

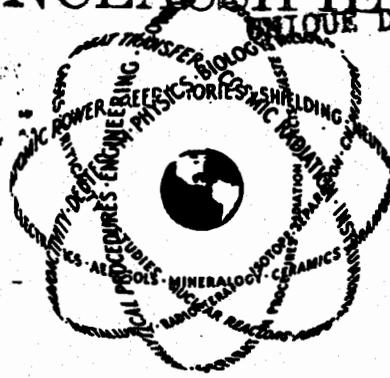
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AN INTRODUCTION TO NUCLEAR WEAPONS (u)

By
Samuel Glasstone

March 1963
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University of California, Los Alamos Scientific Laboratory
and
University of California, Lawrence Radiation Laboratory, Livermore

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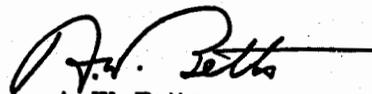
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FOREWORD

While this document has been published as a Headquarters, U. S. Atomic Energy Commission publication, it has as its genesis two 1954 Los Alamos Scientific Laboratory reports identified as LA-1632 and LA-1633, titled "Weapons Activities of LASL." These publications are well known and used extensively by those interested in nuclear weapons as basic handbooks on the principles of nuclear weapons development and technology. Dr. Samuel Glasstone has revised and consolidated the above reports incorporating information furnished by the Los Alamos Scientific Laboratory, Lawrence Radiation Laboratory—Livermore, The Sandia Corporation, and the Defense Atomic Support Agency.

This document has been prepared solely for reference purposes on the principles of atomic weapons development and should not be considered as a technical guide for designing nuclear weapons.

Since this issue contains highly sensitive atomic weapons information of significance to our national defense and security, all viewers are enjoined to insure its proper security protection at all times.



A. W. Betts
Major General, USA
Director of Military Application
U. S. Atomic Energy Commission

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CHAPTER 1

PRINCIPLES OF NUCLEAR ENERGY RELEASE

INTRODUCTION

Mass-Energy Equivalence

1.1 Any nuclear reaction in which there is a net decrease of mass, i.e., in which the total mass of the products is less than that of the interacting nuclei or nuclear particles, will be accompanied by a liberation of energy. The amount of energy released E (in ergs) is related to the net decrease of mass m (in grams) by the Einstein equation

$$E = mc^2 \tag{1.1}$$

where c is the velocity of light, i.e., 3.00×10^{10} cm/sec. In the study of nuclear reactions it is the common practice to state energies in electron volt (or ev) or million electron volt (Mev) units, 1 Mev being equivalent to 1.60×10^{-6} erg. Nuclear masses are generally expressed in atomic mass units (or amu), these being the masses on a scale in which the mass of the common isotope of carbon (C^{12}) is taken as precisely 12.0000. In terms of familiar mass units, 1 amu is 1.66×10^{-24} gram. Upon making the appropriate substitution into equation (1.1), it is found that

$$E(\text{Mev}) = 931 m (\text{amu}) \tag{1.2}$$

Consequently, the energy in Mev accompanying a nuclear reaction is equal to the decrease in mass in amu multiplied by 931.

Fission and Fusion

1.2 Two types of nuclear reactions, in which there is a decrease of mass, are used for the large-scale release of energy in weapons. These are (a) fission, i.e., the splitting of a heavy nucleus into a pair of lighter ones, and (b) fusion, i.e., the combination of two very light nuclei to form a somewhat heavier one. The underlying reason why these processes are accompanied by a liberation of energy (and decrease in mass) is that in each case the total energy of attraction (or binding energy) among the constituent protons and neutrons, i.e., the nucleons, is smaller in the initial nucleus (or nuclei) than it is in the products of the reaction. It is a fundamental law of nature that the rearrangement of a system from a weakly bound state to a more tightly bound state must be accompanied by a release of energy.

Binding Energy

1.3 The magnitude of the net attractive energy, i.e., the binding energy, of the nucleons in any nucleus can be calculated from the masses of various particles. Consider an atomic

species (or nuclide) of atomic number Z and mass number A , so that the nucleus of the atom contains Z protons and $A - Z$ neutrons. For electrical neutrality, the atom as a whole must have, in addition, Z extranuclear electrons. If m_p , m_n , and m_e are the masses of the proton, neutron, and electron, respectively, the sum of the masses of the constituents of the atom is then $Zm_p + Zm_e + (A - Z)m_n$. Suppose that the actual atomic mass, as determined by the mass spectrograph or in other ways, is M ; then the mass defect (M.D.) of the particular isotope is defined by

$$\text{M.D.} = [Z(m_p + m_e) + (A - Z)m_n] - M = Zm_H + (A - Z)m_n - M$$

where $m_p + m_e$ has been replaced by m_H , the mass of the hydrogen atom, to which it is essentially equivalent.

1.4 From the arguments given above, it can be seen that the mass defect is a measure of the energy which would be released if the individual Z protons and $A - Z$ neutrons combined to form the given nucleus.* This energy is numerically equal, but opposite in sign, to that which would have to be supplied to break up the nucleus into its constituent nucleons, i.e., the binding energy of the nucleus. Consequently, the mass defect of a nuclide can be related to the nuclear binding energy (B.E.) by utilizing equation (1.2); thus,

$$\text{B.E. (in Mev)} = 931 \times \text{M.D. (in amu)} \quad (1.3)$$

Since the mass of the proton and neutron in amu are well known and M can be determined, the M.D. can be derived from experimental data and from this the B.E. can be readily obtained for any nuclear species.

1.5 A useful quantity for practical purposes is the binding energy per nucleon, i.e., $\text{B.E.}/A$, where A is the mass number which is equal to the number of nucleons in the nucleus. The values of $\text{B.E.}/A$ for many stable nuclides have been determined, from their known atomic masses, and when plotted against the respective mass numbers, as in Fig. 1.1, the results are found to fall on, or very close to, a continuous curve. The significant aspect of this curve, for

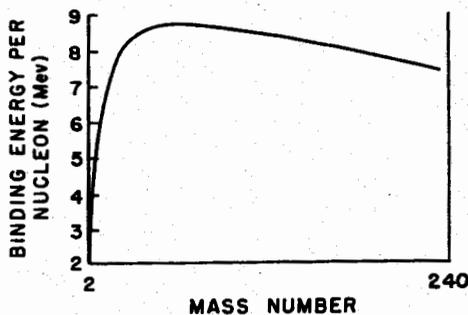


Figure 1.1

the present purpose, is that the mean binding energy per nucleon is less for the lightest and for the heaviest nuclei than it is for those of intermediate mass. It is this fact which accounts for the liberation of energy that accompanies either fission of heavy nuclei or fusion of light nuclei. In each case, the total binding energy in the initial nucleus (or nuclei) is less than that in the reaction products.

