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NUCLEAR POWER FOR COMMERCIAL VESSELS

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THE INSTITUTE OF MARINE ENGINEERS

Nuclear Power for Commercial Vessels

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To be read on Tuesday, 20th December 1955, at 5.30 p.m., at 85 Minories, London, E.C.3, and re-presented on Thursday, 29th December 1955, at 7.30 p.m., in the small hall of the Institution of Engineers and Shipbuilders, 39, Elmbank Crescent, Glasgow, C.2.

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 seem 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	$3,482 \times 10^9$, tons	$72{\cdot}2 \times 10^{18}$
Oil	186×10^9, tons	$7{\cdot}6 \times 10^{18}$
Gas	560×10^{12}, cu. ft.	$0{\cdot}6 \times 10^{18}$
	Total conventional	$80{\cdot}4 \times 10^{18}$
Uranium	25×10^6, tons	$1,700 \times 10^{18}$
Thorium	1×10^6, tons	71×10^{18}
	Total nuclear	$1,771 \times 10^{18}$

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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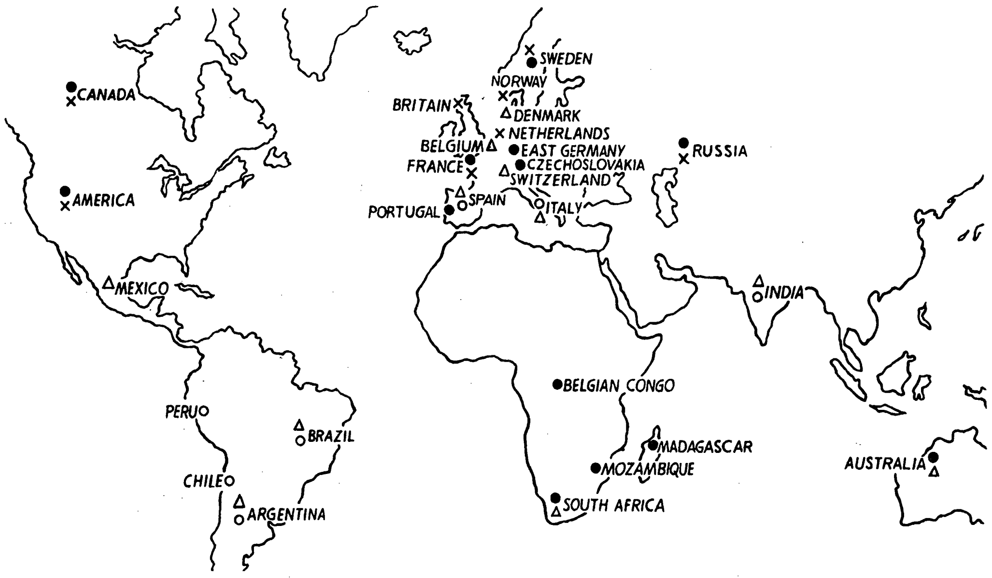


By courtesy of Standard Oil (New Jersey)

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 43×10^9 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 is a fertile material, which can be converted to a fissile material in a breeder type reactor. (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.

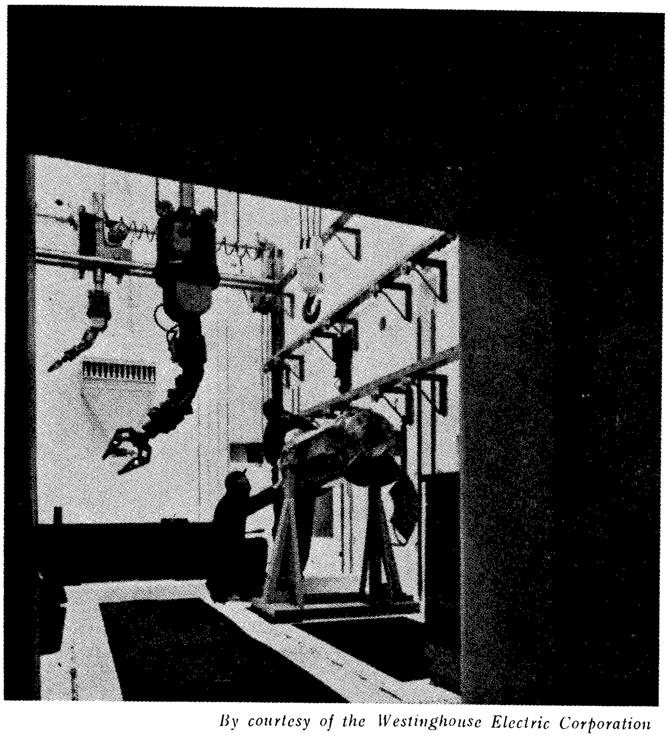
A reactor is said to be regenerative if it replaces all or part of the fissioned (burned up) fuel by creating new fuel from non-fissionable fertile material. If this replacement is equal to the amount of fuel consumed plus some excess, then the reactor is known as a breeder.

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

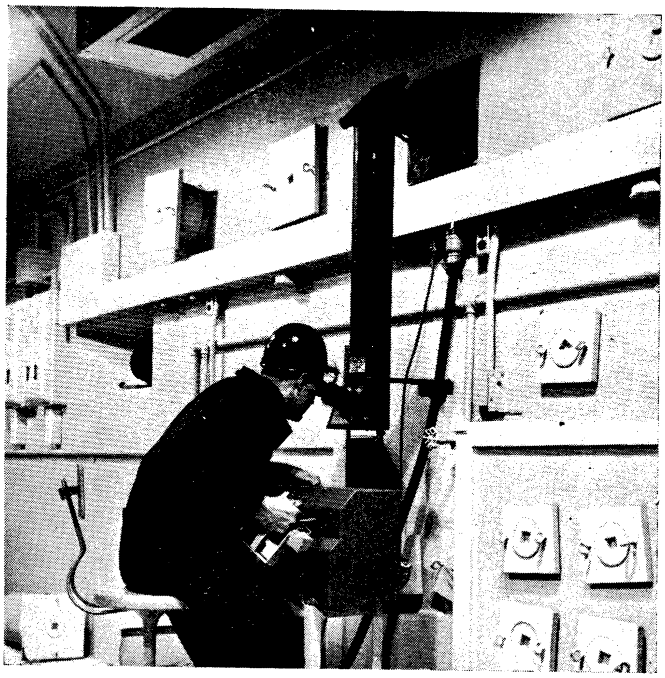
Unlike the oil fired boiler furnace where the fuel is pumped in, atomized and burnt in a continuous process, the nuclear fuel supply for a complete run between refueling ports would be carried in the core of a reactor (this excludes the homogeneous reactor). The quantity of fuel so carried would be determined 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

