Manx cat. What better mark of esteem could be given to the individual who will sail in charge of this unique power plant than to use the funnel as housing for a suite of rooms for "The Chief"?

CONCLUSION

Following a study of the information now available on the various types of nuclear reactors and power plants, the author selected the helium-cooled reactor with a closed-cycle gas turbine power plant as the most attractive for commercial marine use. The economic comparison shows that this plant can compete with the oil fired steam turbine plant for high powered ships once the design values used in the paper have been verified in practice and the first cost of the plant proven to be of the order suggested. The latter will only be so when the components of the plant are in normal production by the equipment suppliers.

Here, then, on both counts, the time factor governs the date on which nuclear power will be adopted for ship propulsion. Whatever type of nuclear plant is selected, a vast amount of research and development work must yet be accomplished. This will require the combined efforts of an integrated team of engineers, physicists, chemists, metallurgists, mathematicians and probably the representatives of other professions. These men are available and the British shipbuilding industry and their equipment suppliers undoubtedly have the potential to tackle the many problems peculiar to this new source of power. If this paper is instrumental, to whatever small degree, in fostering the necessary interest in this concept of marine power, then the author will be well satisfied.

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A personal word of thanks is offered to Dr. Tom Sawyer and Messrs. Harold Ohlgren and Marx Weech for their helpful criticism and to the author's colleagues in the Naval Architecture and Marine Engineering Department of the University of Michigan for their encouragement.

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Discussion

MR. H. N. PEMBERTON (Member of Council) said that Mr. Maddocks had made it all look very easy. Nevertheless, he had made his main point that it was time marine engineers made a serious study of the possibilities of nuclear energy for ship propulsion.

The attendance, especially during Christmas week, showed the interest which marine engineers had in this subject. There was no question that this was the threshold of the atomic energy age, and many of those present would undoubtedly see nuclear reactors fitted in merchant ships.

The value of Mr. Maddock's paper lay not so much in its discussion of cycle efficiencies and economics, both of which would have changed a great deal by the time reactors were put into ships, but in its basic description of present-day reactors. To those new to the subject the paper was a good introduction.

He suggested, however, that one must keep a sense of proportion. Reactor design was a changing and developing art. The reactors which were designed today for certain Central Electricity Authority power stations were not necessarily the reactors which would be fitted in subsequent power stations. The reactors which would eventually be used in ships might be very different as compared with those described in the paper.

The need for nuclear propulsion in ships arose from estimates of the world resources of solid and liquid fuels. If it were true that these would be expended during the next century, then consideration must be given to alternative sources of power. Mr. Maddocks stated in the paper that a nuclear reactor must develop a minimum of about 15,000 s.h.p. fully to exploit the advantages of fissile fuel. Such powers were required for ships of about 12,000 gross tons and over. If for convenience ships of 10,000 gross tons and over were regarded as those which could be powered by nuclear reactors, then that represented no more than 5·8 per cent of the 32,492 steam and motor ships at present listed in Lloyd's Register book. It followed that the saving in world oil consumption to be obtained by converting these large ships to nuclear propulsion was comparatively small. The trend must therefore be either towards more large ships or towards developing nuclear reactors which would be efficient over a wider range of power output.

It would be found that the author skated rather superficially over some of the more serious problems concerned with the application of nuclear reactors to ship propulsion. This was particularly true in regard to safety. Yet safety and reliability were among the first considerations in the choice of propelling machinery.

The gas-cooled reactor had many desirable features which related to safety in operation. Nevertheless, this alone did not eliminate the serious hazards which might arise due to errors in design, construction and operation. Moreover, in the marine application the effects on the reactor plant of collision damage and wreck were also a major concern. He did not need to remind anyone that collisions and wrecks did occur with distressing frequency. There was also the possibility of sabotage, which could not be disregarded.

The main hazard which must be kept in mind and which could result from a breakdown caused by the failure of automatic controls, failure of ancillary systems, failure of the human element, design or constructional weakness, collisions, sabotage and so on was the rupture of the reactor and the dissipation of the fission product into the surrounding areas. This possibility emphasized the importance of good design, a high standard of workmanship in construction, satisfactory maintenance and satisfactory measures for safeguarding the security of the plant.

Difficulties arose in devising suitable methods of maintenance and inspection. Experience was building up in health physics which resulted in progressive improvement in protective clothing for maintenance workers and more comprehensive knowledge of human tolerance of radiation effects. Side by side with this, experienced engineers were at the moment working out practical methods of inspecting reactors.

In existing reactor plants in the United Kingdom, including Calder Hall, the radiation level in the vicinity of the plant was so low as to be negligible. Nevertheless, elaborate steps were taken to safeguard the health of those who had to work near the plant. It could, he thought, be said that the health of engineers responsible for reactor operations, whether in power stations, submarines or merchant ships was even now adequately safeguarded.

At the present stage of development, he agreed that the helium-cooled reactor was probably the most suitable for marine propulsion; but in his view it was far too soon to predict which types of reactor would in fact be fitted into ships. The gas reactor using enriched fuel would probably be the ultimate answer. But it would be remembered that Sir John Cockcroft had indicated* that it would be some twenty years before sufficient of the necessary enriched fuel was available in this country for commercial applications.

To sum up, the very real problems of safety, maintenance and repair must be solved, and they were not solved yet. Merchant shipowners were not particularly interested in pioneering scientific progress. They would only consider nuclear propulsion provided the risks involved were no more severe than for orthodox marine power plant, and that stage had not been reached yet. Moreover, they would require to be assured that their nuclear-powered ships would have free access to the ports of the world. Undoubtedly, some form of international convention would be necessary.

Finally, the advent of nuclear power for ships posed problems for the naval architect as well as the engineer. He would not deal with those problems but would merely suggest that they were mainly associated with the siting of reactors and shielding. It was interesting to speculate on how soon there would be atomic energy ships. He was a brave man who ventured into prophecy, but he would suggest that whilst there might be one or two "show-boats" during the next

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*Cockcroft, J. 1953. "Atomic Propulsion—with Special Reference to Marine Propulsion". Trans.I.Mar.E., Vol. 65, p. 105.

four or five years, it would be in ten years' time that nuclear power for ships would become a matter for the serious consideration of merchant shipowners.

DR. T. W. F. BROWN (Member) observed that the paper was timely, since the application of nuclear power to the propulsion of merchant ships was now receiving active consideration in this country.

The technique of nuclear power production was still in its infancy, and stability was not likely to be achieved until experience had been gained with the various full-scale reactors being developed by the American Atomic Energy Commission and the British Atomic Energy Authority. The marine application provided the many additional problems mentioned by Mr. Pemberton, including collision and wreck, so that it would not be clear what type of reactor should be used in marine work until a great deal more work had been carried out. Nevertheless, even at this stage it would appear that given a fairly high load, and a high load factor, economic operation might not be far away. He noticed that the author quoted a design study giving 10,000 s.h.p. as the lower limit, although he himself inclined to the higher figure of 15,000 s.h.p.

After a brief summary of reactor types, the author chose a helium-cooled reactor operating in conjunction with a closed-cycle gas turbine. There was one great advantage in this system. If a major failure did occur contamination would not spread over a very large field. There was also the great simplification in eliminating the steam generator and coolant pumps handling radioactive fluids.

The author chose 1,400 deg. F. as the temperature of the gas leaving the reactor, apparently without consideration of the reactor design. It was usual, however, using uranium, to keep the temperature at the centre of the fuel elements below the α-β transition temperature of 1,220 deg. F. Sir Christopher Hinton, in his paper* to the Institution of Mechanical Engineers in 1954, had stated that the limiting gas outlet temperature in a gas-cooled reactor would be 400 deg. C. (752 deg. F.). This was the first great discrepancy in the paper. There was not a clue as to how to get these high temperatures, using enriched uranium or even using fuel elements which were wholly uranium 235. At a temperature of 752 deg. F. the gas turbine would be barely self-driving and would develop no power.

A second difficulty was to make a gas-cooled reactor small enough to go conveniently into a ship's engine room. The author implied that this could be effected if helium at high pressure (1,000lb. per sq. in. gauge or more) was used as coolant. Would he give the size of such a reactor, particularly if the low pressure drop of 1½ per cent is to be achieved?

The overall efficiency of the gas turbine—40·4 per cent was claimed—was high, even in relation to a study for a 60 MW set, to which the figures really applied. It was clear that in using the reactor as a heat source the funnel loss of, say, 6—7 per cent was eliminated, but even so the figure was too high for a marine set of 16,500 s.h.p. The use of helium at high pressure did lead to lower pressure drops, and secondary surfaces with small flow passages could be used to improve the performance of closed-cycle heat exchangers, but on the other hand the effect of leakage losses at these high pressures would certainly lower efficiency. Further, some cooling might be required in the h.p. turbine if long life was to be achieved at an inlet temperature of 1,400 deg. F. Such losses must be allowed for.

He would like further information on the type of glands which were leak-proof with helium. It would be essential to have the glands tight but it was surely necessary to provide a reduction in pressure before coming to the final "leak-proof" section of the gland, however this was contrived. That would involve internal leakage losses with a corresponding loss in efficiency. The arrangement shown in Fig. 16 would require six glands under high pressure if normal oil-lubricated bearings were used. The author mentioned helium bearings, and it was true that a lot of work was being done on bearings using water, steam or nitrogen as lubricant, but he did not think they had reached a stage at which they could seriously be put forward for a design which was to be studied and which might be used in construction.

There was a claim that the closed-cycle gas turbine plant, because its power output was controlled by the pressure level, therefore maintained its efficiency even at low powers. That was only true if the output turbine remained at constant speed. If the speed of the output turbine followed the propeller law,

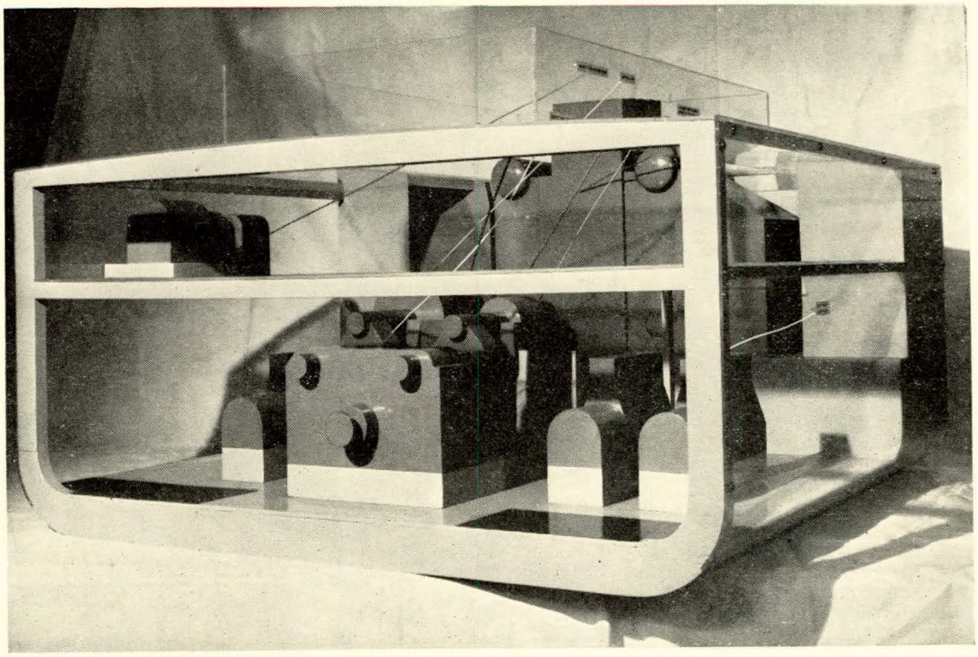

FIG. 31—*Perspex model of steam turbine machinery*

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*Hinton, C. 1954. "Nuclear Reactors and Power Production". Proc.I.Mech.E., Vol. 168, p. 55.

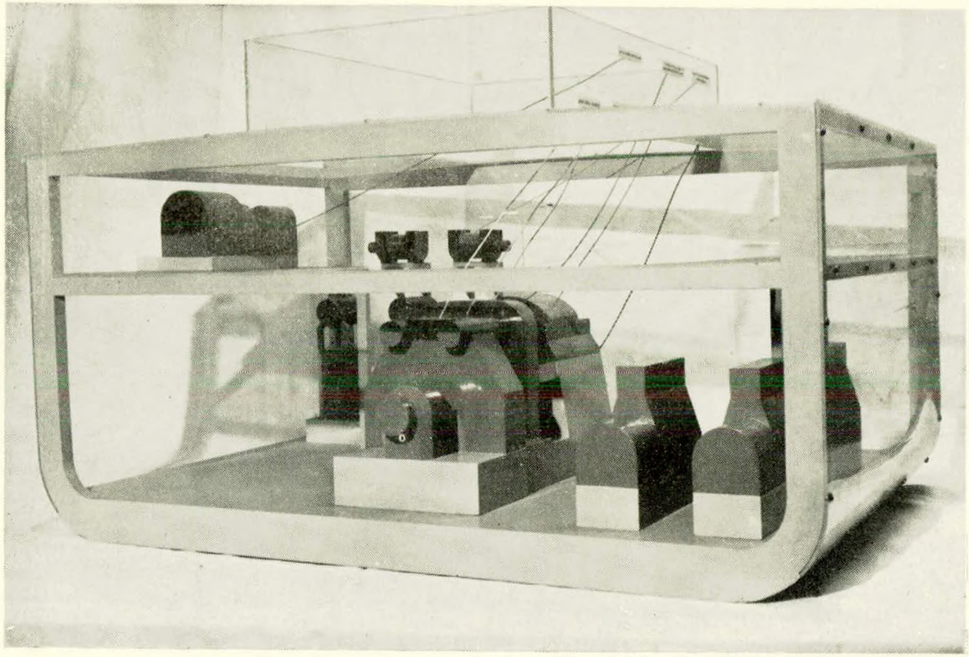
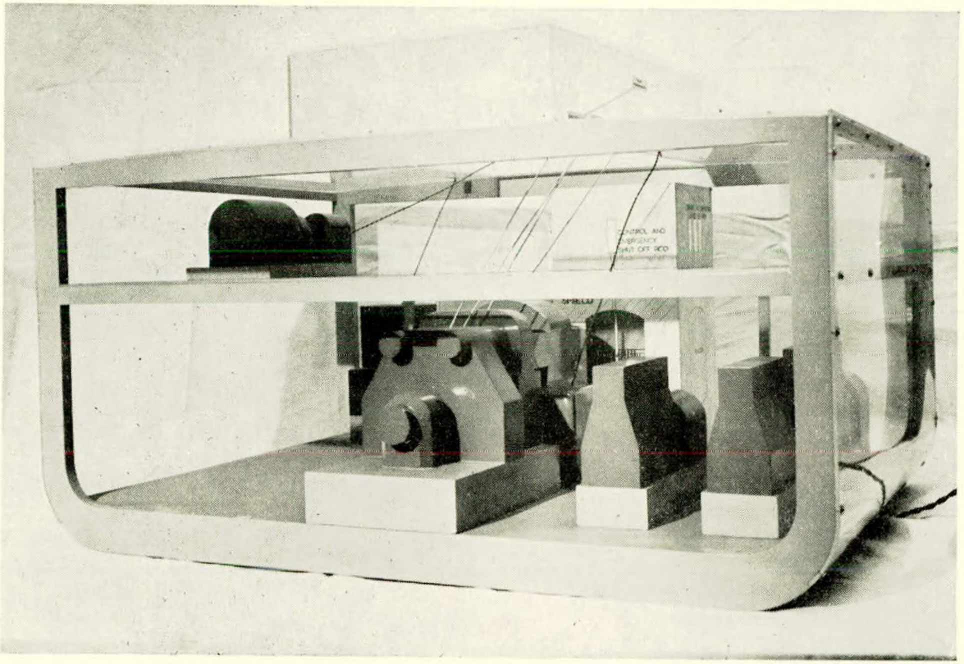
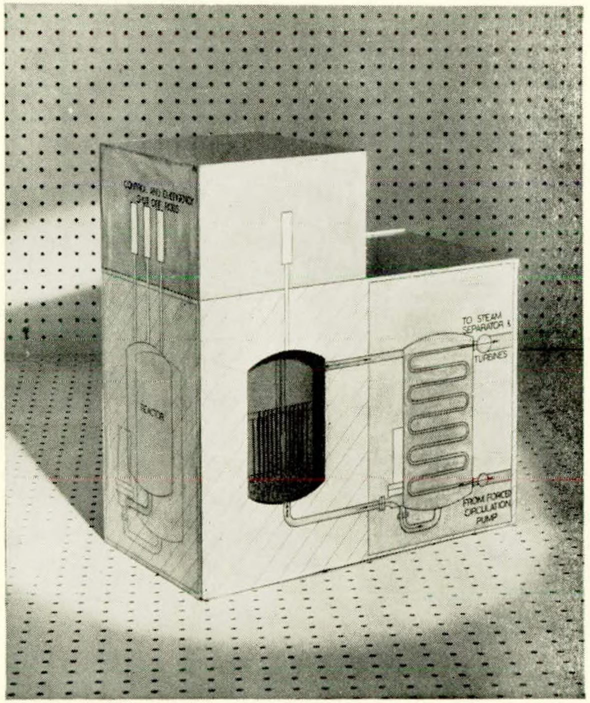


Fig. 32—*High-temperature installation operating with pressure combustion*





Figs. 33 and 34—*Nuclear power plant incorporating a pressurized-water reactor*

Fig. 34

as would be the case with the methods of transmission likely to be used in practice, the efficiency would fall off appreciably at low powers.

In computing the cost of nuclear fuel the author took the price as 25 dollars per gram, which was presumably the cost of pure uranium 235. This expensive commodity would surely not be used in a thermal type reactor which was intended to be economic. Natural uranium with its uranium 235 content increased to some extent would be used, and the cost would be correspondingly less. There would also be some gain due to the plutonium produced—offset, of course, by the cost of treatment to recover it.

It was assumed in the calculations that the ship was at sea for forty-seven days out of forty-eight. An accurate comparison should take into account "outages" required for survey and overhaul, since capital charges, which differed widely in the comparison, operate over these periods.

The value of the paper would have been enhanced if estimates could have been given of weight and space requirements for the nuclear power plant.

A comparison of three machinery installations developing 10,000 s.h.p., including a nuclear power plant, were given in Figs. 31-35.

Fig. 31 showed a Perspex model of steam turbine machinery with the main machinery elements represented by block models. The installation was a conventional modern high-temperature steam turbine set operating with steam conditions of 650lb. per sq. in./950 deg. F., and followed Mr. Ewen Smith's paper* in the recent Symposium on advanced machinery held by this Institute.

