POWER REACTOR FUNDAMENTALS

BY

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This paper is an attempt to summarize the essentials of reactor physics, and their influence on the associated engineering problems. Questions of control and transient conditions, instrumentation, and health physics, all of which are of great importance, have not been considered. The aim has been to give enough of the basic concepts and definitions to act as a guide to the copious published literature.

ATOMIC STRUCTURE AND THE SOURCE OF NUCLEAR POWER

It will be appreciated that reactor science is the first instance in mechanical technology where the application engineering is at only one remove from the transcendental laws of nature. Therefore, although it is necessary to have some visualization of the physical basis of the process used, such visualization must be accepted only as a more or less successful effort at describing the, at present, 'undescribable'.

Despite many failings in detail, the Bohr Rutherford atomic model is still used with remarkable success in explaining and even predicting atomic behaviour and, from the engineer's viewpoint, is a reliable and perfectly adequate foundation. This model consists of an exceedingly dense mass of protons and neutrons, termed the nucleus, surrounded by a diffuse region of orbital electrons, equal in number to the protons, the resultant electric charge being zero.

A number of other ultimate particles are considered to exist, some authorities allowing up to twenty-three, although many of these have independent existences limited to a fraction of a microsecond. Fortunately, these other particles have little significance in a non-fundamental view of reactor theory, but a unifying and simplifying theory of atomic structure involving this wide and expanding range of particles is being energetically sought.

The mass and charge of the three basic atomic components are tabulated below :—

	Mass	*Charge*
Proton	1·007593	+1
Neutron	1·008982	0
Electron	0005488	−1

the masses being in terms of the atomic mass unit (A.M.U.), which is defined as one-sixteenth the mass of the oxygen atom $^{16}_{8}O$, or $1{\cdot}66 \times 10^{-21}$ gm.

The chemical nature of the atom is decided by the number, Z, of the orbital electrons, and the mass of the atom by the total, or mass, number, A, of protons and neutrons (referred to jointly as nucleons). The atom produced by a particular system of nucleons under consideration is termed a nuclide. The symbol for any atom is then $^{A}_{Z}S$, or SA where S is the chemical symbol for the element. For example, O is the chemical symbol for oxygen, whose chemical nature is decided by its possessing eight orbital electrons. The commonest form of oxygen atom has a nucleus of eight neutrons and eight protons ($A = 16$), and is therefore denoted by $^{16}_{8}O$, or O16.