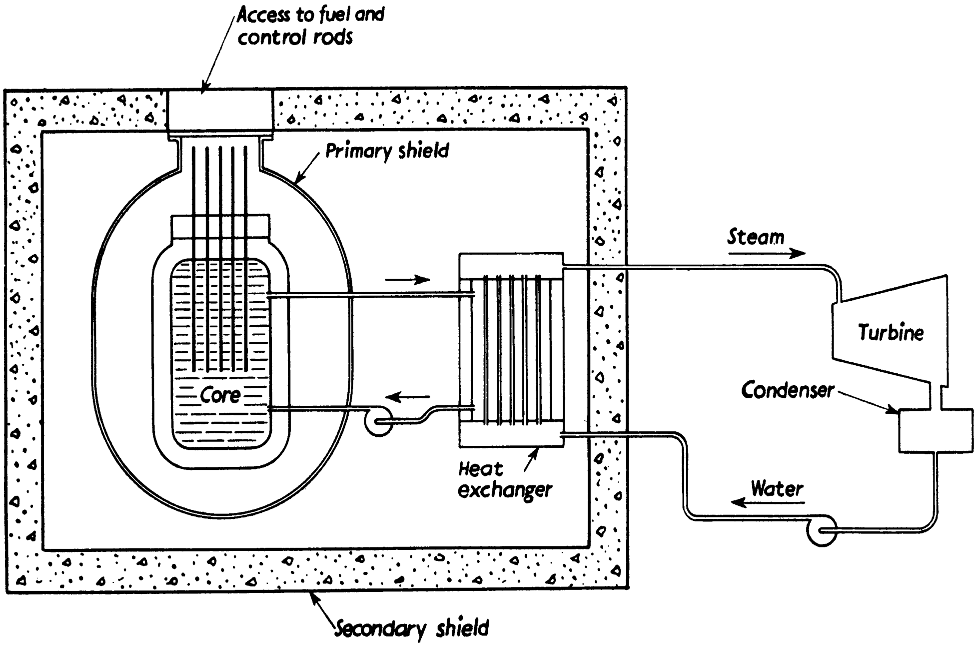


FIG. 4—*Pressurized water reactor*

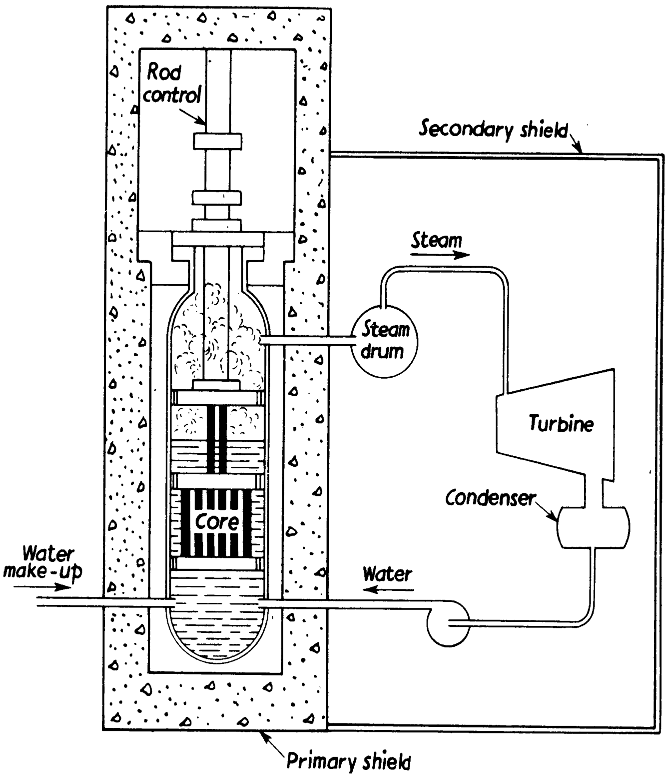


FIG. 5—*Boiling water reactor*

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 300,000 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

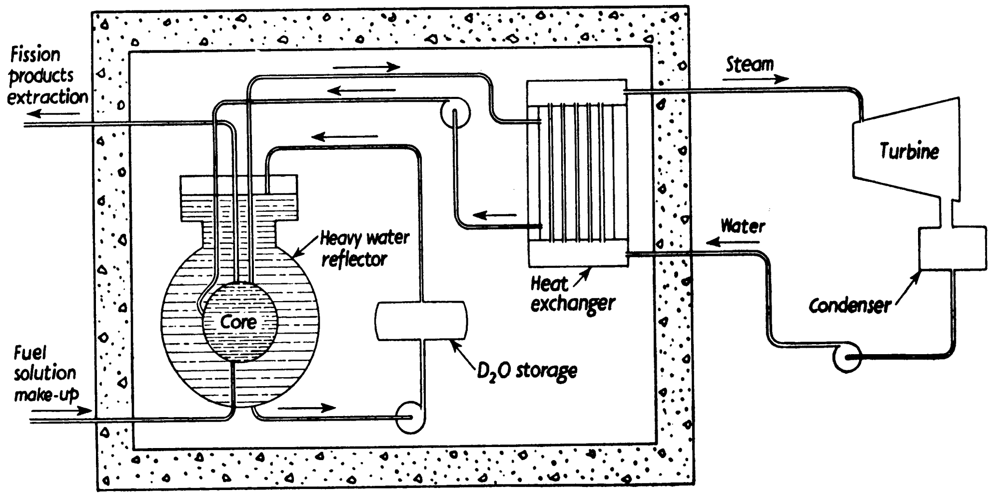


FIG. 6—*Homogeneous reactor*

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 temperature of about 1,000 deg. F. 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.

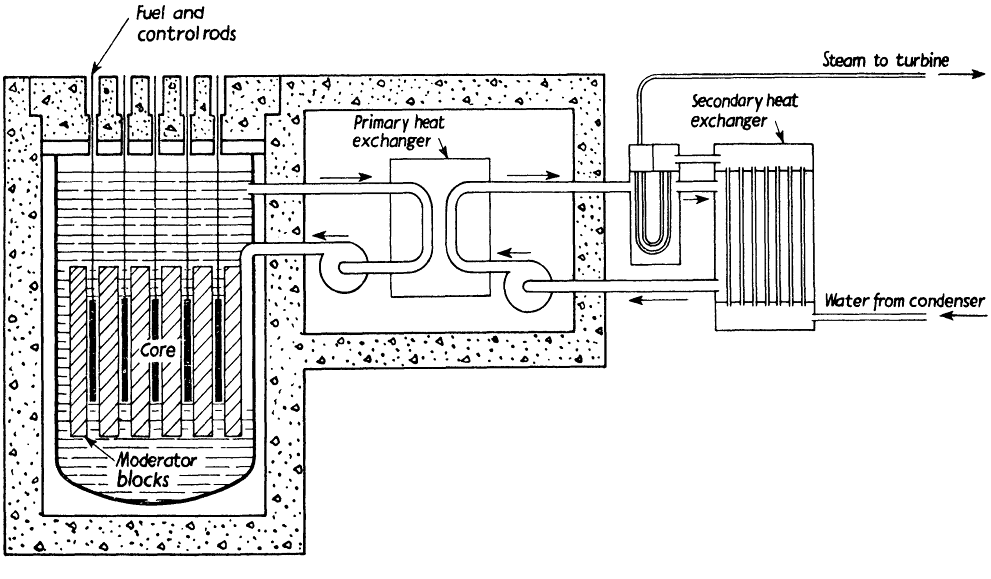


FIG. 7—*Sodium loop reactor*

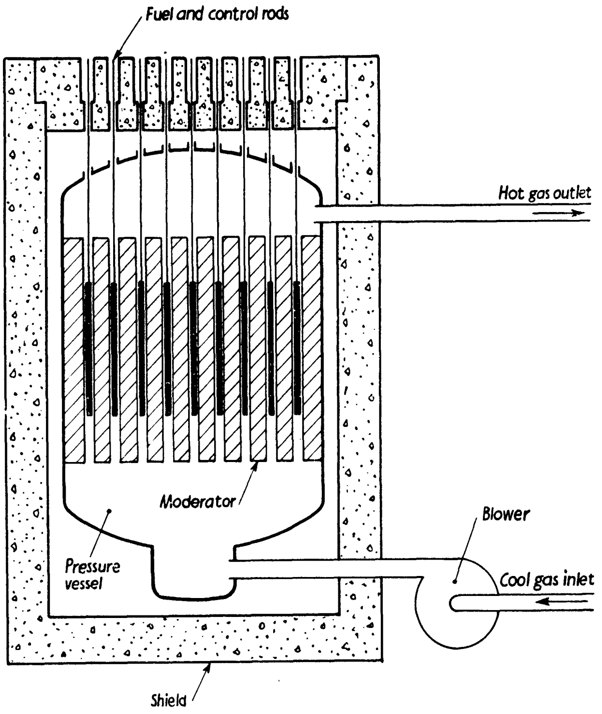


FIG. 8—*Gas-cooled reactor*

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, aluminium or stainless steel to minimize neutron absorption. 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

