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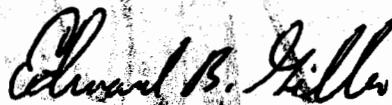
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FOREWORD

While this revision of WASH-1038 and the original issuance have been published as Headquarters, U. S. Atomic Energy Commission documents, they have as their genesis two 1954 Los Alamos Scientific Laboratory reports, LA 1632 and LA 1633, both entitled "Weapons Activities of LASL." We are indebted to LASL for these early reports. Although the previous LA and WASH reports received extensive use as basic handbooks on the principles of nuclear weapons development and technology, they were not to be considered as technical guides for designing weapons. Similarly, this revision of WASH-1038 is not to serve as such a guide.

In the preparation of this document, Dr. Samuel Glasstone has reviewed, coordinated, and edited data provided by members of the Los Alamos Scientific Laboratory, the Lawrence Livermore Laboratory, the Sandia Laboratories, and the Defense Nuclear Agency. The exceptional cooperation of these organizations and the outstanding work of Dr. Glasstone have permitted the Atomic Energy Commission to publish this revision to WASH-1038. Further, we wish to recognize the very significant contributions of Dr. Leslie M. Redman in the preparation of this issuance.

This publication contains highly sensitive nuclear weapon design information of significance to our national defense and security. Viewers are enjoined to ensure its proper security protection at all times.



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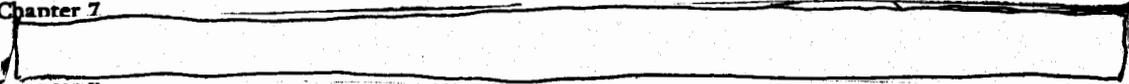
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CONTENTS

	Page
FOREWORD	2
PREFACE	4
Chapter 1	
PRINCIPLES OF NUCLEAR ENERGY RELEASE	5
Chapter 2	
THE FISSION PROCESS IN WEAPONS	23
Chapter 3	
FISSION WEAPONS DEVELOPMENT	38
Chapter 4	
IMPLOSION SYSTEMS	48
Chapter 5	
NUCLEAR SYSTEMS	78
Chapter 6	
BOOSTING	89
Chapter 7	
Chapter 8	
WEAPON VULNERABILITY AND HARDENING	107
Chapter 9	
WEAPONS SAFETY AND SAFEGUARDS	115
APPENDIX	121
INDEX	123
DISTRIBUTION	128



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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. For a given set of conditions, however, 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

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

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^gS 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^gS 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^gS 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 thus determined by the availability of the prompt neutrons, without regard to those which are delayed. This situation is often described as prompt critical. Since more than 99 percent of fission neutrons are prompt, the neglect of the delayed neutrons has little effect on the value of ν . In other words, the data in Table 1.1 may be taken as being approximately applicable to weapons. Critical masses determined by experiment (§ 1.29) include the contribution of delayed neutrons, so that the prompt critical mass applicable to weapons is very slightly larger than the value measured in the laboratory. Again, the difference is small, although corrections can be applied if necessary.

Factors Affecting Critical Mass

1.22 The critical size (or mass) of a given fissile material depends on a number of factors, as mentioned earlier. For example, the shape (or geometry) of the system has an influence on criticality because of the variation in the ratio of volume to surface area. As seen in § 1.17, this ratio determines the fraction of neutrons lost by leakage from the system. The optimum condition of minimum critical mass is obtained for a

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 considerable 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 steady source emitting S neutrons per second is used, then all generations will be present in the system, so that the total rate of neutron production is $S + kS + k^2S + \dots$. The ratio of the rate of neutron formation to the source strength is called the neutron multiplication, M ; thus,

$$M = \frac{S + kS + k^2S + \dots}{S} = 1 + k + k^2 + k^3 + \dots$$

For a subcritical system, k is less than unity; the series $1 + k + k^2 + \dots$ is then convergent and for a large number of generations it is equal to $1/(1 - k)$. Consequently,

$$M = \frac{1}{1 - k} \tag{1.5}$$

Since $1 - k$ is finite and positive, M has a finite value for a subcritical system. For a critical system, however, $k = 1$; $1 - k$ is then zero and M becomes infinite.

1.31 For the determination of critical masses, it is more convenient to consider the reciprocal of the multiplication, i.e., $1/M$; by equation (1.5), this is given by

$$\frac{1}{M} = 1 - k.$$

Provided the system is subcritical, $1/M$ is finite but less than one, but for criticality $k = 1$ and so $1/M$ is zero. The neutron multiplication is observed for several subcritical systems containing different masses of fissile material, and the experimental values of $1/M$ are

plotted against the masses. The extrapolated mass corresponding to $1/M = 0$ is then the critical mass under the existing conditions.

