NUCLEAR PROPULSION

Most of the literature on the use of nuclear power for marine propulsion has either been of the popular and imaginative variety, or has been written by physicists with little appreciation of the practical limitations of marine engineering. This article, which is an abridged form of 'Atomic Power on Shipboard—Let's be Practical', by H. F. Crouch, in the Journal of the American Society of Naval Engineers for May 1954, *deals with the subject from a more realistic aspect.*

In June 1951, the keel was laid for the world's first atomic-powered submarine. At the ceremony, the President of the United States said : 'The military significance of this vessel is tremendous. The engine of the *Nautilus* will have as revolutionary an effect on the navies of the world as did the first ocean-going steamship 120 years ago. But the peaceful significance of the *Nautilus* is even more breath-taking. When this ship has been built and operated, controllable atomic power will have been demonstrated on a substantial scale.' In January 1954, the public was informed that this vessel had been launched.

Nuclear Reactors

The statement by the President referred to the ‘ engine ’ as the revolutionary feature of the heralded vessel. This is not quite true. We have to go farther back in the propulsion plant than this, to the primary heat source which generates the steam. Here, we find the conventional marine boiler and fuel oil supplanted by a nuclear reactor and nuclear fuel. It is the nuclear reactor—its design and operation—that comprises the basis of the new technology, and not the engine proper. Fundamentally, then, nuclear reactors are an alternative source of heat for the generation of steam. This, in essence, is the scope of ‘ atomic power.’

Nuclear reactors, when substituted for ordinary boilers and fuel tanks, represent the primary equipment for converting the energy of nuclear fission into forms of useful power. They are complicated, expensive, and subject to a great variety of conceivable designs. They provide man with the most concentrated source of energy thus far devised and, in the imagination at least, have unlimited potentialities. They point to significant savings in space and increased cruising time without the necessity for refuelling.

From *theoretical* mass-energy relationships, one pound of nuclear fuel, if completely fissioned, is approximately equivalent to 250,000 gallons of fuel oil, or to forty billion B.Th.U.s of heat. And, one pound is slightly larger than one cubic inch.

Such a relationship is impressive. But it leads to all kinds of distorted conclusions. Converting this tremendously concentrated quantity of heat into superheated steam, to say nothing of the biological hazards involved, is a difficult practical matter. The conversion process requires a substantial array of complex coolant piping, critical control mechanisms, remote fuel-handling equipment, massive shielding, novel heat exchangers, and so forth. Technical problems, though not insurmountable, are not separable into neat little packages which can be solved one at a time. The result is a physical complexity involving methods for utilizing the fuel, fluid mechanics, damage by nuclear radiation, and the corrosion and structural properties of highly specialized metals and materials.

Consequently, enthusiastic forecasts about the ultimate potentialities of nuclear energy aboard ship should be tempered. For example, the idea of a chunk of fissionable material occupying space about the size of a football being capable of energizing an entire aircraft carrier for a year or two at a time is fantastic. On the other hand, after an extensive programme of applied research and development, it is probable that the *saving* in space may approach, though it may never exceed, say 30 per cent. of the combined space now used on board ship for the generation of steam. And it is conceivable that a vessel could steam for as long as six months without having to recharge or recycle her reactor. Even this degree of compactness and fuel economy is justification for the study of nuclear fuels and reactors. Whether the operating efficiency and maintenance requirements of nuclear equipment can compete favourably with existing ships’ boilers, remains to be seen.

Uranium-235

Nuclear fuels liberate heat by the fissioning of atomic nuclei of certain materials. There are only three known types of such fuels, namely : uranium-233, uranium-235 and plutonium-239. The figure following each material represents the sum of the neutrons and protons in the centre or nucleus, of *each atom* of that material. The nuclear characteristics of these materials are such that the addition of one more neutron will compound them into an excited state and, subsequently, will cause them to break apart. The resulting kinetic energy of the fission fragments is dissipated in the form of heat and other radiation.