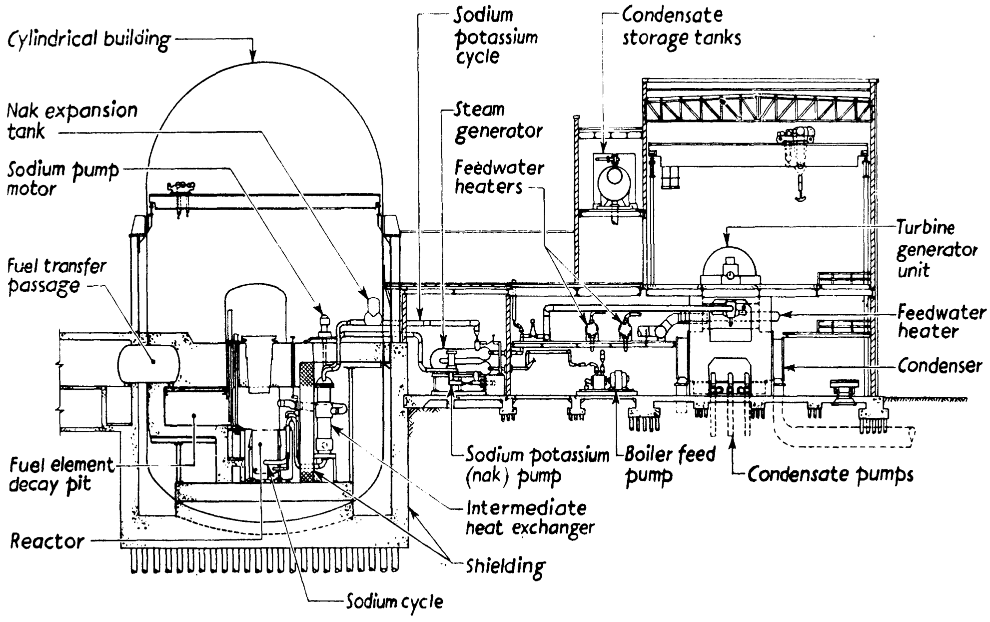
While these figures appear to favour the use of helium, their validity awaits the result of a good deal of development work to confirm a number of assumed factors.

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

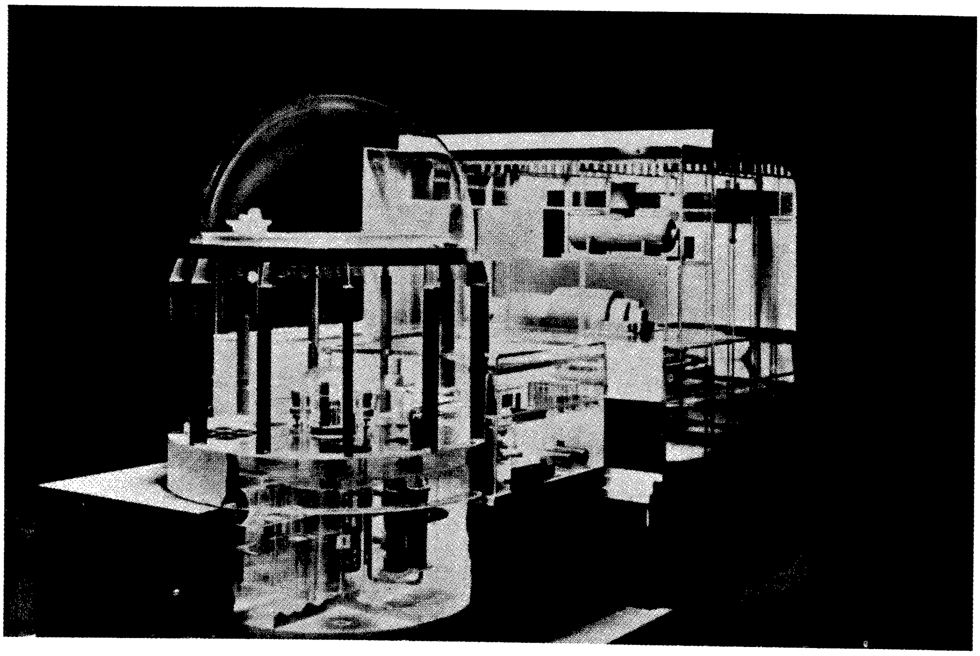
Although not likely to be used as a shipboard power producer, some mention of this type of reactor is justified in that it seems likely that it will provide a definite link in the application of nuclear power to marine propulsion. This link could well be the production of fissile fuels, available to 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 with thorium 232 which captures an additional neutron to become Th.233 and then decays to U.233.



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*

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

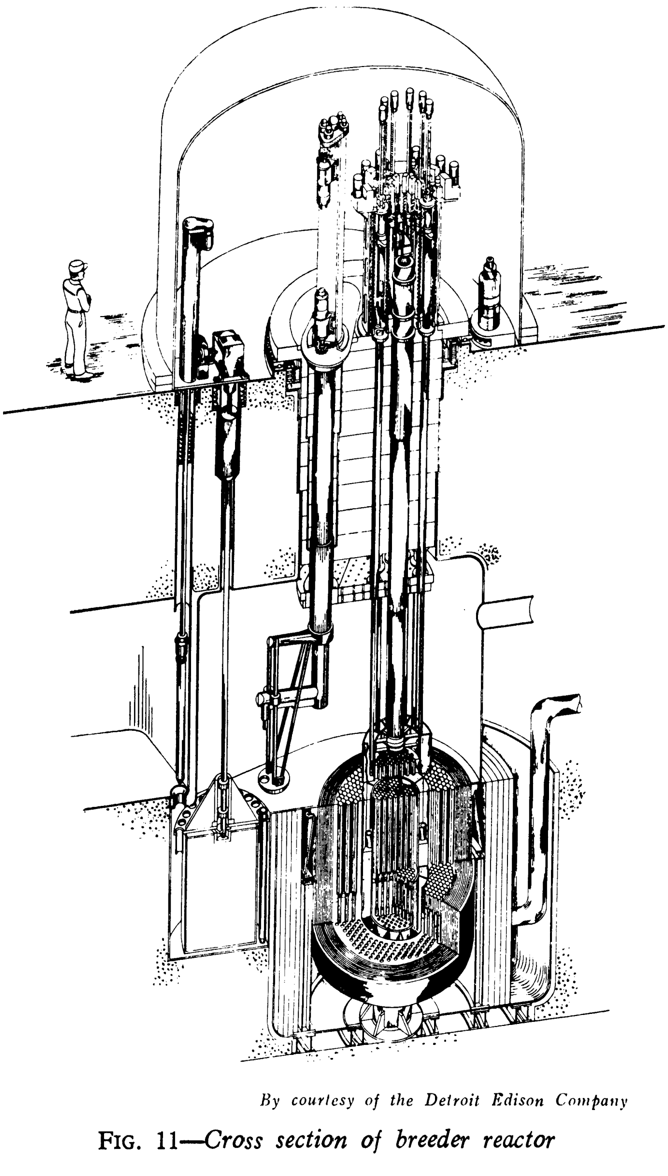
There are, of course, many ways of modifying the various types of reactors already discussed to take advantage of this nuclear phenomenon. The homogeneous reactor, for instance, could be made into a breeder by replacing the heavy water neutron reflector by a thorium solution " blanket ". In the heterogeneous 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 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.