*The Z electrons contribute a small amount of energy, but this is largely allowed for in the replacement of $m_p + m_n$ by m_H .

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RELEASE OF FISSION ENERGY

Calculation of Fission Energy

1.6 The most accurate method for determining the energy released in fission is from the known masses (in amu) of the nucleus undergoing fission and of the nuclei formed in the process. A simple, although less exact, procedure is the following. It will be seen shortly that fission of uranium-235, for example, can result from the absorption of a neutron, and in the process two lighter fission-product nuclei and two or three free neutrons are formed. The uranium-235 nucleus contains 235 nucleons and so the fission-product nuclei will have a total of $235 + 1 - 2$ (or 3), i.e., 234 (or 233) neutrons, depending upon whether two or three neutrons are released; the latter number will be used for the present calculation. In uranium-235, the mean binding energy per nucleon (Fig. 1.1) is about 7.6 Mev; hence, if the 235 nucleons which make up the uranium-235 nucleus were combined, the energy released would be given by

$$235 \text{ Nucleons} \rightarrow \text{Uranium-235} + (235 \times 7.6) \text{ Mev}$$

Nearly all the fission-product nuclei have mass numbers in the range from 95 to 140, and for such species Fig. 1.1 shows that the mean binding energy per nucleon is roughly 8.5 Mev. Consequently, the combination of the 233 nucleons to produce two fission-product nuclei can be represented by

$$233 \text{ Nucleons} \rightarrow \text{Two fission-product nuclei} + (233 \times 8.5) \text{ Mev}$$

Upon subtracting the two energy expressions, it is seen that

$$\text{Uranium-235} \rightarrow \text{Fission product nuclei} + (233 \times 8.5) - (235 \times 7.6) \text{ Mev}$$

The free neutrons absorbed and released in the fission process can be neglected in this calculation. Hence, the fission of a uranium-235 nucleus is accompanied by the release of $(233 \times 8.5) - (235 \times 7.6)$ Mev, i.e., about 200 Mev, of energy. The significance of this amount of energy in terms of more familiar units will be given below.

The Fission Process

1.7 The fission of heavy nuclei can be brought about in several different ways, but there is only one that is of importance for the practical release of nuclear energy. This is fission initiated by neutrons. The reason is that the fission process is always accompanied by the release of neutrons, which can produce fission in other nuclei. Hence, once fission by neutrons has been initiated in a quantity of material, a chain reaction, carried on by neutrons, is possible with the continuous release of energy. Only three nuclear species, namely, uranium-233, uranium-235, and plutonium-239, need be considered here for use in a fission chain process for two reasons. First, although these substances are radioactive and decay with the emission of alpha particles, they have relatively long half-lives and so are moderately stable.* All other fissile nuclides have such short half-lives and decay so rapidly that they have no practical value; in any event their strong radioactivity would make them difficult to handle. Second, of the relatively stable species, the three mentioned above are the only ones which will undergo fission as a result of the capture of neutrons of all energies, e.g., from less than an electron volt (slow neutrons) to millions of electron volts (fast neutrons).

1.8 The common isotope uranium-238, which constitutes about 99.3 percent of the element in nature, requires neutrons of about 1-Mev energy to cause fission at an appreciable

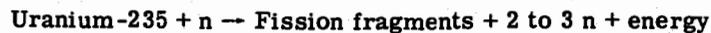
*The half-lives are as follows: uranium-233, 1.6×10^5 years; uranium-235, 7.1×10^8 years; plutonium-239, 2.4×10^4 years.

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rate.* Most of the neutrons produced in fission actually have higher energies, but they lose energy rapidly in (inelastic) collisions, so that they are brought below the threshold of about 1 Mev for significant fission of uranium-238. Consequently, the maintenance of a chain reaction in uranium-238 is impossible. Nevertheless, fission of this isotope by fast neutrons does take place and the energy released can make a significant contribution to the total energy produced in nuclear weapons.

1.9 Of the three fissile species, only uranium-235 is found in nature; the other two are produced by artificial nuclear reactions (§1.53). Furthermore, only two, namely, uranium-235 and plutonium-239, are being used in weapons. Although uranium-233 has fission characteristics which would appear to make it of interest for use in certain types of artillery shells of small caliber, the strong gamma-ray activity of associated products introduces serious fabrication and handling problems.

1.10 The fission process may be regarded as yielding three types of products: (a) lighter nuclei, called fission fragments, (b) neutrons, referred to as fission neutrons, and (c) energy. Thus, taking uranium-235 as typical, the fission act may be represented by



where n indicates a neutron. These products will be considered in turn. It may be mentioned that the general discussion of the fission process given below is applicable to all three fissile substances. Such differences in behavior as do exist arise from differences in the average number of neutrons produced when fission occurs and in the relative probabilities (or cross sections) of fission and nonfission reactions for neutrons of a given energy.

Fission Products

1.11 Uranium-235 (and other) nuclei split up in about 40 different ways, although some of these modes of fission are more probable than others. This means that roughly 80 different nuclides (fission fragments) are formed in fission in various proportions. Nearly all, if not all, of the fission-fragment nuclei are radioactive, emitting beta particles and frequently also gamma rays. On the average, each fission fragment undergoes three stages of beta decay before attaining stability, so that there are ultimately formed over 200 different nuclear species, most of which are radioactive. The mixture of fission fragments and their decay products is referred to by the general name of fission products. As just indicated, it is a very complex system containing many radioisotopes, the half-lives ranging from a small fraction of a second to a million years. It is the fission product mixture which contributes nearly all of the radioactivity of the fallout produced by a nuclear explosion.

Fission Neutrons

1.12 The number of neutrons released when a nucleus undergoes fission varies somewhat with the particular mode of fission, but the average number of fission neutrons is well defined. The value depends on the energy of the neutrons which cause fission, and increases to some extent with increasing neutron energy. The results of estimates based on experimental measurements are given in Table 1.1 of the average number (ν) of neutrons produced per fission caused by (a) slow neutrons, i.e., neutrons of essentially zero energy, (b) neutrons of about 0.5 Mev energy, which is roughly the average energy of the neutrons which maintain the chain in a simple fission weapon, and (c) neutrons of 14-Mev energy which contribute greatly to the fission energy of boosted (§1.49) and many two-stage (§7.38) devices.