The only natural-occurring nuclear fuel is uranium-235. The other two fuels must be produced artificially. Following more than a decade of experimentation and study, more is known about the characteristics of U-235 than of either of the artificial fuels. As a consequence, it is the most common fuel for nuclear reactors today.

One of the primary challenges to the design physicist in computing the fuel requirements for a nuclear reactor is to minimize both the total amount of uranium used and its enrichment level. This is not only because of its high cost but also for conservation reasons. Uranium is a vital national resource, not necessarily unlimited in quantity.

A word about the physical properties of uranium : it is a very dense material, half again as heavy as an equal volume of lead. When oxidized in air, it looks very much like lead, although when freshly cut it is lustrous and white. It is a metal with a melting point in the neighbourhood of 2,000°F. It is malleable and ductile, and can be machined or cast to any desired configuration. When finely powdered, it is highly inflammable. But this has nothing to do with its use as a nuclear fuel.

Heat from Metal

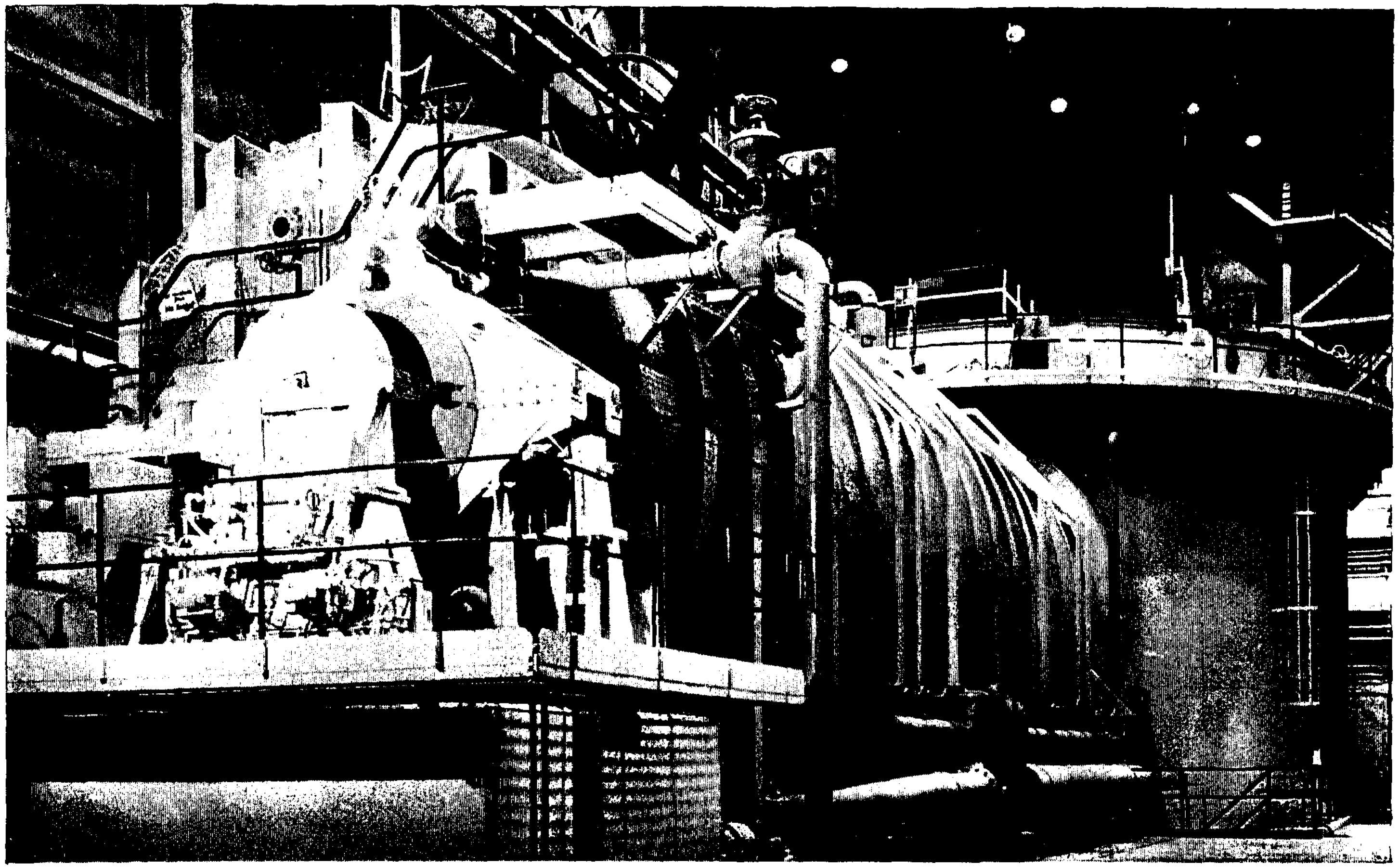
We are discussing a *metal* being used as fuel, and we cannot shovel it into a reactor like coal, or melt it and pipe it in like oil, and expect it to generate heat. In the first place, there is a certain minimum amount, or ‘ critical mass,’ that we must have. It has been found that, for a given enrichment level, there is a specific minimum quantity of fuel that will sustain a fissioning ‘ chain reaction.’ Any quantity less, of course, will not produce the nuclear phenomenon desired. And secondly, we must arrange the fuel with minute care for purposes of control and heat transfer.

