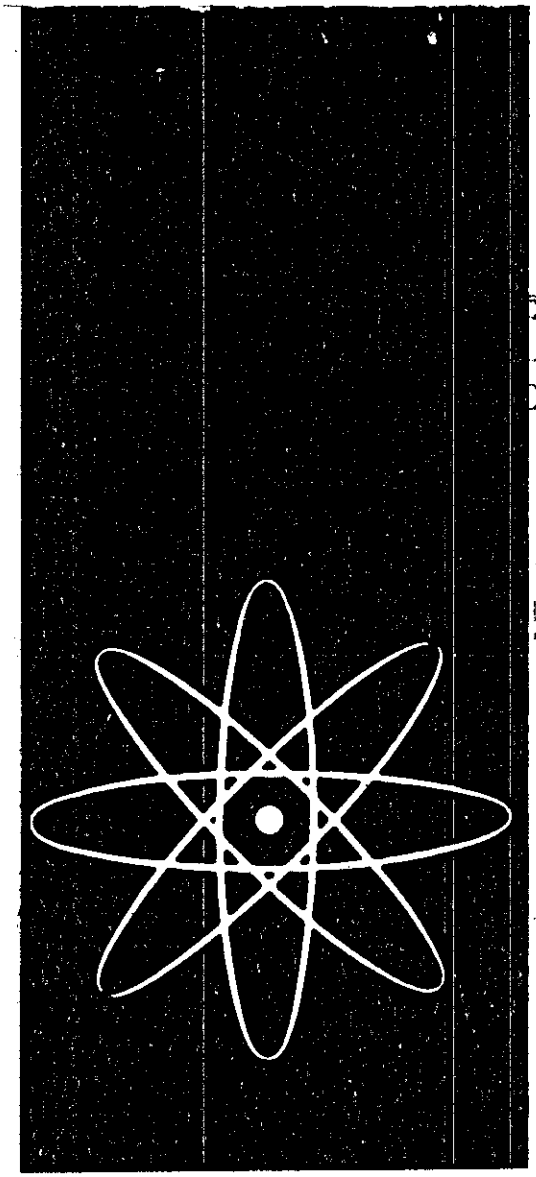
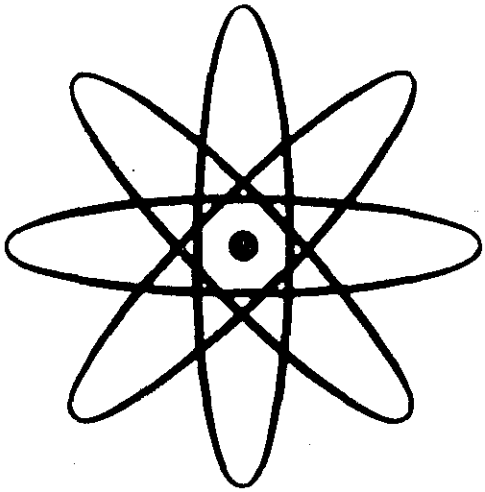


REACTOR OPERATING PHYSICS

IPD - RPC *Series 1*

IRRADIATION PROCESSING DEPARTMENT
HANFORD ATOMIC PRODUCTS OPERATION
GENERAL ELECTRIC



REACTOR OPERATING PHYSICS

PREFACE

The text and the charted material for a three-lecture series are repeated in this manual. The purpose of the series is two-fold:

(1) To present briefly, yet completely those concepts of reactor physics which the operator is expected to know and understand.

(2) To ensure that every reactor operator has the chance through classwork and personal study to overcome any deficiencies he may have in minimum basic background. This three-part series covers all of the physics material on which Reactor Personnel Certification questions will be based; other material supplied in Chapter 1 of the "IPD Reactor Training Text" and in HW-51856, "Reactor Physics Primer", provide useful background for supplementing this text.

In preparing the text material the author has been guided by two assumptions. The first is that many of the people who study this material will have had neither high school chemistry nor physics background. The second assumption regards the aim of instruction—that the operator should learn the "whys" of reactor physics sufficiently to understand the bases for reactivity variables and their prediction, and for operating safety in startup and level controls. He should understand the "language" as well as the concepts involved in order to read, question, and apply the physics information provided for him in control room charts, logs, and oral and written instructions. Although ultimately desirable, it is not expected that the operator having studied this material will be able to calculate various operating reactivity values; but it is expected that he will have the basic tools necessary to subsequently pick up a working knowledge of the quantities as well as the concepts involved in the reactivity control of his reactor.

Discussion questions are included with each of the three lectures. If the person studying this material really understands the concepts behind these questions, he should have no trouble with the questions of similar content and complexity to be included in subsequent certification testing. Good Luck.

George C. Fullmer

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Manager, Operational Physics
Research and Engineering Section
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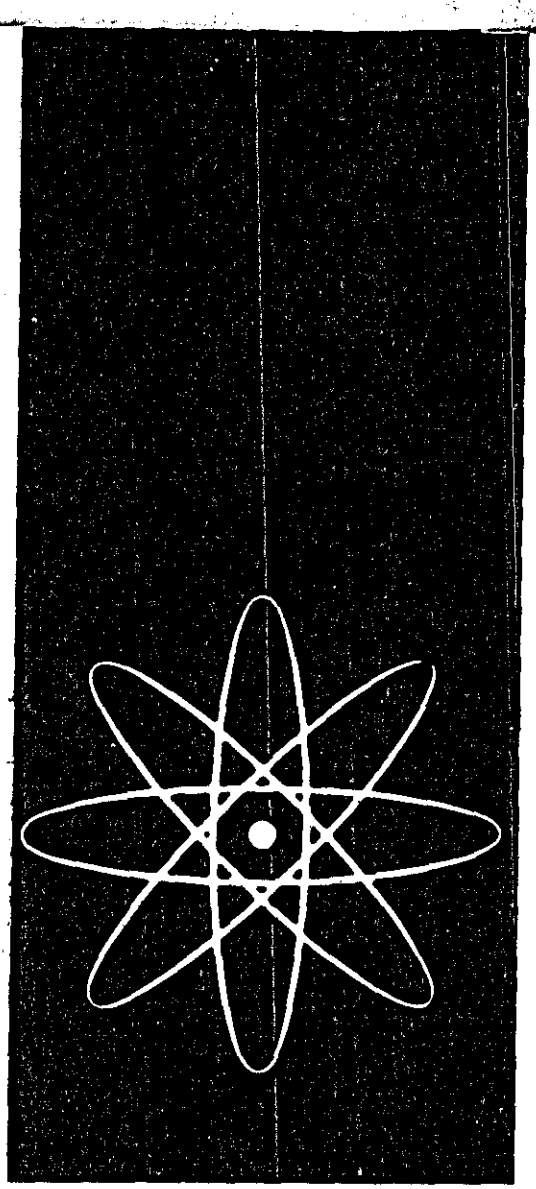
CONTENTS



Section A

ATOMIC THEORY

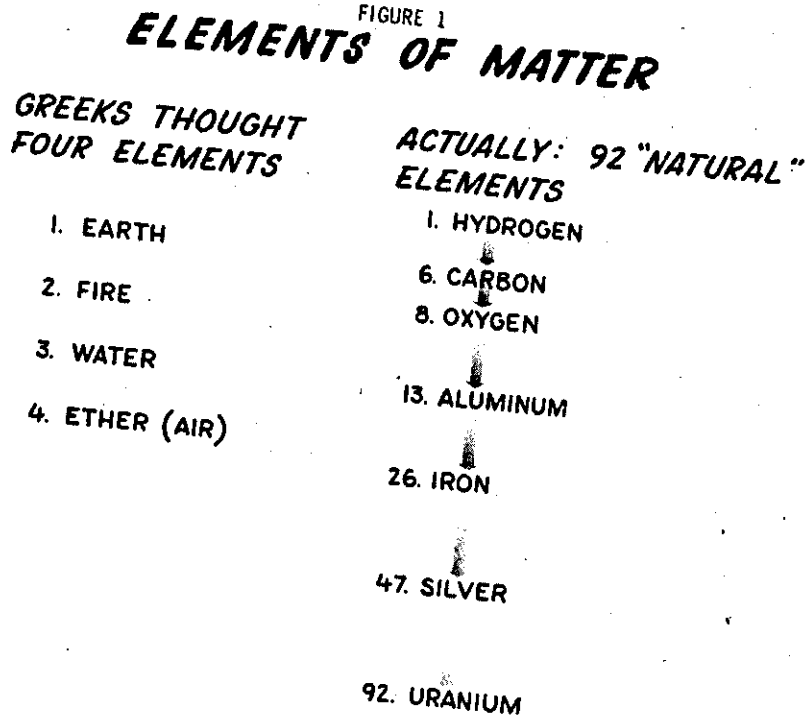
SECTION A.—ATOMIC THEORY

The other two sections in this series, "Chain Reaction Theory", and "Physics Aspects of Reactor Operation", apply more specifically to the reactor and its operation. The purpose of this section is to ensure an understanding of the nuclear particles involved in the later reactor discussions, the types and characteristics of reactions among them, and the requirements for their detection and shielding.

1. Structure of the Atom

Figure 1 shows the difference between our concept of matter's classification and that of the ancient Greeks. Whereas they thought that all matter represented some combination of only four basic elements—earth, fire, water, and air, chemists have long since classified 92 natural elements. The second column lists some of the more common elements such as number 1 Hydrogen, number 8 Oxygen, number 47 Silver, and number 92 Uranium.

FIGURE 1

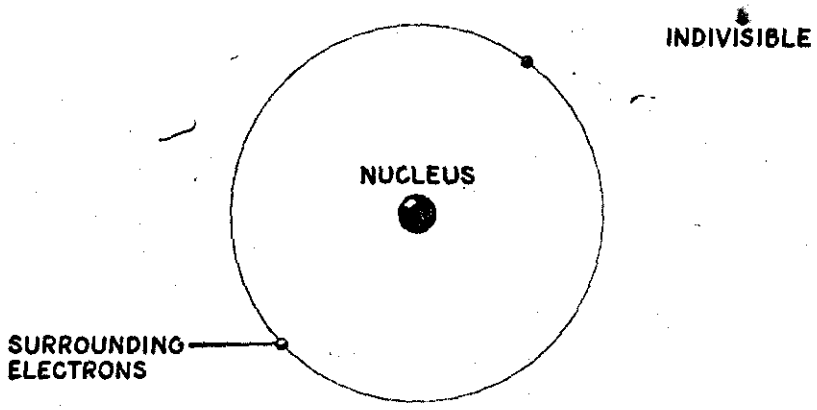


What constitutes an element? What would the smallest particle look like which could still be identified as an element? Figure 2 illustrates such a particle, known as an atom, a word from the Greeks meaning "indivisible". Although much too small to be seen individually, an atom behaves as though composed of a nucleus, or center, surrounded by minute planets. These planets, each having an electrical charge (arbitrarily called negative), are called electrons. Whether an atom belongs to one element or to another depends upon

the number of orbiting electrons it has. For example, an atom of element number 1 (Hydrogen) has one electron, an atom of element number 26 (Iron) has 26 electrons, and an atom of Uranium (element number 92) has 92 electrons surrounding its nucleus.

FIGURE 2

SMALLEST PARTICLE OF ELEMENT - ATOM



FROM 1 TO 92 ELECTRONS - DEPENDING ON ELEMENT NUMBER

PROPERTIES OF ELECTRONS

1. CHARGE OF ELECTRICITY (NEGATIVE, -)
2. NEGLIGIBLE WEIGHT COMPARED TO NUCLEUS

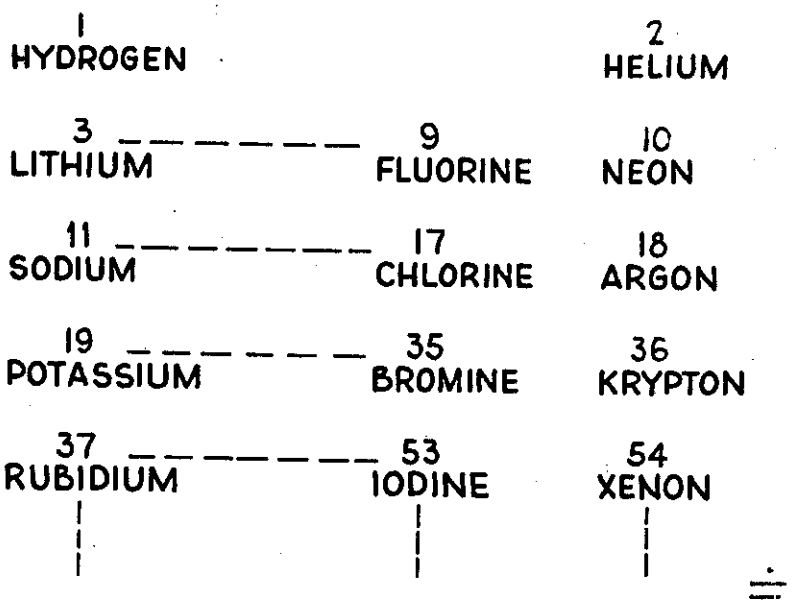
Chemists have prepared a chart of the elements, from 1 to 92, but arranged by "families" having related tendencies to combine with certain other elements to form chemical compounds. The way in which an atom of one element combines with an atom of another to form a chemical compound is to share outer electrons between the two atoms. Figure 3 illustrates three typical chemical families. Even without chemistry background a person might guess that fluorine, chlorine, and iodine might react similarly, as indeed they do. Likewise one might guess that helium, argon, krypton, and xenon—"inert gases"—should belong to the same chemical family. Such family relations exist because of a similarity in arrangement and numbers of electrons in their respective outer orbit shells.

A closer inspection of the three chemical families shown in Figure 3 helps to explain chemical bonding, or sharing of electrons between atoms. The family of inert gases in the right-hand column happens to have a "filled" pattern of electrons in its outer ring; therefore it has no lack nor excess of outer electrons to share. The family whose atomic number is respectively one less in each case (the fluorine, chlorine, bromine family) must, therefore, lack one

FIGURE 3

CHEMICAL FAMILIES-PERIODIC CHART

(CHEMICAL REACTIONS : ELECTRON SHARING)



electron in its outer shell; similarly the family whose atomic number is respectively one higher than the inert gases in each case (the lithium, sodium, potassium family), must have a spare electron starting a new orbit, or shell. One would expect that the chemical family including lithium, sodium, and potassium should favor sharing its spare electron with the fluorine-chlorine-bromine family which needs another electron. This is indeed the case as evidenced by so many common chemicals: Sodium chloride (common table salt), potassium chloride, lithium fluoride, HCl (hydrochloric acid), HF (hydrofluoric acid), etc.