By courtesy of the Detroit Edison Company

FIG. 11—*Cross section of breeder reactor*

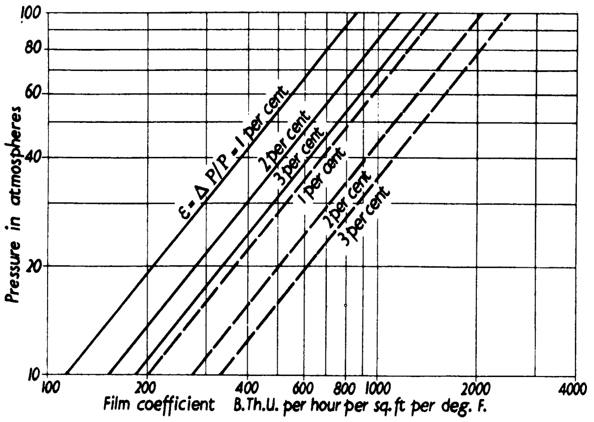
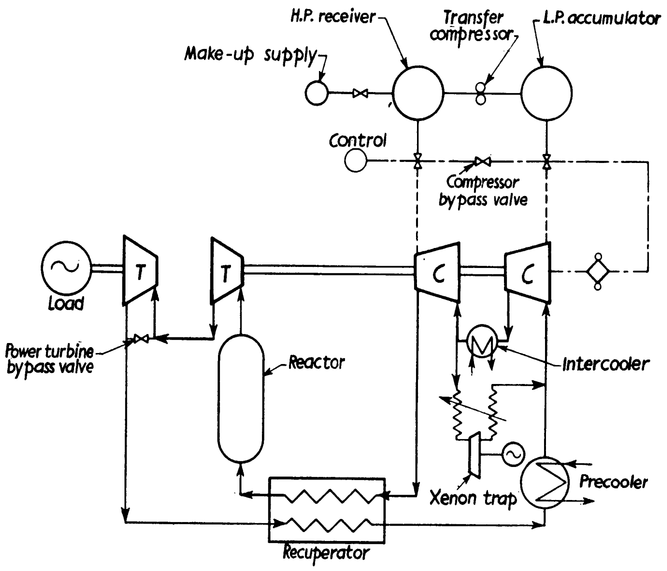


FIG. 12—*Helium-air heat transfer characteristics*



By courtesy of the American Turbine Corporation

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

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.

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. 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

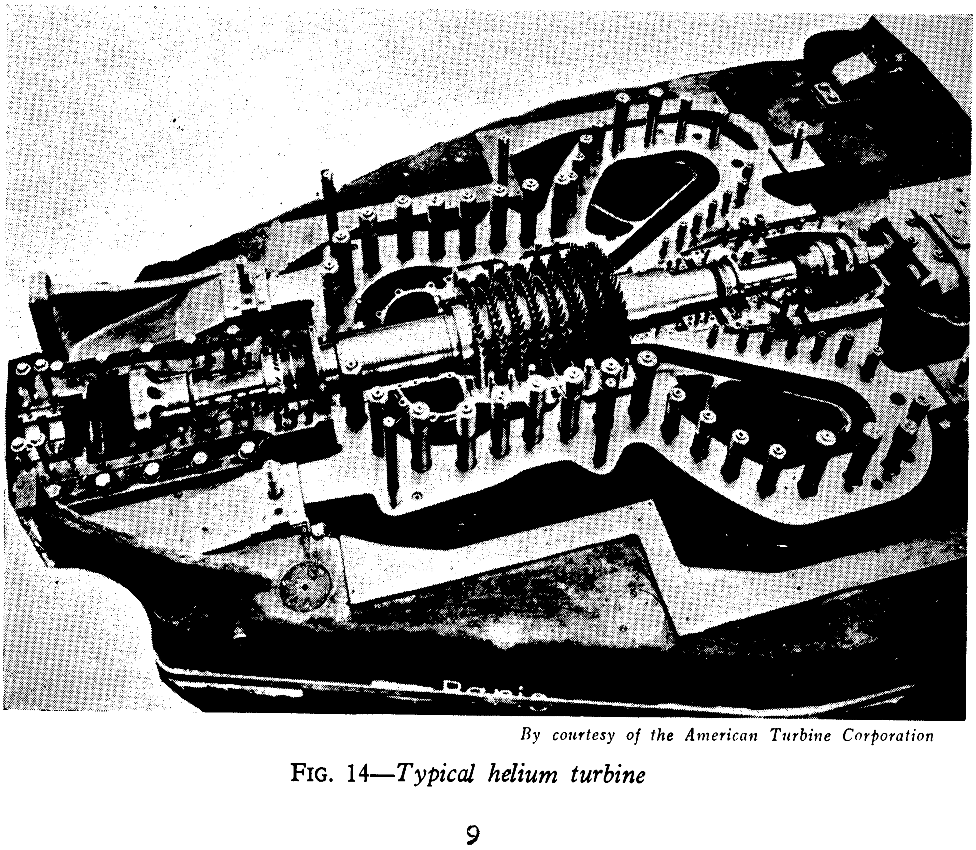


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FIG. 14—*Typical helium turbine*

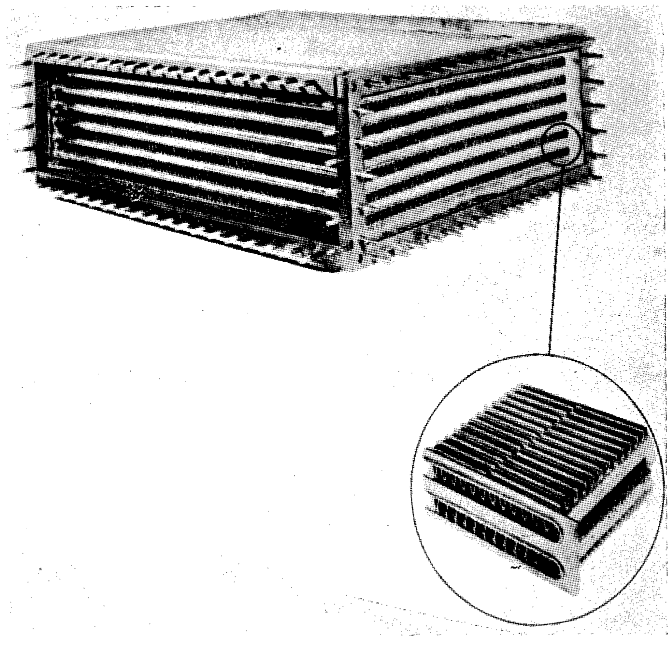


FIG. 15—*Griscom Russell plate fin heat transfer surface*

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

(1·25 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.