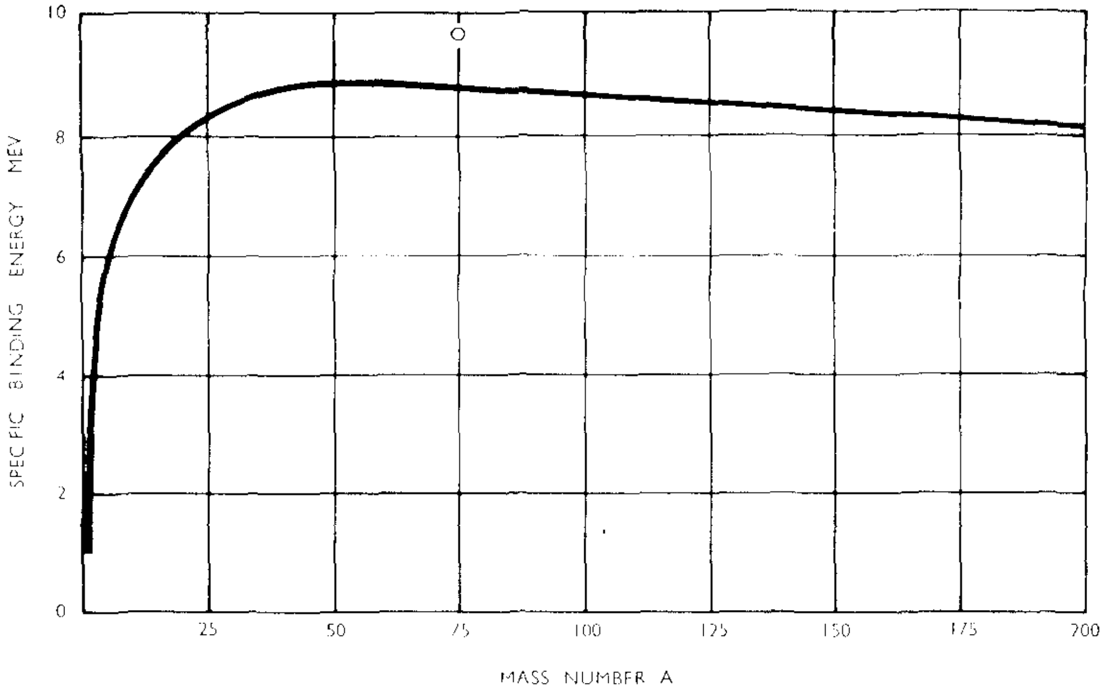

Fig. 1—General Form of Variation of Specific Binding Energy with Mass Number

Despite their chemical importance, the orbital electrons are of negligible importance in reactor physics, which is essentially a study in dynamics, owing to their very small mass, and it is generally possible and preferable to consider atomic behaviour in terms of the nucleus only. In contrast, for the chemist, owing to the stability of the nucleus under normal conditions, it is equally legitimate to consider the electrons only.

It is possible, by varying the numbers of protons and neutrons, to obtain atoms of common A but varying Z, or vice versa. In the first case, such atoms, of equal mass but differing chemical nature, are termed isobares ; in the second case, those having identical chemical natures but different masses, are termed isotopes. Of the 92 elements ($Z = 1$—92) occurring in detectable amounts in nature, there are over 320 natural isotopes, and if the six artificial elements ($Z = 93$–102) and all the artificial isotopes yet produced are included, the total is well over a thousand.

If the mass of an atom of known composition is calculated from the masses of its constitutent particles, and compared with the actual mass, the latter is always found to be less, e.g., for oxygen $^{16}_{8}O$:

Mass of atom by definition = 16 A.M.U.
Mass by addition = $8 \times 1{\cdot}007593$
+ $8 \times 1{\cdot}008982$
+ $8 \times {\cdot}0005488$

16·136992 A.M.U.

This mass difference or mass defect represents the binding energy of the nucleus, liberated in its formation from its nucleons, and which would be required in order to disrupt it into those nucleons again. This energy is given by the equivalence $E = mc^2$, derived by the special theory of relativity, where c is the velocity of light. When considering atomic transmutations, the specific binding energy or b.e. per nucleon, is more convenient, and a curve showing the variation of this specific b.e. with A is shown in Fig. 1. It will be seen that the specific b.e. for the lighter and heavier elements are lower than for those in the middle. If, therefore, light nuclei can be combined, or heavy nuclei disrupted, to yield nuclei in the middle range (the total number of nucleons being invariant) there will be a surplus of energy, which will be released. The first of these processes is usually known as fusion, and is exemplified by the hydrogen bomb (note the exceptionally small s.b.e. of hydrogen $A = 1$), various experimental devices, and in all probability by the stars, and the latter, known as fission, by the atomic bomb and, in a more controlled manifestation, is the basis of power reactors.

The variation of b.e. can be accounted for in elementary terms by dynamic analysis of the nucleus as a system of charged (proton) and neutral (neutron) particles, but in the special conditions prevailing in the nucleus, this analysis can hardly be taken seriously, the true explanation lying in the far more subtle theories of structure now being developed.

THE FISSION PROCESS

The fissile fuel, consisting of a heavy element or mixture of elements, in elemental or compound form, is fissioned into lighter elements, thus releasing energy which mostly appears ultimately as heat. The greater part of this is removed by circulating a fluid coolant, and then utilized, at present, by standard thermal techniques.

The key particle in the process is the neutron, owing to its combination of relatively large mass and no charge, which enables it to pass comparatively freely through the fuel. Side effects due to other particles occur, but are of negligible importance in reactor conditions. (In the special conditions existing in particle accelerators, where very high velocities are generated, fission or transmutation by other particles frequently occurs). The reaction consists of the impact of a neutron on a fuel nucleus, causing division of that nucleus into two nuclei of lighter elements, release of the binding energy in various forms, and emission of various particles, including further neutrons. If, on the average, one or more neutrons in turn causes a fission, the reaction is self-sustaining, and the reactor in which it occurs is termed divergent or critical. The controlled achievement of this level of activity is the aim of reactor design.