Chemistry is thus a science of planetary electron sharing between atoms of different elements, as illustrated in Figure 4. However, the reactions involved in the nuclear reactor process are, as the name implies, involved with the nucleus and its changes.

2. The Nucleus, and Transmutation

The nucleus of the most simple atom, hydrogen, is seen in Figure 5 to consist of a single particle which has an electrical charge opposite that of the single electron in the surrounding orbit. In other words the charge of this single particle in the normal hydrogen nucleus, called a proton, is positive. Arbitrarily calling this particle's weight one atomic mass unit (1 a.m.u.), the information about this atom is written with its atomic number as the subscript, its chemical symbol, then its atomic weight as a superscript, or $_1H^1$.

FIGURE 4

CHEMISTRY VS. NUCLEAR PHYSICS

CHEMISTRY

ATOMS SHARE ELECTRONS TO FORM CHEMICAL COMPOUNDS.
(e.g.: WATER, H_2O = H-O-H)

NUCLEAR PHYSICS

CONCERNS PARTICLES INSIDE NUCLEUS AND THEIR REACTIONS.

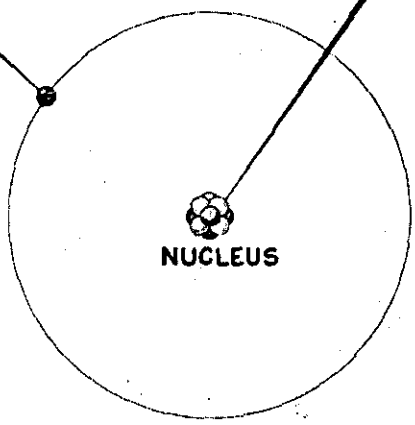


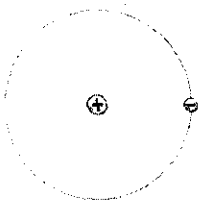
FIGURE 5

NUCLEAR PARTICLES - THE PROTON

⊕ PROTON

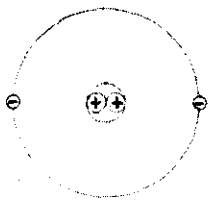
(1) CHARGE OF ELECTRICITY (POSITIVE, +)
(2) WEIGHS ONE ATOMIC MASS UNIT (1 a.m.u.)

SIMPLEST ATOM - HYDROGEN



$_1H^1$

ONE PROTON IN NUCLEUS FOR EACH ORBITING ELECTRON



$_2He^{(?)}$

The next element in atomic number, helium, is seen to have two protons in its nucleus. Examination of higher atomic number atoms shows that the number of protons in the nucleus always corresponds to the atomic number of the element. There is thus always one proton in the nucleus for each electron in the surrounding orbital pattern. There is still something unexplained about the helium atom in Figure 5, however. Although it has two protons in the nucleus as expected, the helium atom, shown as $_2He^?$, weighs more than twice as much as the hydrogen atom.

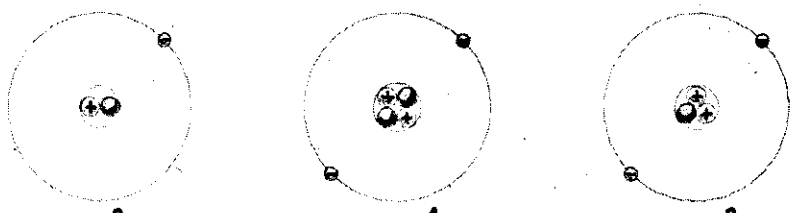
Figure 6 explains the reason for this weight discrepancy. The normal helium atom, which has a weight of four atomic mass units, is seen to have two additional particles in its nucleus which provide weight but no charge; thus our information about the normal helium atom is shown as $_2He^4$ These extra particles, having weight close to that of the proton but no electrical charge (neutral), are called neutrons.

FIGURE 6

NUCLEAR PARTICLES - THE NEUTRON

NEUTRON
(1) NO ELECTRICAL CHARGE (NEUTRAL)
(2) WEIGHS APPROXIMATELY 1 ATOMIC MASS UNIT

NEUTRON'S IMPORTANCE:
INCREASES ATOM'S WEIGHT WITHOUT CHANGING ELEMENT. ATOMS OF SAME ELEMENT BUT DIFFERENT WEIGHT CALLED *ISOTOPES*.



$_1H^2$ ("HEAVY" HYDROGEN-DEUTERIUM)

$_2He^4$

$_2He^3$

Sometimes a difference in numbers of neutrons will exist between the nucleus of one atom and another of the same element. This is illustrated in Figure 6 by the existence of "heavy" hydrogen, $_1H^2$, and a lighter helium atom, $_2He^3$. Different weight atoms of the same element are called **isotopes**. This phenomenon is important to remember; although the chemistry of a given atom is almost unaffected by its isotopic status, there is a marked difference in nuclear physics behavior among isotopes of the same element.

Before looking at the way the nuclear physicist arranges the elements in a table form, a review of nuclear particles is in order (Figure 7). We have previously seen that a proton is the same as a normal hydrogen nucleus, having a positive charge and a weight of 1 a.m.u. (atomic mass unit). The neutron also has a weight of about 1 a.m.u. but no electrical charge. One of the earliest particles found in natural decay of very heavy atoms, called the alpha particle, was found to be the same as the nucleus of a normal helium atom.

FIGURE 7

PRINCIPAL PARTICLES TO REMEMBER

1. PROTON, p	⊕	SAME AS HYDROGEN NUCLEUS
2. ALPHA PARTICLE, α	⊕⊕ ⊕⊕	SAME AS HELIUM NUCLEUS
3. BETA PARTICLE, β	⊖	SAME AS ELECTRON, BUT EJECTED FROM NUCLEUS. (NEUTRON CHANGES TO PROTON PLUS ELECTRON) $\bigcirc \rightarrow \oplus + \ominus$
4. GAMMA RADIATION, γ	≋	WEIGHTLESS & UNCHARGED RADIATION EMITTED DURING MOST NUCLEAR REACTIONS
5. NEUTRON, n	○	
6. ION	+, ++, −, ETC.	ANY SMALL *CHARGED* PARTICLE (e.g., AN ATOM MISSING AN ELECTRON WOULD BE 'IONIZED')

The beta particle turns out to be encountered quite frequently in radioactive decay processes, many of them cascading over several events. The beta particle, actually an electron, is produced in a unique manner; in case of an unfavorable balance between neutrons and protons in a nucleus, a neutron may suddenly change into a proton, which remains, and an electron, which is emitted; the emitted electron traveling through space is called a beta particle.

In case a proton, alpha particle, or beta particle is released from a nucleus, that nucleus undergoes a change in its number of enclosed protons. In other words it changes its atomic number; a transmutation from one element to another has taken place. This was the dream of the alchemists in the middle ages, but we can see that they could never have changed the element by chemical reactions, which involve only the orbiting electrons.

Following a transmutation or other nuclear event, there may be an attempt by the remaining nucleus to assume a more favorable

energy state by releasing a limited amount of energy without undergoing further transmutation. Such an energy release will be in the form of electromagnetic energy which is of the type but generally much "harder" than x-rays; this energy form is called gamma radiation.

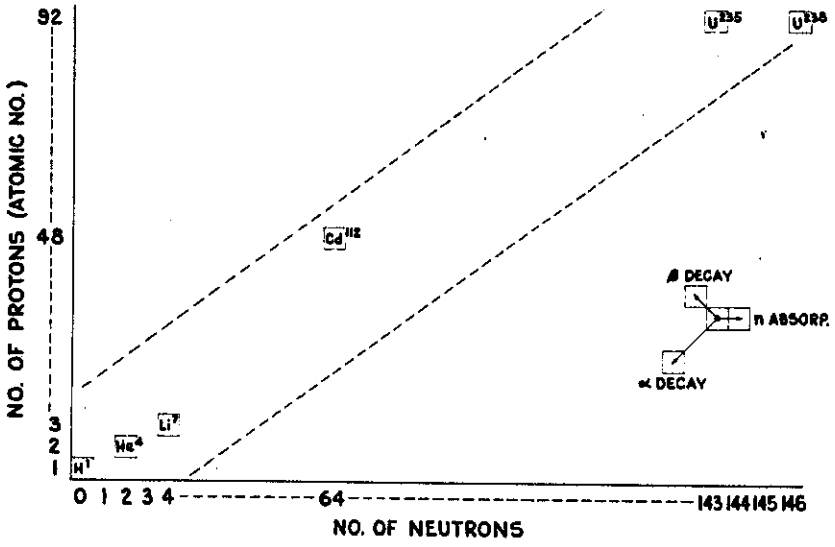
The above transmutation and energy release events usually do not take place instantaneously, but over a period of time which is inversely related to the degree of energy upset involved. Although the specific instant when a given unstable atom will undergo its expected change can't be predicted, there is a definite time probability which can be assigned to each type of unstable isotope which makes it possible to predict what porportion of the atoms of that isotope will have changed in a given time. The concept of half-life for radioactive decay is used in predicting such events statistically. For example, of a million atoms of some isotope with a half-life of 90 days, 500,000 atoms will be left after three months, 250,000 after six months, etc.

Although they should be considered more chemical than nuclear in nature, the characteristics of **electrically charged** particles are very important in the detection and stopping (shielding) of nuclear particles. Charged particles are called **ions**, and may include any particle, from a beta particle to a cluster of atoms, provided there is an excess electrical charge of either negative or positive sign. Attraction or repulsion of other particles by a moving ion may cause other nearby atoms to lose or gain electrons, or to become "ionized" also.

Now we are ready to look at the way a chart of the nuclei, or nuclides, would be arranged (Figure 8). This chart is arranged sim-

FIGURE 8

CHART OF THE NUCLIDES

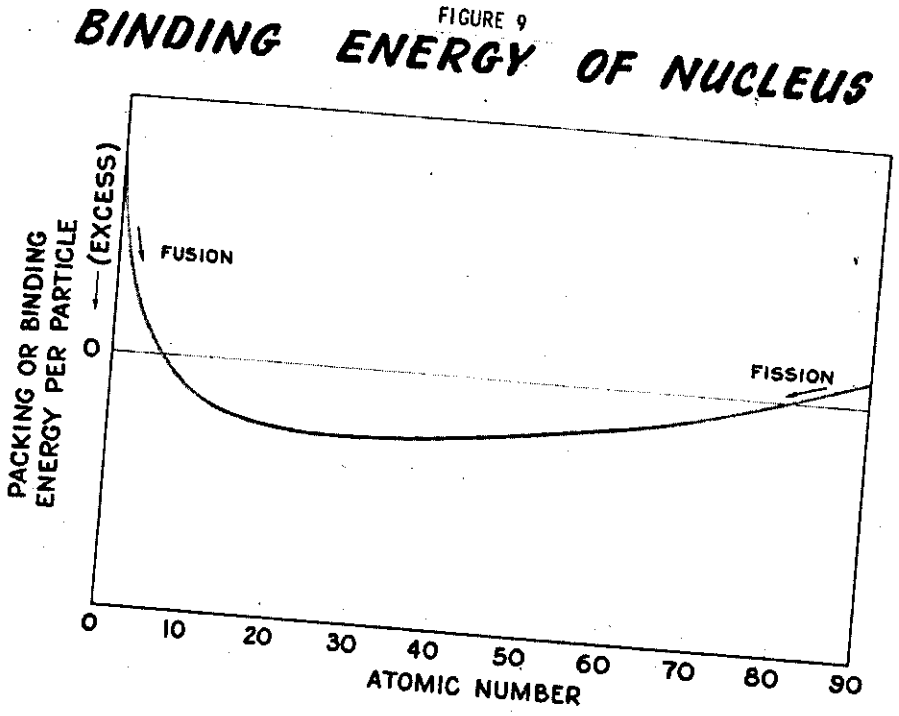


ply with a vertical scale of atomic number (number of protons) and a horizontal scale of number of neutrons; the familiar KAPL wall chart of the nuclides has the vertical scale cut into three pieces and shown side by side. Squares along the same horizontal line (constant atomic number) represent isotopes of the same element, whereas squares on the same diagonal going upward to the left represent atoms of equivalent atomic mass units. The inset in Figure 8 shows the way to determine what atom would result from a neutron capture, a beta decay, or an alpha decay from a parent atom; by determining whether an atom loses or gains one or more neutrons and/or protons in a given reaction, one may easily deduce whether the transition involves a change in atomic number, in atomic mass units, and/or in number of neutrons.

3. Fission, Fusion

Although the like charges of the protons would tend to drive a nucleus apart, there are other short range nuclear forces which tend to hold it together. The resultant force within any given nucleus is called its binding energy. The particles in the middle weight atoms are most tightly bound, whereas the particles inside low-atomic-number nuclei are very loosely bound, and those in the very high-atomic-number atoms are not so tightly bound as those of the middle weight atoms. Figure 9 illustrates the fact that more energy would be required to break apart nuclei in the range from atomic

FIGURE 9

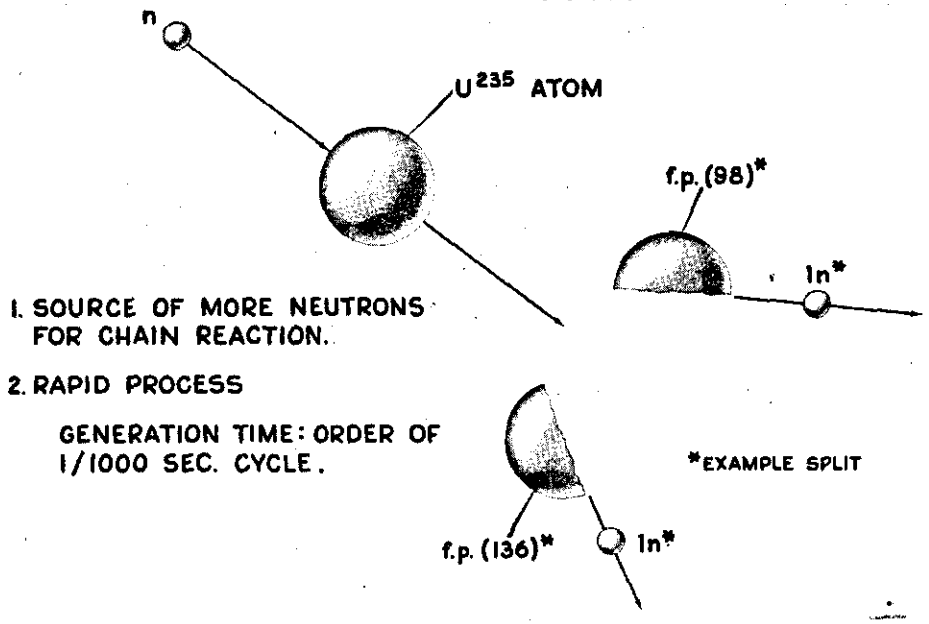


number 8 to atomic number 80 than could be recovered from the reaction. On the other hand, combination of very light atoms with each other to form heavier atoms—fusion—would release extremely large amounts of energy, and the breaking apart of very heavy elements into middle weight atoms—fission—would release substantial amounts of energy. A simple analogy is to consider the binding energy curve shown to represent hill and valley terrain with a water wheel located at the zero elevation; if the water wheel were supplied by water already above that elevation, a net gain in usable energy would be possible. The fusion or combining process takes place in the sun and stars, whereas the fission or splitting process is the one occurring in nuclear reactors. On the order of 200,000 times as much energy is released in one uranium atom fission as is given off in the chemical combination of one carbon atom with oxygen in ordinary combustion.

