SURVEY of ATOMIC POWER for MARINE PROPULSION

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PREFACE

This paper was prepared by the author while working for the degree of M.S.E. at the University of Michigan during the spring semester of 1954. All of the data and information contained in this paper were taken from unclassified sources. This paper has no connection with work the author is now doing. All of the opinions expressed are those of the author.

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INTRODUCTION

To most of us, the introduction to atomic power came with the announcement by President Truman on August 6, 1945, that an American airplane had dropped an atomic bomb on Hiroshima. On August 9, a second atomic bomb was dropped on Nagasaki. The following day the Japanese offered to surrender. The tremendous power that was unleashed by a bomb that devastated a large city in a single blast, and ended a war with another blast immediately appealed to the press. Since the military refrained almost entirely from releasing factual information about atomic energy, a field day was had by Sunday-supplement scientists, after-dinner physicists, and other self-styled experts on atomic energy. The world was flooded with a tide of fact, fancy, and fallacy about atomic energy. Some pictured a rosy future in which the atom would perform all the work, and mankind would be relieved of his burdens. More gloomy prophets foresaw a bomb capable of complete destruction of the earth. It was in such an atmosphere that atomic energy was introduced to the world.

Much of the popular concept of atomic energy even today in 1954 is based upon wild "imagineering." It is the purpose of this paper to attempt to give a clear picture of the present status of atomic energy with special reference to ship propulsion insofar as published information permits. This author takes no stand for or against the feasibility of applying atomic energy either to ship propulsion or to central power station electrical generation.

In spite of the fact that known deposits of coal and oil are increasing every year, it must be clear to anyone that at best these sources represent but a finite source of energy, and when expended cannot be replaced. Recent studies have shown that there is a possibility of deriving from uranium and thorium an amount of energy some ten to twenty times the energy in available coal and oil resources. The indications are that the next fifty years will see the end of the utilization of coal and oil for power generation. With the increasing scarcity of coal and oil, the competitive position of atomic power will improve more and more. The replacement of conventional energy sources is likely to be a gradual transition rather than a sudden change. In parts of the world where coal and oil are already relatively scarce, there will be more rapid development of atomic energy for power production. For some special applications--such as submarine propulsion, naval and commercial surface vessel propulsion, aircraft propulsion, and power generation in remote areas--there is already considerable and growing interest. There is the very real possibility that atomic energy may be able to bridge the gap between fossil fuels and the effective utilization of solar energy. There seems to be no doubt that atomic energy will someday become an important source of power. However, there are wide differences of opinion concerning the role that atomic energy will play and how soon atomic energy will replace coal and oil. Certainly, every effort should be made to determine whether or not atomic energy is a practical power source, and to develop the technology needed to apply it.

THE SOURCE OF ATOMIC ENERGY

According to the modern theory of matter, the smallest discrete particle of any element is an atom of that element. An atom consists of one or more electrons revolving in orbits around a concentrated mass called the nucleus. The electrons are small particles of matter with a negative electrical charge. The nucleus is made up of positively charged particles called protons and uncharged particles called neutrons. Protons and neutrons have about the same mass, nearly two thousand times the mass of the electron, and the two are collectively referred to as nucleons. In an atom that is not ionized, the number of electrons is equal to the number of protons, so that the net atomic charge is zero. A nucleus of atomic number Z and mass number A consists of Z protons and A - Z neutrons. The simplest atom is the hydrogen atom, which consists of one electron revolving about a nucleus of one proton.

When two or more nucleons come together to form a nucleus, the total mass of the resultant nucleus is less than the sum of the masses of all the component nucleons. The difference between the mass of the nucleus and the sum of the masses of the component nucleons is converted into energy and is referred to as the binding energy (B.E.) of that nucleus. It follows naturally, that an amount of energy at least equivalent to the binding energy must be provided in order to break up the nucleus, or cause a nuclear fission. The amount of energy that is given off when two or more nucleons join together to form a nucleus is proportional to the change in mass according to Einstein's law:

$$\text{Energy} = \text{mass} \times (\text{velocity of light})^2$$

The average binding energy in m.e.v. (million electron volts)* per nucleon is shown in Fig. 1. The binding energy of the nucleus of most of the atoms is many millions of times the chemical binding energy holding the electrons in the atom. It is this chemical binding energy that is utilized in the extraction of energy in combustion. It is obvious then, that if only a small part of this nuclear binding energy could be released and put to use that a vast source of energy might be tapped.

Although the exact nature of the forces holding the nucleus together are not known, an analysis which considers the nucleus as a sort of liquid drop is very useful for talking purposes, and also gives good agreement with many observed phenomena. This model of the nucleus was first introduced by Bohr. Using such a model, an equation for the binding energy of any nucleus can be formulated:

$$\text{B.E.} = 14.0\,A - 13.0\,A^{2/3} - 19.3\,\frac{(A-2Z)^2}{A} - 0.585\,\frac{Z^2}{A^{1/3}} \pm \frac{33}{A^{3/4}}$$

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*One electron volt is equivalent to the energy gained by an electron accelerated through a potential difference of one volt.

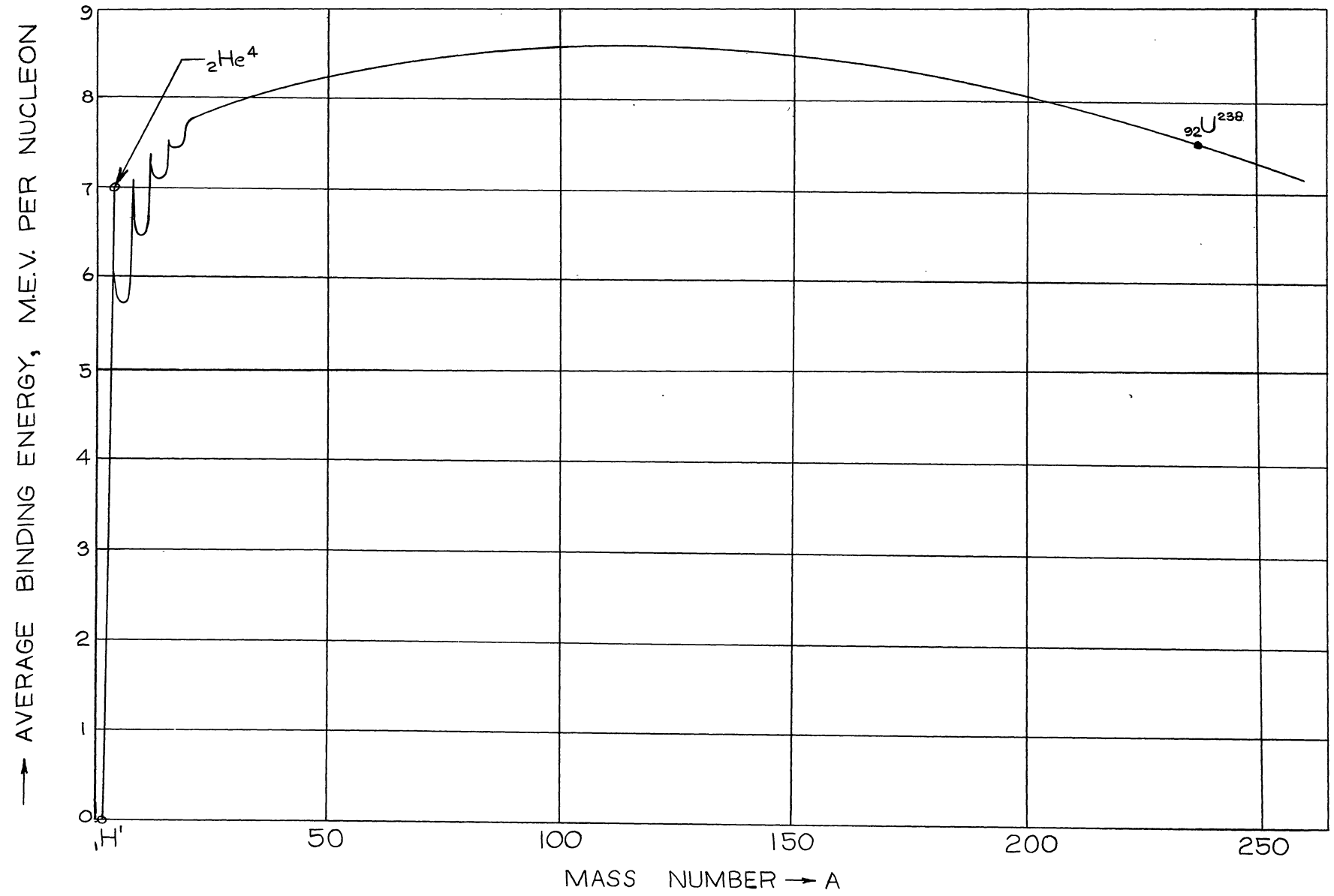

FIG. 1 AVERAGE NUCLEAR BINDING ENERGY VS. MASS NUMBER

This equation may be found in The Elements of Nuclear Reactor Theory by Glasstone and Edlund. The binding energy is given in m.e.v. and is the total for the nucleus. The first term represents the attractive cohesive force of the total mass present. This force is a very short-range force, acting only through distances comparable to the radius of the nucleus. The second term is considered to be the effect of the surface and is therefore proportional to surface area. The third term accounts for the composition of the nucleus. The fourth term is the repulsive force between protons together in the nucleus. The last term is the effect of spin of the component parts. It is positive for nuclei having an even number of both neutrons and protons. The last term is negative for nuclei having an odd number of both neutrons and protons. For all other cases the last term is zero.

It is helpful in understanding nuclear reactions to consider the potential energy of the nucleus with reference to a unit positive charge. As shown in Fig. 2, the potential energy for a typical nucleus increases according to the coulomb law of repulsion between like charges, until a point B is reached, where the nuclear attractive forces take over, and the potential energy decreases to a value A. This is referred to as a potential well. The potential energy of the two points A and B can be calculated. The value of A depends on the binding energy of the nucleus, and the value of B is calculated from the coulomb law of repulsion. Curves of the two are shown in Fig. 3. It is seen that the potential energy at A is negative for nuclei of mass number below about 90. This means that below 90, the nuclei are very stable. The curves are seen to cross at mass number 260, which indicates the upper limit for stable nuclei. Above 260 there would be no potential well, and the nucleus would fly apart due to the coulomb repulsion between the protons.

Whenever the mass of the nucleus exceeds that of the fragments into which it can be divided, the former will tend to be unstable with respect to the latter. This condition applies to all elements of mass number exceeding about 100, and hence for such elements spontaneous fission is theoretically possible. The reason why it is not observed is that the nucleus must acquire a certain critical energy before it can break up. For nuclei below about 210, this energy is so high that fission can occur only by bombardment with neutrons or other particles having energies exceeding 50 m.e.v. The potential energy inside the nucleus must be raised to a level equal to or greater than the energy at point B in Fig. 2. For nuclei approaching the upper limit, this excitation energy required is seen to be much less, due to the crossing of the curves at 260.

Returning to the liquid drop model, consider a large nucleus as a spherical drop, as shown in Fig. 4(a). Due to absorption of a particle, the drop would begin to oscillate to a shape like Fig. 4(b). If the amount of excess energy is large, the nucleus may take the shape of a dumbbell as shown in Fig. 4(c). Once this stage is reached, the excited nucleus is unlikely to return to its former spherical shape, but will rather split into two fragments due to the strong repulsive force between the protons in the two ends of the dumbbell. Unless an amount of energy is added to deform the nucleus to the state

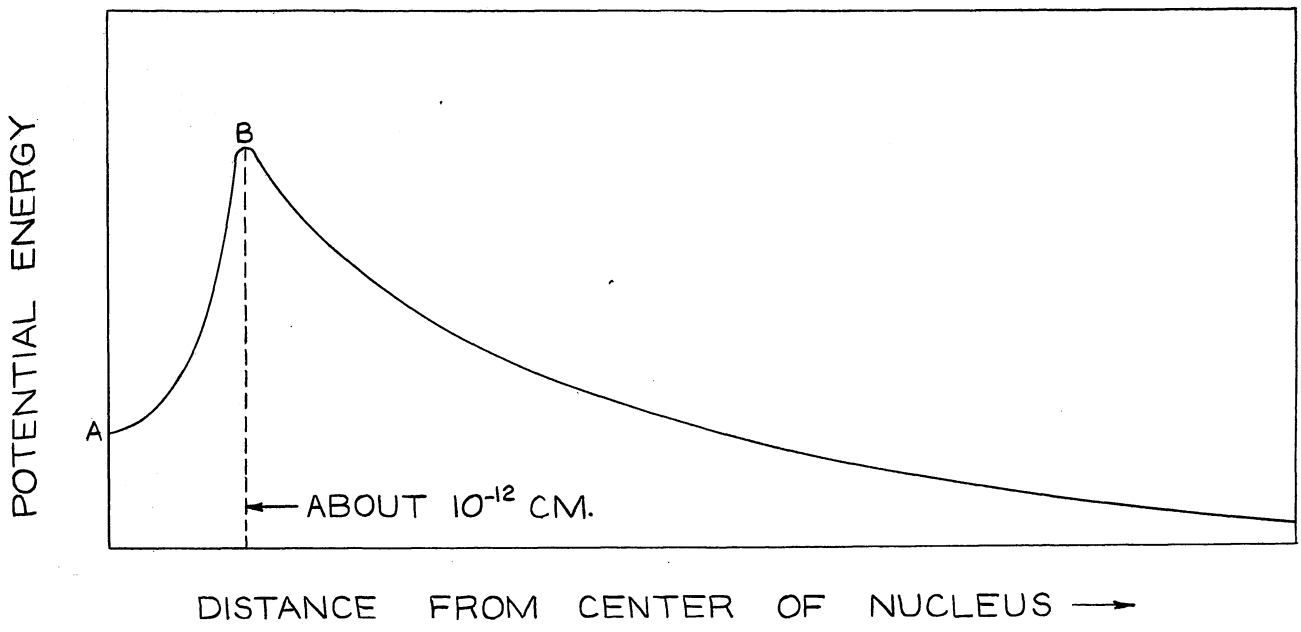

FIG. 2 POTENTIAL ENERGY VS. DISTANCE FROM CENTER OF NUCLEUS.

