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Samuel K. Allison

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Los Alamos Technical Series

Volume 3

A GENERAL SURVEY OF THE WORK OF THE LOS ALAMOS LABORATORY

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FOREWORD

The Problem of Los Alamos

In the most general terms, the problem of Los Alamos was to produce a fission bomb of military importance using the neutron-linked chain reaction in uranium 235, in plutonium 239, or in some combination of the two materials. There was a general impression, at the beginning of the work, that such bombs releasing less than the energy produced by the high order detonation of 1000 tons of TNT would be decidedly uninteresting[1].

(1) The energy release per ton of TNT is rather arbitrarily considered to be 4×10^{16} ergs. The energy release per gram of fissions of uranium 235 or plutonium 239 is taken as 7×10^{17} ergs.

Little consideration was given to any other method of delivery than by airplane and this set some limits on the weight and size of the completed bomb assembly. In order to make use of existing bombing planes with sufficient range is seemed advisable to make a bomb that could be carried in a B-29 with only minor alterations. This meant that weights over about 10 tons and cross section dimensions greater than 60 by 132 inches were undesirable for the completely assembled object, if it were designed to fit into a single bomb bay.[2]

(2) The "fast" gun for the plutonium bomb was at one time designed to extend through both bomb bays and required removal of the partition between them. The gun program for plutonium was abandoned in favor of implosion.

The bomb must be used in such a way that the release of energy would be accompanied by the maximum destructive effect, and since new orders of magnitude of energy release from a single bomb were contemplated, this meant a thorough examination of the theory of damage from high explosives in order to extrapolate to the new conditions.

It was also considered part of the Los Alamos problem to keep investigations going on methods of augmenting the energy release from the fission bomb by inducing thermo-nuclear reactions in the light nuclei such as deuterium and tritium.

This volume attempts to give a general survey, without details, of the effort at Los Alamos to solve these problems. Although some mention is made of the period before the Laboratory was opened, the following account concentrates on the period between the opening in April 1943 and the end of the Japanese war on August 16, 1945.

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CHAPTER 1

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THE PROBLEM OF THE CRITICAL MASS

Samuel K. Allison

1.1 An Elementary Mathematical Treatment of the Critical Mass Problem

The fact that a divergent chain reaction linked by the neutrons liberated in the fission of U-235 is possible was demonstrated by the Metallurgical Laboratory at the University of Chicago on December 2, 1942. The type of chain used there, however, was quite different from that which could give a satisfactory energy release in a fission bomb, because thermal neutrons were an essential link in the process. The fast neutrons liberated in fission were slowed down to thermal energies before absorption in uranium to continue the chain. The lifetime of thermal neutrons in the inhomogeneous mixture of metallic uranium and graphite used there, that is, the period between the arrival of the energy of the neutrons at thermal values and the absorption of the neutrons into uranium, is of the order of milliseconds. This slows down the period of the chain to such an extent that in an uncontrolled reaction the liberation of heat would break up the reactor and the reaction would stop through neutron leakage out of the fissures before any considerable energy release had been attained. A fission bomb must operate on fast neutrons, so that the reaction proceeds to the point where thousands of tons of T. N. T equivalent energy have been released before the inertia of the heavy nuclei of the active material can be overcome to the point of dispersal of the bomb and cessation of the chain reaction.

One of the most typical features of a chain reactor is the phenomenon of critical size. When the size of the aggregate which is to chain-react is subcritical, so many of the neutrons produced leak out through the boundaries that the chain cannot continue without limit. The critical size of the graphite-uranium heterogeneous aggregate as determined in 1942 gave very little information relevant to the amount of material needed for a fission bomb, because the proper-

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ties of the fissionable nuclei with respect to neutrons of thermal energy and of a few million volts' energy are quite different.

The gross features of the situation will be illustrated by applying a classical diffusion theory to a finite, homogeneous lump containing fissionable material, or more precisely, to the problem of the active sphere without a neutron reflector around it. This seems to be the natural method of introduction to the mathematical treatment of the subject, but results which are more than qualitative indications are not to be expected.

Some of the approximations being made will be pointed out in the course of the treatment, but a major one is that the type of theory used is designed for a case in which the mean free path of the moving particles (neutrons) is negligibly short compared to the dimensions throughout which the macroscopic structure is homogeneous. This is not the case in the active material of fission bombs, as will be seen later.

Let $\phi(x,y,z,t)$ be the number of neutrons per cubic centimeter near the point (x,y,z) in the aggregate of fissionable material at time t. The time dependence of ϕ is found by considering the balance between the sources and sinks of neutrons.

In the case of the fissionable substances U-235 and Pu-239, there are always sources of neutrons throughout the aggregate due to the action of alpha particles on the light elements present as impurities. In the case of U-235 the majority of the alpha particles come from the shorter-lived U-234 (1) which it con-

(1) The U-235 supplied from the Clinton Engineer Works contained about one part in 120 of U-234; the half life of U-235 is 7.07×10^8 years, and that of U-234 is 2.33×10^5 years.

tains; in Pu-239 the alphas arise from its disintegration to U-235 with the char-

actinistic half life of [illegible] years. Actually, in Pu-239 prepared in the Hanford plant, more neutrons arise from the spontaneous fission of the Pu-240 present than from the (α,n) reaction.

Neutrons also appear in the materials because of their generation by fission. If ν is the average number of neutrons emitted per fission and τ the mean life of these neutrons in the material, the number of neutrons captured per cubic

(2) The simplified theory presented here supposes that the fraction of neutrons which escape directly from the material without collision is not great enough to affect the mean life appreciably; this is simply another form of the limitation (mean free path) << (dimensions) mentioned previously.

centimeter per second is simply $\phi\tau^{-1}$, and the number produced $\nu\phi\tau^{-1}$, so that the net increase due to fission is $(\nu-1)\phi\tau^{-1}$.

Neutrons enter and leave the region near (x,y,z, by diffusing through its boundaries. The net gain per cubic centimeter in the region is given by

$$D\nabla^2\phi \equiv D\left(\frac{\partial^2 d}{\partial x^2} + \frac{\partial^2 d}{\partial y^2} + \frac{\partial^2 d}{\partial z^2}\right) \qquad (1$$

where D is the so-called "diffusion coefficient". Using q to represent the uniformly distributed rate of production of neutrons through (α,n) reactions or through spontaneous fission, we have,

$$\frac{\partial d}{\partial t} = D\nabla^2 d + (\nu-1)d\tau^{-1} + q \qquad (2)$$