1.13 The neutrons emitted in fission fall into two categories, namely, prompt neutrons and delayed neutrons. The former are all released within something like 10^{-14} sec of the fis-

*A distinction is sometimes made between the "fissile" nuclei, such as uranium-235, etc., in which fission can be produced by a neutron regardless of its energy, and the "fissionable" nuclei, such as uranium-238 and thorium-232, which require neutrons of high energy to cause fission.

sion process, but the latter continue to be emitted for a few minutes. For uranium-235 fission, the prompt neutrons constitute 99.35 percent of the total fission neutrons and for plutonium-239 they represent nearly 99.8 percent. Because the time scale in nuclear explosions is very short, delayed neutrons play essentially no part in the fission chain reaction. In reactors for the controlled release of nuclear energy, however, these neutrons are of great significance.

Table 1.1—Neutrons Released per Fission

Nuclide	Neutron Energy		
	~0 Mev	0.5 Mev	14 Mev
Uranium-235	2.43	2.49	4.1
Plutonium-239	2.80	2.85	4.9
Uranium-233	2.45	2.51	4.2

Fission Energy

1.14 The rough estimate made earlier indicated that about 200 Mev of energy are produced per nucleus undergoing fission. More precise calculations, based on nuclear masses, and experimental measurements have shown that this is a good approximation for both uranium-235 and plutonium-239. The atomic mass in grams, i.e., 235 grams of uranium-235, contains 6.02×10^{23} nuclei, and the complete fission of this amount of uranium-235 would yield $6.02 \times 10^{23} \times 200 = 1.20 \times 10^{25}$ Mev or 1.93×10^{19} erg, since 1 Mev is equal to 1.60×10^{-6} erg. Making use of the fact that 1 calorie is equivalent to 4.18×10^7 ergs, it can be readily shown that complete fission of all the nuclei in 1 kilogram of fissile material would result in a total energy release of 2.0×10^{13} calories.

1.15 Only part of the energy of fission is immediately available in a nuclear explosion, since most of the radioactive decay energy of the fission products is released over a long period of time. It is usually accepted that about 90 percent of the fission energy contributes to the explosion, so that in a weapon the fission of 1 kilogram of material would produce explosive energy of about 1.8×10^{13} calories. The energy liberated in the explosion of 1 ton of TNT is taken to be 10^9 calories, and so 1 kilogram of fissile (or fissionable) material is equivalent in explosive power to 18,000 tons, i.e., 18 kilotons (or 18 kt), of TNT.* From these results it is readily found that complete fission of 0.056 kg (or 56 grams) or of 1.45×10^{23} nuclei of fissile material produces the equivalent of 1 kt of TNT of explosive energy. In other words, the energy per fission is 7.03×10^{-24} kt TNT equivalent. In stating the energy yields (or, in brief, the yields) of nuclear weapons, the basic unit, for very low yields, is the ton, with the kiloton (or 1,000 tons), i.e., 1 kt, and the megaton (or 1,000,000 tons), i.e., 1 Mt, of TNT equivalent being used for higher yields.

THE FISSION CHAIN REACTION

Condition for Chain Reaction: Critical Size

1.16 The condition for a self-sustaining fission chain reaction is that, on the average, the neutrons released in one act of fission shall cause (at least) one subsequent fission. Since the average number of neutrons produced in an act of fission is greater than two (see Table 1.1), it would appear, at first sight, that a chain reaction in uranium-235 or plutonium-239 would be inevitable. However, this is not so, because an appreciable proportion of the neutrons pro-

*In some calculations, the equivalent of 1 kg of uranium-235 is assumed to be 17 kt whereas for plutonium-239 it is 19 kt. The value 18 kt per kg is a good average for most fission weapons.

duced are lost in various ways. In a nuclear fission weapon, for example, an important source of loss is by leakage (or escape) of neutrons from the reacting material. Thus, many neutrons avoid being captured by a fissile nucleus by escaping from the system entirely. Some neutrons are also lost by parasitic capture, i.e., by capture in nonfission reactions of various kinds, either by the fissile species itself or by other nuclides which may be present.

1.17 The fraction of neutrons escaping from a system in which fission is occurring can be decreased by increasing the mass, i.e., by increasing the size at constant density of fissile material.* Since neutrons are produced by fission throughout the whole volume, whereas loss by escape takes place only from the exterior surface, it is evident that the escape probability will decrease as the volume-to-area ratio of the system is increased. This can be achieved, for a given geometry (shape), by increasing the dimensions of the fissile material at constant density.

1.18 In a very small mass of fissile material a self-sustaining chain reaction will not be possible, under normal circumstances, because of the large proportion of neutrons that escape. But as the size is increased (at constant density), the fraction of fission neutrons lost will decrease and ultimately a point is reached when one neutron will be available to carry on the fission chain for every neutron causing fission. The system is then said to be critical, and a self-sustaining chain reaction is just possible. If a system is smaller than the critical size (or mass), it is referred to as subcritical, and if larger, it is supercritical. In the latter case there are more neutrons available for fission at the end of any generation than were captured in fission reactions at the beginning of that generation. It will be seen shortly that the critical size (or mass) is dependent on the nature of the fissile material, its shape, and several other factors. However, for a given set of conditions, the critical size (or mass) has a definite value which can be determined by experiment or can sometimes be calculated.

Convergent, Stationary, and Divergent Chains

1.19 If ν is the average number of neutrons produced in each act of fission, for the existing neutron energy distribution (or neutron spectrum), and l is the number lost by escape and in other ways, e.g., by nonfission capture, then $\nu - l$ is the number of neutrons which can cause further fission; let this be represented by k , called the effective multiplication factor, i.e.,

$$k = \nu - l \quad (1.4)$$

Thus, for every neutron causing fission in one generation, k neutrons will cause fission in the next generation. Alternatively, k may be defined as the ratio of the number of neutrons in any one generation to the number in the preceding generation. Hence, in accordance with the statements made above, k is less than unity for a subcritical system; in a critical system $k = 1$; and in a supercritical system k is greater than unity.

1.20 Suppose S neutrons are introduced into a mass of fissile material and cause fissions to occur; then kS neutrons will be present in the next generation, k^2S in the third, and so on. Since, for a subcritical system, $k < 1$, it is evident that as g , the number of generations, increases, $k^g S$ will approach zero. In other words, the number of neutrons present will gradually decrease from one generation to the next, because more neutrons are lost in various ways than are being produced by fission. There is, consequently, a convergent or decaying chain which gradually dies out. For a system of critical size, $k = 1$ and then $k^g S$ is always equal to S . The number of neutrons thus remains constant from generation to generation; this is referred to as a stationary chain. Finally, if $k > 1$, as is the case for a supercritical system, $k^g S$ increases steadily. The fission chain is then said to be a divergent or expanding chain.

1.21 In the foregoing discussion no distinction has been made between the prompt and delayed fission neutrons. As stated earlier, however, it is essentially the prompt neutrons only which are significant in fission weapons. The effective critical size (or mass) of a weapon is

*The reason for specifying constant density of fissile material will be apparent later (§1.40).

into the fissile core. By reducing the fraction of neutrons which escape completely, a smaller size (or mass) can become critical. Such a scattering material, on account of its function, is sometimes referred to as a neutron reflector.

