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GENERAL CONSIDERATIONS ON EXPLOSIONS AND EXPLOSIVES

A Report of the AAF Scientific Advisory Group

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by
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General *Considerations*

ON

EXPLOSIVES AND EXPLOSIONS

A REPORT PREPARED FOR THE AAF
SCIENTIFIC ADVISORY GROUP

By

G. GAMOW

The George Washington University, Department of Physics

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Dr. von Karman gathered about him a group of American scientists from every field of research having a bearing on air power. These men then analyzed important developments in the basic sciences, both here and abroad, and attempted to evaluate the effects of their application to air power.

This volume is one of a group of reports made to the Army Air Forces by the Scientific Advisory Group.

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TABLE OF CONTENTS

	<i>Page</i>
The Process of Explosions	3
Thermal Explosions	4
Chain Explosions	6
Molecular Explosives	8
Maximum Explosive Power	8
The Problem of Sensitivity	9
Focusing of the Explosive Power	11
Atomic Explosives	17
Nuclear Metastability and the Energy Liberation in Nuclear Reactions ..	18
Activation Energy of Nuclear Transformations	21
Thermonuclear Explosive	23
Nuclear Chain Explosions	29
"SBXA" Explosives	34
Summary and Conclusions	35
Recommendations for Future Work on High Explosives	37

**GENERAL CONSIDERATIONS ON EXPLOSIVES
AND EXPLOSIONS**

by

G. Gamow



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THE PROCESS OF EXPLOSION

An explosive can be defined in general terms as "a substance in the metastable state of internal equilibrium which, being subjected to a comparatively small external activation, turns instantaneously into a hot, dense gas producing a very high local pressure." The necessary condition for the effectiveness of explosion is that complete transformation of the entire charge takes place at constant volume, thus securing the maximum possible increase of local pressure and originating a powerful shock wave in the surrounding medium. If the material is permitted to expand while the transformation is still in progress, the pressure will never reach its maximum possible value and the damage produced will be considerably lessened; besides, such a premature expansion can easily extinguish the transformation process itself, thus leading to only a partial explosion. Since the maximum pressure developed by the explosive materials is much higher than the tensile strength of any possible confinement, the premature expansion can be prevented only by the inertial resistance of the explosive material itself, or that of the surrounding walls or medium. In other words, the transformation of the original material into the hot gas must be completed before any appreciable acceleration is communicated to any part of the charge under the action of pressure rising to its maximum value. This condition puts definite lower limits on the velocity with which the activation process propagates from the point at which the explosion was first initiated, as well as on the reaction rate which determines the time period between the moment when the material is activated and the moment when its transformation is completed. In respect to the propagation-velocity of activation process it is evidently necessary that it will be not smaller than the propagation-velocity of mechanical action, or in other words the velocity of the shock wave corresponding to the maximum pressure developed in the reaction. This condition will be evidently satisfied if the shock wave itself represents the activating agent as in the case in ordinary detonation wave where the reaction is started by the sudden rise of temperature resulting from the adiabatic compression of the material in the shock front.

The second condition requires that the reaction started by the temperature increase in the shock front be completed within the time period τ which is shorter than the time

t necessary for the shock wave to cross the average diameter of the charge. Since the shock-wave velocity corresponding to the maximum pressure P_m is known to be of the order of magnitude $\sqrt{\frac{P_m}{\rho}}$, where ρ is the density of the material, the condition for the propagation of the explosion in the charge of the geometrical dimensions can be written in the form:

$$t = \delta \sqrt{\frac{\rho}{P_m}} > \tau (T_m) \quad (1)$$

where the temperature T_m in the shock front is in its turn a function of P_m . The dependence of T_m on P_m can be calculated from the known equation of state of the material. Since the practicable sizes of the explosive charges vary from few centimeters to few meters, the condition (1) puts definite requirement on the reaction state of metastable substances which can be considered as practicable explosive. Indeed we would not be interested in explosives which would detonate only in charges of several miles in cross section. It must also be noticed that condition (1) give actually the relation between the necessary reaction rate and the explosive power as characterized by maximum pressure P_m . Thus, for example, in ordinary chemical explosives, where P_m is of the order of magnitude of $10^5 \text{ atm} = 10^{11} \frac{\text{dynes}}{\text{cm}^2}$, the detonation will propagate if τ amounts to several microsec. On the other hand, in atomic explosives where the pressures developed are several million times higher, the reaction times necessary to secure the propagation must be measured in millimicrosec.

Turning to the transformation process itself, it must be remembered that a metastable substance must be considered as an aggregate of particles in which every single particle (in straight explosives) or a combination of two or more particles at the moment of mutual collision (in explosive mixtures), being communicated a certain energy, excess E (activation energy), can break up into several parts, which we will call "transformation fragments," with the liberation of additional large amounts of energy Q (reaction energy).

The reaction energy liberated in each individual transformation of metastable particles will be communicated through the processes of mutual collisions to other as yet untransformed particles, thus causing a self-accelerated transformation process which we will call "the growth of explosion."

THERMAL EXPLOSIONS

The simplest assumption which can be made in the theory of self-accelerated transformation consists in considering the process as running through a sequence of instantaneous equilibrium states, the energy liberated in each individual transformation being immediately distributed uniformly between the other particles. With such an assumption, one is justified in speaking about a definite temperature of the reacting substance at any given moment, and to write the relation between the reaction rate at a given moment and the corresponding value of the temperature. Due to the fluctuations of energy in an ordinary thermal equilibrium there is always, for any value of temperature, a certain percentage of particles with the energy in excess of the critical activation value E . In case of a single metastable particle this activation energy is concentrated in the vibrational degrees of freedom of individual particles, whereas, in mixtures it can be divided between the translational and vibrational degrees of

freedom of the particles participating in collision. According to the Boltzmann's principle the relative number of single particles, or pair particles, with the total energy excess E , is given by the factor $\exp\left(-\frac{E}{kT}\right)$ where T is the absolute temperature and k -Boltzmann's constant.

For the rate of the reaction one obtains the classical Arrhenius formula:

$$W = Z \cdot e^{-\frac{E}{kT}} \quad (2)$$

where the coefficient Z corresponds to the individual vibrational frequency of single metastable particles in straight explosives, or to the collision frequency between the particles forming an explosive mixture.

The rate of temperature increase due to the energy liberated in the reaction is subject to the equation:

$$C \frac{dT}{dt} = QZ \cdot e^{-\frac{E}{kT}} \quad (3)$$

where C is the heat capacity.

This equation can be approximately integrated in the form:

$$t - t_0 = \frac{Ck}{ZQE} \left(T_0^2 e^{\frac{E}{kT_0}} - T^2 e^{\frac{E}{kT}} \right) \quad (4)$$

which indicates that the temperature increases first slowly and then rises suddenly to the maximum value corresponding to completed reaction. Defining the explosion period τ as the time interval between the moment when the material was first subjected to the temperature T_0 and the moment of the sudden temperature increase corresponding to the completed reaction, we have:

$$\tau = \frac{CkT_0^2}{ZQE} \cdot e^{\frac{E}{kT}} \quad (5)$$

In order that a metastable substance with the reaction energy Q and the reaction constants E and Z can be considered as practicable explosives, it is necessary that the reaction rate calculated from this formula for the shock-front temperature, as determined by Q and the equation of state, should satisfy the relation (1).

In considering the process of thermal explosion we have assumed that all the heat developed by the reaction remains within the material and serves to accelerate the process of further transformations. It must be remembered, however, that in case of comparatively small samples of explosive substance, part of the developed heat will escape through the surface of the charge into the surrounding medium. If the heat losses resulting from this effect exceed the heat production by the reaction, no explosion will take place and the transformation process will continue at a slow rate until the original substance is finally transformed. Since the heat losses into the surrounding medium increase in direct proportion to the temperature of the charge, whereas, the heat-production changes exponentially with that temperature, it follows that for any size of the charge there exists a certain critical temperature above which the explosion is possible. The value of this critical explosive temperature decreases with the increasing size of the charge, and theoretically speaking, a sufficiently large charge of ordinary explosives will explode through self-heating even at the room temperature. The notion of critical explosive temperature is of particular importance for atomic explosives in which, due to the very high temperatures involved, the heat losses into the surrounding medium are especially large.

CHAIN EXPLOSIONS

The above simple picture of purely thermal explosion can be, however, considerably modified if the fragments formed in each elementary transformation do not represent the final stable products of the complete reaction. In fact, due to the violence of the breaking up process, the constituent elements of the original metastable particles may not have time to rearrange themselves into the most stable combinations, so that the break up results in the formation of certain intermediary products which are able to enter into the subsequent reactions between themselves or with the original metastable particles. Thus, for example, in the case of metastable molecules, as TNT, instead of getting the final stable products CO_2 , CO , H_2O and N_2 , we may get the intermediary particles of NO_2 which oxidize and cause the further break up of new TNT molecules with which they collide. As we shall see later a similar occurrence takes place in some atomic reactions as, for example, that of the uranium fission, where the free neutrons produced in the break up of uranium nucleus activate and break up other uranium nuclei with which they collide.

If each elementary transformation gives rise to only one active fragment we have the so-called simple chain (Fig. 1) which will continue until one of the active fragments

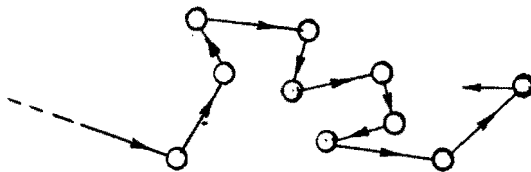


Figure 1

fails to produce the next transformation, either due to its escape through the surface of the charge or due to its collision with some foreign particles (impurity) which may be present within the original metastable substance. In ordinary chemical reactions, cases are known where simple chains have as much as several million links (for example in the chain $\text{H Cl}_2, \text{HCl Cl}; \text{Cl H}_2, \text{HCl H}$ etc.).

If more than one active fragment is produced in each elementary transformation we have the case of a branching chain (Fig. 2) which can very rapidly consume the entire material. In fact, if the breaking up of each particle induces the same process in two other particles (as assumed in Fig. 2) the number of particles involved after the chain had n branchings will be 2^n . Since there are about 10^{24} particles per gram-particle (i.e., grammolecule or gramatom) the entire substance will be transformed after only $\frac{24}{\lg 2} = 30$ branchings.

In the theory of branching chains, one must also take into account that some of the fragments forming the chain may fail to produce the reaction due either to their collision with some inactive foreign particles, or to their escape through the surface of the charge. The condition for the continuation of a branching-chain reaction is evidently that the active fragments produced in an elementary transformation process would

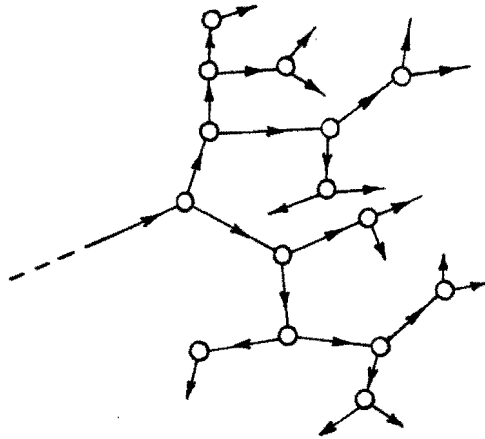


Figure 2

induce on the average more than one subsequent transformation among the surrounding particles.

It may be added in conclusion that we may very often have mixed cases where the transformation which started as an ordinary thermal explosion goes over into a chain process when the temperature of the reacting material rises above a certain limit.

MOLECULAR EXPLOSIVES

All explosives, as well as all fuels, used at the present stage of human civilization, are based on chemical transformations of matter, i.e., on the rearrangement process of loosely bound atoms forming various metastable molecules into more stable configurations corresponding to the molecules of the reaction products.

In choosing among the large variety of all possible chemically metastable (pure compound or mixtures) those which can be used as practicable explosives, we must satisfy the conditions of maximum power and optimum sensitivity.

MAXIMUM EXPLOSIVE POWER

The power of an explosive is essentially determined by the maximum pressure developed in its isochoric transformation, which in its turn is given by the energy liberated per unit volume.* Thus in choosing powerful explosives we must pay attention not to the energy liberation per gram, as is often done, but to the energy liberation per unit volume i.e., to the product ρQ . As an example one can mention that a mixture of liquid oxygen and solid hydrogen which is known to give the energy liberation of $3200 \frac{\text{cal}}{\text{gm}}$ (as compared with only $1000 \frac{\text{cal}}{\text{gm}}$ for TNT) is not at all more powerful than TNT since its density is only 0.45 as compared with 1.5 for TNT. Thus a missile of a given size filled with liquid H₂-O₂ mixture will have only an effectiveness of $3200 \times .45 = 1450$ as compared with $1000 \times 1.5 = 1500$ for TNT.