Fig. 32 represented a really high-temperature installation operating with pressure combustion. The steam conditions

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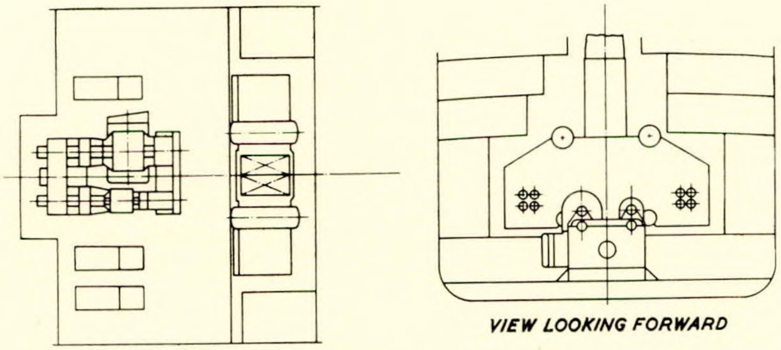
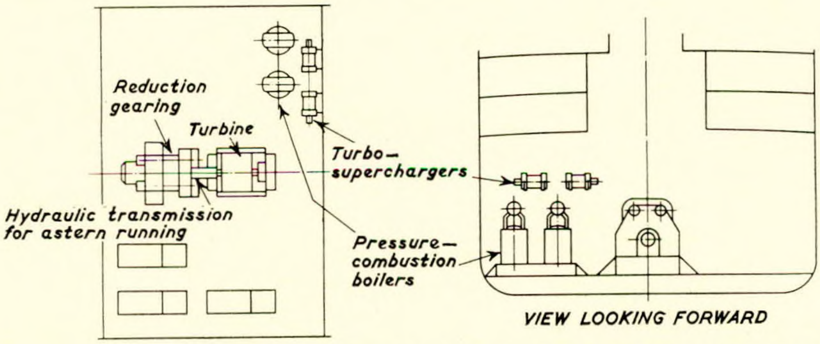
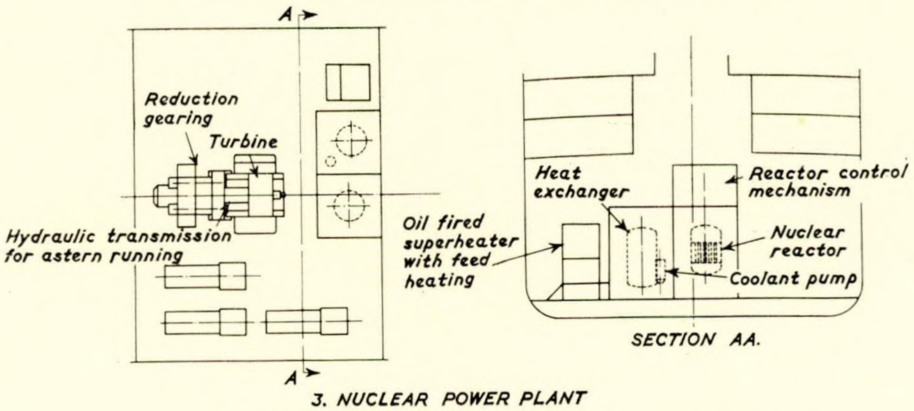
*Smith, E. H. 1955. "Steam Turbine Machinery". Paper No. 5 in Symposium entitled "Advanced Machinery Installations Designed for a Maximum Saving in Weight and Space". Trans.I.Mar.E., Vol. 67, p. 323.



1. STEAM TURBINE MACHINERY WITH CONVENTIONAL BOILERS
STEAM CONDITIONS 650 LB. PER SQ. IN. (G) 950° F.



2. STEAM TURBINE MACHINERY WITH PRESSURE-COMBUSTION BOILERS
STEAM CONDITIONS 650 LB. PER SQ. IN.(G) 1200° F.



3. NUCLEAR POWER PLANT

FIG. 35—*Showing the three installations* (FIGS. 31-34) *to scale*

were 650lb. per sq. in. gauge/1,200 deg. F. The steam turbine at 1,200 deg. F. was a distinct possibility in the near future; it had been running for a large number of hours at 1,150 deg. F.—1,200 deg. F. in an experimental way, and was certainly as nearly possible as a nuclear reactor in a ship. The figure showed a single casing turbine with pressure combustion boilers and double reduction gearing.

Figs. 33 and 34 represented a nuclear power plant incorporating a pressurized-water reactor in which natural water was used as moderator and coolant. The fuel charge consisted of about 7½ tons of enriched uranium, the degree of enrichment corresponding to an increase in the uranium 235 content of 30 per cent. Steam at 350lb. per sq. in. gauge (saturated) was generated in a heat exchanger by the reactor cooling water and in order to give a good turbine design was then heated in an oil fired superheater to 750 deg. F. At 10,000 s.h.p. the oil fuel used would be about 1,000lb. per hr., or 10·8 tons for 24 hours.

The reactor cooling water was γ-active and the primary coolant circuit must therefore be shielded to protect personnel. The generated steam could not become contaminated even in the event of a fuel-element failure.

Fig. 35 showed the three installations to scale, and the following table summarized the main findings with regard to these three types of machinery:—

TABLE III

	Steam turbine: 650lb. per sq. in., 950 deg. F.	Steam turbine: 650lb. per sq. in., 1,200 deg. F.	Nuclear power steam turbine: 350lb. per sq. in., 750 deg. F.
Main engine weight, tons ...	314	138	460
Total machinery weight ...	740	564	910
Engine room length... ...	52ft. 6in. + 7ft. 6in. recess	44ft.	50ft.
Total machinery weight + fuel for 20 days full power steady...	1,875	1,635	1,126
+ fuel for 40 days full power steady... ...	3,010	2,705	1,342

The figures indicated that a nuclear power plant of the type assumed would require a slightly smaller engine room than a conventional modern high-temperature steam turbine, but not as small as could be achieved with pressure combustion boilers. With regard to weight, the important consideration was total weight of machinery plus fuel for a given length of voyage, and in this respect the present-day steam turbine would be equalled by the nuclear installation in four days' steaming. Taking fuel for twenty days at full power, the nuclear powered installation was actually some 750 tons lighter than the present-day steam turbine installation, and with fuel for forty days' steaming was about 1,700 tons lighter. There was therefore a great deal to be gained by nuclear propulsion.

It might be asked, why use separately-fired superheaters in conjunction with nuclear reactors? The answer was that it might in the end lead to a cheaper type of turbine design. Taking steam at 350lb. per sq. in. gauge saturated and expanding to 28·5-in. vacuum along an expansion line corresponding to a turbine efficiency of 82 per cent, which was a reasonable value, gave an exhaust wetness of 20 to 21 per cent.

It was not easy to get the water out of the steam. Indeed, it was extremely difficult, and one would have to be very clever to take out 30 per cent of the water present. It was not there in big enough drops to get hold of: it was like a very thick London fog. If a nuclear powered installation was suitable for other reasons it would seem better to work with lower temperatures in the reactor and to jack up the steam temperature a little by means of oil firing.

LIEUT. CDR. F. G. RIGHTON, R.N., apologized for the absence of Captain Harrison-Smith, the head of the Naval Section at Harwell. He had hoped to take part in the discussion but unfortunately he had been unavoidably detained and had asked him (Lieut. Cdr. Righton) to speak on his behalf.

The author was to be congratulated on collecting information from such wide sources and collating it in the paper. He had not given sufficient justification, however, for his selection of the gas-cooled reactor, closed-cycle gas turbine installations, and several important points had been too lightly glossed over. The last two speakers had touched on several of these, but they could not be too greatly emphasized.

The operating temperatures that the author had selected for use in the gas turbine installation appeared very optimistic in the light of present-day practice and would require the development of such fuels as uranium oxide and uranium carbide. It should be noted here that the author was talking in terms of a five-year development period.

Bearing in mind that for a plant developed in a reasonable time-scale the inlet temperature would probably be greatly reduced and noting the high turbine and compressor efficiencies and the high recuperator effectiveness that the author had quoted, it would appear that the overall cycle efficiency of 42·5 per cent was probably over-ambitious.

In general, it was felt that he had painted an unduly optimistic picture of this system unless he accepted the view that it could not possibly be brought into use in this country for a very considerable time, due to the large amount of development work that would be required. Any such project would also be dependent on the availability of suitable fissile material, with the associated competing requirements for it.

The author did not state the exact type of reactor he had in mind when considering the gas-cooled system, and further details would be interesting. However, the figures quoted for the investment of fissile material appeared to indicate that he hoped to obtain a heat output of approximately 4 megawatts per kg. of Uranium 235. As the bulk of experience in this country lay in the thermal reactor range, it might be preferable to consider a thermal reactor, though with the transient poison problem which would occur with manœuvring, a more modest heat rating would be necessary. This would, of course, involve the use of a greater quantity of fissile material of which the increased initial cost and the considerable reprocessing charges—which had been ignored in the economic survey in the paper—might well rule this system out of court.

The importance of a high conversion factor on the economics of the plant had also been ignored. This was most easily achieved, particularly in these early days, by using a system with a high nuclear efficiency employing natural or near natural uranium as a fuel. Unfortunately, the majority of these systems were large and, with their biological shield, extremely heavy. Perhaps the only practical one of these systems was the pressurized-water reactor. The mechanical disadvantages of this system were admirably outlined by Dr. Kay and Mr. Hutchinson in their paper* before the British Nuclear Energy Conference a few evenings previously, but even so its economic advantages should not be too lightly dismissed, particularly when one considered that the natural or near natural fuel requirements were more easily met and construction should be possible at an early date.

One of the major mechanical doubts the author had raised in his mind was whether the direct use of the reactor cooling medium in prime movers was acceptable. A twofold danger existed. Firstly, the failure of a fuel element can, with its associated release of fission products into the gas stream, would produce a radioactive hazard in the way of the unshielded portions of the circuit, with an even greater

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*Kay, J. M., and Hutchinson, F. J., 1955. "The Pressurized Water Reactor as a Source of Heat for Steam Power Plants". British Nuclear Energy Conference.

hazard should gland leakage occur. Secondly, there was the difficulty of keeping the helium in a sufficiently pure state so that one could rely on it not to become radioactive. This was a tall order when one considered the risk of contamination by lubricating oil from the bearings and by any leakage of oxygen in from the atmosphere.

The author put in a xenon trap, but it was thought that he had underestimated the effect of a can failure on the overall activity of the circuit. Like Dr. Brown, he himself felt that the type of fluid bearing in which the author had such confidence was a thing very much of the future and should not be considered seriously for a study which might take place in a few years' time. It seemed doubtful whether such a system should be accepted in this early stage of development of nuclear power for ships.

As had already been announced by the First Sea Lord in a recent speech, the Admiralty in conjunction with industry and the Atomic Energy Authority was designing a nuclear-powered submarine, but unfortunately the present security regulations did not allow him to indicate the type of systems which were being considered. It was hoped, however, that as design progressed it would be possible to release certain information which might be of great interest to British shipbuilders and shipowners.

MR. W. R. HARVEY (Member of Council) congratulated Mr. Maddocks on his paper which he regarded as a perfect sequel to Sir John Cockcroft's paper and of great importance to marine engineering. It stated in bold and broad outline the possibilities of nuclear power in merchant ships. As it was obvious that many of those present would ask technical questions and make technical criticisms, he would like to confine his own remarks to the subject in general.

In his experience the only question which influenced the shipowner in installing a different type of machinery was the probability that it would, in the long run, prove more economical and therefore cost him less than the installations he had at present.

Nuclear power had not reached that stage yet. In consequence it would seem that the responsibility reverted to the government of the day to step into the breach and assume the financial responsibility for a new type of power which in time would undoubtedly solve the problem of the fundamental scarcity of coal and the possible scarcity of oil and would prove more economical than either.

This, in its natural sequence, resolved itself into the Royal Navy sponsoring the design and building of not only a warship powered by nuclear energy but also a supply ship with the same power. He would suggest that if at the same time they were to do a real service to the Merchant Navy in this country, this supply ship should be designed on similar lines to a normal merchant ship.

However, he was glad to say that more than one company in this country was today prepared not only to make a design study for such a ship but would actually accept an order to manufacture the machinery.

He thought sufficient knowledge was available to commence a design study at once. As he saw it, the fundamental question which would arise in such a project was the type of fuel which could be supplied. At this stage surely this must be answered on a national basis according to what was available. It seemed evident that the ultimate aim, as suggested by the author, should be a reactor coupled to a closed-cycle gas turbine. Whilst he himself felt that this was correct, he would suggest that the present time was not opportune for a serious experiment or development of a merchant ship with this type of machinery. Surely it was better to continue with the development of the gas turbine for operation at sea before coupling it to another unknown, the nuclear reactor.

It would seem that the most suitable reactor, and the one about which most was known, was the pressurized water reactor where apart from the reactor itself the heat exchanger, steam turbine, and so on could follow normal practice. Bearing in mind that the machinery under consideration was fitted in a ship at sea, some safeguard should be provided to keep the ship manœuvrable should trouble occur. This could be done quite simply by fitting an auxiliary boiler working at the same pressure and temperature as the heat exchanger. Under normal circumstances this could supply the hotel services of the ship, and possibly auxiliary equipment, and could be used for manœuvring. It could also be used in an emergency to drive the vessel, probably at a slower speed.

He would like the author's comment on the possibility of using the superheater in this boiler to superheat the steam which was produced by the heat exchanger, thus obtaining a more efficient prime mover.

He would also appreciate the author's suggestion as to the means which could be adopted in a merchant ship to use the heat given off by the reactor in cooling down. Would it be a reasonable proposition to use this heat through the heat exchanger to run turbogenerators which might supply the power necessary for deck auxiliaries in the cargo ship or cargo pumps in an oil tanker?

There was one important point which was of considerable interest to others besides himself: the fuel in the reactor had to be replenished during the service of the ship. There was, he thought, a general impression amongst engineers at the present time that once the fuel had been placed on board, it would last the life of the ship. This was evidently not the case; and to his mind it raised a very interesting and important problem as to how the replenishment fuel could be stored and handled. Any further information the author could give would be most welcome.

MR. E. P. HOTCHEN, M.Sc., said it was a pleasure to add his congratulations to Mr. Maddocks upon his presentation of a most interesting thesis. Having selected a high-temperature gas-cooled reactor, the elimination of an indirect steam cycle by the substitution of a gas turbine was at once attractive.

Design studies of such a system, using rather less ambitious maximum temperatures, had already been carried out, and these had shown improved efficiencies together with substantial reductions in rotating machinery, space requirement and cooling water flow. The relative magnitudes of gross turbine output and net shaft output tended, however, to reduce the apparent gain.

It was common knowledge that if a gas turbine cycle was to give a satisfactory thermal efficiency, the maximum gas temperature must be of the order of 1,200 deg. F.

The cycle proposed in the paper concerned a maximum cycle temperature of 1,400 deg. F. This figure, as the author had shown, gave an excellent result from the cycle efficiency standpoint, but before accepting it as a basis of evaluation, it was first necessary to examine the design requirement for the reactor itself.

In this respect, the author had no doubt been handicapped by security restrictions, and this probably accounted for his having considered the propulsion unit in considerable detail without enquiring too closely into the ability of the reactor to fulfil his requirements.

Apart from the fact that helium was not readily available in this country and that its price was roughly 4/- per cu. ft., the main reactor problem, as Commander Righton had emphasized, was one of temperature. If the gas temperature at the turbine inlet was to be 1,400 deg. F., it was—as Dr. Brown had pointed out—unlikely that the corresponding maximum uranium temperature would be below about 1,600 deg. F. This was approximately 250 deg. F. higher than the beta/gamma phase transition and some 500 deg. above the current declassified limit of 1,100 deg. F.

Since, moreover, the author's selected range of temperature embraced both the alpha/beta and beta/gamma phase transitions of uranium, at certain stations in the core, fuel elements would be subjected to these critical temperatures and provision must therefore be made for the structural changes which such transitions involved.

To prevent fission products contaminating the coolant, the fuel elements in a reactor were encased in cans, and when, as in the system considered, can surface temperatures exceeding 1,350 deg. F. were contemplated, even alloy steels were ruled out—not on account of creep strength requirement but because iron formed a liquid eutectic with uranium at this temperature.

Resort might be had, of course, to alternative materials, notably niobium, vanadium tantalum and zirconium, but not without a substantial increase in cost.

The metallurgical difficulties attendant upon the use of high reactor temperatures supported the author's choice of a very inert coolant. Indeed, at temperatures of the order considered, helium was the only gaseous coolant available. The justification for the coolant selection in Table II of the paper was, however, perhaps rather over brief—and it had shown helium to great advantage by a comparison of plant systems rather than coolants.

The reactor design considerations which he (Mr. Hotchen) had mentioned belonged to the present, and as Sir Christopher Hinton had emphasized, in reactor design, their present types were probably comparable with that of the Rocket in locomotive design.

It seemed probable, therefore, that the existing metallurgical difficulties would shortly be circumvented and that the temperatures and heat ratings envisaged by Mr. Maddocks would not only be entirely practicable but substantially exceeded.

All in good time, however, for just as the status of the gas turbine in the propulsion field had now become clear, so in due time would that of the nuclear reactor. This was not a period of delay but of development, during which design techniques and the industrial availability of materials would become sufficiently settled for complete economic assessments to be made.

As Mr. Maddocks had himself pointed out, nuclear power for marine propulsion required an extensive development programme, and whilst nearing competitive running cost, it was still far outweighed on capital charge.

This paper, however, in providing both an interim analysis and an interesting forum of discussion, had clearly served the need of industry, since only in this way would most rapid advantage be taken of the momentous possibilities of nuclear power.

MR. G. B. R. FEILDEN, M.A., M.I.Mech.E., said that Mr. Maddocks had rendered a very useful service in presenting his paper.

He had obviously had to limit himself to considering relatively few types of reactor system. There were, however, as many of the audience would be aware, several hundred different types of reactor systems which were known to be possible. Some were very much better than others, of course, and the requirements of fuel and initial investment varied substantially.

The important point was that amongst the possibilities there were certain types which were suitable for operation at the temperatures postulated by the author and at higher temperatures, and some types which would not require handling of the fuel elements for long periods. He was speaking of years rather than weeks or months. The time these reactors would take to develop into practical working propositions suitable for marine use was still uncertain, but the outlook was sufficiently promising for detailed studies to be started at the present stage.

It was encouraging to hear of the thought which had already gone into design studies for possible marine power plants. An impetus would also be given to the development of nuclear power plants of moderate output from quite a different angle. He was speaking here of medium power land installations in localities where fuel costs were very high. For instance, in some of the mines in Central Africa power was generated at a cost of fourpence per unit by large Diesel-engined power stations. He suggested that, for the initial development stage, sites like this might well be the places where moderate-sized nuclear power plants would be put in. Experience gained on land, where the additional problems Mr. Pemberton had so rightly pointed out, did not arise, must be obtained before a marine installation could be contemplated. This experience would, he felt, enable the first marine nuclear power plant installations to be made with confidence.

Much had been heard about economics. This was an essential aspect, and in the present state of the art the exact cost of generating power in any specified nuclear system must depend largely on the variable cost of the fuel, which depended so much on government policy and on the state of world politics.

He also wished to mention another interesting possibility in the development of nuclear power plants. Where boiling or pressurized water reactors were considered, a very worth while increase in output and overall efficiency could be obtained by superheating the saturated steam from the reactor by the exhaust heat from an oil-burning gas turbine. In this case, a very high overall utilization of the fuel burned in the gas turbine was obtained, and the availability of a separate source of power which could be quickly put into operation independently of the reactor was a most important advantage.

He thought, however, that it could confidently be said that with some of the reactor schemes at which he had been hinting, moderate-sized nuclear power plants would compete favourably with conventional power even on present figures. The experience so gained would open the way towards a realistic assessment of the possibilities of marine applications. It was to be hoped that this country which had already paved the way in both the naval and the merchant marine applications of the gas turbine would take a similar lead in the nuclear field.

MR. G. A. PLUMMER (Member) said that at this time of year perhaps he might be allowed to continue the author's gastronomic analogy. He had indeed placed before the meeting a feast, and he was to be congratulated on the wealth of ingredients he had compounded in this feast. It provided ample food for thought, but some of the ingredients might be considered a little rich and indigestible and would require considerable mastication.

At the present time in the United Kingdom the nuclear diet was fairly plain bread in the form of natural uranium, and it would be a few years yet before enriched fuel was available for wide application in the power generating field. In the meantime, one was restricted mainly to the use of natural uranium necessitating the employment of large gas-cooled graphite moderated reactors.

In due course, however, enriched or highly fissionable fuels would inevitably be available and the author had in his paper provided a valuable review of the possibilities which merited very careful consideration. Even now it had been shown that nuclear power could compete with coal for power generation, the actual nuclear fuel cost being less. This, together with the reduction in space and weight of bunkers, and the fact that the weight of fuel was the same at the end of a voyage as at the beginning, made nuclear power an attractive proposition for the merchant navy.

As and when highly fissionable fuels became available, the field would be open for a wide range of possible reactors of comparatively small size and thus suitable for marine application. Even so, restrictions on operating temperature levels would still remain, limited mainly by the physical properties of the fuel and fuel diluents, coolants and reactor vessel materials.

He felt that the author rather summarily dismissed the use of steam as a working medium in favour of gas turbines. It would be seen from the thermal cycle chosen by him as indicated on page 116 of the paper that a gas inlet temperature of 1,400 deg. F. to the turbine was chosen. Such a high temperature would apparently indicate the requirement of employing either the liquid metal fuel reactor using uranium-bismuth solution or the sodium-cooled graphite moderated as described on page 110 of the paper.