1.32 The neutron multiplication is determined by placing a steady neutron source inside an assembly of active material of prescribed shape and composition and of known mass. The measured rate of arrival of neutrons at a counter located outside the assembly is proportional to $S + kS + k^2S + \dots$. The rate of arrival from the same source in the absence of fissile material is proportional to S . Hence, the ratio of the measurements with and without the assembly of active material is equal to the multiplication M . Determinations of M are made in this manner, with the same source and detector location, for a number of assemblies of increasing mass, and $1/M$ is plotted against the mass, as in Fig. 1.3. The extrapolated mass for $1/M = 0$ is the critical mass. By changing the position of the detector, the apparent multiplication is changed, but the $1/M$ values should always extrapolate to the same point, as shown by the two curves in the figure.

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

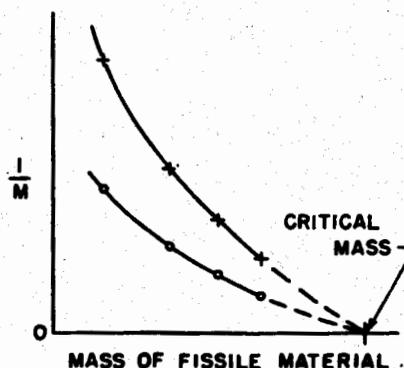


Figure 1.3

components, e.g., fissile substances, are the same as would be used in the weapon, whereas others, e.g., high explosive, are 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. The critical masses of spheres of metallic uranium-235 (93.2 weight percent enrichment) of the alpha- and delta-phases of plutonium-239,

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[redacted] 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 off [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.

Table 1.2 CRITICAL MASSES OF SPHERES

Fissile Material	²⁴⁰ Pu (wt %)	Density (g/cm ³)	Bare	Critical mass (kg)			
				U	U	Be	Be
Uranium-235 (93.2 wt %)		18.8	52.5	[redacted]	[redacted]	[redacted]	[redacted]
Plutonium-239 (α)	4.8	19.7	10.5	[redacted]	[redacted]	[redacted]	[redacted]
Plutonium-239 (δ)*	4.8	15.8	16.6	[redacted]	[redacted]	[redacted]	[redacted]
Plutonium-239 (δ)*	21	15.8	18.8	[redacted]	[redacted]	[redacted]	[redacted]

*Contains ~1 wt % gallium.

[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.

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 is generally referred to as the gun method of assembly. Two portions of material of subcritical size are brought together very rapidly, for reasons given below, 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:

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 more than two neutrons are liberated per fission, on the average, this means that 1 gram of plutonium-240 emits over 1000 neutrons per second.

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 will be little

*It is purely a coincidence that in most nuclear artillery shells the gun type of assembly is used [redacted]

[redacted] there is, however, another type of artillery shell which does not employ gun assembly (§4.23).

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or no explosion, since the neutron density will not increase rapidly and energy, resulting from fission, will not be produced fast enough; the reasons for such behavior will be apparent later. On the other hand, uranium-235 has a small neutron background and therefore can be used in a gun-type weapon. If assembled rapidly enough, there is little probability of premature initiation, or "preinitiation," as it is called, immediately upon the system becoming critical. When maximum supercriticality is attained, neutrons are introduced deliberately from a suitable source to initiate the fission chain reaction. In this way, the optimum efficiency can be realized in the use of the fissile material.

Compression Method (Implosion Weapon)

1.39 Because of the probability of preinitiation, and low efficiency, of a gun-assembly weapon using plutonium-239, an alternative method for attaining criticality (or supercriticality) was developed, based on the compression of the subcritical fissile mass. This procedure turned out to be so successful and gave so much better efficiency that the gun type of assembly has been utilized only in a relatively few weapons for special purposes, e.g., in artillery-fired shells and in rugged, impact-resistant bombs designed to penetrate some distance into the ground before exploding. Apart from these particular cases, the compression method is invariably used to attain supercriticality in fission weapons.

1.40 The principle of the method is that if a mass of fissile material is compressed, the rate of production of neutrons by fission in the subcritical state is essentially unchanged, since it depends mainly on the number of nuclei present. Actually, there will be some increase in the neutron production in convergent chains. On the other hand, the number of neutrons lost by escape is decreased as a result of compression because of the smaller surface area of the given mass. Consequently, a quantity of material which is subcritical in the normal state can become supercritical when compressed. The introduction of neutrons to initiate the fission chain at (or close to) the time of maximum compression—and, hence, of maximum supercriticality—results in an efficient use of the fissile material in causing an explosion.

1.41 In practice, the compression occurs very rapidly.



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1.42 The compression in these weapons is achieved by the use of a powerful conventional (chemical) high explosive which surrounds the core of fissile material. By the use of explosive charges of special design much of the energy of the explosion is directed inward, thereby causing the material in the interior to be compressed in a spherically symmetric manner. It is for this reason that the term "implosion" is applied to weapons of this type.