There is an inclination for atoms to seek a "best balance" between number of protons and number of neutrons. This balance condition is sufficiently tenuous in many very heavy atoms that combination with another neutron makes such an atom so unstable that is splits into two middle weight atoms (fission products) and simultaneously releases two or three neutrons (Figure 10). The two or three neutrons released are then free to collide with other heavy atoms, causing other fissions and potentially maintaining a chain reaction. Provided that at least one of the neutrons emitted

FIGURE 10

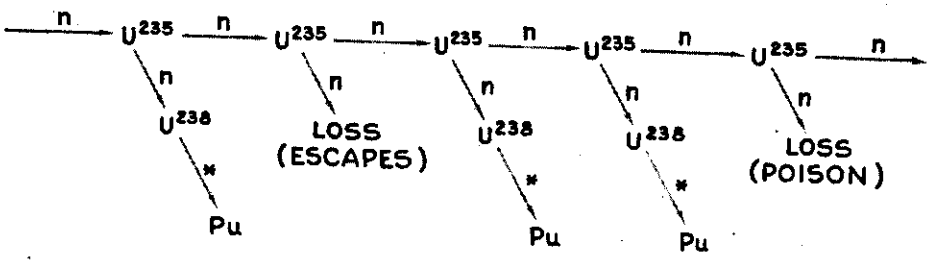
FISSION EVENT



after each fission collides with another heavy atom to cause another fission, the chain reaction will continue. Figure 11 shows this continuation of the chain reaction in Uranium 235. Those neutrons in excess of one per fission are not needed to keep the chain reaction going; they may escape or they may be lost to nonfission captures. Those absorbed by U^{238} start a beta decay chain from U^{239} to Np^{239} to Pu^{239}, the intended end result of the production reactor process, as shown in the inset of Figure 11.

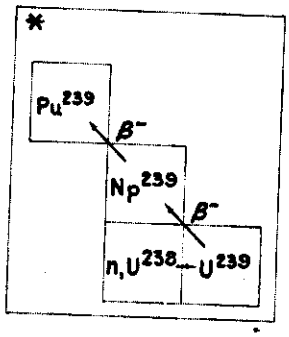
FIGURE 11

CHAIN REACTION



1. AT LEAST ONE NEUTRON *MUST* KEEP REACTION GOING.

2. ALL NEUTRONS DO NOT CAUSE A U^{235} FISSION (PRODUCTION AND LOSS)



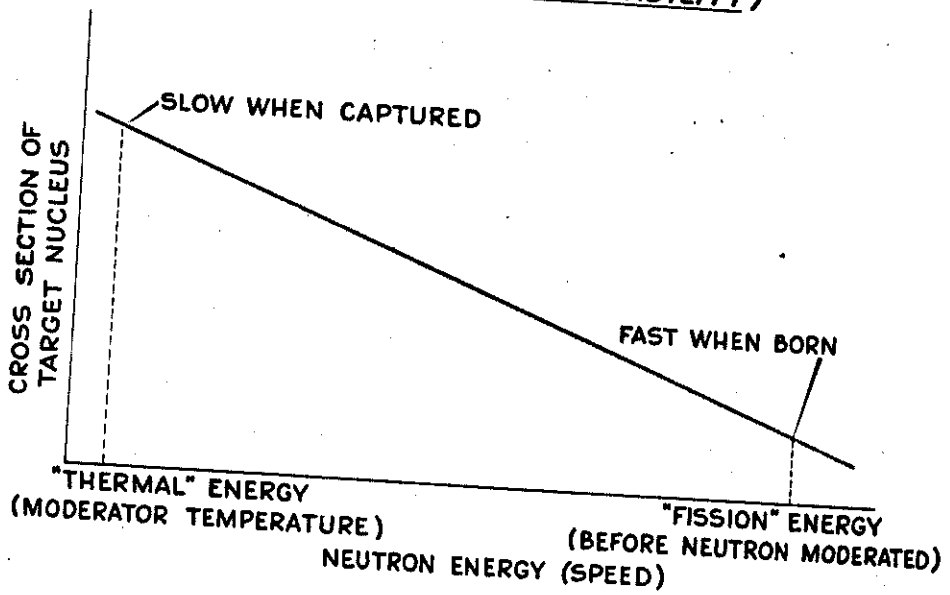
4. Cross Sections of Nuclei

The apparent target size which a particular nucleus presents to an oncoming neutron is quite sensitive to that neutron's energy, or speed. It is customary to describe the probability that a nucleus will react with an approaching neutron as a "cross section", or apparent target area, in terms of barns (a barn is an almost infinitesmal unit of area equal to 1×10^{-24} cm^2).

Every isotope of every element has a cross section pattern (vs neutron energy) which is peculiar to that particular nuclide. Although many of these patterns are erratic, there is a general tendency for the cross section to be much larger at low than at high neutron energies; a "well behaved" nuclide cross section pattern is said to have a "one over v" (1/velocity) cross section. Figure 12 shows how a 1/v cross section plot would look, where the vertical

FIGURE 12

CROSS SECTION
(NUCLEAR REACTION PROBABILITY)



scale would represent the cross section in barns, and the horizontal scale the neutron energy in ev (electron volts). Both coordinates are generally plotted on a logarithmic scale. The neutron's energy when it is released by fission is on the order of 2,000,000 ev (2 Mev), and its speed is many thousands of miles per second. By the time the neutron has collided sufficiently to vibrate at the speed of atoms in the reactor structure, its energy is reduced to much less than one-tenth of one ev, and its speed is on the order of that of a rifle bullet—one or two miles per second. Approximately one hundred collisions in graphite are required to slow the neutron down to the vibration speed of the atoms of the reactor core. The latter speed is determined by the temperature of those atoms (the graphite temperature). The process of slowing neutrons down is appropriately described as "moderation" of the neutrons to "thermal" energy.

There are thus three types of probabilities for neutron reaction in which we are interested (Figure 13): Capture to produce fissions, absorptions in nonfission events (parasitic capture), and scattering. The fission events provide the neutrons necessary to sustain the chain reaction and thus may be thought of as contributing to reactivity. Nonfission captures rob neutrons from the chain reaction, behaving as a damper, or "poison". Finally, the scattering event is necessary to get the neutrons slowed down to the range in which target cross sections become large enough to cause the neutrons' capture before too many escape from the reactor.

FIGURE 13

TYPES OF CROSS SECTION-IMPORTANCE

1. NEUTRON FISSION CROSS SECTIONS
   (REACTIVITY)
2. NEUTRON SCATTERING CROSS SECTIONS
   (MODERATOR - SLOWING DOWN)
3. NEUTRON ABSORPTION CROSS SECTIONS
   (POISON, POSSIBLY PRODUCTION)

COMPETITION FOR NEUTRONS AFFECTED BY:

1. CHOICE AND AMOUNTS OF MATERIALS

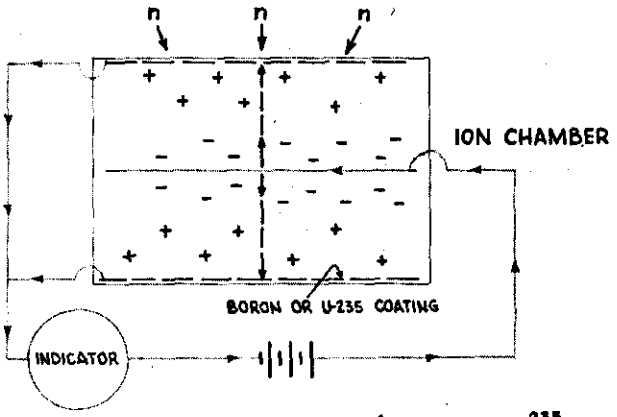
2. NEUTRON SPEEDS - PRIMARILY MODERATOR AND FUEL TEMPERATURES

5. Measuring Neutron Level

A gas containing ionized particles will conduct electricity in proportion to the degree of ionization; that is what happens in a fluorescent light which passes electric current through an electrically charged gas instead of through a wire filament. This effect may be exploited for measuring the population density of charged nuclear particles, such as protons, beta particles, and alpha particles. Figure 14 illustrates how this might be done with an

FIGURE 14

MEASURING NEUTRON LEVEL



1. NEUTRONS MUST BE MEASURED INDIRECTLY (BORON OR U^{235} COATING ON CHAMBER)
2. ION CURRENT VS PROPORTIONAL COUNTING (DEPENDS ON HI VOLTAGE)
3. TYPES OF INDICATORS: AMMETER ($\mu\mu$ AMMETER - BECKMAN), GALVANOMETER (SINGLE OR OCTANTS), SUB CRIT. MONITOR (COUNT RATE METER)

ion chamber which has electrodes of different polarity separated by a gas gap.

Neutrons would not be detected directly, however, because they carry no electrical charge, or ionization. By coating a chamber wall with some material which will absorb neutrons and emit charged particles, the population density of neutrons, or neutron flux level, may nevertheless be indicated.

If the voltage supply to the chamber is in a favorable "plateau" range, the current through the chamber will be smooth and in direct relation to the neutron density; a chamber operating in this plateau range is referred to as an ion chamber. The current through the chamber circuit may be read by any of several types of indicators. An ammeter (usually reading in the millionth to billionth ampere range) is generally used to indicate the current through one or possibly more chambers (e.g., octant chambers). Instead of deflecting a needle in an ammeter, however, the current can be made to deflect a small mirror; in this case a beam of light may be reflected as a spot onto a translucent scale (galvanometer).

If the voltage is increased considerably beyond the plateau reading, an arc-like discharge may occur every time an ionization takes place within the chamber. In this case, the chamber is said to act as a "proportional counter" (PC), and the pulsing activity may be registered by putting a counting scaler into the circuit, or a count rate meter. The latter principle is used in conjunction with U^{235}-coated (fission) chambers in the Subcritical Monitor System to provide especially sensitive detection at very low neutron levels.

6. Shielding of Radiation

As in the case of radiation detection, the **ionization** phenomenon is important in eventually stopping all forms of nuclear radiation; but the uncharged forms—neutrons and gamma radiation—are particularly difficult to stop. The principle employed in shielding out neutrons is to provide moderating materials (of low atomic number) to scatter and "thermalize" the higher energy neutrons in conjunction with other materials of relatively large absorption cross section to capture the "thermalized" neutrons. Secondary radiation may be formed in the neutron capture, of which the gamma activity is most bothersome.

Gamma radiation is mostly stopped by electrons—either by knocking electrons out of atomic orbits by direct collision (Compton effect) or by creating electron-positron pairs in a conversion of part of the gamma energy into matter (the positron is almost immediately annihilated by combination with another electron to produce some more gamma radiation, but of lower energy than the initial gamma ray). This ion-pair production takes place in the

field of a high density nucleus. Both of these gamma-stopping effects are thus accomplished most effectively with high density materials.

Figure 15 indicates the types and rough magnitudes of shielding materials needed to attenuate different forms of radiation. Charged particles, such as beta and alpha radiation, are seen to be stopped by small amounts of common materials.

Shielding effectiveness of a particular material for neutron and gamma radiation is generally expressed in terms of inches of material required to reduce the incident radiation by a given factor, such as by a factor of e(2.718) or a factor of 10. For example, if a foot of ordinary concrete reduced a given gamma radiation energy by a factor of ten, two feet would reduce it by a factor of 10x10 or 100, three feet of concrete by 10x10x10 or 1000, etc.

Finally, protection against radiation may be provided by distance alone. Provided that the radiation source is small compared to how far away it is, the radiation intensity will decrease in proportion to the square of the distance. For example, the radiation reading ten feet from a discharged fuel element in air would be only 1/100 as great as at one foot away.