Since the energy liberation in a molecular transformation can be expressed as the difference between the binding energy of the original metastable molecules, and the binding energy of the reaction products, the way of getting most powerful explosives is to select the atoms which form the most stable simple molecules and to bind them together "in a most unnatural way" into complex metastable molecules with the minimum binding energy. Due to the complexity of atomic and molecular structure it is, of course, impossible to predict theoretically in which particular combination of all known chemical elements the maximum energy liberation will be obtained. One can, however, make two statements which must be true in the way of approximation; first, the binding energy per atom remains of the same order of magnitude throughout the periodic system of elements in as far as it is determined by the motion of external valence electrons which move in all cases in about the same central field produced by the screening of nucleus charge by other internal electrons; and secondly, atomic volumes of different elements are also of the same order of magnitude through the entire periodic system of elements.

Since the atoms are closely packed together in various molecules, and since the molecules are also packed together in the solid and liquid state of matter, it follows

* The relation: pressure = $\frac{2}{3}$ (energy density), which is strictly true for ideal gases, holds also approximately for highly compressed gases formed in the explosion of solid or liquid substances.

that the maximum energy liberation per unit volume of various chemical explosives must be approximately the same to within a factor of two, say, independent of their constitution.

This conclusion is illustrated by the following table:

	ρ	Q	ρQ
Lead Azide.....	4.5	365 cal/gm	1650 cal/cc
TNT.....	1.57	1080	1700
Mixture of liquid hydrogen and oxygen.	.45	3200	1440
Torpex.....	1.72	1820	3130

The above considerations lead us to the tentative conclusion that one can hardly hope to develop chemical explosives which would have considerably higher power by order of magnitude than the explosives now in use. On the other hand it is, of course, possible that by choosing particularly effective atomic bindings (such as Al + O atoms) in final products, and building metastable molecules in still more unstable ways (RDX being at present the most unstable known molecule), one will be able to achieve an increase of explosive power which will be of importance in military practice.

THE PROBLEM OF SENSITIVITY

Another important condition which each practicable explosive must satisfy is the condition of optimum thermal sensitivity, i.e., the relation between the reaction rate and the temperature.

The reaction rate, which is in principle always different from zero, must be, however, so low at normal temperatures (say below 50°C or 320°K) that no appreciable transformation would take place at this temperature during a period of many years.

On the other hand, the explosive must be able to propagate detonation in charges of normal size, which means that the temperature of the shock wave corresponding to the pressure developed in the completed reaction must result in a reaction time of only a few microsec.

The temperature in the shock wave propagating through a solid or liquid material under the pressure of chemical explosion (ca 100,000 atm) is estimated to be of the order of magnitude of 1000°K, so that the above two conditions could be written in the form:

$$\omega_T \cong 300 < 10^{-10} \text{ years}^{-1} = 10^{-8} \text{ sec}^{-1} \quad (6)$$

$$\omega_T \cong 1000 > 10^5 \text{ sec}^{-1} = 10^5 \text{ sec}^{-1} \quad (7)$$

These two conditions put rather narrow limits on the values of activation energies E and frequency factors Z for practicable chemical explosives.

Indeed, a metastable chemical compound with the activation energy, say twice as small as that of TNT, and the same value of Z would be stable only at the temperatures below 180°K (-113°C) and would be of no use under the conditions existing on our globe. On the other hand, material with activation energy twice that of TNT, though being a potential explosive, would not be able to carry the detonation in charges of a reasonable size, since its reaction time corresponding to the temperature of the shock wave would be measured in days or years.

Looking through the tables of activation energies and frequency factors for various chemical explosives now in use, we find, as must be expected, that they all satisfy the conditions for stability and detonation as given by the formulas (6) and (7).

A considerable complication in the problem of ordinary explosives now in use is brought in by the fact that instead of being continuous as contemplated in the ordinary theory of the detonation process, they represent, on the contrary, a noticeably heterogeneous material. This is true in the case of pressed granular explosives as well as in the case of cast explosives where heterogeneity is due to irregular microcrystalline structure and the pockets of air liberated from the melted material in the process of solidification. To sustain this statement it is enough to glance at the visibly porous material representing a piece of cast torpex charge from an opened depth bomb.

It is obvious that the absence of homogeneity changes in a radical way the entire picture of heat liberation in the explosive material subjected to a rapid compression. Instead of being uniformly distributed through the entire substance, the heat will now be liberated in individual friction points between separate particles of the compressed granular material or between separate fragments produced in the heterogeneous cast material by a sudden compression.

The temperature of these so-called "hot spots" will be in general much higher than would correspond to a uniform heat distribution, and they will serve as the ignition centers from which the reaction will spread out engulfing rapidly the entire substance. The theory of hot-spot initiation presents immense mathematical difficulties due to the irregularity of the process and its dependence on size, shape, and accidental distribution of grain of the crushed fragments of the material, but it is clear without any calculations that the presence of heterogeneity in the explosive substance will considerably increase its sensitivity to mechanical action of any kind.

Since, as we have seen above, the uniform adiabatic temperature increase in the shock front of a detonation wave in an ordinary explosive is already enough to secure a sufficiently high reaction rate, the presence of hot spots does not represent a necessary condition for the propagation of the detonation process. They will only modify the activation process and influence the length of the reaction zone; in fact, we have abundant evidence concerning the effect of granulation of the explosive material on the detonation process. On the other hand, there is little doubt that the detonation will also propagate through completely homogeneous explosives where the activation is entirely due to uniform adiabatic heating.

Quite different is the situation in the case of minor impacts where the average energy liberation is considerably smaller than in the shock front of a detonation wave. On the continuous theory of initiation, the temperature increase due to weak shock waves, such as can be produced, for example, by an impact of a heavy hammer, would be by a large margin not enough to cause any appreciable increase of the reaction rate. On the other hand, in the case of heterogeneous material, even a small impact can cause an explosion if the energy of impact is accumulated in comparatively few hot spots causing local but high temperature increases. This is apparently what takes place in all ordinary explosive materials under the conditions of a standard impact test, or in unlucky cases of rough handling of ammunition.

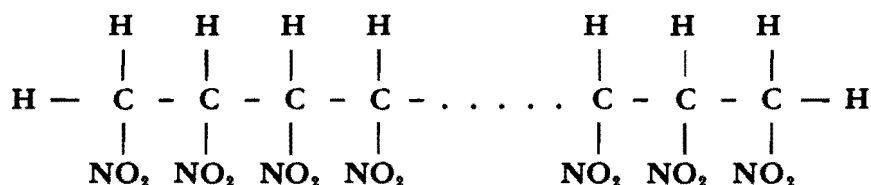
In fact, all the existing empirical material pertaining to the impact sensitivity of explosive samples of various size (from 10^{-2} gm to 10^2 gm) indicates that explosions

take place 50 times out of 100 when the energy delivered by the impact amounts to about $5 \cdot 10^8$ erg or 10 cal/gm of the material.

This energy being distributed uniformly would raise the temperature of the explosive sample by some 50°C which is, of course, quite insufficient to cause an explosion (even at temperatures of about 100°C the reaction time is measured in days).

On the other hand, the above value closely corresponds to the total mechanical work which is necessary for the static compression of granular explosive material, and is undoubtedly liberated in the form of heat along the friction surfaces between the grains.

Thus we come to the conclusion that the granular nature of ordinary explosive now in use makes them unduly sensitive to small impacts, without contributing anything to the ease of the detonation process. Considerable progress has been made at present in reducing the sensitivity of heterogeneous explosive materials by coating the surfaces of separate grains with a thin layer of wax, which reduces the possibility of local ignition. It seems, however, that the complete solution of the problem of sensitivity will lie in the development of explosives which will be quite homogeneous and not brittle, being similar to the so-called "plastics" which are now widely used in various branches of industry. In fact, it does not seem impossible in principle to nitrate long aliphatic molecular chains, forming various plastics which are so popular today, in order to get the explosive molecules of the type:



If such "explosive plastics"* can be successfully developed, they will represent absolutely uniform transparent substance of very high strength and small brittleness. The complete absence of heterogeneity and the low brittleness would make such materials extremely insensitive in respect to any accidental shocks of minor nature. On the other hand, they will be able to propagate the detonation process, and will be set off by a fuse or a booster just as easily as the explosive materials now in use. In this case it will probably be possible to make shells, bombs, or torpedo warheads entirely from explosive plastics without any metallic cover at all, unless one needs the metal cover for the purpose of fragmentation. A 1000-lb bomb of explosive plastic will really contain 1000 lb of explosive, instead of only half that amount in the bombs of today.

FOCUSING OF THE EXPLOSIVE POWER

In many practical cases, in particular for the purpose of penetrating heavy armor plates, it is desirable to concentrate most of the explosive power in a certain direction.

At the present time one widely uses for that purpose the so-called Munroe or shape-charge-effect which is essentially based on the fact that during the very first

* These "explosive plastics" should not be confused with what is known at present as "plastic explosives." The latter should be rather called "putty explosives" being formed by the oily mixture of explosive granular material, and having about the same impact sensitivity as ordinary granular explosives.

stages of expansion following the explosion of the charge, the high-pressure explosion gases move in the direction perpendicular to the surface of the charge. If the charge is originally of a convex shape, its expansion will lead to a rapid decrease of original pressure as the gases begin to expand. If, however, some part of the surface of the charge is concave, the gas streams, starting from the walls of the cavity, will run into one another merging into a thin jet with much higher local pressure. A schematic presentation of a typical shape-charge-action is shown in Fig. 3.

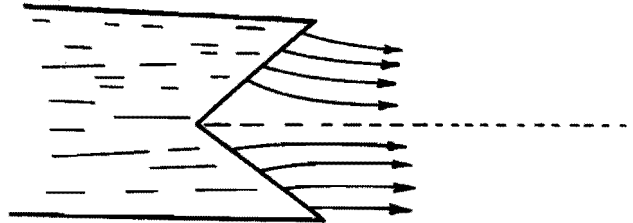


Figure 3

If the cavity of the shaped charge is lined with a metallic layer, the expansion of gases will squeeze the metal into a jet and a heavy slug moving with a high velocity along the axis of symmetry. These fast moving jets and slugs are known to be very effective in the penetration through the thick armor plates.

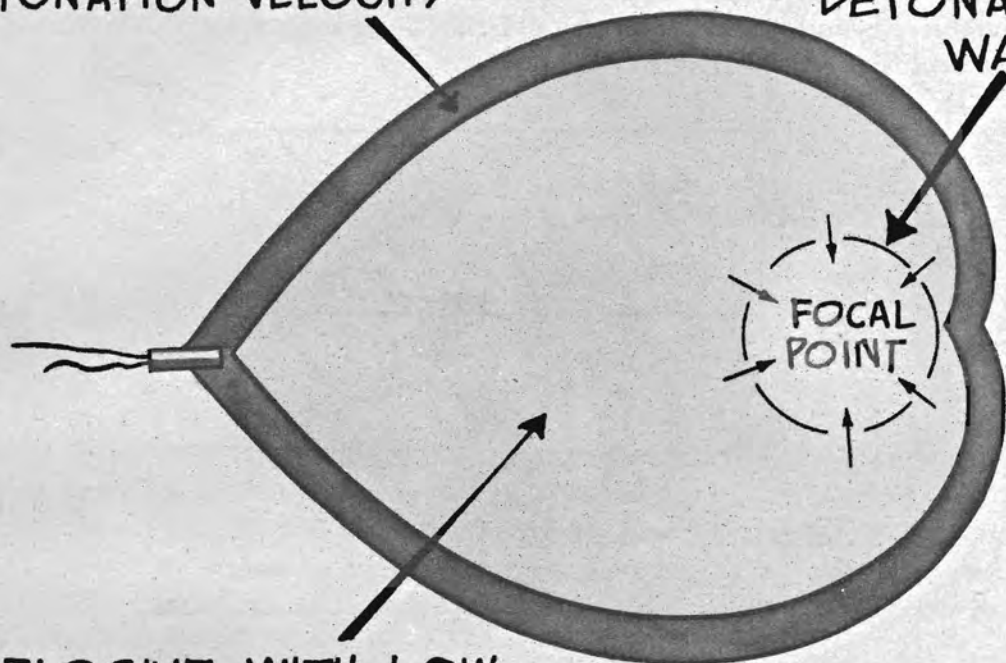
As can be seen from the above description, the effect of the shape-charge is based mainly, if not entirely, on the pressure of the gases produced in the detonations, and the directional effect arises essentially from the subsequent expansion of the explosion gases.