The author, however, appeared to favour for this very high temperature cycle the gas-cooled reactor, which would seem to involve several practical difficulties, for example:

1. Bearing in mind the necessity of compact plant and therefore high neutron flux with its greater heat removal problems, it was difficult to appreciate how overheating of the fuel elements was to be avoided when using helium or, indeed, any other gas coolant.
2. Would the author indicate what gas pressure and gas velocity was envisaged through the fuel channels?
3. Would the author indicate what material might be used for the reactor pressure vessel?
4. Also, what proportion of the total power developed by the gas turbine was absorbed in the compressor? in other words, what was the ratio of gross heat output from the fuel to the shaft horsepower delivered to the propeller?

At the present time, and in the absence of information on the foregoing questions, he personally was of the opinion that the pressurized water reactor as described on page 108 or the boiling water reactor as described on page 109 of the paper, with the addition of a separately fired superheater and employing a conventional steam turbine, offered extremely attractive possibilities from the engineering and economic points of view.

Finally, he would again like to thank the author for presenting such a stimulating and, indeed, timely paper.

CDR. E. TYRRELL, R.N., said Mr. Maddocks was to be heartily congratulated on the scope and clarity of the material he had presented. It filled, for the marine engineer, a long-felt want and might enable an assessment to be made of the probable and most fruitful line of research for the ultimate introduction of nuclear power for ship propulsion.

From what had been said already and from the information available in the paper or from other sources, such as Kay and Hutchings, the pressurized water reactor seemed to offer the best chance of successful development within a reasonable time. The boiling water reactor and the homogeneous reactor were not sufficiently advanced to enable them to be considered seriously at this stage. The sodium loop reactor, with the great dangers which would attend its use should a leak and contact of sodium and water occur, seemed to be ruled out for shipboard use. From the long-term aspect Mr. Maddocks's proposals of the gas-cooled reactor coupled with a closed-cycle gas turbine plant using helium as the working fluid were undoubtedly attractive.

Shipowners had to be cautious in the use of untried machinery, as a breakdown at sea could be very costly. They would regard with concern the use of a new and untried gas-cooled reactor coupled with an equally new and untried closed-cycle gas turbine using helium, and if the use of nuclear power for ship propulsion was to be achieved in the foreseeable future, it would be necessary to use the smallest possible number of untried components in any one installation.

Previous speakers had remarked that Mr. Maddocks had failed to show that a cycle using a pressurized water reactor with a heat exchanger to generate saturated steam could show a considerable improvement if a separately fired superheater was used to raise the temperature of the steam to well-tried and conventional levels of, say, 850-950 deg. F. If this were done, the problem of using saturated steam in the steam turbine would disappear and the turbine would conform to normal modern practice.

Fig. 36 showed a separately fired superheater for a steam flow of 118,000lb. per hr. required for 16,500 s.h.p., raising the temperature of steam from 486 deg. F. to 950 deg. F.

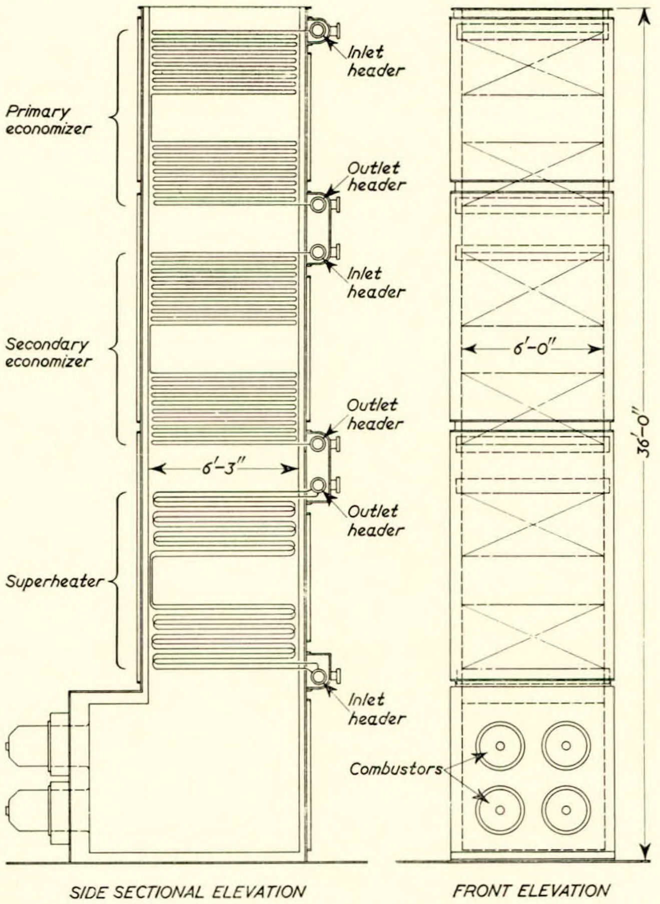

FIG. 36—*Independently-fired superheater and economizer*

Fig. 37 showed the type of burner suggested for the superheater. It was of the gas turbine can non-luminous type, and hence the problem of safeguarding the superheater against radiant heat could be dismissed. This solved one of the major problems of separately fired superheaters today. The gas turbine had been successfully developed for the combustion of heavy fuel.

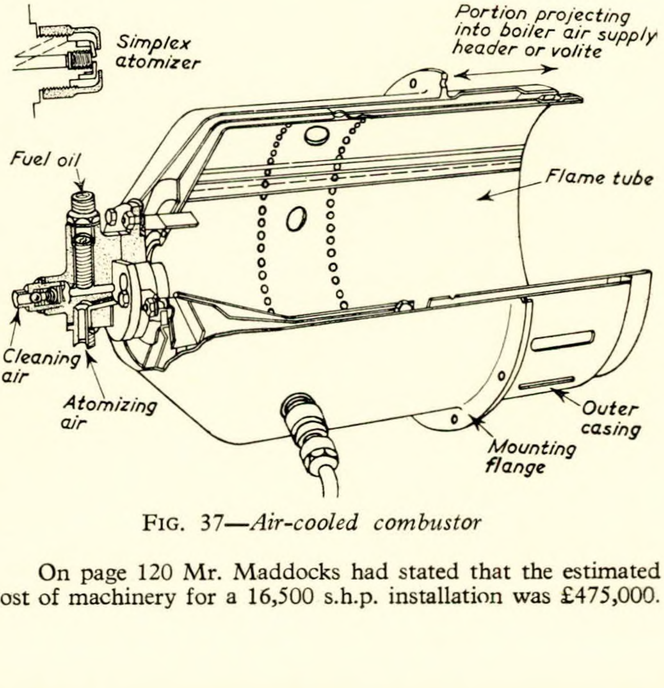

FIG. 37—*Air-cooled combustor*

On page 120 Mr. Maddocks had stated that the estimated cost of machinery for a 16,500 s.h.p. installation was £475,000.

This figure fell considerably short of the actual cost today and rather less than double would give a more realistic picture.

The cycle shown in Fig. 38, if provided with a boiler in place of the nuclear reactor and separately fired superheater, would have a fuel rate of 87·4 tons per day, as opposed to the 93·6 tons per day quoted by Mr. Maddocks. He himself had rather improved on his steam set, and that was possible in present-day knowledge. Using the boiling water reactor to supply saturated steam at 600lb. per sq. in. gauge and raising the temperature of that steam to 950 deg. F. in a separately fired superheater would require 35·9 tons of fuel per day. This would cost £11,789 for the round voyage on the assumptions made by Mr. Maddocks. It would also use 1,533 grams of the gas turbine set was quoted at 40·4 per cent. However, Mr. Maddocks stated on page 15: "The detailed estimate of the first cost of the gas-cooled reactor is outside the scope of this paper, but using the limited information available the figure of £1,000,000 agrees with the majority opinion". He would not question this figure, but the author had failed to give any information on the extra cost which would be involved in the use of the helium gas turbine, and he did not know if this had been included, but he suggested that this might well again be of the order of £1,000,000, in which case the cost of running a plant to his cycle as compared with that of the pressurized water reactor and separately fired superheater turbine set would not be dissimilar.

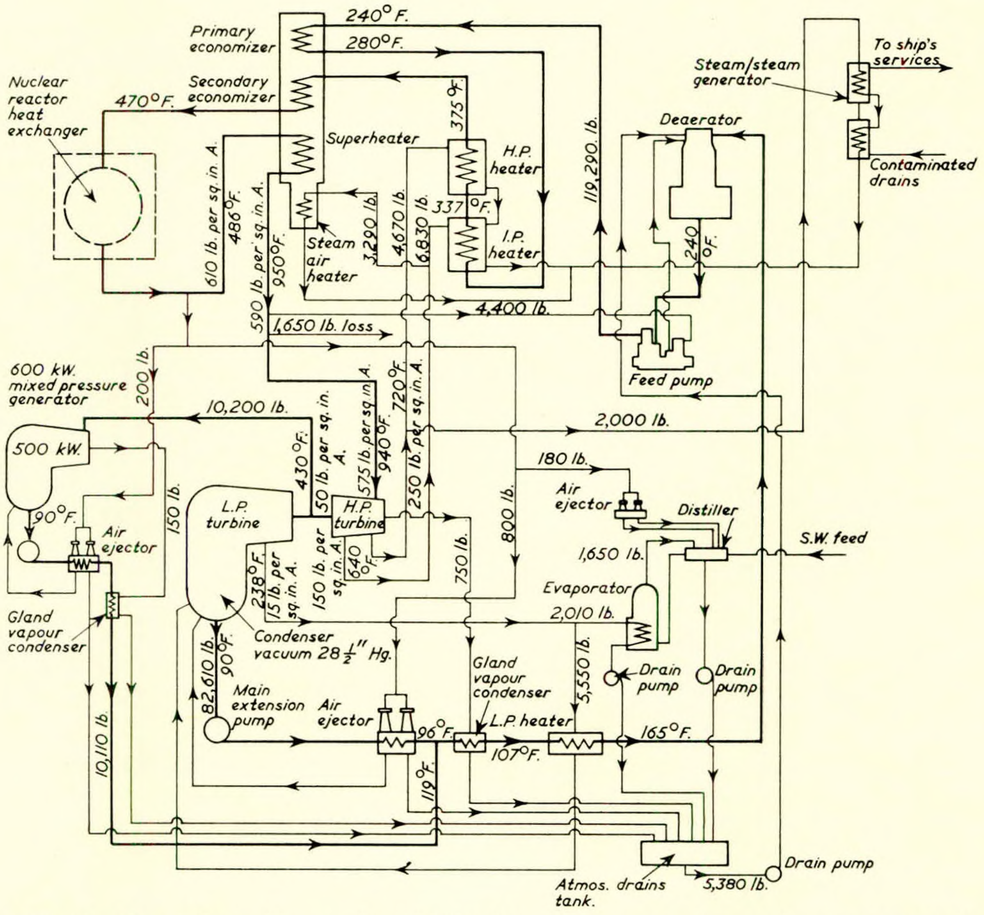

FIG. 38—*Heat balance diagram for 16,500 s.h.p. Steam generating equipment composed of pressurized water reactor and separate oil fired superheater; main turbine non-bled steam rate 5·55lb. per s.h.p. hr. allowing 97 per cent gearing efficiency*

of Uranium 235 per voyage. Once again, assuming the cost of the nuclear reactor to be £1,000,000, the Uranium 235 fuel at £x per gram equalled £26,169 + 1,559 x. To break even with the equivalent orthodox steam plant with a fuel rate of 0·494 as opposed to 0.53 as quoted by Mr. Maddocks, the cost of Uranium 235 must then be $x = £32{,}800 - \frac{£26{,}169,}{1{,}599}$ say £4 2s. 0d. per gram. The detailed calculations for this were shown in Fig. 38.

Therefore it was apparent that using more conventional methods than the helium gas turbine proposed, it would be necessary for the price of uranium to fall between one-half and one-third of its present cost before its use became an economic proposition. The difference between this figure and that quoted by Mr. Maddocks was due to the overall efficiency of the steam turbine set being 27·5 per cent while the efficiency

From the commercial aspect, therefore, the use of nuclear power for merchant vessels even using conventional machinery had nothing to offer at this stage. But he did not doubt that it would in the future. He agreed that the time had come for the Admiralty to step in and help: in this respect there were companies in this country capable of designing and building such a plant and he would add that there were also companies capable of building the ship and installing that plant.

Mr. Maddocks had several times taken care to emphasize that the use of nuclear power for ship propulsion depended upon the use of automatic controls and stated that these controls, although complex, were extremely reliable. Similar types of controls could be used to ease the watchkeeping load for engineers at sea with conventional steam turbine machinery. These controls also ensured that the machinery operated more nearly at its designed efficiency. However, this type of control had recently been rejected in some circles, and the reason given had been that the quality of engineer available at sea today was such that he was not equal to the increased complexity which automatic controls presented. This, to his mind, was a fallacious argument. The modern motor car was far more complex, had far more automatic controls, yet it was far more reliable, had better performance and was more comfortable than its counterpart of twenty or more years ago. Furthermore, he did not believe that the young men of today were inferior to those of previous generations, and given the chance to show their mettle they would respond to the faith shown in them. He had discussed this problem with seagoing engineers and the general consensus of opinion was that they preferred the machinery to be automatic in operation. The argument was that the automatics worked for 90 per cent or more of the time, and while they worked, the results were better than those that could be achieved by hand control. Seagoing engineers would prefer to have their machinery automatic and, should the automatics fail, control the machinery by hand in the normal way. The automatics could then be repaired by better qualified members of the staff.

He had made this point because it was apparent that the use of nuclear power for ship propulsion was dependent upon the proper working of just these automatics. Their use in conventional steam turbine machinery today could only result in the improvement in overall reliability and performance. If this type of automatic was introduced now and became well known and relied upon for steam turbine machinery, its eventual adoption for nuclear power would be easier and attended with fewer difficulties.

Mr. R. E. Wigg thought this paper might be considered a milestone as it was only the second to be presented in this country which attempted to justify the use of gas turbines as an economical means of converting nuclear heat into power. A closed-cycle gas turbine coupled to a gas-cooled reactor was so fundamentally simple in conception that it seemed certain that a great deal of effort would henceforward be devoted to bringing this system to reality.

For commercial applications such as the author was referring to, there would always be an economic compulsion to burn as much as possible of the naturally occurring material, U.238 or Thorium 232, and as such there would in future be a great incentive to develop reactors having a high conversion factor. A high percentage burn-up was desirable in order to stretch as far as possible the intervals between reprocessing. The homogeneous gas-cooled, and also liquid metal-cooled reactors of suitable design offered sufficient promise in these directions to warrant the carrying out of design studies of complete power plants at the present time. Such reactors could be envisaged for the heat output in question, namely about 30 MW., which would have a sufficiently high conversion factor to make them economically attractive for a variety of applications, either on shipboard or in such locations and circumstances on land as had been mentioned by Mr. Feilden.

Sufficient parallels had already been drawn with the history of technological advance in other spheres to make it superfluous for him to add that the knowledge gained as a result of the first few pioneer installations, even though these would be specially chosen ones in order to give an economic return, would, if history was to be repeated in the case of nuclear power, increase the number of applications in which it was competitive.

The development of a suitable closed-cycle gas turbine, with its controls integrated with those of the reactor, was itself a major project, and was not one which could be left to the last moment. Although some closed-cycle gas turbines already existed, there was still a great deal of design and experimental work to be done before a machine, completely leak tight, capable of sustaining rapid changes in load and coupled, as part of a harmonious whole, to a reactor (whether gas-cooled or liquid-metal cooled), could be marketed, and it seemed to be high time that active work in this country was started. Some form of secondary surface in the recuperator was essential if sizes were to be kept within bounds. This would have to withstand very high pressure differences, anything from 500 to 1,000lb. per sq. in. across the primary surface.

Fig. 39 was a comparison of heat exchanger sizes using helium and air. This emphasized Mr. Maddocks's statement about the good heat transfer characteristics of helium. The top diagram showed relative sizes of the various components for the same pressure loss in the case of air and helium. The lower diagram showed relative sizes assuming pressure losses were adjusted to give the same overall efficiency of the plant for air and helium. In each case, the saving in face area and volume should be noted, consequent upon the use of helium. It should be mentioned that the distribution of pressure loss in the various components had been chosen arbitrarily in both the upper and lower diagrams. This complicated the comparison, but did not obscure the trend.

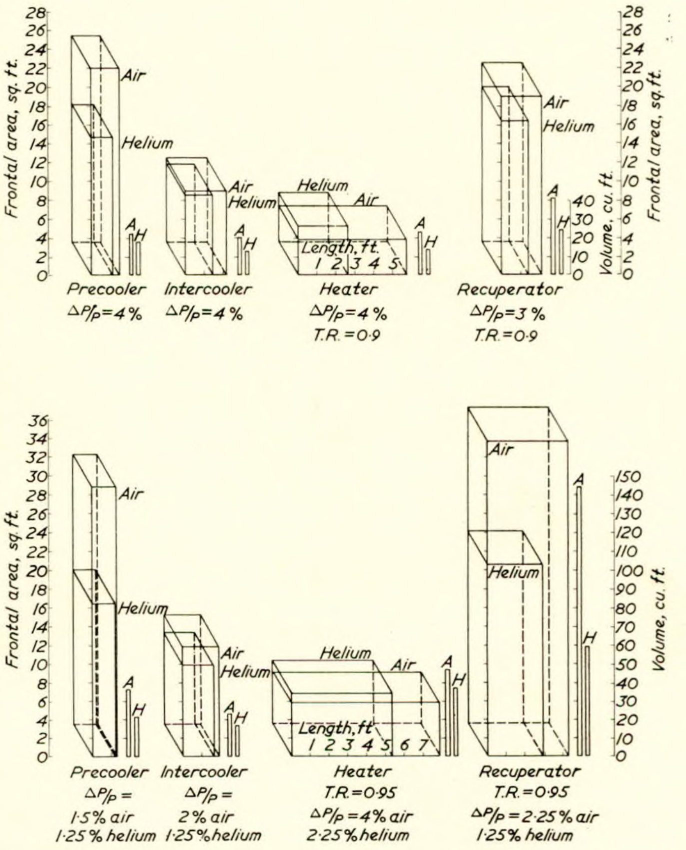

Fig. 39—*Heat exchanger matrix sizes for air and helium cycles (upper) at optimum compressor pressure ratio for maximum efficiency air compressor* $\Delta T = 210$ *deg. C.* η *overall* $= 29·5$ *per cent; helium compressor* $\Delta T = 150$ *deg. C.* η *overall* $= 26.6$ *per cent; (lower) with pressure losses adjusted to give 37 per cent overall thermal efficiency at optimum compressor pressure ratio*

Finally, Fig. 40 showed a component arrangement which might well be the ultimate in compactness. A heater was shown, making it suitable for use with a liquid metal-cooled reactor. Removal of the heater and the substitution of two ducts leading to and from a gas-cooled reactor would be even simpler. This was an original design conception by Mr. Comyns-Carr.