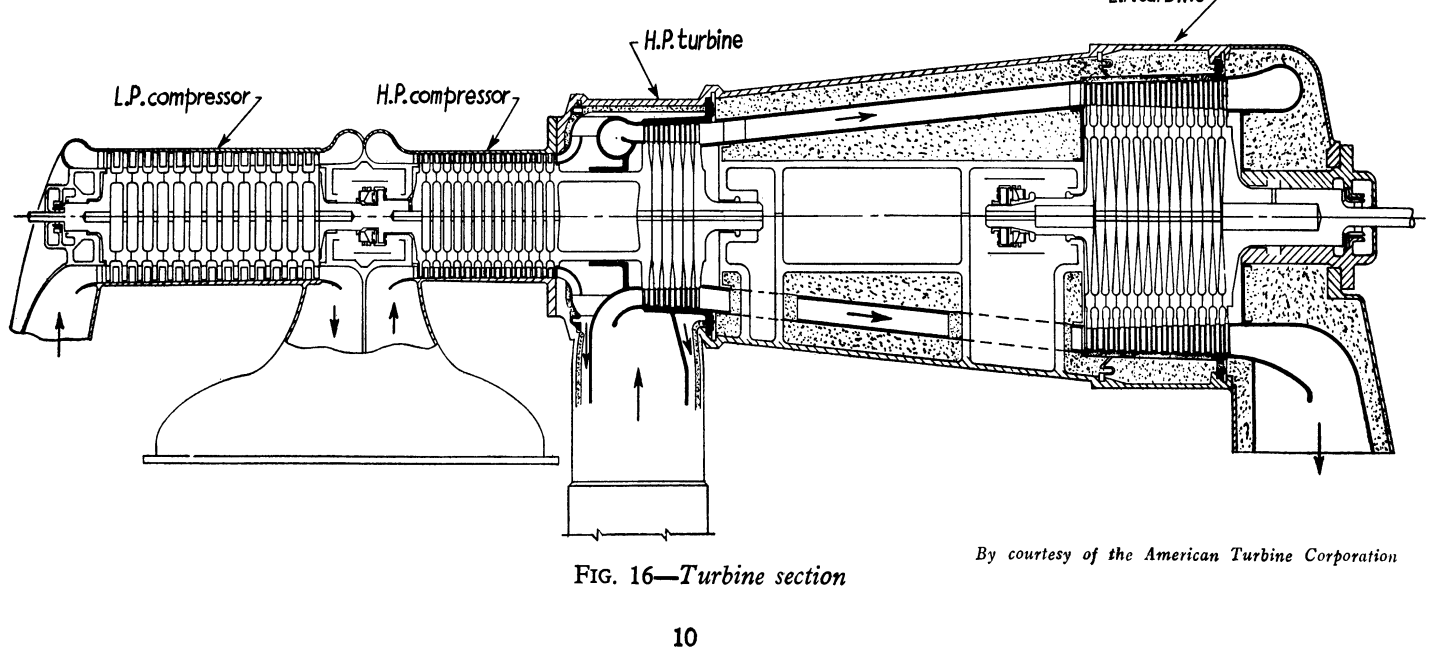
Control System

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 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,



By courtesy of the American Turbine Corporation

FIG. 16—*Turbine section*

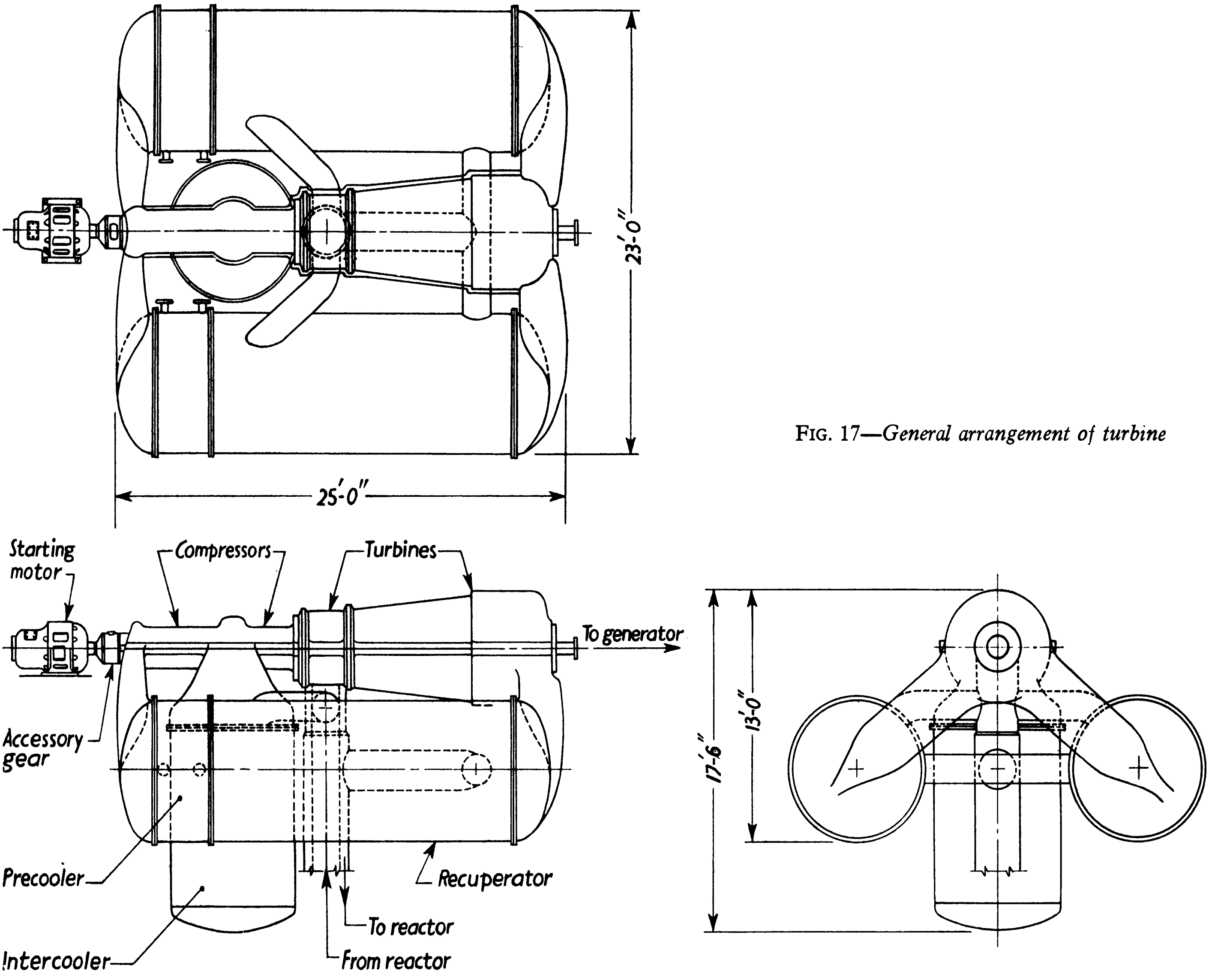


FIG. 17—*General arrangement of turbine*

By courtesy of the American Turbine Corporation

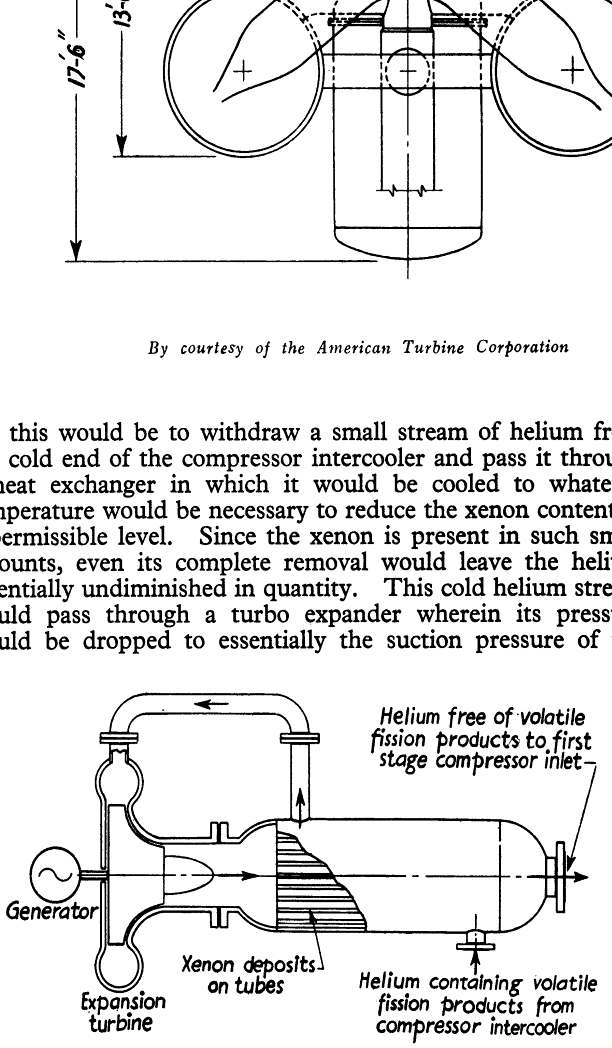
the power turbine overspeed governor trips the system pressure regulator, resulting in the discharge of the contents of the system to the receiver. Simultaneously, the control rods are dropped into the reactor, reducing the heat input to the system.