In other words, the processes connected with the propagation of the detonation through the charge do not contribute to the effect, and a shape-charge would have worked as well if it were possible to explode every part of the charge exactly at the same moment.

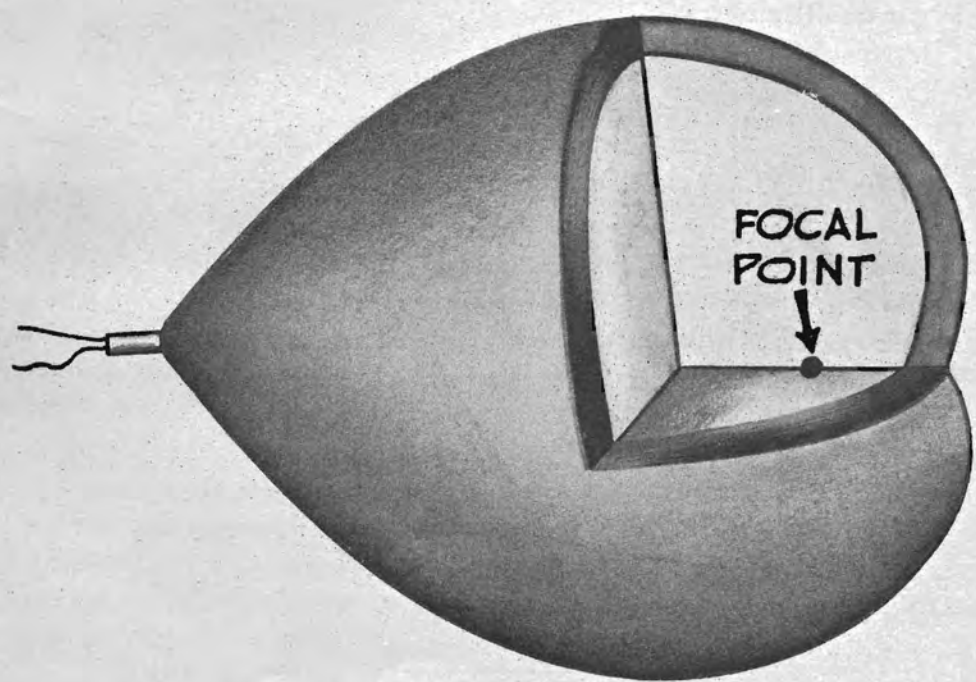
It must be remembered, however, that the detonation wave itself possesses certain directional features, since, as it is well known, the material behind the detonation front moves forward with a velocity (mass velocity) which is only two or three times lower than the propagation velocity of the wave. The kinetic energy of this motion is about one-half of the total energy liberated in the explosion, and one can expect a very large concentration of power in a certain direction or at a certain point near the surface of the exploding charge if one can produce a detonation wave converging towards this particular point. The propagation process of a detonation front is in many ways similar to the propagation of light-wave front as governed by the Huygens principle, and one can develop a "geometrical optics of detonation" along the lines of ordinary geometrical optics by using detonation refractive indices (i.e., the ratio of detonation velocities in two substances) in the same way as we use refractive indices in optics. We can speak indeed about "detonation lenses" and even about "detonation lens systems." To illustrate this point we will discuss the arrangements for the production of a plane and of a convergent detonation wave.

EXPLOSIVE WITH HIGH
DETONATION VELOCITY

CONVERGENT
DETONATOR
WAVE



EXPLOSIVE WITH LOW
DETONATION VELOCITY



1. In order to form a plane wave propagating along the axis of an explosive cylinder, which is important in some experiments, one can use a "detonation collimator" shown schematically in Fig. 4 in which one places between the fuse and the main explosive cylinder a material with different detonation velocity which contacts the main explosive along a spherical surface.

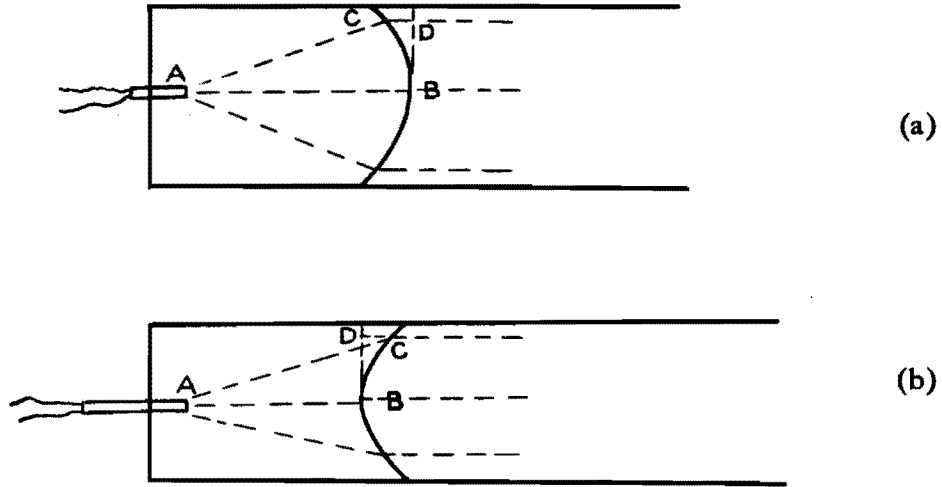


Figure 4

The condition for obtaining a plane wave in the main cylinder is apparently that the propagation time along the line AB is the same as along the line ACD. Using the familiar consideration of geometrical optics we find that the surface must be convex or concave towards the fuse depending on whether D_1 is larger or smaller than D_0 , and that the radius of curvature R of that surface is connected with the distance F from the fuse by the familiar relation:

$$\frac{1}{F} = \frac{N-1}{R} \quad (8)$$

where

$$N = \frac{D_0}{D_1} \quad (9)$$

2. A much more interesting arrangement of detonation optics is shown in Fig. 5 and is serving to produce a converging detonation wave. It consists of a heart-shaped mass of an explosive with the detonation velocity D_0 , coated thin layer of another explosive with the higher detonation velocity D_1 . If the shape of the charge is such that the optical length ABO is the same as optical length ACO, etc., the wave started by the fuse at A will cause a convergent spherical wave with O as the focus.

Introducing polar coordinates at O we can write the above condition in the form:

$$\frac{dr}{D_0} = \frac{1}{D_1} \sqrt{dr^2 + r^2 d\phi^2} \quad (10)$$

which gives after integration:

$$r = r_0 e^{\pm \frac{\phi}{\sqrt{\left(\frac{D_1}{D_0}\right)^2 - 1}}} \quad 0 \leq \phi \leq \pi \quad (11)$$

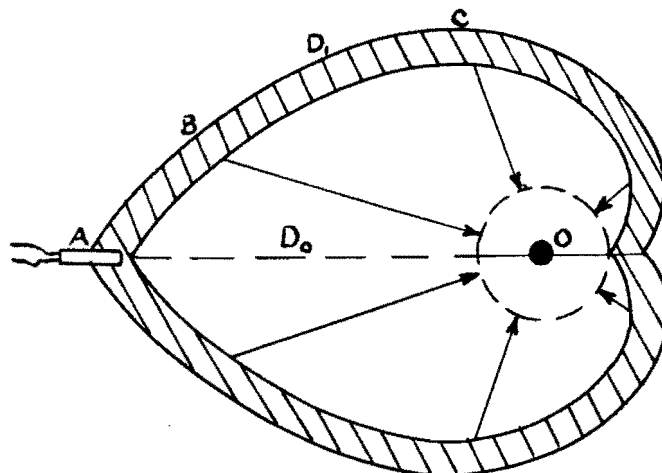


Figure 5

Thus the surface of the charge must be limited by the arcs of a logarithmic spiral. The convergent spherical detonation wave which can be obtained by means of such an arrangement can be expected to lead to extremely high pressure in its focus, which can be used in the attempts to start a thermonuclear reaction in a substance placed in that focus. We will discuss this possibility in some more detail in the following section.

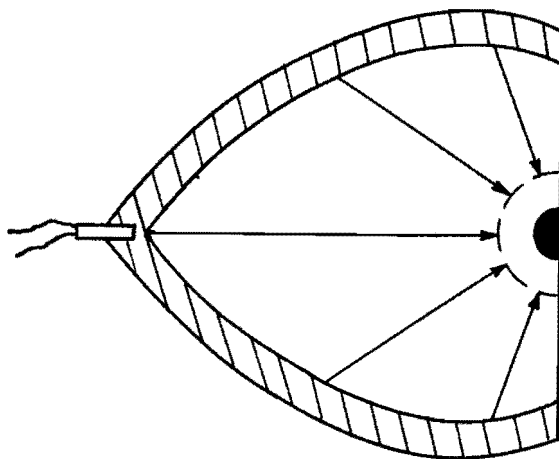
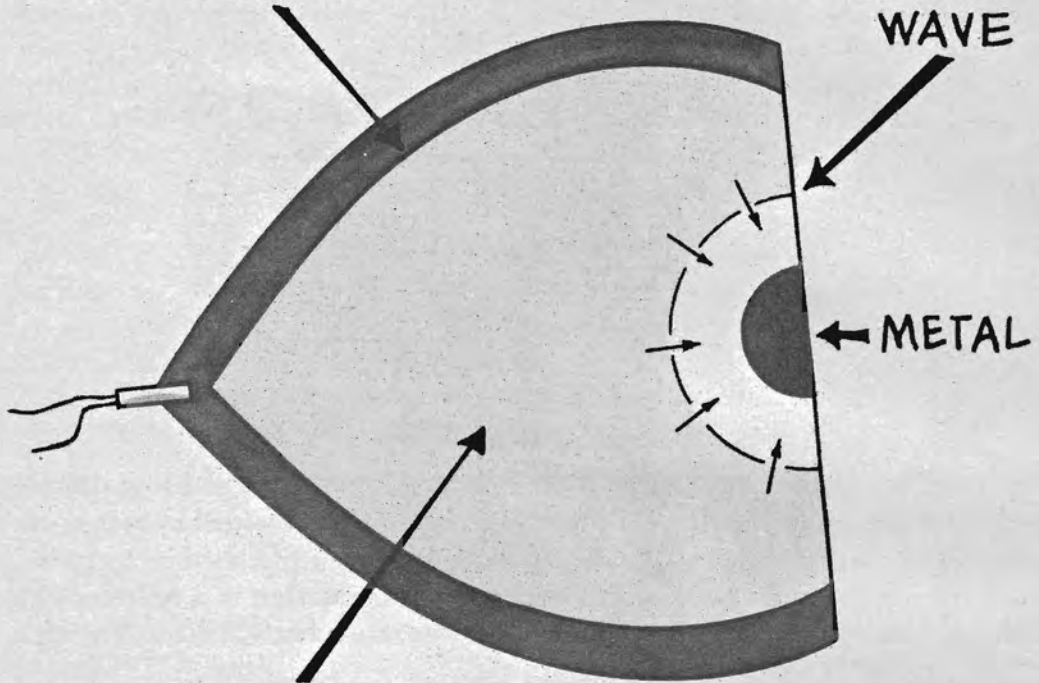


Figure 6

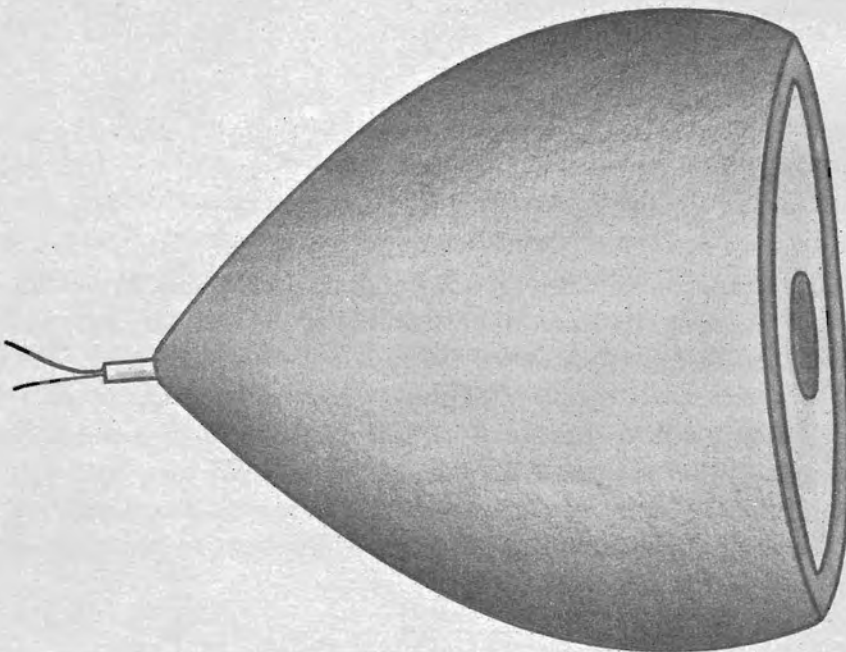
By cutting the charge represented in Fig. 5 through its focal point, and using only its fuse part, one obtains an arrangement which is similar to the ordinary shape charge (Fig. 4) as it is used today. The metal lining of the ordinary conical shape charge must be substituted here by a semispherical piece of metal placed at the focal point. It may be expected that the focusing arrangement shown in Fig. 6 will have a number of advantages over the conventional conical shaped charge, in particular due to the absence of the stand-off. It must also be noticed that the above focusing arrangement will be less affected by the rapid rotation around the axis of the missile, and thus can be used successfully in fast rotating shells.