The general plan was that the gas turbine components

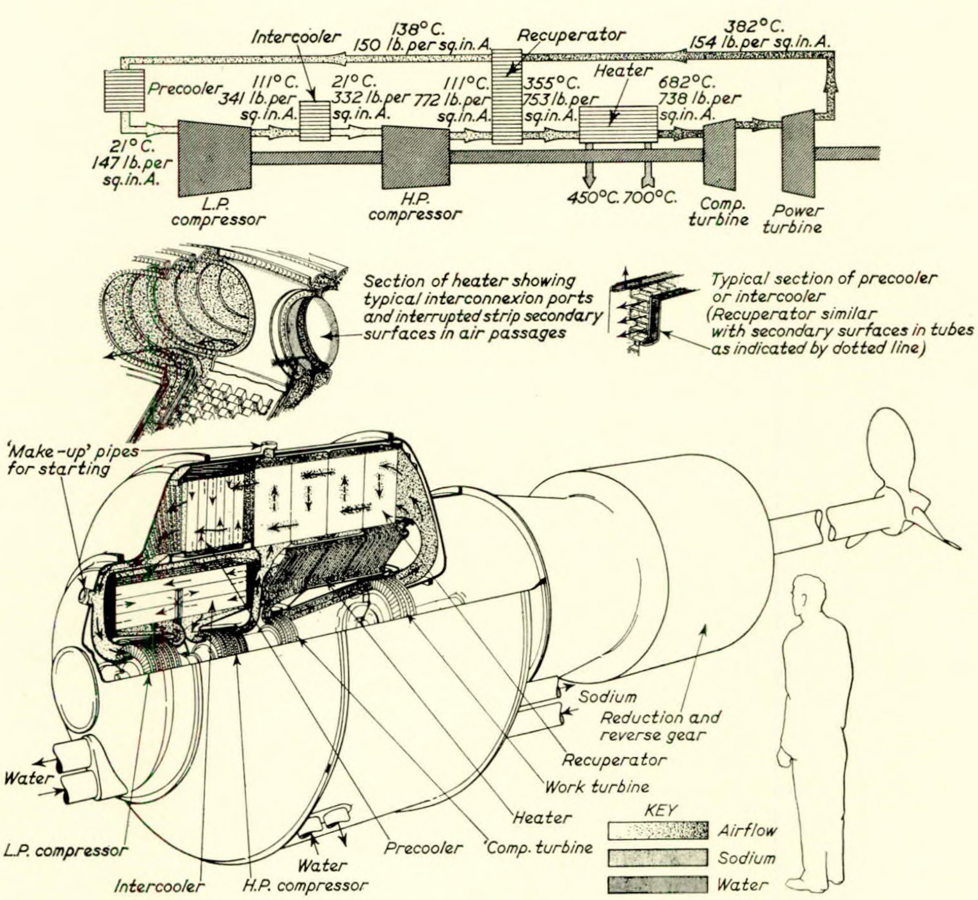

FIG. 40—*15,000-s.h.p. closed-cycle air gas turbine (air to air recuperator)*

were along the axis of the cylinder. The compressor was in two stages with an annular intercooler, delivering into an annular recuperator of the cross-flow type, with four cross-flow passes on the high-pressure side. An annular heater, using sodium or other suitable alloy, led the gas from the recuperator to the compressor-driving turbine inlet. Subsequently the gas flowed through the independent power turbine and back through the recuperator to the precooler, completing the cycle.

In conclusion, he thanked Rolls-Royce, Ltd., for permission to publish Figs. 39 and 40.

MR. R. E. ZOLLER, B.SC. (Member) said the author had elected to cover such a wide field that it was impossible to criticize any of the systems other than the closed-cycle gas turbine. If a similar paper were being read on propulsion it would cover such widely differing prime movers as reciprocating engines, Diesels and steam turbines; all these would be condensed into half a paper, the remainder of which was devoted to the rather uncommon closed-cycle gas turbine. The description of the direct use of a gas turbine with an atomic pile had been criticized by Dr. Brown and subsequent speakers and little more could be said, so he would discuss the first part of the paper.

There were so many passing references to atomic piles of widely differing conception that the reader had to imagine what the author had in mind; this might account for some of the comments being irrelevant. Any paper read at this time was in the nature of being educational and some of the statements needed correction. On page 106 it might not be clear that all piles converted fertile material into fissile to varying extent. U233 was produced from Th232 in both thermal and breeder piles and one of the former was now being built at Peckskill, but the degree of conversion would be less than it would be in a breeder pile. In the same way Pu 239 was obtained from U238 in varying amounts depending upon the type of pile.

The maximum temperature of the coolant water was fixed by pile limitations and the high rate of pumping was chosen to obtain a high mean water temperature rather than to keep the rise to a minimum (see page 108). If there were 10 degrees drop between the pile and the heat exchanger this radiation would represent more heat than was usefully converted into power because the total temperature change was usually less than 50 degrees. Radiation represented only about one degree in practice.

The published output of the A.E.C. reactor at Shippingport was 200 MW of heat producing 60 MW of power with the possibility of boosting the heat output to 340 MW, when the electrical power would be 100 MW.

The sodium reactor was discussed on page 110 and freezing was mentioned. The auxiliary boiler needed would already be on most ships because there were so many uses for steam when the pile was shut down. The heat exchangers would not be large if the sodium were cooled below 1,000 deg. F. so the pumps need not handle this very hot fluid. Off load pile cooling was essential in all types and the pumps would need duplication, so it was hard to reconcile the author's hope that the Diesel auxiliary might be eliminated when the shipowner had more confidence. The reactor could be designed for the sodium-potassium eutectic similar to that used in the breeder (page 112).

The gas-cooled reactor had a greater temperature range and superheating to quite moderate temperatures was economic. Today it was possible to have steam at 600 deg. F. and this relieved the problem of high moisture in the turbine exhaust. Helium had the political disadvantage that it was unobtainable outside the United States of America in sufficient quantities for pile cooling. The impression was given that stainless steel had a low neutron absorption, which was not so in comparison with zirconium and aluminium.

The problem of control was oversimplified. A steamship could be controlled by regulating the oil supply to the furnace but in practice this was not as easy as regulating the steam pressure and other elements. In the same way an atomic ship could be controlled by moving the control rods to change power level, but this did not make the complete unit as easy to operate. The rate of gas circulation and its return temperature needed regulation to avoid cyclic temperature variations of the pile vessel and the fuel element. Most atomic power piles needed enclosing in pressure vessels that were difficult to construct and their absolute reliability would be realized only if the operating conditions were made as simple as possible.

It was unfortunate that these comments were not constructive but they were confined to those atomic piles that were described in such vague terms that more detailed discussion was not possible.

MR. D. H. ROSS said that Dr. Curt Keller had planned to attend the reading of this paper and contribute to the discussion. Unfortunately, he was unable to attend, being in America in connexion with the Cleveland Nuclear Engineering and Science Congress at this time. At Dr. Keller's suggestion, therefore, he had included some material on the historical background of the closed-cycle turbine and its place in the marine field, together with his own comments on the paper.

Professor Maddocks should be congratulated on his stimulating presentation and analysis of the nuclear power role in commercial marine propulsion. This application of the single-circuit helium cooled reactor and closed-cycle gas turbine to the commercial vessel was unique in the unclassified literature. Since in this nascent field of nuclear energy many divergent opinions were to be found, no doubt there would be some people who would not concur with the author's selection of this power plant. Therefore, it might be in order to discuss some supplementary material which helped to confirm this choice of power plant.

To gain a historical perspective, it should be noted that the marriage of the closed-cycle gas turbine and the nuclear reactor had been proposed for some time as an ideal union. The realization of this relationship had been delayed while the reactor had been developing in America and the closed-cycle turbine in Switzerland. The advantages of light gases in closed circuit turbines (including helium machines) were discussed in Keller's 1945 A.S.M.E. paper.* The discussion was based on theoretical work by Professor Ackeret of the Swiss Federal Technical Institute. "Applied Atomic Power" by Smith, Fox, Sawyer, and Austin, published in 1946, included a chapter on the use of a closed-cycle gas turbine with a nuclear reactor. The latter work also pointed out some of the advantages of employing helium as a working fluid. Extensive discussions of this plant could be found in the paper by S. T. Robinson, "The Closed Cycle Gas Turbine Nuclear Power Plant", presented at the Ceramic Information Meeting, Oak Ridge National Laboratory, in 1953, and published with restricted circulation only. Therefore many of the basic ideas had been in the public domain for a decade. In addition, the experience of firms working with the closed-cycle gas turbine for over twenty years could be readily applied to the plant.

The gas-cooled reactor working at a temperature high enough to be useful in a gas turbine cycle (650 deg. C.—800 deg. C.) was obviously the foundation of this scheme. The high temperature gas-cooled reactor (as distinct from the low temperature types such as the British Calder Hall and the French Saclay installations) had received comparatively little publicity and was, therefore, less well-known than many other forms. The success of such a reactor depended upon two items; the production of fuel and moderator elements able to withstand the temperatures involved, and the employment of a highly pressurized gas (10-100 atm.), having suitable heat transfer and neutron absorption properties.

Various types of solid homogeneous and heterogeneous fuel and moderator combinations had been proposed in Europe and America. Security and proprietary interests prevented detailed discussion on this point, but it was felt that there was no basic obstacle to prevent attainment of reactor temperatures, which would equal or exceed the requirements of a practical closed-cycle gas turbine. Obviously, the high temperature gas cooled reactor would require a type of construction which solved or bypassed the problem of natural uranium phase changes at temperatures lower than the design point envisaged here.

The technical problem of carrying away the large amount of heat from a small reactor core could be solved for the gas-cooled reactor by the use of a high pressure gas having good heat transfer properties and low thermal neutron capture cross section. Helium was outstanding in both respects and Fig. 12 of the paper should be re-examined to appreciate the extremely high film coefficients possible at the pressures involved in this design study. Swiss scientists of the nuclear energy study group, working from unclassified data, had determined that a practical core for a reactor of the type and power output discussed, need be no larger than a right circular cylinder 5 to 6 feet high and of equal diameter. The relative pressure drop, $\frac{\Delta p}{p}$, of such a reactor was in the range of 1 per cent to 2 per cent.

Programmes were underway to develop optimum turbomachinery for helium and other gases. Theoretical results to date indicated that the mechanical design of good helium machinery would be less difficult than it might appear from first principles. If the number of turbomachine stages were inversely proportional to C_p, then a helium plant would have about five times as many stages as a comparable air unit. However, when the entire plant characteristics were included in the analysis and geometric factors other than the number of stages were held constant, it appeared that the helium machine would have only about 2½ times the number of stages as the air machine. In addition, since the pressure ratio was extremely low, the helium machinery would look very much like the conventional open-cycle air types operating at higher pressure ratios. The helium plant also gave very high efficiencies, so high that the number of stages might be reduced by designing the plant to work at a pressure ratio below that of optimum efficiency, while still retaining a useful efficiency value. In the above calculations, turbomachine tip speeds for helium were limited by conservative structural criteria. The speed of sound in helium was three times that of air, however, with the consequent disappearance of gasdynamic compressibility restrictions on tip speed. Special high tip speed compressors, therefore, might be developed using titanium and advanced mechanical design. The number of stages could be reduced as a result.

The single circuit helium-cooled reactor and closed-cycle gas turbine combination was extremely attractive for reasons of simplicity, safety and high efficiency. Based on present technology, it appeared to be the optimum type of nuclear plant for many applications, particularly where space and weight were important. However, this system was not the only one in which the closed-cycle gas turbine/nuclear reactor combination could be used to advantage. There were gases other than helium which had reasonably good properties also. If nitrogen were used in an arrangement similar to the one in the design study, existing or projected air turbomachinery

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*Keller, C. 1946. "The Escher Wyss-AK Closed-Cycle Turbine, Its Actual Development and Future Prospects". Trans.A.S.M.E., Vol. 68, p. 791.

could be employed. Two loop systems with an intermediate heat exchanger were also possible.

One extremely important advantage of the closed-cycle gas turbine over its open-cycle cousin in a two-loop system was the much smaller and more effective heat exchanger possible with pressurized gas on the power plant side. Also, the circulation of a clean gas resulted in the absence of plugging, fouling, and cleaning problems, an additional advantage for two reasons. First, the clean surfaces eliminated the additional thermal resistance of a dirt film; and second, the removal of the necessity for cleaning allowed the use of tubes having small hydraulic diameter and consequent improved heat transfer characteristics. Professor F. Daniels of the University of Wisconsin had proposed a system with a reactor cooled by helium at a pressure of 10 atm. and outlet temperature of 1,300 deg. F., transferring heat to an air circuit containing the closed cycle machinery. The small dimensions of pressurized gas heat exchangers could be demonstrated by a unit calculated by Escher Wyss for Daniel's layout at 15 MW output, using 0·16-in. diameter plain tubes, not extended surface types. The tube bundle would be about 41 inches in diameter and 22·5 feet long. The use of commercial extended surfaces could reduce the length to a fraction of the figure quoted.

To gain experience with a closed-cycle gas turbine in nuclear service together with reactor types operating today, or to operate in conjunction with a breeder, a liquid sodium-cooled type of reactor could be used. The high film coefficients of liquid sodium and pressurized gases ensured small dimensions for a carefully designed heat exchanger. At present unclassified sodium-cooled reactors were working at the lower limit of temperatures that could be usefully employed in a closed-cycle gas turbine and the next stage of development was expected to bring the temperatures into the desirable working range.

The closed-cycle turbine power plant had several advantages in marine service. The system of load regulation by varying the circuit pressure level at constant temperature and speed meant that efficiency was constant with load, in theory at least. In practice the efficiency was nearly constant down to extremely low loads, say 10-20 per cent, and then began to drop off, due to the relatively large role played by mechanical and other residual losses (see Figs. 41 and 42). Further, by adjustment of the recuperator surfaces, it was possible to cause the maximum efficiency point to occur at part load (say $\frac{1}{2}$ or $\frac{1}{4}$ load) without excessive sacrifice of full load efficiency. This was of great interest for applications where most of the running time was spent at considerably less than full load. The Keller and Spillmann paper (reference 16) discussed this point and other interesting features of marine plants.

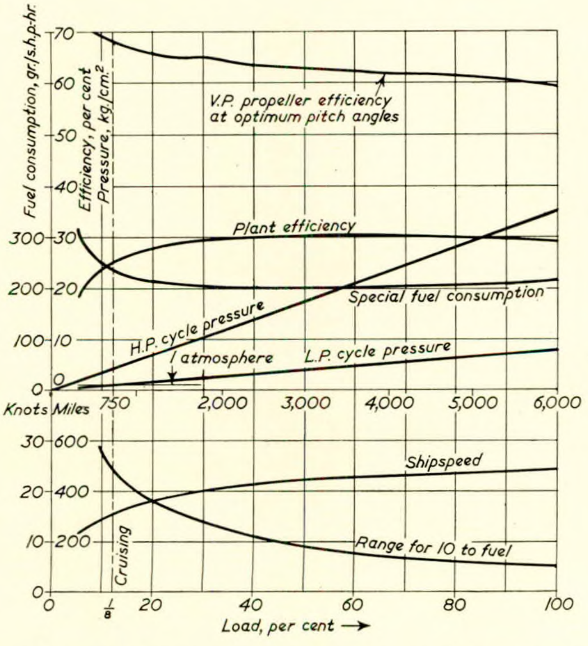

FIG. 41—*Marine vessel, with 6,000-h.p. closed cycle plant*

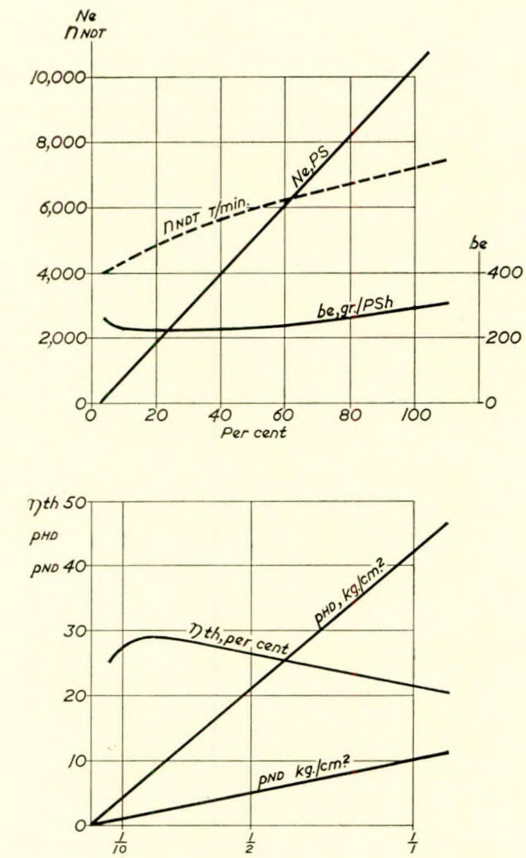

FIG. 42—*Calculated performance of a 10,000-s.h.p. closed-cycle plant for a naval vessel, the most significant characteristic being high thermal efficiency at part loads*

Fig. 43 showed a naval power plant consisting of two 10,000 h.p. closed-cycle turbomachine sets and an oil fired air heater. Note the comparatively large proportion of the machinery space occupied by the air heater. This would be replaced by a reactor in the set described by the author. Fig. 44 showed the machinery group and heat transfer apparatus of this 20,000-h.p. plant in greater detail. Fig. 45 presented the machinery group of a similar set. This cylindrical or "sausage" layout was characteristic of the marine power plants designed and studied by his company.

It was natural for the careful and frugal shipping fleet owner to examine the nuclear propulsion field with a sceptical eye. He had learned that claims for economy in operation were best proved in his account books and reliability in his log books. He could not be expected to play the role of technical innovator with his carefully balanced economic system. However, he should be prepared to recognize that new propulsion systems were being developed now which promised improved economies in direct operating cost and personnel in addition to new standards of reliability. It was believed that the closed-cycle gas turbine in combination with the nuclear reactor would eventually fit that description.

The first steps in the development of this system would almost certainly parallel that of another power plant of great promise and technical advance, the aircraft jet engine. Here

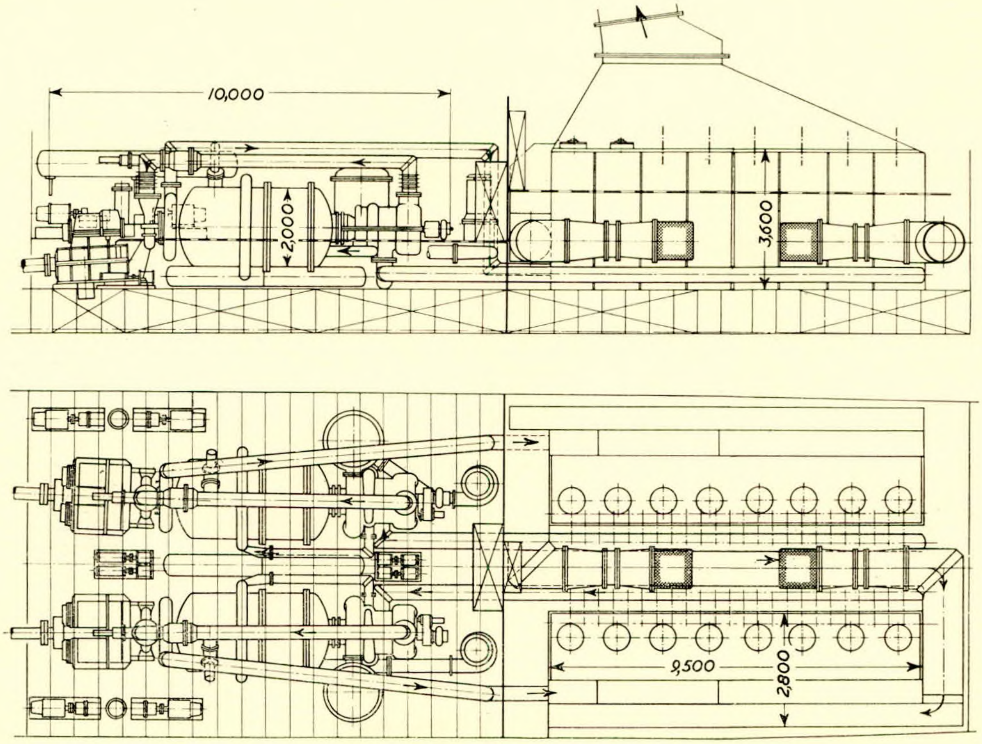

FIG. 43—*Installation of two 10,000-s.h.p. closed-cycle gas turbine plants (including oil fired air heaters) in a naval vessel*