1.43 An approximate derivation of the relationship between the degree of compression and the critical mass of fissile material is the following.† The total mean free path of a neutron is the average distance it travels before it interacts in any way with a nucleus. The proportion of neutrons which do not interact but escape from the system may be expected to be determined by the ratio of the dimensions, e.g., the radius of a sphere, to the mean free path. It may be concluded, therefore, that for a given fissile (core) material, under specified conditions, the critical radius should be approximately proportional to the neutron mean free path; thus, if R_c is the critical radius and λ is the mean free path in the material,

$$R_c \propto \lambda. \tag{1.6}$$

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

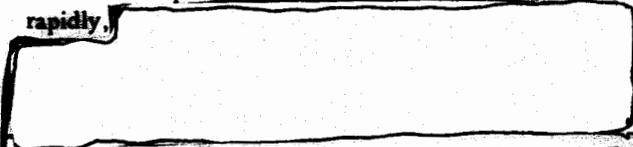
$$\lambda \propto \frac{1}{\rho}. \tag{1.7}$$



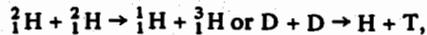
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†The purpose of the discussion in §1.43 through §1.47 is to provide a general basis for understanding the effect of compression on criticality. It is not intended to imply that the methods are currently used. At present, computer calculations, which can take many variables into consideration, are employed to derive criticality conditions. The term "crit" in §1.46 is now more or less obsolete in weapons calculations.

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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 In a mixture of deuterium and tritium, the main reaction is between a deuteron and a triton which results in the formation of a neutron as one of the products. In deuterium alone, a neutron is also a product in one of the deuteron-deuteron (D-D) reactions. In the other D-D reaction, a triton is formed and this 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 late 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 under the circumstances by the D-T fusion reaction is, however, 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 93.2 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, because at one time it contained 0.38 percent uranium-235, although greater depletion has been regularly achieved. 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

*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 material highly enriched in uranium-235.

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If the plutonium were to be used in the alpha phase, however, the presence of a relatively large proportion of plutonium-241, which would decay to americium-241, could lead to a phase change to the delta form. The accompanying decrease in density would then result in dimensional instabilities. To test this point, a sample of alpha-plutonium containing 12.3 percent of plutonium-241 has been under observation since February 1964. A decrease in density from 19 to about 17.8 g/cm³ occurred between 56 and 64 months, when the americium content was roughly 2.7 weight percent, but x-ray examination showed that the material still consisted entirely of the alpha phase. The significance of the results is uncertain and the observations are being continued.

Composition of Weapons Plutonium

1.69 In addition to plutonium-239 and -240, which are the main components, weapons-grade plutonium contains small quantities of isotopes of both higher and lower mass numbers. These are produced in a reactor by various neutron reactions either (n,2n) or (n,gamma). The average isotopic compositions of plutonium from Hanford and Savannah River plants reported in June 1968 are quoted in Table 1.5; these may be regarded as typical of current production.

Table 1.5 COMPOSITION OF WEAPONS-GRADE PLUTONIUM IN WEIGHT PERCENT

	Hanford	Savannah River
Plutonium-238	<0.05	<0.05
Plutonium-239	93.17	92.99
Plutonium-240	6.28	6.13
Plutonium-241	0.54	0.86
Plutonium-242	<0.05	<0.05

Possible Weapons Materials

1.70 Several fissile nuclides, with atomic number exceeding 94, are known, but they are of no practical value for weapons purposes because of their short half-lives. A region of stability has been predicted, theoretically, however, for very heavy species in the vicinity of those having "magic numbers" of both protons and neutrons, e.g., 114 protons and 184 neutrons, i.e., ²⁹⁸114X, and 126 protons and 184 neutrons, i.e., ³¹⁰126X. Such nuclides might have half-lives up to 10⁶ to 10⁸ years, and would be expected to be capable of sustaining a fission chain with neutrons.

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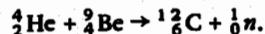
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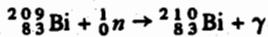
Production of Neutrons

1.73 In a fission weapon, the chain reaction is initiated by the introduction of neutrons into a critical or supercritical system. Consequently, the general methods for producing neutrons in weapons will be reviewed here. One of the simplest procedures for obtaining neutrons is by the action of alpha particles on certain light elements, notably beryllium; processes of this kind are referred to as (alpha,n) reactions. Recalling that the alpha particle is actually a helium nucleus, the reaction is represented by

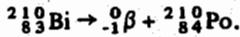


1.74 A convenient source of alpha particles, which was used extensively at one time in fission weapons, is

the radioelement polonium-210. This isotope has certain advantages, associated with corresponding drawbacks. It does not emit gamma rays, so that there is no neutron production by the (γ, n) reaction which might otherwise occur even when the polonium-210 and beryllium are separated in such a manner as to prevent access of alpha particles to the latter. Moreover, the polonium-210 is easy to produce by exposure of ordinary bismuth to neutrons in a nuclear reactor, when the (n, γ) reaction