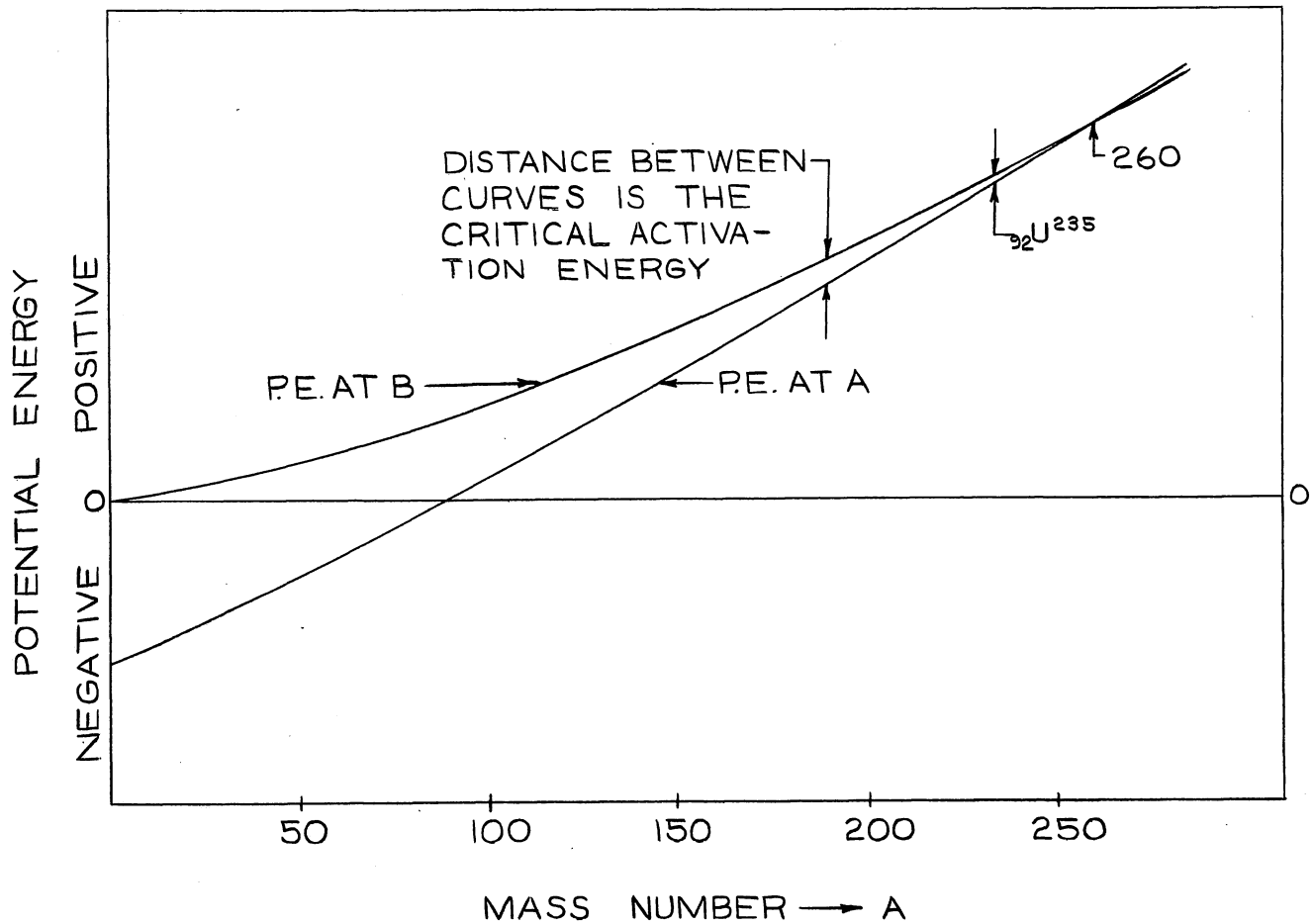

FIG. 3 CRITICAL ACTIVATION ENERGY VS. MASS NUMBER OF NUCLEI.

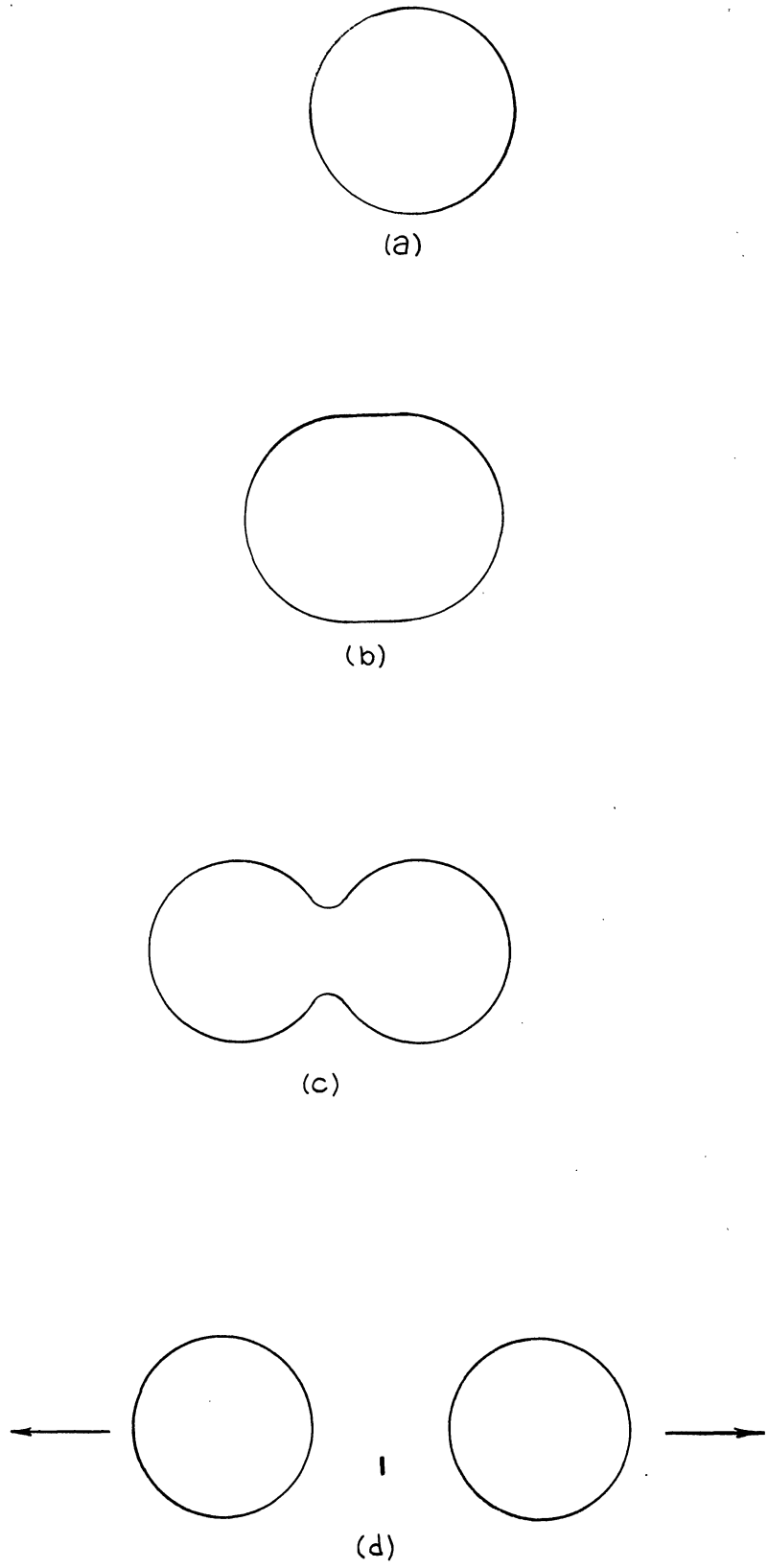

FIG. 4 LIQUID DROP MODEL OF NUCLEAR FISSION

shown in Fig. 4(c), fission will not occur, but the nucleus will return to its original spherical shape. The amount of energy that must be added to the original nucleus to cause critical deformation and fission is called the critical energy.

When a target nucleus captures a neutron of zero kinetic energy, the excitation energy of the compound nucleus formed is the difference between the total binding energy of the compound nucleus minus the total binding energy of the target nucleus. Referring to the equation for binding energy, it is apparent that for capture of a neutron with zero energy, the maximum excitation energy will occur when the target nucleus has a spin term either zero or negative, and the compound nucleus has a spin term that is positive. However, with negative spin term, which is characteristic of nuclei having odd numbers of both neutrons and protons, the nucleus will be inherently unstable and hence the species do not occur. But nuclei with an odd number of neutrons and even number of protons do occur, and when they capture a slow neutron the compound nucleus has a very high excitation energy.

There is only one nucleus occurring in nature that will undergo fission with slow neutrons. This is an isotope* of uranium, $_{92}U^{235}$, occurring with the non-fissionable isotope $_{92}U^{238}$. The fissionable material constitutes only 0.7 percent of pure natural uranium. A simple calculation will show why $_{92}U^{235}$ will fission with slow neutrons. The excitation energy is about 6.8 m.e.v., and the critical energy for fission has been estimated to be about 6.5 m.e.v. It will be noted that $_{92}U^{235}$ is an odd-even nucleus. There are two other odd-even nuclei which may be produced artificially. One is $_{92}U^{233}$ which may be produced by neutron bombardment of an isotope of thorium, $_{90}Th^{232}$, which then decays to $_{92}U^{233}$. The other is $_{94}Pu^{239}$ which may be produced by capture of a neutron in $_{92}U^{238}$ which decays to plutonium, $_{94}Pu^{239}$. As might be expected, both $_{92}U^{233}$ and $_{94}Pu^{239}$ are fissionable by slow neutrons.

On the other hand, if $_{92}U^{238}$ captures a slow neutron, the calculated excitation energy of the compound nucleus is only 5.5 m.e.v., due to the adverse effect of the spin term. The critical deformation energy of $_{92}U^{238}$ is about 7.0 m.e.v. Thus, it may be seen that slow neutrons will not cause fission in $_{92}U^{238}$. However, neutrons with kinetic energy above about 1.1 m.e.v. may cause fission of $_{92}U^{238}$. However, $_{92}U^{238}$ is a very heavy, inherently unstable nucleus, and would be expected to undergo spontaneous fission. This is indeed

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*Isotopes are elements having the same atomic number Z but different mass number A.

the case, for it is observed that $_{92}U^{238}$ undergoes spontaneous fission at the rate of about 20 disintegrations per gram per hour. These provide a source of neutrons to start a chain reaction.

When a fissionable nucleus captures a neutron and is raised to an energy level above the critical deformation energy, the nucleus almost instantaneously splits into two fragments which fly apart at very high speed, due to the repulsive force between the positive charges. These fragments are not the same size but are roughly in the middle of the periodic table. It may be seen from Fig. 5 that when a heavy nucleus near the end of the periodic table splits up into two nuclei near the center of the periodic table, these fragment nuclei will have an excess of neutrons. Since these nuclei are also in a very excited state, one or more neutrons will be ejected, along with gamma radiation, to bring them to a stable condition. Most of these neutrons are ejected within a very short interval of time, about 10^{-14} seconds. However, a small percentage of the neutrons are not ejected until the fragment nucleus goes through a radioactive decay, usually emission of a beta particle. The neutrons that appear later are called delayed neutrons. This phenomenon of delayed neutrons is of vital importance in reactor control, as will be shown later.

When a nucleus fissions, the fragment nuclei are of assorted sizes. Using $_{92}U^{235}$ as an example, the distribution of fragment size for a large number of fissions is shown in Fig. 6. It is seen that the sizes vary from mass number about 72 to mass number about 162. The curve that appears on Fig. 6 is based on an analytical study of the liquid drop model. This curve gives the probability distribution of size between the fragment droplets when a liquid drop splits up and is seen to correlate the observed data very well. Also to be noted from Fig. 6 is the fact that the most likely products occur at mass numbers near 95 and also at mass numbers near 139. It is apparent that thermal-neutron fission of $_{92}U^{235}$ is far from a symmetrical process, since only about 0.01 percent of nuclei fission into equal fragments. In most cases, when a nucleus fissions, there is one heavy fragment nucleus and one light fragment nucleus, which agrees with the probability distribution based on the liquid drop study.

Referring again to Fig. 1, it is seen that the binding energy per nucleon of nuclei near the center of the periodic table is about 0.9 m.e.v. greater than the binding energy of nuclei near the end of the periodic table. Since there are about 230 nucleons in the original fissionable nucleus, the total difference in binding energy between fissionable $_{92}U^{235}$ and the fission products is about 200 m.e.v. This amount of energy is therefore released when fission takes place. A complete energy balance, indicating the approximate distribution of the energy per fission, is given in the following table:

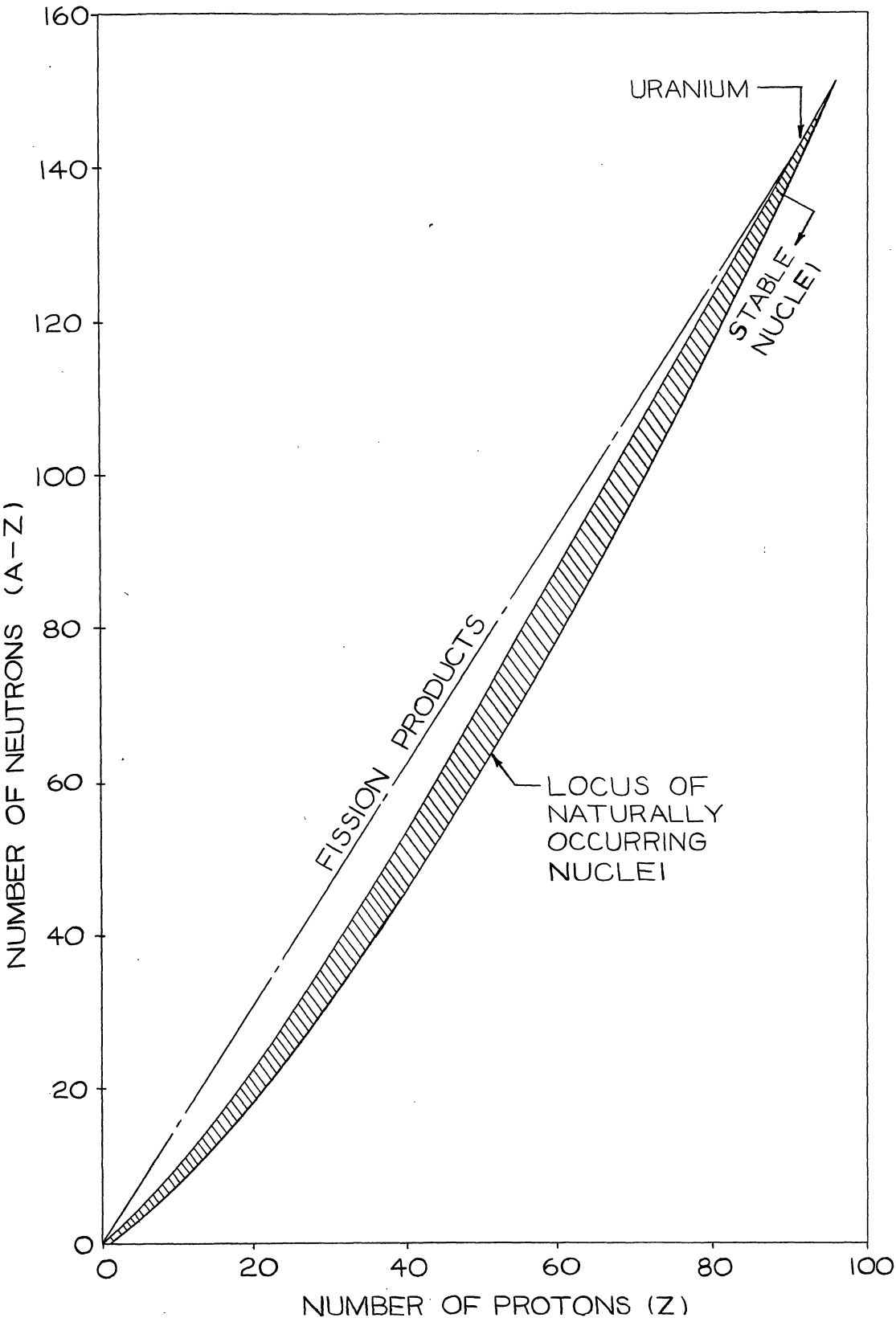

FIG. 5 RATIO OF NEUTRONS TO PROTONS IN NATURAL STABLE NUCLEI

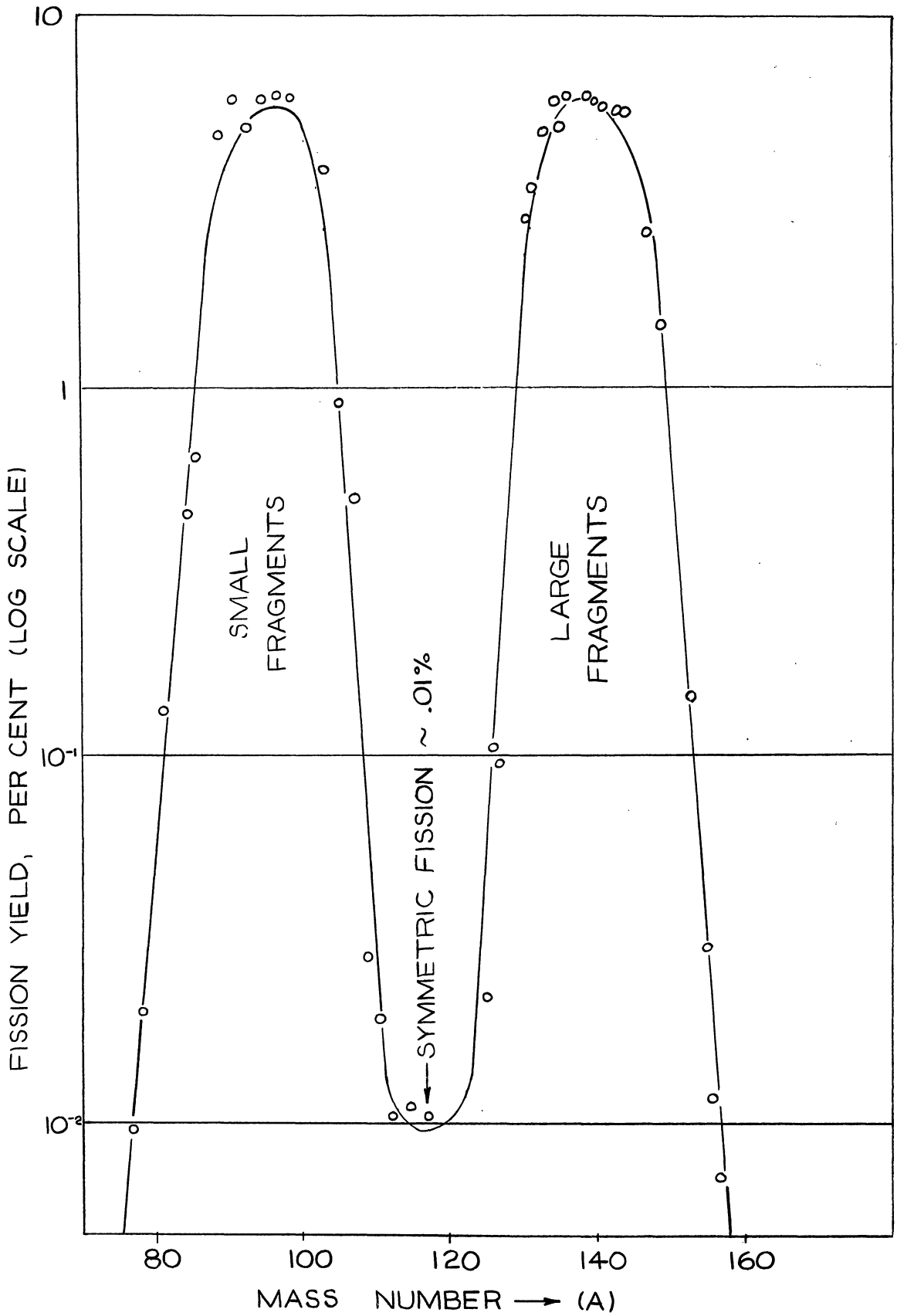

FIG. 6 DISTRIBUTION OF FRAGMENT MASS FOR A LARGE NUMBER OF FISSIONS.

Table I

Distribution of Fission Energy

Kinetic energy of fission fragments	162 m.e.v.
Beta* decay energy	5 m.e.v.
Gamma** decay energy	5 m.e.v.
Neutrino*** energy	11 m.e.v.
Energy of fission neutrons	6 m.e.v.
Instantaneous gamma-ray** energy	6 m.e.v.
Total fission energy	195 m.e.v.

The kinetic energy of the fission products appears immediately as heat, and the neutron energy and instantaneous gamma-ray energy are quickly degraded to heat energy. The beta and gamma energies of the fission products are released gradually as the radioactive product nuclei decay to stable forms. However, after a reactor has been in operation a short time, the heat release rate will reach an equilibrium value of about 184 m.e.v. per fission. The neutrino energy does not appear as heat in the reactor, since these small uncharged particles leave the vicinity of the reactor before they give up any of their energy. The 184 m.e.v. per fission represents the sum of all the sources with the exception of the neutrino energy assumed to be lost. Converting to conventional units of energy,**** it is seen that if all the nuclei in one gram of $_{92}U^{235}$ could be fissioned in one hour, then 230,000 kilowatt-hours of energy would be produced. This is several million times as much energy as could be obtained from one gram of coal or oil.

Because of the very high kinetic energies of the fission fragments, much higher temperatures are theoretically possible in a reactor than could be obtained by any chemical reaction. The theoretically attainable temperature for heat release is several million degrees centigrade, as compared to several thousand degrees centigrade possible with chemical reactions. If a heat engine could be made to operate between even one million degrees centigrade and atmospheric temperature, thermal efficiencies approaching 100 percent could be obtained. Unfortunately, there does not appear to be any possibility of utilizing this high potential due to the metallurgical and operational problems involved.

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*Beta particles are electrons moving with high energies.

**Gamma rays are electromagnetic radiation similar to X-rays, but which come from the nucleus.

***Neutrinos are very small uncharged particles.

****1 m.e.v. = 1.6×10^{-13} watt-sec and one gram of $_{92}U^{235}$ contains 2.6×10^{-21} nuclei.

As yet, there appears to be no way of converting the energy released in fission directly into electrical energy or mechanical energy, at least not on a scale large enough to be useful as a power source. Thus, the energy of the atom must be put to work as heat energy, which means some kind of heat transfer medium to remove the heat from the reactor and some kind of heat engine to convert that heat energy into electrical or mechanical energy. It is obvious, then, that atomic energy will not cause any revolutionary changes in our present method of obtaining power. In an atomic power plant, the conventional coal or oil fired steam generator will be replaced by a nuclear reactor with heat exchangers in which steam is generated. The steam piping, turbines, gears, condensers, and most of the auxiliary equipment will be the same as with a conventional steam generator, except insofar as the peculiar heat release properties of the reactor used cause minor modifications.

NUCLEAR REACTOR THEORY

When a fissionable nucleus captures a neutron and undergoes fission, a large amount of energy is released. If this were the end of the story, nuclear fission would hardly have gained more than academic interest. However, almost as soon as nuclear fission was identified in the late Thirties, it was found to be accompanied by the release of several neutrons per fission. One nucleus, $_{92}U^{235}$, was found to fission with slow neutrons, accompanied by the release of about 2-1/2 neutrons per fission. The possibility of setting off a nuclear chain reaction was studied by many scientists. However, not all the neutrons produced in a fission are available to produce further fission and continue the chain reaction. If the reacting mass is of finite size, some of the neutrons will leak from the surface. Also, some neutrons will be captured by nuclei present without causing a fission. In order for the chain reaction to continue, at least one of the neutrons produced by the fission of a nucleus must be captured by another fissionable nucleus.

The reactions that take place between a neutron and a nucleus can be better understood if we consider the neutron as a projectile and the nucleus as a target. There are three reactions possible if the neutron hits the target. First, the neutron may collide with the nucleus and rebound, possibly giving up some of its energy. Second, the neutron may be absorbed by the nucleus without causing fission. Third, the neutron may be absorbed by the nucleus and cause fission. The probability of any one of these reactions taking place is proportional to the cross section of the target nucleus. A convenient unit for measuring nuclear cross section is 10^{-24} cm^2, which is referred to as one barn. This unit was probably named after the item which the poor marksman could not hit the side of. All of these neutron-nucleus reactions are dependent in some manner on the neutron energy. Thus, if a neutron is approaching a nucleus at a certain speed, the target for non-fission capture might look much larger than if the neutron had another speed. At speeds near some resonance speed, the target for non-fission capture might appear to the neutron to be many thousands of times larger than the actual size of the nucleus. The same applies to scattering and to fission capture. In Fig. 7 are shown cross sections in barns for several neutron-nucleus reactions as a function of the neutron energy in m.e.v. A very comprehensive report of cross sections of many nuclei has been published by the Atomic Energy Commission. If a nucleus has a high cross section for some neutron reaction at some particular neutron energy, this means that there is a high probability that that reaction will occur if a stream of neutrons of the given energy is directed at the nucleus.

The neutrons that are released in fission have a wide range of energies. For $_{92}U^{235}$ the average energy is a little less than 1 m.e.v. These neutrons undergo collisions with surrounding nuclei and are quickly reduced in energy. The nucleus $_{92}U^{238}$ has a resonance point for nonfission capture of neutrons with energies near 7 electron volts. The cross section for nonfission capture near the resonance point is several thousand barns. Because of this, natural uranium in a