If the required amount of fuel for criticality were arbitrarily assembled into one mass, we would have an atomic explosion rather than a nuclear reactor. This poses the problem of segregating the fuel into small components to facilitate delicate criticality adjustment, and to provide reserve material to keep the chain reaction going as the fissionable nuclei are burned-up. Unlike shipboard boilers, reactors have no air registers to adjust nor oil pressures to regulate. Such regulation and control is, in part, accomplished by the configuration, design, and spacing of the fuel within the reactor.

Another reason for dividing the fuel into small segments is to permit the passage of a coolant for the removal of the generated heat. In an ordinary boiler, the chemical combustion of the fuel produces gases which pass along and around coolant tubes in a simple flow pattern. This is not the case in reactors. Instantaneous heat is developed deep within the metal fuel and the only effective way that it can be removed is by a direct interface contact between the coolant and the fuel itself. Unless this is done, the fuel will melt, and so will the structural members of the reactor. The removal of heat, therefore, is one of the crucial problems in the design of nuclear reactors. This problem is partly met by the fabrication of the fuel into numerous separate ‘ fuel elements.’

Fabrication of Fuel Elements

In order to meet these spacing requirements, fuel elements must be formed into thin plates, small-diameter rods, pins, bars, pellets or other suitable shapes.



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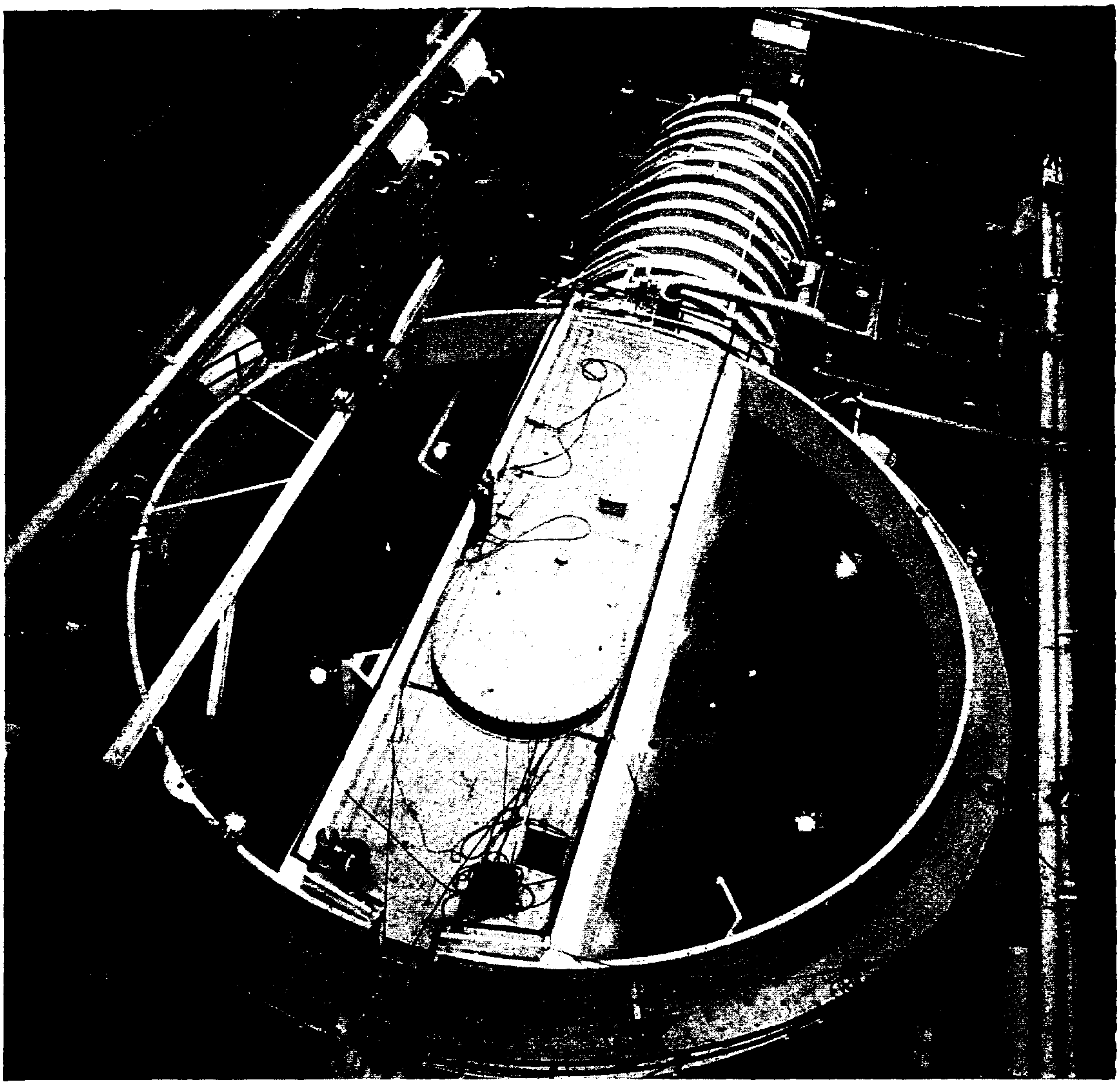

A THREE-QUARTER VIEW OF THE PLANT