EXPLOSIVE WITH HIGH
DETONATION VELOCITY

CONVERGENT
DETONATION
WAVE



EXPLOSIVE WITH LOW
DETONATION VELOCITY



ATOMIC EXPLOSIVES

The discovery of radioactivity by H. Becquerel and the subsequent brilliant experiments of Lord Rutherford and his school opened a new epoch in our knowledge of internal structure and transformations of matter. It was indeed shown that atomic nuclei, that is the heavy positively charged cores of atoms, possess a rather complex internal structure and, under certain circumstances, can be transformed into one another with the liberation of enormous amounts of latent energy. The energy liberated in such atomic or, as they can be justly called, alchemic transformations exceeds by a factor of many millions the energy liberation in ordinary chemical transformations, which opens new wide perspectives of new fuels with unbelievably high heat liberation and new explosives with fabulous destructive power. As an example it can be stated that nuclear transformation of uranium known as "fission" liberates 2.10^{10} cal/gm as compared with only 1000 cal/gm for TNT. Remembering that the demolition area is approximately proportional to the total energy liberated in the explosion, we conclude that a uranium-fission bomb will damage an area some twenty million times larger than a TNT bomb of the same weight. Since the demolition area for 100 lb TNT is about 1000 sq ft, a 100-lb uranium bomb can be expected to destroy everything within 2.10^{10} sq ft or 1000 square miles.

Speaking about atomic explosives it must be stated first of all that the mixture of chemical elements forming our globe (or for that matter the rest of the universe) is very far from being in the state of lowest energy corresponding to the stable alchemic equilibrium, as it is for example in case of ordinary chemical compounds. This absence of equilibrium between elements is interpreted as the result of their formation at the very early stage of the evolution of our universe when the general conditions were entirely different from what they are now.

Indeed the exact calculations show that the present relative abundances of various chemical elements correspond actually to an equilibrium at the temperature of about eight billion degrees and densities of about a million water densities, which, according to the data of modern astronomy, were prevailing throughout the space some three or four billion years ago. The subsequent expansion and progressive cooling of the universe, observed at present in the rapid recession of distant stellar groups, caused this distribution to "freeze" at the point at which it was in a distant past, since as the result of the rapid decrease of temperature the rate of nuclear transformations had dropped almost to zero.

Whereas, the problems of expanding universe and the origin of chemical elements are of no immediate concern to military practice, the fact remains that due to the lack of alchemic equilibrium at the present evolutionary stage of the universe, we are literally living within an alchemic powder box being surrounded from all sides by alchemically metastable substances representing potential fuels and explosive materials. The fact that all the universe does not "go up in smoke" is due to the extremely high ignition point and extremely low mechanical sensitivity of atomic transformations.

Thus the problem of developing atomic explosives lies not so much in preparation of some special substance ordinarily nonexistent in nature (as one does in preparing TNT or RDX) but rather in selecting among the great variety of all known chemically metastable substances those which possess the highest sensitivity, and in inventing a special fuse or booster which is powerful enough to set them off.

We are here mainly handicapped by a large gap between the minimum activation energy necessary to set off an atomic explosive and the maximum energy, liberation by ordinary chemical explosives which could be used for boosting purpose.

NUCLEAR METASTABILITY AND THE ENERGY LIBERATION IN NUCLEAR REACTIONS

The first question to be answered in the study of atomic explosive pertains to the conditions of nuclear metastability and the amount of energy which can be liberated in various nuclear transformations. From a purely theoretical point of view, the problem of atomic explosives is much simpler than the corresponding problem in the field of ordinary chemical transformations, since the structure of atomic nuclei is in many respects much simpler than the structure of molecules. This accounts for the fact that it is possible to predict in some details many properties of atomic explosives, although to the knowledge of the present author, no such explosives have been as yet actually produced in practice. It goes without saying that the clear theoretical picture of various possibilities involved in the atomic-explosion process must be very helpful for the future experimental research work in this field.

According to the present views, atomic nuclei represent an aggregate of two types of elementary particles: positively charged protons, and electrically neutral neutrons, held together by strong cohesive forces very similar in their nature to the van der Waals forces holding together the molecules in an ordinary liquid. In fact, apart from the scale, atomic nuclei are very similar to little droplets of liquid and one can also speak in this case about the nuclear surface tension forces which are responsible for their spherical shape. In drawing such a close analogy between an atomic nucleus and a small water droplet one must remember, however, that the scales in the two cases are widely different. Thus the radius of an average atomic nucleus is only about 10^{-12} cm, its density equals $1.5 \cdot 10^{14}$ water densities, and the surface energy is measured to be $9.3 \cdot 10^{19} \frac{\text{erg}}{\text{cm}^2}$ instead of $75 \frac{\text{erg}}{\text{cm}^2}$ for water; besides, the largest atomic nucleus, that of uranium, contains only 238 constituent particles (protons and neutrons). Another important difference between atomic nucleus and an ordinary water droplet is that the former is always carrying a larger electric charge due to the fact that about half of its constituent particles are protons.

From the point of view of the above described nuclear-droplet model, the process of nuclear transformations should be considered either as a fusion in which two smaller nuclei unite into a single big one, or a fission in which a large nucleus breaks up into two or more smaller ones. If the cohesive forces between protons and neutrons were the only forces acting within the nucleus, the fusion which leads to the decrease of the total free surface would always be an exothermic process, whereas the fission which increases free surface would always be an endothermic one. However, the presence of coulomb repulsive forces between proton charges turns the table in favor of

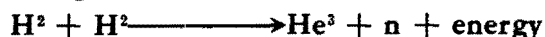
fission for heavily charged nuclei, and makes the nuclei of large atomic number unstable in respect to fission. By combining theoretical considerations with the vast empirical material concerning nuclear binding forces, Bohr and Wheeler were able to calculate the energy changes resulting from breaking up (fission) of atomic nucleus into two halves. Their results are represented graphically in Fig. 7 from which we see that the energy balance is positive for all elements with the atomic number above 45. This means that all chemical elements located beyond (approximately) silver in the periodic system can be considered as potential straight atomic explosives.

On the other hand, since it is the process of fusion which is exothermic for lighter nuclei, any mixture of two light elements with the combined atomic number less than that of silver is an explosive mixture.

It must be indicated here that in the case of a metastable nuclear mixture the union of two light nuclei does not usually lead to the formation of a single heavy nucleus, since in such a case the energy would have to be liberated through a comparatively improbable process of gamma radiation. Much more probable in this case is the process of rearrangement of constituent particles of two reacting nuclei, leading to the formation of two new nuclei with stronger total binding. Thus, for example, in the case of collision between two deuterons the reaction does not go according to the equation:



but rather according to the equation:



One can say in general that in case of metastable nuclear mixtures we must expect a binuclear reaction which corresponds to the lowest possible binding energy of the reacting products.

In Table I, we give the reaction energies (as well as the activation energies to be discussed later) of some typical nuclear reactions.

Table I
Reaction and Activation Energies of Nuclear Reactions

<i>Reaction</i>	<i>Reaction energy</i>		<i>Activation energy</i>	
	<i>MeV per process</i>	<i>cal/gm</i>	<i>MeV per process</i>	<i>cal/gm</i>
<i>Binuclear reactions</i>				
$H^2 + H^2 \longrightarrow He^3 + n$	3.2	$1.8 \cdot 10^{10}$	0.6	$0.34 \cdot 10^{10}$
$Li^7 + H^1 \longrightarrow 2He^4$	17.0	$4.8 \cdot 10^{10}$	3.5	$1.0 \cdot 10^{10}$
$B^{11} + H^1 \longrightarrow 3He^4$	8.7	$1.6 \cdot 10^{10}$	5.5	$1.1 \cdot 10^{10}$
<i>Mononuclear reactions</i>				
$Sn^{118} \longrightarrow 2Mn^{59}$	10	$0.22 \cdot 10^{10}$	50	$1.4 \cdot 10^{10}$
$Hg^{200} \longrightarrow 2Zr^{100}$	110	$1.2 \cdot 10^{10}$	9	$0.1 \cdot 10^{10}$
$U^{235} \longrightarrow 2Pd^{118}$	200	$1.9 \cdot 10^{10}$	5	$0.045 \cdot 10^{10}$
$Pu^{240} \longrightarrow 2Ag^{120}$ ca	220	$2.1 \cdot 10^{10}$	3.7	0.0340^{1810}

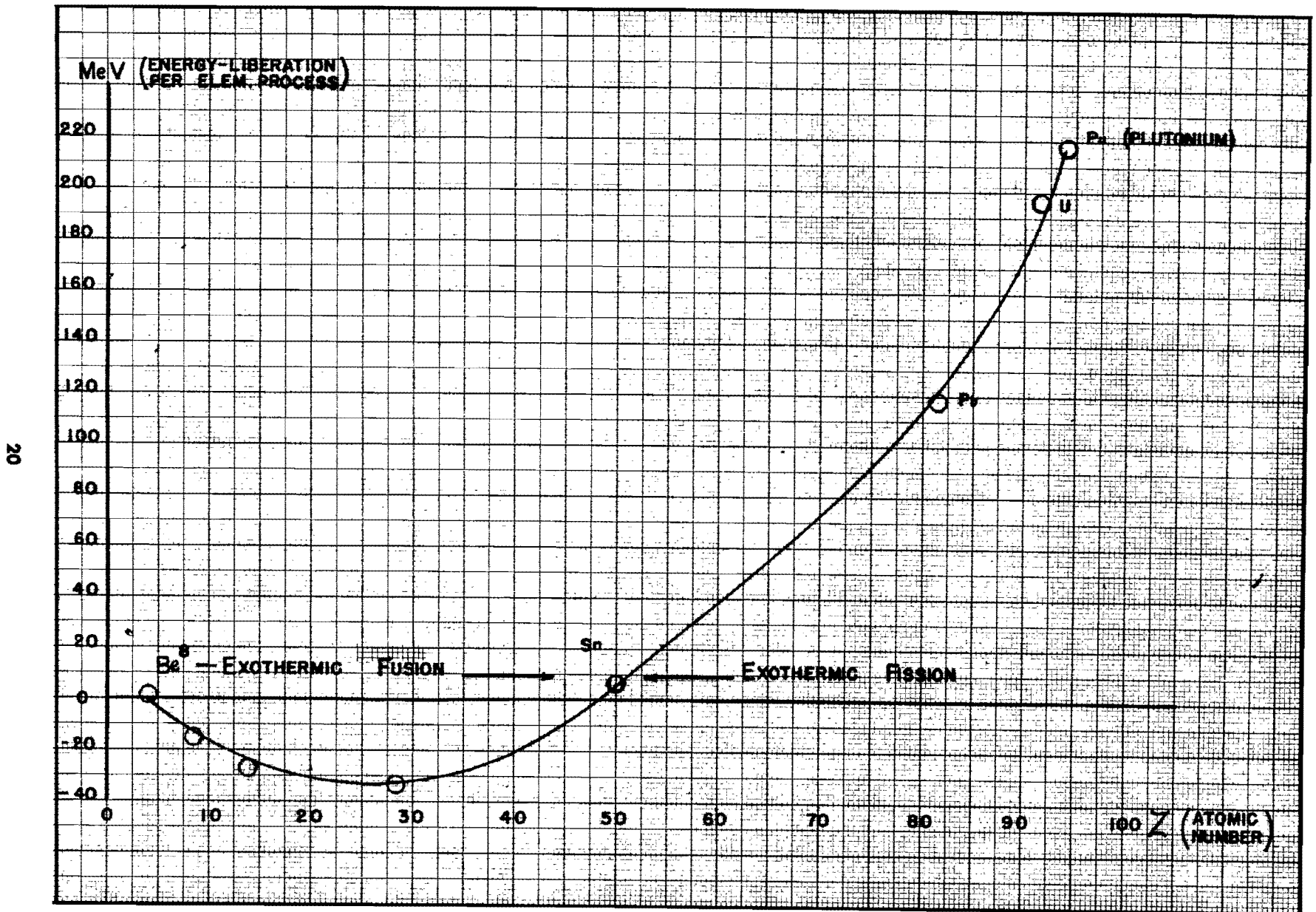


Figure 7 — Reaction-Energy of Nuclear Transformations

ACTIVATION ENERGY OF NUCLEAR TRANSFORMATIONS

1. Explosive nuclear mixtures.

In order that two colliding nuclei could enter into the reaction with one another, it is necessary that they approach within the range of the mutual cohesive forces, or in other words that they would come into a bodily contact. Since all the nuclei, except of course free neutrons, carry a positive electric charge such a close approach is classically possible, only if their mutual kinetic energy exceeds the value $Z_1 Z_2 \frac{e^2}{R}$ where Z_1 and Z_2 are atomic numbers of two reagents and R their combined nuclear radius.*