This process is quite distinct from that of radio-activity, which consists of the spontaneous decay of a nucleus to one slightly lighter by the emission of particles and radiation. Radio-activity is of great, though secondary, importance, in its influence on :

The production of delayed neutrons
The decay of fission products, and poisoning, both of which are briefly discussed below, and
The health and safety of operators and maintainers, a major problem which can only be mentioned here.

The characteristic of a radio-active process of leading interest in the reactor context is its half-life, i.e. the time required for half of any given quantity of a radio-active nuclide to decay to the next nuclide in the chain, which may or may not be itself radio-active. No variation of ambient conditions ever achieved on earth or observed in the stars appears to have any effect on the half life.

The behaviour of fissile fuels with neutrons varies greatly with neutron velocity. This velocity is expressed as the kinetic energy in electron-volts. (The energy unit ‘ electron-volt ’ (e.v.) which is in common use in nuclear physics is the kinetic energy gained by a particle carrying the electronic charge ‘ e ’ when it has been accelerated through a potential difference of one volt.) There are two ranges of speed in which significant fission rates can be attained, termed

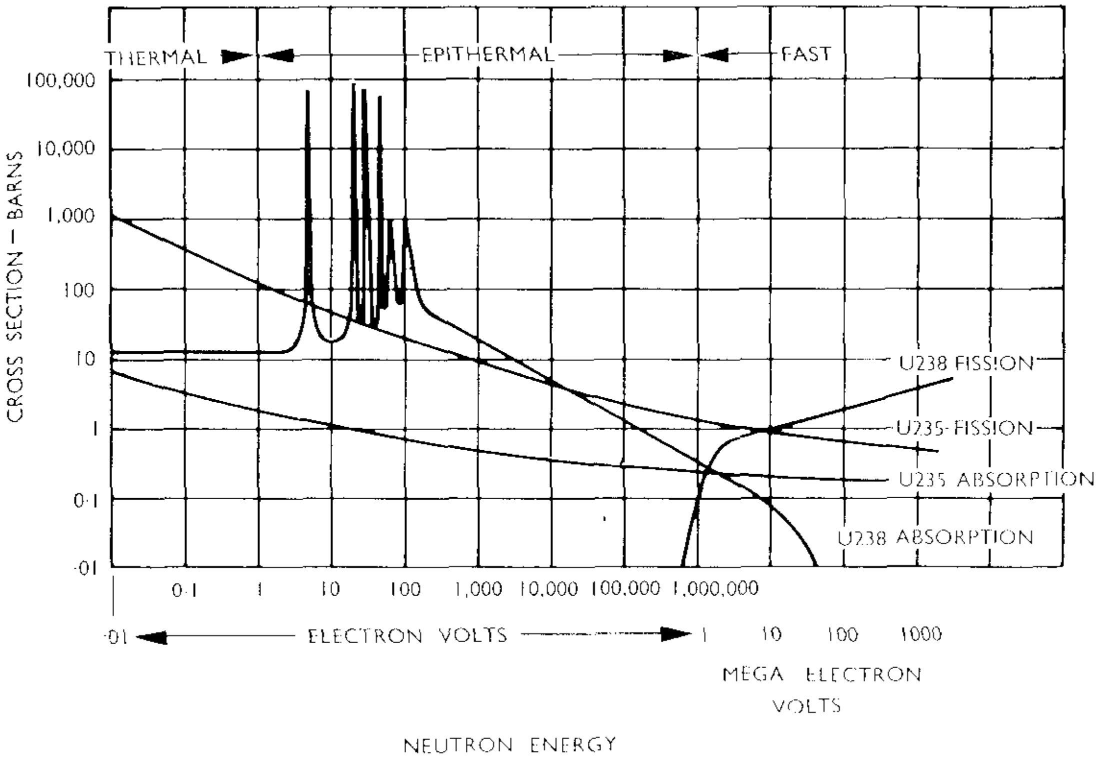

FIG. 2—FISSION AND CAPTURE NEUTRON CROSS-SECTIONS OF U235 AND U238
(*N.B.*—Logarithmic scales)

fast (energy exceeding 0·5 mega electron-volts) (Mev), and thermal (energy less than 1 e.v.). The range between, termed epithermal, although not at present used for fission, is of prime importance from the point of view of neutron losses, discussed below. The term thermal is derived from the fact that in this range the neutron velocities are of the same order as those corresponding to normal ambient temperatures in the kinetic theory.