Experience with partial differential equations of this type has shown that solutions of physical interest may be obtained in the form

$$\phi(x,y,z,t) = F(x,y,z)\,T(t) + Q(x,y,z) \qquad (3)$$

$\phi(x,y,z)$ is the solution of the time-independent differential equation

$$D\nabla^2 Q + (\nu-1)Q\tau^{-1} + q = 0 \qquad (4)$$

[redacted]

and furthermore, in spherical symmetry, there is a value of the radius at which $q = 0$, corresponding to the outer boundary of the material. Substitution of equation (3) in (2) leads to

$$F\dot{T} = TD\nabla^2 F + D\nabla^2 Q + (\nu - 1)\tau^{-1}(FT + Q) + q \tag{5}$$

and using equation (4) we obtain

$$F\dot{T} = TD\nabla^2 F + (\nu - 1)\tau^{-1} FT \tag{6}$$

The variables may be separated through division by FT, leading to

$$T^{-1}\dot{T} = DF^{-1}\nabla^2 F + \frac{(\nu - 1)}{\tau} \tag{7}$$

The time-dependent and space-dependent parts of this separated equation must actually be constant; it is convenient to call this constant $\frac{(\nu' - 1)}{\tau}$. Thus we have

$$\frac{1}{T}\frac{dT}{dt} = \frac{\nu' - 1}{\tau} \tag{8}$$

and

$$\frac{1}{F}\nabla^2 F = \frac{\nu' - \nu}{\tau D} \tag{9}$$

Equation (8) clearly has the solution

$$T(t) = \exp\left\{\frac{(\nu' - 1)}{\tau}\right\} t \tag{10}$$

the implications of which we shall consider later. Since D itself has the dimensions of area per unit time, the product $D\tau$ which appears in equation (9) has the dimensions of an area, and will be represented by L^2. Let us now limit the generality of equation (9) by postulating spherical symmetry. This means that

if $\nabla^2 F$ is expressed in spherical coordinates (r,θ,ϕ), only those terms in r will be retained. Thus equation (9) becomes

$$\frac{1}{r^2 F}\frac{d}{dr}\left(r^2\frac{dF}{dr}\right) = \frac{\nu'-\nu}{L^2} \tag{11}$$

The standard method of solution is to introduce a new variable $S = rF$, which leads to the form:

$$\frac{1}{S}\frac{d^2S}{dr^2} = \frac{\nu'-\nu}{L^2} \tag{12}$$

The solutions of this well-known differential equation, after replacing F, are

$$F = r^{-1}\left(c_1 e^{\frac{ir\sqrt{\nu-\nu'}}{L}} + c_2 e^{-\frac{ir\sqrt{\nu-\nu'}}{L}}\right) \tag{13}$$

A real solution of equal generality can be found by making c_1 and c_2 conjugate complex numbers. We then obtain

$$F = r^{-1}c \sin\left(rL^{-1}\sqrt{\nu-\nu'} + \delta\right) . \tag{14}$$

and the condition that F remain finite at $r = 0$, discard δ. We can summarize our results thus far by writing

$$\phi(r,t) = r^{-1}ce^{\frac{(\nu-1)t}{\tau}} \sin\left(\frac{r\sqrt{\nu-\nu'}}{\tau}\right) + Q(r) \tag{15}$$

It now remains to find the function $Q(r)$, which is the solution of equation (4). Expressing the La Placian in terms of spherical symmetry, and rearranging slightly, we obtain

$$\frac{1}{r^2 Q}\frac{d}{dr}\left(r^2\frac{dQ}{dr}\right) + \frac{q}{DQ} = -\frac{\nu-1}{L^2} \tag{16}$$

which, after the usual substitution $S = rQ$, becomes

$$\frac{d^2S}{dr^2} + \frac{qr}{D} = -\frac{\nu-1}{L^2}S \tag{17}$$

This equation is of the type form

$$\frac{d^2y}{dx^2} + \alpha x + \beta y = 0 \tag{18}$$

and methods of its solution can be found in any treatise on differential equations. The solution is, after replacement of Q,

$$Q = r^{-1}\left(c_1 e^{\frac{ir\sqrt{\nu-1}}{L}} + c_2 e^{-\frac{ir\sqrt{\nu-1}}{L}}\right) - \frac{qL^2}{D(\nu-1)} \tag{19}$$

or in trigonometric form, with a finite at $r = 0$:

$$Q = r^{-1} c \sin\left(\frac{r\sqrt{\nu-1}}{L}\right) - \frac{q\tau}{(\nu-1)} \tag{20}$$

The constant c can now be evaluated from the condition that $Q(R) = 0$, where R is the radius of the active material. This gives

$$c = \frac{q\tau}{\nu-1}\left(\frac{R}{\sin\frac{R\sqrt{\nu-1}}{L}}\right) \tag{21}$$

and the solution for $Q(r)$ is

$$Q(r) = \frac{q\tau}{\nu-1}\left\{\frac{R\sin\left(\frac{r\sqrt{\nu-1}}{L}\right)}{r\sin\left(\frac{R\sqrt{\nu-1}}{L}\right)} - 1\right\} \tag{22}$$

which is zero at $r = R$.

Further information may be obtained by returning to the time dependent term in equation (15) and realizing that for all times it must remain zero $r = R$. This gives us the condition that

$$\frac{R\sqrt{\nu-\nu'}}{L} = n\pi \tag{23}$$

where n is an integer. Thus there [illegible] set of values of the con- [illegible] ν' [illegible]

$$\nu_n' = \nu - \frac{\pi^2 L^2 n^2}{R^2}$$

for which there are acceptable solutions. Thus the solution of physical interest for spherical symmetry can be written

$$\phi(r,t)=r^{-1}\sum_n c_n \exp\left[\frac{1}{\tau}\left\{\nu-1-\left(\frac{n\pi L}{R}\right)^2\right\}t\right]\sin\left(\frac{n\pi r}{R}\right)+\frac{q\tau}{\nu-1}\left\{\frac{R\sin\left(\frac{r\sqrt{\nu-1}}{L}\right)}{r\sin\left(\frac{R\sqrt{\nu-1}}{L}\right)}-1\right\} \quad (25)$$

1.1-1 The Critical Radius and Critical Mass

If the exponent in any one of the time-dependent terms of equation (25) becomes positive, the number of neutrons per cubic centimeter throughout the sphere of active material will increase without limit. If we construct bigger and bigger spheres, criticality is reached at

$$R_c=\frac{\pi L}{\sqrt{\nu-1}} \quad (26)$$

according to the rough theory presented here. The corresponding critical mass M_c would be

$$M_c=\frac{4}{3}\pi^4\rho L^3(\nu-1)^{-\frac{3}{2}} \quad (27)$$

where ρ is the density.

Let us consider experiments with a set of spheres having radii smaller than, but comparable with, the critical radius. In the sphere of subcritical radius, the time-dependent term of equation (25) can have only transient effects, because the exponent is negative, and they rapidly die away. They can be momentarily excited, for instance, by turning on a source of neutrons nearby, and, if desired, their rate of decay can be studied.

The steady state is given by the time-independent term which can be written

$$\phi(r)=\frac{q\tau}{\nu-1}\left\{\frac{R}{r}\,\frac{\sin\left(\frac{\pi r}{R_c}\right)}{\sin\left(\frac{\pi R}{R_c}\right)}-1\right\} \quad (28)$$

In a series of spheres of increasing R, we have

$$\lim_{R\to R_c}\phi(r)=\infty$$

and in the larger spheres the neutrons present from (α,n) and spontaneous fissions are multiplied many fold. Multiplications of 5-fold have been observed at Los Alamos in such tests. The spheres, were, however, surrounded by neutron reflectors, which will now be discussed.

1.1-2 The effect of a Reflector.