FIGURE 15

RADIATION SHIELDING

PARTICLE		APPROX. SHIELDING-REDUCED TO <10%
** α ALPHA		THIN PAPER, CLOTHING
** β BETA		THIN ALUMINUM
γ GAMMA		1"-2" LEAD, 1'-2' WATER, OR 1' CONCRETE (HI-DENSITY MATERIALS BEST)
n NEUTRONS		6" WATER, OR 1' CONCRETE

(1) FAST n's-HI AND LOW ATOMIC #'s (ELASTIC AND INELASTIC SCATTERING)

(2) INTERMED n's-LOW ATOMIC # MATERIALS (ELASTIC SCATTERING)

** IONIZED

(3) SLOW n's - LARGE ABSORPTION CROSS (THERMAL) SECTION (USUALLY HI-DENSITY)

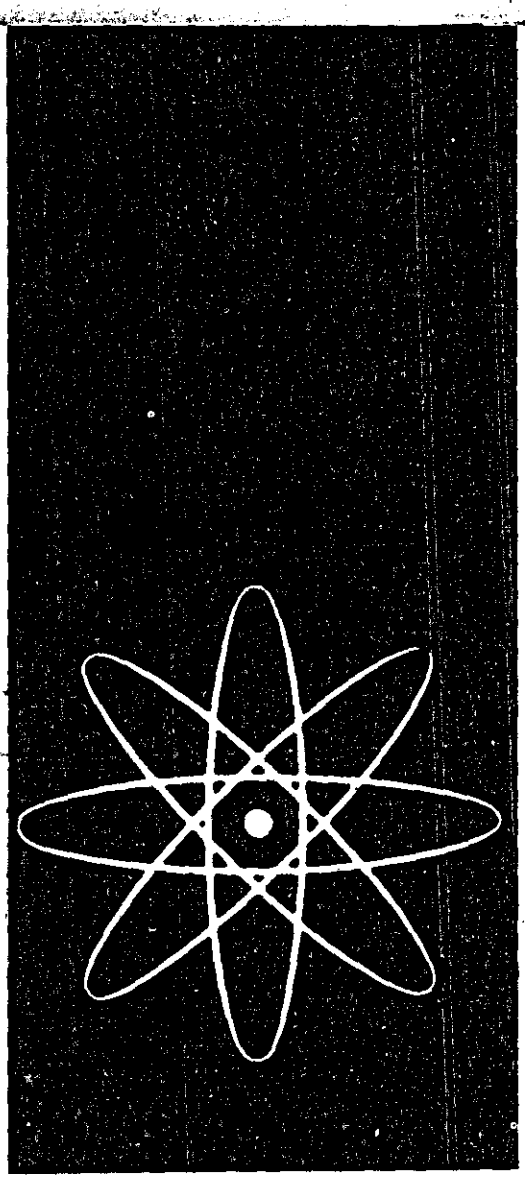
In this section we have developed a background on the particles involved in nuclear reactions. Specifically we have established:

(1) The structure of the atom and the nucleus.

(2) The transmutation from nuclide to nuclide.
(3) The concepts of fission, fusion, and binding energy.
(4) The concepts of cross section—fission, absorption, and scattering.
(5) The importance of ionization in measuring and shielding radiation.

REVIEW QUESTIONS ON SECTION A, ATOMIC THEORY

1. To the nearest round number, there are about 10, 100, 1000 or 10,000 elements?
2. The smallest particle of matter which may still be identified as an element is called (a, an)_____.
3. Chemical compounds are brought about by a sharing of _____ between atoms.
4. Name the two principle particles in the nucleus.
5. Under the right circumstances, a neutron may change into what two particles?_____
6. An atom with a different weight from another atom of the same element is called (a, an) _____
7. Electrically charged particles are called _____
8. The breaking apart of a heavy atom into two middle weight atoms is called _____.
9. What phenomenon in the fission process makes a neutron chain reaction possible? _____
10. Use another word or phrase to describe the concept of cross section. _____
11. In general, the faster the on-coming neutron's speed, the _____ is the target material's cross section.
12. Name the three types of neutron reaction events for which cross sections are important _____.
13. The phenomenon **eventually** employed to detect neutrons or to stop them (or their reaction products) is called _____
14. Which two of the following five particles require appreciably more shielding than the other three: Neutrons, alpha, beta, gamma, protons? _____
    Why (in a word or short phrase)? _____
15. Iodine 135 initiates the following beta decay chain:
    $_{53}I^{135}$——Xe——Cs——Ba
    a. Write in the atomic numbers as subscripts for xenon, Cesium, and barium._____
    b. How many neutrons do each of the latter three nuclei have in the above decay chain? _____



Section B

CHAIN REACTION THEORY

SECTION B—CHAIN-REACTION THEORY

The first section covered the basic particles of the nucleus and the nuclear events which make a chain reaction possible. This section defines the terms used for describing the chain reaction, both at a constant rate (steady state) and with change in time (kinetics). The third section will include the changes in chain-reaction properties due to operation, such as with heating and with fission product buildup.

1. Steady State—Multiplication Factor (k), and Critical Mass

The discussion on atomic structure included the reaction of a neutron with an atom of uranium 235—namely, a splitting of the uranium atom into two large fission products and the release of two or more neutrons and a large amount of heat (Figure 10). The two neutrons released could subsequently cause other fissions, and the total elapsed time between the release of one of these neutrons and its absorption would be very short. The fission phenomenon thus makes possible a multiplying, or chain-reacting, process using neutrons whose generation time from birth (fission release) to disappearance (capture) is of the order of only a thousandth of a second.

Figure 11 illustrated the condition necessary to sustain a chain reaction: At least one of the neutrons emitted from each fission must be absorbed by another U^{235} atom to produce another fission. How the spare neutrons are lost from the cycle—whether they help to make useful product or whether they escape altogether—does not matter to the chain reaction as long as at least one of the neutrons given off from each fission is captured by another U^{235} atom to cause another fission, and so forth.

The chain reaction can be seen to have somewhat the same characteristics as a problem in principal and interest. In fact, the mathematics is quite similar. Corresponding to the increase in principal a term called "multiplication factor" (multiplication rate) is used in describing the chain reaction. If the chain reaction is not only holding its own but is increasing, a term similar to compound interest rate must be used which is denoted as "reactivity". You are already familiar with this subject—all we're going to do is to introduce terms which can be used to logically describe the reactor process.

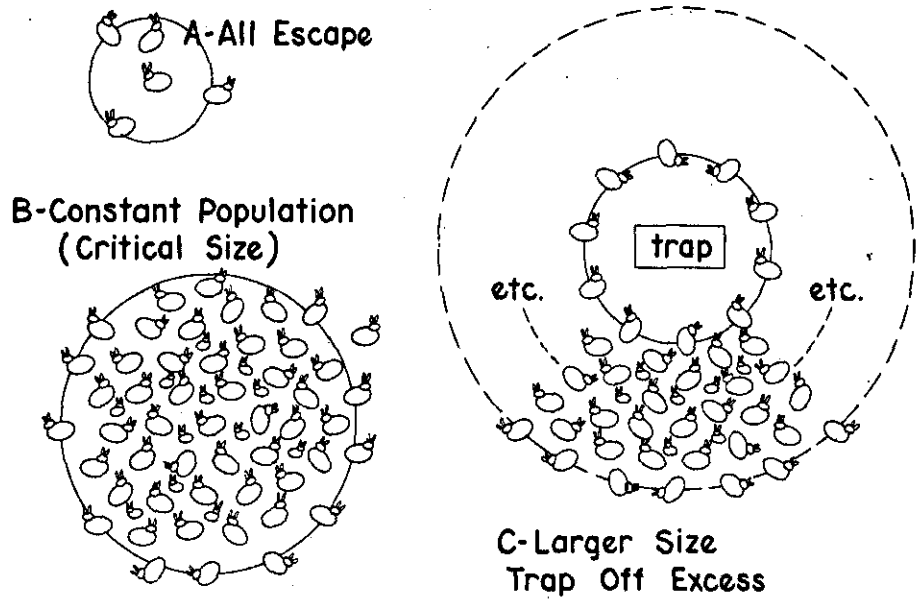
An analogy to a population problem at this point may help to show why such terms are useful. Suppose we have a rabbit farm, and the only material available for containing these rabbits is coarse corral fencing through which any rabbit may, with some effort, escape.

First we try building a small enclosure which holds only a half dozen rabbits. We put in a half dozen rabbits, and soon observe

that they have all escaped. This situation is illustrated in Figure 16, part a. Next we try a larger enclosure and fill it with rabbits. An interesting phenomenon is seen to occur. There are more rabbits working their way through the fence than in the first case, but now there are also many rabbits in the interior area which must await their turn before getting to the fence; while the interior rabbits are awaiting their turn, baby rabbits begin to appear. This leads to an interesting possibility: there must be some size of enclosure, which we can determine by experiment, in which the birth rate among the interior rabbits will just exactly make up for the rate of rabbits escaping through the fence. When we've determined that "critical size" of enclosure (Figure 16, Part b), we can make some measurements and derive some population data. The size of the enclosure can be determined with a tape measure. The population enclosed can be closely estimated from the size of the calculated area divided by the average space required per rabbit. Using a timepiece we can count the rate at which rabbits escape—the number per minute. With the above information we can then calculate the rate at which rabbits are being born and can express it in terms of number born per thousand per month. Or, knowing the average lifetime of a rabbit, the number could be in terms of number born per thousand per generation, or their reproduction factor.

FIGURE 16

RABBIT ANALOGY



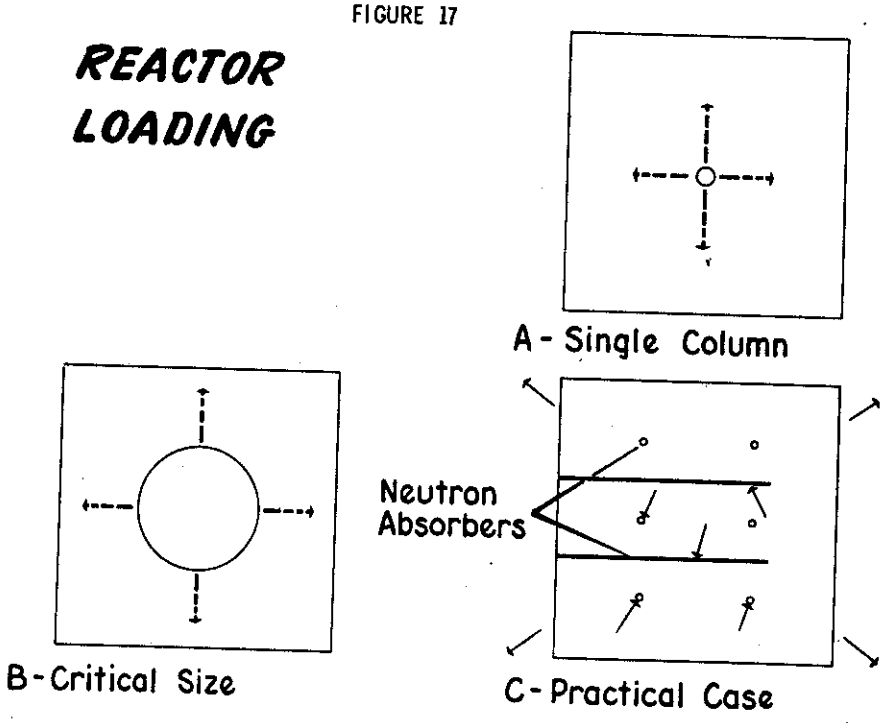
What would happen if we decided to make the enclosure larger than "critical size"? An even larger proportion of rabbits would have

to wait their turns before having a chance to escape through the fence; consequently the rate of rabbits being born in the interior would outweigh their rate of escape, and the population would go up and up. Even so, the population of rabbits in the large enclosure could be held constant by installing an interior trap to keep removing the excess rabbits (Figure 16, Part c). Thus, even though the large enclosure presented a potential population-explosion situation, the "effective" rate of reproduction could be controlled by proper use of the trap to maintain a constant population inside the large enclosure.

Of course the critical size enclosure we determined applied to only that particular breed of rabbits, say white rabbits. Pink rabbits might have a different birthrate and therefore a different critical size enclosure, gray rabbits another birthrate and critical size, etc.

Now to change the story from a chain reaction in rabbits to one in neutrons. Figure 17, Part a, shows how any neutrons which may be produced in a single uranium column, from such events as spontaneous fission or stray cosmic radiation, will escape entirely. On the other hand, a critical size loading is reached when only a fraction of the available columns in the reactor are loaded with uranium (Figure 17, Part b). When the entire reactor is loaded with uranium, as in Figure 17, Part c, the excess neutrons must be trapped off by materials which act as parasites, such as boron or cadmium in control rods or poison columns, in order to keep the "effective" chain reacting rate at the level desired.

FIGURE 17



There is only one step left after the concepts just discussed in the rabbit story and the reactor loading comparisons—to put a name on the concepts. The name assigned to the reproduction rate in neutrons is the "multiplication factor", denoted by the letter "k". Figure 18 shows the basic definition of the term k: The ratio of the number of neutrons in a given generation to the number existing in the preceding generation. If the number is increasing, there is a compounding chain reaction which is referred to as a supercritical condition. If the number in each succeeding generation is held constant, such as during an extended period of operation at the same power level, the chain reaction is said to be exactly "critical". If the reactor is shut down completely or if the number of neutrons in each succeeding generation is dropping off, the chain reaction condition is "subcritical".

FIGURE 18

MULTIPLICATION FACTOR - K

Definition : $k = \dfrac{\#\text{ Neutrons in this generation}}{\#\text{ Neutrons in preceding generation}}$

For Example	$\frac{99}{100}$	$k = .99$	Subcritical (shut down or shutting down)
	$\frac{100}{100}$	$k = 1.00$	Exactly Critical (constant level)
	$\frac{101}{100}$	$k = 1.01$	Supercritical (rising period)

Reactor Operates at $k = 1.00$

k_{∞} — Useful theoretical term measured by critical size.

The reactor designer finds it desirable to know the potential k which a reactor could theoretically achieve if it contained no disturbing influences other than the basic lattice and fuel design and if it lost no neutrons out the sides due to leakage. Only a reactor whose sides were infinitely far apart would have no leakage; thus, this potential theoretical term is called "k infinity", or k_{∞}. It is a useful term for theoretical calculations, and it can be determined from critical size measurements as our potential rabbit birth rate was estimated, but it is not a useful number for actual reactor operation.

For operation we wish to know what the chain reaction is actually doing, or its "effective" value (Figure 19). Thus we talk about a "k effective", or k_{eff} of exactly one if in the as-built, as-loaded, and as-controlled reactor the process is exactly chain-reacting, or critical. If the reactor is shutting down or is shut down, the k_{eff} is less than one. And if the neutrons are increasing with a rising period, k_{eff} is greater than one. In the latter case, the amount by which k_{eff} is greater than one is called "k_{excess}", or more commonly "reactivity". Stated in a mathematical sentence: $k_{ex} = (k_{eff} - 1)$.

FIGURE 19

USE OF MULTIPLICATION FACTOR-K

Operating Terms : k_{eff} ("k effective") and k_{ex} ("k excess")

Subcritical : $k_{eff} < 1.000$ (is less than) — Either shut down or shutting down

Critical : $k_{eff} = 1.000$ — Constant Level

Supercritical : $k_{eff} > 1.000$ or $k_{ex} > 0$ (is greater than) — Rising Period

Theoretical Term : k_{∞} ("k infinity") — measured at critical size (useful in calculations—not for operation)

Thus the terms k_{eff} and k_{ex} refer to the reaction as would be actually detected by an instrument—not to some theoretically potential reaction. A term frequently used in practice of "excess held in rods" really refers to "potential k_{excess} should those rods suddenly be withdrawn". But the true definitions of k_{eff} and k_{ex} refer to the actual compounding rate of neutron formation in the operating reactor.

