ATOMIC ENERGY FOR SHIP PROPULSION

by

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The development of power from atomic energy is a problem which is occupying much attention in the world to-day. A new field of natural resources in the form of uranium and thorium may be opened up as alternatives to the conventional fuels of coal and oil.

The application is of particular interest to the navy in that adequate power may be produced from very small quantities of these new fuels. Endurances of ships powered by atomic energy may be much greater than those powered by existing plants.

A further need for this form of propulsion lies in the existing type submarine; nuclear units could be constructed so as to be independent of oxygen supply. These enhanced endurances would therefore apply to the submerged as well as the surface condition.

Owing to the effort involved in manufacturing the fuel in a suitable form and in constructing these new units, a number of years will elapse before this application will take place. The research and industrial effort needed is much greater than the work required to convert the navy from coal to oil in the past.

Since the war Great Britain has embarked on a programme of research into the possibility of the production of power from atomic energy. Units for the production of nuclear fuels in a suitable form are under construction.

During the war years and since, America has produced nuclear fuels in quantity for atomic bombs, and, with considerable research experience gained in recent years, is embarking on a power programme. One of the units called reactors, is destined for naval use. This has been described in a United States Atomic Energy Commission press release dated 9th February, 1949 :— " The navy reactor is now being developed by the Argonne National Laboratory and arrangements have just been completed with the Westinghouse Electric Corporation to carry these designs through to the construction and operation of a reactor which we hope will serve as the land-based prototype for a power source for a naval vessel. Much work remains to be done before this reactor will become a reality. To-day the plans for the land-based unit are not yet finished, but we hope that they will be completed and that actual construction on this unit will be started in about one year."

RAW MATERIALS

The starting point in any atomic energy programme is the acquisition of natural uranium which forms quite a high percentage of the earth's crust but occurs in only a few places in a reasonably concentrated form. In Canada and in the Belgian Congo ore is mined which contains up to 2% of natural uranium. There are many other less concentrated deposits from which it requires more effort to extract the uranium.

Natural uranium contains three isotopes (chemically the same but physically different) in the following percentages U-238 99.3%, U-235 0.7%, U-234 0.004%. Of these three constituents only U-235 is directly useful as a nuclear fuel.

The initial supply difficulties are therefore apparent. There is hope in the future however for an alleviation in the supply of raw materials in that thorium occurs more plentiful than uranium ; one deposit is in Travancore, India. Like U-238 it has no direct use as a nuclear fuel but both thorium and U-238 can be converted into a more readily useful fuel.

CONVERSION OF RAW MATERIAL

The readily useful part of natural uranium, U-235, can (by virtue of its slightly differing physical properties) be separated from the other constituents. There are several ways of performing this operation which are extremely costly, absorbing large quantities of electric power. An American plant built for the purpose required an electric generating plant to be built on the site which was the largest single unit in the world.

An alternative plan is to convert U-238 in natural uranium to a new element called plutonium which is a more readily useful fuel and, since it is a different element from uranium, it can be separated chemically.

The process of conversion has to take place in a pile. The natural uranium pile is a very large affair and as so far envisaged does not produce power which is readily available. The American plutonium production piles were cooled by water. This type of pile is large as natural uranium is the only fuel available at the outset and it contains such a small percentage of the useful constituent U-235.

MECHANISM OF THE PILE REACTION

When a free neutron (an un-charged nuclear particle) enters the nucleus of U-235 atom the nucleus splits into two approximately equal parts with the release of a large amount of energy. This is the so-called fission process and heat is derived from the kinetic energy of the fission fragments. In addition a number of neutrons are ejected and so there is the possibility of a chain reaction, for the neutron which caused the original fission has been replaced by a new neutron, which, if not lost from the system, can cause further fission.

There are several ways in which the neutrons may be lost from the system :—

(1) escape.
(2) competitive capture by impurities.
(3) capture in U-238.

For a chain reaction to occur it is necessary that, after these losses have been allowed for, there is at least one neutron left to carry on the reaction. As escape is more probable for neutrons born near the surface of a system (say a sphere of fissile material) it is clear that the larger the sphere, and hence the larger the volume/surface ratio, the smaller will be the proportion of neutrons lost from the surface. Losses by (2) and (3) are not affected by size. The size at which the chain reaction is just possible is called the ' critical size '. Above this size one neutron gives rise in the system to more than one neutron and there is an increase from generation to generation of the total neutrons in the system. Below this size the chain reaction cannot proceed. The ratio of the number of neutrons in one generation to the number in the preceding generation is usually called the multiplication factor and denoted by k.