NEUTRON CROSS-SECTION

When a neutron approaches a fuel nucleus, it may either pass by without any reaction, be scattered or deflected, cause fission, or be captured or absorbed. Likewise, when approaching any other nucleus, it may pass by, be scattered, or captured. The probability of these occurrences is expressed as the cross-section of the nucleus for a neutron moving at a particular speed. A fissile nucleus has a total cross-section consisting of scattering, fission, and capture components. The term cross-section is derived from the fact that it represents the effective target area for the nucleus. Neutron cross-sections are of decisive importance in the design of all parts of a reactor. The unit is the barn, pleasingly alleged to have been derived from the expression 'as big as a barn door', one barn being equivalent to an effective target area of 10^{-24} sq cm.

The general form of the variation of cross-section for the two components of natural uranium U238 (99·3 per cent) and U235 (0·7 per cent) is shown in FIG. 2, from which it will be seen that:

(*a*) Sharp local peaks occur in the U238 capture cross-section in the epithermal range. This phenomenon, referred to by mechanical analogy as resonance, causes a risk of catastrophic capture of neutrons. It is, therefore, necessary to isolate the majority of epithermal neutrons from the fuel if prohibitive neutron loss is not to occur. Hence, reactors employing thermal neutrons are characterized by having concentrated fuel elements widely (by atomic standards) separated by large masses of moderator, whose prime function is to decelerate the fast neutrons generated during fission through the epithermal range, without excessive loss by absorption.

(*b*) The fissile cross-section of U238 virtually vanishes below 1 Mev, while that of U235 increases with neutron deceleration. In fact, no nuclear fuel of wide occurrence in nature is subject to thermal fission.

FISSILE FUELS, ENRICHMENT, AND BREEDING

The only fissile fuels at all likely to be used are :

Thermal fission : Uranium U235 and U233
Plutonium Pu239
Fast fission : Thorium Th232
Uranium U233, U235 and U238
Plutonium Pu239

Of these fuels, only U235, U238 and Th232 occur in nature in significant quantity. The others are obtained by nuclear reactions as follows :

U233 : Th232 + n (neutron) → Th233 → Pa233 → U233
radio-active
decay
Pu239 : U238 + n → U239 → Np239 → Pu239

The concentration of U235 in natural uranium is adequate to attain criticality with good neutron economy, and thermal reactors can be fuelled with natural uranium if they are of adequate size to meet this condition. Thermal reactors with poorer neutron economy, due to small size or other factors, and fast reactors, will not attain criticality, and their uranium fuel must be enriched by adding more U235. As this can only be obtained by elaborate fractionating methods from natural uranium, enriched fuel is exceedingly expensive, and enrichment considerations may well be decisive in the economics of mobile reactors. Degree of enrichment is expressed as the percentage of U235 atoms present.

Thorium 232 is not easily fissionable, and is not suitable for direct use as a fuel. It is, therefore, envisaged that it be charged into a reactor fuelled on uranium or plutonium, and converted by neutron capture to U233 as shown above. If a net gain of fissionable fuel is achieved in this process, it is termed breeding. Similarly, with U238, breeding is achieved if there is a net gain of fissionable material in the form of Pu239. If breeding is established as a practicable process, it will be possible to burn all U238 and Th232 as fission fuel, representing a hundredfold gain in the utilization of natural uranium, as well as all the much more abundant supplies of thorium. Plutonium production, on a non-breeding scale, occurs in all U238 reactors, and the balance between fission and hence power and plutonium production, can be varied by altering the reactor parameters, and the time for which the fuel charge is kept in the reactor. Military reactors, e.g. Hanford and Windscale, are weighted as heavily as possible to plutonium production, Calder Hall is a compromise, and the later commercial reactors are weighted strongly to power production, although even they will inevitably yield considerable quantities of plutonium. Plutonium, although a good fissile fuel, in general, exhibits unfortunate instabilities under certain conditions, particularly temperature, besides possessing unacceptable ingestion hazards and difficult handling qualities, and the success achieved in using the large quantities inevitably produced will be another decisive factor in the economic balance for non-military purposes.