It is known that the density of all nuclei, light and heavy, is about the same so that their radii must vary as cube roots of their atomic weights. We have $R = 1.5 \cdot 10^{-13} \sqrt[3]{A}$ cm. Thus we can write for the height of the potential barrier separating two nuclei, or what is the same for the activation energy of the reaction, the expression:

$$U = \frac{Z_1 Z_2 e^2}{1.5 \cdot 10^{-13} \left(\sqrt[3]{A_1} + \sqrt[3]{A_2} \right)} \quad (12)$$

We see that, even for lightest nuclei (as in the case deuterium-deuterium reaction with $Z_1 = Z_2 = 1$, $A_1 = A_2 = 2$), the value of activation energy is millions of times higher than in case of molecular reactions. With the increasing atomic numbers of the reagents, the value of activation energy increases accordingly. In Fig. 8 we give the values of activation energies corresponding to the collisions between two identical nuclei of different elements. Because of only slight dependence of activation energy on atomic weights the values corresponding to the collisions between two different nuclei with the atomic numbers Z_1 and Z_2 could be read from the graph at the point $\sqrt{Z_1 Z_2}$.

2. Straight nuclear explosives.

As was stated above, every atomic nucleus heavier than silver possesses an internal metastability, and can go through the process of exothermic fission, provided it has communicated enough internal vibrational energy to be deformed beyond the breaking point. The energy which must be communicated to the nucleus in order to cause the fission was calculated by Bohr and Wheeler on the basis of droplet model. By using the best available data on nuclear structure these authors have studied the balance between the surface-tension forces originating in a deformed nucleus and trying to return it to the original spherical shape, and the coulomb forces which tend to disrupt the nucleus into two halves. They have shown that up to a certain critical value of deformation the nucleus will necessarily return to its original shape, whereas beyond this limit a rupture will necessarily follow. In Fig. 8, we give the values of this critical deformation energy for different elements which represent the activation energy of nuclear fission process. We see that the activation energy for fission has very high values for the elements just beyond silver where the fission first becomes possible, and drops to much smaller values towards the end of the natural system of elements. Indeed the nonexistence of chemical elements heavier than uranium is due to the complete fission instability of more massive nuclei.

* As we shall see later wave mechanics permits some penetration also for lower energy values.

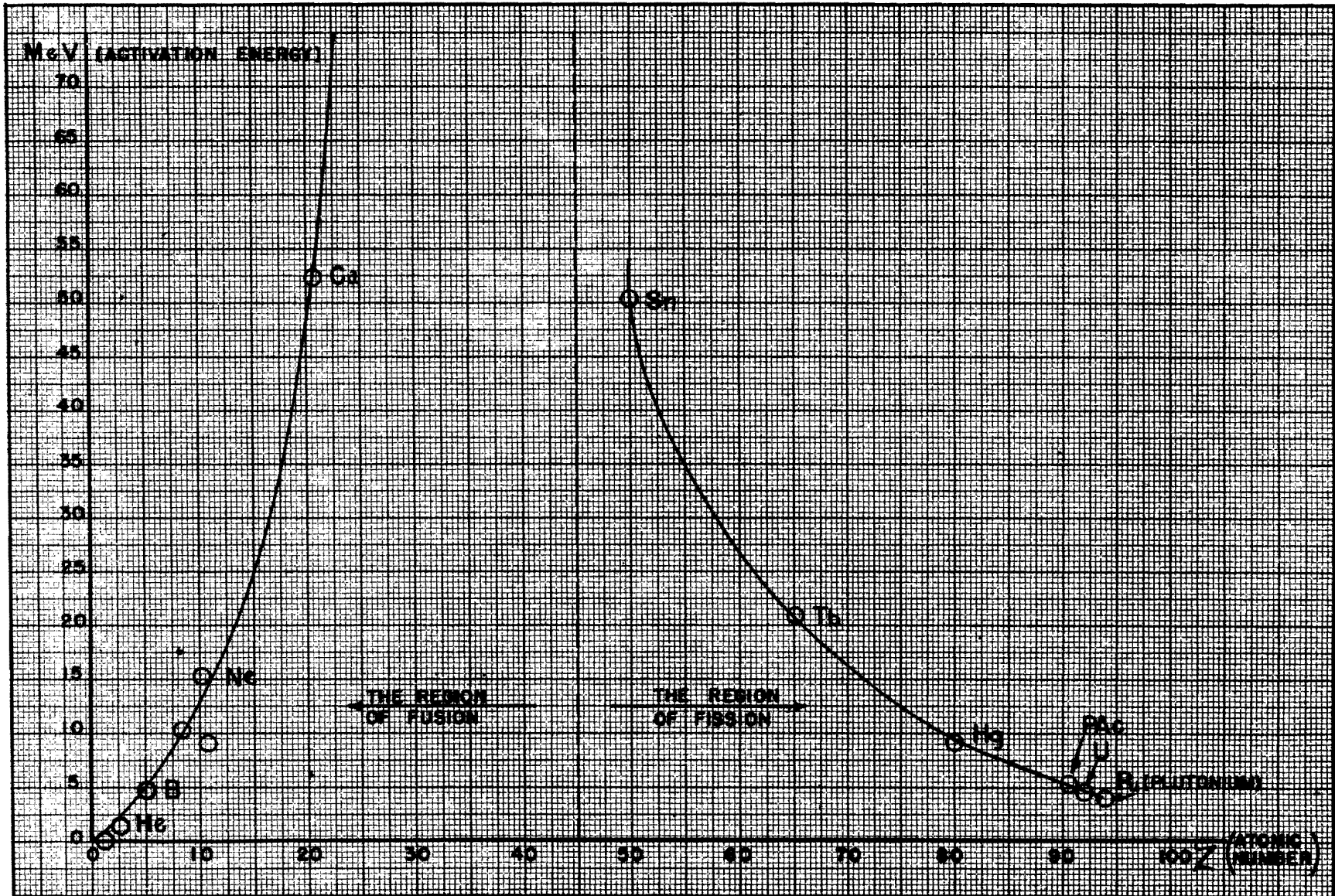


Figure 8 — Activation Energy of Nuclear Transformations

In surveying the results discussed in this section, we find that the smallest values of activation energy and consequently the highest thermonuclear reaction rates must be expected either for binuclear reactions of lightest elements, or for the mononuclear fission process in the heaviest elements.

Thus the two most promising atomic explosives are: the explosive based on the thermonuclear reaction



in deuterium, and the explosive based on the thermo fission process in uranium



However, the situation changes quite considerably if we take into account the possibility of chain reaction which, as we shall see later, plays an important role in the fission processes. We will find in fact that due to chain processes involving free neutrons, one can develop a straight uranium explosive in which the reaction can run at a very high rate quite independent of thermal conditions.

THERMONUCLEAR EXPLOSIVES

Due to very high values of the activation energy of nuclear transformations, thermonuclear reactions can go with appreciable velocity only at extremely high temperatures, of the order of magnitude of several hundred thousand degrees. At such high temperatures the violent thermal collisions completely strip the atoms of their electronic shells, so that the material can be considered as a mixture of nuclear and electron gases. Since nuclear and electron gases remain ideal up to extremely high densities,* all nuclear reactions can be treated as gas reactions, a fact which facilitates quite considerably the theory of the process.

The formula for the reaction rates of thermonuclear processes differs, however, from the ordinary Arrhenius formula for chemical reactions, due to the fact that the phenomenon of wave-mechanical transparency of potential barriers (which is of comparatively little importance in ordinary molecular reactions) plays a very important role in the case of nuclear transformations.

The theory of thermonuclear reactions was first developed by Atkinson and Houtermans in 1929 for the purpose of explaining the energy sources of stars, and was later improved by Gamow and Teller.

In the case of metastable nuclear mixtures the expression for the reaction rate ω can be obtained by multiplying the Maxwell expression for the number of particles possessing certain thermal energy by the corresponding probability of the reaction at the moment of collision, and integrating over the entire range of energies; the finite expression can be written in the form:

$$\omega = \frac{4}{3^{5/2}} \frac{\rho X_1 X_2}{m_1 m_2} \frac{\Gamma}{\hbar} a R^2 \left(\frac{4R}{a} \right)^{1/2} \tau^2 e^{-\tau} \quad (13)$$

$$\tau = 3 \left(\frac{\pi^2 m e^4 Z_1^2 Z_2^2}{2 \hbar^2 kT} \right)^{1/3}$$

Here X_1 and X_2 are the concentrations of the two reagents, Z_1 , Z_2 , m_1 , m_2 , their atomic numbers and atomic names, R the combined nuclear radius and Γ the a priori proba-

* The deviations from the ideal gas law will begin here only when the distance between the particles becomes comparable with their diameter (10^{-12} cm), i.e., for the densities of $10^{14} \frac{\text{gm}}{\text{cm}^3}$.

bility of the reaction. Applying this formula for the deuterium-deuterium reaction, which, as we have seen above, possesses the lowest activation energy and will therefore go at the highest rate at any given temperature, we must put in the above formula:

$$Z_1 = Z_2 = 1, \quad m_1 = m_2 = 3.3 \cdot 10^{-24}, \quad X_1 = X_2 = 1$$

Taking the deuterium at the density $\rho = 1$, and remembering that the energy liberation q per process in this case is $5.2 \cdot 10^{-6}$ erg, we obtain for the rate of energy liberation as the function of temperature the values represented graphically in Fig. 9.

We can now apply to the above thermonuclear reaction, a procedure similar to that used in the calculation of thermal explosion of ordinary chemically metastable substances (Equation (3)) writing:

$$C \frac{dT}{dt} = q \omega(T) \quad (14)$$

which gives for the explosion time:

$$\tau = \int_{T_0}^{\infty} C \frac{dT}{q \omega(T)} \quad (15)$$

The values of τ for different initial temperatures T_0 were calculated by the method of numerical integration and the results are represented graphically in Fig. 10. We see that the reaction time being about one second at the temperature of $1,000,000^\circ\text{C}$ drops to only a few microsec at $4,000,000^\circ\text{C}$ and to still smaller values at higher temperatures.

As we have seen in the first section, the necessary conditions for the explosion require that: first, the rate of energy production at the initial temperature must be higher than the heat losses into the surrounding medium since otherwise the self-heating process will not take place and the reaction will rapidly die out; and second, the reaction time corresponding to the initial temperature must be shorter than the time necessary for the shock wave corresponding to the maximum pressure to cross the average diameter of the charge.

Assuming that the charge consists of one gram of deuterium, which in the case of complete explosion is equivalent to about 20 T of TNT, we can calculate that the heat losses become equal to the heat production at about $1,200,000^\circ\text{K}$ (comp. Fig. 9). Thus the value of $1,200,000^\circ\text{K}$ represents the critical temperature of deuterium explosive in the same way as the values of about 600°K represent critical temperatures of ordinary chemical explosives. However, even at this high temperature one cannot yet expect a complete explosion unless the second condition pertaining to the premature expansion of the charge is also satisfied. As we have seen in the first section of this paper, the premature expansion of the charge subjected to the maximum pressure of atomic transformation will not take place unless the reaction is completed in less than one thousandth of a microsec. From the Fig. 10, we find that this condition would require the initial temperature of many millions degrees so that in the interval between $1,200,000^\circ\text{K}$ and $4,000,000^\circ\text{K}$ only a partial explosion can be expected.