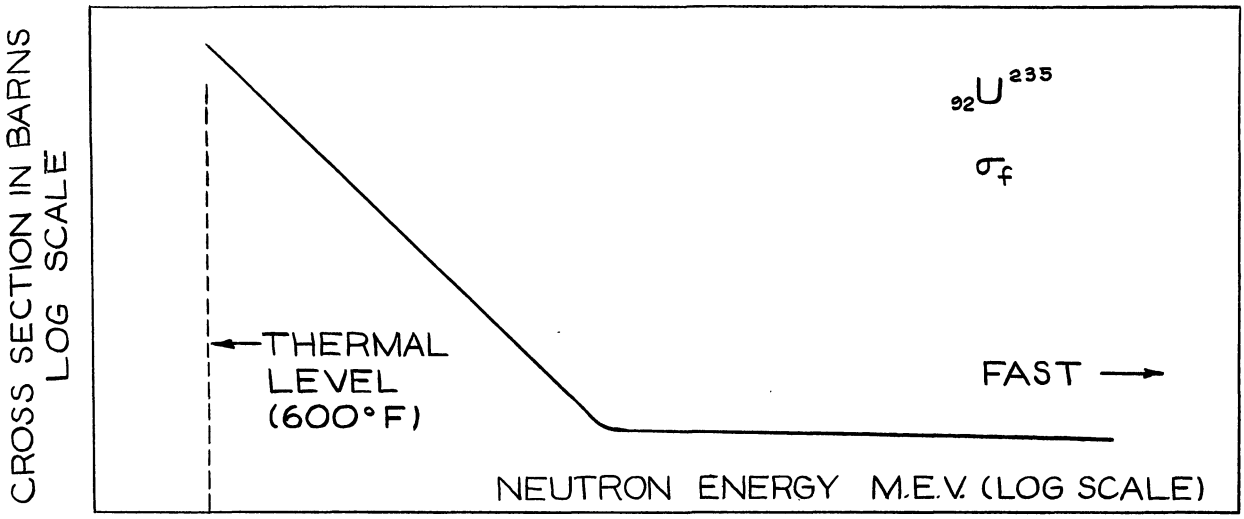

FIG. 7(a) FISSION CAPTURE CROSS SECTION OF $_{92}U^{235}$ VS. NEUTRON ENERGY

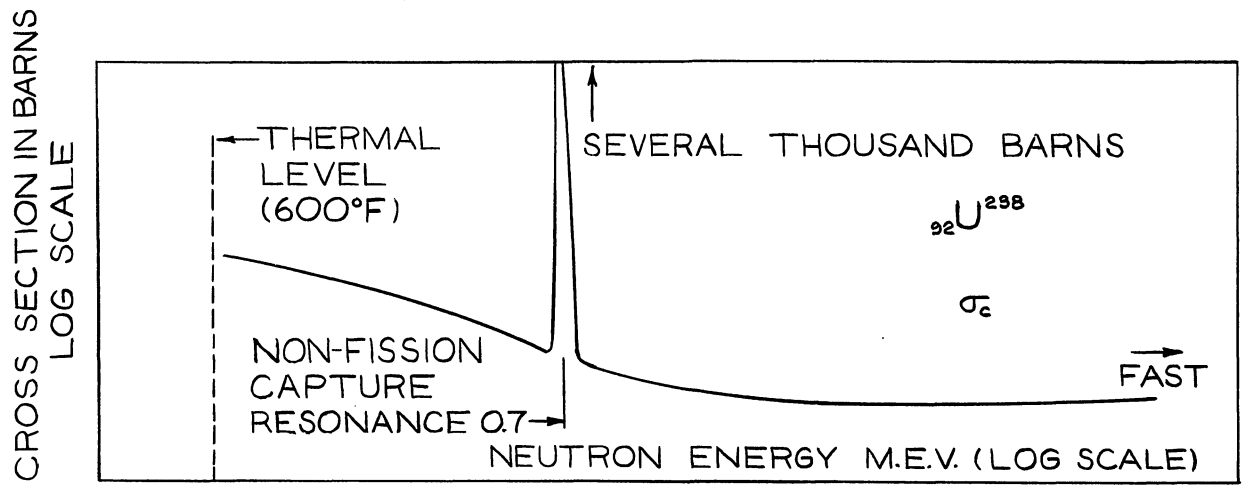

FIG. 7(b) CAPTURE (NON-FISSION) CROSS SECTION OF $_{92}U^{238}$ VS. NEUTRON ENERGY

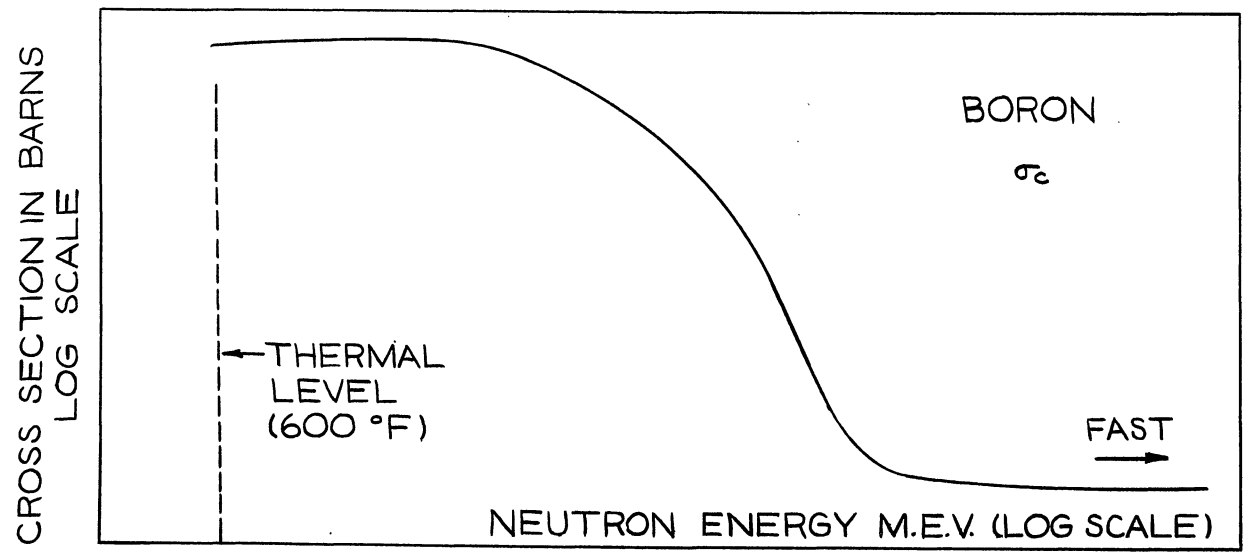

FIG. 7(c) CAPTURE CROSS SECTION OF BORON VS. NEUTRON ENERGY

homogeneous condition cannot be made to sustain a chain reaction, no matter how large the reactor is made. However, if lumps of natural uranium are placed in a lattice arrangement and surrounded by a moderator, then a chain reaction will take place when a favorable size and shape is attained. A moderator is a material containing light nuclei with low absorption cross section and high scattering cross section. A chain reaction will take place in a reactor of the type just described because of the following reasons. If the natural uranium is contained in small lumps or rods, then a large part of the neutrons formed by fission are ejected into the surrounding moderator where they quickly come to thermal equilibrium with their surroundings. Neutrons with thermal energy are continually entering the fuel element by diffusion from the moderator. At thermal energy, neutrons are not as likely to be captured by the $_{92}U^{238}$. Thus we have succeeded in slowing the neutron down to energies below the resonance point for nonfission capture in $_{92}U^{238}$ without letting that capture take place.

The relative abundance of $_{92}U^{235}$ in uranium may be increased by several methods, although all are expensive. Such uranium is referred to as enriched uranium. It is evident that if enriched uranium is used the critical size of the reactor may be reduced, depending on the amount of enrichment. By using a homogeneous mixture of uranium and moderator it is possible to obtain a chain reaction under certain conditions. The following table gives a comparison of moderating materials used as diluent and moderator in homogeneous reactors.

Table II

Comparison of Optimum Homogeneous Mixtures of Natural Uranium and Moderating Materials

Moderator	Optimum R*	Maximum k**
H_2O	5.7	0.62
Be	340	0.66
Graphite	440	0.84
D_2O	170	1.33

The value of k in the table is for a pile of infinite size. For a pile of finite size, the value of k must be at least unity for chain reaction to occur. It is apparent from the table that the only homogeneous mixture that will sustain a chain reaction using natural uranium is one employing D_2O (deuterium oxide or heavy water) as a moderator-diluent. If heavy water is not used in a homogeneous reactor, then the uranium must be enriched by some amount, depending on which moderator is used.

From the foregoing discussion it may be seen that there is a very wide range of possible reactor types. However, it is evident that for any given fissionable fuel, moderator, geometric configura-

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*R is the optimum ratio of moderator to $_{92}U^{238}$.

**k is the reproduction constant for neutrons.

tion, and amount of neutron-absorbing material in the core structure, that there will be a very definite amount of fissionable fuel that will just sustain a chain reaction. When just a sufficient number of fissionable nuclei are present to support a chain reaction, a reactor is said to have reached critical size. The concept of critical size is very important in nuclear reactor design because it puts rather narrow limits on the actual physical size of a reactor depending on the type of fuel, shielding, moderator, and reactor poisons that may be present. It is important to note that the critical size does not directly depend on the power level at which the reactor is operating. The power level is determined by the number of nuclei undergoing fission per unit of time, but the critical size is determined by the number of fissionable nuclei present.

Thus, it may be seen that once critical size has been attained, a reactor may be operated at any desired power level as long as the heat generated can be removed and criticality maintained. However, for practical purposes, a very small reactor is not likely to be operated at very high power levels due to the inability of available heat transfer media to remove the heat. Nevertheless, the possibility of obtaining a very concentrated source of high power which requires no oxygen, and a fuel supply of very small weight for the amount of energy produced looks very appealing for some special powering applications. The critical size for different types of reactors varies over quite a large range. Natural uranium graphite moderated reactors in which the fuel is placed in cylindrical holes in the graphite core require a core size of about 20 feet in diameter. On the other hand, a highly enriched uranium reactor operating with fast neutrons may have a critical size as small as one foot in diameter. Provided the heat could be effectively removed, both these reactors could be operated at the same power level. For reasons connected with control, reactors are built so that they are very close to their critical size. One does not make a rough calculation of the approximate size desired, assemble the materials, and then sit back to see what happens. The results might be devastating. On the contrary, the critical size is approached very carefully so that the reactor may be effectively controlled. If the pile is below critical, the reaction will not start. If the pile is only a few percent over critical, the reaction will build up with explosive violence.

A detailed study of nuclear reactor theory is beyond the scope of this paper. This author has endeavored to point out some of the more important points. A complete treatment of the subject may be found in The Elements of Nuclear Reactor Theory, a book by Glasstone and Edlund.

The reactor designer has a very wide variety of designs to choose from. Some of these designs have advantages in certain respects, but no one type of reactor appears to be the optimum design. Reactors may be classified on several different bases. Table III gives the various classifications of nuclear reactors.

Table III

Classifications of Nuclear Reactors

Basis of Classification	Types of Reactors
Effective utilization of fuel	Non-regenerative, Regenerative, Breeder
Energy of fission neutrons	Fast, Intermediate, Thermal
Arrangement of fuel	Homogeneous, Heterogeneous
Reactor coolant	Light water, Heavy water, Helium, Cargon dioxide, Sodium, etc.
Moderator	Light water, Heavy water, Graphite, Beryllium, etc.
Kind of fissionable fuel used	Natural uranium, Enriched uranium, Plutonium, etc.
Purpose of reactor	Power, Experimental, Research, Production, etc.
Pressure on core structure	Pressurized, Unpressurized

It is obvious from Table III that there are many possible types of reactors. Not all of these would be suitable for marine propulsion. To one familiar with conventional steam propulsion power plants, this maze is a bit overwhelming. One does not find a wide variation in the basic design of oil-fired steam generators. A fireman or engineer going from one ship to another usually finds the same basic components in both plants. However, in a nuclear reactor steam power plant, there are several quite fundamentally different types of reactors. An analogy in conventional plants would be a boiler in which the fire was placed inside the steam drum, and the combustion air was replaced by helium. The test of time will no

doubt narrow down the range of technically and economically feasible types of reactors. In the meantime, however, there is very little real information on the relative merits of the various types.

The property of regeneration and breeding deserves some explanation. As was stated earlier, the fissionable part of pure natural uranium is only 7/10 of 1 percent. If this were the only source of energy from the fission process, it would not be likely to have much effect on commercial power production, at least not in the foreseeable future. The cost of such a fuel would be very high for the amount of energy obtained, and the total available amount of fissionable fuel is not significant compared to other sources of energy. However, it will be remembered that more neutrons are produced by fission than are needed to carry on the chain reaction. If part of these neutrons could be used to convert nonfissionable nuclei into fissionable nuclei, the potential source of energy might be greatly increased. This can be achieved in several ways. By proper regard to neutron economy one may increase the amount of neutrons available for capture in certain nuclei to convert them into fissionable nuclei, while still maintaining the chain reaction. This is not an easy task, but careful choice of moderator, structural materials, reflector, etc., can minimize the number of neutrons that are wasted. Also, if fast neutrons are used for fission, a larger proportion of the $_{92}U^{238}$ nuclei will undergo fission, thus adding to the available supply of neutrons.

A reactor in which only fissionable nuclei are present will be a non-regenerative reactor. In this type of reactor there is wide latitude in choosing structural material and coolant since neutron economy is not so important. Also, this type of reactor will have high power in a small size. However, the fuel costs for such a reactor could be justified only in an application such as a submarine or military aircraft, where fuel costs are a minor consideration.

If natural uranium or slightly enriched uranium is used in a reactor, then there is a possibility of achieving some conversion of fertile material to fissionable material. By fertile material is meant that which may be transformed into fissionable material under neutron bombardment. At present, two such fertile materials are known, namely $_{92}U^{238}$ and $_{90}Th^{232}$. Under neutron bombardment, the $_{92}U^{238}$ is transformed into $_{92}U^{239}$, which decays to $_{94}Pu^{239}$. Similarly, $_{90}Th^{232}$ is changed to $_{90}Th^{233}$ under neutron bombardment, which then decays to $_{92}U^{233}$. As was seen earlier, both $_{94}Pu^{239}$ and $_{92}U^{233}$ are fissionable by slow neutrons. If there are two and one-half neutrons produced per fission, and one neutron is used to continue the chain reaction, then one and one-half neutrons are potentially available to cause conversion of fertile material to fissionable material. The extent of conversion depends on how much of the potentially available one and one-half excess neutrons can be utilized for conversion. If, for every neutron captured by a fissionable nucleus, one of the product neutrons could be used to convert a fertile nucleus into a fissionable nucleus, then the total number of fissionable nuclei in the reactor would remain a

constant and the conversion efficiency would be 100 percent. Thus, the reactor could be fueled with fertile material. Instead of 7/10 of 1 percent of natural uranium, the energy source consists of the total supply of uranium as well as much of the total supply of the fertile thorium isotope. Reactors in which a substantial part of the fertile material is converted to fissionable material are referred to as regenerative reactors.

There is no reason, in principle at least, why the conversion efficiency may not exceed 100 percent. In this case the reactor would produce more fissionable material than it used up. This excess fissionable material would occur by conversion of fertile material to fissionable material in excess of the amount required to replace the fissionable material used up. Thus, such a reactor would be able to produce fissionable material as well as power. This type of reactor is called a breeder reactor. Breeding has been successfully accomplished by the A.E.C. However, expensive and complex chemical processing equipment is needed to process the fuel and fertile material, and keep the reactor poisons to a minimum. It is not likely that this type of reactor will ever be used in marine propulsion. It is very likely to be used in central station power generation, and may provide an economic source of enriched fuel for marine propulsion reactors.

Always present in reactor design and operation is the problem of the products of the fission process. In a conventional steam boiler, most of the products of combustion are in a gaseous state, and are easily disposed of by dissipation into the atmosphere. Removal and disposition of fission products is not quite so simple. As was noted in Fig. 6, there are a wide variety of ways in which the $_{92}U^{235}$ may break up after absorption of a neutron. The most frequent type of fission gives products of mass numbers 95 and 139. However, this takes place in only 6.4 percent of the total number of fissions. Referring again to Fig. 5, it may be seen that the products of fission will be in a very unstable state, even after ejection of one or two neutrons. The result is that all the products of fission are radioactive, giving off beta and gamma radiation until some stable isotope of some element is formed. There are probably some 60 different radioactive nuclei produced in fission, and since each is, on the average, the precursor of two others, there are about 180 radioactive species present among the fission products after a short time.

The radioactive decay of the fission products is accompanied by a sizeable release of energy, much of it in the form of heat. Depending on the type of reactor and the fuel used, as much as 5 to 10 percent of the energy developed in a reactor may initially be in the form of latent radioactive decay energy. If a power reactor has been operating at full power for some time, there will be a considerable amount of radioactive decay products present. If it is desired to shut down the reactor, and the fission process is stopped, there will still be a considerable release of energy dying out rather slowly after the fission has stopped. This make it imperative to insure that sufficient coolant be circulated through the reactor to remove this heat to prevent overheating and damage after shutdown.

Many of the fission products are avid neutron absorbers. Thus, if a reactor has been operating for a time and the fission products are allowed to remain inside the reactor, then these products may absorb enough neutrons to slow down or even stop the chain reaction. For this reason they are referred to as reactor poisons. On the other hand, their removal and disposition is no easy task. If the fuel is in the form of solid rods or capsules, then the whole fuel element must be removed, put through a complex chemical processing plant to recover the fissionable and fertile material remaining, and dispose of the radioactive fission products. An idea of the problems involved in such a chemical fuel processing may be seen from the fact that all handling must be done by remote control and behind heavy shielding because the materials are highly radioactive. The fissionable and fertile material recovered must then be returned to the reactor in the form of a solid rod or capsule. Due to the value of the materials, the chemical processes must have a very high efficiency, better than 99.9 percent.

The situation is only slightly changed if the fuel is dissolved in a solution or if liquid fuel is used. The fuel will then be removed either in batches or by continuous processes and put through a chemical processing plant the same as before. The only saving over the solid fuel system is in the metallurgy involved in reducing, casting, machining, and cladding usually needed with the solid fuel elements. One of the problems connected with the fission products is the amount of burnout that can be obtained from a certain quantity of fissionable material before chemical processing becomes necessary. It may be readily imagined that the type of chemical processing just described is not likely to be an inexpensive proposition. Therefore, the amount of processing must be reduced as much as possible. On the other hand, if reactor poisons build up in a reactor, then the neutron economy is greatly reduced, and more fuel is needed to produce the same amount of power. Breeding and regeneration are seriously hampered. Also, many of these poisons are highly corrosive both to the fuel and to the core structural materials. Some of the poisons are highly active and dangerous gases. Obviously, some compromise must be made between these opposing factors. It may well be that the cost of fuel processing to remove poisons will determine the economical utilization of nuclear atomic power. This is indeed a far cry from the gaseous products of combustion and the smoke stack found on conventional steam boilers.