This completes the discussion on the concept of multiplication factor k. A good understanding of this concept will make the following discussion on change with time, or reactor kinetics, much easier; a review of the questions at the end of the section about the term k may be helpful in ensuring that this concept is understood.

2. Reactor Kinetics

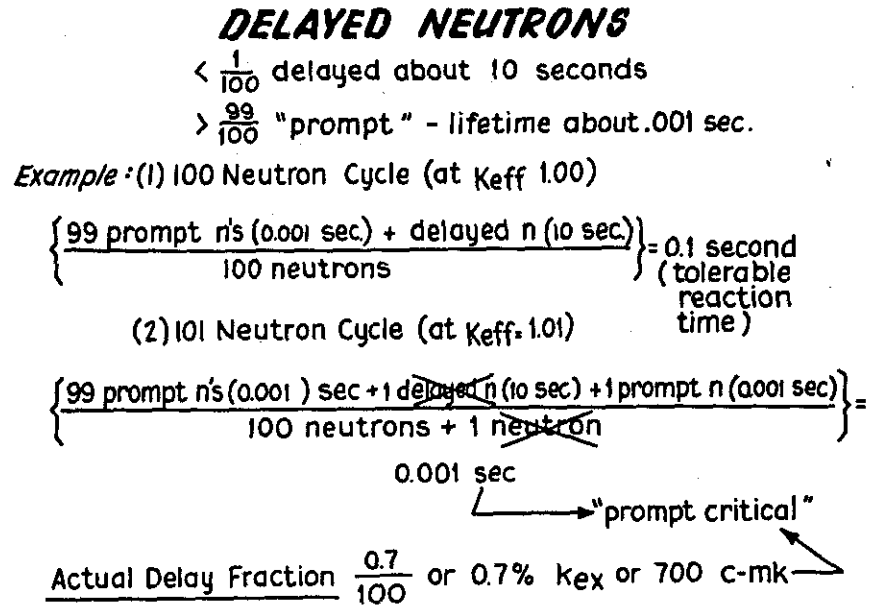
a. Delayed Neutrons

We have just discussed the idea of the chain reaction and the term k used to describe whether it is an increasing, decreasing, or "steady state" reaction. If the reaction is proceeding at a steady rate, the neutron generation time, or "lifetime" is not of concern, but if the reaction is increasing or decreasing, it is necessary to know the neutron lifetime in order to describe, with the help of the term k, how fast the reaction is dying off or building up.

The neutron "lives" only a very small part of a second—on the order of a thousandth of one second—from the time it is emitted from a fission particle until it has undergone enough collisions (about a hundred in graphite) to slow it down to "thermal" energy at which it is almost immediately captured. A neutron generation might thus be considered to be about a thousandth of a second, an undesirably short interval compared to human observation and reaction times. However, there is an important natural phenomenon which hasn't been discussed yet which changes this picture in a favorable way—delayed neutrons. On the average, seven out of every thousand neutrons are not emitted from the fission particles immediately but are released a little while later; the delay in release time may be a few tenths of a second later, or a minute or two later, but the average time of delay is about ten seconds. The effect of delayed neutrons is almost as drastic on chain-reaction rates as would be the effect on human-population trends if one person in every family lived to the age of Methuselah.

Figure 20 illustrates the approximate effect of the delayed neu-

FIGURE 20



tron phenomenon; the 7 per thousand neutrons are rounded in the example to 1%, and the delay time is rounded to the average 10 seconds. In example number 1 it can be seen that the average lifetime of a hundred neutrons thus averages 1/10 second instead of 1/1000 second—a reasonable time for human observation and reaction.

Example 2 in Figure 20 shows the approximate effect of an increasing chain reaction in which 101 neutrons are born each generation in place of each 100 which "died". Assuming for our crude example that the 101st neutron was the "delayed" one, the chain reaction in the first 100 neutrons can be seen to proceed almost without waiting for the delayed one to be emitted; in other words, the effective average lifetime of the 100 neutrons needed to keep the reaction going is only 1/1000 second, and any extra neutrons will cause the reaction to multiply at an almost uncontrollable rate. The actual fraction delayed, instead of being "about 1%", is 0.7%. When there is an excess k of 7/1000, or 0.7%, the reaction is defined as "prompt critical". This 0.7% excess corresponds in our normal reactivity units to 700 c-mk. The table in Figure 21 shows a number of examples of the direct relation between $k_{effective}$, k_{excess}, c-mk (centi-milli-k), and pile period; this chart deserves careful study until the relations between these terms are clearly in mind.

FIGURE 21

OPERATING APPLICATION - K

$k_{effective}$ - Actual reproduction rate going on in reactor

k_{excess} - Actual excess reproduction in rising period

$$k_{eff} - 1.00 = k_{excess}$$

Examples :

k_{eff}	k_{ex}	c-mk	Period
.999	–	–	None
1.000	0	0	None
1.00001	.00001	1	Extremely long
1.001	.001	100	Reasonable
1.0025	.0025	250	Too fast
1.007	.007 (0.7%)	700	Extremely short (prompt critical)
1.01	.01 (1%)	1000	Even shorter (prompt critical)

A review of the delayed neutron discussion impresses one with two important aspects:

(1) That a law of nature exists by which a small fraction of the neutrons are delayed, making possible a controllable reaction.

(2) That any excess multiplication should always be kept well within this small delayed neutron fraction if the reaction is to be considered controllable.

When these two aspects are well understood, reactor startup monitoring and rate control may be seen to be quite straightforward.

b. Startup Control (Pile Periods)

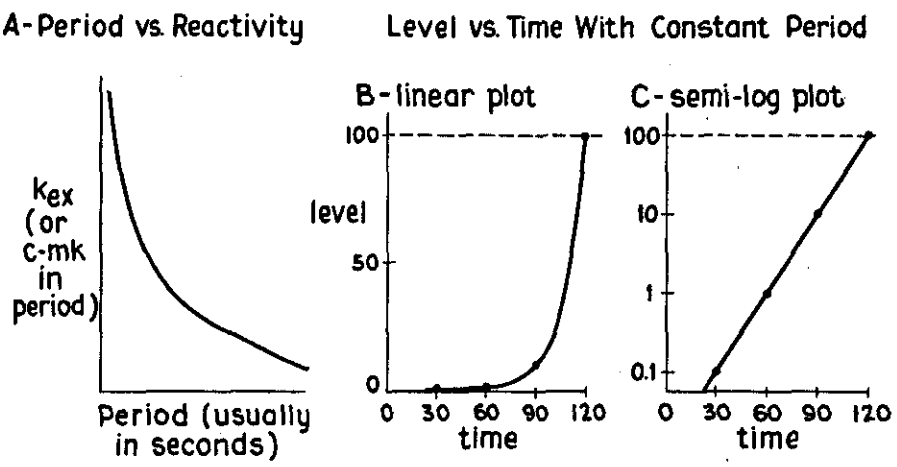
With some given $k_{effective}$ greater than one, the reactor neutron population (and likewise its power level) will have a compounding rate of increase. The compounding rate will be proportional to the amount of k_{excess}; the greater the k_{excess} the faster will the reactor level multiply. It is customary to use another term, called pile period, as a measure of compounding rate; the greater the k_{excess}, the shorter the pile period. The pile period is arbitrarily defined as the time for the reactor to multiply its level by 2.718 (the value of "e", a number which occurs in all kinds of natural population problems and is therefore convenient to use in reactor calculations).

As indicated in Figure 22, Part a, the relation between long periods and corresponding k_{excess} is direct, but for short periods the relationship becomes complicated by the specific lagtimes of different delayed neutron groups and must be obtained from a formula with

FIGURE 22

PILE PERIODS

Definition : Time for level to increase by factor of e (2.718)



several terms. A chart of the form shown is provided for the control room by the physicist; a "feel" of working values may be obtained from Figure 21—in terms of $k_{effective}$ and k_{excess} as well as the more familiar operating term c-mk (centi-milli-k).

It is customary to plot startup data on a logarithmic scale of level—one in which multiples of numbers are equally spaced. The logarithmic scale has two main advantages: (1) It permits a multiplying plot to be readable over a wide range of magnitude—tens, hundreds, thousands, etc., and (2) A continuing compounding rate resulting from a given k_{ex} will give a straight-line plot on such a scale. Figure 22, Part c, shows a customary period plot on a logarithmic scale, whereas Part b shows how the same data would look on standard (linear) graph paper.

It is quite understandable that an instrument could be designed to compare its reading between two times and thus to give a rate signal, especially a compounding rate signal, or period. It is desirable that such an instrument be capable of showing compounding level indications over several ranges of decimal place. Instruments with such characteristics and range have been provided as "period" meters and have been installed with the Subcritical Monitor detection systems.

The range of this system actually extends into the background level. Fortunately, an increasing level in the subcritical background range also causes a signal on the period meter which has physical significance; this "apparent" period gives advance information that criticality is being approached, thus giving the operator an indication of reactivity status before even the critical condition is reached. Figure 23 shows the simple mathematical formula on which the

FIGURE 23

APPROACH TO CRITICAL

Sub-Critical Background Proportional To $\frac{1}{1-k_{eff}}$

Example : 10% sub-critical : $\frac{1}{1-.90} = \frac{1}{.10} = 10$ ~ (count rate)

1% sub-critical : $\frac{1}{1-.99} = \frac{1}{.01} = 100$ "

0.1% (100 c-mk) sub-crit : $\frac{1}{1-.999} = \frac{1}{.001} = 1000$ "

Period Meter Response :

During Rod Withdrawal : "Apparent" period

When Rods Stopped :

1. Steady count rate if still subcritical

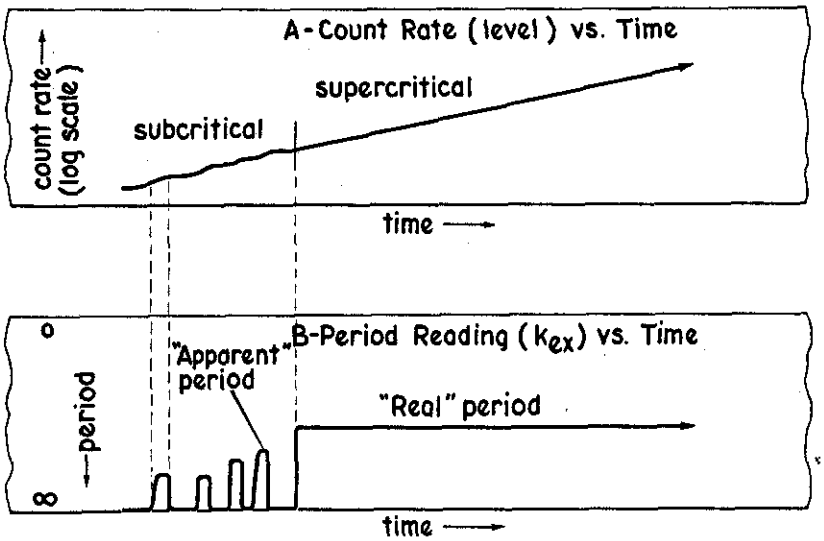
or 2. "Real" period if now supercritical

idea of "apparent" period is based. The example shows that as critical is approached, the withdrawal of a given increment of rod will cause a larger multiplying effect on background level. Thus the "apparent" period indication would restrict the operator to more conservative approach rates as the reactor approached critical. It turns out that the operator would not exceed the allowable rising period at time of going supercritical if he did not permit the allowed supercritical compounding rate to be exceeded at any time during the subcritical withdrawal stage of "apparent period" indications.

Figure 24, Part a, shows a typical recorder plot of level vs. time during rod withdrawal and the initial supercritical period. Figure 24, Part b, shows the readings which would be observed simultaneously on a period meter; an "apparent period" would be observed during rod pulls, and no period (infinite length period) would be indicated during the background level-outs between successive rod pulls.

FIGURE 24

TYPICAL STARTUP INSTRUMENT READINGS



In this section we have covered some of the most important concepts of reactor physics:

(1) The necessary condition for a chain reaction of fissions—one neutron from each fission reaction must keep the reaction going.

(2) An accounting system for chain-reacting ability—$k_{effective}$ and k_{excess}

(3) Critical Mass—the condition when chain-reacting ability exactly balances leakage of neutrons to the outside.

(4) Delayed Neutrons—the phenomenon of nature which permits the reaction to be controllable (within the limits of the delayed fraction).

(5) The relation between multiplication factor (k) and pile period, both real and "apparent".