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 would be dropped to essentially the suction pressure of the



By courtesy of the American Turbine Corporation

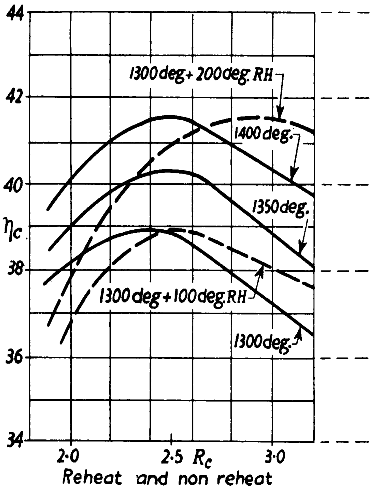
FIG. 18—*Xenon trap*

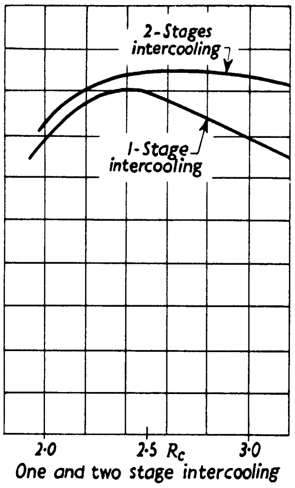
compressor. In passing through the expander, the helium would be cooled sufficiently so that it could act as the refrigerant for cooling the xenon cold trap exchanger. A typical arrangement of this type of trap is shown in Fig. 18.

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.





By courtesy of the American Turbine Corporation

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 γ = 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 $= \sqrt{2{\cdot}4} = R_c$ = 1·55:1
$R_c^{(\gamma-1)/\gamma}$ = 1·191
$1—R_c^{(\gamma-1/\gamma)}$ = 0·191
Adiabatic temperature rise ΔT_{ad} = 105°F.
Adiabatic efficiency $\eta_{com.}$ = 0·88
Actual temperature rise ΔT = 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.
ΔT_{com} = 240°F.
T_7 = 1,620°R.
Adiabatic efficiency $\eta_{exp.}$ = 0·888
Adiabatic temperature drop ΔT_{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 $R_{e\ HP} = (1{\cdot}17)^{2{\cdot}51}$ = 1·48:1

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

Recuperator
T_8 = 1,402°R.
T_4 = 670°R.
Available temperature range δ_t = 732°F.
Effectiveness, per cent η_r = 92·3
Increase in temperature in recuperator ΔT = 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) ΔT_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.

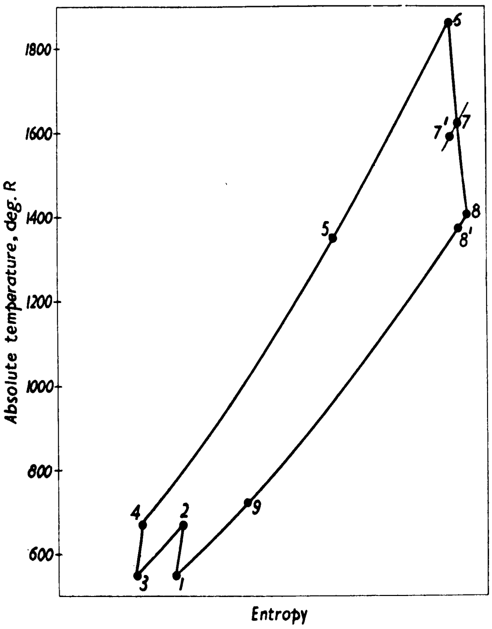


FIG. 21—*Proposed cycle for helium plant*

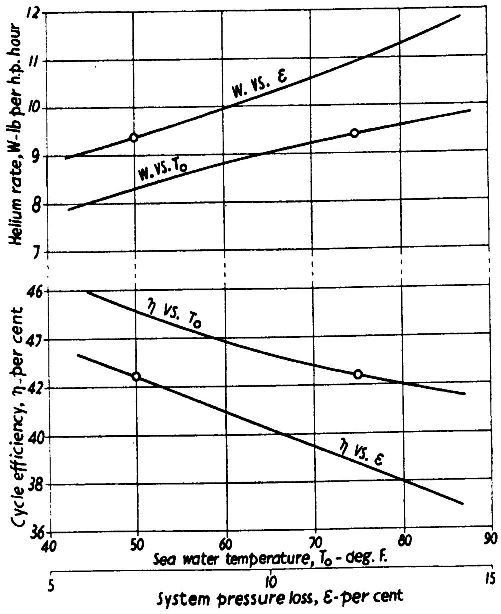


FIG. 22—*Correction for off-design conditions*

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.

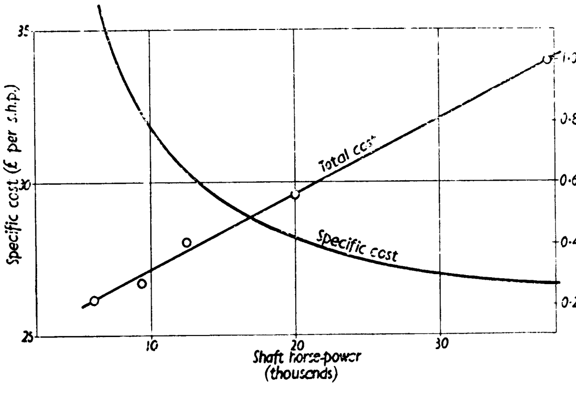


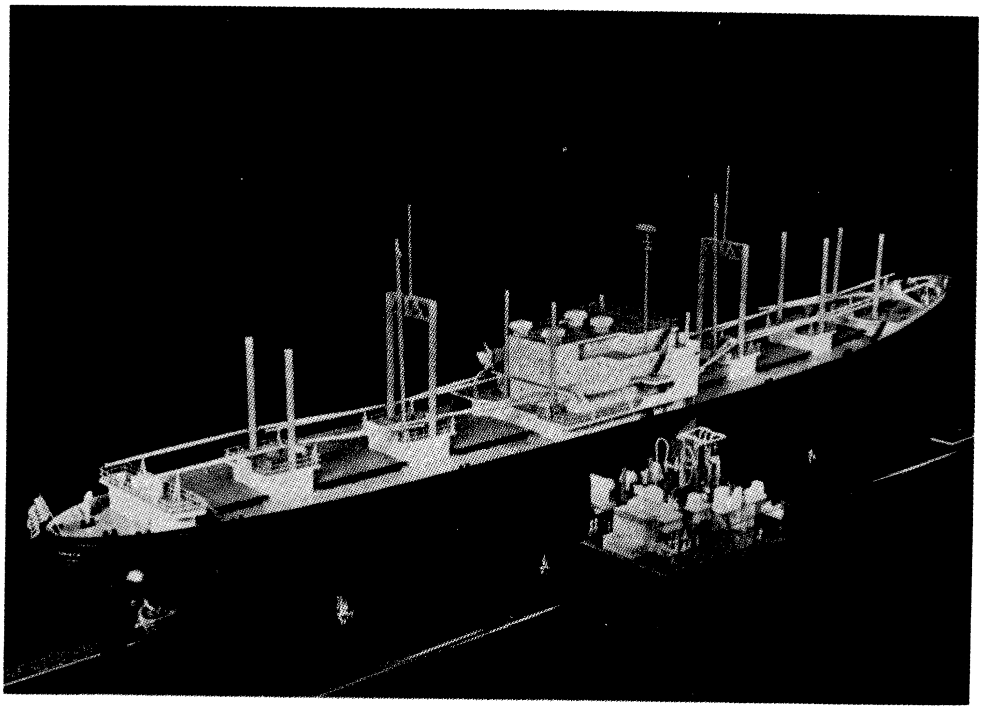
FIG. 23—*Graph of cost estimates for steam turbine machinery*

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 presumed that a sodium loop reactor would be used to provide steam of sufficiently high superheat. 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.