The time for which a charge is kept in the reactor is expressed either as the percentage of fuel atoms fissioned or, for power reactors, as the power extracted, in megawatt-days per tonne (M.W.D./T). To a first approximation, one gram of U235 would burn up completely to one M.W.D. : natural uranium fuel, therefore, has a maximum burn-up of 7,000 M.W.D./T, until all U235 is gone. However, owing to the formation of Pu239, which immediately proceeds to act as a fuel, this is not the limit of theoretical burn-up. In fact, the limit of burn-up is set, not by availability of fissile atoms in the fuel, but by poisoning or radiation damage (v.i.).

Materials such as U238 and Th232 when used to make fissile fuels are termed fertile materials. It is obviously attractive to dispose them round the outside of the reactor core, where they serve the triple purpose of :

(i) Preventing neutrons and radiation passing out, viz. shielding
(ii) Reflecting some neutrons back into the core, thus aiding neutron economy
(iii) Forming fissile fuel.

This disposition and use of the fertile material is termed blanketing.

REACTOR DESIGN VARIANTS

The basic division of reactors is into fast and thermal types. It is intended here to discuss principally the thermal type, to which all present power reactors belong.

Principal design variants are :

Neutron energy : Fast or thermal. The principal problems in the fast reactor, once the necessity for a concentrated fast fissile fuel is accepted, are those of controlling and removing the heat from the very intense fission zone. The thermal reactor, in contrast, is dominated by neutron economy, and arrangements of fuel and control to obtain maximum burn-up.

Core arrangement : homogeneous or heterogeneous. All working power reactors are heterogeneous, principally for ease of design and to allow physical separation of fuel moderator and coolant.

Moderator. This must have the following properties :—

(i) High scattering cross-section
(ii) Very low capture cross-section
(iii) Stability under neutron irradiation.

In addition to these essential nuclear properties, it should :—

(iv) Be cheaply obtainable in high purity
(v) Be chemically inert to other reactor materials, especially the coolant, if different
(vi) Withstand reasonably high temperatures.

It is fortunate, and surprising, that there is a fair choice of moderators meeting these conditions more or less, viz. :—

Graphite
Water, either light, H_2O or, much better, heavy, D_2O
Beryllium oxide
Various synthetic organic fluids.

At present, most power reactors in operation on shore use graphite, but water has many attractions, and if heavy water were available at a reasonable price it would sweep the field.