Some advanced reactor designs utilize the fuel in its molten state or as a fused salt, but these fuel element designs are beyond the discussion here. So far, the major attention has been given to the technology of solid fuel elements.

Now, if we were to take the required number of bare fuel plates or rods and arrange them in a reactor, what would happen ? In the first place, because of the intensity of the fission, microscopic heat ' spikes ' or bumps would appear on the surface of the fuel metal and present restrictions to the coolant flow. The seriousness of these surface irregularities would depend upon the form of fuel and the type of coolant. At the same time, radioactive contamination would join the coolant cycle. Even without fission, the flow of the coolant will corrode the fuel, particularly so, at high temperatures. Furthermore, the action of a fluid coolant will flake-off, erode, and cause partial solubility of the fuel in the coolant in such a way as to cause deposits of the fuel material elsewhere in the system. These deposits have an adverse effect on criticality control and heat transfer and, consequently, a greater amount of costly make-up fuel is required. It is apparent, therefore, that the fuel elements cannot be placed directly in the coolant medium like the plates in a wet storage battery. Instead, we must add a protective cladding or container jacket.

The cladding material may be aluminium, stainless steel, zirconium or other metal which has the desired nuclear and structural properties. The container metal stops recoiling fission fragments and minimizes the radio-active contamination of adjacent reactor materials. Corrosion and erosion of the fuel, also, are minimized. In short, the metallurgical preparation of the jacket completely seals the fuel and its fission products into small manageable units or segments.