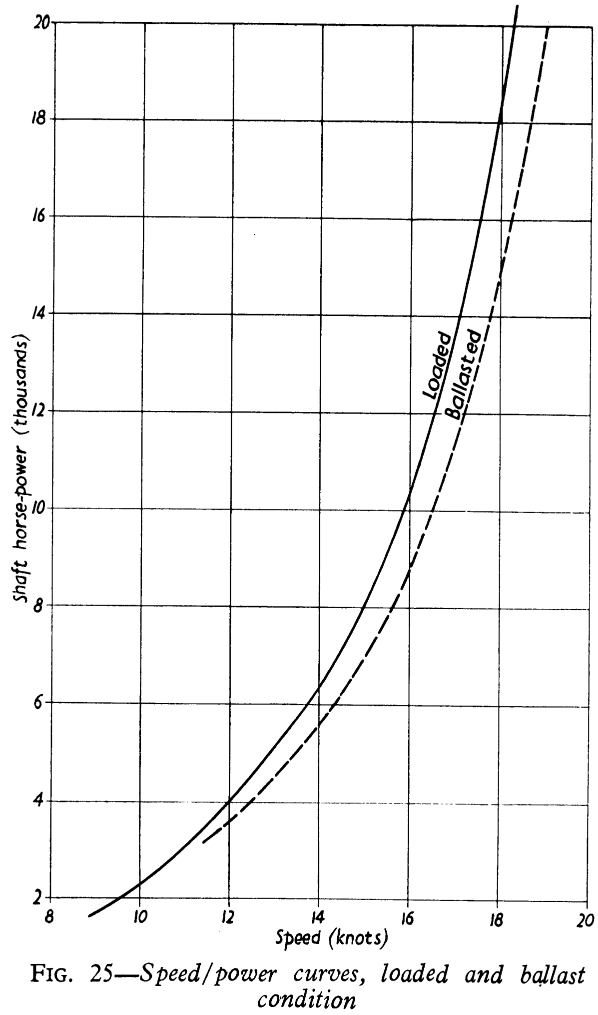


FIG. 25—*Speed/power curves, loaded and ballast condition*

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 $\frac{20{,}000}{13{\cdot}2 \times 24}$	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 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:

	£
Fixed charges = $\frac{48 \times 11}{365 \times 100}\left(1{,}000{,}000 + 5{,}862\mathrm{X}\right)$	$= 14{,}480 + 85\mathrm{X}$
Fuel at £X per gram	$= 1{,}954\mathrm{X}$
	$14{,}480 + 2{,}039\mathrm{X}$

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

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

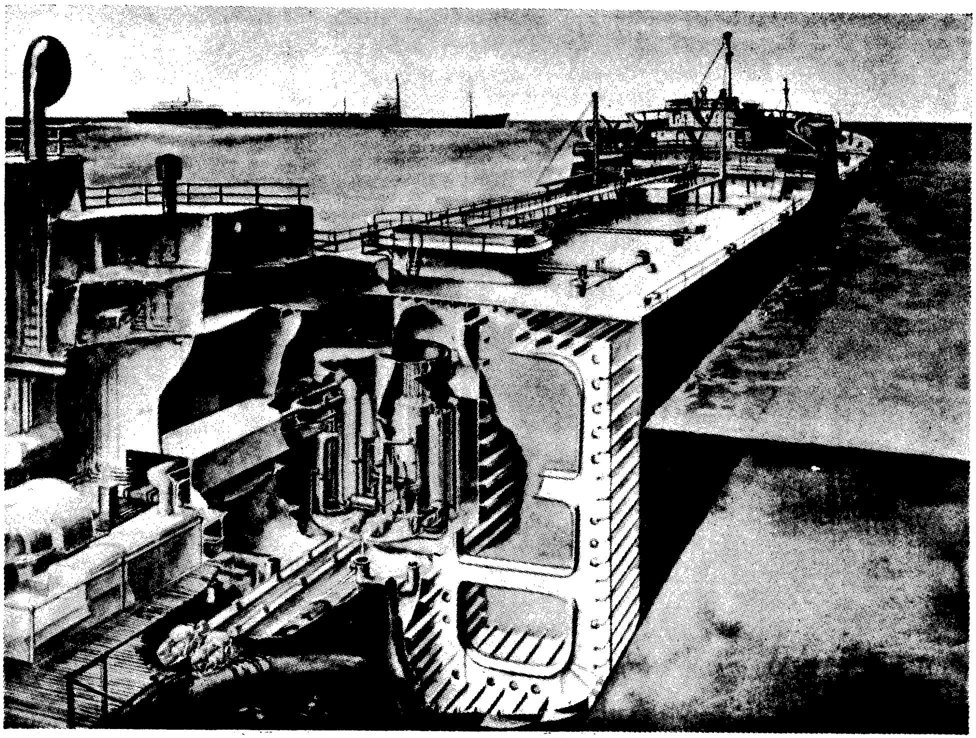
At the international conference on the peaceful uses of atomic energy held in Geneva in August 1955, the price of uranium was quoted at \$25.00 per gram of U.235. It was not stated whether or not this figure included an allowance for fuel element fabrication. Even allowing for some error in this figure, 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.

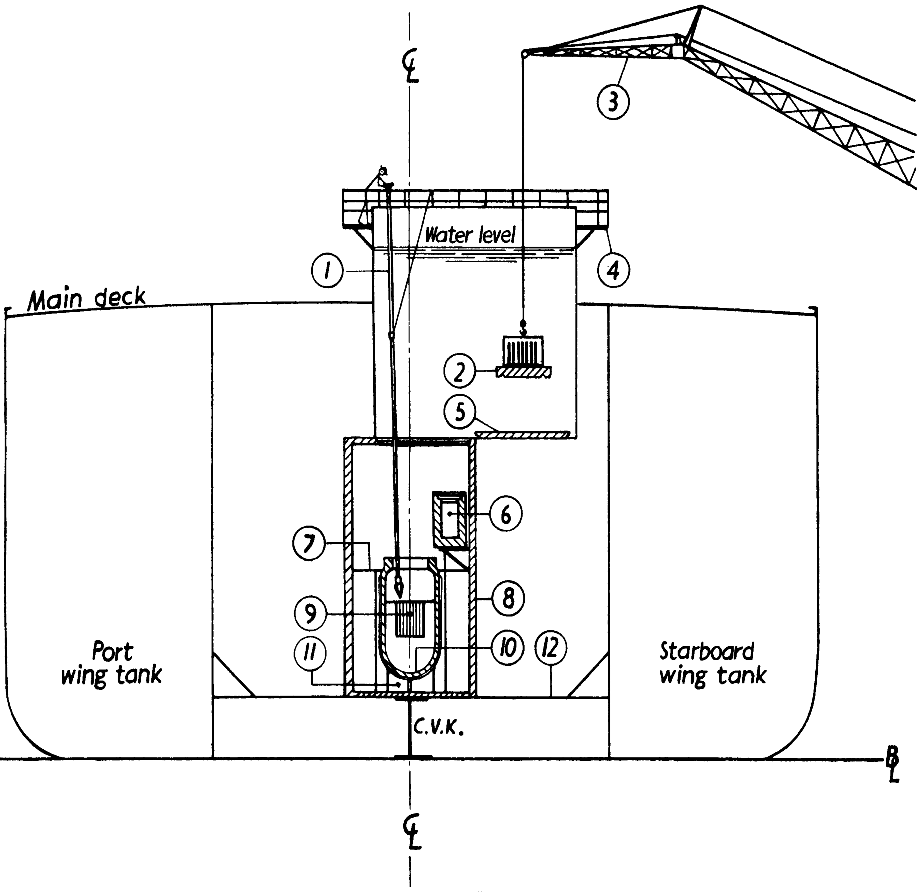
No account is taken of the additional investment to cover the charge of helium, but it is not expected that this would unduly affect the comparison.