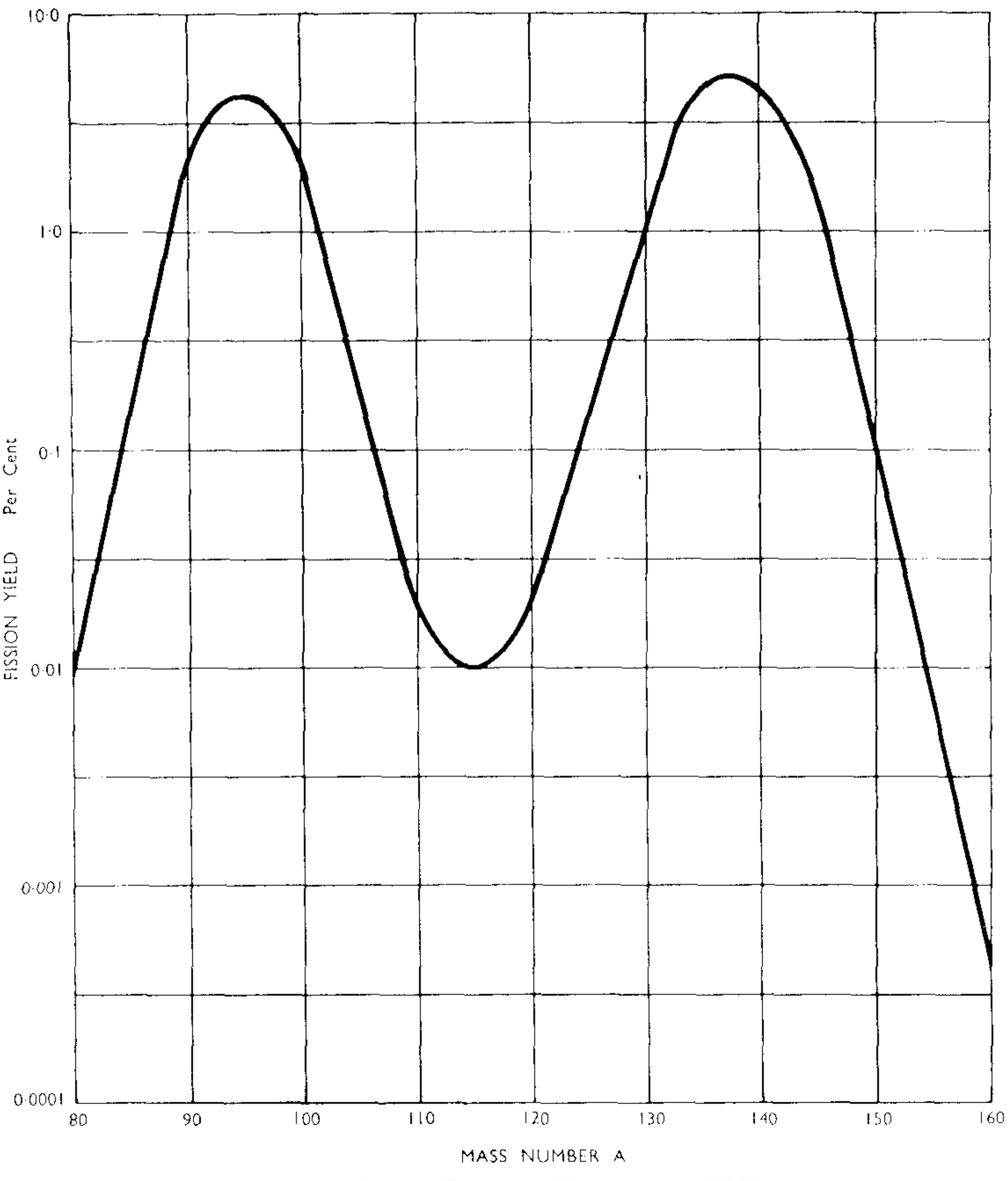

FIG. 3—FISSION PRODUCT YIELD FROM U235

Heat transfer medium : gas, water, or liquid metal. Water or liquid metal are necessitated by space considerations in marine applications, and the extreme technological difficulties of the latter have made the use of water almost certain in all future designs. The high vapour pressure of water unfortunately requires the reactor to be at a high pressure if reasonably high temperatures and hence Carnot efficiencies are to be attained. The water may remain as such in the pressurized water (P.W.R.) reactor, or may boil and transfer the heat largely in latent form in the boiling water (B.W.R.) reactor, or remain in the form of steam throughout. The B.W.R. offers considerable problems in securing stable and controlled boiling, but if this can be done it offers such advantages that its ultimate success seems assured.

Fissile principle. U235, U233, or Pu239.
Fertile principle. U238 or Th232
Degree of enrichment
Design burn-up.

CONTROL

Any practicable reactor is designed to have a neutron multiplication factor k_{eff} (the factor by which each generation of neutrons exceeds its predecessor) slightly exceeding one, say 1·02. This gives the necessary flexibility for control, which is exercised by introducing strongly neutron-absorbent material, usually in rod form, into the reactor thus reducing the number of neutrons available for fission. The total volume of control material is usually divided into two unequal parts, a small volume for continuous control, and a large volume, spring or gravity fed, for emergency shut-down or ' scram '.

The practicability of control depends on the existence of delayed neutron emission. Fission times are virtually instantaneous, and no control system could function if the neutrons produced were all able to react forthwith. In fact, about 0·7 per cent of the neutrons are produced by a short term radioactive process with a half life of the order of 10 seconds, and their presence, therefore, increases the average life of a neutron generation to about 0·1 second, a controllable situation. Should the reactivity of a reactor rise to the point where the neutron factor exceeds one, neglecting the delayed neutrons, it is termed prompt critical, and uncontrolled fission and heat release will occur, unless it is scrammed forthwith.

The other dominant characteristic in the control of a reactor is its temperature coefficient, i.e. change of k_{eff} with varying average core temperature. If this is negative, the reactor will be stable and largely self-regulating. By good fortune, it is relatively easy to ensure that the normal types of power reactors do have a negative characteristic.

FISSION PRODUCTS AND POISONING

The elements formed by fission, neglecting those of very short life involved in delayed neutron emission, are distributed over a range of approximately A/3 to 2A/3, referring to the fissile fuel. The distribution for U235, with thermal neutrons, is shown in FIG. 3.