One of the most important considerations in reactor design is the effect of strong neutron bombardment on the materials used. Many effects must be considered, of which only a few examples will be mentioned. The absorption of neutrons by the structural material not only causes loss of neutrons but also leads to transmutation of some nuclei of the structural material to radioactive isotopes. This causes a serious contamination problem and makes maintenance or repair extremely difficult because many of the isotopes formed give off dangerous radiation that persists at a high level for a long time. Also, the chemical and physical properties may be vastly altered by neutron bombardment. Lattice structures of metals may be changed. Growth, distortion, and many other phenomena could be initiated or accelerated.

If the preceding is coupled with the fact that a reactor will probably have to be constructed to last the whole life of the unit without the necessity for repairs, then one begins to realize the tremendous engineering problems involved in reactor design. If water is used to cool a reactor, under intense neutron bombardment considerable dissociation of the coolant water takes place with release of highly explosive mixtures of hydrogen and oxygen.

Many of the properties most important in materials used in reactors depend only on the specific nuclei present. Chemical and physical properties have little or no effect on nuclear properties. Thus, we are forced to use elements such as zirconium because these elements have favorable nuclear properties, even though their chemical and physical properties may not be the most desirable. Also, the materials most favorable from the standpoint of nuclear properties may be quite rare, or very difficult to purify, or nearly impossible to fabricate. Most of the time they prove to be rather expensive. The Materials Testing Reactor was recently put into operation by the A.E.C. for the specific purpose of testing materials under bombardment by an intense neutron flux. The design of future reactors will lean heavily on such experiments conducted under conditions simulating actual operation in a power reactor.

There are many problems facing reactor designers today. Chemical processing of fuels is a complicated and expensive business. This cost and complexity must be reduced. Expensive fuel element fabrication must be reduced or eliminated. Means must be found to reduce corrosion caused by moderators, coolants, and liquid fuels. Equipment must be designed that will be leakproof throughout the life of the unit to handle liquid metal coolants. Methods of breeding must be improved. Adequate control devices need to be worked out for fast and intermediate reactors. Better construction materials which have good nuclear properties must be developed. Reactor construction is at present much too complicated. Design and construction must be simplified. Methods must be devised for handling and disposing of radioactive wastes.

REACTOR KINETICS AND CONTROL

The controlling factor in reactor kinetic behavior is the density of the neutron flux. By neutron flux is meant the number of neutrons crossing a unit area per unit time at a given point in the reactor. The amount of power that is generated by a reactor is controlled by the neutron flux since this determines the number of fissions per second that take place. At any instant in a reactor, neutrons are being created by fission and neutrons are being lost through capture or escape from the surface. The ratio between the number of new neutrons produced and the number of neutrons lost is referred to as the neutron multiplication factor k. If k is equal to unity, the neutron flux remains constant, and heat is generated at a uniform rate. This is the steady-state condition. If k is less than one, the neutron flux is decreasing, and the power level of the reactor is falling. If k is more than one, the neutron flux is increasing, and the power level of the reactor is rising. The rate of change of the power level depends on the multiplication factor and on the neutron mean life in the reactor. For thermal reactors the mean life is about 0.001 second. Neutrons in fast and intermediate reactors have much shorter mean lives. Suppose a reactor has been operating at some power level under steady-state conditions and the multiplication factor is increased from 1.000 to 1.005. The reactor power level would increase exponentially with time as shown in Fig. 8. At the end of one second, the power level would be about 150 times that at the start of the change. Such a reactor would be impossible to control.

Fortunately, not all the neutrons produced by the fission process make their appearance immediately. Some fraction β of the neutrons produced make their appearance after a certain period of time. These are referred to as the delayed neutrons. The exact percentage depends on the type of reactor and the fissionable material used as fuel. These delayed neutrons have a much longer mean life than the prompt neutrons. Instead of 0.001 second, the average mean life is about twelve seconds. The effective multiplication factor may be thought of as consisting of two parts. One part, representing the prompt neutron multiplication, will be equal to $k(1 - \beta)$. The other part, representing the delayed neutron multiplication factor, will be given by $k\beta$. If the quantity $k(1 - \beta)$ is less than or equal to unity, then the rate of increase of neutron flux and power level will be controlled by the delayed neutrons. For thermal fission of $_{92}U^{235}$, $\beta = 0.0075$. Therefore, the condition of $k(1 - \beta)$ equal to or less than unity will be met if the effective multiplication factor is below 1.0075. Using the same multiplication factor as before, that is an increase in k from 1.000 to 1.005, it is found that in one second the neutron flux and power level increase by a factor of 1.05. The power rise is thus seen to be much slower than the factor of 150 times per second if all the neutrons were prompt.

If the effective multiplication factor (k) is such that $k(1 - \beta)$ is just equal to unity, the condition of the reactor is described as prompt critical. If k exceeds this value, then multiplication will

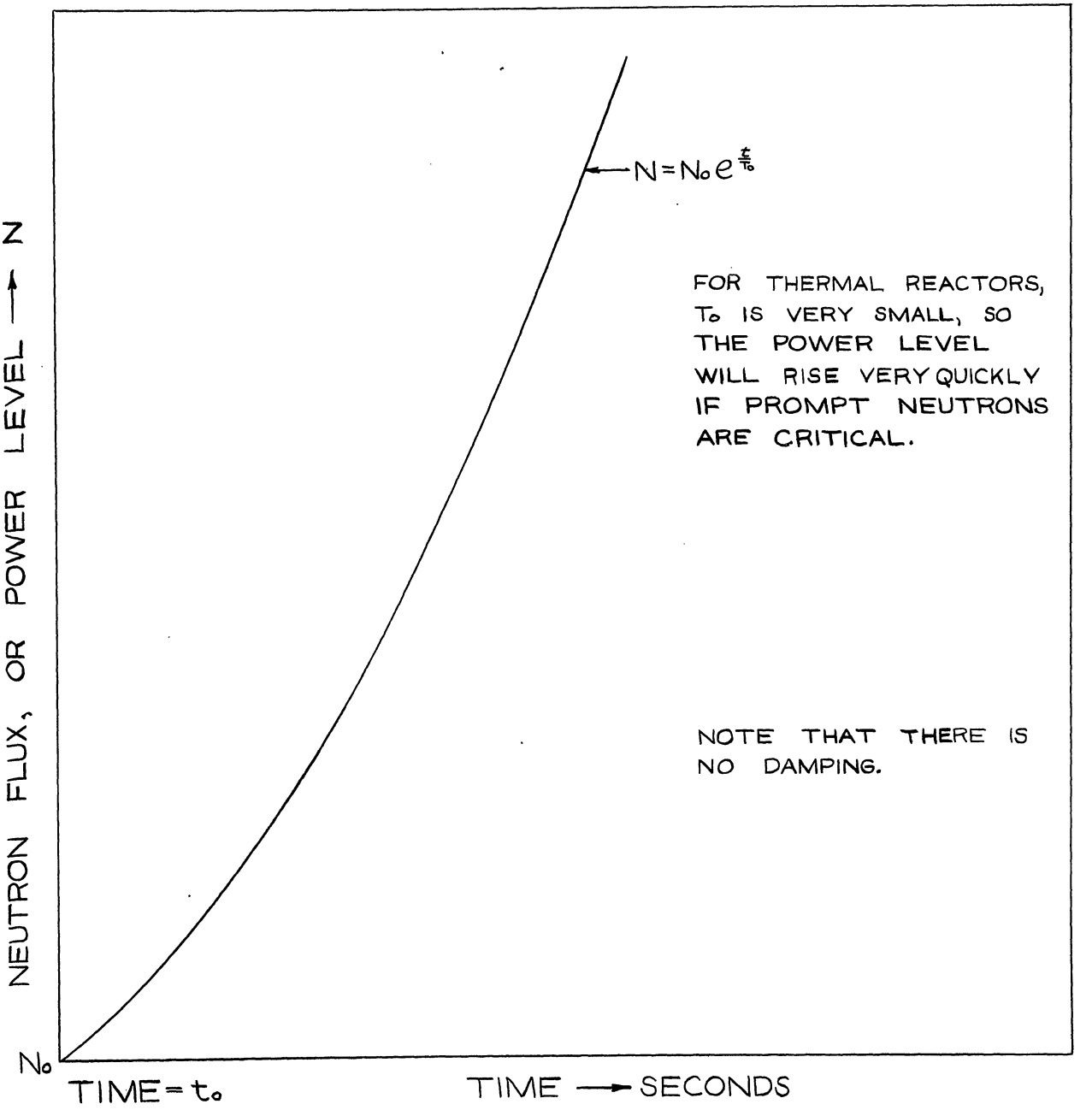

FIG. 8 EFFECT OF EXCESS CRITICALITY CONSIDERING PROMPT NEUTRONS ONLY.

occur due to prompt neutrons and the power level will rise very rapidly. A reactor in this condition would be very difficult to control. In Fig. 9 is shown the power level rise when k is below the prompt critical value. It will be noted in Fig. 9 that there is a sharp initial rise in power. This is due to the sudden increase in prompt neutrons, and is called the impulse rise. The rate of increase quickly decreases and is controlled after a very short time by the delayed neutrons. If the multiplication factor is maintained at the value of 1.005, the power level will slowly increase. If, after a certain length of time, the multiplication factor were returned to unity, the power level would stabilize at some higher value and steady operation at the higher power level would be maintained.

The time required for the neutron flux to change by a factor of e* is referred to as the reactor period. The reactor period is a measure of the rate of change of power level, and is very important in reactor control. If the period were very short, the power level might rise to dangerous levels before a power level control could operate. Reactor control systems are always set up to limit the reactor period to be above some definite time in order to prevent damage to the reactor or any part of the system due to too rapid a power rise. Reactor periods vary widely, depending on type and use. For a large graphite experimental reactor, the period might be several days. For a power reactor in a submarine, the period might be a few minutes. Due to physical limitations of materials, the period is not likely to be as short as a few seconds.

Reactor response to a change in k is also affected by temperature change. Higher temperatures have an adverse effect on the fission reaction. If the fuel is in liquid form, an increase in power level may be accompanied by an increase in temperature and decrease in density due to expansion. This also has an adverse effect on the fission reaction. It is beyond the scope of this paper to go into the details of reactor kinetics when temperature, density, and other factors are taken into account. The general appearance of the response will still be similar to that shown in Fig. 9. Over a long period of time, some means must be provided to maintain the reactor in a critical condition in spite of the poisoning effects of the fission products. Some of the means used will be described later in connection with control devices.

The principles of reactor control are fairly simple. The amount of power being produced is directly proportional to the average neutron flux. The flux may be measured by means of an ionization chamber placed at a strategic point near the reactor core. The voltage obtained from the ionization chamber is proportional to the neutron flux, and can be calibrated to represent the power level of the reactor. Reactors are usually operated by automatic controls. The voltage output from the ionization chamber is compared with the voltage representing power demand, and control devices are operated automatically to bring the output and demand together. Some means must be

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*e is the base of the natural logarithmic system and has a value of about 2.7.

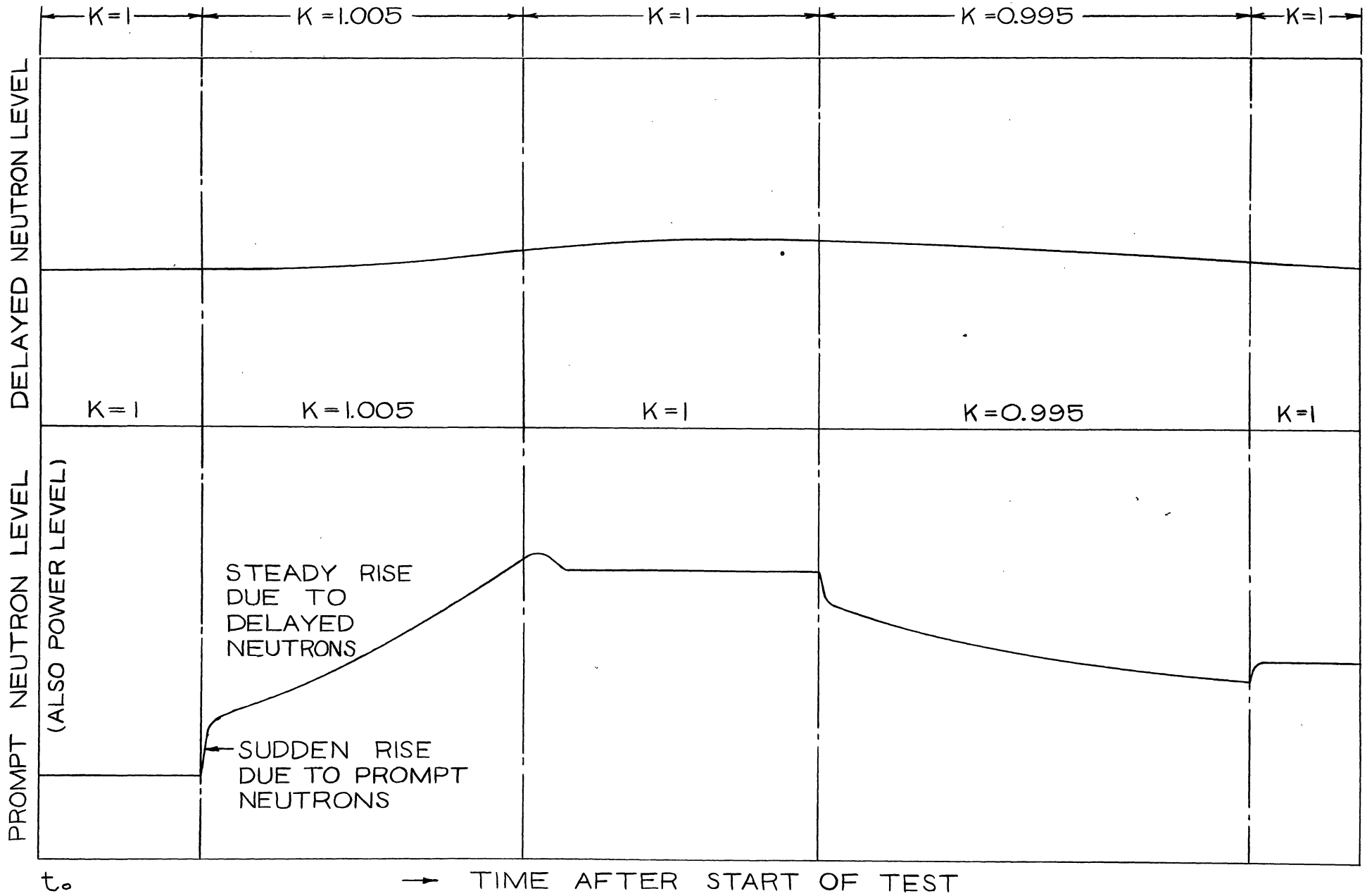

FIG. 9 KINETIC BEHAVIOR OF A POWER REACTOR WHEN BOTH PROMPT AND DELAYED NEUTRONS ARE CONSIDERED AND WHEN REACTOR IS OPERATING BELOW PROMPT CRITICAL.

provided to prevent exceeding prompt criticality, so a period-measuring device is incorporated in the control system to limit the period to some set value. A reactor control system that provides for constant calibration of the output signal is shown in Fig. 10.