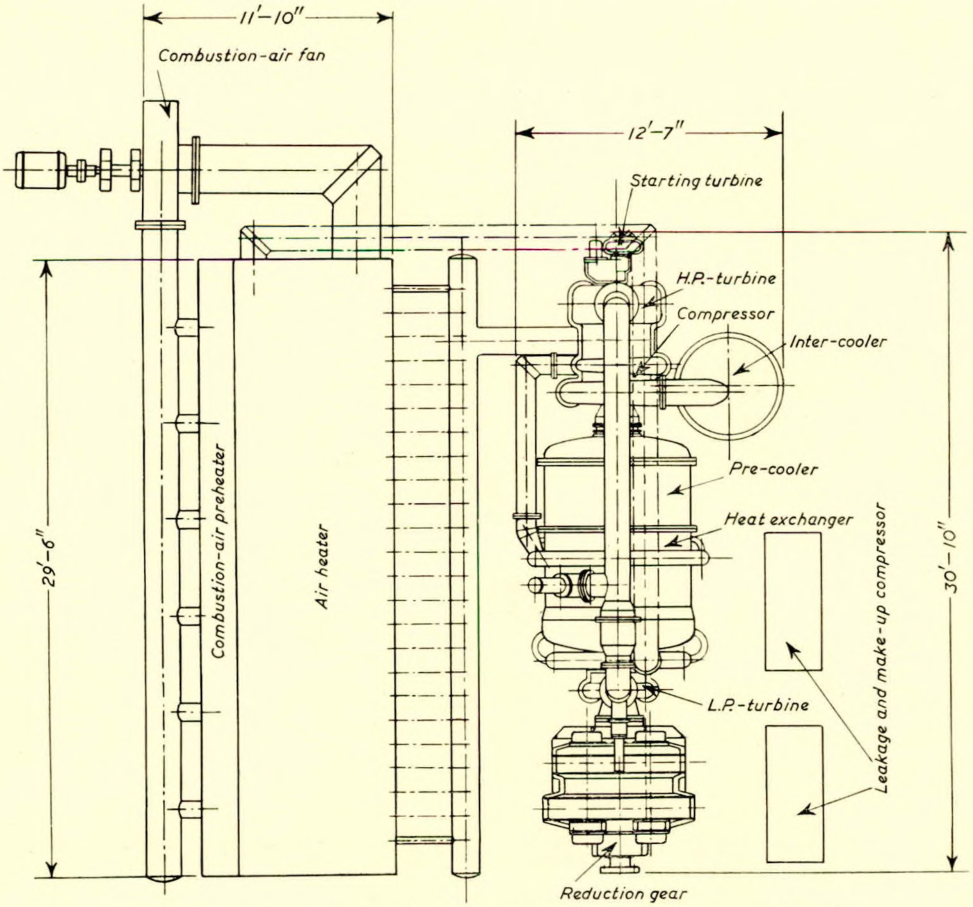

FIG. 44—*Closed-cycle set of 8,500 s.h.p. with oil fired air heater alongside*

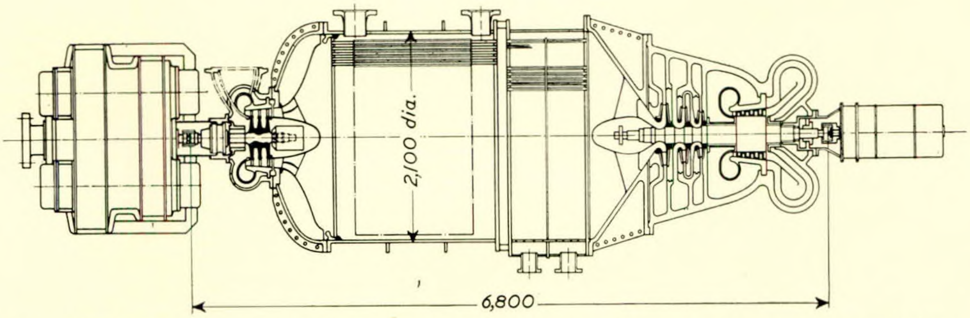

FIG. 45—*Cross section of turbomachine set and heat exchanger apparatus for a 10,000-s.h.p. marine plant. The components shown, from left to right, are: gear set, power turbine, recuperator heat exchanger, precooler, radial compressor group, high pressure turbine, and starting motor generator. Dimensions are in millimetres*

military and governmental financial support established the performance potential of the type. The sheer performance advantages resulted in substantial military procurement, thus establishing a background of experience and confidence in the power plant. Only at this stage did the dollar and cents (or pounds and shillings if preferred) operator begin to translate his dreams into functional hardware.

The naval application of the nuclear plant certainly appeared promising. Extended periods of cruising without need to refuel and increased independence from land bases were advantages any naval officer appreciated. True submarines were possible for the first time. Extensive naval experience with the nuclear power plant at sea could well serve to answer many of the questions in the mind of the commercial vessel operator.

Another, and more direct, approach was for governmental agencies to underwrite commercial vessel prototype programmes today for application to the fleets of the future. An outstanding example of this philosophy was found in the Liberty ship repowering programme of the United States Maritime Administration. This programme comprises a prototype construction and ship installation schedule involving the latest types of marine power plants. It was not too much to expect that the Maritime Administration would shortly expand its experimental programme to include nuclear power plants. This sort of governmental financial assistance and risk-taking pioneering to gain experience under actual merchant marine conditions would be followed with interest by ship constructors and fleet owners everywhere.

DR. J. E. RICHARDS (Associate Member) said he would like to stress the importance of the efficient utilization of nuclear fuels. The author contended in the introduction that "one of the main factors will be the source of supply of fissionable fuel at a reasonable price and this must probably await the actual operation of a land power station using a breeder reactor". Later in the paper he was extremely optimistic in saying fissile material might be available at a price lower than that at which uranium could be mined, processed and marketed. It was difficult to anticipate the future price of pure fissile material, but by contending that marine development must depend on the supply of fissile materials at a reasonable price, the author was being very pessimistic about the future of nuclear propulsion for merchant ships. It might be twenty or thirty years before cheap fissile material was available, and, because of the demand for other applications, doubt could be expressed as to whether it would ever be economical to burn pure fissile material in a merchant ship reactor.

In the immediate future the most inefficient and costly way of utilizing nuclear power was to burn pure fissile material as it could be used to generate new fissile material, and the author was proposing to combine what was equivalent to a poor efficiency boiler with a very high efficiency of utilization of heat energy.

Surely in considering the application of nuclear power to merchant ships it was most logical to consider first what fuel was available and what reactor could be used, before considering the prime mover in any great detail. It might well be that safety considerations would limit the choice of reactor and a discussion of the hazard involved in the use of nuclear power would have been most useful.

The paper was, in his opinion, misleading in many respects, but he confined his attention to fuel utilization because he thought that this subject was of the greatest importance at this stage of the development of nuclear power.

MR. B. E. G. FORSLING, CIV.ING. (Member), congratulated the author on an interesting paper which was of importance for the future. He proposed to restrict his observations to nuclear energy in connexion with the gas turbine, also a newcomer in the marine field.

The gas turbine as a main propulsion unit offered one advantage which the author made use of, viz. supplying the heat from the reactor directly to the working fluid of the thermodynamic cycle. As the heat exchanger was thus eliminated, a somewhat higher turbine inlet temperature could be permitted. A gas-cooled graphite moderated reactor was at present limited to a maximum gas outlet temperature of about 750 deg. F. (400 deg. C.). An inlet temperature of 1,100-1,200 deg. F. (600-650 deg. C.) was, however, required in order to make the gas turbine an attractive proposition; the author suggested 1,400 deg. F. (760 deg. C.). Could such high temperatures be considered at present, or did they represent a future expectation?

When the working fluid was heated directly by the reactor, the closed cycle must be adopted. This cycle permitted a free choice of working fluid. In this instance, however, the working fluid must be selected considering radioactivity as well as thermodynamic properties. In view of its importance, he wished to deal with the choice of working fluid, particularly the implications of using helium.

Simple expressions could be obtained for determining the pressure ratio, which gave the maximum output and the highest efficiency, by making the following simplified assumptions.

The working fluid was a perfect gas, that was to say, the specific heat was constant, the adiabatic compressor and turbine efficiencies remained constant and the pressure losses in the system were accounted for in the turbine efficiency which was reduced accordingly.

For a simple cycle with or without heat exchanger, the pressure ratio for maximum output was

$$\frac{T_a}{T_o} = \left(\frac{P_1}{P_o}\right)^{\left(\frac{\gamma - 1}{\gamma}\right)} = \sqrt{\eta_c \, \eta_t \, \frac{T_1}{T_o}}$$

where T_o = compressor inlet pressure
T_1 = turbine inlet temperature
P_o = compressor inlet temperature

P_1 = compressor exit pressure.
γ = coefficient for adiabatic expansion (assumed constant)
η_c = compressor efficiency
η_t = turbine efficiency
T_a = adiabatic temperature for pressure ratio P_1/P_0 and initial temperature T_0

It should be noted that only the optimum pressure ratio of the cycle depended upon the coefficient of the adiabatic expansion and not the temperature ratio of the compressor, which would be the same. At the optimum point the basic temperatures of the cycle, compressor inlet, compressor exit, turbine inlet and turbine exit would therefore remain the same for any ideal gas.

Assuming the compressor inlet temperature at 90 deg. F., as in the paper, the turbine inlet temperature at 1,200 deg. F., and taking two values of the efficiency product—0·72 and 0·75, representing a good and a high value for a cycle with heat exchanger, the optimum pressure ratio worked out at:

Efficiency product $\eta_c \eta_t$			0·72	0·75
One atomic gas	$\gamma = 1·67$	$\frac{P_1}{P_0} =$	2·64	2·78
Two atomic gas	1·4		3·89	4·19
Three atomic gas	1·3		5·37	5·89

These figures were used for comparison only. A more accurate estimate based on independent assessment of pressure losses and allowing for the variations of specific heat with temperature would give somewhat higher values for the optimum pressure ratio.

On the simplified assumptions the pressure ratio giving the maximum thermal efficiency was somewhat lower, the pressure ratio falling with increased heat exchanger effectiveness. If due allowance was made for the pressure drop in the heat exchanger, the maximum efficiency practically coincided with the point for maximum output for a wide range of heat exchanger effectiveness (75-50 per cent).

As the temperature throughout the cycle would be the same for any gas, the net output of the cycle would be proportionate to the product of mass flow and specific heat. If 1 mol was selected as the unit for massflow and the lower pressure of the cycle was fixed, the compressor inlet and the turbine exit volumes would be the same for any gas. (If the higher pressure of the cycle was fixed the compressor exit and the turbine inlet volumes would be the same.) The output obtainable from the cycle would thus be proportionate to molecular specific heat at constant pressure, which was 5 for a one-atomic gas, 7 for a two-atomic gas and 9 for a three-atomic gas. This meant that for the same volume flows, the one-atomic gas gave the lowest output. A two-atomic gas gave a 40 per cent and a three-atomic gas an 80 per cent larger output. The lower output with a one-atomic gas depended upon the lower pressure ratio at the same temperature ratio.

A serious drawback with helium was its low density and therefore high specific heat per unit weight. For the same cycle and temperatures the gas turbine operating on helium would therefore, as mentioned by the author, require five times as many stages as the set operating on air. This was an embarrassingly large number of stages, even if, as a compromise, a pressure ratio below optimum was adopted. If argon, which had ten times the density of helium, could be used, the number of stages would be reduced to a tenth, that was to say, half the number for the equivalent air cycle. Carbon dioxide was also an attractive working fluid.

A further objection to helium was the high price.

In the circumstances, the possibility of solving the problem of radioactivity by neutron trapping should be seriously considered in view of using argon or carbon dioxide.

Gas turbines were today operating with inlet temperatures of about 1,400 deg. F. (760 deg. C.), but as rotor and casing materials available could not withstand temperatures in this region, such high inlet temperatures in long life gas-turbine sets were always associated with a high temperature drop in at least the first stage, in combination with cooling. In gas turbines of this type some sacrifice in efficiency was unavoidable in the high temperature region and as some further loss in power resulted from the use of air (working fluid) for cooling, aiming at such a high turbine inlet temperature did not necessarily represent the best proposition. There was, in fact, a good case for adopting a turbine inlet temperature only slightly in excess of that which the material could withstand and aiming at a high turbine efficiency.

A large temperature drop in the first stage was, unfortunately, out of the question when helium was used, due to its high specific heat. A multi-stage high temperature turbine must be used and the inlet temperature therefore limited—at present to about 1,200 deg. F. (650 deg. C.), which corresponded to 1,250 deg. F. (675 deg. C.) on air.

If, however, argon could be adopted as the working fluid the number of turbine stages for the same conditions was only half of that using air. With argon it should thus be possible to operate with a high temperature drop on the first stage and still obtain a high turbine efficiency.

The effectiveness, or thermal ratio, of the heat exchanger of 92·3 per cent appeared to be rather on the high side, even for a pressurized closed cycle.

Under ideal conditions of perfect contraflow and for the same gas velocities, the heat exchanger surface became four times as large and the pressure drop quadrupled by increasing the thermal ratio from 75 per cent to 92·3 per cent. Greater departure from contraflow at very high thermal ratios and the necessity of keeping down the pressure drops led to a still larger increase in heating surface. He would therefore recommend reducing the heat exchanger to about one-quarter of the present size and fitting a low pressure steam boiler after the heat exchanger for auxiliaries and heating. This would partly offset the loss in performance due to the reduction in the thermal ratio of the heat exchanger.

If the turbine inlet temperature was lowered and the thermal ratio of the heat exchanger reduced, the thermal efficiency of the cycle would fall below the 42 per cent estimated by the author, but was such a high efficiency really necessary and would it be worth the cost and complications if it could be achieved? Overall efficiencies of 25-30 per cent were today obtainable even for comparatively small sets, using quite simple cycles and layouts. Some improvement on this figure could be expected in due course. The efficiencies which could be expected at present should be sufficient to make the gas turbine a practicable proposition. The keynote in gas turbine design for marine propulsion should be simplicity and hence improved reliability, which was of over-riding importance at sea.

In the closed gas turbine cycle variations in load could be achieved by varying the pressure levels in the cycle, maintaining constant temperatures and speeds. For a marine propulsion unit the speed of the power turbine would, of course, vary in accordance with the propeller law, which would lead to some loss in efficiency at reduced power.

This method of operation was primarily suitable for slow variations in power. During manœuvring, however, it was often required to go quickly from ahead to an appreciable torque astern. In order to achieve this by varying pressure it would be necessary to bring the pressures in the cycle right down very rapidly and then very rapidly up again. In view of the large volume in the system this did not appear to be a practicable proposition. Could the author say how the propulsion machinery was to be unloaded during rapid manœuvring? This was really a closed-cycle gas turbine problem.

MR. J. R. FRANK said that as a visitor to the Institute he felt privileged to present a contribution to the paper. The interesting discussion which the paper had provoked, together with the full attendance, were evidence of the value of this stimulating paper.

His contribution was on behalf of the Vickers-Armstrongs Nuclear Team, who had studied the paper with interest and who had the following points to contribute to the discussion.

Too much confidence had been placed in unproven techniques. An example of a practical approach to this new engineering problem was in the nuclear power station programme for the next ten years, which involved the construction of simple well-proved types of reactors, mainly graphite moderated, gas-cooled or liquid-cooled reactors using slightly enriched uranium. Experience with such reactors dated back to 1942 in the U.S.A. and to 1947 in the United Kingdom, so about twelve years elapsed before useful power was produced.

A long development period had proved necessary for the simplest reactor system and serious development work on the type of reactor envisaged by the author for his helium gas turbine system had not even started, so it was unrealistic to discuss the marine use of such an advanced system at this stage. It was true that experimental work had been carried out on gas turbines with an inlet temperature in excess of 1,400 deg. F. using a clean fuel, but considerations of safety, simplicity and reliability had always dictated the use of well-proven systems for ship propulsion. Even the oil-fired closed-cycle air turbine had not reached the stage of being accepted as a reliable prime mover for marine work, and current experience with the limited number of large closed-cycle sets had not yet given grounds for confidence in them.

The author had explained that his review of reactor types was intended for the newcomer rather than the expert, and this certainly provided a starting point for the discussion.

In the pressurized water reactor the lack of superheat was not such a disadvantage as the author claimed. There was considerable experience in the use of saturated steam in turbines, and the braking loss and erosion in the l.p. turbine could be reduced to an acceptable amount by interstage water drainage. By raising the condenser absolute pressure the diameter of the final wheels and hence the blade tip speed could be reduced, and this in turn reduced the erosion difficulties. The Team agreed with the author that erosion shields on the blades would be necessary, but there was nothing new in this.

It was considered that the first seagoing nuclear powered vessels were likely to use pressurized water systems which might be similar to the machinery fitted in the U.S.S. *Nautilus*.

A considerable effort was being directed to the development of the boiling water reactor, using either water or heavy water as working fluid. However, the variation of reactivity mentioned by the author, which resulted from the boiling process, was a serious problem. As an intermediate step it would be possible to avoid generating steam in the reactor, by passing the coolant from the reactor into a flash tank where its pressure would be reduced and steam generated. This pressure drop would increase the coolant pumping power and reduce the available work in the steam.

The advantages of the homogeneous reactor which might have been mentioned in this paper were that no fabrication of fuel elements was required, no metallic phase-change problems were involved, no structural material lay within the core, a high fuel rating could be achieved, and continuous processing of fuel and blanket was possible. However, control was more difficult than in an orthodox reactor, since delayed neutrons were lost in the external circuit, and because the solution returning from the external circuit might provide a source of reactivity whose level lagged behind the level in the core. Nevertheless, as the author pointed out, the system was inherently stable, and this was due to the positive temperature coefficient of absorption in D_2O as well as to the increase of neutron leakage consequent on a reduction of moderator density.

Control of this type of reactor was not quite as described by the author. For any given fuel concentration there was a unique temperature at which the reactivity would be unity and, whatever the power, the reactor would run at substantially this mean temperature. Increased power could be obtained merely by taking more steam from the heat exchanger and so reducing the mean temperature in the reactor for long enough to allow the flux to build up to the new desired value. The flux stabilized at a level which would maintain the reactor mean temperature constant. Temperature control was by alteration of the fuel concentration and required the use of evaporators associated with the fuel storage tanks. The latter must be designed so that, even with the coldest and most concentrated solution possible, criticality could not be attained in the tanks.

In the sodium graphite reactor the presence of large quantities of hot, highly radioactive, sodium was not likely to be welcomed on board ship and unless the problem of containment could be satisfactorily solved, it was unlikely that this type of reactor would be used at sea until it had been well proved on land.

There was a very great difference between the gas-cooled reactors at present operating and the type envisaged by the author for the helium gas turbine cycle. The Calder Hall reactors used conventional materials (slightly enriched uranium, graphite, magnesium alloy and carbon dioxide) and this imposed severe limitations on the reactor coolant outlet temperature which could be attained. To attain a temperature of 1,400 deg. F. would require the use of moderators such as beryllia together with ceramic or cermet fuel elements. The development of these materials was at such an early stage that high-temperature gas-cooled reactors were not likely to be available in the foreseeable future. Published information suggested that no reactor of this type was even in the project stage, although a design study for such a reactor was completed in the United States of America in 1949. This was known as Daniels Power Pile III and was to have been a 12 MW helium-cooled beryllia-moderated pile, using a dispersion of UO_2 in BeO as the fuel material. The gas outlet temperature was to be 1,400 deg. F.

Fig. 12 showed the heat transfer coefficients of helium and air for various Reynolds numbers, but it should be made clear that the percentage pressure drop referred to a 1-in. diameter tube 100 inches long.

Although helium was shown to be an ideal working fluid, its chief disadvantage was touched on only lightly. This was the fact that it was virtually unobtainable in this country. Even if it were available, the difficulty of maintaining a leak-proof system and of avoiding contamination of the helium would be insuperable. In order to achieve a compact plant, the minimum system pressure at full load would be of the order of 300lb. per sq. in., so that gland sealing would be difficult. Helium separation from the turbine lubricating oil would be necessary in a similar manner to the hydrogen separation on hydrogen cooled turbo-alternators. If the total compressor and turbine gland losses were only 0·001 per cent of the gas flow, the circuit would lose nearly a ton of helium on a round voyage of 48 days.

Referring to the cycle analysis, the author had chosen values of efficiency and regenerator effectiveness which if not actually unattainable were certainly optimistic. It was perhaps significant that in a similar design study carried out by Allis-Chalmers (Report NP 3683 of 1952), turbine and compressor adiabatic efficiencies of 82 per cent and 80 per cent respectively were used, together with a regenerator effectiveness of 50 per cent. Using these more cautious values in a cycle having a 3 : 1 compression ratio and a turbine inlet temperature of 1,400 deg. F., an overall efficiency of 28·5 per cent was expected. These appeared to be more realistic than the author's figures.