The majority of products are strongly radio-active, and in their decay to more stable nuclides emit radiation which is largely responsible for the biological hazard. In some cases, notably the decay of Tellurium 135 to Xenon 135, according to the sequence :

Te135 → I135 → Xe135 → Cs135 → Ba135
1 min 6·7 hour 9·2 hour $2\cdot10^{6}$ year Half life

a build-up of products having excessive capture cross-sections may occur, Xe135 having a capture c.s. of $3{\cdot}5. \times 10^{6}$ barns for thermal neutrons. This may necessitate reprocessing of fuel to remove the fission products before this is economically desirable or metallurgically necessary. An equilibrium condition is usually reached under criticality conditions, but when a reactor is shut down the fact that Xe135 has a longer half-life than its parent I135 means that its concentration will build-up with time to a peak value. This may well be such that the reactor cannot attain criticality, so that it is out of action until the poisoning products finally decay, which may be a period of many hours or even days. This entails that, in order to allow the necessary flexibility and availability for marine use, either a substantial base load must be maintained, or the reactor must have a substantial neutron surplus to allow restarting against maximum poisoning concentration.

MATERIALS

It is only intended to mention here some of the special material requirements imposed by reactor conditions.

Behaviour Under Irradiation

All materials in a reactor are subject to intense radiation. This has a deleterious effect in almost all cases, as for example, gradual embrittlement of many steels, and the Wigner distortion of graphite, which indirectly caused the fire, and final shutdown, at Windscale. Uranium itself suffers very severe asymmetrical swelling and distortion, which in many cases dictates the end of fuel element effective life.

Cross-Sections

Owing to the general need for neutron economy, all materials in the reactor except absorbers must have tolerably small capture cross-sections, and be free of impurities having higher cross-sections. One of the exasperating features of this is that elements having near-identical chemical and physical properties, and hence resisting separation from each other, may have such different nuclear properties that this separation is imperative. The best example of this is, of course, the mixture of U235 and U238.

Ease of Working

The complex geometry and tight tolerances of both moderator and fuel elements dictated by thermal and nuclear design requirements necessitates fairly easily worked material.

Corrosion

Only very low corrosion rates can be tolerated.

These stringent and conflicting requirements necessitate, in the present state of the art, the use of expensive and scarce materials. However, there is hope that, especially by the use of ceramic and cermetallic materials, the traditional progress of new technologies from rare to relatively normal materials and techniques may soon be under way. In the commercial field, this is being strongly stimulated by the need to get costs down if nuclear power is to be competitive in this century.

MISCELLANEOUS DATA

Some Constants

Velocity of light c $= 3 \times 10^{10}$ cm/sec.

Diameter of nucleus $\simeq 30 \times 10^{-11} A^{\frac{1}{3}}$ cm (an empirical formula depending upon mass number A).

1 AMU $= 1{\cdot}66 \times 10^{-21}$ gm $\sim$ 931 Mev $\sim 1{\cdot}49 \times 10^{-3}$ ergs.

1 fission $\sim$ 200 Mev energy release.

1 Watt $= 10^7$ erg/sec $\sim 3 \times 10^{10}$ fissions/sec.

Radiation Occurring In and Around Reactors

α particles	—Two protons combined with two neutrons, i.e. nuclei of helium —very low penetrating power.
β particles	—Electrons.
γ rays	—Highly penetrating electro-magnetic radiation of the same nature as X rays—the major biological hazard.
X rays	—These are generated in a reactor by extra-nuclear processes, especially the deceleration of neutrons, as opposed to γ rays which are always nuclear in origin.

Nuclear Reactions

These are represented in full thus :—

$$\mathop{\mathrm{Th}}\limits^{232}_{90}\,(n,\ \gamma)\longrightarrow \mathop{\mathrm{Th}}\limits^{233}_{90} \xrightarrow[\mathrm{O}^{e}_{-1}]{23\cdot5\ \mathrm{min}} \mathop{\mathrm{Pa}}\limits^{233}_{91} \xrightarrow[\mathrm{O}^{e}_{-1}]{27\cdot4\ \mathrm{days}} \mathop{\mathrm{U}}\limits^{233}_{92}$$

This portmanteau example, for the breeding of U233 from Th232, shows that :

> Thorium 232 captures a neutron and emits a γ ray in forming Th233, which decays with a half-life of 23·5 minutes to Palladium 233, emitting a β particle. The Pa233 decays in turn to Uranium 233 with a half-life of 27·4 days, again emitting a β particle.