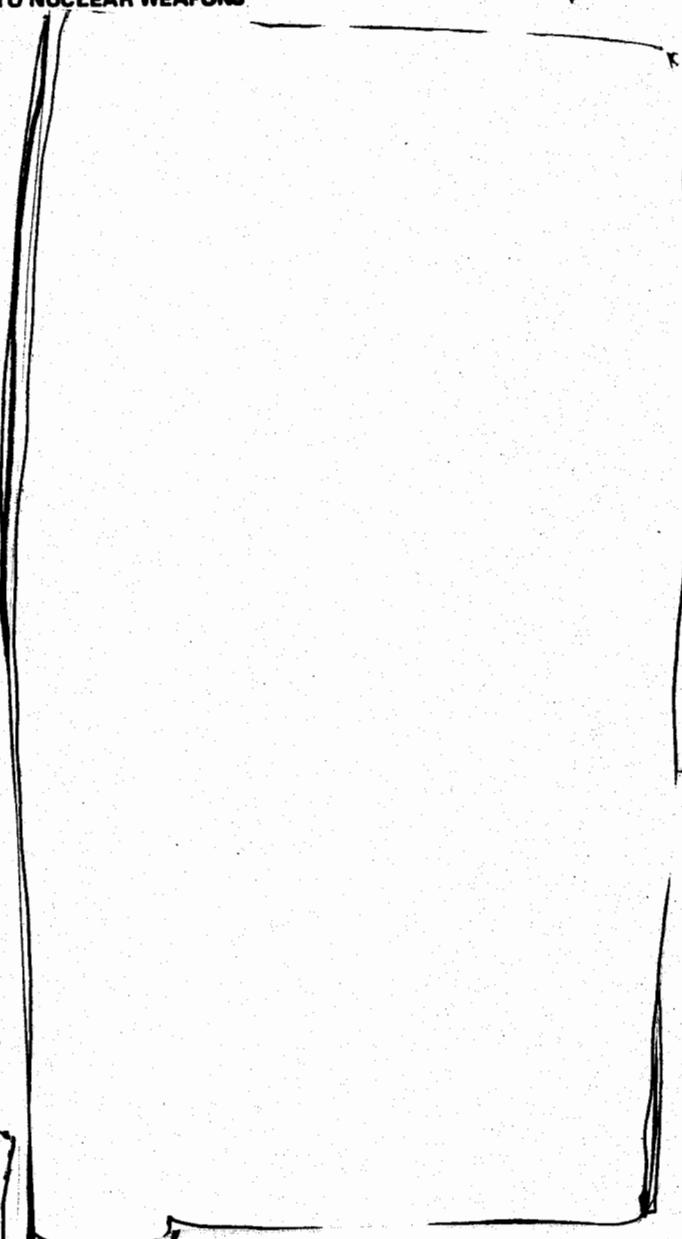


takes place. The bismuth-210 is a beta emitter with a half-life of 5 days, so that it soon decays to form polonium-210; thus,



However, the production of polonium-210 in this manner means that fewer neutrons are available for the conversion of uranium-238 into plutonium-239.

1.75 As a result of the moderately short half-life of polonium-210—138.4 days—it emits alpha particles rapidly and a small quantity can thus provide a strong neutron source in conjunction with beryllium. But the short half-life is also a serious disadvantage, because the activity falls off relatively rapidly. In one year, the alpha activity, and hence the rate of neutron production, will have decreased to 18 percent and in two years to 2.6 percent of its initial value.



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utilized
chain in nuclear weapons (§ 5.25).



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1.80 In the great majority of weapons of recent design the neutrons required for initiation are produced by the fusion reactions described in § 1.48. The procedures involve either the D-D or D-T reactions at high temperatures (thermonuclear reactions) or the interaction of accelerated tritons with a deuterium target (electronuclear reactions). The methods used for achieving these processes in weapons are described in Chapter 5.

Production of Deuterium and Tritium

1.81 Deuterium (in the form of the mixed oxide, HDO) is present to the extent of about one atom to 6500 atoms of hydrogen, i.e., 0.015 atom percent, in ordinary water. In spite of this very small proportion, concentration of the deuterium in water is not too difficult, and heavy water of about 99.75 percent purity, i.e., 99.75 mole percent D₂O, is now produced on a large scale.

1.82 Three main processes are used to separate the two hydrogen isotopes in water; these are (a) isotopic (or chemical) exchange, (b) distillation, and (c) electrolysis. Several isotope exchange processes have been considered but the most satisfactory appears to be one involving reaction between hydrogen sulfide gas and liquid water. The exchange reaction results in a relatively higher proportion of deuterium in the liquid phase than in the gas. By utilizing a countercurrent flow of gas and liquid in several stages, in a system operating at two different temperatures, considerable enrichment in deuterium can be achieved in the liquid.