The critical mass of active material necessary for a divergent chain reaction can be considerably decreased by enclosing the sphere in a neutron reflector. In the fanciful case of a perfect reflector none of the neutrons would escape and they would remain inside, splitting the fissionable nuclei until the active material was transformed or the neutrons absorbed in the accumulating fission products, and thus any amount of active material could be made critical. Besides reflecting neutrons back into the active material, the jacket or "tamper" may, because of its inertia, delay the expansion of an exploding bomb and keep the core hypercritical longer, allowing more energy to be released. Another desirable feature of such a jacket, from the point of view of a destructive nuclear explosion, might be transparency to the electromagnetic radiation from the hot core, since radiation pressure is a potent factor in dispersing the material.

The following simple treatment of the reflector will use the diffusion equations and hence give only qualitative results. Furthermore the treatment will assume that in the active material and the reflector the neutrons have the same diffusion coefficient D. This assumption is not strictly applicable to any reflector material seriously considered at Los Alamos.

Consider a core of active material of radius R surrounded by a spherical shell of radius ρ, so that the thickness of the shell is $\rho-R$, as in figure 1. The product $D\tau$ is considered different in the core and the reflector, so that we have

$$L_c \neq L_r \qquad (3.)$$

We are interested in finding the effect of the reflector on the critical

size, where $R = R_c$, the multiplication of neutrons is so great that the neutron distribution function

$$\phi_c(r) = \frac{q\tau}{\nu - 1}\left\{\frac{R}{r}\,\frac{\sin\frac{\pi r}{R_c}}{\sin\frac{\pi R}{R_c}} - 1\right\} \qquad (3)$$

becomes essentially

$$\phi_c(r) = cr^{-1}\sin \pi r / R_c. \qquad (3')$$

In the reflector, where the sources q are negligible, the steady state is given by the time-independent part of ϕ, that is equation (14) with $\nu = q = 0$ so that we obtain

$$\phi_r(r) = r^{-1}\left\{c_1 \exp(-r/L_r) + c_2 \exp(r/L_r)\right\}. \qquad (4)$$

This can also be written

$$r\phi_r(r) = A \sinh(r/L_r) + B\cosh(r/L_r). \qquad (4')$$

In setting up the core-plus-reflector problem, we have, then

region	Form of the neutron concentration function
$0 < r < \rho$	$\phi_c = cr^{-1}\sin(\pi r\sqrt{\nu - 1}/L_c)$
$R < r < \rho$	$\phi_r = r^{-1}\left\{A \sinh(r/L_r) + B\cosh(r/L_r)\right\}$
$r > \rho$	$\phi = 0$

The boundary conditions which must be satisfied are

(1) The two functions ϕ_c and ϕ_r must have the same value at $r = R$.

(2) The neutron concentration function must be zero at $r = \rho$.

(3) Since the flux of neutrons from the core to reflector is proportional to the slope of ϕ, the derivatives $d\phi_c/dr$ and $d\phi_r/dr$ must be equal at $r = R$.

The [illegible] (4) [illegible]

Figure 1

Relation of Active Core Radius (R) with a Reflector (radius ρ) to Active Core Radius (Rc) without a Reflector.

$$A \sinh \beta R + B \cosh \beta R = \sin \alpha R \tag{35}$$

$$A \sinh \beta + B \cosh \beta \rho = 0 \tag{36}$$

where $\beta = 1/L_r$ and $\alpha = \pi/R_c$ (37)

Solving for A and B in these equations leads to

$$A = \frac{-\cosh \beta \rho}{\sinh \beta(\rho - R)} \sin \alpha R \tag{38}$$

$$B = \frac{\sinh \beta \rho}{\sinh \beta(\rho - R)} \sin \alpha R \tag{39}$$

Now we must use the condition on the first derivatives, which leads to the expression

$$\left\{\beta \coth \beta(\rho - R) - \rho^{-1}\right\} \sin \alpha R = \alpha \cos \alpha R - R^{-1} \sin \alpha R \tag{40}$$

or $$\tan(\pi R/R_c) = (\pi L_r/R_c) \tanh\left\{\frac{(\rho - r)}{L_r}\right\} \tag{41}$$

If the thickness of the reflector, $\rho - R$, is zero, we should get the maximum value of R for a divergent chain reaction. We see that equation (41) gives, under this condition, $\tan(\pi R/R_c) = \infty$, meaning that the angle must be π, and $R = R_c$, which is the critical radius without reflector. Presence of a reflector will decrease the radius of the active material; so we obtain

$$R = R_c \left[1 - \frac{1}{\pi} \arctan\left\{\frac{\pi L_r}{R_c} \tanh \frac{\rho - R}{L_r}\right\}\right] \tag{42}$$

Here R_c is the critical radius of the active material without a reflector, R is the critical radius of the encased core, and L_r is a length characteristic of the reflector. For an infinitely thick case ($\rho - R = \infty$), we have

$$R = R_c \left\{1 - \frac{\arctan(\pi L_r/R_c)}{\pi}\right\} \tag{43}$$

through gases it is shown that the coefficient of diffusion, D, is given by

$$D = \frac{1}{3} \lambda_{tr} v \tag{44}$$

where v is the speed of the moving particles, and λ_{tr} is the "transport mean free path", or the average distance between collisions multiplied by a factor giving the effectiveness of the average collision in advancing the particle across a plane boundary in the substance. It has become customary at Los Alamos to write

$$\lambda_{tr} = (n\sigma_{tr})^{-1} \tag{45}$$

where n is the number of nuclei per cubic centimeter and σ_{tr} is the transport cross-section per nucleus in square centimeters, given by

$$\sigma_{tr} = \sigma_i + \sigma_f + \int \sigma_e(\theta)(1-\cos\theta)\,dr \tag{46}$$

In this expression $\sigma_e(\theta)\ dr$ is the cross-section for elastic scattering through angle θ into the elementary solid angle dr. σ_i is a cross-section for inelastic scattering, in which the neutron loses energy by raising the nucleus to one of its excited states, as contrasted to elastic scattering, where the energy loss is given by the conservation of momentum and energy between neutron and nucleus. In the absence of any detailed knowledge about inelastic scattering, its cross-section is assumed to be independent of the scattering angle. σ_f is the fission cross section.

The mean life before absorption of the neutron, in terms of nuclear cross-sections, is

$$\tau = (n\sigma_f v)^{-1} \tag{47}$$

where σ_f is the fission cross-section. Thus we have

$$L^2 = D\tau = (3n^2 \sigma_{tr} \sigma_f)^{-1} \tag{48}$$

In the reflector, the L involves the same concepts, but in reflectors of nonfissionable material σ_f in equation (48) should be replaced by an ordinary absorption cross-section σ_a. It is clear that the concepts just presented are very rough, and that a careful study of the diffusion of neutrons in ordinary and in fissionable materials will lead to a much more detailed understanding of the gross features we have labelled σ_i, σ_e, and σ_a.