A few comments on the author's economic study might be worth while. One would have expected a higher rate of interest (say 4 per cent) to be applicable and, if this was so, the reactor system was penalized. Another penalty which the reactor must carry was the cost of reprocessing the fuel elements and this was not included in the analysis.

It was noted that the author applied a capital charge of 11 per cent to the cost of fuel, but this seemed unreasonable, since no allowances for depreciation and maintenance were necessary. A better figure would be about 6 per cent. This was to the benefit of the reactor system.

It would be interesting to know whether the author's estimate of £1 million for the cost of a gas-cooled reactor and heat exchanger included the cost of the initial fuel charge. Even at £8 10s. 0d. per gram (which was much lower than the price currently quoted in this country) an initial charge of 35 kg., which implied a reactor flux of about 3×10^{13}, would cost about £300,000 and would involve capital charges of about £2,200 per round voyage. An estimate of the cost of the initial helium charge and the cost of helium required to make up losses would also be of interest.

In conclusion, it should be remembered that however unfavourable the economics might seem and however formidable the technical problems appeared, it was inevitable that nuclear energy would very soon be applied to marine propulsion and the author had done a useful service in awakening the interest of marine engineers to the possibilities that lay ahead.

Commander H. T. Meadows, D.S.C., R.D., R.N.R. (Member) said that the author informed them that since Sir John Cockcroft's paper on the subject in 1953, much information had been released. He did not tell them that much progress had been made. If the figures were correct, startling progress! So startling that one wondered if any errors had occurred regarding fuel cost and minimum horse power.

Sir John Cockcroft had informed them that a very rough cost of fissile fuel would be twopence per b.h.p. per hour. From the figures given in the author's paper, he had calculated that the fuel cost was 0·4d. per s.h.p. per hour.

In "The Motor Ship" for May 1955, extracts were given from an article by Holmes F. Crouch on "Will Nuclear Fuel run Merchant Ships?" published in a recent issue of "United States Navy Service Journal". One of these extracts stated: "It has been concluded that submarines and destroyers are about the smallest practicable size for mobile nuclear power. If we discard tonnage comparisons between Naval and Merchant vessels, we can accept the submarine propulsion load as the general index to technical feasibility. Submarines of the nuclear-powered class are known to develop in the neighbourhood of 25,000 s.h.p." Tonight the author informed them that a minimum of 15,000 s.h.p. was indicated.

According to his interpretation, the shipowner who was determined to have a nuclear power plant willy-nilly had had the estimated fuel cost reduced from over £4,000 a day to £600 a day in two years. In view of this vast difference, would the author confirm the figures given in the paper for fuel consumption, and also confirm the possibility of producing such a low s.h.p. as 15,000.

The author mentioned a leakage tolerance in one of the reactors of 1 c.c. in ten years. By this, did he envisage that a reactor was to work continuously for ten years? Would it not be essential for it to be opened up for survey from time to time as in the case of pressure vessels associated with orthodox machinery? If so, could the author give any idea how long it would take the radioactivity to "cool"? Such time would have to be added to the time required for the actual survey work.

In his economical analysis the author had not mentioned insurance. It might be desirable to have on record in the discussion on this paper the information that Lloyd's underwriters were keeping abreast of the developments in this field. A paper* had been read by Mr. A. B. Stewart at the International Union of Marine Insurance Conference in September that year. The author was a Lloyd's underwriter but the views set out in the paper were his own. Having studied the information available, Mr. Stewart saw no problem or difficulty in connexion with the insurance of hulls or cargoes but said "As regards 'running down costs' and liabilities we can have further cover by separate policies, always with a limit but that limit substantial". Commander Meadows understood that "running down costs" in marine insurance was similar to third party insurance on a motor car. He presumed that further cover would require further premiums and suggested that this should be allowed for in the economic analysis.

It would seem that if developments on this subject were as great as they had been led to believe, it would be desirable to know in the not too distant future what would be the views of harbour authorities, bearing in mind the strict regulations governing tankers in some ports.

Captain H. F. Atkins, R.N. (Member) said that having worked with both steam and gas turbines, he thought he was fairly unbiased, but that it did seem to him for the reasons so clearly stated by Dr. Brown, Lt.-Cdr. Righton and other speakers, the cooling fluid leaving the pile would for some years yet be limited to a temperature which made the use of a gas turbine unprofitable if not impossible. The attempt to justify the author's use of 1,500 deg. F. reactor outlet temperature from behind a security smoke screen was quite unconvincing, as all information released to date suggested that reliable reactors could at present operate at only about half that reactor outlet temperature.

In this field, it would seem that the steam turbine was likely to have a long lease of future life. The stupidity of people speaking of "steam radio", as though steam were out-of-date was again made obvious.

The Royal Navy was very interested in the nuclear power submarine. It was imperative to build some at once, as the best, if not the only, counter to an enemy nuclear submarine.

So far, the merchant navy requirement had been studied as something different, but he would like to suggest that in fact they were the same. Everyone would be aware that to propel a vessel submerged, if she were designed only for submerged operation, required only about half the h.p. for the same tonnage and speed. He would suggest that in the future one must look forward to cargo vessels being submarine and passengers prone to seasickness might prefer to cross the ocean in the calm waters beneath the waves.

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*Stewart, A. B. 1956. "Nuclear Fission". Report of the Conference of the International Union of Marine Insurance, Monte Carlo, September 1955.

Correspondence

Professor Harry Benford, B.S.E., considered that Professor Maddocks's timely paper represented a valuable addition to the growing fund of material relative to nuclear propulsion of merchant ships.

There was today a clear realization among ship operators and designers that nuclear power was not only looming over the horizon, but was coming at them, whether they liked it or not, at full gallop. There were certain trade routes which were conducive to economic use of the new energy source. If expected advances in atomic knowledge were realized, conventional machinery might be non-competitive in less than a dozen years on such routes. In the meantime, it behove them to learn what they could about nuclear power.

Their governments could be of real assistance in aiding their marine industries in the move towards nuclear power. The two principal directions of such aid should be to remove as quickly as possible all useless restrictions on the dissemination of knowledge and to provide financial backing for the construction of experimental ships.

Nuclear engineers must continue their work along the lines of increasing the overall plant efficiency. They must also begin to think in terms of money economy. Drastic reductions in construction costs and nuclear fuel costs must be made before nuclear power could hope to overtake present-day Diesel or steam turbine economies. No one could doubt that these cost reductions would eventually be achieved. The only question now was the matter of time. If they continued to follow the military lead they would find themselves forever removed from economic realities. Commercial interests must develop their own reactor concepts and go their own independent way, and be prepared to spend money and make a few mistakes in so doing.

There were one or two very minor points which he wished to call to the author's attention:

(1) Since the limits on draught were set by the Suez Canal, the bunker oil consumed on the way there from the oil fields could not be credited as extra pay load available to the nuclear plant. This would reduce the author's figure from 4,500 tons to about 3,300 tons.

(2) In the carriage of crude oil, it was frequently found desirable to take on bunkers either at the discharge port alone or at both ends of the run. Bunker oil was of course cheapest at the refinery itself. Alternatively, bunker oil might be taken on at Sidon or other Mediterranean ports after clearing the Suez Canal.

While these reservations would change the economic picture somewhat, their overall influence would be slight and would in no way alter the general picture.

MR. F. D. BRAND wished to comment on Mr. Harvey's point concerning the "hotel" services of the vessel. Had the author taken into consideration in his estimated costs the necessity for providing some form of auxiliary boiler for port use?

With the steam turbine proposal it would be possible to make use of pass-out steam for the provision of hot water or steam for the space heating, galley and domestic requirements included in the normal hotel services of the vessel.

However, with the closed-cycle helium gas turbine proposal this heat form would not be available unless heat from the intercoolers and heat exchanger could be utilized, although it would appear from previous speakers' points that for safety reasons this would not be acceptable.

Even in the case of the steam turbine proposal it would be necessary to provide a donkey boiler for port use when obviously the reactor and turbine would be inoperative.

Perhaps it was considered that these services could be provided by electric generation, using the Diesel alternators, in which case space heating and galley requirements could be by electric heaters and cookers and the domestic hot water requirements supplied by waste heat recovery from the Diesel exhaust.

MR. G. H. CORNISH, B.Eng. (Member) thought they should be grateful to Mr. Maddocks for having ploughed through the great mass of published information to produce this survey of reactor types suitable for the propulsion of merchant ships. To the designer, two most important factors were temperature and pressure. The limiting temperature was that of the fuel and its can. Hence the gas-cooled reactor was at a disadvantage, particularly where space was limited. The water-cooled reactors had the advantage of higher heat release rates but operated at high pressure. Reactor vessels were designed for these pressures but they were more complicated structures than boiler steam drums.

It was thought, therefore, that more consideration should be given to the sodium loop type of reactor. This offered high temperatures at pressures below 50lb. per sq. in gauge.

At first sight, the presence of sodium at sea might appear to be a major fire hazard. This was not necessarily so. In recent years the technique of welding stainless steel had been brought to a very high standard. A sodium loop circulated by an electro magnetic pump was a very reliable piece of equipment. It had no impeller, no valves, and no glands. Therefore it did not present a maintenance problem. The oxide was corrosive but sodium itself was not, hence a closed system with an inert gas blanket did not suffer corrosion.

The author's reference to pumping liquid metal at 1,000 deg. F. was a bit misleading, as also was the statement that an electro-magnetic pump had a low efficiency. The pump did not handle high temperature metal, because it was placed at the inlet to the reactor. The temperature was tied to that of the economizer inlet and might be 400 deg. F. It was true that the efficiency of an electro-magnetic pump was only about 30 per cent but in this application it was of little importance because the loss appeared as heat which entered the liquid metal and so was returned to the system. In a sodium system, as Mr. Maddocks pointed out, a separate source of heat must be available for starting up. It was possible, however, to operate with an alloy of sodium and potassium which was liquid at 60 deg. F. This involved some reduction in reactor output, but the resultant simplification in operation might make it worth while for shipboard use.

He greatly admired Mr. Maddocks because he was one of the first men brave enough to discuss the question of cost. No matter how interesting a topic might be it rarely received serious attention until somebody started to talk about the price. The present assessment must be treated with reserve, however, because the assumed "burn up" of 25 per cent for a heterogeneous reactor was higher than they could expect to achieve in their present state of knowledge. This of course was reflected in the capital investment. The assessment had nevertheless performed a very useful function in bringing to their attention the fact that a nuclear powered vessel might be economically possible as well as physically possible.

CAPT.(E) N. J. H. D'ARCY, R.N.(ret.) (Member) asked whether the author could tell them what rate of increase of power and what rate of decrease of power was practicable with modern designs of reactors. What was the minimum output at which the reactor would continue to function? Or, put in another way, could a reactor be completely shut down without recourse to cooling?

In the various steam cycles described there was a good deal of mechanism within the radiation shield. This machinery would be inaccessible whilst the core was in place and perhaps for some time after its removal. He concluded, therefore, that atomic engineers had either evolved machinery which was one hundred per cent reliable and required no attention whatever between core changes, or were they perhaps over-optimistic in this respect? If such machinery could be absolutely depended upon to function exactly as required for as long as required without attention, what new principles of machine designs had been evolved and could these be applied to the more prosaic machinery which they were installing at the present time?

In the event of the reactor being broken open as a result of collision, stranding or war damage, what were the additional hazards to be expected, especially if the damage occurred in harbour?

MR. S. H. DUNLOP (Member) wrote that the author had outlined in a detailed fashion the numerous prospects for the development of nuclear power in the marine sphere. Its application as an economical proposition had limitations and the theoretical conclusions confined this application to specified trades and tonnage. This restricted application narrowed its interest and it was logical to suggest that the acknowledged propulsion units would predominate so long as the conventional fuel supplies were available.

The research field was travelling so rapidly it was proving difficult for the practician to assimilate the facts necessary for the production of a simple, reliable and economical nuclear marine unit.

The paper had succeeded in bringing practical perspective to the wealth of information released this year under their declassifying arrangement with the United States and Canada. Of the many possible reactor designs he had ably selected five of the twelve best known types for a rational assessment of their marine merits and demerits. His final choice of the moderated gas-cooled reactor accorded with British policy and the proposed 300-ton marine reactor was of this type and would contain about 7 tons of enriched uranium, costing £300,000, with an effective life of three years and a heat rating of 35 megawatts.

More controversial was the author's preference for the gas turbine, which had yet to find favour in marine practice; moreover, he proposed an ambitious form. Although the cycle efficiency of 42 per cent was attractive, an objection to helium was that it became toxic when irradiated and complete sealing was scarcely attainable. Argon and neon, which had low specific heats, might warrant investigation; also, they were more plentiful and less costly. An impressive feature was the high efficiency of the recuperator or heat exchanger, which conferred a temperature increment of 675 deg. F. on the gas passing to the reactor. Were such recuperators already in use? The comprehensive analysis of the system as a whole was most useful.

While a high temperature system must remain the final objective, development should proceed on the principle of walls before roof and experience with a nuclear powered merchantman fitted with large saturated steam turbines should be the first aim. With such a vessel at sea the first task would be to make it reliable and safe, and this experience would allow of the development of more advanced installations. Only when the development hurdle had been cleared would operating costs become the dominant factor. Nuclear prototyping was expensive, the annual cost of studying a reactor being £300,000, apart from the high cost of machinery. The British Atomic Energy Authority was spending large amounts on pioneering nuclear power plant and could undertake parallel development at sea through the marine scientific institutions. In showing that nuclear operating costs would be comparable with those for oil powering, the author did not take into account the credit value of £300 per oz. for the plutonium generated. Publications suggested that this allowance would reduce the cost of power from 0·76d. per unit to 0·6d. per unit. Eventually, atomic power would have to be made economic for shorter voyages and for freighters of the 10,000-ton class, calling for fast breeder reactors such as the Detroit-Edison type. Meanwhile, all must be impressed by the calculated equivalence of 4·35lb. of uranium-235 to 4,350 tons of fuel oil.

Concerning the availability of nuclear fuel, any temporary shortage in this country applied less to natural uranium than to the enriched form, which was required in quantity for the land power reactors. The plutonium generated in these plants would be used in the later reactors, but within the next five years, without waiting for fast-breeder reactors, supplies of enriched fuel would be ample. Already, the United States and Britain alike were prepared to supply fuel for exported nuclear power plant. With regard to the suggested terminal facilities for handling radioactive material it might prove as satisfactory to go for three years without refuelling as to change a few elements at a time. Distortion of the elements might be overcome by using uranium oxide in place of uranium metal.

Normally, the energy provided by the nuclear reactor would cover all requirements, but there were strong arguments for fitting an auxiliary Diesel generator for emergency purposes and for use in port during general overhaul of auxiliary units.

The author had brought nuclear power for merchant ships a stage nearer and they were indebted to him for his stimulating investigation.

Mr. A. F. Harrold, B.Sc. (Associate) thought the methods for handling replenishment and spent fuel and waste products were likely to be complicated and expensive. For ships engaged in world-wide trade such as tankers, this was likely to be an important consideration and the steaming range offered by a given reactor design became a vital factor. It was assumed that an extensive network of bunkering stations as now operated by the oil companies would not be required. However, widely varying statements regarding the steaming range to be expected had been made and while the author appeared to base his proposals on a voyage of 10,000 miles it was felt that great advantages would accrue in being able to carry sufficient fuel to steam a vessel between annual dry-docking periods.

Automation and instrumentation were essential to the operation of nuclear plant and these factors need not constitute a deterrent. It was significant in this respect, however, that while automatic combustion control equipment was now standard on high pressure boilers it was still necessary to have a telegraph in the stokehold and successful manœuvring was largely dependent on speedy response in the lighting and extinguishing of burners by the boiler operator. In the case of the nuclear plant the co-ordination of controls presented a more complex problem. Could they yet be sure of control stability throughout the complete power range and response to rapid changes of load which were inevitable when manœuvring the ship?

In this connexion also it would appear that instrumentation deserved special attention. Unreliability of quite simple instruments on board ship was still a common experience and in this case, where instrumentation would be vital to the safety of both ship and personnel, the importance of proving durability and reliability of instruments for shipboard use needed to be emphasized.

Detailed design to achieve a leakproof installation would be one of the major problems associated with a helium turbine. In this connexion mention might be made of the quality of castings which would be required and the frequency with which porous castings were still encountered when using strictly conventional steam pressures and temperatures suggested that higher casting specifications would be called for.

Mr. M. P. Holdsworth, M.Eng. (Associate Member), having been unable to contribute to the verbal discussion due to the lateness of the hour, took the liberty of reviewing the occasion.

The paper and subsequent discussion constituted probably one of the more unusual meetings held by the Institute. Unusual in that an air of mystery permeated the whole proceedings, which, in other circles, might well have been entitled "The Case of the Missing Reactor".

The mystery was first apparent in the paper itself, from which two alternatives arose. Either the author, at the time of writing, did not know of any reactor design which might produce reliably such high temperatures as were demanded by his gas turbine proposal; or, alternatively, he did know and was prevented by security or proprietary reasons from even mentioning the fact.

From a rereading of the paper one was left with a distinct impression that the former might be true. For even the barest assurance that such a reactor was possible, or shortly would be possible, would have done much to allay the feelings of even the well-informed contributors that Mr. Maddocks was ten to fifteen years too early with his gas turbine proposals.

Had the author been able to give this assurance the paper would have been less incomplete and his proposals immediately attractive. Then, surely, he would not have needed to be at such pains to show gas cooling in so favourable a light.

For instance, in Table II helium was made out to be a most superior coolant for a submarine reactor. Some explanation might have been given at this point why sodium cooling had been chosen for the *Sea Wolf* and subsequent boats.

Further, on page 111, the author stated "The gas-cooled reactor, as indicated in the recent White Paper, is Britain's choice for development as a power reactor ashore." Mr. Maddocks, however, did not quote paragraph 12 from that same White Paper, which reads: "Developments in reactor design such as the introduction of liquid cooling should gradually lead to much higher heat ratings without much increase in capital cost. This would reduce still further the capital cost per kilowatt and thus reduce the overheads". This attitude that gas cooling was a presently reliable but only temporary stage in reactor development was confirmed by authoritative speakers at the recent first meeting of the British Nuclear Power Conference.

In his introductory remarks the author did nothing to dispel these impressions and studiously avoided mentioning the reactor, other than briefly illustrating its possible position in the ship.

The mystery was then further deepened by the fact that it was left to a little known (but welcome) visitor to give some information about this high temperature reactor of revolutionary design.

From a search of current declassified literature from both sides of the Atlantic and from the contributions of their few well-informed members it seemed certain that little or nothing generally could so far be known or published on this design. The Institute could congratulate itself, therefore, that the first general release of information of such far reaching import had been made within its walls.

If what Mr. Ross had said was true, then Mr. Maddocks had done great service in putting forward his gas turbine proposals for early consideration and development. However, it surely now behoved Mr. Maddocks, in his reply, to come out into the open and tell as much as he knew about the high temperature reactor. For unless his paper was rounded off in this way and the mystery of the missing reactor clarified, he feared the author's express intention of reducing the conservatism of the present-day outlook in nuclear and marine engineering circles would not be realized. Indeed, the general suspicion that safe and economic nuclear propulsion was still far in the future might well be deepened.

Coming from the general to the particular, he would ask the author to clarify his section headed "Estimate of U235 Burn-up during Voyage". As it stood, this section appeared to be misleading in two aspects. Firstly, no allowance seemed to be made for the fissionable material bred in, and remaining in, fuel elements returned for reprocessing. It was realized that the extent of such allowances must still be guesswork but their ultimate value would be considerable and, in time, should reduce the effective cost of fuel approximately down to the cost of reprocessing and refabrication of fuel elements. Secondly, this section might give the impression that the total fuel carried in the reactor was of the order of 6 to 8 kg. While such a reactor was no doubt a possibility, the very small core would greatly increase the already immense heat transfer problem and, unless the reactor was a circulating homogeneous one with full shipboard reprocessing, the whole fuel would require to be removed and replaced once each voyage even on the author's futuristic figure of 25 per cent burn-up. It seemed likely, therefore, that the fuel investment of the reactor would be many times 6 kg.