Reactor response to an increase in power demand may be illustrated by the following example. Suppose that the reactor were operating under steady conditions at some power level, and that the demand for power were increased to some higher level. The demand for more power is inserted into the comparator. This results in an error voltage appearing at the output of the comparator. This error is amplified and a signal sent to the actuator mechanism that changes the multiplication factor (e.g., by moving out rods). The multiplication factor will be increased and the power level will begin to rise. As the power level rises, the error signal becomes smaller and will eventually be reduced to zero. This will satisfy the comparator, but the multiplication factor must be returned to unity or the power level will continue to rise. Thus, as soon as the comparator is satisfied, the actuator mechanism will reverse itself and return the multiplication factor to unity (e.g., by reinserting the rods to their previous position).

Some means must be provided to prevent damage to the reactor from overloading. Safety trips are usually provided at 150 percent full power to reduce quickly the reactivity to values well below critical. This is referred to as scramming, and should only be used in emergency shut-downs. In thermal and intermediate reactors, some strong reactor poison such as boron is projected into the reactor core to kill the chain reaction and reduce the power generated. It is important that positive means such as gravity be used to insert the scram rods to insure operation in case of electrical power failure. In addition to the 150 percent power level trip, a reactor must be protected against operating with too short a period. Devices called period meters are incorporated into the circuit and can actuate the scram mechanism if the period becomes dangerously short. It is very important that no time delays be incorporated in the circuits actuating the scram mechanism to prevent quick operation.

Automatic control of a reactor under normal operation can be effected over a range from about 1 percent to 100 percent full power. If the reactor must be started up from dead cold condition, auxiliary instruments must be used and manual operation employed until the power level approaches the automatic range. Start-up from zero is the most dangerous part of reactor operation because the period-measuring instruments are most inaccurate at very low levels. A sudden increase in k to dangerous value might cause a serious build-up and overload before the automatic controls could take over. If the reactor has been scrammed after operating at full power, considerable build-up of reactor poisons may require many hours or days delay before the reactor would be able to be started up again. Starting up from 1 percent to 100 percent power does not present any problem. However, some means is usually provided for varying the period as the reactor goes from low power to high power so that the level will rise gradually as shown in Fig. 11 without over-shooting. Period changes may be either manual or automatic.

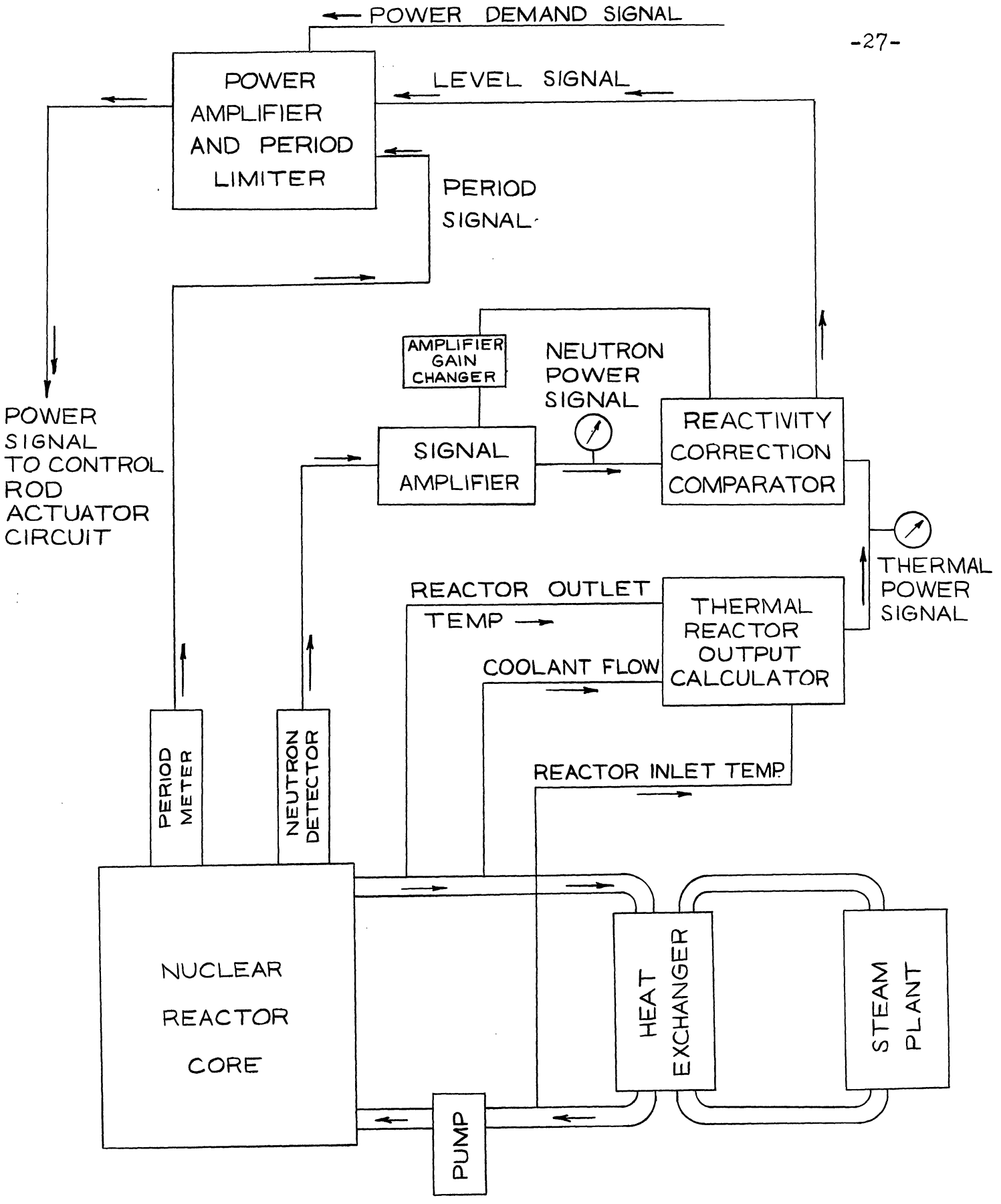

FIG. 10 BLOCK DIAGRAM OF A SIMPLIFIED REACTOR CONTROL CIRCUIT WITH PERIOD CONTROL AND CONTINUOUS CALIBRATION.

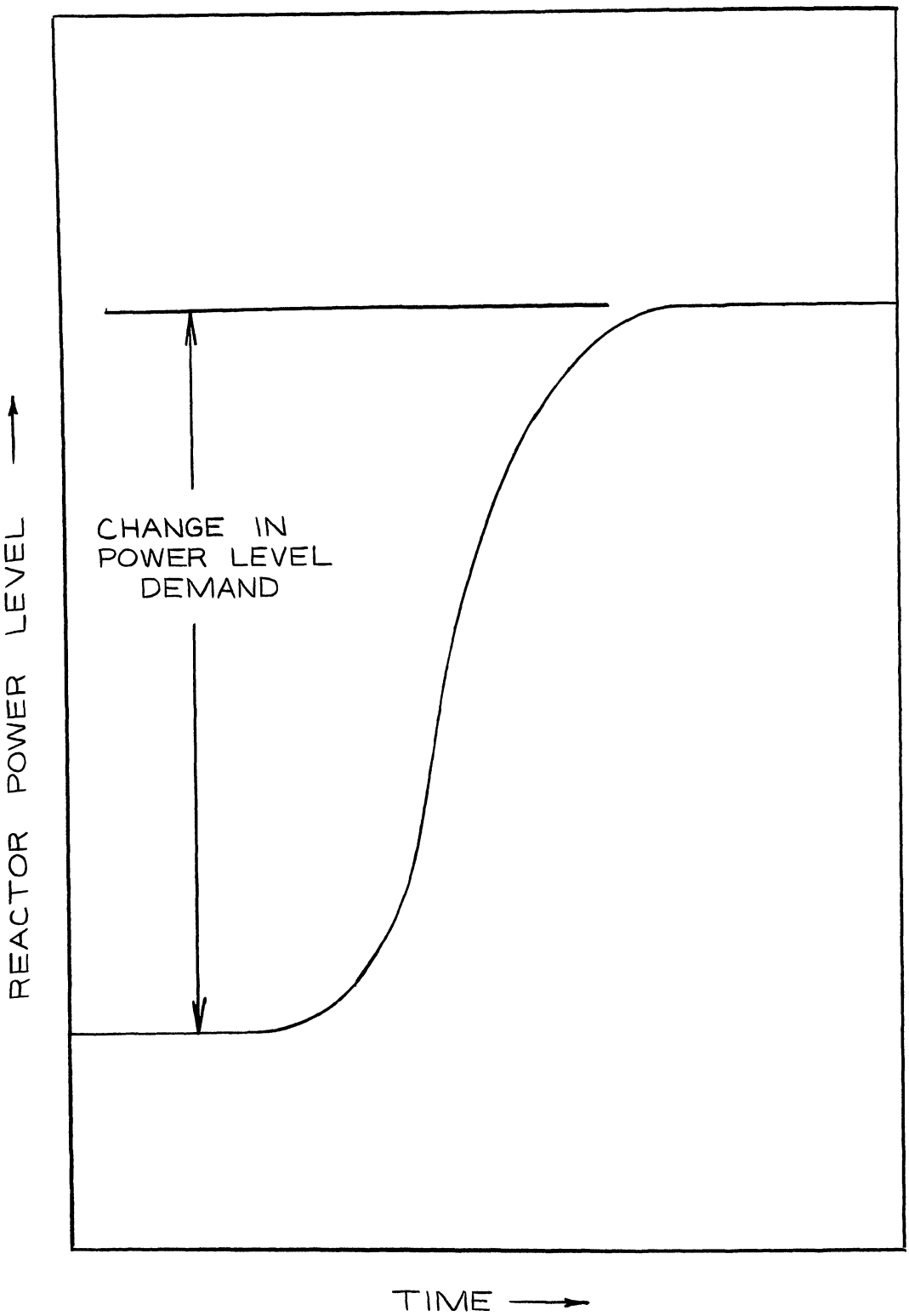

FIG. 11 REACTOR POWER LEVEL CHANGE USING AUTOMATIC CONTROLS WITH ADJUSTED PERIOD

Thermal reactors may be effectively controlled by positioning one or more rods in or near the reactor core. These rods act as strong neutron absorbers and reduce the average neutron flux in the pile. Intermediate reactors are responsive to a lesser extent to such control, but still effective control can be made with some modifications. However, the control of fast reactors presents a very serious problem. Effective control cannot be achieved using rods because the fast neutrons are not as readily absorbed. There is some indication that effective control can be maintained using temperature and density effects, since most fast reactors are of the homogeneous liquid type. Much work needs to be done in this connection. Most of the work already done has not been declassified.

The electronics industry has been rapid in developing circuits and instruments for use in reactor control. Many very reliable reactor control circuits have been developed. Also, good servomechanisms, ionization chambers, and such related equipment have been made widely available. The ease with which the electronics engineers have tackled their end of the reactor development problem certainly places a challenge before the other technologies to come up with similar results.

REACTOR MATERIALS

Probably the most difficult factor in reactor design is the selection of materials used in reactors. Most of the usual engineering problems are present. Since reactors are fundamentally devices for generating heat energy, all the problems involved in such machines are present in reactor design. The familiar requirements such as high strength at elevated temperature, creep resistance, corrosion resistance, high heat transfer rates, and many others, are also placed upon materials used in reactors. However, in addition to the ordinary engineering requirements, materials used in reactors must have favorable nuclear properties, which means that the neutron absorption and scattering characteristics of the material must suit the reactor design. Since nuclear properties have little or no relation to physical and chemical properties, there is no reason to expect that the familiar engineering materials will also have suitable nuclear properties. Unfortunately, most of the materials most familiar in high-temperature engineering practice have very unfavorable nuclear properties. Materials used in a reactor must be able to withstand intense neutron bombardment, primary gamma radiation, and attack by reactor poisons. This is a serious requirement since the crystal lattice structure of many metals undergoes transformation under intense neutron bombardment.

After a reactor has been operating for some time, the materials in the reactor core will become highly radioactive, and the difficulties involved in repair or maintenance become extremely serious. Many materials (e.g., iron) form isotopes which have very long half-lives and give off dangerous intensities of gamma radiation. All repair or maintenance would have to be done by remote control. It becomes obvious then that a reactor designer must think in terms of essentially zero maintenance or repair for the useful life of the reactor. The routine cleaning of furnaces and tubes familiar to the marine engineer has no analogy in reactor operation. The coolants used in reactors may be of a highly active nature. For example, the integrity of a system that handles sodium at high temperature must be of a very high order. If we also demand that the system retain this integrity over a period of years under conditions of thermal shock, erosion and corrosion of the liquid metal, and intense neutron bombardment, then the difficulties of material selection and fabrication in reactor design begin to be appreciated.

Reactor materials are usually classified according to the purpose or function they serve in the reactor. These divisions are not mutually exclusive, since some materials may perform several functions. The classifications of reactor materials are:

1. Fuels and fertile materials
2. Moderators and reflectors
3. Coolants
4. Cladding and structural materials
5. Control rods
6. Shielding material

These divisions will be discussed in order.

Fuels and Fertile Materials

The fuels are the fissionable isotopes: $_{92}U^{235}$, $_{92}U^{233}$, and $_{94}Pu^{239}$. These are necessary to sustain the chain reaction. The fertile materials are $_{92}U^{238}$ and $_{90}Th^{232}$, which are converted to fissionable material by neutron capture. Since the nucleus is the only part of the atom that is important in the fission process, the fuel may be present in pure form, in aqueous solution, as a slurry in a diluent, or as a combination of fused salts. Any compounds or diluents used must be such that the fission process is not interfered with. The condition in which the fissionable and fertile materials are present in the reactor depends to a large extent on the reactor type and purpose. In a heterogeneous reactor, the fuel is present in tubes or in packets, arranged in a lattice. In a homogeneous reactor the fuel is evenly distributed throughout the diluent.