1.26 In nuclear weapons, the fissile material is surrounded by a tamper or, more specifically, an inertial tamper, the mass of which delays expansion of the exploding material and permits a higher energy yield to be obtained from the system undergoing fission, as will be seen later. This inertial tamper also serves as a neutron reflector or neutronic tamper. In some cases, however, the neutronic aspect is more important than the inertial character of the tamper.

1.27 As is to be expected, increasing the thickness of the tamper decreases the escape of neutrons and thus makes possible a smaller critical mass of the core of fissile material. However, it has been shown by calculations and verified experimentally that when the neutronic tamper thickness reaches a certain value, there is little more to be gained by a further increase of thickness (Fig. 1.2). Thus, when the thickness is about two neutron scattering mean

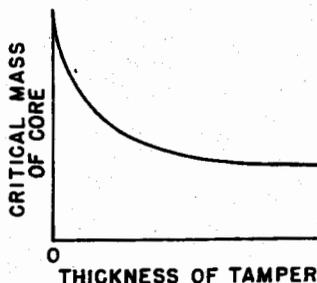


Figure 1.2

free paths, the effectiveness in decreasing the critical mass is within a few percent of that for an infinitely thick tamper.* In natural uranium, which is sometimes used as a tamper, the scattering mean free path of fast (1 Mev) neutrons is about 4 cm, i.e., 1.6 in., in metal of normal density. The value is proportionately less in compressed uranium of higher density. In weapons of low mass, beryllium is a common tamper material; the scattering mean free path is somewhat longer than in uranium because of the lower density.

1.28 Another important factor which affects the critical size is the energy (or speed) of the neutrons causing fission. For several reasons, some of which will be explained later, nuclear weapons are designed so that the fission chain is maintained by fast neutrons, with energies in the range of approximately 0.1 to 2 Mev. In the subsequent treatment it will be assumed, therefore, that fast-neutron fission makes the main contribution to the chain reaction.

Determination of Critical Mass

1.29 Critical masses can now be calculated with a fair degree of accuracy, provided all the conditions are known exactly. It is desirable, however, to check these values by experimental measurements. Because of the danger involved in handling critical assemblies, the general procedure is to extrapolate from observations made on a number of subcritical systems of increasing mass.

1.30 It was seen in §1.20 that the introduction of S neutrons into a fissile material results in the presence of kS neutrons in the first generation, k^2S in the second, and so on. If a

*The scattering mean free path is the average free-flight distance a neutron travels before undergoing a scattering collision with a nucleus in the given tamper material.

1.33 The procedure described above can be used to determine critical masses for both tamped (reflected) or untamped assemblies. It can also be applied to actual mockups of fission weapons. Some of the components, e.g., fissile substances, are the same as would be used in the weapon, whereas others, e.g., high explosive, would be simulated by other materials with similar neutronic properties.

1.34 Under precisely specified conditions, and for a given core material, there is a definite mass that is just critical; this is called a "crit." The critical masses of spheres of metallic uranium-235 (93.2 weight percent enrichment) and of the alpha- and delta-phases of plutonium-239 for fast-neutron fission are given in Table 1.2. Values are quoted for bare, i.e., untamped spheres, as well as for spheres with tampers of [redacted] beryllium, respectively. The effect of the neutronic tamper in reducing the critical mass is very striking. It will be noted, too, in accordance with remarks made earlier, that the critical mass of delta-plutonium is larger than that of the alpha form, whereas both are smaller than the critical mass of uranium-235. DOE
b(3)

FISSION WEAPONS

Gun Method of Assembly

1.35 As long as a mass of fissile material is less than the critical value for the existing conditions, that is to say, provided the system is subcritical, there is no danger of a divergent, or even a stationary, chain reaction. But, if energy is to be released in a nuclear explosion, the system must be made critical and, in fact, highly supercritical, as will be seen shortly. There are two general ways utilized in weapons whereby a subcritical system of fissile material is rapidly converted into one that is supercritical.

1.36 The first may be referred to as the gun method of assembly. Two portions of material of subcritical size are brought together very rapidly, so that the combined mass is supercritical. If a burst of neutrons is then introduced, a divergent fission chain is initiated and a rapid release of energy occurs in a very short time. This is the principle used in the so-called "gun-type" weapons: one [redacted] DOE
b(3)

[redacted] the name gun-type originates from the fact that in devices of this kind the two pieces of fissile material, [redacted] are located near opposite ends of a gun barrel.* DOE
b(3)

1.37 Although the gun assembly method for attaining criticality is satisfactory when uranium-235 is the fissile material, it has a serious drawback when plutonium-239 is used. This arises from the presence of the higher isotope, plutonium-240. Because of the way it is produced (§1.53), plutonium-239 is invariably associated with a certain proportion—generally from about 2 to 7 percent—of the higher isotope, plutonium-240. The latter happens to have a high probability for undergoing spontaneous fission, i.e., without the intervention of neutrons. The spontaneous fission rate of plutonium-240 is, in fact, about 440 fissions per second per gram. Since nearly three neutrons are liberated per fission, this means that 1 gram of plutonium-240 emits well over 1000 neutrons per second. [redacted] DOE
b(3)

1.38 An efficient use of the fissile material in a simple gun-type weapon requires that the chain reaction be initiated by neutrons only when the assembly has attained its maximum criticality. [redacted] the considerable neutron background, arising from the presence of plutonium-240, may result in initiation of a self-sustaining chain reaction as soon as the assembly becomes just critical. If this occurs, there DOE
b(3)

*It is merely a coincidence that in most nuclear artillery shells the gun-type of assembly is used. [redacted] There is, however, another type of artillery shell which does not employ gun assembly (§4.37). DOE
b(3)

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$$R_c \propto \lambda \quad (1.6)$$