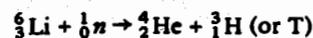
1.83 The distillation method for separating the isotopes of hydrogen depends on the fact that heavy water (D₂O) has a slightly higher boiling point, i.e., slightly lower vapor pressure, than light water (H₂O). Consequently, a partial separation can be achieved by fractional distillation, preferably under reduced pressure.

1.84 When an acid or alkaline aqueous solution is electrolyzed, the hydrogen gas liberated at the cathode contains relatively more of the lighter isotope (H₂) than does the residual water. By repeated electrolysis in stages, heavy water of a high degree of purity can be obtained.

1.85 Each of the three foregoing procedures has certain advantages under appropriate conditions. Hence, in the production of heavy water in quantity, ordinary water is first partially enriched in deuterium by the isotopic exchange process with hydrogen sulfide. The deuterium is further concentrated by fractional distillation of the enriched water under

reduced pressure, and then it is brought up to 99.75 percent purity by electrolysis. Deuterium gas can be released from heavy water by any of the familiar chemical processes used to prepare hydrogen gas. It can then be very simply converted into any compound that may be required, e.g., uranium deuteride (UD₃), lithium deuteride (LiD), etc., for weapons applications.

1.86 The third isotope of hydrogen, i.e., tritium, is a radioactive beta emitter, with a half-life of 12.33 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,



1.87 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.

Enrichment of Lithium

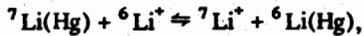
1.88 For the production of tritium, described above, it is not necessary to separate the lithium-6 from the more abundant lithium-7. Natural lithium is consequently used for this purpose. For certain applications, e.g., in some thermonuclear weapons, however, it is required that the lithium, which is employed as a hydride,* be enriched in the lighter isotope. Such material, with a lithium-6 enrichment of up to 90 percent, is produced by the counter current flow of

*Used generically, the term hydride refers to a binary compound containing any of the isotopes of hydrogen.

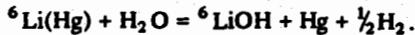
lithium amalgam, Li(Hg), and an aqueous solution of lithium hydroxide, Li⁺OH⁻, in a cascade of packed columns. The amalgam is obtained by the electrolysis of lithium hydroxide solution using a mercury cathode.

A portion of the resulting (enriched) lithium hydroxide is drawn off as the product and the remainder is refluxed to the cascade. The recovered mercury is returned to the amalgam maker at the head of the cascade.

1.89 The lighter isotope is concentrated in the amalgam by the exchange reaction



and is recovered by decomposing the amalgam with pure water in the presence of a graphite catalyst, i.e.,



1.90 The hydroxide enriched in lithium-6 is neutralized with hydrochloric acid; the resulting aqueous solution of lithium chloride is concentrated by evaporation and the salt is allowed to crystallize. Lithium metal is then obtained by electrolysis of the molten lithium chloride. For the production of various lithium hydrides enriched in ⁶Li, the metal is reacted at a suitable temperature with the appropriate isotope of hydrogen under pressure.



"incubation time" (Fig. 2.1). The time between first critical and explosion (or maximum supercriticality) is here called the "assembly time."*

2.24 Because of the rapid increase in the neutron population during the propagation of the fission chain reaction, the fission energy is released at a very high rate. The heat generated causes the temperature to increase and the fissile material expands (or disassembles) rapidly. Soon the volume becomes so large that the system becomes subcritical and the divergent chain reaction ceases. The point at which the material passes through the critical stage during expansion is called "second critical" (§ 2.59).

2.25 The number of fission generations corresponding to the explosion time for a spherical (imploded) core can be calculated in a semiquantitative way in the following manner.† If the reasonable assumption is made that the pressure in the assembly has a parabolic distribution, then the pressure P at a distance r from the center of the core of radius R is

$$P = P_0 \left(1 - \frac{r^2}{R^2} \right), \quad (2.11)$$

where P_0 is the pressure at the center. If \bar{P} is the average pressure in the core then, as shown in the appendix to this chapter,

$$\bar{P} = \frac{1}{5} \rho R a, \quad (2.12)$$

where ρ is the density of the core material and a is the acceleration at its surface.

2.26 If the change in velocity at the surface of the core at a time t after initiation of the chain reaction is represented by Δv , then

$$\Delta v = \int_0^t a dt. \quad (2.13)$$

Furthermore, with an exponentially increasing neutron population, as indicated by equation (2.6), the ac-

*In weapons test, a measured time interval is that between firing the HE system and the first appearance of gamma rays from the explosion; it is called the "HE transit time" or simply the "transit time."