Natural uranium is a fairly well behaved metal. It has fair strength and may be cast, machined, and fabricated if proper procedures are used. Less information is available about plutonium, but it is known that plutonium is also a metal and that it can be cast. Uranium is very susceptible to corrosion and erosion at high temperatures. Also, under intense neutron bombardment, uranium undergoes considerable physical transformation. After some fraction of the fissionable isotope has fissioned, there will be disintegration products present, which could contaminate the coolant. For the reasons just stated, it is usually desirable in heterogeneous reactors to clad the fuel with a protective metal. Alternatively, the fuel may be contained as an alloy or dispersion in a protective metal.

The problem of fuel disintegration is removed in a homogeneous reactor. In this type the fuel is evenly distributed throughout the diluent. There are several ways this may be accomplished. The fuel may be present as a fine powder dispersed in a solid material. Or the fuel may be in the form of a compound dissolved in a suitable solvent. Another possibility is a slurry in which the fuel forms a fine suspension. Still another possibility is a fused mixture of low-melting salts. The diluent used in a homogeneous reactor depends on the energy level of the fission neutrons. For a thermal homogeneous reactor, the diluent must have low absorption for thermal neutrons and have good moderating properties. For intermediate and fast reactors, the diluent should have less moderating properties and have low absorption for intermediate or fast neutrons. All diluents used should have adequate heat transfer properties to permit removal of the heat generated without excessive thermal gradients.

Moderators and Reflectors

Moderators and reflectors must have the ability to reduce rapidly the energy of neutrons, and must have a low absorption of neutrons. The best moderators and reflectors are elements of low

mass number. The efficiency of moderation is given by the moderating ratio, which is the ratio of the slowing-down power to the capture cross section. In Table IV are given the moderating properties of the most likely elements.

Table IV

Mass	Element	Slowing-Down Power	Moderating Ratio
1	H	0.85	65
2	D*	0.072	47,500
4	He	0.0123	infinite
7	Li	0.024	0.0083
9	Be	0.146	133
11	B	0.071	0.00073
12	C	0.058	162
14	N	0.045	0.74
16	O	0.0215	316
19	F	0.014	6.1

It can be seen from Table IV that good moderators will be composed of elements such as deuterium, oxygen, carbon, beryllium and hydrogen. Other elements may be used to provide useful compounds provided the neutron absorption is low, and there is a high density of good moderating elements. Moderators are usually present in the solid or liquid states since it is difficult to obtain high atomic density with gases. All the elements in Table IV form compounds except the gas helium. Some of the solid or liquid compounds used as moderators are: beryllium oxide, beryllium carbide, light water, heavy water, hydrocarbons, deuterocarbons, and organic compounds. The material having the best moderating ratio is heavy water (deuterium oxide), but this material is very expensive. Organic materials are usually not considered because of their sensitivity to radiation damage. Reflector materials are made from the same elements as moderating materials, but may or may not be an extension of the moderating material. At present it is not considered desirable to permit boiling of the moderator, so the reactor must be pressurized if the moderator boils at the operating temperature. This may present a serious structural problem.

Coolants

A reactor is a device for generating heat energy. Therefore, some means must be provided to remove the heat from the reactor core. One of the best, and also the cheapest, coolants is ordinary water. However, for power reactors of the type considered here, the heat release rate per unit volume of reactor core may be considerably higher than could be adequately removed with water as a coolant. For very large heat release rates per unit area of cooling surface, the

*Deuterium, an isotope of hydrogen.

the low-melting metals appear to be the answer. In Table V are given pertinent properties of some reactor coolants.

Table V

Properties of Reactor Coolants

Material	Neutron Capture	Moderating Ratio	Heat Trans. Coeff.	Freezing Point	Boiling Point
Water	0.60	250	6,030	32°F	596°F
Sodium	0.45	0.89	15,200	208	1621
Na-K	1.10	0.225	7,630	66	1518
Lithium	65	0.006	14,100	354	2403
Pb-Bi	0.17	0.56	7,150	275	3038
Air	1.4	0.82	342	--	--
Helium	0.008	83	289	--	--

Heat transfer coefficients are given in Table V as Btu's per sq. ft. per hour per °F. For the liquids, the heat transfer is given at 500°F without boiling. For air the density is 1.385 lbs. per cu. ft. For helium the density is 0.1940 lbs. per cu. ft. The heat transfer coefficient of helium may be greatly increased by putting the system under several atmospheres pressure. However, it will never be as high as can be obtained with the liquid coolants. It is obvious from Table V that sodium has very desirable properties as a coolant for reactors. The heat transfer coefficient is more than twice that of water. Neutron absorption is fairly low, but moderating ratio is also low. The boiling point is high enough so that the system need not be pressurized. However, there are disadvantages connected with using sodium. Sodium is very active chemically and reacts with water with explosive violence. Therefore, elaborate means must be taken to prevent contact between the hot sodium and the atmosphere or water. Also, sodium has a melting point well above atmospheric temperature so means must be provided to prevent solidification of the sodium in the system during shutdown of the reactor. Alloys of lead and bismuth do not appear to offer much promise because of high pumping costs. The serious disadvantage of water is the fact that high pressures are required to prevent boiling at the operating temperature. Also, ordinary water cannot be used in natural uranium reactors because of too high neutron absorption. The gas coolants, particularly helium and carbon dioxide, may be used in the form of a closed-cycle gas turbine plant. Helium will not become radioactive in passing through the reactor so no external shielding is necessary. Helium is not corrosive at high temperature. However, helium is rather expensive, unless leakage is very low. Also, the pumping power is high.

Cladding and Structural Materials

The number of metals suitable for structural use in thermal reactors is severely limited since only aluminum, beryllium, magnesium, and zirconium have thermal neutron absorption cross sections

of less than 0.5 barns. Aluminum and magnesium are very well known, but have very poor properties at elevated temperatures. Beryllium and zirconium are both very difficult to reduce and purify. Even minute traces of impurities have a tremendous effect on the nuclear properties. Beryllium has a high melting temperature, high strength at elevated temperature and has very good nuclear properties. However, beryllium oxidizes readily at elevated temperatures and must be protected by cladding or used in inert atmospheres. Beryllium forms a very serious health hazard, and considerable care must be exercised in melting, handling, and fabrication of the metal to prevent fatal poisoning of the personnel. Zirconium has excellent corrosion resistance, good mechanical properties at high temperature, and is relatively easy to fabricate. Welding must be carried out in a completely inert atmosphere. Although zirconium occurs in many minerals, the difficulty of obtaining the necessary pure metal causes the price to be very high.

Materials for fast reactors need not have such a low neutron cross section. Therefore, in fast reactors, such materials as stainless steel, titanium, molybdenum, and Inconel may be used. If temperatures are to be very high, then the only suitable material will be some type of ceramic or cermet.

Control Rods

Materials for control must have high cross section for absorption of neutrons. They should also have some strength, be fabricable, and have reasonable corrosion resistance in the reactor coolant. Boron and cadmium meet the requirements and have been used extensively for control rods. Hafnium looks very promising, as do some of the rare earths.

Shielding Materials

The core of a power reactor in operation is equivalent in radiation effect to a radium source of many pounds. Adequate shielding must be provided to prevent damage to personnel, equipment, and instruments. There are, in general, five functions of a reactor shield:

1. The fast neutrons must be stopped. This is best done by elements with high density and high atomic number. The fast neutrons are stopped by inelastic scattering. Since this produces gamma rays, the fast neutron shield should be near the reactor core, inside the gamma radiation shield. Materials for fast neutron shielding are: tantalum, tungsten, lead, thorium, iron, and barium.

2. The intermediate neutrons must be stopped. This is best done by hydrogen in the form of water. The neutrons are stopped by elastic scattering. The water is usually present as water of hydration in some dense concrete.

3. Thermal neutrons must be absorbed. Boron is usually used for this, because of its very high cross section. Also, boron captures neutrons without emitting dangerous gamma radiation.

4. The gamma radiation must be stopped. There are generally two gamma-ray shields. One, near the core, stops fission radiation. The other, near the surface, stops secondary gamma radiation caused by neutron reactions in the shield itself. Materials used for gamma-ray shielding are tantalum, tungsten, thorium, lead, iron, barium.

5. The shield proper must be protected from the hot core. This is usually provided by iron or steel. This part is usually cooled by some means.

Since neutrons and gamma rays are most effectively stopped by nuclei, and since the nucleus is a very small target in most matter, the most important consideration in shielding is to provide a lot of material between the core and the shielded area. Therefore, the most economical shield is one that provides the most nuclei per cu. ft. per unit cost. As it works out, this usually means high density concrete. This material is very important in reactor shielding.

EXAMPLES OF REACTOR SYSTEMS FOR MARINE POWER PLANTS

The following reactor systems are discussed to point out some of the features that might be included in an actual future marine atomic power plant. It is very unlikely that any of the systems shown here would actually be used. However, some very similar system might be used. Much of the future development in reactor design depends on the solution of problems concerning materials, heat transfer, and control.

Gas-Turbine, Gas-Cooled Reactor System

A line diagram for this system is shown in Fig. 12, and a sketch of a possible heterogeneous gas-cooled reactor is shown in Fig. 13. This system has several advantages. If helium is used as the cooling gas, then there will be no necessity for shielding the system outside the reactor, because the helium nucleus is very stable under neutron flux and does not become radioactive. Also, helium has very good heat transfer properties under moderate pressure, and is non-corrosive. On the other hand, unless leakage is held to very low amounts, the cost for make-up helium would be prohibitive. Another gas that might be used for reactor cooling is carbon dioxide. This gas is considerably less expensive than helium, and has fairly good heat transfer properties. However, this gas becomes radioactive when passing through the reactor, and introduces a very serious shielding problem if used in a gas turbine system.

The reactor used with this system would probably be of the heterogeneous thermal variety. The reactor core is constructed of blocks of moderator with tubes to hold the fuel elements and allow the cooling gas to pass through. The fuel elements are fed into the front of the reactor, and spent fuel elements are removed out the back of the reactor. The fuel elements must be clad with some material such as zirconium which will not absorb many neutrons. The tubes may be constructed of zirconium also. If enriched fuel is used, titanium or stainless steel may be used. The fuel would probably be machined or cast before cladding, although there is the possibility of having the fuel in liquid or powder form sealed in a metal container. This could considerably reduce fuel reprocessing costs. However, contamination hazard from broken elements is increased. The moderator might consist of either carbon blocks or beryllium oxide. The reactor would have to be built to take a considerable pressure, and be absolutely leakproof to prevent leakage of radioactive coolant or loss of expensive helium. The reactor would be of rather large size because of the very large amount of heat transfer surface needed when gaseous coolants are used. The shielding would be very large and heavy because of the large size of the core. However, control of the reactor is very easy and very safe.

The gas-turbine system has some very good features. Control of the power output may be achieved by control of the system pressure or by bypassing the low-pressure turbine. The amount of gas in the system can be varied by changing the pressure in the accumulator. If means

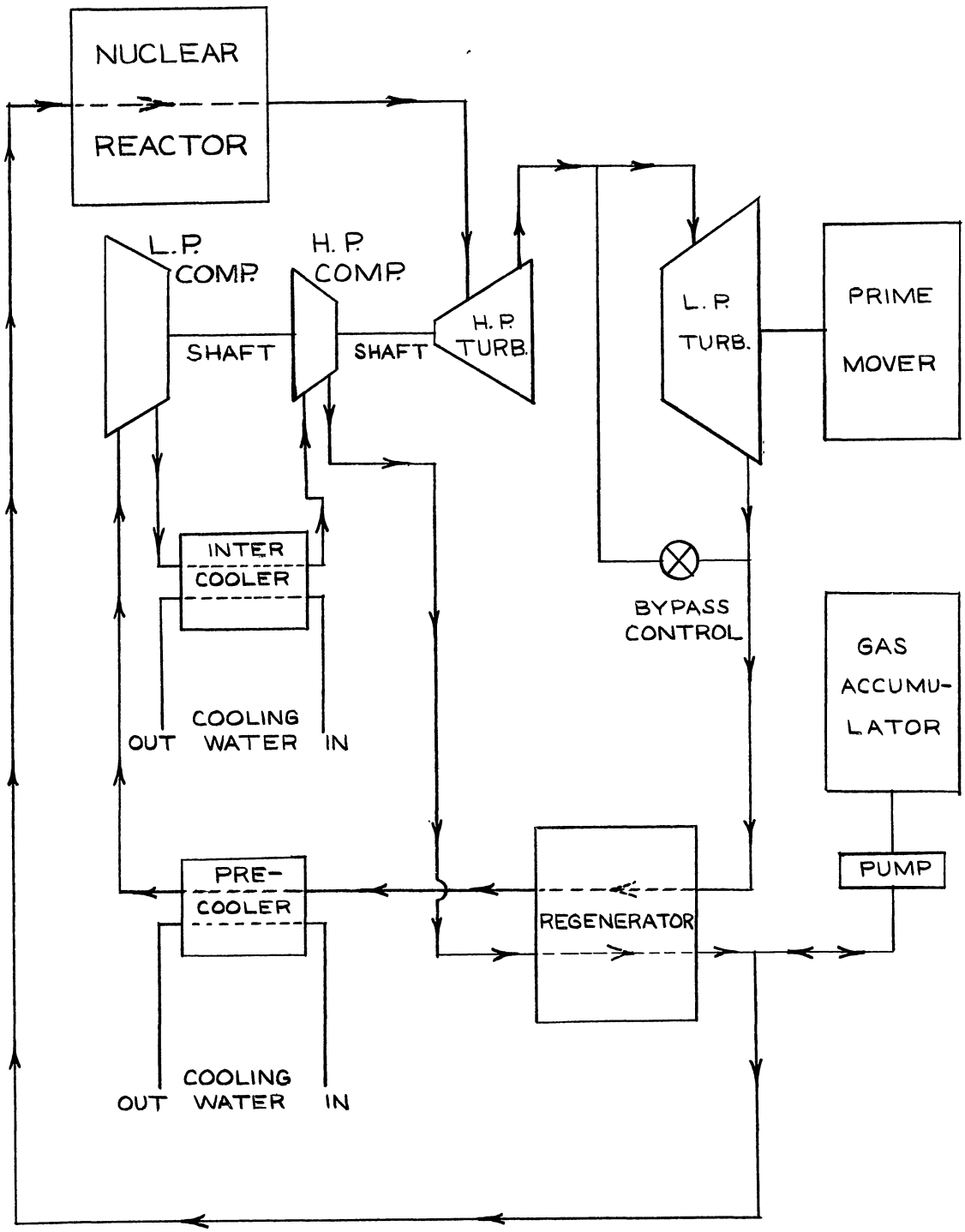

FIG. 12 GAS-TURBINE, GAS-COOLED REACTOR SYSTEM FOR MARINE PROPULSION

can be devised to limit the leakage to very small amounts, then helium could be used in this system to very good advantage.