Although the initial temperatures necessary for the thermal explosion of deuterium are much higher than anything yet attained in practice, one may hope to attain them for a very short time by using the convergent detonation wave device discussed in second section, page 6. In fact, when a detonation wave propagates through an explosive the burned gases immediately behind the detonation front move in the

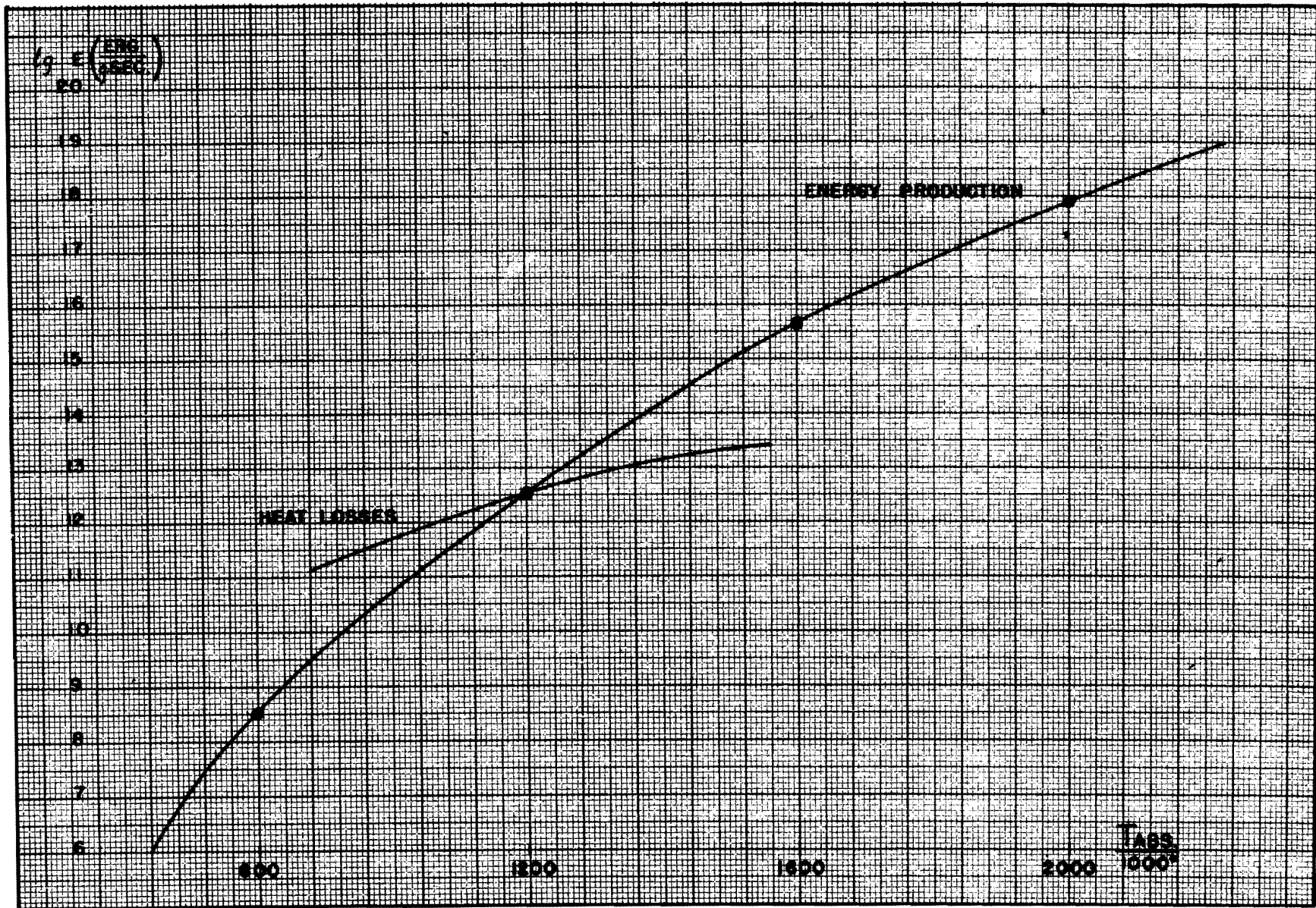


Figure 9 — The Rate of Thermonuclear Energy-Production in Deuterium as Compared with Heat Losses

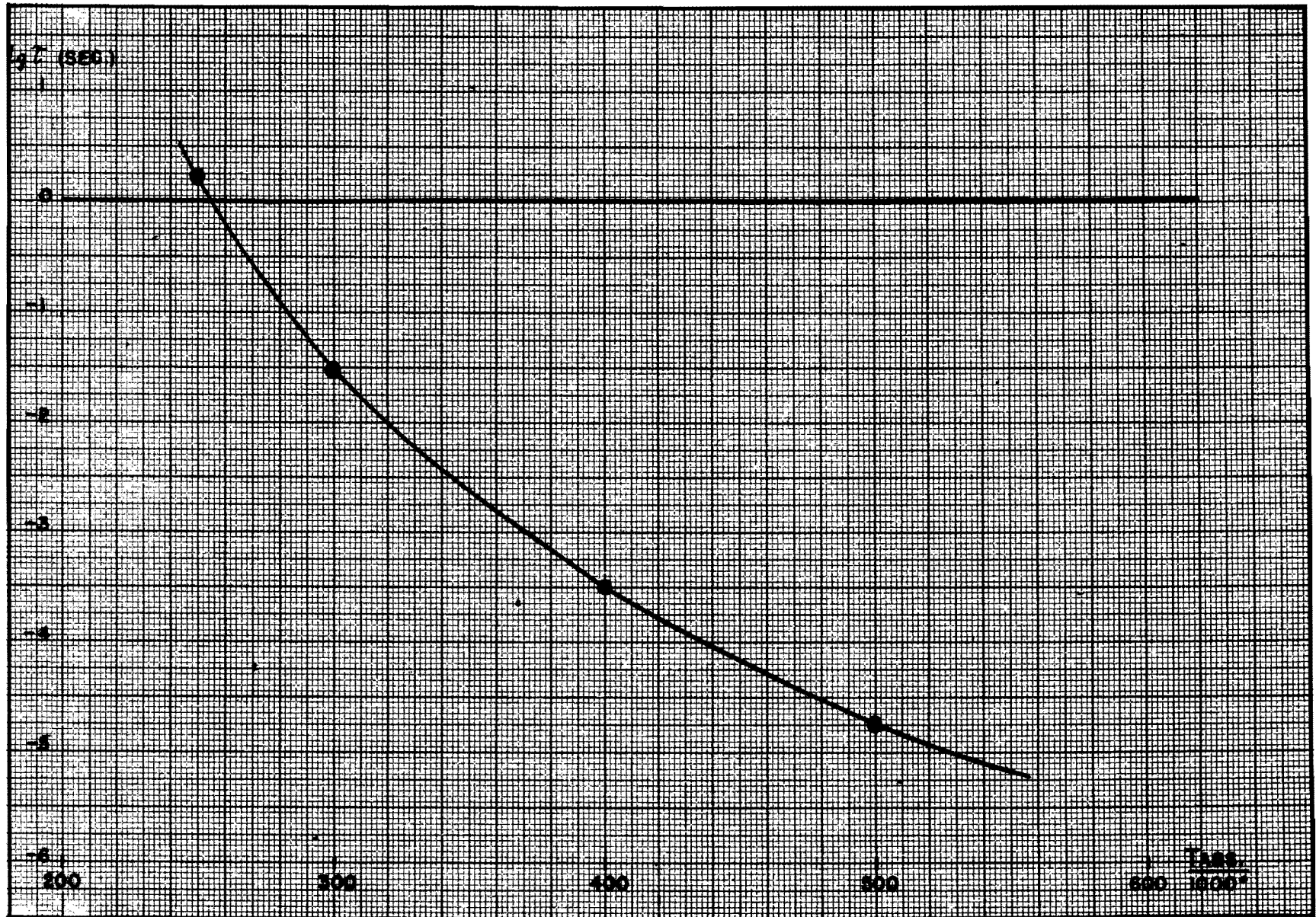


Figure 10 — Explosion Time of Deuterium as the Function of Temperature

forward direction with the velocity of several km/sec. In the case of cylindrical charges, however well confined, lateral expansion always takes place a short distance behind the detonation front, so that the forward moving column of gases known as the detonation head can never become very long.

In case of a spherical convergent wave, of course, no lateral expansion is possible, and from the law of conservation of mechanical momentum, one can expect that the length of the detonation head will be equal to about one half of the radius of the charge. Let us consider a small spherical cavity in the center of the charge filled up with a deuterium gas, and let us calculate the temperature which will be reached by the gas as the result of adiabatic compression produced by the onrushing masses of the charge exploding around it. Suppose for example that the spherical charge has a radius of 20 cm so that burned gases (at the density of about 2) forming a spherical layer converging towards the central cavity has the total mass of about $\frac{4}{3} \pi (10)^2 \cdot 2 = 8 \cdot 10^3$ gm.

If we take for the velocity of gases in the detonation head the value of $2 \frac{\text{km}}{\text{sec}}$, the total kinetic energy comes out to be:

$$\frac{1}{2} \cdot 8000 (2 \cdot 10^5)^2 = 1.6 \cdot 10^{14} \text{ erg} = 4 \cdot 10^6 \text{ cal.} \quad (16)$$

Most of this energy will be given to the gas filling the cavity raising its temperature to the value which can be calculated from the well-known formula for adiabatic compression. One can estimate this way that the temperature of the central cavity will rise to about a million degrees which is just enough to start a partial atomic explosion of deuterium.

The above rough estimate of the temperatures and pressures in the center of a convergent detonation wave, is only very approximate, and in order to answer the question in a more definite way the exact numerical calculation of the process is necessary. Some information on this subject can be obtained from the recent report by Bureau of Ships Comp. Project No. 11, in which the characteristics of a convergent detonation wave with the original radius of 200 cm, and the original velocity of $4.8 \frac{\text{km}}{\text{sec}}$ were given. The values of pressures, and the gas velocities at different stages of propagation (down to about one third of original radius) as obtained from these calculations, are shown in Fig. 11. We see that, as the radius of the wave decreases, the pressure and temperature begin to rise rather rapidly, thus indicating that very high values could be expected near the point of convergence. Thus it seems that the above device can serve for obtaining at least a partial atomic explosion of the deuterium placed in the central cavity.

It may be added that if one uses a substance containing deuterium,* for the chemical explosive which produces a convergent detonation wave, it is entirely possible that the explosion of deuterium in the central cavity will produce the detonation of deuterium of the entire charge, thus multiplying the power of the explosion by a factor of many thousands.

* Such as for example "heavy TNT" in the molecules of which ordinary hydrogen atoms are substituted by heavy hydrogen atoms.