1.44 The greater the probability of the interaction of a neutron with a nucleus, the smaller will be the distance the neutron travels before interacting. Hence, the neutron mean free path is related inversely to its interaction probability. This probability is proportional to the number of fissile nuclei per unit volume, and hence to the density; if ρ is the density of the core material, then

$$\lambda \propto \frac{1}{\rho} \quad (1.7)$$

It follows therefore from equations (1.6) and (1.7) that

$$R_c \propto \frac{1}{\rho} \quad (1.8)$$

1.45 The critical mass, M_c , is equal to the product of the critical volume, which is $\frac{4}{3} \pi R_c^3$, and the density of the fissile material; hence,

$$M_c = \frac{4}{3} \pi R_c^3 \rho$$

Upon substituting equation (1.8) for R_c , it is seen that

$$M_c \propto \frac{1}{\rho^2} \quad (1.9)$$

The density of the material is dependent upon the degree of compression; thus, if η is the compression ratio, i.e., the ratio of the volume before to that after compression, then

$$\rho \propto \eta$$

and substitution in equation (1.9) leads to the result

$$M_c \propto \frac{1}{\eta^2} \quad (1.10)$$

The critical mass of a given fissile material, under specified conditions, is thus inversely proportional to the square of the compression ratio. The proportionality constant is readily derived by writing M_{c0} for the critical mass of the uncompressed material, i.e., when $\eta = 1$. It follows then from equation (1.10) that

$$M_c = \frac{M_{c0}}{\eta^2} \quad (1.11)$$

1.46 An alternative way of stating this result is in terms of the number of crits (or critical masses), C , present in the compressed core. If M is the actual mass of fissile material, the number of crits in the compressed state is defined by

$$C = \frac{M}{M_c}$$

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Combination with equation (1.11) then yields

$$C = \frac{M\eta^2}{M_{c0}} = C_0\eta^2 \quad (1.12)$$

where M/M_{c0} has been replaced by C_0 , the number of crits before compression.

The introduction of neutrons into this highly supercritical system resulting from compression will cause a very rapidly divergent fission chain reaction to develop. In these circumstances there is very efficient use of the fissile material for the release of energy. It is the high degree of supercriticality (and increased efficiency) attainable by compression that constitutes the great advantage of implosion-type weapons over those of the gun type.

1.47 Strictly speaking, the relationship of the number of crits to the square of the compression holds only for a bare core. For a tamped core, a more correct form of equation (1.12) is

$$C = C_0\eta_c^{1.2}\eta_t^{0.8}$$

where η_c is the compression of the core and η_t is that of the tamper. Since the tamper is generally compressed less than the core, a good approximation for weapons is to write

$$C = C_0\eta_c^{1.7}$$

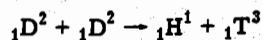
The effect of compression is still substantial, although not as large as is implied by equation (1.12).

Fusion Reactions in Fission Weapons

1.48 It was stated in §1.2 that the large-scale release of energy in weapons is possible by making use of fusion reactions in which two very light nuclei combine (or fuse) together to form particles of greater mass. However, apart from the application of nuclear fusion reactions as a source of energy, described in Chapter 7, certain fusion processes are important in the design of fission weapons for another reason. The significance of these reactions does not lie in the energy released but in the neutrons which are produced. Three fusion reactions, involving the less common isotopes of hydrogen, namely, deuterium (D^2) and tritium (T^3), are of interest in this connection. Two of these reactions are between pairs of deuterium nuclei (deuterons) only, i.e.,



and



which take place at about the same rate, and the third is a much more rapid interaction between a deuteron and a tritium nucleus (triton), i.e.,



1.49 It is seen that when two deuterons interact, a neutron is formed in one case and a triton in the other; the triton then readily reacts with a deuteron to produce another neutron. Both deuteron-deuteron (D-D) and deuteron-triton (D-T) reactions are employed to provide

neutrons for initiating fission chains. In addition, the high-energy (14 Mev) neutrons liberated in the D-T reaction are used in many fission weapons to achieve what is known as "boosting." Neutrons from the D-T reaction are introduced at a later stage of the fission chain in order to maintain and enhance the progress of the fission reactions. There is a considerable increase in the energy released because of the greatly improved efficiency in utilization of the fissile material. The energy contributed by the D-T fusion reaction is quite small in comparison with that from fission.

PRODUCTION OF WEAPONS MATERIALS

Uranium-235

1.50 The two important fissile materials, namely, uranium-235 and plutonium-239, are both produced from natural uranium but by entirely different procedures. Ordinary uranium contains about 0.7 percent of uranium-235, together with about 99.3 percent of uranium-238 and a trace (0.006 percent) of uranium-234. The proportion of uranium-235 is increased by a process involving diffusion or, more correctly, effusion through porous barriers of the vapor of uranium hexafluoride (UF_6) made from natural uranium. The hexafluoride of the lighter isotope diffuses more rapidly than does that of the heavier species, and by the use of several thousand diffusion stages enrichments of over 90 percent are obtained, i.e., the material produced contains over 90 percent of uranium-235. The most common product for weapons use consists of about 93.5 weight percent uranium-235, the remainder being mainly uranium-238 and a small proportion of uranium-234. This product is commonly known as "oralloy," the two initial letters standing for Oak Ridge, where the material was first made in quantity.*

1.51 The highly enriched uranium hexafluoride obtained from the gaseous diffusion plant is converted into the tetrafluoride (UF_4) by reduction with hydrogen (mixed with some fluorine). The tetrafluoride, which is a solid with a high melting point (close to 1000°C), is mixed with calcium and heated in a closed steel vessel lined internally with a refractory material. The calcium reduces the uranium tetrafluoride to uranium metal which is separated from the slag of calcium fluoride. Volatile impurities are removed by heating the liquid metal in a vacuum and the resulting product is of a high degree of purity.

1.52 The residual material from the isotope separation (gaseous diffusion) plant consists of uranium hexafluoride which has been depleted in uranium-235. In other words, it contains more than the normal 99.3 percent of uranium-238. This is converted into uranium metal by a procedure similar to that described above. It is referred to as depleted uranium or, in the weapons program, as D-38. At one time it was called Q-metal, but this name is not now in common use.

Plutonium-239

1.53 The element plutonium does not occur in nature, except in insignificant traces. Consequently, the plutonium-239 used in weapons is obtained artificially by a series of nuclear reactions resulting from exposure of uranium-238 to slow neutrons in a nuclear reactor. A nuclear reactor is a device in which a fission chain reaction is taking place in a controlled manner, as against the deliberately uncontrolled chain reaction in a weapon. If a material of low mass number, called a moderator, is present, in addition to fissile material, the fission neutrons are slowed down. Such a nuclear reactor is thus a good source of slow neutrons.

*The "alloy" part of the name originated from the designation Tube Alloys Limited applied to the British wartime atomic energy project. Natural uranium metal was thus called "tuballoy," a term still in common use, and then oralloy was adopted for the uranium-235 enriched material.