MR. H. KAY, B.Sc. (Associate Member) thought his principal remarks and questions regarding the gas-cooled reactor proposed by the author were adequately covered by other speakers during the discussion which followed the reading of the paper in London, and he looked forward to the author giving in his replies more details of the core of his proposed high temperature, heterogeneous reactor with approximate weights and dimensions of the core, pressure vessel and biological shield.

In view of the interest taken in this paper he would add a word of warning regarding the author's figures on the economics of the system. Under the heading "Estimate of U.235 Burn-up during Voyage", the author gave 1,954 grams fissile material as the "burn-up" during the voyage and implied that the reactor would go critical on less than 6 kilograms of fissile material and that the fuel was changed and processed every forty-eight days—a costly business. Processing and refabrication costs were not readily available but figures in a paper* read by J. A. Jukes at the international conference held in Geneva appeared to suggest that £3 per gram of fissile material would be a reasonably low figure for reprocessing fuel elements. Using this value the author's calculations might read:

Fixed charges =

£

$$\frac{48 \times 11}{365 \times 100}(1,000,000 + 5,862x) = 14,480 + 85x$$

Reprocessing 5,862 gm. at £3 per gm. = 17,586

Fuel at £x per gram = $1,954x$

$32,066 + 2,039x$

To "break even" with the equivalent orthodox steam plant, the U235 must be obtained free of charge.

He did not for one moment suggest that this was a true statement or that nuclear power could not be competitive in the marine field. He contended that the author's approach to fuel utilization and his method of calculating running costs were wrong and his figures misleading. Unfortunately, it was not possible to prepare an alternative set of figures without knowing the details and nuclear characteristics of the reactor.

MR. I. SWIECICKI was gratified to note that the author considered the controllable-pitch propeller to be the most promising line of development for the future in the application of nuclear powered closed-cycle helium turbines for marine propulsion.

While it was true that no one had yet experienced satisfactory operation with a controllable-pitch propeller utilizing as much as 16,500 s.h.p., it should be pointed out that there was no practical limit in size which would not also apply to fixed-pitch propellers. Actually, machining and transportation limits would favour the manufacture and shipment of large controllable-pitch propellers. His company's extensive experience with large diameter Kaplan adjustable-blade hydraulic turbines was the basis for these statements.

The writer's company was prepared to design and build controllable-pitch propellers for any foreseeable physical size or horsepower rating. Strength considerations and the blade pitching mechanism required a larger hub than would be incorporated in a comparable fixed-pitch propeller design.

However, the various blade design details could be so adjusted for this larger hub that the hydraulic performance at any given pitch was as good as for a fixed-pitch propeller with a smaller hub.

The failure to transmit 14,000 s.h.p. with a controllable-pitch propeller on an American vessel (the destroyer *Dahlgren*) should not be attributed to the pitching mechanism but to the basic blade design. A fixed-pitch propeller with the same design of blades set at maximum pitch would also have failed to transmit the full engine capacity. The difficulty was due to the high blade loading for a propeller only 8·5 feet in diameter, and this would not be a factor in the case of a propeller 22 feet in diameter transmitting 16,500 s.h.p.

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*Jukes, J. A., August 1955. "P.390—The Cost of Power and the Value of Plutonium from Early Nuclear Power Stations". Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva. (Not yet published.)

Author's Reply

The response to this paper had far exceeded that anticipated at the time of writing and the author was grateful to the gentlemen who so ably contributed to the comprehensive discussion. As the paper had received such wide publicity and the subject matter proved so controversial in nature, a brief review of the origin of the paper should first be made to obtain the correct perspective before dealing with the specific questions raised.

The author at no time had access to classified material and had no connexion with any of the commercial organizations referred to in the paper. Thus the opinions expressed were not hampered by security restrictions and remained a personal responsibility. In undertaking this survey of such a wide field, errors and omissions occurred which it was hoped would be minimized as a result of the discussion. One of the main reasons for selecting a particular plant as most suitable for marine application was to be objective in providing a forum for discussion rather than to impose a dogma. More specifically, an attempt was made to prevent the mistaken impression that the terms "marine nuclear power plant" and "pressurized water reactor" were necessarily synonymous; although, in view of the majority opinion, it would appear that the pressurized water reactor was in fact the most probable line for immediate development. The paper was in no way intended even to approximate to the design study which must precede a more serious consideration of any nuclear power plant. As stated in the conclusion, such a design study required the combined efforts of a team of specialists and therefore the many additions and refinements suggested, while invaluable for future work, must remain in abeyance.

A time background had been superimposed into this survey in discussing development possibilities and it was significant to remember that at the time of writing the author had not been in personal contact with the British marine industry for over two years and it was difficult to assess from the scant literature available what lines of thought, if any, had already been devoted to this subject. He was pleased to acknowledge that the discussion had indicated that his original assumptions were over-pessimistic.

It was admitted that the paper was written in a manner calculated to arouse controversy for the reasons outlined above. Having incited this bombardment, it now remained to apply moderating action in the hope that the final publication would provide a report as complete as possible at the present stage of development.

Mr. Pemberton fortunately picked out the main point of the paper in emphasizing that the time had arrived for marine engineers to make a serious study of nuclear energy for ship propulsion. Later contributions confirmed that such study was at present under way for naval application. It would be a pity and indeed a folly if, as Mr. Pemberton suggested, ten years should elapse before British merchant shipowners considered the matter seriously. The solution of the very problems Mr. Pemberton mentioned, viz. safety, maintenance and repair, could no doubt be assisted by the results of naval development work, but each would have angles peculiar to commercial practice. Health protection and other safety problems were discussed at length in a recent publication(33) by the United States Government Printing Office.

Mr. Pemberton's extract from Lloyd's Register of Shipping could not be challenged, but it should be emphasized that the 5·8 per cent referred to the number of vessels, all in the top horsepower bracket and presumably on long voyages. It therefore did not follow, as was suggested, that the saving in fuel consumption would be comparatively small if these ships were converted to nuclear power. A more relevant survey to demonstrate the advantages of the conversion would require computation of the weight of bunkers carried.

The author concurred that an international convention would be necessary to formulate the code outlining the attitude of port and canal authorities to the use of facilities by nuclear powered ships. The necessity for such an agreement was now established and such negotiations were bound to require ample time, thus there seemed to be no justification for delay in action.

Dr. Brown's contribution first criticized the apparent weakness of the case outlined for the closed-cycle helium plant and then added an alternative scheme using the steam turbine. Both provided authoritative suggestions for future development. The criticism, based on present day standards, was in the main quite valid. It was never intended, however, that the proposals made should be considered to justify such prompt action.

The author agreed that the lack of details of a reactor suitable for supplying gas to the turbine at 1,400 deg. F. might be considered a serious defect in the paper. As confirmed by Messrs. Fielden, Wigg and Ross, such a reactor was quite a feasible proposition. It now appeared that either the fissioning liquid metal type or fluidized bed type of reactor would eventually be suitable for this service even if the design problems associated with the better known types proved insurmountable. Referring to the former, the author was indebted to Mr. Lincoln Stoughton of Brookhaven National Laboratory for permission to refer to a recent communication on the experimental work on LMFR at Brookhaven (see reference 33, Table VII). Their present work was directed towards 1,050 deg. F. top temperature for use with a steam cycle, but they visualized that this reactor would be capable of combination with a closed-cycle gas turbine plant operating at the temperatures proposed in the paper, pending further work on the fuel container as described in the following verbatim extract from the letter: —

". . . . .The problem at elevated temperature is not with the fuel itself (a solution of uranium in liquid bismuth) but rather with the container material for the fuel. We visualize a number of possible approaches: (1) pass the cycle working fluid directly through the reactor core or (2) circulate the liquid fuel outside the core to a heat exchanger wherein the cycle working fluid may be heated.

In case (1) the graphite moderator acts as a barrier between the fuel and the cycle working fluid. Our only experimental work to date at 1,800 deg. F. has indicated that the use of inhibitors will prevent any reaction between the graphite and uranium, bismuth, or fission products under non-radioactive conditions. In case (2) a metallic tube wall is visualized as the barrier between the liquid fuel and the power plant working fluid. The tube wall obviously must withstand corrosion and have suitable strength for this case. It is believed that a combination of either a low chrome ferritic steel (presently being studied by BNL), molybdenum or tantalum for corrosion resistance with an austenitic steel for strength would make a suitable tube wall. This matter is not at present being investigated by BNL. . . . ."

Meanwhile, Mr. Ross's figure of approximately 160 cu. ft. for the core volume of a high pressure gas-cooled reactor agreed with the layout shown in Figs. 28 and 29.

An electric drive was suggested for use with the gas turbine and this would largely invalidate Dr. Brown's criticism of reduced efficiency at reduced powers. The point was not likely to be of major consequence in tanker operation.

The cost of nuclear fuel quoted in the paper was assumed to apply to all degrees of enrichment of uranium, not merely pure U235. Since it was the 235 isotope which immediately fissioned, it was considered reasonable to base the price of the whole on the U235 content. The authoritative opinions now expressed during the discussion all inclined to the view that the cost figure used was too low.

The author agreed with Dr. Brown's preference for the use of a separate oil fired superheater in conjunction with a water-cooled reactor rather than accept the problems inherent with the use of wet steam. Dr. Brown suggested the use of a 10,000-s.h.p. set of machinery which presumably would require a total heat supply of say 30 MW. The required output from the pressurized water reactor would be 24 MW. The author suspected that a reactor designed for such a low output would be unduly penalized in first cost as the cost of general construction, control gear and instrumentation would probably not vary appreciably for reactors within range of power outputs up to say 40 MW.

Lieut.-Commander Righton's comments on reactor and turbine design were appreciated and would materially assist the future evaluation of the subject. The design values used for machine efficiencies and surface effectiveness were not considered over-ambitious by the author for a long term project. Also, in discussing development policy, the author would not agree to the philosophy of eliminating one of the major advantages of the system by reducing the inlet temperature in order to circumvent the design and development problems attached to a particular reactor.

Commander Righton had surely confused the author's introductory prediction that, "Probably one, and possibly two, nuclear powered merchant ships will be in operation within the next five years", with the development period considered necessary for the closed-cycle gas turbine proposal.

While acknowledging the economy in using a high conversion factor for a mobile reactor, where minimizing weight was a prime consideration, some priority could be given to the allocation of enriched fuel to achieve this end.

Mr. Harvey's appraisal of the subject in general was in accord with that of the paper. Whether or not the Royal Navy should administer what would amount to subsidized development of a commercial vessel, was part of the problem which it was hoped would be tackled by an interested government department in the not too distant future. The author was encouraged by noting the confirmation of his opinion that a worth while design study could be commenced as soon as required.

Mr. Harvey's repetition of Dr. Brown's suggestion for a separate oil fired superheater in conjunction with the pressurized water reactor was amplified by Commander Tyrrell's contribution, which largely answered the points raised.

A variation on this proposal, which was attractive for experimental purposes with a dry cargo ship, was that an existing vessel be converted for nuclear propulsion by housing a pressurized water reactor in the hold immediately forward of the midships engine room. The existing steam raising and power plant would not be removed and the two steam systems interconnected. The separately fired boiler superheater could be used either in series with the reactor or, in the case of emergency and for port use, as part of the originally designed totally oil fired installation. This arrangement removed the fuel handling access space from the undesirable location in the midship accommodation area, as shown in Dr. Brown's proposal in Fig. 35.

A valuable paper(34), coinciding in both title and date of presentation, reviewed in greater detail the probable rôle of the pressurized water reactor, the liquid metal-cooled reactor and the boiling water reactor.

Regarding Mr. Harvey's question on utilization of decay heat, which it was assumed applied to the pressurized water reactor, reference (34) indicated that on shut-down the reactor would produce 3 per cent or more of its rated power for about 16 hours. Means could no doubt be devized to use this heat as Mr. Harvey suggested. Otherwise it would have to be dumped to some sink such as a condenser.

Mr. Hotchen's remarks were appreciated as they again reflected the reactor design aspects, which had been forcibly neglected in the paper.

The question of availability and cost of helium was recognized as a very real one attached to the closed-cycle gas turbine proposal, but neither should be insurmountable.

Mr. Hotchen would no doubt agree that Table II was by no means the only argument advanced in the selection of helium as coolant. It was again encouraging to note Mr. Hotchen's reference to the eventual entire revision in reactor design concepts with the consequent attainment of gas temperatures of the order of 1,400 deg. F. and above.

Mr. Feilden's remarks merely required commendation, particularly to the unconverted. It could no longer be doubted that the open-cycle gas turbine had established itself in the marine field and was particularly attractive for auxiliary power generation. Dr. Keller and others had suggested the use of open-cycle turbines in place of the Diesel auxiliaries, when commenting on the author's proposals which led to the arrangements shown in Figs. 28 and 29.

The author hoped that by the time Mr. Plummer had read this far, any digestive troubles encountered earlier would be assuaged. Replies to Mr. Plummer's first three questions had already been made as complete as possible. The fourth was answered by reference to the cycle analysis on pages 116 and 117. The work or heat quantities were there considered as the equivalent increments or decrements in temperature. Expressed in absolute temperatures, as plotted in Fig. 21, the ratios became:—

$$\frac{\text{Total work absorbed in the h.p. and l.p. compressors}}{\text{Total work developed by h.p. and l.p. turbines}} = \frac{T_6 - T_8}{T_6 - T_7} = \frac{240}{458} = 52{\cdot}4 \text{ per cent}$$

$$\frac{\text{Work delivered by l.p. turbine}}{\text{Heat supplied from reactor}} = \frac{T_7 - T_8}{T_6 - T_5} = \frac{218}{514} = 42{\cdot}4 \text{ per cent as quoted on page 117.}$$

Further refinement, to include a value of the power delivered to the propeller, entailed allowance for transmission losses between the l.p. turbine and the tailshaft similar to that made on page 119.

Commander Tyrrell's remarks undoubtedly outlined correctly a sound appreciation of the overall picture. His detailed consideration of an alternative steam plant provided a valuable adjunct to the paper, but one major omission warranted mention. The "considerable improvement" effected by using a separately fired superheater and economizer included the burning of 35·9 tons of oil per day which would amount to some 1,650 tons for the voyage considered. The gain in payload claimed for the nuclear powered ship (but not credited in the cost analysis) was 4,000 tons. Reducing this revenue earning capacity by 41 per cent to accommodate the superheater fuel was certainly no part of an "improvement" and that was the main reason the scheme was not discussed in the paper. This should be read as complementary to the author's remarks on the same scheme as proposed by Dr. Brown.

Commander Tyrrell's correction of the estimated first cost of orthodox steam turbine machinery was of particular value as it affected a subject difficult to investigate. A check of the figures available to the author, in the light of this criticism, had shown that the prices used in the paper were low due to an error in allocating a sufficiently high proportion of the auxiliary and piping costs.

Further controversy on the various suggestions for modifying the figures used in the economic comparison would serve no useful purpose at this juncture. Such a procedure should then logically lead to a refinement of the calculations. It was apparent that there were too many criteria still on the classified list for any conclusions so reached to be beyond question. Why then was an attempt included in the paper? Mr. Cornish deduced that once cost was mentioned, serious consideration could be expected. If this motive be still suspected of intention to mislead, as was suggested by later contributors, then the author recommended a further reading of the conclusion on page 121.

Mr. Wigg provided the second respite from the bombardment in strengthening the case for the closed-cycle gas turbine.

The compact 15,000-s.h.p. plant was another excellent example of what could be done once the reserve attached to that type of propulsion unit was overcome. The upper temperature of 1,257 deg. F., even though applied to an air cycle, also warranted emphasis.

The author thanked Mr. Zoller for his notation of apparent errors in the first part of the paper. The applicable corrections had been made to the text.

The combined contribution of Mr. Ross and Dr. Keller provided a more authoritative appraisal of the potential of the closed-cycle gas turbine plant than it was possible to give in the paper. As such, the contribution would be recognized as that supplying answers to many of the questions raised regarding feasibility of the author's proposals. It also provided more detail of the mechanical development work yet required on the turbine which was aimed basically at reducing the number of stages.

It was apparent that at this stage of development it was not possible, or indeed desirable, to make a choice of the most suitable reactor or gas. The author could add no more to the former consideration but, as a closure in considering the choice of gas, it was no doubt significant that in the recent Parsons Memorial Lecture to the Institution of Civil Engineers(35), an eminent British authority referred to a 15,000-s.h.p. nuclear powered marine set using a closed-cycle helium turbine.

Mr. Ross's closing remarks on methods of financing the necessary development work should not be overlooked. Based on opinion formed during residence in the United States of America and clearly appreciating the variation in basic economy between the British and American shipping industries, the author particularly commended Mr. Ross's second proposal as worthy of further detailed study by the eventual "ways and means committee".

In reply to Mr. Forsling, the gas temperature of 1,400 deg. F. had already been well discussed and the time required for its attainment in practice was still undefined. However, the author suggested that Table VIII in reference 33 be studied as another example of the gas-cooled reactors at present considered feasible. A maximum fuel element temperature of 1,800 deg. F. was quoted with air as the primary coolant.

Mr. Forsling's deductions on the choice of gas were quite correct from strictly thermodynamic considerations. The final answer must also take into consideration the nuclear properties of the gas used and neutron trapping was one approach.

The question of rapid change in power level could well be a major factor in favour of reducing the gas volume in the turbine system by incorporating one or more coolant loops in the reactor. Otherwise, the author agreed that in directly expanding the reactor coolant, the pumping (or compressing) problem would be quite appreciable.

The contribution of the Vickers-Armstrongs Nuclear Team was of great value to the paper, representing as it did a consensus of informed opinion. The author also acknowledged the necessary corrections to the text.

Replies had already been given to criticism of design values used for the cycle study and suggestions for refinement of the economic analysis, similar to those made by the team. It should not be overlooked that in the unlikely event of precise and complete solutions being available for the many problems raised during the discussion, doubt might be raised as to the necessity for a nuclear design team. The author hastened to add that he felt sure the team would be adequately employed during the design and development period which lay ahead.

Commander Meadows's alarm at the apparent increase in attractiveness of nuclear power would be quite justified assuming that the figures used in the paper were intended for use in the immediate future. They were not.

Two main points of contention were raised, fuel cost and minimum shaft power. It was apparent from the discussion that the fuel cost used in the analysis was too low and the author had no further information to offer. Commander Meadow's argument in contesting the selection of 15,000 s.h.p. as feasible for commercial use was by no means complete. The author was unaware that any figures had been published for the power of the nuclear submarines. Even if these were available, he failed to see why this power governed the technical feasibility of a commercial marine plant. A variety of reactors were technically feasible to provide power over the whole range which would interest the ship operator. Whether or not any of these technical feasibilities proved attractive for commercial use would be decided by applying lines of thought similar to those on page 118 *et. seq.*

The leakage tolerance of 1 c.c. in ten years referred to the pumping of molten sodium, a specialized case. No implication was made that a reactor using this coolant would necessarily run continuously for such an extended period, but reference had been made in the discussion that certain types of reactors were visualized as being capable eventually of continuous operation for an unspecified number of years, if required.

Mr. Frank's implied criticism of the gas-cooled reactor, in particular the Daniels pile, was totally invalidated by a recent report(36).

Captain Atkins's suggestion that the hull designer should keep abreast of machinery developments in exploiting the advantages of nuclear power represented a very welcome line of advanced thinking that should not be treated lightly. Commercial submarines could well be an attractive possibility once nuclear power had been accepted for ship propulsion. Captain Atkins's statement regarding the reduced power requirements for submerged operation should include the proviso that model tests showed that the benefit of eliminating the wave making resistance was only apparent for speed/length ratios in excess of about 1·4. (For a 400-ft. vessel this implied speeds in excess of 28 knots.) For speeds less than this, the increased wetted surface would probably reverse the powering comparison between the submarine and the equivalent surface vessel.

The author accepted Professor Benford's modification of the weight of bunkers that could be saved by a nuclear powered tanker if the draught limitation for the Suez Canal passage was a design criteria.