1.2-1 The Problem of the Energy Distribution of the Fission Neutrons

All the cross-sections which must be measured in a "differential" attack upon the critical-mass problem vary with the energy of the neutrons, so that it is important to measure them at energies which are likely to be effective in the bomb. The energies effective in the bomb, in turn, depend on the energy spectrum of the neutrons emitted in fission, and a study of these energies in U-235 and Pu-239 was obviosuly needed. The problem is difficult one from the experimental point of view. Three different techniques of measureing neutron energy were tried at various times: observation and measurement of recoils in a Wilson chamber, measurement of length of recoil tracks in a photographic emulsion, and measurement of pulse heights from the ionization of hydrogen gas by the recoiling protons. One of the diffuculties is to be certain that an observed recoil or pulse really comes from a fission neutron which has not been scattered before producing the recoil which is detected. Also one must know within reasonable limits the angle through which the neutron was deflected in the recoil process. Furthermore the neutron must not have been of the delayed type, emitted by one of the fission products after one or more beta-dacays. Such delayed neutrons occur in roughly 1 per cent of the neutron emissions in U-235 and Pu-239. The action of a fission bomb of acceptable efficiency is so fast that these delayed neutrons cannot contribute to the energy release.

The problem was attacked at Stanford University as part of the atomic bomb project before the opening of the Los Alamos Laboratory, and continued as part of the program during the first eighteen months. The methods and results are discussed in Volume 3 of the Technical Series. A graphical indication of the data which are judged to be the most reliable is given in Figure 2. It is of interest that direct evidence of the presence of neutrons of higher than 9-mev. energy in the fission spectrum is obtained from the observation that effluent water from a water-cooled chain reactor has the 8-second activity of nitrogen -16, from the reaction:

$$_{8}O^{17} \quad (n,p) \quad _{7}N^{17}$$

The masses involved are well enough known to establish that this reaction is endothermic to the extent of 9.3 Mev.

1.2-2 Measurements of the Cross-Sections for High Energy Neutrons.

Figure 2 shows that the average fission neutron has an energy of about 1.7 Mev, and indicates the energy region through which the values of the nuclear cross sections needed for the calculation of the critical mass must be measured. It was therefore important to have sources of high-energy neutrons of known energy available for the investigations. These sources were

(1) The high-potential van de Graaf generator.

(2) The DD source.

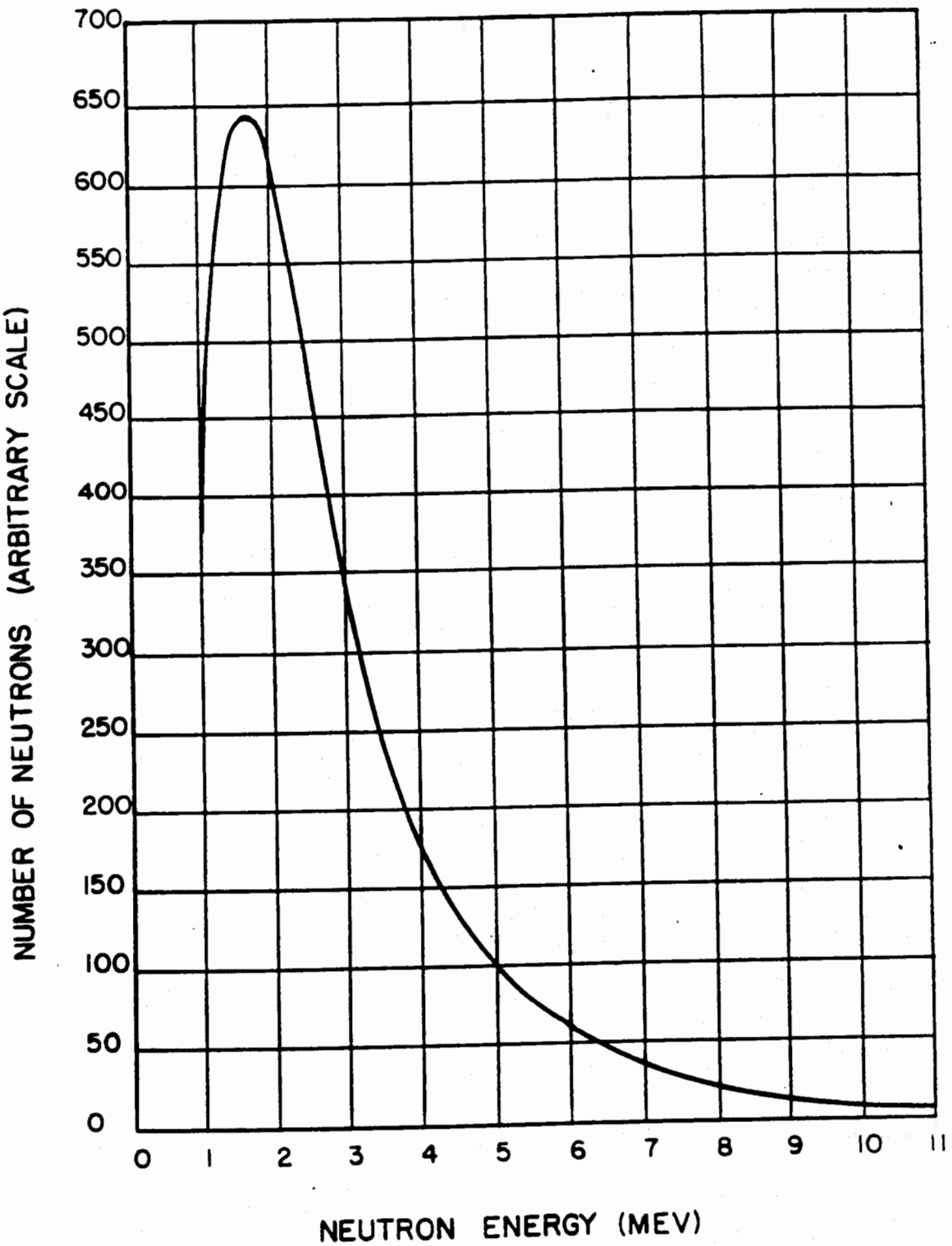
(3) Photo-neutron sources.

Two pressure van de Graaf generators were brought to the Los Alamos Laboratory from the University of Wisconsin. For the production of high-energy neutrons they used the reaction

$$_{3}Li^{7} \quad (p,n) \quad _{4}Be^{7} \quad ; \quad Q = -1.63 \text{ Mev.}$$

Figure 2

Relationship of Neutron Energy to the Number of Neutrons (The Energy Spectrum of Fission Neutrons)


NUMBER OF NEUTRONS (ARBITRARY SCALE)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11
NEUTRON ENERGY (MEV)

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ence of hydrogen, with its high moderating efficiciency, makes theoretical calculation diffucult. When it became apparent that although the presence of hydrogen lowered the critical mass, it reduced the efficiency disastrously, the hydrogenous bomb was dropped.(3) The albedo measurements were continued, however,

(3) See Part III, Chapter 2.

on metallic reflectors. A small heavy-ice target was placed in a cavity in the reflector material and the fission rate at another point in the cavity was measured directly with a U-235 fission detector. U-238 fission detectors, which are sensitive to neutrons above 1 Mev were also used. Protoactinium has a fission threshold at about 400 kev. Milligram amounts were acquired for the Laboratory by purchase from a private stock and made into detectors. Later neptunium-237 was found to have a threshold approximately equal to that of protoactinium and to be easier to handle chemically and to plate out on foils. Some 17 milligrams of this substance were obtained from a special run at the Hanford Plant, carried out at the joint request of the Los Alamos and Metallurgical Laboratories, in which roughly 20 milligrams were turned out.