1.77 The third isotope of hydrogen, i.e., tritium, is a radioactive beta emitter, with a half-life of 12.26 years. It is found in natural waters to an insignificant extent only and the cost of extraction would be prohibitive. Consequently, tritium is produced by nuclear reactions resulting from the exposure of lithium (as a suitable compound) to neutrons in a reactor. The less abundant lithium-6 isotope, present to the extent of 7 atomic percent in natural lithium, readily captures slow neutrons and undergoes the (n,α) reaction



with the formation of tritium. The more common isotope, lithium-7, reacts with fast neutrons to some extent and this process also leads to the production of tritium; thus,



1.78 After irradiation by neutrons for a length of time, the lithium compound is removed from the reactor and the gases, consisting mainly of tritium and helium, with other hydrogen isotopes as impurities, are separated from the residual solid. Purification is achieved by a gaseous diffusion process. Compounds of tritium can be prepared from the gas by reactions similar to those employed for deuterium and ordinary (light) hydrogen.

where α is the specific rate constant for the process which is responsible for the change in the number of neutrons. In nuclear weapons work this constant is called the multiplication rate or merely "alpha." Comparison of equations (2.3) and (2.4) shows that for a fission chain reaction

$$\alpha = \frac{x}{\tau} \quad (2.5)$$

2.4 The foregoing results are applicable regardless of whether x , and hence α , is positive, zero, or negative. For a subcritical system, $k < 1$ (§1.20), i.e., $k - 1$ is negative; in these circumstances x is negative and so also is α . It follows from equation (2.4) that dn/dt is then negative and the number of neutrons in the system will decrease with time. Consequently, in agreement with previous conclusions, the fission chain in a subcritical system will eventually die out because of the steady decrease in the neutron population. When the system is just critical, $k = 1$, and x and α are both zero; the number of neutrons will thus remain constant. Finally, for a supercritical system, $k > 1$, and x and α are positive; there will then be a steady increase in the neutron population. Since dn/dt is proportional to n , by equation (2.4), it is evident that in a supercritical system, the number of neutrons will grow at increasingly faster rates as n increases.

2.5 Another aspect of the significance of α becomes apparent when equation (2.4) is written in the form

$$\frac{dn}{n} = \alpha dt$$

If α is assumed to remain constant, this expression can be readily integrated between the time limits of zero, when the number of neutrons present is n_0 , and t , when the number is n . The result is

$$n = n_0 e^{\alpha t} \quad (2.6)$$

where, as usual, e is the base of natural logarithms. This expression, like those given above, is applicable regardless of whether α is positive, zero, or negative. If α is known, equation (2.6) can be used to calculate the neutron population at any time t relative to the value at any arbitrary zero time. It can also be seen from equation (2.6) that $1/\alpha$ is the time period during which the number of neutrons changes by a factor e ; consequently, $1/\alpha$ is often referred to as the e -folding time, i.e., the time in which there is an e -fold change in the neutron population.

Determination of Alpha

2.6 The value of α is a highly important quantity in weapons design, as will shortly be apparent. Attempts are made to estimate it theoretically from the neutronic and hydrodynamic characteristics of the system, but there are many uncertainties involved and experimental measurements are desirable. In weapons tests, the determination of alpha is one of the most important diagnostic requirements. The methods used under these circumstances are described in Chapter 8. The present treatment will be restricted to procedures which can be used in the design phase without an actual test of the weapon.

2.7 Since a supercritical (or even a critical) mass cannot be handled safely under ordinary conditions, experimental measurements of α are made with a mass that is slightly subcritical. Into this assembly is injected a burst of neutrons and these neutrons initiate a large number of chains. However, since the system is subcritical, α will be negative and so the number of neutrons will decrease after the initial increase. By determining a quantity proportional to the neutron population as a function of time, with neutron counters located outside the assembly, it is possible to determine α by means of equation (2.6). The α obtained from the decrease in neutron population in the early stages is the so-called prompt value, required for weapons studies in which the delayed neutrons play no part.

$$n \approx n_0 e^{t/\tau} = n_0 e^g \quad (2.11)$$

where t/τ , represented by g , is the number of generations in which the neutron population increases from n_0 to n . This means that in a fission explosion the number of neutrons increases by a factor of e per generation, i.e., by a factor of 10 in every 2.3 generations; thus,

$$n \approx n_0 10^{g/2.3} \quad (2.12)$$

2.19 Before a fissioning system can explode, i.e. before the material begins to move outward, a certain energy density must be attained.

[REDACTED]

DOE
b(3)

2.20

[REDACTED]

DOE
b(3)

It was stated in §1.15 that the energy released per fission is equivalent to about 7×10^{-24} kt.

[REDACTED]

DOE
b(3)

2.21 The liberation of the remaining energy requires an increase by a factor of 10^3 in the number of fissions, and this will occur in a time period of only about 7 generations ($10^{7/2.3} \approx 10^3$).

[REDACTED]

DOE
b(3)

Most of the energy, however, is liberated during the final few shakes. Even in a boosted weapon the overall situation is much the same.

[REDACTED]

DOE
b(3)

2.22 The foregoing calculations are not exact; for one thing it was assumed that the total number of fissions which have occurred by any particular time is equal to the neutron population at that time. Nevertheless, a more precise treatment leads to conclusions in general agreement with those reached above.

[REDACTED]

DOE
b(3)

Within this period, the core volume is assumed to remain essentially constant. In a pure fission system, although not in a boosted device, the value of α also remains roughly constant after initiation and it is this particular value which largely determines the efficiency of the weapon. During the next 5 to 10 generations, or so, depending on the total energy release, almost all of the energy is liberated. The resulting very high temperatures—several tens of million degrees—cause large pressures to develop within the core and thus rapid expansion occurs.

2.23 Soon after expansion commences, the fission chain reaction gradually dies out, because the increasing rate of neutron escape causes α to decrease and eventually to become negative.

[REDACTED]

DOE
b(3)

to attain a high efficiency, i.e., to consume as much as possible of the fissile

[REDACTED]

DOE
b(3)

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material, expansion of the core should be delayed. This important function is fulfilled by the inertial tamper. In boosted weapons, the introduction of neutrons from an extraneous (D-T) source results in a considerable increase in the fission rate before the system expands appreciably. The inertial tamper is then less important than in an unboosted device.

2.24

In some weapons, however, there will be many neutrons present at the time of initiation. If, for example, there are 100 neutrons, i.e., 10^2 or $e^{4.6}$, there will be the equivalent of nearly 5 "generations" of neutrons at the start of the chain.

EFFICIENCY OF FISSION WEAPONS

Definition of Efficiency

2.25 The efficiency, ϕ , of any weapon may be defined as the ratio of the energy actually developed when it explodes, i.e., the energy yield, to the total energy available; thus,

$$\phi = \frac{\text{Energy yield}}{\text{Energy available}} \quad (2.13)$$

In other words, the efficiency is the fraction of the total energy available which is actually released in the explosion. In the case of a fission weapon, this is equal to the ratio of the quantity of fissile material which actually suffers fission to the total amount present in the weapon. The efficiency of a weapon is generally expressed as a percentage, and so it is equal to ϕ , as defined by equation (2.13), multiplied by 100. There are several factors which determine the efficiency and some of these will be discussed below.