REVIEW QUESTIONS ON SECTION B, CHAIN-REACTION THEORY

1. What is the term used to designate "multiplication factor"?
2. In the reactor as **actually operating**, the term for "multiplication factor" is called _____.
3. What is the reactor's condition if its k excess is greater than zero? If $K_{ex} = 0.000$? _____
4. Rounding off to the nearest value, the **average** time when a **delayed** neutron is released is .001, .01, .1, 10, 100, or 1000 seconds after the fission took place?
5. Rounding off to the nearest value, the fraction of neutrons which are delayed is $\left\{\frac{1}{1000}, \frac{1}{100}, \frac{1}{10}, \frac{99}{100}, \frac{9}{10}\right\}$
6. "Prompt Critical" corresponds to approximately _____ c-mk.
7. On semilog graph paper (see enclosed form), show a 90-second rising period over a seven-minute interval, assuming the reactor is at 2 MW at the start of the seven-minute interval. (Useful data: $e = 2.718$).
8. Approximately what would be the level in the above problem at the end of seven minutes? _____
9. What would cause an "apparent" period? _____
10. How would an "apparent" period be indicated by a period meter? _____
11. How would an "apparent" period be indicated by a level recorder? _____
12. Is the reactor subcritical, critical, or supercritical during an "apparent" period? _____
13. The longer the "real" rising period, the _____ the k excess.
14. A reactor is and has been operating at constant level for some time with two control rods inserted, each worth 0.5% k.
    a. What is the reactor's k effective? _____
    b. What is its k excess? _____

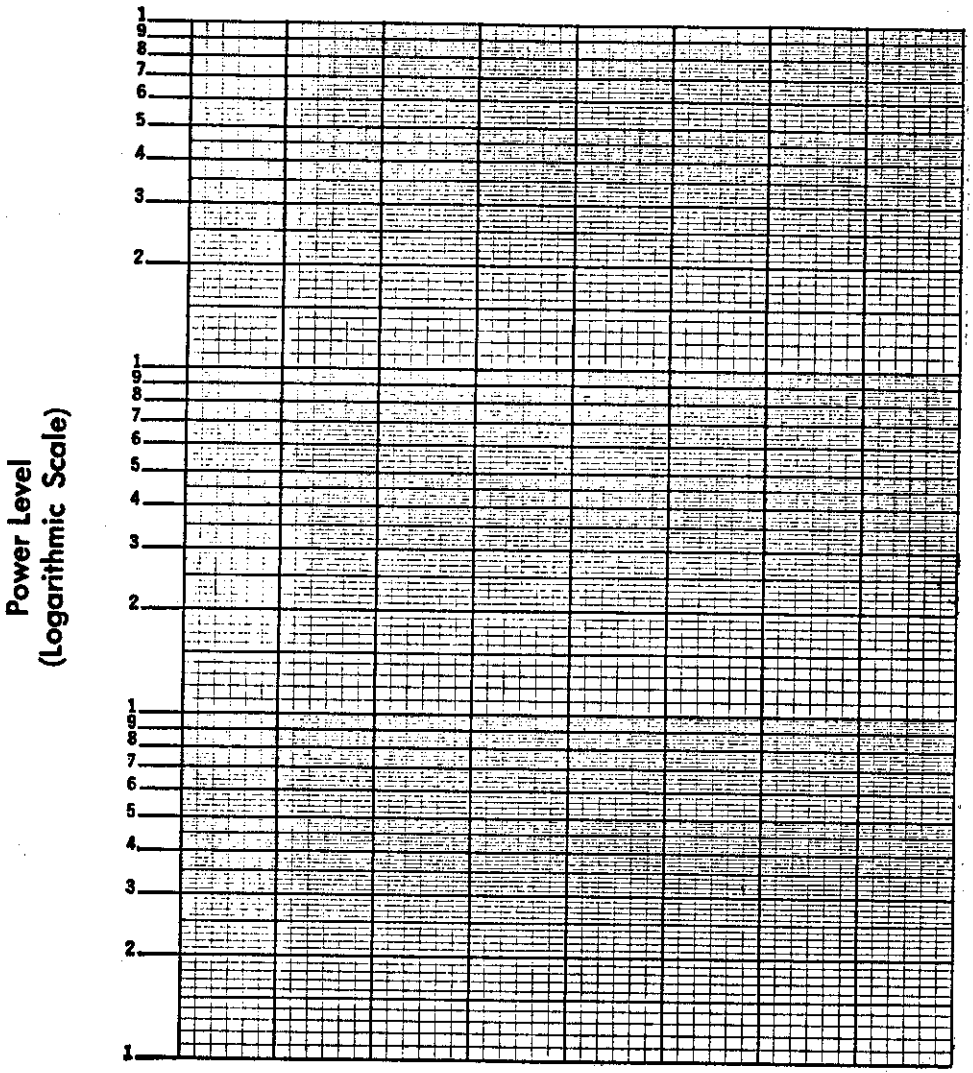
15. From the reactor in problem 14, one of the control rods which has been inserted is suddenly withdrawn.

a. What is now its k effective? _____

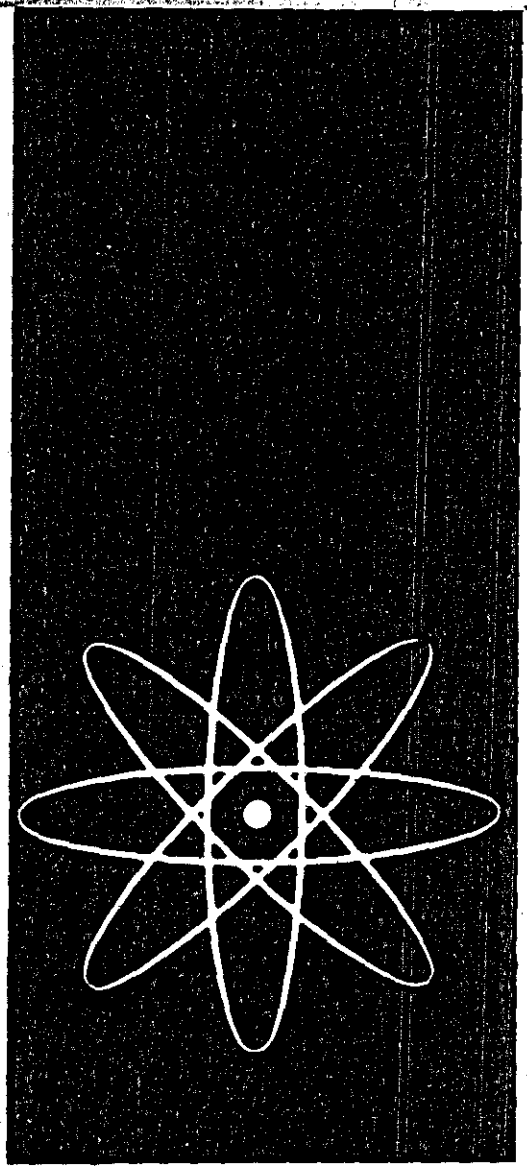
b. What is now its k excess? _____

c. If the second control rod were reinserted, and a third one of equal strength inserted, what would be the k effective? _____

3-Cycle Semi-Log Paper



Time
(Linear Scale)



Section C

PHYSICS ASPECTS OF REACTOR OPERATION

SECTION C—PHYSICS ASPECTS OF REACTOR OPERATION

In the first section the basic particles in the atom and its nucleus and their reactions were described. The second section covered the accounting system used to keep track of the chain reaction, and the importance of the limited percent of delayed neutrons in both permitting and limiting control of the reactor process. In this final section we will consider the changes which operation itself makes on the reactor's chain-reacting ability. Potential changes in operating reactivity, called reactivity transients, also dictate the rates with which the reactor must be shut down and the amounts of control capacity required to keep it shut down; the latter two aspects are generally referred to as "speed of control" and "total control". Finally, consideration is given to the control of flux distribution, of importance primarily to operating efficiency.

1. Reactivity Changes With Time (Transients)

a. Short Term Reactivity Changes (Order of seconds to hours)

Changes with time of the reactor's chain-reacting ability are referred to as "reactivity transients". These transients, or changes, are called "short term" if they are of the same order of time rate as the operator's reaction time (seconds) or even of his time at the console or in the control room during the shift (minutes to hours). The short term reactivity transients of primary interest are caused by temperature changes within the reactor (temperature coefficient effects) and by fission-product atoms having high cross section but relatively rapid decay characteristics (xenon).

(1) Temperature Coefficients of Reactivity

In the first section of this series we saw how cross sections of different materials varied with neutron speed, or neutron "temperature" (Figure 12). In the operating case we want to know how much a certain change in temperature will change the reactivity; so we must use an appropriate **multiplier** for estimating the reactivity change over a given range in temperature (or in power level). Another term for multiplier is "coefficient", the term we will use from now on instead of the word multiplier.

(a) Competition for Neutrons

As outlined in Figure 13, three types of cross sections are competing for neutrons in the reactor—fission, scattering, and absorption. Furthermore, these three cross sections all vary with temperature; therefore, changes in temperatures of the reactor components (and thus energy of the neutrons) will change the competitive advantages or disadvantages for fissions, scattering, or absorption of the neutrons.

(b) Moderator Coefficient

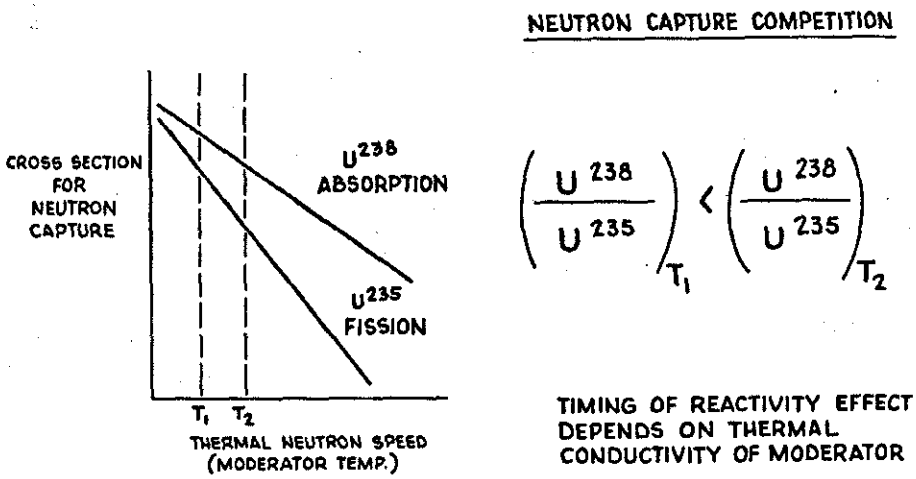
The competition for moderated, or thermalized, neutrons between Uranium 235 and Uranium 238 is illustrated qualitatively in

Figure 25. If the moderator temperature is raised from temperature T_1 to temperature T_2 the proportion of neutrons captured in U^{238} compared to those captured in U^{235} goes up. The effect of the particular competition shown would thus be a loss in reactivity with increasing moderator temperature, or a negative temperature coefficient of reactivity.

FIGURE 25

MODERATOR TEMPERATURE COEFFICIENT

COMPETITION FOR NEUTRONS



In the actual reactor case, there would be a competition for neutrons not only between U^{235} and U^{238}, but also with absorptions in other reactor components and materials, and with scattering effects of the moderator and coolant. The net resultant coefficient may thus include several terms, of both plus and minus sign, and any one of which may be as large as the net coefficient. For example, the buildup of the fissionable atoms of plutonium with increasing fuel exposure may have a significant effect on the magnitude and/or sign of the moderator coefficient.

The rate of reactivity change with time due to the moderator coefficient effect is closely related to the rate of heat transfer from the moderator to the coolant. In a water-moderated reactor the effect may be nearly instantaneous, whereas in a liquid-cooled graphite-moderated reactor the rate of heat transfer from moderator to coolant may cause transient effects over many minutes or even hours. In the latter reactor type, which includes the Hanford production reactors, the slowing down of fast neutrons and attenuation of some of the gamma radiation causes heat to be generated

in the graphite, which heat must subsequently be transferred to the coolant channels.

(c) Metal (Fuel) Coefficient

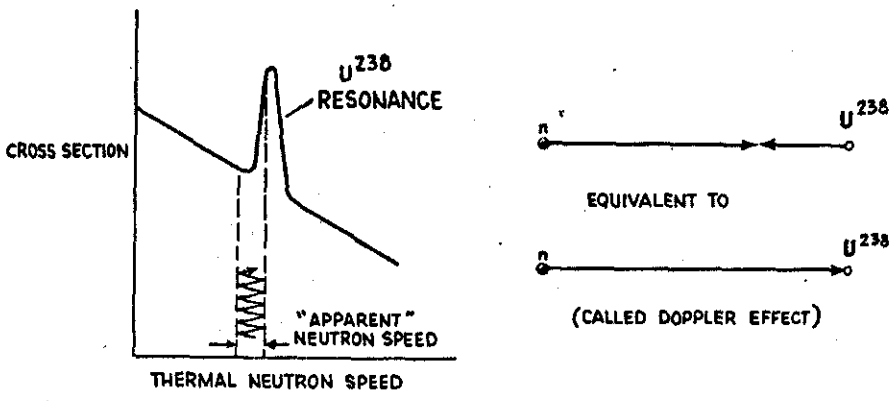
Due to vibration of the uranium atoms during fuel heating the speed with which neutrons collide with these atoms is sometimes greater and sometimes less than the original speed of the oncoming neutron itself. This effect, similar in nature to the net collision speed of two moving cars, is known as the "Doppler Effect".

Although the cross section of Uranium 238 generally varies inversely with neutron speed, there are several points of exception, called resonances, at which the cross section becomes quite large within a very narrow energy range. One of these resonances occurs just above the "thermal" range, as shown in Figure 26. As fuel elements are heated, the U^{238} atoms vibrate faster, affecting the collision speed of the oncoming neutrons. Because the cross section in the resonance region to the right of the indicated energy band is larger than the cross section to the left of the band, there is a net increase in the total number of neutrons captured in the Uranium 238 as a result of the metal's heating. Since Uranium 238 captures generally do not result in fission, the reactor loses neutrons to the chain reaction as a result of this increase in U^{238} captures. In other words, the fuel temperature coefficient, associated almost entirely with Uranium ^{238}, is negative.

FIGURE 26

METAL TEMPERATURE COEFFICIENT

U^{238} ATOM SPEED



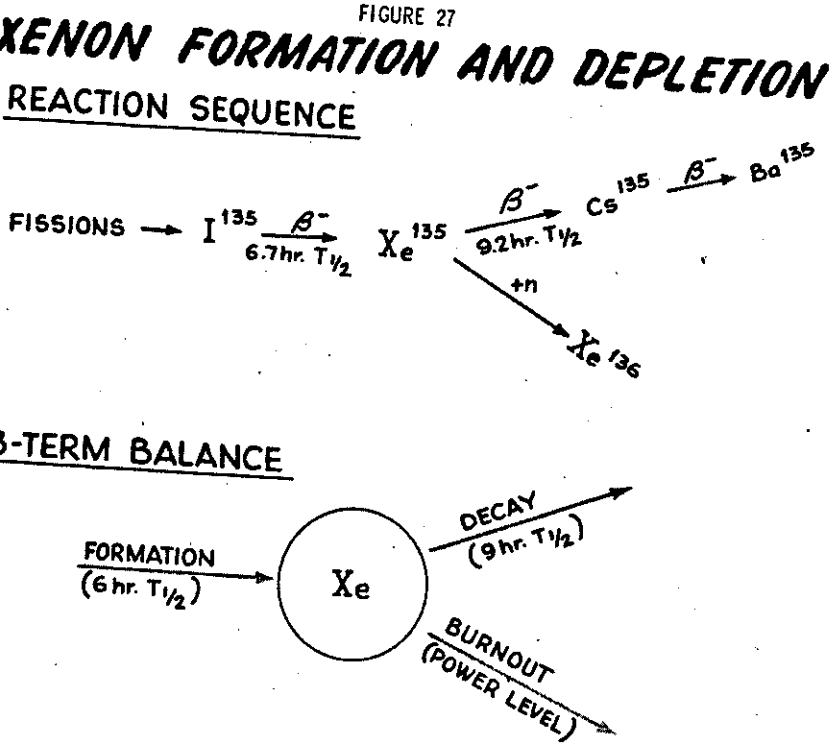
The major portion of the energy given off in each fission is changed into heat by the stopping of the fission-product atoms. Because these fission-product atoms are stopped almost instantaneously within the metal, metal temperature changes occur almost instantaneously with changes in power level. The negative metal temperature coefficient due to U^{238} thus has a desirable fast-acting damping effect on sudden power rises. Conversely, this fast-acting effect requires more control rod insertion to effect a power cut than would otherwise be necessary.