The result of measurements on the scattering cross sections and actual albedoes of many substances, combined with considerations of availability, mechanical properties, and ease of fabrication finally led to the selection of tungsten carbide and natural uranium metal as the most promising possibilities.

[redacted]

Photo-neutron sources such as yttrium-Be-beryllium, and later, antimony-124-

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ysis and interpretation of the experimental results and to devise more accurate methods of calculation of the critical mass from the cross sections and albedoes observed. The elementary theory as presented in this volume was entirely superseded, as can be seen from Volume 4 of the Technical Series. The lack of uniformity in the neutron energy in the bomb was treated by introduction of a two-group and later a four-group theory in which neutron groups of different energies were postulated.

By December 1944, before any critical assemblies had actually been made, the "differential" measurements and theory had led to the following predictions

Critical Masses in Spherical Geometry
Estimated from "Differential" Experiments

Core	Reflector	Critical Mass of Core Kg
Plutonium metal density 19.6	None	11.5
"	tungsten carbide 9" O D	3.9
"	natural uranium metal, 9" O D	4.8
72% U-235, 28 % U-238, metallic	none	111
"	tungsten carbide 9" O D	30.5
"	natural uranium metal, 9" O D	32

The accuracy of these estimates may be obtained from comparison with the actual results quoted in the next chapter. Also, the critical mass was estimated to vary inversely as the 1.8 power of the concentration of U-235 in the incompletely separated uranium.

Figure 3 shows an early organization chart for the Los Alamos Laboratory, about June 1943. The emphasis on the physical measurements in the differential

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critical critical mass program is clearly indicated.

1.2-3 The Interral Method of Finding Critical Masses

(1) Reasons for using the active substances in metallic form, and the importance of metallurgy.

Because of the great difficulty and expense of preparation of the active substances U-235 and Pu-239, it seemed obvious that they should be used in such a form as to give the lowest critical mass. Later it was found that the implosion method necessitated qualification of a statement as simple as the foregoing, but if altered somewhat to fit this case, it remains true. In equation (27) for the critical mass the density appears explicity but also implicitly since L is inversely proportional to ρ as seen from equation (48). Thus the elementary theory predicts that the critical mass varies inversely as the square of the density. This result remains strictly true in the more exact treatment, and it is also true for an active core encased in a reflector if both core and reflector densities are altered by the same factor. More elaborate calculations show that the dependence on separate changes of core and reflector densities is roughly

$$M_c \sim \rho_t^{-1.4} \rho_r^{-.6} \qquad (49)$$

The greatest concentration of nuclei per cubic centimeter is attained in the metallic forms of the active materials, so that from the very beginning it was clear that the metallurgy of uranium and plutonium needed development at Los Alamos. Another reason is that the gun method of producing hypercriticality, which will be elaborated upon later, required materials which could stand the accelerations without breaking, and which could be machined, or otherwise fabricated, to the close tolerances demanded in a gun.

Fortunately, in the case of U-235, the metallurgy could be studied in advance by the use of natural uranium. Considerable work has been done at the Metallurgi-

to be due to an oxide of plutonium. Other diffraction patterns were too complex to be readily interpreted. In the meantime, experiments on the density of the metal by a direct displacement method were undertaken in which a tiny globule of the metal moved the meniscus of a liquid in a capillary tube. These measurements indicated densities of 18 to 19. A reliable density was not obtained for the form stable at room temperature until gram amounts were available when it was established that the so-called alpha phase has a density of 19.6.

Plutonium is remarkable for the number of its allotropic modifications and their peculiar properites. The alpha phase, which is stable up to about 116°C, has a crystal structure not yet decipherable and a density of about 19.6. There are beta and gamma phases stable in the region above the alpha phase and below 300°C. The delta phase, which proved to be of great interest in the implosion bomb, is stable above approximately 300°C, but may be produced in the super-cooled state if a few atomic per cent of aluminum or gallium is added to molten plutonium before solidification. Metallurgical studies of this type proved to be of the greatest importance in the development of the Los Alamos program.

Another problem indicated by the use of the active materials in metallic form is that of protection against corrosion. Both metals oxidize rapidly under atmospheric conditions, and the oxide does not form a protective coat, but flakes off, exposing more metal. The necessity of storing the metallic U-235 before use necessitated some corrosion protection. In the case of plutonium, an added reason for coating is the intense alpha activity which creates a physiological hazard if the bare metal is handled. Preparations were made for attempts to coat the metals by electrolysis, sputtering, evaporation, etc., of protective films.

The main chemical effort on plutonium, however, was the attempt to find methods

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Figure 4

First Enriched Water Pile
or "Lobo"

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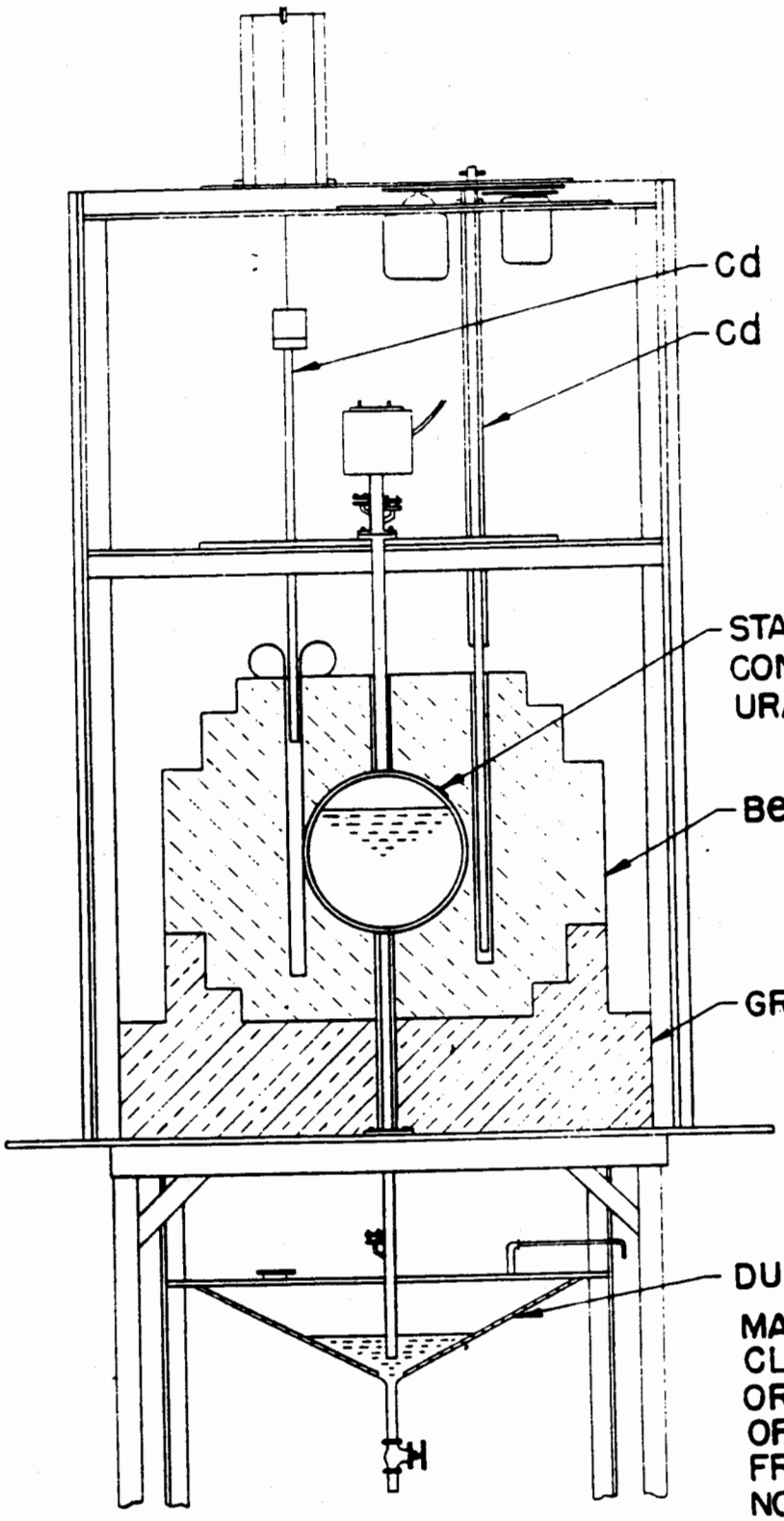