The point might be of considerable significance if enlarged. Since it was clear that the advantage of the nuclear powered ship was reduced by reduction in draught, the solution could well be offshore loading and discharge and routing via the Cape. In evaluating the latter question, consideration must be given to the restrictions, if any, that would be applicable to nuclear powered ships passing through the Canal and also the possibility of closure of the Canal in an emergency.

Mr. Cornish's remarks were helpful in obtaining a balanced appreciation of the use of liquid metal coolants. The author apologized for stating that the temperature of the metal as pumped would necessarily be 1,000 deg. F. The text had been amended accordingly. No apology, however, seemed due for describing the published efficiency of the electro-magnetic pump (35 per cent) as "low".

A further suggestion which might strengthen the case for the use of liquid metal coolants was contained in the paper by Johnson and Johnson(34), which stated:—

"Still in the development stage, but an interesting possibility, is a heat exchanger design that will possibly eliminate the need of coolant pumps in the liquid metal system. The heat exchanger is built around the reactor vessel and pumping is accomplished by electro-magnetic forces. This pumping action will result from an electric current flowing between the pole pieces of a cylindrical horseshoe magnet mounted in the heat exchanger. The electric current will be generated by a thermocouple effect resulting from the temperature gradient normally existing between the hot and cold tubes of the heat exchanger. The pumping action will be largely self regulating, but in addition will have an electrical control. This means of circulating the liquid metal coolant eliminates much of the piping and valves ordinarily used and also gets away from some of the problems involved in the use of conventional pumps. If this design is successful, the size and weight of the primary system could be reduced appreciably."

In answer to the questions raised by Captain D'Arcy, the author submitted the following:—

The operational characteristics of reactors would vary appreciably between types. The PWR was claimed to be capable of producing steam from a cold "light-up" in the same time as a conventional oil fired boiler. Reduction in power demand could likewise be accomplished by control rod movement down to about 10 per cent of designed output. Below this power level excess steam would be dumped to the condenser.

The disadvantage of having machinery handling radioactive fluid and therefore inaccessible within the shield while the reactor was in operation had already been discussed in the paper. This was one of the points in favour of the use of helium as reactor coolant.

It now seemed reasonable to expect that the PWR, or the BWR, could be designed to operate for at least a year between refuelling. This was surely not an over-optimistic period to expect the machinery to run between overhauls.

The question of safety and the hazards to be expected had already been mentioned by Mr. Pemberton and others. In an attempt to prevent release of radioactive material in the event of such emergencies as collision, the shield would be constructed to include strength considerations, probably in the form of a cylindrical pressure vessel. This in turn would require a compact arrangement of units within the shield.

Mr. Dunlop's comments were mainly in accord with those contained in the paper, thus minimizing the reply required.

The author was not aware of any recuperator in operation at present with an effectiveness of 92·3 per cent as used in the cycle analysis. However, he did not consider this an unreasonable figure to expect from future development.

Mr. Dunlop and Dr. Richards had expressed differing opinion on fuel choice and availability. It would appear, therefore, that the matter became one of allocating supply priority.

The author agreed with Mr. Harrold that refuelling a ship reactor would be a relatively complicated procedure on account of safety considerations. This was inevitable in the operation of any reactor and would no doubt be an important design consideration. As had been mentioned during the discussion, no difficulty was foreseen in designing a mobile reactor requiring only annual refuelling.

The results of Mr. Holdsworth's investigation left the author in doubt both of the validity of the criticism and indeed of the contributor's professed appreciation of the basic principles of criminology. The author hoped that his reply, when read in its entirety, would clarify the apparent mystery.

The author was not favoured by the confidences of the U.S. Navy Department regarding the choice of sodium cooling for the *Sea Wolf* reactor and was unable to enlarge on the observations made on page 110.

Mr. Holdsworth was quite correct, however, in his first criticism of the method of estimating the nuclear fuel bill. No allowance had been made for the plutonium produced during operation of the reactor. Accepting Mr. Dunlop's suggested figure of ten guineas per gram of plutonium, this would appreciably offset the additional cost for reprocessing the fuel elements as suggested by Mr. Kay.

The author also agreed with Mr. Holdsworth and Mr. Kay that it might well prove more attractive to design for annual refuelling and accept the additional investment in fuel carried in order to avoid both the small reactor core and the expense of refuelling, say, seven times each year.

Mr. Swiecicki answered one of the problems considered by the author while formulating his proposals for the machinery arrangement of the closed-cycle gas turbine machinery. In confirming the feasibility of a controllable pitch propeller to absorb 16,500 horsepower, Mr. Swiecicki's contribution would be of great interest to many members of the profession.

CONCLUSION

Several detailed questions were raised by more than one contributor to the discussion and to avoid repetition as far as possible while maintaining continuity, a complete reply to each was not attempted.

The author was satisfied that the aim in writing this paper had been achieved and following a resurvey of the whole subject in the light of the discussion, saw no reason to modify the original conclusion.

REFERENCES

33. Background Material for the Report of the Panel on the Impact of the Peaceful Uses of Atomic Energy to the Joint Committee on Atomic Energy, Vol. 2. January 1956. U.S. Government Printing Office, Washington, D.C.
34. JOHNSON, C. H., and JOHNSON, P. V. 1955. "Nuclear Power for Merchant Vessels." S.N.A.M.E. (Gulf Section). December 1955 meeting.
35. ROXBEE COX, H. 1956. "The Development of the Gas Turbine" (Sir Charles Parsons Memorial Lecture, 1955). Proc.I.C.E. (Part I), Vol. 5, p. 121 (March 1956).
36. DANIELS, F. 1956. "Small Gas Cycle Reactor Offers Economic Promise". Nucleonics, Vol. 14, No. 3 (March 1956).

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting Held at the Institute on Tuesday, 20th December 1955

An Ordinary Meeting was held at the Institute on 20th December 1955, at 5.30 p.m., when a paper entitled "Nuclear Power for Commercial Vessels", by K. Maddocks, B.Sc.Tech. (Associate Member), was presented and discussed. Mr. W. J. Ferguson, M.Eng. (Chairman of Council), was in the Chair. Members and visitors present totalled 191 and sixteen speakers took part in the discussion; owing to the lateness of the hour several others who wished to speak agreed to send in their comments in writing.

A vote of thanks to the author, proposed by the Chairman, was accorded by acclamation. The meeting ended at 8.20 p.m.

Lloyd's Register of Shipping Award

The awards for the two best letters from students describing their visit to London on 20th December last, sponsored by Lloyd's Register of Shipping, have been made; the first prize of £6 6s. 0d. to D. E. Gue (Kingston-upon-Thames Technical College), and the second prize of £2 2s. 0d. to I. Bennett (Constantine Technical College). The choice was made by Lloyd's Register of Shipping.

Several of the reports were of considerable merit and in view of the difficulty in making the final choice, consolation prizes for other students have been given by Lloyd's Register of Shipping of copies of extracts from the Society's "Machinery Rules". These prizes have been awarded to A. G. T. Tosh of Glasgow, A. Scott of Cardiff, J. R. Whitehead of London and R. V. Parsons of Glasgow, and were handed to the students by the local Principal Surveyors, so that contact was established between the students and Lloyd's Register of Shipping.

There is no doubt that the visit was a great success and, judging by the letters received, much appreciated by the apprentices.

Student Meetings

5th December 1955

A meeting of the Student Section was held at 85, Minories, London, E.C.3, on Monday, 5th December 1955, at 6.30 p.m., when a paper entitled "The Paxman Engine" was read by Mr. A. G. Howe, M.B.E., J.P., A.M.I.Mech.E. Fifty-seven members and visitors were present and eight speakers took part in the discussion.

A vote of thanks proposed by the Chairman was accorded by acclamation. The meeting ended at 7.40 p.m.

16th January 1956

A meeting of the Student Section was held at 85, Minories, London, E.C.3, on Monday, 16th January 1956, at 6.30 p.m., when a paper entitled "Turbo-electric Propulsion Machinery" was read by Mr. R. J. Hayes, B.Sc. (Eng.), A.C.G.I. Thirty-two members and visitors were present and seven speakers took part in the discussion.

A vote of thanks proposed by the Chairman was accorded by acclamation. The meeting ended at 7.50 p.m.

13th February 1956

A meeting of the Student Section was held at 85, Minories, London, E.C.3, on Monday, 13th February 1956, at 6.30 p.m., when a film was shown and a lecture entitled "Boilers" was given by Mr. W. C. Carter, B.Sc., M.Inst.F. (Member).

Fifty-one members and visitors were present and twelve speakers took part in the discussion.

A vote of thanks proposed by the Chairman was accorded by acclamation. The meeting ended at 8.10 p.m.

19th March 1956

A meeting of the Student Section was held at 85, Minories, London, E.C.3, on Monday, 19th March 1956, at 6.30 p.m., when a paper entitled "A Ship and Its Services" was presented by D. G. Alcock (Member of Council). The lecture was illustrated by a film entitled "s.s. *British Sovereign*". Forty-eight members and visitors were present and eleven speakers took part in the discussion.

A vote of thanks proposed by the Chairman was accorded by acclamation. The meeting ended at 8.20 p.m.

Election of Members

Elected on 14th March 1956

MEMBERS

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Felix Edward Barbat
Edward James Brown, Lieut., R.N.
John Griffiths Byers
David Christie
Philip John Paterson Conchie, Sen. Cd. Eng., R.N.
Albert Guy Davis
Kurt Axel Joel Eriksson
Eric Selwyn Green
Anders Gustafsson
Leo Francis Halpin, B.E.M.
Clyde Everett Hawthorne
George Hickson
George Hutchison
John Nicol Jarvie
Edward Reed Jeffrey
Robert Kellie
Frederick Wilfred Larkman, Lt.-Cdr., R.N.
Carl Walter Lund
Anton Engelbrecht Nelson
Albert William James Newling, Lieut., R.N.
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Wilfred Hope Emerson Peters
George Frederick Rimmer
Henry John Stokes
John Carleton Woollard
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Zaminbeg Nadarbeg Mirza
Peter Waite Moore
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Achanta Rama Rao
Sven Schierwagen
Robert Scott
Norman Frank Shute
Ian Gordon Stewart
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Derek George Reeves Hall
Keith Francis Joseph Knowles
Gordon Luhrs
Robert Cedric Richardson
Peter Stanley Robinson
S. F. Setna
Edward Sidney Whitworth

STUDENTS
Abdul Aziz
George Charles Loughborough
James Robert Taylor
Francis James Thomas

PROBATIONER STUDENTS
William John McCallion
Richard Francis Power

TRANSFER FROM ASSOCIATE MEMBER TO MEMBER
Donald Marshall Andrew, Lt.-Cdr., R.N.

TRANSFER FROM ASSOCIATE TO MEMBER
Leonard Charles George Alford
William Cairo Beeley
George Cokayne
Reuben Dixon Seabrook, Lieut.(E), R.N.(ret.)

TRANSFER FROM ASSOCIATE TO ASSOCIATE MEMBER
Maurice Breen
Norman George
John Hicks
Dennis Hodgson
Angus Macdonald
Brian Mackenzie
Eric Joseph Ostle
Dennis Keith Tappin
Robert Edgar Westwood
Richard Walter Wilkinson

TRANSFER FROM STUDENT TO ASSOCIATE MEMBER
Martin Joseph Lawlor

TRANSFER FROM STUDENT TO GRADUATE
Bibekananda Bonnerjee
Anthreas Nicholas Charcharos, B.Sc.

TRANSFER FROM PROBATIONER STUDENT TO STUDENT
Joseph Barry Cull
John Mason

Elected on 9th April 1956

MEMBERS
Charles Frederick Barnard
John Dale Brown
Denis Leslie Brownlow, M.B.E.
John Colquhoun
William Anderson Cousins
Cecil Gerald Crabtree
Albert Deakin
Kohe Nigel Dunn
Harry Edgar Durrant
Edward Ernest Haywood
William McIvor Hughes
Allan David McCready
Ernest McHaffie
I. G. Maclean, Rear-Admiral
Robert Nicholson
Sven Obo
Herbert Evason Recknell
Thomas Hardie Smeaton
David Reid Todd
James Francis William Turnbull
Robert Tyrrell Young

ASSOCIATE MEMBERS
James Alan Atkinson
Peter John Barker
John Edmund Bayram
Donald West Brown
Denis Burn
Lyall Craig
Carmel Cuschieri
William Devlin
Maurice Vincent Fernandez
James Findlay
Malcolm Fry Hammond Francis
David Grahame Harold Hindman
Ravalnath Ananth Kamath
Douglas Wylie Kerr, B.Sc. (Durham)
Donald Henry George Lambert
Frederick William Lonie
Derek Loudon
John Joseph McCormack
Noshir Cavashaw Madan
Donald Walter Mitchell
Andrea Mortola
Stanley Law Munn
Stanley George Oxnard
Edward Parr
Robert Charles Rampling
Ian Balfour Smail, B.Sc.
Percival Edmond Lewis Somers
Robert Steven
Jeffery William Taylor
Alan Walter Veal

ASSOCIATES
Ronald William Charles Apps

George William Askew
William Burns James
John MacDiarmid Shaw
John McKay Wainwright
Alan Bruce Webb

GRADUATES
Arthur Edwin John Burley
Kersy Tehmurasp Chinoy
Colin Cooper
Derrick Anthony Geoffrey Fernando, Lieut.(E), Royal Ceylon Navy
Lambert Anthony Wenceslas Fernando
Peter Austin Frowley
Leonard Gordon Garland
Arthur George Gonsalves
William Keith Highfield
Pothamsetti Prabuddha Kesava
Nari Gokaldas Kirpalani
Stewart Harry David Livingstone
Anthony George Lucas
Donald Brian Nixon
Albert Parkinson
Joseph Patrick Ryan
Joseph James Sewell
Alexander McKenzie Shaw
John Meriton Stirling
John Kenneth Brian Turk
Edward Cherk Kin Young, B.Sc.

STUDENTS
James Wilson Johnston
Amilcas Ion Livas

PROBATIONER STUDENTS
Richard Douglas Allen
Archibald Hill
Peter Leslie Edward Jones
Kenneth Ian Taylor
Michael Parry Williams

TRANSFER FROM ASSOCIATE TO MEMBER
Thomas Drysdale

TRANSFER FROM ASSOCIATE TO ASSOCIATE MEMBER
Edward Barnett
Walter Brown
Alfred Thomas Oswald Howell
John Reginald Mitchell
Peter Bramwell Myerscough
William Baird Robertson
Donald Grant Stewart

TRANSFER FROM PROBATIONER STUDENT TO STUDENT
John Benton
Frederick Brian Longstaff
Patrick Andrew Sparrow
Arthur Terence Tuffee

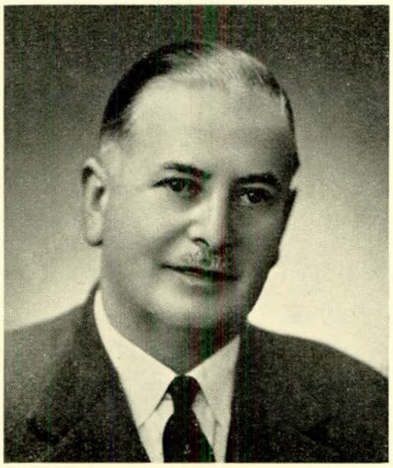
OBITUARY

HENRY COLBECK MURRAY

It is announced with regret that Mr. H. C. Murray, a Senior Ship and Engineer Surveyor to Lloyd's Register of Shipping on the Chief Engineer Surveyor's Staff at Headquarters, died on the 7th February at the age of 58.

During his thirty years' service, Mr. Murray had been stationed at London, Liverpool, Antwerp, Leith, Antwerp and Headquarters.

Mr. Murray was apprenticed with the Wallsend Slipway and Engineering Co., Ltd., with whom he remained for a few months in the drawing office. He held a commission in the Royal Flying Corps during World War I. He had five years' sea service and three months' shore service with Shaw, Savill and Albion Co., Ltd., and for six months before joining the Society he was a draughtsman on Diesel design with Swan, Hunter and Wigham Richardson, Ltd. He held a First Class Board of Trade Steam and Motor Certificate.



On his appointment to Lloyd's Register in 1926, Mr. Murray was stationed on the London Outdoor Staff. From February 1930 to November 1938 he was stationed at Liverpool and from November 1938 to May 1940 at Antwerp. He returned to the United Kingdom upon the invasion of Belgium and was stationed at Leith until November 1944. Upon the liberation of Belgium Mr. Murray returned to Antwerp and stayed there until May 1955. He was then transferred to the Reports Department of the Chief Engineer Surveyor's Staff at Headquarters, where he remained until his death.

Mr. Murray was a Member of the Institute from 1924 and was Local Vice-President in Antwerp from 1951 until his return to England in May 1955.

GEORGE HOLDSWORTH HURLEY (Member 7405) was born in 1899. He was apprenticed to the Tydfil Engineering and Ship Repairing Co., Ltd., Cardiff, and then sailed as fourth to second engineer with various South Wales companies including Watts, Watts and Co., Ltd., Merrett Bros., Ltd., and the Sydney Rees Navigation Co., Ltd. In 1924 he joined the Hain Steamship Co., Ltd., and remained in their service as second and chief engineer until 1937, having obtained a First Class Board of Trade Certificate. He then joined the Ministry of Aircraft Production and was stationed as examiner at Bristol until 1944; this was followed by periods at Accrington, Heywood and Quedgeley. In 1953 he was appointed acting resident A.I.S. inspector of the Flying Board Storage Unit at Stranraer, the appointment he was holding at the time of his death on 2nd March 1956.

Mr. Hurley was elected a Member of the Institute in 1933.

WILLIAM NICOL (Member 11589), who was born in 1886, was educated at Dollar Academy, Dollar, and served an apprenticeship with John Brown and Co., Ltd., Clydebank. He was at sea for many years with the Prince Line, including the 1914-18 war years, when he was wrecked in the *Tuscan Prince* off Vancouver. He obtained a First Class Steam Certificate, with Motor Endorsement, and sailed as chief engineer before coming ashore in 1928 to an appointment with J. C. Kennaugh and Partners, Liverpool, who were the Athel Line's consulting engineers at that time. In 1931 he joined the Athel Line as chief engineer and was appointed assistant chief superintendent in 1944, the position he gave up in 1950 owing to coronary thrombosis, from which he died on 4th February 1956. Mr. Nicol had been a Member of the Institute since 1947.

CYRIL DAVID PUGH (Member 9527) served an apprenticeship with Elliott and Jeffries at Barry Docks from 1920-25 and then went to sea as fourth engineer with the Hain Steamship Co., Ltd., subsequently serving with the Court Line, Abbey Line and the Wing Line; he obtained a First Class Board of Trade Certificate and sailed as chief engineer from 1936. He was appointed maintenance fitter with Guest, Keen and Nettlefolds, of Cardiff, in 1938 but after several years he returned to sea with Constants, Ltd. He died suddenly on 7th March 1956, aged fifty-two.

Mr. Pugh had been a Member of the Institute since 1943.

THOMAS HALLIDAY TURNER (Member 10142) was born in Newcastle on Tyne in 1892. He was apprenticed to R. and W. Hawthorn Leslie and Co., Ltd., St. Peter's Works, from 1908/13 and continued working in their drawing and design offices until 1918. For the next two years he was turbine designer and leading draughtsman at Palmers Engine Works, Jarrow. He attended Rutherford College for a mechanical engineering course during his apprenticeship, winning the Marshall Trophy in 1912, and then went to Armstrong College for three years for a course on turbine and condenser design. He then went to Fraser and Chalmers Engineering Works at Erith and from 1919/46 was their turbine designer, engaged on many turbo-electric propulsion schemes and installations in liaison with shipowners and on turbo-generators with the Admiralty. In 1946 he was transferred from the Erith Works to the General Electric Company's marine department in London, where he maintained his liaison work on these schemes between the company, shipowners and shipbuilders until his retirement on account of ill health on 31st December 1955. Mr. Turner died only a few weeks later, on 9th February 1956. He was elected a Member of the Institute in 1944.