†The purpose of this treatment is merely to provide a general understanding of the core behavior. In weapons design studies, more exact calculations are made with the aid of computers.

celeration, as well as the energy density and the pressure, will vary as $e^{\alpha t}$; hence,

$$a = A e^{\alpha t},$$

where A is a constant. If this result is substituted into equation (2.13), it is seen that

$$\Delta v = \frac{a}{\alpha}. \quad (2.14)$$

2.27 Suppose the unperturbed velocity of the core surface during assembly, i.e., before it is affected by the fission energy, is v_0 ; then the assembly motion will be halted when

$$\Delta v = v_0, \quad (2.15)$$

and this corresponds to explosion time. Consequently, from equations (2.14) and (2.15), at explosion time

$$a = v_0 \alpha,$$

and from equation (2.12)

$$\bar{P} = \frac{1}{5} \rho R v_0 \alpha. \quad (2.16)$$

This is the average pressure in the core at explosion time.

2.28 The application of equation (2.16) may be illustrated by considering the hypothetical case of a core with a density, ρ , of 20 g/cm³, and a radius, R , of 5 cm. The unperturbed rate of assembly v_0 may be

and α is set at 1 gen/shake, i.e., 10⁹ gen/sec.

If these values are substituted into equation (2.16), it follows that at explosion time

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2.29 At explosion time, the core will be effectively a gas at very high pressure and it may be considered to

‡The unit 1 bar is equivalent to a pressure of 10⁶ dynes/cm²; the megabar, i.e., 10⁶ bars, is then 10¹² dynes/cm². The standard atmospheric pressure (760 mm of mercury) is 1.013 bars; thus a pressure of 1 atm is approximately 1 bar.

which the shell is subjected, i.e., pressure \times area, is then

$$dF = dP \frac{dV}{dR} = \frac{dP}{dR} dV, \quad (2.19)$$

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

$$\frac{dP}{dR} \approx \frac{P}{R}, \quad (2.20)$$

where P is the total difference in pressure from the center of the core to the outer surface before expansion occurs. Hence, from equations (2.19) and (2.20),

$$dF \approx \frac{P}{R} dV. \quad (2.21)$$

2.50 The time required for the core to expand from radius R to $R(1 + \delta)$, i.e., a distance of $R\delta$, is about 7 generations, as seen in § 2.38. However, as a rough approximation, this may be taken as $1/\alpha$, where α is the multiplication rate just prior to explosion time. The mean outward acceleration of the core material, and of the shell dV , may consequently be expressed as $R\delta\alpha^2$. The mass of the shell is ρdV , where ρ is the core density; hence, by Newton's second law of motion, i.e., force = mass \times acceleration, the force dF acting on the shell is given by

$$dF \approx \rho dV \times R\delta\alpha^2.$$

Upon comparing this result with equation (2.21), it is seen that

$$P \approx \rho R^2 \alpha^2 \delta. \quad (2.22)$$

2.51 As in the calculation of the explosion time, the total energy of the core, assuming there is negligible loss during the initial expansion, is expressed by equation (2.17), namely,

$$E = \frac{PV}{\gamma - 1}, \quad (2.23)$$

where γ is the ratio of the specific heats of the gas. Using equation (2.22) for P and writing M/ρ for the volume of the core, M being the mass, equation (2.23) becomes

$$E \approx \frac{MR^2 \alpha^2 \delta}{\gamma - 1}. \quad (2.24)$$

2.52 If ϵ is the energy released in the complete fission of unit mass of core material, then the total energy available in the core is $M\epsilon$, and the efficiency, according to equation (2.18), is $E/M\epsilon$, where E is given by equation (2.24); consequently,

$$\phi = \frac{E}{M\epsilon} \approx \frac{R^2 \alpha^2 \delta}{(\gamma - 1)\epsilon}. \quad (2.25)$$

It should be pointed out that in the foregoing derivation no allowance has been made for depletion of the core material as fission proceeds. For low efficiencies, to which most of the other approximations made are applicable, the depletion is not significant and can be neglected. Moreover, no allowance has been made for the inertial effect of the tamper on the efficiency. For the present purpose, which is to obtain a qualitative guide to some of the factors determining the efficiency, this can also be ignored. Hence, replacing the quantity $1/(\gamma - 1)\epsilon$ by a constant, K , equation (2.25) can be written as

$$\phi \approx KR^2 \alpha^2 \delta, \quad (2.26)$$

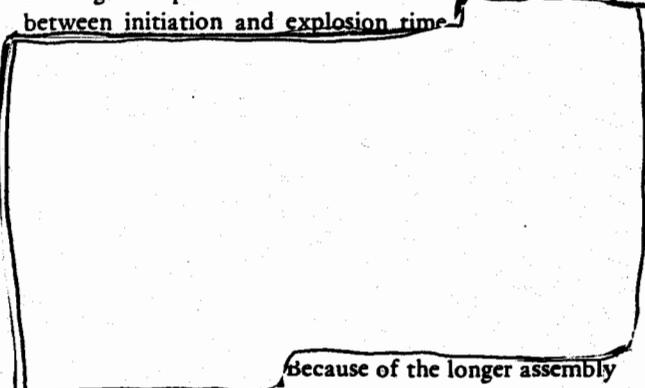
which is a version of the Bethe-Feynman formula that was developed for slightly supercritical systems. The efficiency of a fission weapon is seen to depend on the factors R , α , and δ .