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(3) Integral experiments on the critical masses of uranium 235 and plutonium 239.

The gross features of the behavior of a set of spheres of active material with increasing radii is given by a study of equation (28), considered as a function of R, namely

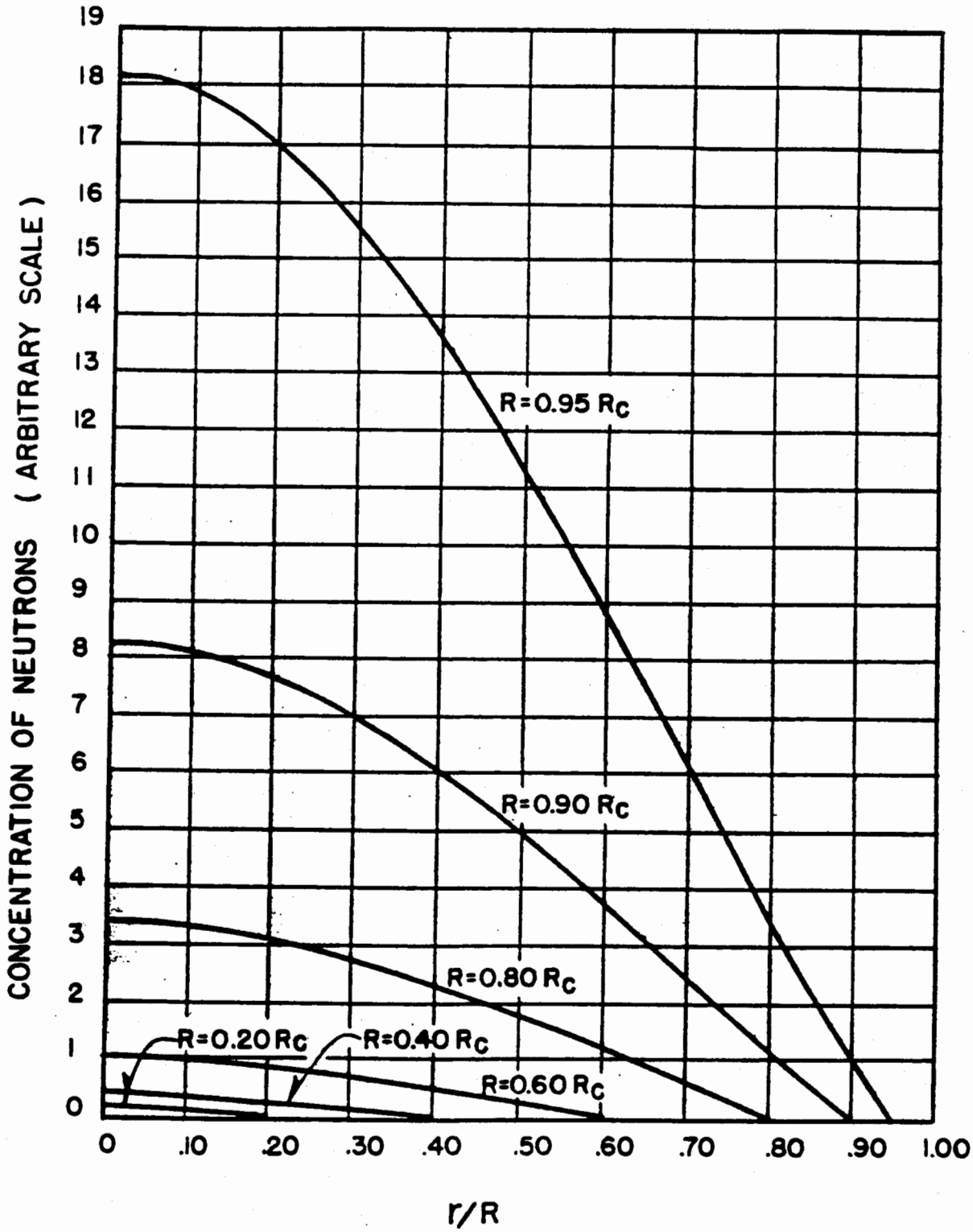
$$M(R) = \frac{q}{\pi^2 D} R_c^2 \left\{ \frac{R}{r} \frac{\sin\left(\pi r/R_c\right)}{\sin\left(\pi R/R_c\right)} - 1 \right\} \qquad (5C)$$

which has been derived for the case of a source uniformly distributed through the volume. For sources of other geometry, such as a point source at the center, the neutron distributions at low values of R/R_c, where there is little multiplication, would be altered, but near criticality all but traces of the original source distribution would have disappeared. Some illustrative curves are shown in Figure 6.

The first critical assemblies in solid form were made using mixtures of U-235 and hydrogen. The amount of U-235 needed to reach criticality in a hydride gadget with a reflector is roughly 5 kilograms depending on various factors such as the atomic per cent of hydrogen, the purity of the U-235, the density of the mixture, and the reflector. These amounts were available in the fall of 1944, and the critical assemblies were constructed at Omega site. (4)

(4) See also Chapter III, section 2.

In October 1944, the first all-metal multiplication experiments were made on U-235. Spheres, split along the diametral plane, and with a central cavity for the insertion of a neutron source, were constructed in 1.5, 2.0, and 2.5-inch diameters. They were made of metallic U-235 about 72 per cent pure. This amount was clearly so far below critical that no hazard was involved and the multiplication was measured in the main laboratory. In one type of measurement the mock fission source was placed at a certain distance from one of the special con-


CONCENTRATION OF NEUTRONS (ARBITRARY SCALE)
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
R=0.95 Rc
R=0.90 Rc
R=0.80 Rc
R=0.60 Rc
R=0.40 Rc
R=0.20 Rc
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
r/R

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The assembly was safely subcritical so that the work could be carried out by the Experimental Physics Division in the main Laboratory. It was completed on June 16 and indicated a critical mass of 6.41 kilograms.