2.26 It is of interest to mention, in passing, that the efficiency of the earliest implosion weapons was (\$1.36). This accounts for the fact that devices of the latter type have occupied a secondary place in the development of fission weapons, except for special purposes.

Calculation of Efficiency: Machine Methods

2.27 At the present time, the efficiency or, more correctly, the energy yield of a weapon is determined by machine calculations based on "codes" which have been developed to represent the behavior of the fission chain system.

From initiation up to this time, the material is essentially stationary or is still being compressed and only a small proportion of the total energy has been liberated. The treatment takes into account the neutronic behavior, the hydrodynamics, and heat flow; the motion of a series of concentric shells (or "mass points") is followed until the rate of energy release by fission has fallen almost to zero. The total yield includes the energy released after the system has expanded and become subcritical. Although self-sustaining chain propagation is no longer possible, convergent-chain interaction of the many neutrons and fissile nuclei still present will result in considerable energy production. This may amount to some 30 percent or more of the total yield.

The Bethe-Feynman Formula

2.28 Prior to the development of computing machine procedures, and before data were available from test explosions for comparison and normalization purposes, fission weapon

efficiencies were estimated by the method of Bethe and Feynman. The basic formula is admittedly approximate, since it involves several simplifying assumptions. However, its derivation is useful in the respect that it provides a model of the explosion of a fission weapon and indicates, qualitatively at least, some of the factors which affect the efficiency of the explosion. The treatment given below is applicable to pure fission systems and not after boosting occurs.

2.29 As a result of the energy liberated in fission, very large pressures ($\sim 10^9$ atm) are developed in the core, and the core-tamper interface consequently receives a large outward acceleration. This causes highly compressed tamper material to pile up just ahead of the expanding interface, in an effect referred to as the "snowplow" phenomenon, because of the similarity to the piling up of snow in front of a snowplow. The inertia of the compressed tamper delays expansion of the core, so that a considerable pressure gradient builds up from the center of the core to its outer surface.

2.30 Furthermore, because of the delayed expansion, it may be supposed that the volume of the compressed (supercritical) core remains essentially constant during the [redacted] After this interval, almost the whole of the energy is released within an extremely short period, during which time the supercritical core expands rapidly until it becomes subcritical. Although there is an appreciable release of energy even while the system is subcritical, as mentioned in §2.27, it will be postulated that energy production ceases when the dimensions are just critical. It will be assumed, further, that no energy escapes during the short period of expansion from maximum supercriticality to the point where the system becomes subcritical.

2.31 Let R be the radius of a spherical core at the point of maximum supercriticality; then, in accordance with the postulate made above, this will remain unchanged until explosion time. Subsequently, the energy density of the system becomes so large that mechanical effects begin and the core starts to expand. Suppose that when the core has expanded by a fraction δ , so that the radius is $R(1 + \delta)$, the system is just critical (Fig. 2.1); beyond this point it will be subcritical. The self-sustaining fission chain will then end and, in accordance with the approximation postulated above, there will be no further release of energy.

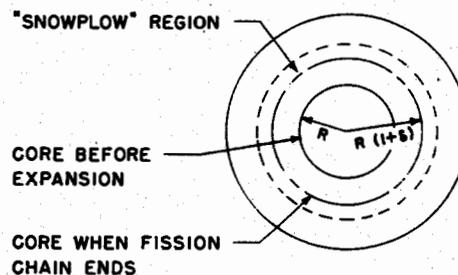


Figure 2.1

2.32 Consider a thin shell of material in the core, of volume dV and thickness dR ; the cross sectional area of the shell is then dV/dR . If dP is the pressure difference on the two sides of this shell, caused by the liberated fission energy, the net outward force, dF , to which the shell is subjected, i.e., pressure \times area, is then

$$dF = dP \frac{dV}{dR} = \frac{dP}{dR} dV \quad (2.14)$$

where dP/dR is the pressure gradient in the given shell. As a reasonable approximation, it may be supposed that the pressure gradient is essentially constant across the core radius, so that

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which is a simplified version of the Bethe-Feynman formula. The efficiency of a fission weapon is seen to depend on the factors R , α , and δ .

2.36 Since the efficiency of a fission weapon may be expected to increase as R^2 , it would be advantageous for the core to be large at the time of the initiation of the fission chain. One way in which this can be achieved in practice, e.g., in a gun-type weapon, is to bring together subcritical masses which are designed to contain a large total mass of fissile material. Thus, for a given compression or, especially, for no compression, the efficiency would be expected to be greater the larger the mass of the assembled core.

2.37 In general, the most important factor in determining the efficiency of a fission weapon is α ; as seen in §2.16, this increases in proportion to the compression. The efficiency, according to equation (2.21), will thus be related, approximately at least, to η^2 (or to $\eta^{1.7}$ if the effect of tamper compression is taken into account). In addition, although of lesser significance, the effect of compression on δ must be taken into account; the more highly compressed the core material at the time of initiation (or at explosion time), the farther will be the distance the core surface must travel during the expansion phase before the supercritical system becomes subcritical. Increased compression should thus result in a marked gain in the efficiency of a fission weapon. It is this fact which is largely responsible for the much higher efficiencies of implosion systems than of gun-type devices.

2.38 The effect of increasing compression in a simple (unboosted) implosion system is indicated by the data in Table 2.1 which are based partly on experimental observations and

Table 2.1—EFFECT OF COMPRESSION ON EFFICIENCY

Average Compression		Efficiency (Percent)
Core	Tamper	
[REDACTED]		[REDACTED]

partly on calculation.