The lifetime of an average neutron between birth and capture depends on the type of pile, varying between one thousandth of a second and a fraction of a millionth of a second. If k becomes slightly larger than one, a catastrophic increase in the number of neutrons in the system would result were it not for the fact that .5% of neutrons resulting from fission remain in the fission fragments for seconds, minutes, and even hours after the fission has occurred. *These delayed neutrons are not available for immediate reproduction.* Thus, in a pile running at a fixed level, 99.5% of the neutrons present are prompt, i.e. they are a result of the fissions which have just taken place ; and .5% are delayed and are the after-products of fissions which have taken place some seconds previously. Provided that (k—.005) is not greater than one, the neutron level cannot increase at an explosive rate as the prompt neutrons do not quite reproduce themselves and the delayed neutron contribution is always lagging behind a rising neutron level.

A reactor is controlled entirely on these delayed neutrons, i.e. k is always less than 1.005.

CONSTRUCTION OF REACTORS

Natural Uranium Piles

It has been stated that the readily useful constituent of natural uranium is U-235 and that a chain reaction with natural uranium is not possible owing to the capture of neutrons by U-238.

A natural uranium pile involves the reduction of the energy of the neutrons to a level at which the ' fission cross-section ' of U-235 is greatly increased and the probability of fission of U-235 is greater than the probability of capture by U-238. This is achieved at thermal energies when the neutrons have an energy corresponding to energy of vibrating atoms at normal temperatures.

The reduction of neutron energies is brought about by collisions with atoms of a ' moderator ' which is introduced for the purpose. The energy transfer by elastic collision between two particles is a maximum when the particles are equal mass and decreases as the ratio of masses increases ; furthermore it is clear that these atoms must not capture neutrons strongly. This limits us in the choice of moderator material to heavy water, carbon (graphite) and beryllium.

In a natural uranium pile, moderation is not quite sufficient in itself to allow a chain reaction since the neutron is passing from fast to thermal pass through an energy level at which U-238 has a resonance for capture. In order to overcome this, the uranium is lumped in the form of rods in a background of the moderator. In this way the probability that the neutrons created in a rod will return or reach another rod before reaching thermal energies is very much reduced.

In order to contain the fission products and prevent corrosion, the uranium rods are canned in a material which has a low capture cross-section for thermal neutrons. Aluminium so far has been the most satisfactory material for this purpose.

When the pile is built up to critical size, control is effected by inserting or removing rods of material such as cadmium or boron which capture thermal neutrons very strongly. Inserting the rods lowers the activity of the pile. Neutron flux levels in the pile are measured by ionization chambers which operate, through electronic systems, the mechanism which inserts or withdraws the control rods.

To extract the heat generated a coolant must be pumped through the pile. Again this coolant must have a low capture cross-section as must all materials in the reactor. Gases and water have been used satisfactorily.

The pile is surrounded by a reflector which reduces the losses of neutrons from the surface. The whole pile and reflector is surrounded by several feet of concrete and steel to protect the operators from the highly penetrating radiation from the pile.

It will be seen that in the struggle to make a chain reacting system with natural uranium, severe restrictions have been placed on the use of the materials in the core. It is with relief that, in view of this and the overall size, we turn to the other possibility, the use of enriched fissile material i.e. material containing a much higher proportion of the more readily useful fuels such as U-235 and plutonium.

The natural uranium pile is a necessary stage in the production as the U-238 is converted by neutron capture to plutonium and, after a time interval, the uranium rods are removed from the pile and chemically processed to separate the plutonium.

Enriched reactors

The use of enriched material allows much wider scope in the design of nuclear reactors :—

(i) We may use highly enriched material without moderator so that the mean neutron energy is not greatly lower than that of fission energy. Such reactors are called ‘ Fast reactors ’.

(ii) We may use relatively small amounts of moderator to reduce the neutron energy to a range above ‘ thermal ’ but below ‘ fast ’. This may be called an intermediate reactor.

(iii) We may use enough moderator to reduce the neutrons to thermal energy giving what may be called an enriched thermal reactor.

In enriched thermal reactors the choice of material is still somewhat restricted although small quantities of sheathing materials more suitable than aluminium from the heat transfer point of view can be used.

In fast and intermediate reactors a much wider choice of heavy metals can be used as structural materials and even as coolants.

It is observed that, with these advanced reactors, the difficulties of the natural uranium piles with respect to outlet temperature and critical size can be overcome and units suitable for replacing the heat source of an engine system in a ship could be built.

The research and development effort required to achieve this end is, however, immense.

Special Considerations for naval reactors

(i) The reactors will have to be small and, as the weight of the shielding is the major part of the reactor weight, the most suitable materials will have to be used.

(ii) After a time the fissile material will become exhausted and arrangements for a servicing organization will have to be provided for the removal of the core or fissile elements.

(iii) When the material has been processed the residue will consist of highly radioactive liquors whose safe disposal is a major difficulty.

(iv) Vulnerability of ship and consequent effect on sea areas if the reactor becomes damaged by enemy action, collision, etc.