For practical reasons, fuel elements are more generally fabricated into cladded plates or pins. Depending on the type of fuel element, a rigid sequence of rolling, machining, drawing, swaging, and inspection for close tolerances is required. For a reactor suitable for shipboard purposes, from several hundred to several thousand of these fabricated elements would be needed. All such fabrication work is done ashore under a ' controlled atmosphere ' due to the inflammable dust and conservation measures involved.

Core and Coolant

The furnace of a reactor is called the core. Here, the fuel elements are positioned to maximize the capture of random neutrons by atoms of fissionable material. In this central fissioning region, a stringent economy of neutrons must be maintained. Any leakage of them outside of the core, or their absorption by non-fissionable nuclei in fuel, coolant and structural materials, would reduce the reactivity and power density of the core. For this reason, all materials used in the construction and operation of a reactor, including even the welding material, must be selected on the basis of their nuclear compatibility with neutron economy requirements. At the same time, such materials must exhibit structural stability and must not be readily damaged by the intense neutron irradiation. This excludes almost all materials used in present-day boiler construction.

The ideal shape of a reactor core is that of a sphere. This presents the best configuration for the maximum conservation and utilization of the trigger neutrons. Upon each fissioning process, the new-born neutrons speed around randomly. The purely random nature of their direction is such that a spherical fuel mass best keeps the chain reaction going. However, the construction of a spherical reactor shape has practical limitations. Not only is it difficult to fabricate, but access for the insertion and removal of fuel and the complex channeling of coolant required, lead to other major objections. The next best shape is cyclindrical but this, unavoidably, leads to some inefficient use of the fuel material.

Any heat generating source requires some medium to remove the heat from the furnace area to other regions for its conversion into steam. In a naval boiler, for example, water-filled tubes perform this function. In reactors, where heat densities are much greater, water may be used but the trend is towards the use of *liquid metals* for the primary coolant. Examples are bismuth, lead, potassium, sodium and alloys thereof. These low melting point metals permit high temperature operation in low pressure systems. High coolant temperatures are necessary for efficient recovery of power from a reactor and low pressures are conducive to simplified designs. Liquid metals also have high heat capacities and good heat transfer properties so that heat exchange surfaces and quantities of coolant used are small.

When any coolant passes through the reactor core, it is exposed to neutrons which may make it radioactive. During the total time that the coolant is in the reactor, there is a continuous birth of radioactive atoms and also a continuous decay. When the coolant leaves the reactor the birth activations stop but the radioactive decay continues, emitting harmful particles and rays. This decay, or induced radioactivity, necessitates the installation of heavy shielding around the entire heat transfer system in order to protect operating personnel. This requirement has led to the development of ' binary ' coolant systems with great and overriding advantages of providing isolation of the steam and turbine section of the propulsion plant from the reactor proper.

Pumps and Heat Exchangers

In most boilers, water and steam circulation takes place by natural convection, that is, cold water flows downwards ; hot water and steam flow upward. In reactors, on the other hand, forced circulation generally must be used. Effective and efficient heat removal requires rapid coolant flows that cannot be accomplished by natural means. This is particularly the case with molten metal coolants.

The pumping of molten metals has introduced new hazards and major problems into reactor system designs. When pumping a liquid metal, say at 1,000°F, careful design must be made to prevent leaks, spills or accidents to the pumps themselves. Aside from the radioactive contamination in the coolant, any metal leak at this temperature would almost certainly start a fire somewhere, or if not, the leaking metal would be difficult to cool and control. As a result, reactor pump leak-tight specifications are very rigid. For example, the usually specified leakage tolerance is *one cubic centimetre in ten years!* Such a specification has eliminated the use of conventional rotating or reciprocating seals or bearings in the primary coolant system.