Homogeneous Liquid Fuel Reactor

There are many ways of arranging this system, two of which are shown in Fig. 14 and Fig. 15. The system shown in Fig. 14 consists of a spherical reactor core through which a liquid fuel is circulated. The heat is removed by circulating the fuel through a heat exchanger inside the shield. The advantage of this arrangement is that the steam and water system remains free of radioactive contamination. Also, the shielding weight is kept to a minimum if high efficiency medium is used to remove the heat. However, the reactor system would be limited to producing saturated steam. For this reason an oil-fired superheater is included in the system. If the oil-fired component is undesirable, then some type of steam separator could be included in the turbine unit, or a series of reheats to reduce the moisture in the turbine to tolerable amounts.

There are several possibilities for the fuel system. The fuel might be an aqueous solution of uranium or plutonium salts. The solvent might be either light or heavy water. If so, the system will have to be pressurized to prevent boiling in the core. Also, means will have to be provided to purge the gas blanket of hydrogen and oxygen gas. Another fuel system possibility is a slurry of fine fuel particles suspended in liquid sodium. Enriched fuel would have to be used, but considerable fuel regeneration might be achieved. The core could be held to very small size because of the high heat transfer efficiency of liquid sodium. If the boiler is outside the shield, then the use of another liquid metal in the external circuit would reduce the size of the heat exchanger inside the reactor, and considerably reduce the weight of shielding required. However, liquid sodium at a red heat is not the most desirable heat transfer medium from a safety standpoint. There is yet another possibility for the fuel system. The fuel might be included in a low-melting glass-like fused salt. There are several advantages to this system, since high temperature may be achieved without the necessity of pressurizing the system. The reactor could be made to operate with fast neutrons if compounds were used with low absorption and small moderating effect. However, dissociation of the fuel mixture might take place, causing release of undesirable gases. Also, the problem of pumping such a fuel mixture might be considerable.

The control of a homogeneous fast or intermediate reactor presents a considerable problem. Effectiveness of control rods is limited by the low absorption of most materials for fast neutrons. The most promising control would appear to be the use of a large negative temperature coefficient to prevent excessive criticality. In a homogeneous liquid reactor, an increase in temperature reduces the density of the fuel mixture and tends to decrease the reactivity. Thus, any sudden increase in reactivity and rise in power level would result in a rise in temperature. This temperature rise tends to reduce the reactivity and return the power level to the previous value. Another method that might be used to control a reactor of this type is control of liquid level in the reactor core. Raising the level increases the

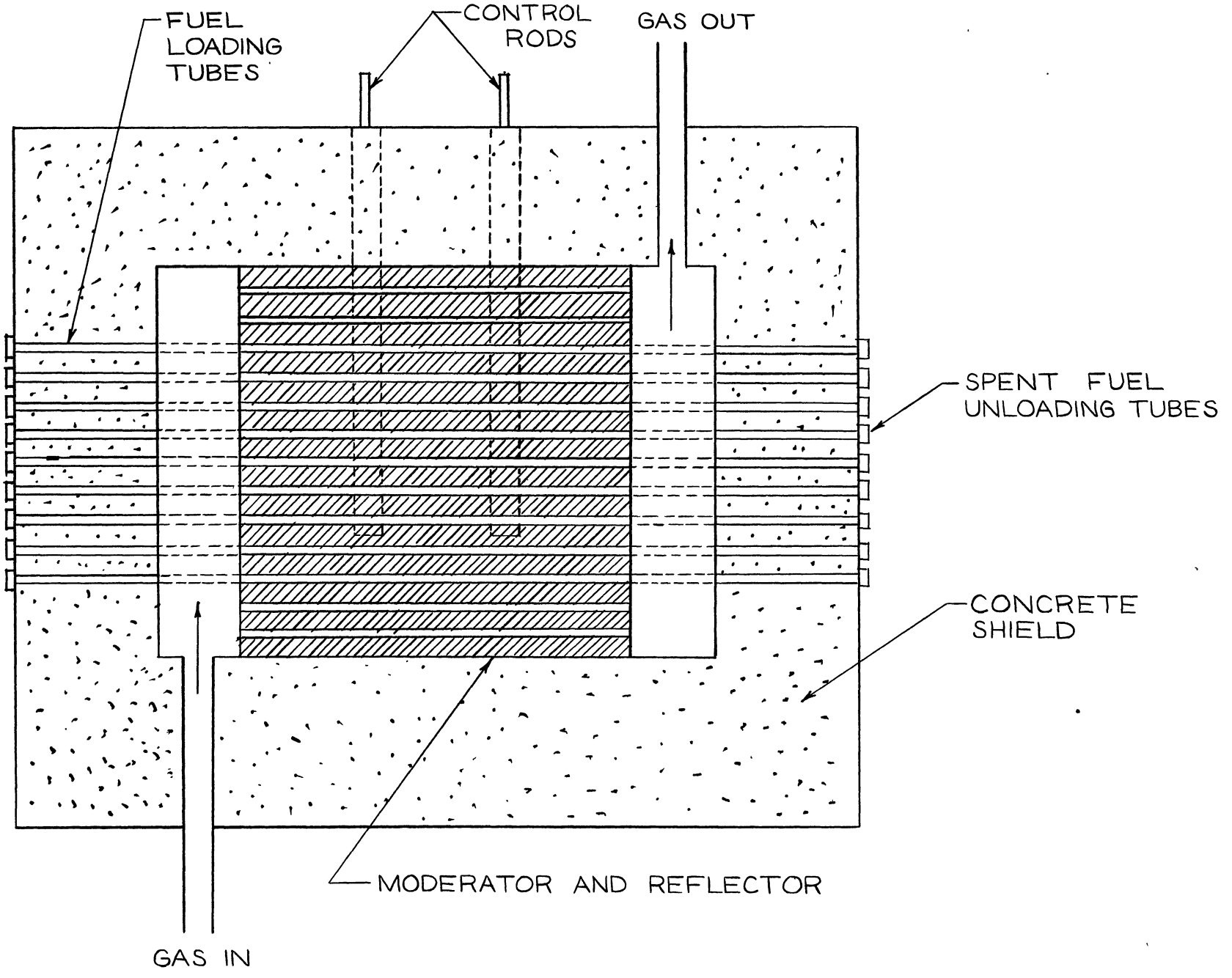

FIG. 13 HETEROGENEOUS GAS COOLED REACTOR

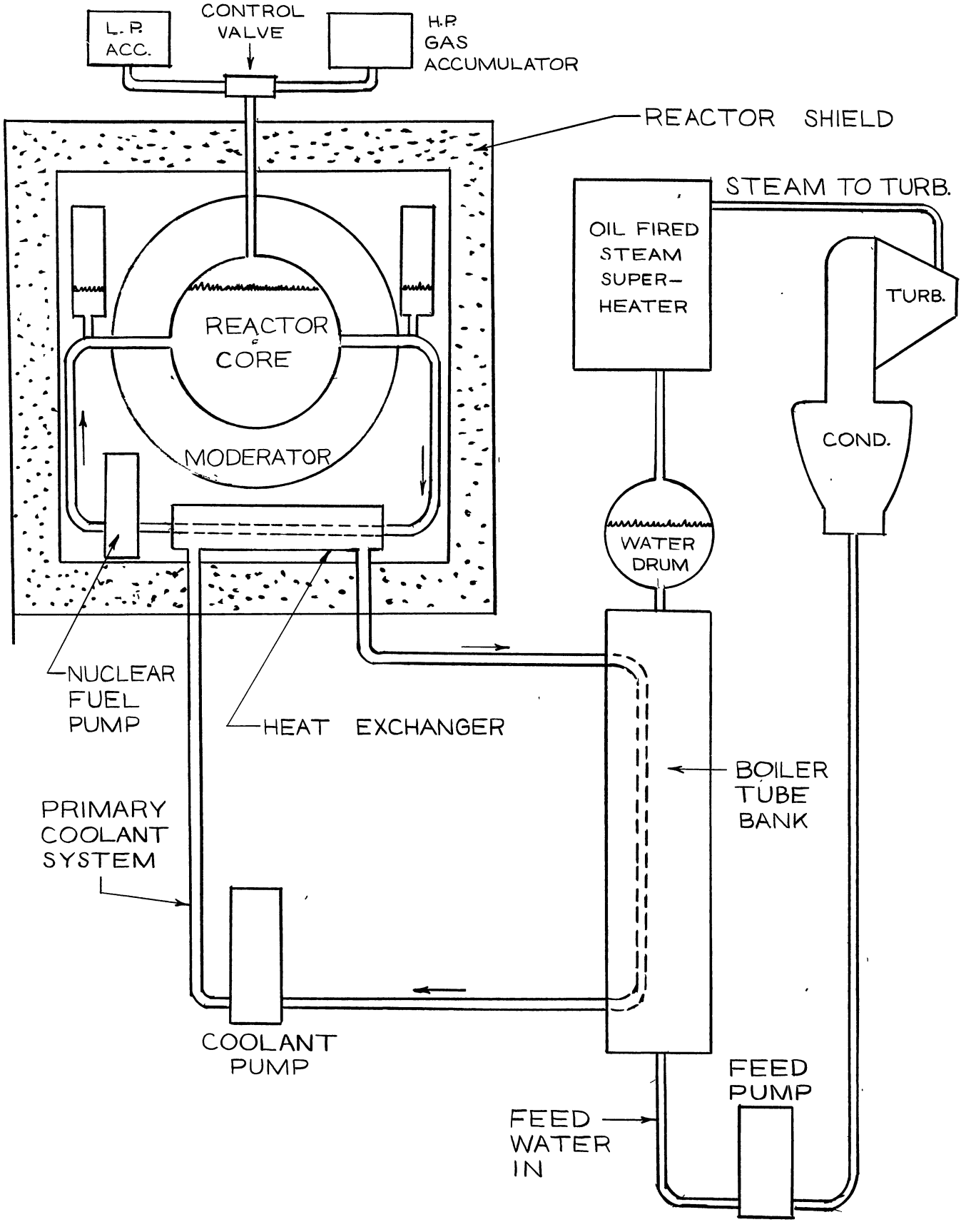

FIG. 14 HOMOGENEOUS — LIQUID FUEL REACTOR WITH EXTERNAL WATER BOILER

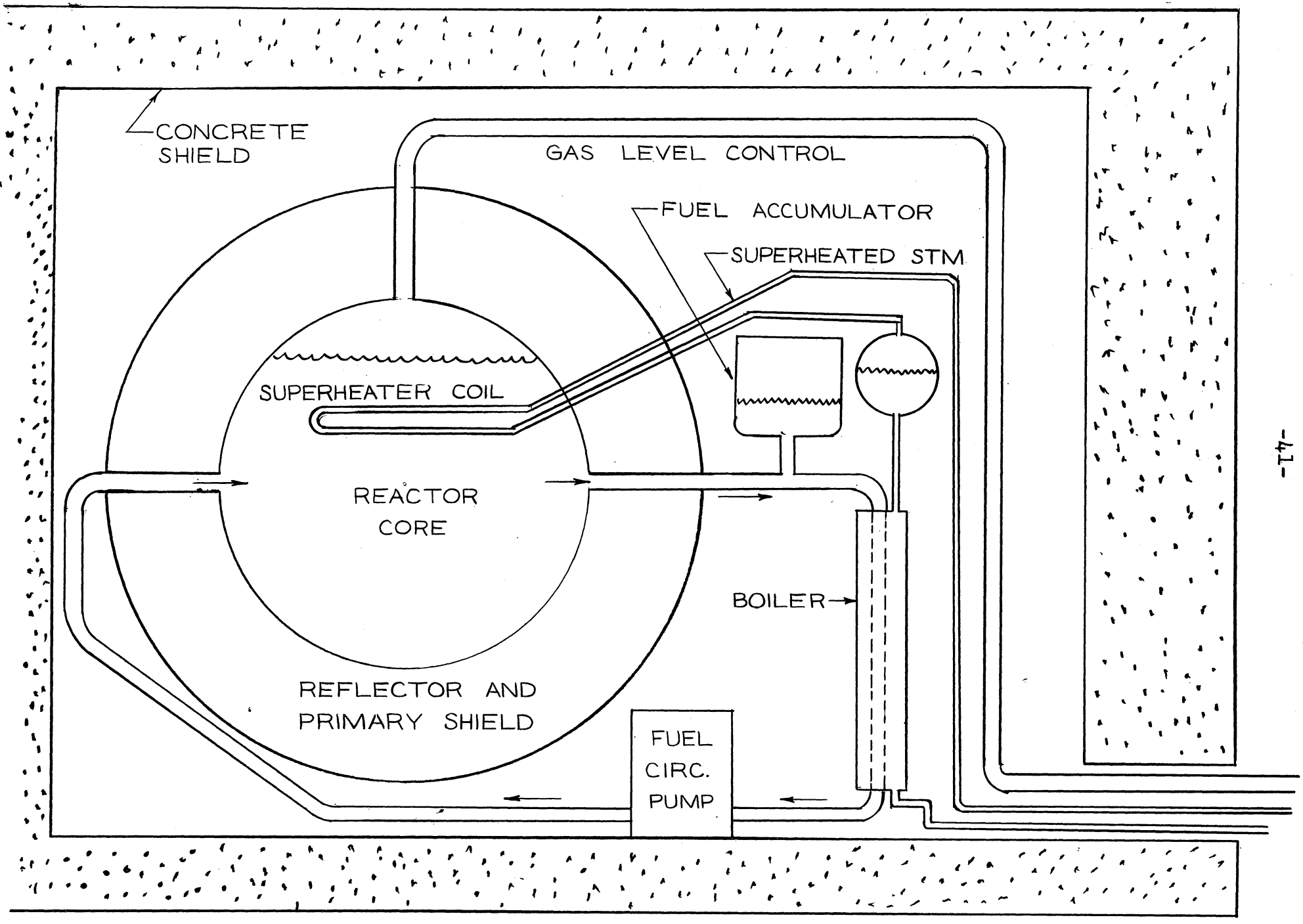

FIG. 15 HOMOGENEOUS — LIQUID FUEL REACTOR WITH INTERNAL WATER BOILER AND SUPERHEATER

reactivity. If helium is used as a blanket, the level may be controlled by allowing gas to pass in and out of gas accumulator tanks.

There may be a possibility of putting the boiler inside the reactor shield and eliminate the double heat exchange system described previously. Such an arrangement is shown in Fig. 15. The liquid fuel is pumped through the boiler to transfer the fission heat directly to boiling water. A superheater coil is shown inside the reactor core. This would provide superheat without necessity of separate oil-fired superheater. However, there may be considerable induced radioactivity in the superheated steam due to the exposure to direct neutron bombardment. Whether this would require extensive shielding of the steam-water system is not yet known. However, even without the superheater, the possibility of boiling directly in the reactor looks very attractive. There are only two systems in which to worry about leaks. However, the large size of the boiler inside the reactor considerably increases the volume to be shielded. This means that the weight of reactor shielding is much larger.

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