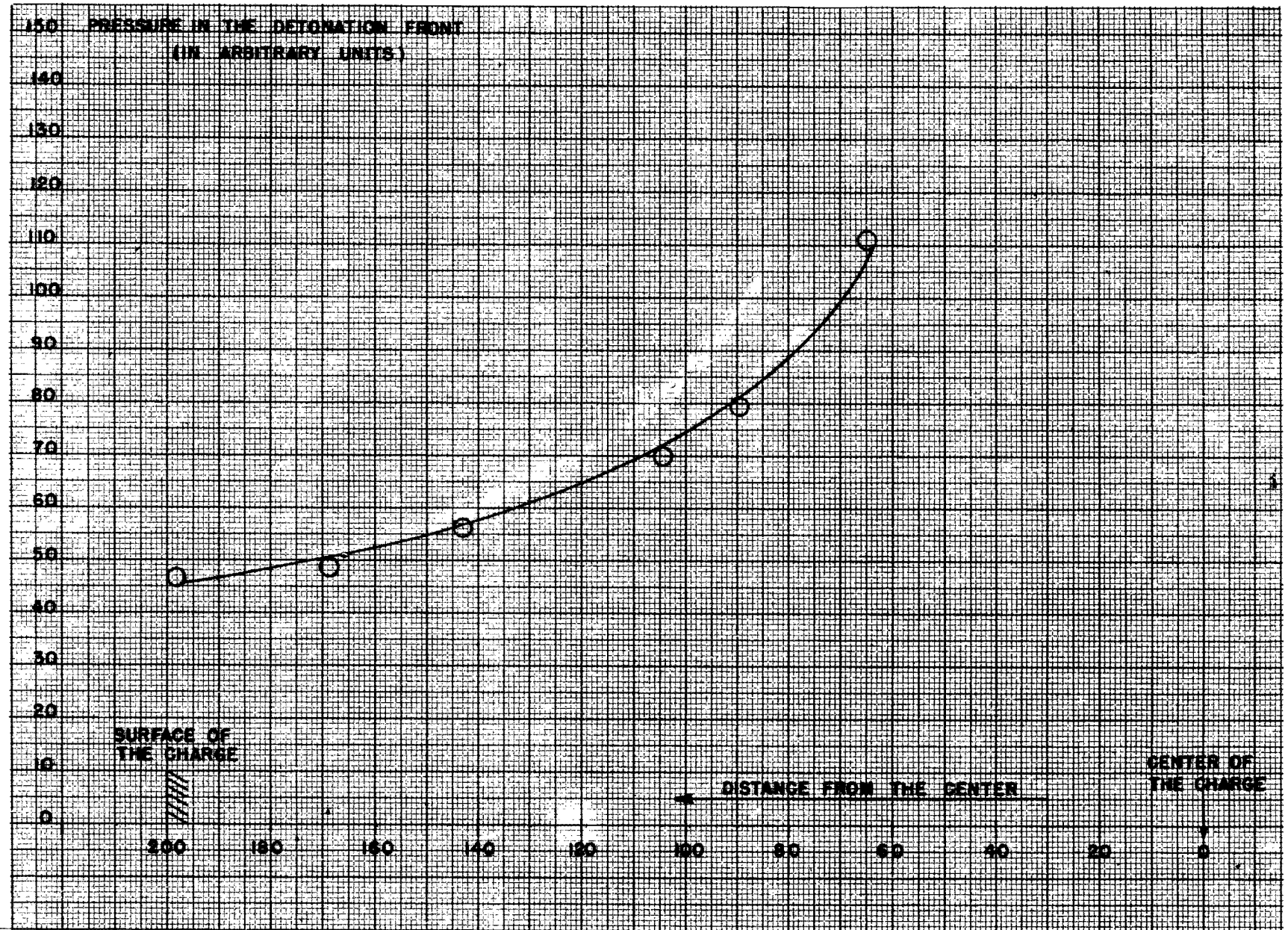


Figure 11 — The Increase of Pressure in a Convergent Spherical Wave

As another possibility of thermonuclear reaction which may be of use in the development of atomic explosives, one can mention the thermofission process in uranium 235 or the newly discovered artificial radioactive element plutonium. As we have seen above, the activation energy for the fission of the heavy nuclei (5 MeV for U^{235} and 3.7 MeV for plutonium) is considerably higher than the activation energy of the binuclear reaction in deuterium, which would indicate considerably lower reaction rate at the same temperature. It must not be forgotten, however, that penetrability through the potential barrier depends not only on its height but also very essentially on its width. From the general picture of fission process as discussed above one would expect the width of the fission barrier to be comparable with the nuclear radius, whereas, the width of the barrier corresponding to the binuclear reaction is many times larger than nuclear radius. The relation between two types of barriers is represented schematically in Fig. 12. As the second factor, one can mention that the frequency factor Z in the reaction rate formula is much larger in the case of thermofission process: in fact, in this case Z represents the vibrational frequency of the nucleus which is of the order of magnitude 10^{21} sec^{-1} , whereas in the case of binuclear reactions Z is the collision frequency and is only about 10^{10} or 10^{11} sec^{-1} .

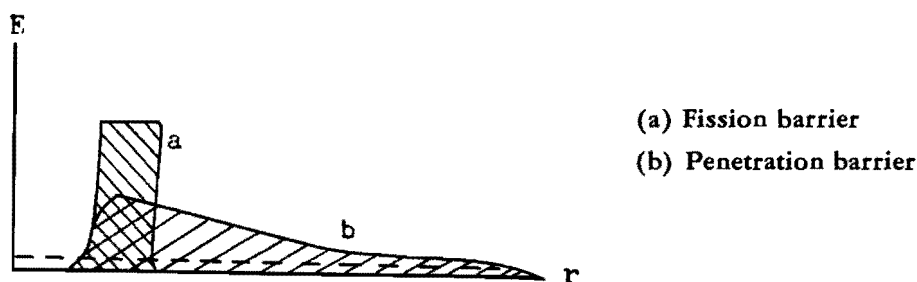


Figure 12

The exact expression for the reaction rate in the mononuclear thermofission process can be developed along the same lines as the analogous expression (13) for binuclear reaction, by applying the general theory of penetrability of potential barriers to the Bohr-Wheeler theory of nuclear fission process.

The exact evaluation of the rate formula involves lengthy calculations and cannot be included in the present report. Should the rate of the thermonuclear fission turn out larger than the rate of thermonuclear reaction in deuterium, U^{235} or plutonium should be preferably used instead of deuterium in the center of convergent detonation wave.

NUCLEAR CHAIN EXPLOSIONS*

As we have seen earlier, an explosion of a metastable substance can take place not only as the result of a self-accelerated heating process, but also through the rapid development of branching chains formed by active transformation fragments emitted in any single transformation process. Since the fragments originating in various nuclear transformations usually possess very high kinetic energies, and in

* The Discussion of this section should be considerably changed according to the new information which became recently available.

many cases can react exothermically with original nuclei, one may expect that chain reaction processes may play an important role in the development of nuclear explosives. There is, however, an important factor which considerably reduces the number of cases in which chain explosions are possible. The point is that any material contains, apart from atomic nuclei, a large number of electrons which form electronic shells of atoms. Since electrons cannot participate in atomic explosion processes (because of very slow rates of processes involving the emission or absorption of electrons), any atomic explosive can be considered as being diluted by non-active electron fraction. It can be shown that as the result of this "electron dilution" of explosive nuclear material, every charged fragment formed in an elementary nuclear transformation will lose its original kinetic energy to the electrons before it has the chance to strike another nucleus. Since, on the other hand, a charged fragment must possess a rather high energy in order to penetrate into the structure of the nucleus with which it collides, it follows that no chain reactions involving charged intermediary fragments are at all possible, and the only possibility of obtaining a branching chain explosion lies in processes where the active fragments are neutrons. In fact, due to the absence of electric charge, neutrons will neither lose their energy to the electrons nor will they have any difficulty in penetrating into nucleus, even if their original high energy is considerably reduced by a number of elastic collisions with other nuclei. Furthermore, it is necessary that not one but several neutrons are emitted in each elementary act. At the moment of emission these neutrons possess a rather high kinetic energy (about 1 MeV) but are in general considerably slowed down by elastic collisions with other nuclei before the collision leading to the subsequent fission finally takes place. Thus all the energy which these active fragments can communicate to the nucleus by which they are finally captured is represented by their affinity towards this nucleus. If this affinity or "capture energy" is higher than activation energy for fission the chain reaction will proceed; otherwise it will be interrupted.

From the general theory of nuclear structure one can conclude that the neutron capture energy by different nuclei is about the same and of the order of magnitude of 5 MeV for all elements of the periodic system. On the other hand, as we have seen in section 2 (Fig. 8), activation energy for fission has very high values for elements immediately after silver, and drops down to about 5 MeV only towards the end of the periodic system. Thus, only the elements at the very end of the periodic system can be used for producing branching chain reactions.

In Fig. 13 we give the detailed relation between the neutron-capture energies, and the fission-activation energies for the heaviest known elements including the new element known as plutonium, which does not exist in nature and was recently produced in an artificial way. We see that from naturally existing elements only the light isotope of uranium U^{235} satisfies the conditions necessary for the chain reaction. However, this isotope is present in ordinary uranium only in small quantities (0.8 percent) which prevents the possibility of chain reaction in natural material. In fact, the neutrons emitted in any accidental fission process of U^{235} nucleus have much larger chance to be captured without fission by more abundant isotope U^{238} than to encounter another U^{235} nucleus. Thus, in order to obtain the material which can be used as an atomic explosive, it is necessary to extract the U^{235} isotope from the natural Uranium, or at least to increase its concentration in the mixture. We will not discuss

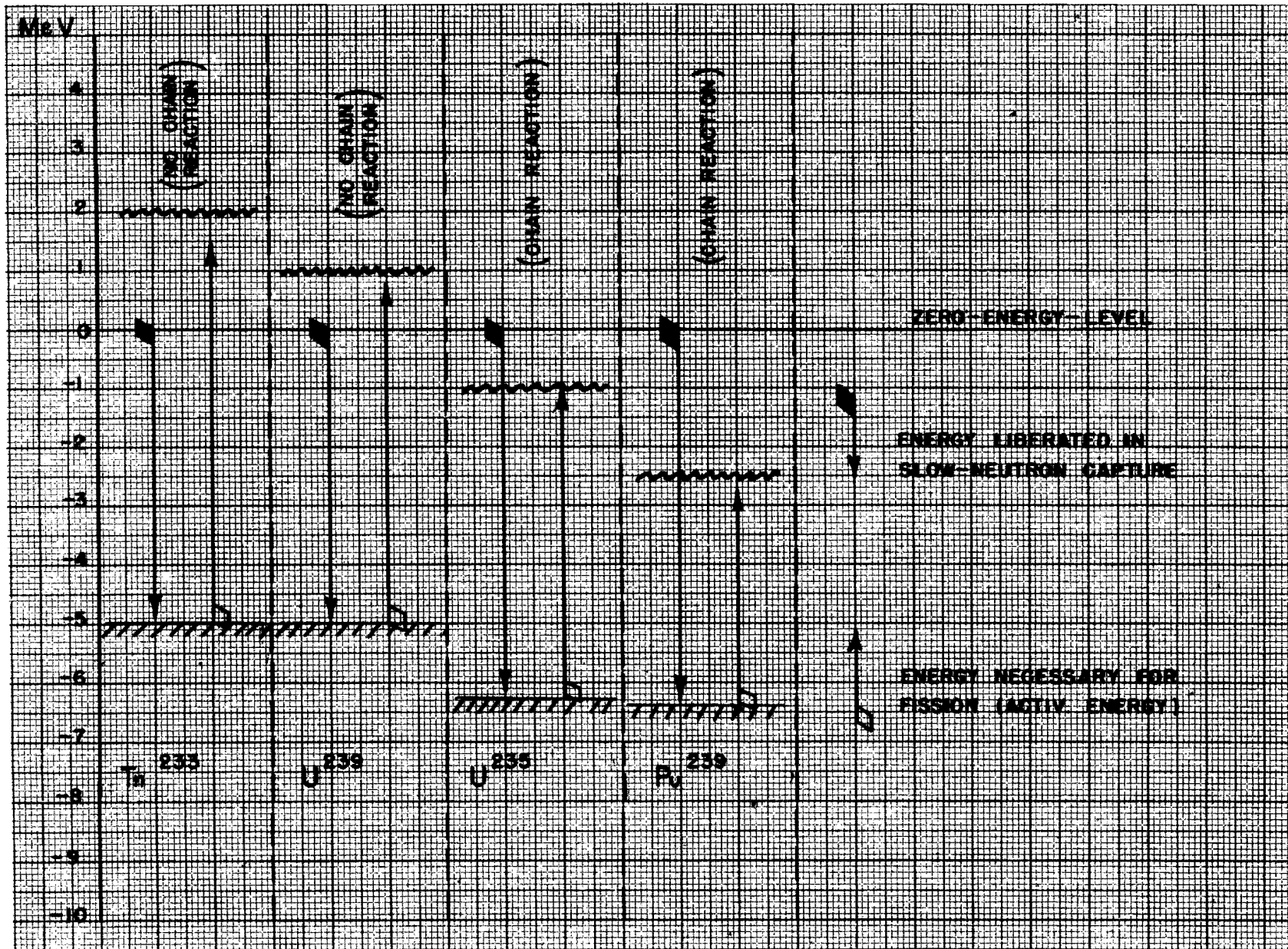


Figure 13 — The Relation Between Energy of Neutron Capture and the Activation Energy For Fission

here various methods which can be used for the separation of U^{235} isotope since they have been covered in great detail in the report on atomic bomb written by Dr. Smyth for the War Department. As it is stated in this report, the separation of light uranium isotope was carried out by the Manhattan project, and appreciable quantities of pure U^{235} have been obtained. It is stated also that it was found more convenient instead of separating U^{235} isotope to produce a new chemical element, plutonium, which in respect to the fission process possesses the qualities similar to those of U^{235} . Referring the reader to Dr. Smyth's report concerning the problems of isotope separation and plutonium production we turn now to the problem of originating an atomic explosion once either of these two substances is on hand.