These experiments were done at Omega site by the group specializing in critical assemblies.

Other critical determinations were made at various times, such as the critical mass of plutonium in aqueous solution, made primarily for the Hanford plant, and the conditions under which a chain reaction will start when an uncoated metallic U-235 surface is immersed in water, in preparation for the possibility that the U-235 bomb might have to be jettisoned in the ocean in a mishap to the plane transporting it.

Figure 2 shows an approximate organization chart of the Los Alamos Laboratory about April 1944, a year after the opening. If comparison is made with Figure 3, the great expansion of the ordnance division, and the attention being given to studies of assembly by the implosion method are outstanding. These developments are discussed in Part II.

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CHAPTER 2

THE PROBLEM OF THE EFFICIENCY

Samuel K. Allison

2.1 ELEMENTARY TREATMENT OF THE EFFICIENCY PROBLEM

The fact that enough of the active materials could be made available to reach assemblies of critical size for fast neutrons during the period of probable duration of the war did not in itself establish the feasibility of using the fast chain reaction as a bomb of military importance. It needed to be demonstrated that significant amounts of energy, the equivalent of that of thousands of tons of high explosive, could be released in the very short time before the breakup of the bomb. It is not obvious, prior to some consideration, that this can be actually accomplished.

The rough theory which we advanced in Chapter 1 showed that the neutron concentrations in a hypercritical spherical assembly without reflector increase as

$$\exp\left[\frac{\nu - 1}{\tau}\left(1 - \frac{R_c^2}{R_0^2}\right)t\right] \qquad (1)$$

where R_c is the critical radius, R_0 the initial radius, t the time and τ the "time of flight" or mean life of the neutron before capture. For convenience we will refer to the coefficient of t in the preceding expression as α.

One of the points of orientation in the discussion is the realization that about 50 generations in the fission process are required before the energy release begins to reach the interesting region. By a generation, we mean an increase in the number of fissions by a factor e. If we take the immediate energy release on fission as 1.7×10^8 electron volts (more energy, of course, comes out later in the activity of the fission products), we find that since

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sum of those preceding its inception. Thus during the 50th generation 1.7×10^{18} ergs are liberated, and added on to the total of 10^{18} liberated at the end of the 49th. For an order of magnitude calculation we can neglect the fact that α becomes smaller as the mass expands, and state that it is the final generation which blows the bomb apart. The increase in radius is $(R-R_0)$ and is accomplished in time $1/\alpha$. The velocity is then $\alpha(R-R_0)$. If we call $R_0 = R_c(1+\Delta)$ and treat Δ as small, we obtain

$$R - R_0 = \tfrac{1}{2} R_c \Delta, \tag{4}$$

so that the material velocity with which the bomb breaks up is $\frac{1}{2} \alpha R_c \Delta$, and the kinetic energy per gram used in the expansion is

$$\frac{1}{8} \alpha^2 R_c^2 \Delta^2 \tag{5}$$

This is proportional to pdv where p is the pressure and dv the volume change, and the total energy content of the material is proportional to pv. Thus the total energy released before breakup is

$$\frac{1}{8} \alpha^2 R_c^2 \Delta^2 \frac{R_0^3}{3R_0^2 (R-R_0)} \sim \frac{1}{12} \alpha^2 R_c^2 \Delta \tag{6}$$

If ξ is the energy released in a gram of fissions, the efficiency is

$$\text{Eff.} \sim \frac{1}{12} \frac{\alpha^2 R_c^2 \Delta}{\xi} \tag{7}$$

Some of the fundamental nuclear constants implicit in this expression are revealed by writing it as follows

$$\text{Eff.} \sim \frac{1}{3} \frac{(\nu-1)^2}{\tau^2 \xi} \Delta^3 R_c^2 \tag{8}$$

For assemblies as large as two critical masses, the expression indicates a low order of efficiency. Using

density	19 gm/cm^3	M_c	76 kg
$\nu - 1$	1.5	R_c	9.6 cm
τ	8×10^{-9} sec	M	140 kg
ξ	7×10^{17} ergs/gm	Δ	0.26

the calculated efficiency comes out around 2 per cent and even a modest

A proportional counter lined with paraffin to produce recoil protons from fast neutrons was enclosed in a foil of U-235 which was produced by the metallurgists. The assembly was placed in a larger vessel which could be evacuated or filled with gas under pressure, thus stopping the fission fragments near their point of origin. If delays in neutron emission were of dangerous time intervals, the neutron counting rate in the pulse chamber for a constant fission rate in the foil should have been greater with the fission fragments stopped close to the foil than with the outer vessel evacuated. No significant effect was observed, showing that the time delay was at least not enough to make a bomb impracticable.

In order to produce fissions in the foil without at the same time unduly increasing the background of fast neutrons in the pulse counter, neutrons produced by the cyclotron and slowed down in graphite were used. At the beginning of the Los Alamos Laboratory it was anticipated that a cyclotron would be required for many problems sure to arise in carrying out the program. The Harvard University cyclotron was obtained, transported to the site, and rapidly put into operation. It will be seen in the subsequent description of the work that through its discoveries were made which profoundly influenced the course of the project.

A thermal neutron flux of 10^5 cm^{-2} sec^{-1} in which the flux of neutrons over 100 kv was less by a factor of 25,000 could be produced by allowing the fast neutrons from the cyclotron to enter a pile of graphite roughly in the form of a cube seven feet on an edge. The conditions mentioned were obtained at a five feet from the entrance face. The Los Alamos Laboratory profited greatly by the extensive studies made at Columbia University and at the Metallurgical Laboratory on the slowing-down and diffusion of neutrons in graphite.

2.3 INTEGRAL EXPERIMENTS ON THE PERIOD OF THE CHAIN REACTION IN THE BOMB

In the first two years of the laboratory, extensive measurements were made

of inelastic cross section of tamper materials, and of the energies to which neutrons are slowed down by inelastic scattering. Much of the work of the theoretical division was devoted to the development of methods for predicting the multiplication rate α from these measurements, and reasonably accurate predictions could be made.

In the spring of 1945, when critical assemblies of U-235 and Pu-239 were available for experimentation, it was possible to make measurements which gave the e-folding time near criticality, and from which theoretical attempts could be made to extrapolate to the period effective in the actual bomb. Finally at the Alamogordo test shot a measurement of the actual period in the Pu-239 bomb was made.

In the laboratory experiments near the critical conditions, the delayed neutr and the sensitivity of the experiment to any moderated neutrons were complicating factors. The first experiments were performed on a U-235 assembly (Figure 1) brought to criticality in a reflector of tungsten carbide. One method used was to irradiate the assembly with a burst of neutrons from the cyclotron, and observe the rate of decay of the neutron intensity produced by the multiplication in the active materials. For this experiment elaborate instrumentation was required. The beam was brought out of the cyclotron and extended out through the shielding around the instrument. It was swept across a target in the slightly subcritical assembly by electrostatic deflection, and the counting rate at subsequent times registered by time delay circuits keyed to the sweep of the beam. The influence of small changes in the amount of active material on the decay period was studied, thus $M\, d\alpha/dM$ was obtained. The periods obtained in the tungsten carbide reflector were longer than expected, but this was attributed to a small number of neutrons slowed down through an unexpectedly efficient inelastic scattering mechanism in tungsten, plus the recoil effects in carbon. Such neutrons could not be effective in the 50 generations in a

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Figure 1

Experimental 2", 2½" and 3½" U-235 Spheres Used in the Integral Method of Finding the Critical Mass.