To meet this situation, two approaches have been made : one, the development of a fluid bearing centrifugal pump, and the other, the development of electromagnetic pumping. Electromagnetic pumps are devoid of bearings, blades, seals and shafts. They are very durable but their capacities and efficiencies are low. Liquid metal centrifugal pumps, on the other hand, attain higher pumping flows but they are subject to general mechanical failures. Nevertheless, successful pumps of both types have been developed to give satisfactory service in temperatures up to 1,000°F.

Because of the radioactivity in the molten coolant and its high temperature, it is desirable to have triplicate pumps at all flows, plus an adequate supply of spares. For example, 10 to 15 pumps might be required for a reactor as compared with two or three feed-water pumps for a boiler. Upon any malfunctioning of a reactor pump, immediate repairs cannot be made. Not only must the inoperative pump be allowed to cool-off thermally, but radioactively as well, before maintenance personnel can disassemble and handle it. This may take days or weeks. If it becomes necessary to disconnect and remove a defective pump from the system, remote-handling hoists with periscope visual aids are required, together with personnel working under a time limit and behind biological shielding. It also may be necessary to discard a pump entirely, either because of persistent radioactivity or solidifying of the metal coolant with internal critical parts of the pump. As an overall consequence, we must anticipate a considerable number of complicated pumps and pump-maintenance problems.

What reactors require in the way of additional pumps is partly compensated by the lack of valves. Indeed, valves are conspicuous by their absence in the primary coolant system of a reactor. To be of use, they would have to be quite large ; they would have to be remotely operated through the reactor shielding ; and they would have to operate in radioactive metal fluids. Packing against leaks would be almost an impossibility. They would cause much trouble, and would be subject to ‘freezing’ in some adverse open-close position. Consequently, as far as practicable, valve regulating functions are designed into the coolant system by ingenious variations in pipe sizes and pump-speed controls.

When the primary coolant leaves the reactor it goes to a heat exchanger-boiler where it gives up its heat to a secondary coolant, usually water. If the primary coolant is liquid metal, obviously it cannot be circulated directly through the turbine. The heat exchanger-boiler (there may be several in the total system) represents the transition from nuclear reactors to regular boiler plant functions. Here, secondary coolant tubes are arranged to extract heat from the primary coolant in adequate quantities and at the optimum steam temperatures and pressures for the reactor plant design. The turbine then is coupled to the total steam plant in the conventional way.

One major feature that distinguishes nuclear heat exchanger designs from ordinary heat exchangers is that the secondary coolant, if water, must never come in contact with the primary coolant, if a liquid metal. There are two reasons for this : firstly, in the event of leaks in the primary tubes, radioactive contamination would spread to areas outside the reactor shielding, to say nothing of the loss of the costly coolant involved ; and secondly, if an alkali molten metal were to meet with water, a violent chemical reaction and explosion would take place. To avoid these possibilities, special concentric-tube construction provides an intermediate barrier or leakage space between the two coolants. When the annulus is filled with, say, lead or mercury, good heat transfer is provided as well as good leak protection and detection.

Starting and Control

The starting of a nuclear reactor, like that of any boiler system, requires a sequence of warming through and checking. This pertains to the primary and secondary coolant loops, sensing instruments, safety devices, control mechanisms and all associated reactor auxiliaries. If we consider only the primary coolant loop, for the moment, we learn that first we must preheat the entire system with a hot inert gas, such as helium, to thermally condition the lines (to avoid cracks and ruptures ; to test for leaks, etc.) before receiving the coolant medium. If such a medium is metal, it must be uniformly heated above its melting point, then circulated through the system, gradually increasing its temperature to the normal operating inlet temperature of the reactor. This may be up to around, say, 600°F. To preheat the coolant to this temperature, a separate oil-fired conventional boiler is needed as an auxiliary.

The lighting-up of a modern marine boiler can be accomplished in several hours. For a reactor, this may require several *days*. Another difference is that the warming through is accomplished without any heat being generated in the reactor core. In a nuclear sense, the reactor would be subcritical or ‘cold.’ Actually, of course, at the preheat temperature mentioned above, the reactor internals would be warmed which is highly desirable in order to avoid sudden and unequal expansion therein.