(2) Xenon Poisioning

One of the isotopes produced by fissions has an absorption cross section for neutrons about a thousand times as great as that for boron or for cadmium, either of which is considered a strong "poison". This tremendously strong absorber, Xenon 135, undergoes a beta decay to Cesium 135 if it has not previously captured a neutron to form the stable isotope, Xenon 136. Although the Iodine 135 mother atom is produced in only a small percentage of the fissions, the xenon atoms which are produced have a significant effect on reactivity of the reactor, both in magnitude and timing.

The basic nuclear reactions in the xenon chain are shown in Figure 27. Part of the fissions yield Iodine 135 which decays with a 6.7 hour half-life to Xenon 135. Xenon 135 may be "burned out"—absorb a neutron to form Xenon 136—or it may decay with a 9.2 hour half-life into Cesium 135 which later undergoes another beta

FIGURE 27



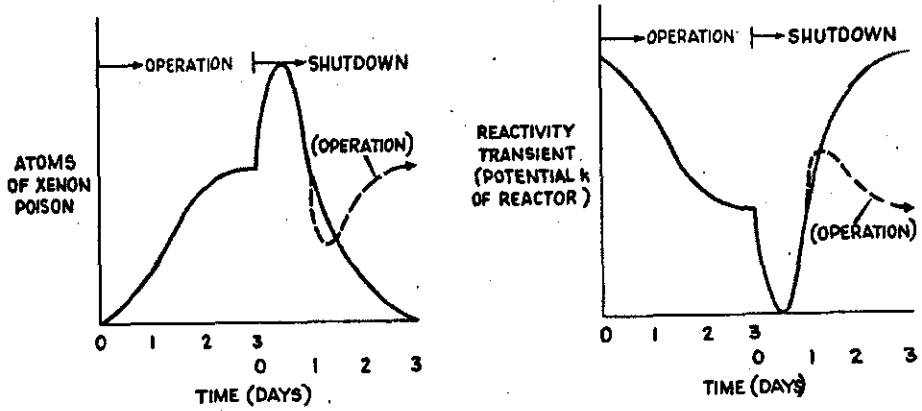
decay to Barium 135. Of the isotopes in this process, only Xenon 135 has a significant cross section. For a practical picture of what happens, then, we can represent the above reactions by the three-term balance diagram in Figure 27—a formation term, a decay term, and a neutron-burnout term. The formation is caused by operation (fissions), but with a time lag due to the iodine decay time. The burnout term is also caused by operation (neutron supply), but acts instantaneously. The amount of xenon decaying depends on the amount of xenon already present and to what extent it's being burned out before it has a chance to decay. Another significant factor in xenon depletion is that its decay half-life is longer than that of the iodine.

A feel for xenon formation and depletion rates may be obtained from this three-term chart. If the reactor's starting up from xenon-free conditions, only the formation term is immediately important, and it lags considerably. After the reactor has operated for two or three days (long compared to the 6.7 hour and 9.2 hour half-lives), the three terms come into balance, or "xenon equilibrium". If the reactor shuts down from equilibrium conditions, the burnout term is suddenly canceled (and so is iodine formation, but again there's a time-lag effect); the net effect of the two half-lives in this case is that the iodine backlog decays into xenon faster than the xenon itself can decay until finally the iodine backlog becomes depleted. If startup is attempted with a depleted iodine backlog, the resumption of the neutron burnout term causes a sudden decrease in the amount of xenon present which is overcome only after the iodine backlog can again build up to provide appreciable decay into xenon.

Figure 28 shows how the above changes would appear if plotted

FIGURE 28

XENON CHANGE WITH TIME
(REACTIVITY TRANSIENT)



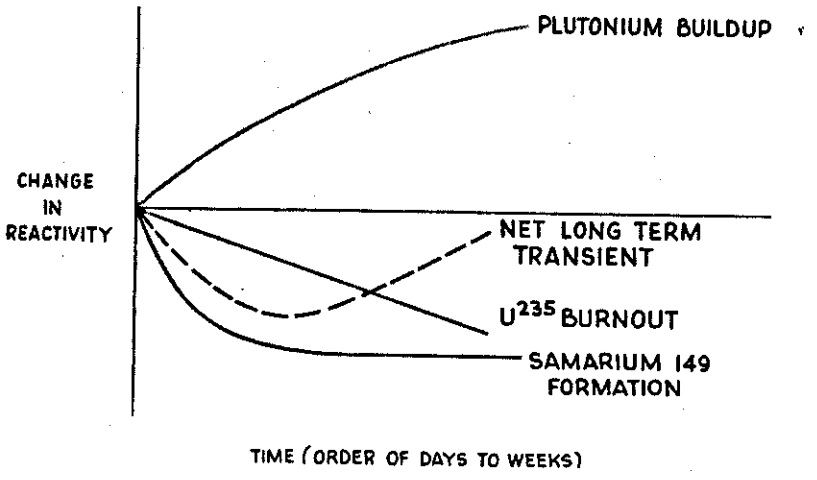
against time. The left chart shows how the numbers of xenon atoms present would vary; note the significant increase in the number of xenon atoms present following a shutdown from equilibrium conditions. The chart to the right in Figure 28, an upsidedown plot of the left chart, shows how **potentially reactive** the pile would be with time due to these xenon buildup and depletion effects. The plot of change in potential chain-reacting capability with time is referred to as the "xenon transient". Plots of this form, adjusted up or down for temperature coefficient and loading-change effects, are generally referred to as "critical prediction charts". The drop in reactivity due to xenon buildup immediately following a shutdown strongly influences the critical prediction chart for scram recovery, or "hot startup". The rising reactivity transient after the minimum reactivity point (during an outage) has been passed corresponds in form to the critical prediction chart for a "cold startup". The maximum reactivity point when xenon formation finally begins to overcome xenon burnout shortly after a cold startup is referred to as "xenon turnaround". A good feel for these effects may be obtained from further study of Figures 27 and 28. Quantitative charts and more detailed explanations of xenon and temperature coefficient effects in the Hanford reactors may be found in Chapter IV (classified) of the IPD Physics Primer which is available at each reactor building.

b. Long Term Reactivity Changes (Order of days to weeks)

As the fissionable atoms of uranium burn out with exposure, the potential reactivity of the pile would be expected to decrease; thus there is a loss with time due to consumption of U^{235} atoms (Figure 29). About as many U^{238} atoms are consumed as U^{235} atoms. Because there are more than a hundred times as many U^{238}

FIGURE 29

LONG TERM REACTIVITY CHANGES



atoms as U^{235} atoms to start with, however, the percentage of consumption of U^{238} atoms is very much smaller; thus there would not be a comparable long-term reactivity gain due to burnout of parasitic absorbers.

The parasitic captures in U^{238} do produce plutonium which subsequently causes a reactivity gain, however. Plutonium 239 atoms are fissionable; in fact, plutonium fission-cross-section and neutron-per-fission properties are somewhat more conducive to reactivity than are those of U^{235}. As the exposure of the fuel is increased, however, the chances of burning out the plutonium atoms are increased until ultimately at very high exposures the rate of plutonium build-up would just be matched by that of plutonium burnout.

In addition to the long-term effects of fuel burnout, some of the fission-product atoms have sufficiently large cross sections to have a significant effect at very high exposures. One of the fission products, Samarium 149, in being both stable and in having a very large cross section, causes large changes in potential reactivity during the first few days after fresh fuel is charged, achieving a saturation effect within the first few weeks.

Figure 29 shows the form of each of these three main long-term reactivity transients with time; their net effect, the sum of the above effects, is shown by the dotted curve. The actual pile transients with time would agree with the dotted curve provided that the reactor, or its central region, were all charged at the same time. A staggered charging schedule and shotgun pattern would tend to minimize long-term transients, however, as some of the columns would be gaining reactivity at the same time other columns at different exposures were losing reactivity.

Long-term reactivity effects should be considered in control configuration selection and trimming plans during long periods of equilibrium operation. The long-term effects are not of immediate concern to the operator during reactor startup and subsequent power ascension, however.

2. Reactivity Transient Demands on Reactor Control

In the second section, Part B of this text, we discussed reactor control in the active multiplying case, as in startup periods. In this section we will discuss the problems due to transients of potential reactivity which must be considered if the desired reactor state—critical, subcritical, or controlled supercritical—is always to be achieved. Achievement of the desired state may involve two aspects: (1) Adequate speed of action and amount of action for assuring that the reactor is shut down and held down if necessary for safety purposes, and (2) Adequate timing, amount, and location of action for assuring that reactor operating efficiency is maintained at a high level.

a. Safety Control

The factors involved in getting the reactor shut down quickly are referred to as "Speed of Control"; the problem of holding it subcritical once it has been shut down is called "Total Control".

(1) Speed of Control

First we should ask ourselves why we are providing nuclear safety protection. We can arrive at our basic nuclear safety requirement by going through some logic statements as follows:

WHAT ARE WE PROTECTING AGAINST?

We want to prevent damage to the public. How?

By preventing escape of fission products. How?

By keeping fission products inside fuel elements. How?

By preventing fuel element melting. How?

By keeping the **Heat Generation Rate** consistent with **Heat Removal Capacity.**

Specifically, this means controlling the reactor in such a way as to ensure that the power level is not allowed to exceed the heat removal capacity of the supplied flow.

There is thus one general axiom good for all reactor operation: ALWAYS KEEP THE **HEAT GENERATION RATE** (power output) WITHIN THE **HEAT REMOVAL** (Coolant system) **CAPACITY.**

If the reactor were operating at a constant power level, the only thing which could cause it to increase its heat generation rate would be a gain in reactivity. If the reactor were not already operating at limiting conditions, a certain amount of gain in reactivity (and consequently in power level) could be tolerated provided that the power rise were stopped before limiting conditions were reached. Satisfactory halting of the excess reactivity condition would depend primarily on two aspects: (1) The physical rate at which reactivity were being introduced (or rate at which poison were being withdrawn), and (2) The response time of safety instrumentation and safety controls.

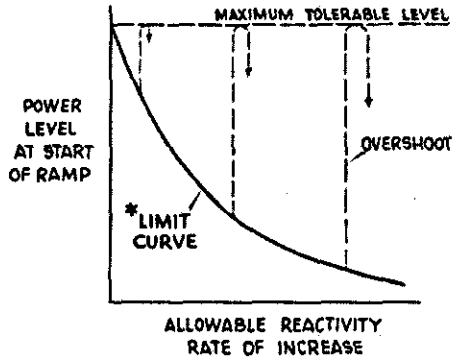
The limiting relation between allowable reactivity introduction rate and response times depends to considerable extent on the power level existing at the time the reactivity increase is initiated. For example, if the reactor is already at full level, no additional reactivity can be tolerated; on the other hand, a power excursion caused by a very rapid ramp may be turned around before limiting conditions are reached if it is initiated and detected at a very low level. The type of relation which would be expected over the possible ranges of reactivity ramps and initial power levels is shown in Figure 30. Provided that the potential combinations of level and reactivity conditions lay below and to the left of the curve, there would be adequate safety protection. Combinations of power levels

and reactivities above and to the right of the curve would cause the maximum tolerable power level to be exceeded before the reactor had been sufficiently shut down.

This aspect of nuclear safety control for assuring that the above level vs. safety system response characteristics are always adequate is referred to as "Speed of Control". As listed in Figure 30, the factors which must be included in speed of control calculations include the size and timing of reactivity coefficients; the sensitivity and responsiveness of neutron detection instrumentation; the timing of safety trip initiation and safety control insertion; and the poison strength of those elements of the safety control system which enter the reactor during the brief power excursion interval.

FIGURE 30

SPEED OF CONTROL
(SHUTDOWN TIME)



*MOST IMPORTANT FACTORS IN ESTABLISHING "LIMIT CURVE"

1. REACTIVITY COEFFICIENTS (SIZE AND TIMING)
2. NEUTRON LEVEL INSTRUMENTATION (SENSITIVITY, RESPONSE TIME)
3. SAFETY ROD SYSTEM TIMING (ACTIVATION, DROP TIMES)
4. SAFETY ROD SYSTEM STRENGTH (POISON VALUE - EFFECT ON k)

The term "Speed of Control" also includes consideration of rapid shutdown in event of sudden coolant loss. Administration of speed of control may result in restrictions of specific power limits consistent with the existing safety and control systems, or it may result in specifications of mechanical characteristics of the safety systems themselves (such as potential rod withdrawal rates, out-of-service rod number limits, and/or response times).

(2) Total Control

This aspect of nuclear safety control refers simply to the assuring of adequate poison compensation to maintain the reactor subcritical as long as desirable regardless of the sequence of events.

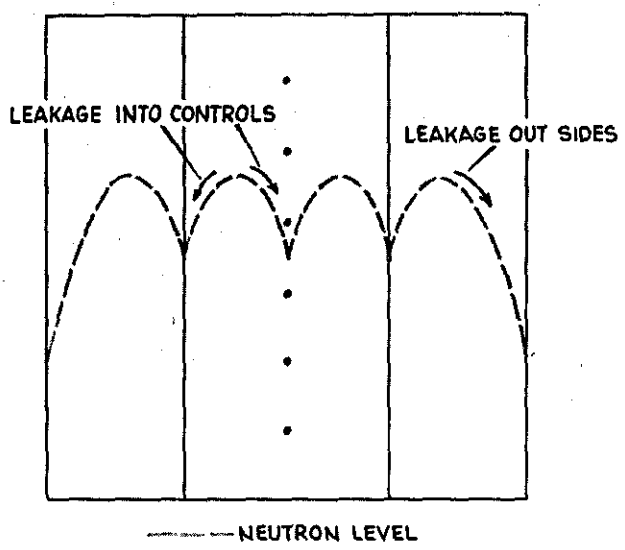
Temperature coefficient effects would not significantly affect shutdown control-capacity requirements provided that coolant system integrity were maintained. However, establishment of total safety-control-system capacity requirements also includes studies of potential reactivity conditions and transients following coolant loss. In event of coolant loss, residual fission product heating in the shutdown reactor may eventually melt components and ruin the reactor core. The drastic changes in lattice geometry which would result from fuel melting and redistribution would tend to reduce the reactivity significantly. The reactor must be held subcritical in the meantime, however, in order to prevent such an event from being accelerated or magnified by a fission chain reaction subsequent to coolant loss.