2.53 Since the efficiency of a fission weapon may be expected to increase as R^2 (at constant density), 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.

2.54 In general, the most important factor in determining the efficiency of a fission weapon is α , and the latter increases in proportion to the compression (§ 2.19). The efficiency, according to equation (2.26), will thus be related, approximately at least, to η^2 (or to $\eta^{1.7}$ if the effect of tamper compression is included (§ 1.47)). In addition, although of lesser significance, the effect of compression on δ must be taken into account; the more highly compressed the core material

fission chain is initiated and energy is released. Between initiation time and explosion time the volume is more or less constant and so also is α (§ 2.40). Rapid expansion, however, results in loss of neutrons at an increasing rate and causes the core to become less and less supercritical; hence α decreases rapidly after explosion time. When second critical is reached, both the neutron population and the rate of fission have their maximum values. Beyond second critical a self-sustaining chain reaction is no longer possible; nevertheless, considerable amounts of energy are produced by convergent chains in the subcritical system.

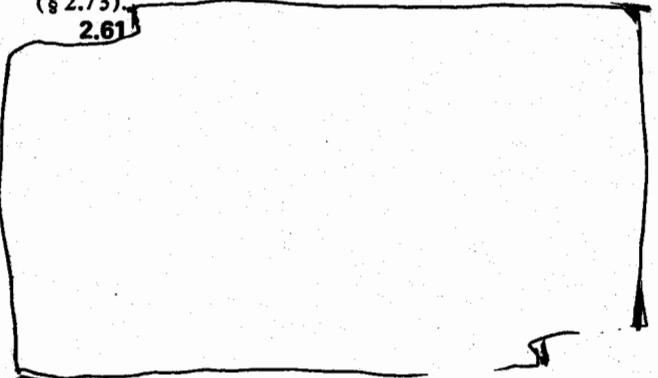
2.60 It is seen from Fig. 2.3 that for the particular type of simple fission weapon under consideration, the assembly time, i.e., between first critical and explosion, is long compared with the incubation time, i.e., between initiation and explosion time.



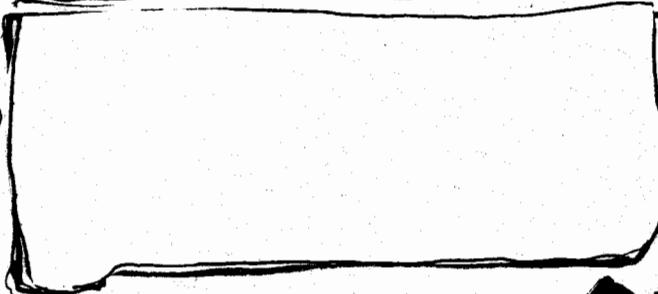
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Because of the longer assembly times, preinitiation is more probable in gun-type than in implosion systems. Some aspects of preinitiation in weapons of the former type are discussed later (§ 2.73).

2.61



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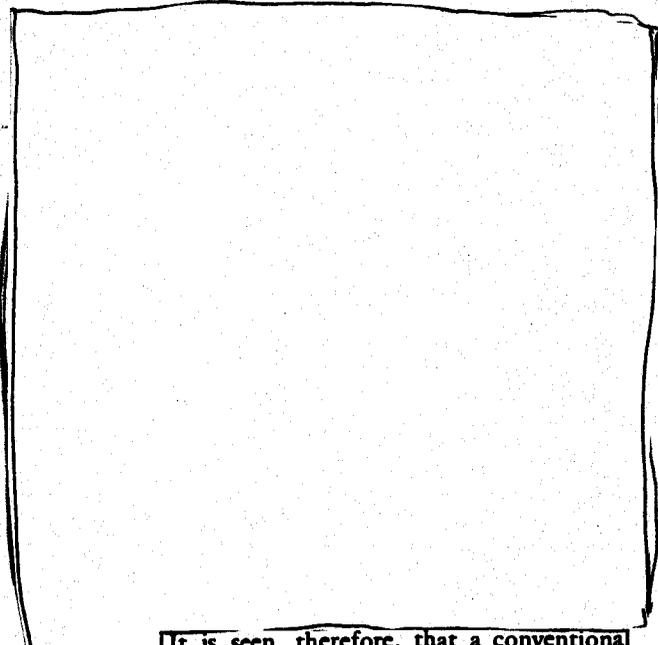
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reaction, or it may initiate a fission chain. Although the probabilities of these three processes are by no means equal, it is sufficient to postulate here that P_2 has a constant average value of 0.3 over the preinitiation period. Hence, for the purpose of making rough estimates, equation (2.27) may be written as