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 maneuvering 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 discussion on Ref. 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.

The auxiliary machinery will all 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% 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 Ref. (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 1500 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 tanker featured in Ref. 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.

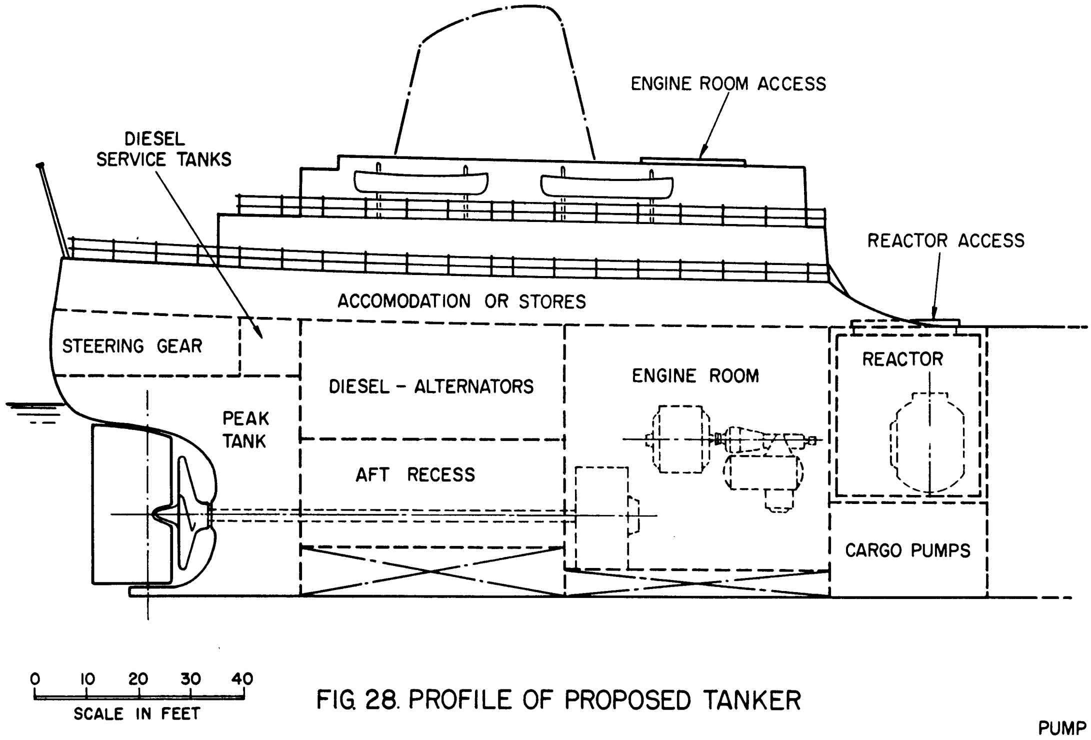


FIG. 28. PROFILE OF PROPOSED TANKER

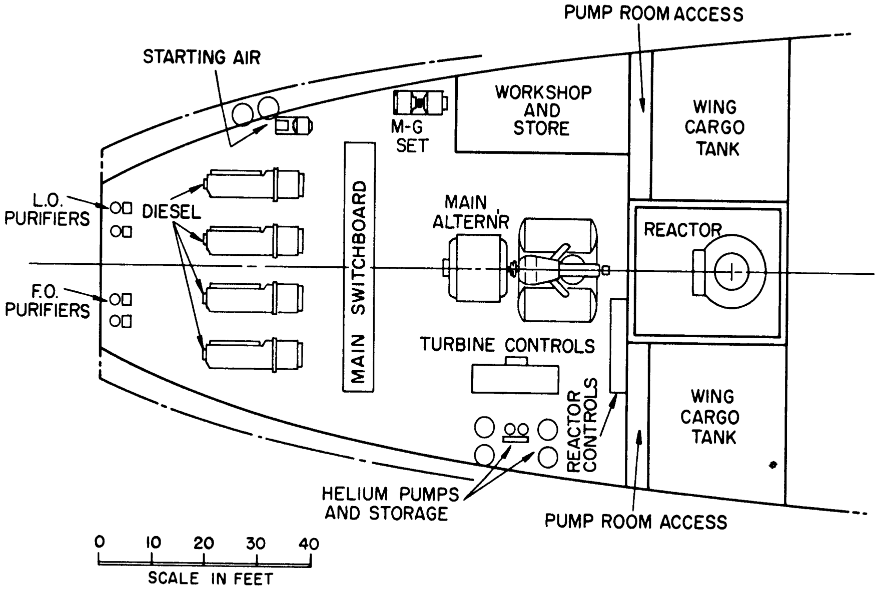


FIG. 29. PLAN AT OPERATING LEVEL

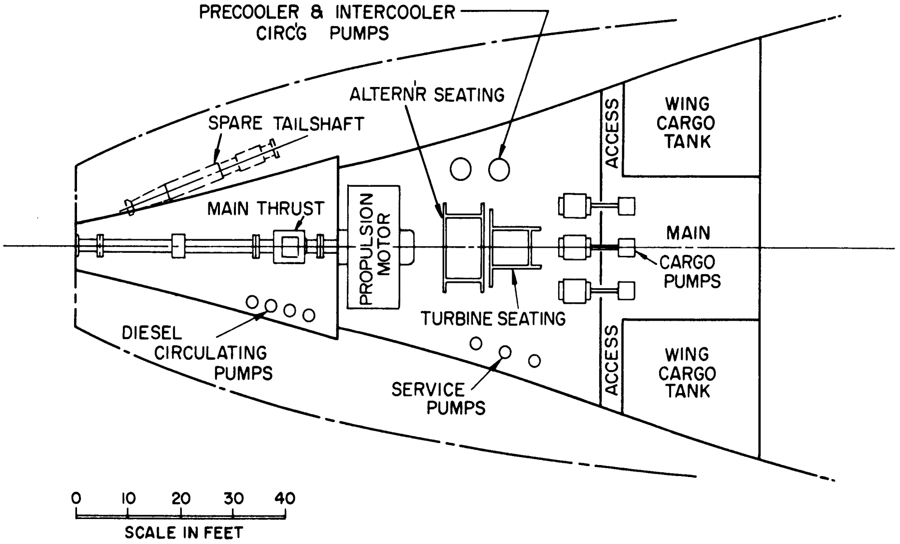


FIG. 30. PLAN AT LOWER LEVEL

(b) The in-line unit could be replaced by a co-axial arrangement in which the alternator and low pressure turbine is 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.

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, then to use the funnel as housing for a luxurious 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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