The physicist's approach to total control administration is simplified by the specification of local poisons to compensate local reactivity excesses (Figure 31); in other words, by making sure that the local k will always be depressed in each part of the reactor to less than one, the physicist assures that the reactor as a whole could not be made chain-reacting.

FIGURE 31

TOTAL CONTROL
(SHUTDOWN CAPACITY)

THEORY: KEEP LOCAL $k < 1$



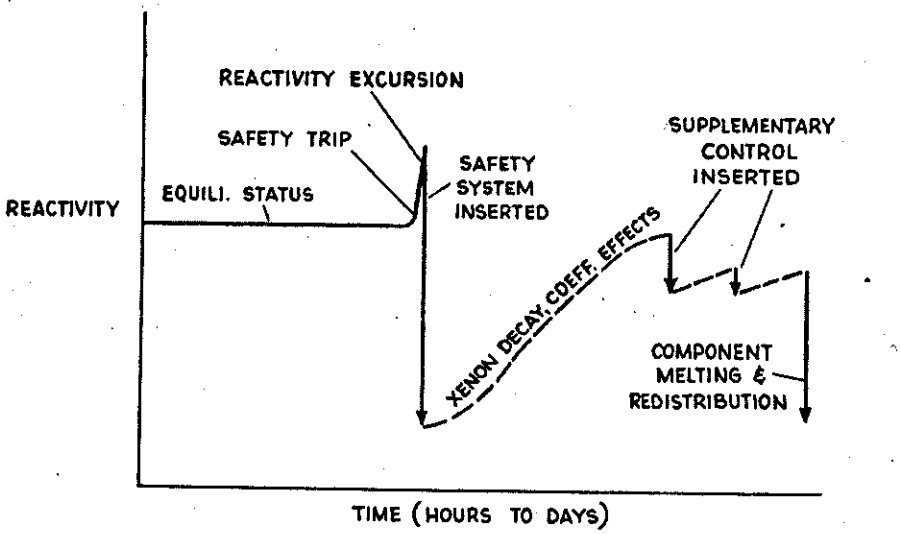
Although the local k may be less than one in all parts of the reactor at a given point in time, subsequent transient effects such as xenon decay may make it desirable to add additional poison

later in the outage as indicated in Figure 32. Since reactor access might be limited in event of coolant loss, control capacity requirements at any point in time must include compensation of any reactivity gains associated with reactor heating and xenon decay subsequent to the coolant loss postulated to occur at that time; thus an ultimate total control case may include a time race between reactivity transient effects and the approach of reactor temperatures to component meltdown conditions.

FIGURE 32

TOTAL CONTROL APPLICATION

KEEP keff < 1 WITH TIME



b. Operating Efficiency Aspects of Control

(1) Flattening

There are strong economic incentives for the average heat generation rate per fuel column to approach the rate in the maximum individual column; otherwise the output of the nonlimiting columns must be reduced unnecessarily by level cuts required to keep the maximum output columns within limits. In other words, there are good reasons to "flatten" the power generation distribution about the reactor—to operate with a flattened neutron level, or flux, distribution.

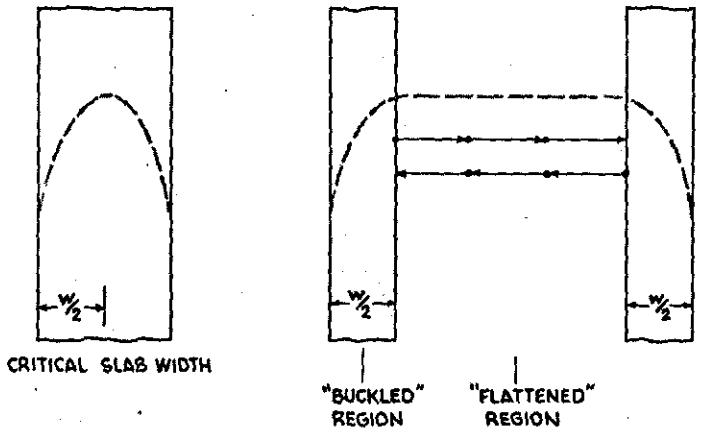
If more neutrons are produced in a local region than escape from its perimeter, the flux will peak in the center of that region. On the other hand, if the same number of neutrons are produced in a given region as are "leaked" uniformly to surrounding regions, the flux pattern in the center of the latter region would be neither

peaked nor dished, but would be flat. Figure 33 shows the peaked distribution which would be observed in a slab loading of exactly critical width; the excess neutrons produced within are "leaked" to the outside. If the two halves of the critical width slab, each of width w/2, were separated by a vacuum as also shown in Figure 33, they should still support a chain reaction; for every neutron lost to the inside by the left side, there would always be one lost from the right side to replace it. So the net leakage from the outer halfslabs to the central region would be zero, allowing neither a buildup nor depletion of local neutron level across the gap, but a flat flux distribution.

FIGURE 33

FLATTENED ZONE

"PASSER" OF NEUTRONS



POSSIBLE "FLATTENED" REGIONS

1. VACUUM
2. LATTICE OF $k_{\infty} = 1.0000....$
or 3. REGULAR LATTICE POISONED TO NET LOCAL k=1.000.....

Now suppose that the central vacuum were replaced by a lattice pattern having a multiplication of exactly one. For every neutron starting from the left side and being absorbed in the central region, there would always be another one born and passed on to the right side; conversely, every neutron leaking from the right into the central region and being absorbed would be replaced by another which could eventually make up for the neutron lost from the left side. This concept is indicated by the arrows across the central region in Figure 33, and in the idealized case would correspond to a region with a k_{∞} of exactly one. Here we get a glimpse, just as in the case of local total control calculations, of why the physicist likes to use a hypothetical k from an "infinite" size reactor in his reactor calculations.

In actual application, the central flattened region may be thought

of as a lattice with an initial k greater than one, but reduced by operating coefficient effects and local poison columns and control rods to a net local multiplication property of exactly one. If the central region is "buckled"—either peaked or dished—it is up to the physicist and the operating crew to readjust the loading and control configurations until all parts of the central region achieve this effective local multiplication of exactly one—until the central region becomes a "passer" of neutrons rather than a source or sink.

(2) Power Distribution Control with Time

Continuing control adjustments during operation for purposes of maintaining good power distribution balance—sometimes referred to as "flux distribution control" and sometimes as "xenon oscillation" or "cycle" control—require that the right amount of control be available for use in the right place at the right time. First we will discuss the control placement, or configuration, requirements; operating control timing requirements will then be considered.

(a) Control Configuration Flexibility

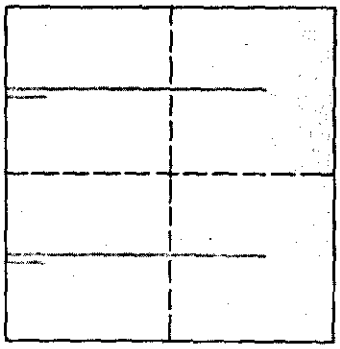
If the local k in each region about the reactor were to remain constant with time, there would be no problem of "flux distribution control"; the initial power distribution would then not change with time. However, operating reactivity effects such as xenon buildup and depletion and temperature coefficients often take place at different rates about the reactor, especially when compensated by rod movements which may of themselves alter the power distribution.

A clue to resolving this problem of potential imbalance may be obtained from the teeter-totter analogy in Figure 34. Suppose the

FIGURE 34

DISTRIBUTION CONTROL

TRADE ROD FOR LOCAL Δk CHANGES



FLEXIBLE ROD CONFIGURATION

TEETER-TOTTER ANALOGY

BALANCE RETAINED WHEN X AND X' ARE EXCHANGED QUICKLY

weights on the left side were exactly balanced by the weights on the right side; the teeter-totter would remain exactly balanced. Now suppose that weight x were removed from the right side, but almost instantly replaced with an equivalent weight labeled x'. If the substitution were made quickly enough, the teeter-totter would never become unbalanced—the left side would never have known that a substitution had taken place on the right side.

The substitution of weight x' for weight x in the analogy is intended to correspond to the substitution of a slight local control rod movement to compensate for a local change in xenon or temperature coefficient effects. Supposing for the moment that we know when the change is needed, there is still the problem of providing a control element tip in each local region where its withdrawal or insertion is needed. The rod configuration illustrated in Figure 34 is seen to have a rod tip in each quadrant of the reactor; this could be considered to be a sufficiently "flexible" control configuration for a small reactor. For larger reactors, more control regions might be required, and in the front-to-rear as well as top-to-bottom and side-to-side directions.

(b) Timing, or Trend Control

The above discussion indicated the way in which needed local reactivity substitutions could be accomplished, but it did not indicate how the need for such action would be determined.

In determining whether or not changes in local k are going on we refer to the pile period concept introduced in the second section of this text. If the level of the entire reactor were increasing, we would say that k effective was greater than one; if the level were decreasing, k_{eff} would be less than one; and if the level were staying constant, k_{eff} would be exactly one. In a similar manner, a slow increase in local level would imply that the k in the local region was greater than one, or a slow decrease in local level would imply that the local k was less than one. This slow increase or decrease in level, as indicated by a local detector of either flux or temperature, is referred to as a "trend" as shown in Figure 35.

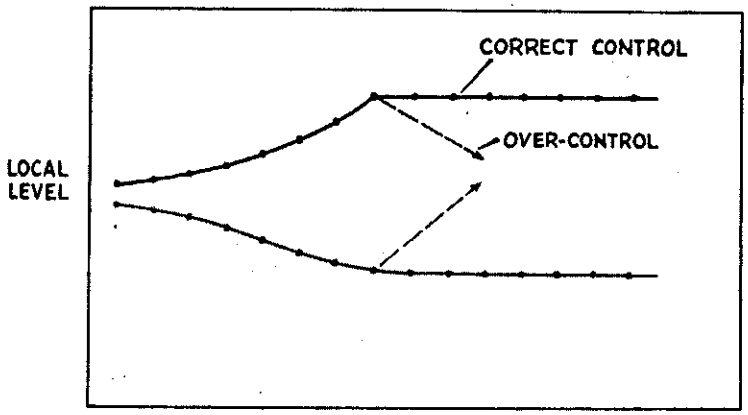
In order to keep the local k constant, the trend should indicate neither an increase nor a decrease in local level with time. The proper correction for an increasing or decreasing trend would thus be to level out the trend indication rather than to reverse it. In other words, the secret of stable flux distribution control is based on local reactivity, or trend, indications rather than on local absolute level values.

In this final section we have applied the knowledge of atomic and nuclear reactions and of the neutron chain reaction process to reactor operating conditions. We have seen that such reactivity effects as

FIGURE 35

TREND CONTROL

MONITORING LOCAL Δk CHANGES



TREND CORRESPONDS TO LONG PERIOD - SHOULD BE LEVELED OUT

xenon, temperature coefficients, and fuel burnout vary in their competition for neutrons with time; consideration of their time variations, or transients, must therefore be included in the procedural and mechanical means provided for ensuring nuclear safety and optimum operating efficiency.

The reactor operator will no doubt have many questions left regarding the physical behavior of his reactor. If this series has helped to stimulate those questions, and to enable the operator to formulate the questions and understand the answers, it will have accomplished its limited goal in the Reactor Personnel Certification program. The ultimate objective of this training series, however, is that each operator will become a recognized authority on the reactivity and control characteristics of his assigned reactor.

REVIEW QUESTIONS ON SECTION C, PHYSICS ASPECTS OF REACTOR OPERATION

1. The multiplier for determining the change in reactivity for a given change in moderator temperature is called the_____

2. The change in reactivity associated with fuel heating is due to the relative speed of a neutron colliding with what isotope primarily? _____

3. Which one of the following nuclei has the smallest neutron-absorption cross section? _____
(Boron, Iodine 135, Cadmium, Xenon 135)
Which one has the largest? _____

4. State whether the number of atoms of xenon 135 **initially** increases, decreases, or remains constant:
After a power raise from equilibrium conditions_____.
After a rapid rise to full level after a one-day outage_____.

5. What isotope formed in the reactor process is a positive contributor to long-term reactivity effects?_____

6. Fill in the missing terms in the following axiom on nuclear safety:
Always keep the ____ ____ rate within the ____ ____ capacity.

7. Which two of the following terms are most important in speed-of-control considerations?
Safety rod drop times _____
U^{239} half-life _____
Xenon cycle time _____
Supplementary control availability _____
Rod withdrawal rates _____
Flattening efficiency _____

8. Which one of the following terms best describes "Total Control"?
Cold, clean reactivity status _____
Sum of rods and poison columns _____
Mass hypnosis _____
Maintain k_{eff} <1 regardless of events _____
Operable number of safety rods _____

9. What is the local k status within a flattened zone? _____

10. What local reactivity change due to xenon effects will occur initially after the local power is raised (assuming the xenon was previously at equilibrium)? _____
What local change will occur ultimately? _____

11. To what term in reactor startup does a local level trend correspond? _____

12. Given the following characteristics for a power reactor which uses pressurized water for both coolant and moderator:
Equilibrium xenon effect = -0.02 k
Fuel temperature coefficient = (-0.00005) k/°C
Moderator temperature coefficient = (-0.0001) k/°C

a. If this reactor is raised from the cold, xenon-free condition at 50°C to equilibrium at 150°C (with 1% potential excess in rods at equilibrium), how much potential excess was held in rods when the reactor was exactly critical at time of startup? _____

b. How many c-mk would be held in each of these effects at the defined equilibrium condition?

Xenon _____ c-mk
Fuel coefficient effect _____ c-mk
Moderator coefficient effect _____ c-mk
Control Rods _____ c-mk