$$P \approx 0.3 P_1. \quad (2.28)$$

2.76 As a result of spontaneous fission, uranium-235 emits, on the average, about 0.70 neutron per kilogram per sec, whereas uranium-238 produces roughly 15 neutrons/kg-sec. Consequently, the neutron background in ordinary alloy (93.2 weight percent uranium-235) is approximately 1.6 neutrons/kg-sec.

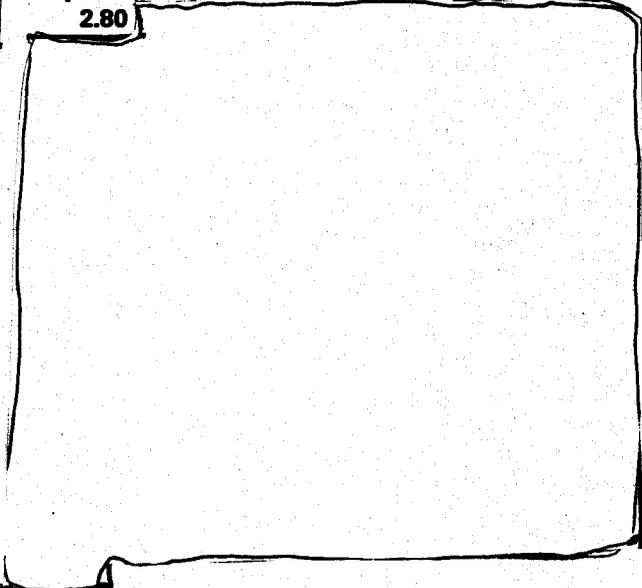


DOE
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It is seen, therefore, that a conventional gun-type weapon, based on plutonium with assembly brought about by a propellant explosive, is completely out of the question. It was the realization of this fact, when plutonium became available, that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

2.80

2.77 According to the numbers quoted above, more than half of the background neutrons in ordinary (93.2 percent) alloy arise from the uranium-238 present.



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2.78 Because of the high preinitiation probability, it is necessary to keep other background neutrons to a minimum in gun-assembly devices. It is for this reason

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APPENDIX

A2.01 The average pressure P in a spherical imploding core of radius R is defined by

$$\bar{P}V = \bar{P}(\frac{4}{3}\pi R^3) = \int_0^R P (4\pi r^2) dr, \quad (2.29)$$

where P is the pressure at the distance r from the center; hence,

$$\bar{P} = \frac{3}{R^3} \int_0^R P r^2 dr.$$

It follows, therefore, from equation (2.11), for a parabolic pressure distribution, that

$$\bar{P} = \frac{3P_0}{R^3} \int_0^R \left(1 - \frac{r^2}{R^2}\right) r^2 dr. \quad (2.30)$$

The integral in equation (2.30) may be evaluated as follows:

$$\begin{aligned} \int_0^R \left(1 - \frac{r^2}{R^2}\right) r^2 dr &= \int_0^R \left(r^2 - \frac{r^4}{R^2}\right) dr \\ &= \frac{R^3}{3} - \frac{R^5}{5R^2} = \frac{2}{15} R^3. \end{aligned}$$

If this result is inserted into equation (2.30), it is seen that

$$\bar{P} = \frac{2}{5} P_0. \quad (2.31)$$

A2.02 Because of the pressure gradient in the core, the material will be accelerated, and this acceleration, $a(r)$, at the radial distance r , is given by the expression

$$a(r) = -\frac{1}{\rho} \frac{dP}{dr},$$

where ρ is the density of the core material. If P is again expressed by equation (2.11), then

$$a(r) = -\frac{P_0}{\rho} \frac{d\left(1 - \frac{r^2}{R^2}\right)}{dr} = \frac{P_0}{\rho} \frac{2r}{R^2}.$$

Hence, the acceleration, a , at the surface of the core, where $r = R$, is

$$a = \frac{2P_0}{\rho R},$$

so that

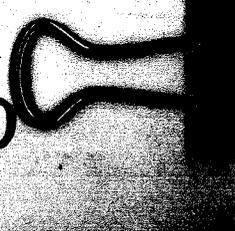
$$P_0 = \frac{\rho R a}{2}.$$

Upon inserting this expression into equation (2.31), it follows that

$$\bar{P} = \frac{1}{5} \rho R a,$$

which is equation (2.12).

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Chapters 3-9 and
the index withheld
in their entirety