There is another contrast between an ordinary boiler and a reactor, and that is the arrangement of the fuel supply. In a boiler plant, the fuel is contained in tanks outside the furnace area, preheated, pumped in and atomized. For a reactor, the entire fuel supply is contained within the reactor core. The quantity of fissionable material must be sufficient to meet critical mass conditions ; to compensate for fuel depletion for the contemplated cycling time of the core (analogous to maximum cruising range) ; and, to provide additional reactivity to ‘override’ the fission product poisoning in the core. The total quantity of fuel can only be packed in the reactor when all control rods are in the full ‘ in ’ or ‘ black ’ position. Otherwise, a dangerous supercritical condition would exist—spontaneously.

Control rods consist of materials, usually impurities or ‘ poisons,’ which have an affinity for the non-fission capture of neutrons. These materials, such as boron and cadmium, are alloyed with steel rods in sufficient quantities to rapidly absorb great numbers of neutrons from the fuel matrix. In so doing, the core cannot go critical and no chain reaction would result.

What is analogous to ‘ lighting-up ’ an ordinary boiler is accomplished by gradually withdrawing selected control rods until a critical state is reached. It is difficult to predict with exactness when this will take place, as it depends on the enrichment level of the fuel material, the design arrangement and configuration of the fuel elements, and the effectiveness of the artificial neutron producing source within the reactor. Nevertheless, as the rods are withdrawn, criticality is approached and the desired nuclear reaction is started.

Control of the reaction is a function of what is called the neutron multiplication factor, or *k* of a reactor. To maintain the chain, each nucleus of fuel material undergoing fission must produce enough neutrons to make at least one available to induce fission of another nucleus. Actually, from two to three neutrons are born in each fission but not all of them survive to cause new fission phenomena. Hence, if *k* is exactly equal to or greater than unity a chain reaction is possible. But if *k* is less than unity, even by a small amount, say 0·9995, criticality cannot be maintained and the reaction will die out.

The value of *k* in any nuclear fuel system is dependent upon the results of four competing processes for the neutrons produced in fission. A fraction of the neutrons may escape entirely from the system ; others may be captured by natural uranium (U-238) which generally is non-fissionable, or by other non-fissionable fuel diluents. Or, there may be parasitic capture of a portion of the neutrons by the coolant, reflector, structural material, extraneous substances and other poisons. Then, of course, some of the neutrons may survive to be captured by the U-235 nuclei. But there is no guarantee that this will take place. The first three processes remove neutrons from the system in a non-productive manner. Only in the latter process are other neutrons born sufficient to produce a net gain in *k* above unity. It is the function of the control rods to adequately regulate *k* to manageable values.

There are three types of control mechanisms of interest. They are (*a*) regulating rods, (*b*) shim control, and (*c*) ‘ scram ’ control. Regulating rods permit fine control and micrometer-type adjustments of *k* and for the shifting of power levels of the reactor. Shim controls, on the other hand, permit larger variations in *k* and play a major role in starting up, shutting down, and compensation for fuel consumed during operation. As a last resort against the reactor going ‘ prompt critical,’ and thus endangering the reactor and personnel, ‘ scram ’ controls are provided. These controls permit an emergency shutdown either by dumping massive amounts of poisons into the core, or by a bundle or more of fuel elements suddenly dropping out of place. When either of these conditions take place, major procedures would be necessary to restore the reactor to normal operation.

Instrumentation and Shutting Down

Unlike the procedure of operating personnel in boiler rooms on shipboard today, reactor operating personnel are not in a position to see, hear or feel the results of their actions or inactions. Their endeavours are entirely dependent upon instruments. They operate in a shielded control room, and all the reactor operation intelligence is fed to them through a complexity of instrumentation. The timely and proper interpretation of these instruments would be one of the most important duties aboard ship. A casualty to the reactor could mean casualty and inconvenience to a great number of other personnel.