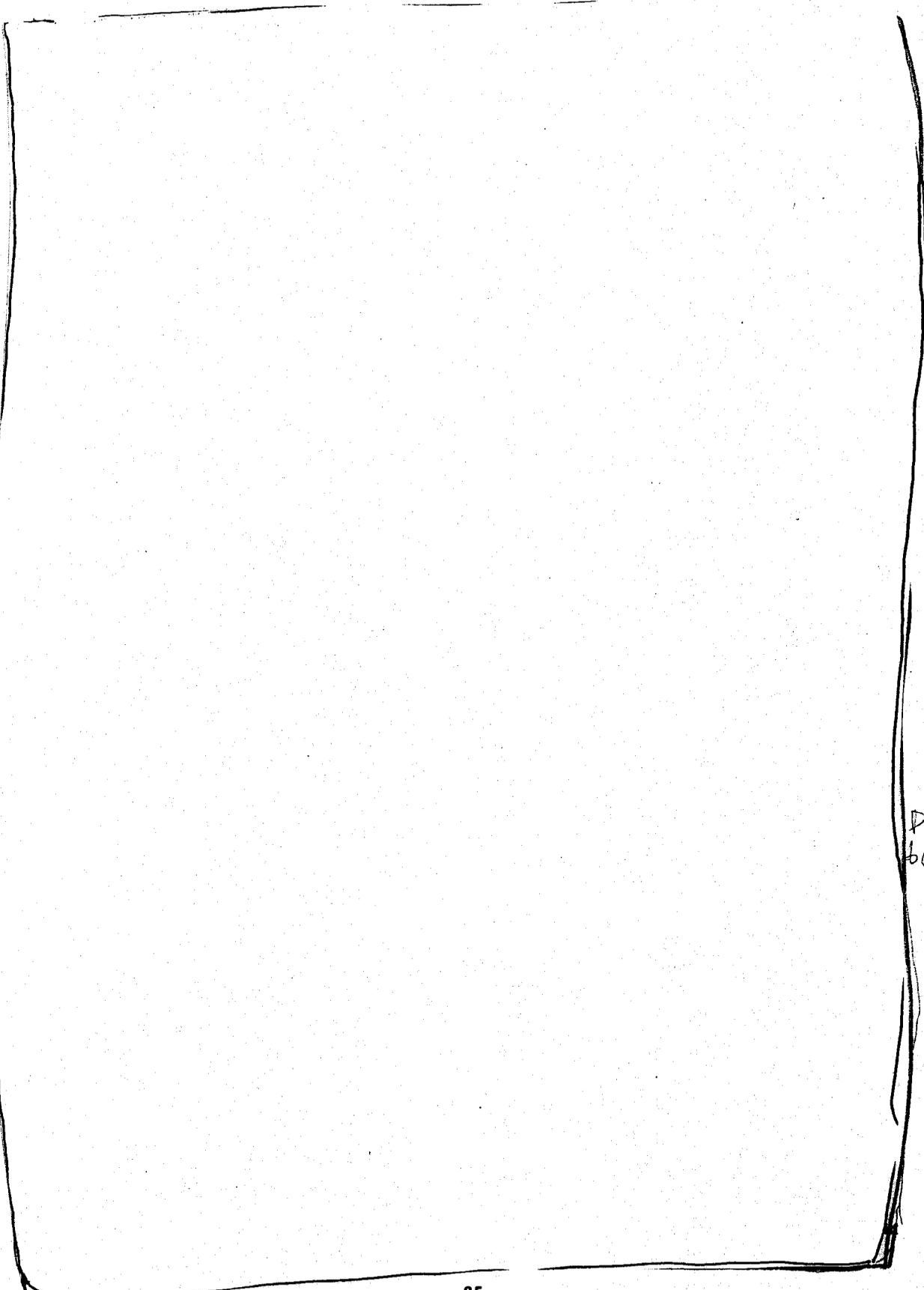
The attainment of high compression has been an important objective in fission weapon design. In the earliest (solid-core) devices the improvement in efficiency was the main purpose. In more recent (hollow-core boosted) weapons, however, the principal objective is to make possible the design of compact systems in which both the high explosive ($\$1.42$) and the fissile material have low masses. The number of crits at maximum compression is not large, so that α is relatively small before boosting. The initial efficiency of the fission chain is, therefore, also small but the total yield is greatly increased by the boosting.

INITIATION TIME AND PREINITIATION

Unboosted Implosion Weapons

2.39 The time at which the fission chain is initiated is of importance in determining the efficiency of a weapon.

fissile core would be highly supercritical.



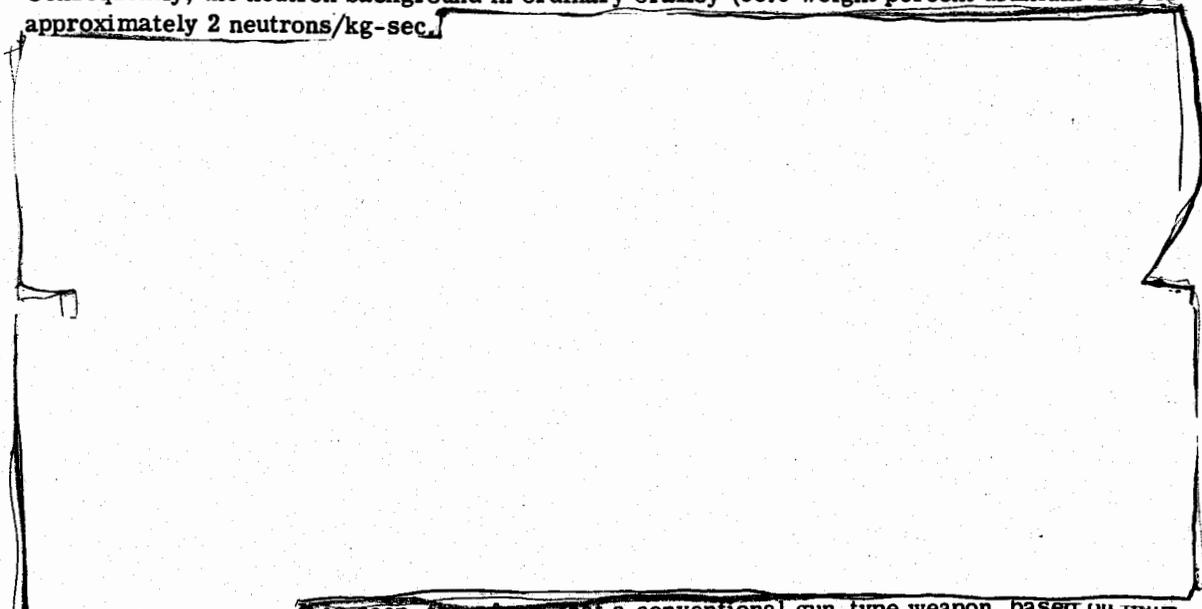
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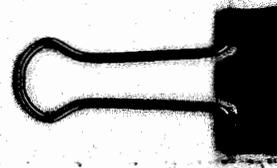
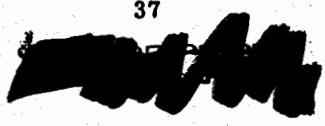
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2.48 As a result of spontaneous fission, uranium-235 emits, on the average about 0.85 neutron per kilogram per sec, whereas uranium-238 produces roughly 17 neutrons/kg-sec. Consequently, the neutron background in ordinary or alloy (93.5 weight percent uranium-235) is approximately 2 neutrons/kg-sec.



It is seen, therefore, that a conventional gun-type weapon, based on plutonium with assembly brought about by a propellant explosive, is completely out of the question. It was the realization of this fact, when plutonium became available, that led to the development of implosion systems (§1.39).





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