It must be stated first of all that since an explosive branching chain reaction can be originated in the substance of that kind of a single stray neutron, and since there is no way of complete shielding of the charge from neutrons which are always present in appreciable quantities coming with cosmic rays, or from the radioactivity of the ground and surrounding objects, one can expect ure U^{235} or plutonium to explode as soon as it is produced. If it were so, the problem of obtaining such substances would be completely insolvable. It must be remembered, however, that the branching chains require some space to develop, so that in the samples of material below a certain critical size the branching process will be cut short by escape of neutrons into the surrounding space. It is easy to give an estimate of the critical size of the charge necessary for the development of branching chains. It is known that the effective cross section for fission of U^{235} is $\sigma = 4 \cdot 10^{-22}$ cm². From this we calculate the free path of a neutron before producing the fission (i.e., the length of one link of the chain) to be:

$$\lambda = \frac{m_n A}{\rho \sigma} \quad (17)$$

where $m_n = 1.66 \cdot 10^{-24}$ g is the mass of hydrogen atom, $A = 235$, and ρ the density of the charge. Taking $\rho \cong 10$ we obtain $\lambda = 5$ mm. On the other hand, we must have about 70 branchings in order to consume all the material in one gram of pure U^{235} .*

According to the "theorem of random walk" the size of the volume occupied by the completed chain will be:

$$r_{cr} = \sqrt{n} \cdot \lambda = \sqrt{70} \cdot 5 \text{ mm} = 4 \text{ cm} \quad (18)$$

If the charge is smaller than that critical size the chains will never develop to any appreciable degree since too many neutrons will be lost through the surface of the charge. If, on the other hand, the charge is larger than r_{cr} , the explosion will immediately follow.

Thus all one has to do in order to produce an explosion of U^{235} (or plutonium) is to take several charges of this material which are below critical size and therefore stable, and put them rapidly together to form one big lump. Simple as it looks, the above described method of "putting rapidly together" several layers of the substance encounters very serious difficulties which are all hidden in the word "rapidly."

* In fact, assuming that each branching produces two new neutrons we find for the number of neutrons after n branchings the value 2^n . If this is to be equal to the total number of U-nuclei per gram (ca 10^{22}) we must have $n = \frac{22}{\lg 2} = 70$.

Indeed, how rapidly should we put together two layers of U^{235} or plutonium in order to produce an effective explosion? It is evident, from what was already said in many places in the present report, that in order to get a complete explosion the two fractions must be mixed up or put together within the time period necessary for the explosion reaction to develop to its completion, or in other words, within the time period comparable to the explosion time. As we have also stated above, the explosion time necessary for a complete atomic explosion must amount to only a few millimicrosec (10^{-9} sec). The same number will be obtained if we try to calculate directly the time necessary for the completion of the fission chain reaction. We have seen that, assuming that each new fission process gives rise to two new neutrons, one comes to the result that there must be about 70 branchings in order to bring the reaction to completion. Since the free path of neutrons is about 0.1 cm, and their original velocity about $10^9 \frac{\text{cm}}{\text{sec}}$, one link of the chain requires $\frac{0.1}{10^9} = 10^{-10}$ sec, and the complete transformation will require $70 \cdot 10^{-10} = 7 \cdot 10^{-9}$ sec. Thus we come to a seemingly inevitable conclusion that for an effective explosion one must bring together the separate plates of atomic explosive material within the time period of 10^{-9} sec. Since the original distance between the plate could be hardly less than 1 cm, they must be moved with the speed of $10^9 \frac{\text{cm}}{\text{sec}} = 10^4 \frac{\text{km}}{\text{sec}}$, i.e., *with about one thirtieth of the speed of light*. It is very difficult to see how such a tremendous speed could be actually obtained. Another possibility of causing an explosion of a metastable nuclear substance consists of taking a spherical atomic charge of the size just a little bit smaller than the critical one, and squeezing it suddenly to somewhat larger density. In fact, it is easy to see that the critical conditions for the explosion depend not only on the geometrical size of the charge but also on its density; in fact, according to the formula (18), the dimensions of the completed branching chain are inversely proportional to the density of the charge. Suppose we have a spherical charge of U^{235} or plutonium which has the radius R just below the critical value r_{cr} given by (18). Suppose now that we rapidly squeeze this charge increasing its density by a factor φ . The critical radius for chain explosion will decrease by a factor φ whereas, the actual radius of the charge decreases only by a factor $\sqrt[3]{\varphi}$. If R was just below the critical value r_{cr} , a slight increase of density may reverse the situation causing the explosion. A rapid squeezing required in this method can be achieved by placing a spherical charge of U^{235} or plutonium with the radius just below the critical value, in the center of the convergent detonation wave described in "Focusing of the Explosive Power" page 9.

The above described method can probably be considerably improved if instead of pure U^{235} or plutonium one uses their mixture with heavy water. In fact, it may be expected that the presence of deuterium nuclei will shorten the free path of neutrons thus permitting the use of smaller amounts of rare U^{235} and plutonium elements. Another important advantage consists in the fact that in the presence of heavy water, it is not necessary to squeeze the charge up to the point where the chain reaction is going full blast. In fact, as soon as the chain reaction in U^{235} or plutonium develops to a degree at which the temperature of the mixture rises to about one million degrees,* thermal explosion of deuterium will immediately follow. Thus the main energy libera-

* In the completed chain reaction the maximum temperature is about eight billion degrees.

tion in the above arrangement is due mostly to deuterium transformation, the rare substances like U^{235} or plutonium only playing the role of a fuzing mechanism.

"SBXA" EXPLOSIVES

In the consideration of the previous section it was tacitly accepted that the neutrons which serve as active fragments in nuclear chain reaction are emitted simultaneously with the fission of the uranium or plutonium nucleus. It is possible however, that these neutrons are actually emitted with a certain delay originating not from the fission process itself but rather from the fission fragments excited by the process of subsequent β decay. In fact, it is well known that some of the fission neutrons come out with the delay of as much as one minute, and the possibility is not excluded that the neutrons which are usually classified as "instantaneous" are actually "delayed" by some small fraction of a second. There is no doubt that this question has been investigated experimentally, but the answer is not known to the present writer. Thus we will discuss in this section the consequences of the assumption that (contrary to the assumption of the previous section) all neutrons originating in fission process are of the delayed nature. This will not essentially change the previous considerations concerning the development of the chain reaction, and the conditions of the critical size of the change, but will have important consequences in respect to the calculation of the time during which the chain reaction develops. In fact, since the delay of neutron emission is due to the β decay of the fission fragments, and since even for very high energies involved the average life for such β decay can be hardly expected to be much shorter than one millisecond (10^{-3} sec), the total reaction time will increase from few millimicrosec estimated in the previous section to one-hundredth or even one-tenth of a second. In such case the possibility of obtaining a real explosion (which leads to the maximum possible local pressure) completely disappears, and the transformation phenomenon becomes rather similar to the effect of the so-called "SBX" chemical explosives where the reaction develops during the expansion of the original substance. It is true that in such a case the explosion is much less effective, but taking into account that nuclear energy liberation exceeds chemical energy liberation by a factor of twenty millions, even such an explosion will be sufficient to produce a lot of damage. The slowness of chain reaction carried by delayed neutrons makes it also considerably easier to bring together several layers of U^{235} or plutonium in order to build a block larger than the critical size. In fact, in such a case the "assembly" of the bomb should be carried not in one millimicrosec, but only in about one millisecond which technically is comparatively simple.

The nuclear transformation of SBX type would not build such a powerful shock wave as the real explosion, and a good part of damage will be produced by high-intensity radiation.

It may be added, in conclusion, that although the phenomenon of the above described type may be less powerful in its destructive power than a regular nuclear explosion and will not be able to start detonation in the surrounding materials, it gives us many more possibilities for the development of nuclear rocket motors than a regular nuclear explosion ever could.

SUMMARY AND CONCLUSIONS

In the field of ordinary chemical explosives, no striking progress can be contemplated beyond the present stage of their development. Some progress can probably be made in reducing the sensitivity of chemical explosives and thus reducing the risk of undesired explosions in the process of handling. Since explosions occurring as the result of comparatively small impacts are due to the granular or microcrystalline structure of the explosives now in use, a considerable reduction of sensitivity can be expected if it is possible to develop explosive plastics by the process of nitration of long aliphatic chains forming different plastic materials. One can also expect some progress in the problem of concentration of explosive power in certain specific directions, which is at present done by using the so-called shaped-charge effect. In fact, by applying the Huygens principle of classical optics to the theory of propagation of the detonation front, one can develop arrangements in which the detonation wave focuses itself on a certain point at the surface of the charge. As compared with the ordinary shaped-charge effect such optical method of focusing the explosive power may have certain disadvantages, due to the absence of stand-off, and also because of the smaller effect of the rotation of the projectile on the convergence phenomenon. Since atomic explosives are some twenty million times more powerful than equal amounts of ordinary explosives, there is hardly any need to discuss the possibility of still larger increase of that power. It may be mentioned, however, that various possible atomic explosives (such as deuterium, uranium 235, or plutonium explosives) have all a comparable power, and that still further increase of that power is just as unlikely as the further increase of the power of ordinary chemical explosives.

Due to the immense concentration of power in atomic explosives, and their extremely high cost, the situation here is rather in reverse and we must ask ourselves whether it is possible to make atomic bombs smaller than those which fell on Hiroshima and Nagasaki. In fact, as we have seen in "Atomic Explosives" (page 17), a couple of pounds of U^{235} or plutonium, which is equivalent to 20,000 T of TNT, is the minimum amount of atomic explosive which can be exploded by the chain reaction process. One can make a tentative estimate of the cost of such an atomic charge as compared with ordinary TNT charge on the basis of the price of the raw materials. One pound of uranium-oxide sells for approximately \$2.00 as compared with the price of coal at the mine of about \$2.00 per T. Remembering that uranium is about 20 times heavier than coal and that the isotope 235 is present in the amount of less than one percent, we conclude that one U^{235} atom considered as the raw material is about four million times more expensive than an atom of carbon. Since the atomic energy liberated per U^{235} -atom is 200 million electron volts as compared with four electron-volts chemical energy per carbon-atom, we conclude that, from the point of view

In the newly opened field of atomic explosives, as in any new field, the possibilities of future development are, of course, almost unlimited.

of raw materials, uranium energy is some twenty-five times cheaper than chemical coal energy. Considering, however, the difficulties of production of pure U^{235} or plutonium, one can probably say that the price of prepared atomic explosive per unit energy is about the same as the price per unit energy of the prepared chemical explosive as TNT. Taking 35¢ per pound for TNT, we find that atomic bomb equivalent to 20,000 T of TNT must cost at least about twenty million dollars, i.e., the price of a good battleship.

Thus, whereas atomic bombs of the size used may be good in destroying cities, it came out at about 50-50 in the use on battleships and is decidedly too expensive for destruction of cruisers or smaller naval fry.

Its power is also much too concentrated for use against the armies in the field.

On the other hand, it does not seem possible to reduce much the atomic charge used in the fission bombs. One can probably try to reduce the amount of straight atomic explosive by mixing it up with large amounts of much cheaper deuterium (heavy water) and using the chain process only to raise the temperature of the mixture to about one million degrees at which deuterium explosion will take place.

Another possibility would be in developing a purely thermal deuterium explosive by the methods discussed "Thermonuclear Explosives," page 23. Even if only a very partial explosion will take place, it may increase the effect of the main charge of TNT tenfold, which is quite an advantage taking into account the comparatively low price of heavy water.



RECOMMENDATION FOR FUTURE WORK ON HIGH EXPLOSIVES

As has been seen from the discussions of the present report, the development of ordinary high explosives with superior explosive power is of importance not only for the obvious reason of using them directly, but also for the improvement of the efficiency of atomic bombs. In fact the present use of a convergent detonation wave for the purpose of squeezing the atomic charge does not lead to entirely satisfactory results since the process of squeezing does not take place sufficiently fast. This leads to only a partial explosion of the U^{235} and Pu charges used in these bombs, and would also give only a very small effect in case of a deuterium charge. The development of high explosives with slightly higher power will considerably increase the efficiency of fission bombs, and may also make possible the bombs based on the thermonuclear reaction in deuterium. It must be emphasized here that the essential point lies in developing high explosives with larger detonation and mass velocities and not only with higher energy liberation per gram. Thus for example an aluminized explosive such as TORPEX does not possess any advantage over ordinary RDX since the additional energy produced by the oxidation of aluminum is liberated too slowly (by a burning process) to contribute anything to the detonation velocity and mass velocity of the wave. If, however, it were possible to put aluminum atoms directly into the metastable molecule, the effect would be quite different. Thus, the efforts must be directed first of all towards the development of chemical high explosives with detonation velocities of 10 or more km/sec. The second important problem lies in the development of very homogeneous explosive substances which is essential for good focusing of detonation waves.

~~TOP SECRET~~

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