The function of the reactor instruments is to monitor the various operating factors (e.g., fuel element distortions, coolant flows, neutron density, control rod positions, etc.) in such a way that they are held within desired limits, automatically. Associated safety and interlock circuits seek to minimize the effect of operating error and equipment failures. In addition, many radiation detection instruments are needed to give warning of X-rays, gamma rays, escaping neutrons, etc. Such radiation hazards could be present in the ventilating system, the sanitary system, and even ‘ scattered ’ from the structural parts of the reactor proper, the vessel’s hull or the water outside.

The sensing probes of many instruments necessarily are located throughout the reactor and other areas where they are subject to damage by neutron irradiation. Unfortunately, in the first place, because of their inherent nature such instruments are not too efficient. And secondly, their useful life and reliability are adversely affected by the nuclear emanations. These conditions result in the necessity for duplicate and triplicate sensing equipment for the critical factors which control the fluctuating power demands of the reactor.

A distinctive feature of reactor operation is that when a reactor is shut down, heat continues to be liberated for a considerable period of time thereafter. This is due, primarily, to the natural decay of fission products in the core. In the decay process, radioactive nuclei emit their excess energy in the form of particles and rays which produce heat. This heat must be removed in order to avoid undue temperature rises and the consequent distortion and melting down of the entire core. To do this, the coolant system must be kept in continuous operation after the reactor is shut down and the excess steam used either for auxiliary equipment or diverted to some form of dummy load. Decay heat is *new* heat generated. It is not like that in a boiler where residual heat continues for a few hours after shutting down so that the steam formed can be blown-off to the atmosphere through safety valves. The time-lag of shutting down a reactor may be several days or longer. It is uneconomic to shut a reactor down very frequently and, therefore, reactor installations should be made where continuous operation is feasible.

When a reactor has run its designed core life, it becomes necessary to replace the spent fuel with new fissionable material. This requires novel procedures and facilities. It is not possible to enter the reactor, disconnect the old fuel elements, and haul them up on deck to drop them over the side or to allocate them to the scrap pile. Instead, because of the radioactive contamination involved, disassembly of the elements must be done with remote-handling equipment using some type of mechanical-tong manipulator projecting through the reactor shield breech blocks. When disconnected, the elements first are transferred or dropped into shielded water storage tanks to allow them to cool off radio-actively. After a few days, they can be transferred to ‘ coffins ’ (made of steel, concrete and lead) for shipment to central plants ashore for processing and disposal.

At the process plants, the spent fuel elements are decontaminated by chemical processes and the unburned fissionable material is separated and recovered. In general, the percentage consumption of fissionable nuclei in the reactor core is quite low so that the spent fuel has a high salvage value.

The final disposal of the fuel waste or ‘ ash ’, after a sequence of channeling through dissolving and settling tanks, is done in strict conformance with radiological safety requirements. This radioactive waste must not be released to any municipal sewerage or garbage disposal system where it could become a public menace. Either it must be buried underground in concrete vaults, and monitored, or it must be embedded in concrete and dumped far at sea.

A Chapter in the Future

One should not conclude from the tenor of this discussion that we are in the midst of an ' Atomic Power Age,' so far as the development and utility of nuclear reactors are concerned. Many problems exist and many technological improvements and simplifications must be made before they can be considered seriously as a competitive method for the generation of steam for shipboard power. It also must be realized that such reactors comprise a field in which there is little or no actual operating experience.

For the immediately foreseeable future, nuclear reactors offer greater opportunity to the Navy than to any other power utilization source. The attractive fuel cycling time and space-saving features, as compared with existing boilers, establish definite tactical advantages. Among these are increased cruising radius, increased speed and increased weapons load. For submarines, the pronounced advantage is that reactors operate independent of air or oxygen supply.

To summarize, then, it can be said that we have a few points on the curve of a new technology, but we should refrain from any arbitrary extrapolation of this curve to a millennium.