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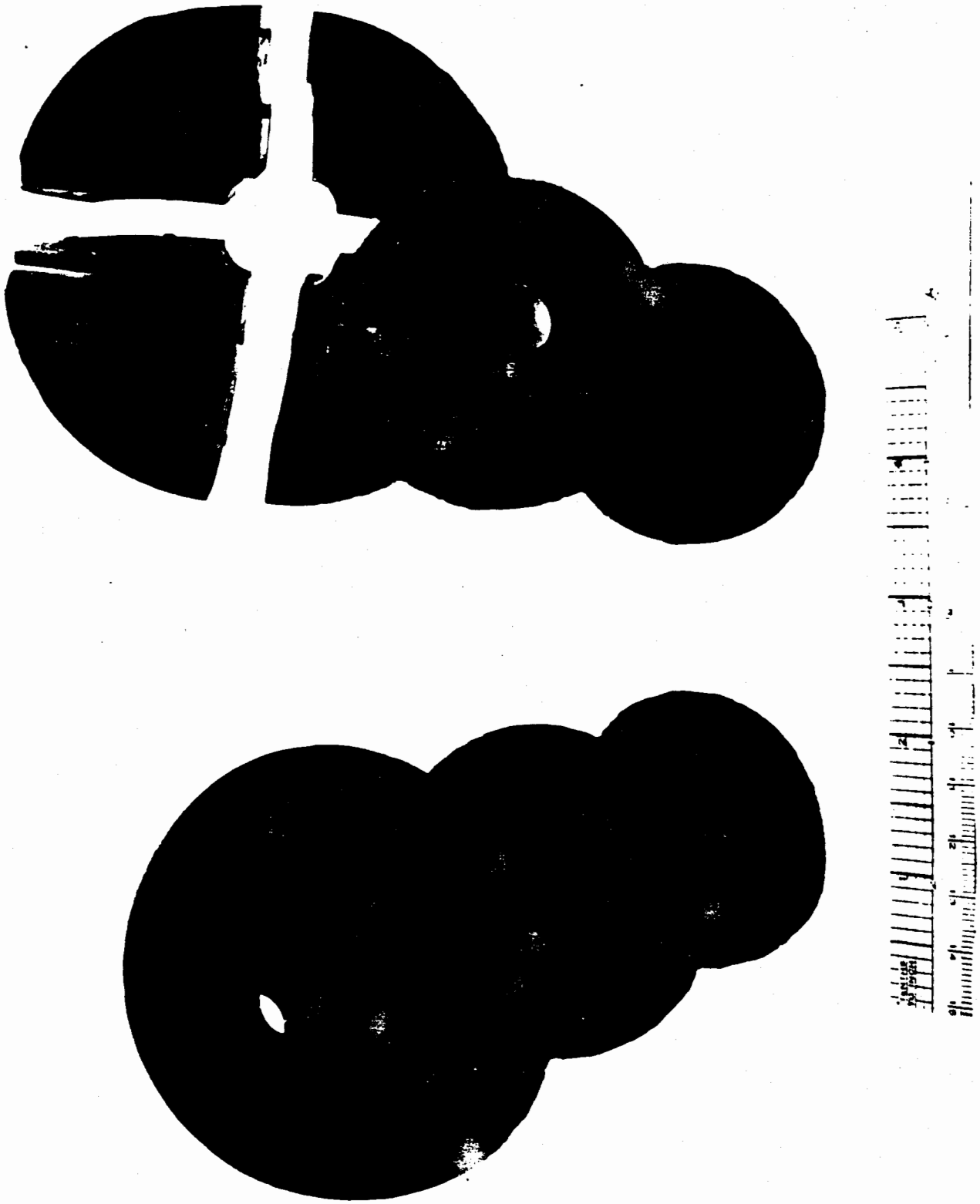

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highly hypercritical assembly, and the slow period observed near criticality was not judged to be grounds for discarding tungsten carbide as a reflector.

A second method was to allow the assembly to activate itself, through neutrons generated by spontaneous fission, the (α, n) reaction, or otherwise. This meant essentially studying the fluctuations in neutron intensity in a slightly subcritical assembly. This was carried out at Omega site, whereas the cyclotron method involved the transportation of the material to the cyclotron building.

The anomalous behavior observed in the tungsten carbide reflector did not appear when U-235 or Pu-239 was encased in a uranium reflector.

At the test shot at Alamogordo air base, two methods of measuring the period were set up. Aside from the great interest in obtaining the period directly from an exploding bomb, the measurement, as were many of those done at the test, was made in an attempt to localize the trouble if the bomb had been a failure. One experiment used electron multiplier tubes installed on the tower a few feet from the bomb to transmit a pulse whose increasing intensity was driven by the growth of γ-ray output as the chain proceeded. This pulse deflected the beam of electrons in a specially constructed tube.

In another method the burst of γ-rays caused ionization in a gas chamber with low collection time and the pulse was transmitted down a special low-impedance line to an oscillograph with a very high-frequency sweep. This instrument was obtained through the collaboration of the Radiation Laboratory at Massachusetts Institute of Technology. The oscillating beam was swept to one side as the pulse grew in intensity.

These experiments required coordination of many phases of the Laboratories' activities, such as instrumentation and fast ion chamber construction. The construction of the fast transmission lines at the test site was in itself a considerable undertaking.

[redacted] Indications of essentially the same α were obtained from the electron multiplier tubes.

2.4 PREDETONATION IN U-235 AND THE GUN PROGRAM

The problems presented by the possibility of predetonation of the bomb were of great interest and importance in the program of the Los Alamos Laboratory. The high explosives division and the "gadget" division of the Laboratory were entirely motivated by the demands of this problem, and additional contributions to their solution came from practically every part of the organization.

By predetonation is meant the initiation of the chain reaction when the bomb is in a slightly hypercritical configuration, but not in the configuration which gives high efficiency. This predetonation could take place from the appearance of a neutron in the active material during the assembly process. The cosmic-ray neutrons are much too infrequent to compare with other sources. In U-235 containing some U-238, the spontaneous fissions of the U-238 give rise to neutrons. The spontaneous fission of natural uranium, first discovered by Russian investigators, provided an unexpected background of neutrons in the first exponential graphite piles built at Columbia University in the attempt to find favorable conditions for the thermal chain reaction in natural uranium. The neutrons from spontaneous fission were multiplied in the subcritical piles until they could be detected by the activity they produced in indium foils, and it was determined that 1.7×10^{-2} neutrons per gram per second were emitted from natural uranium.

It was clear that part of the problem of Los Alamos was the determination of the spontaneous fission rates of all the atomic species likely to be found in the bomb. Preliminary experiments were undertaken at the University of California before the establishment of the Los Alamos Laboratory. Fission

Laboratory, and the results were available to the Los Alamos Laboratory.

Element	Ppm.
Li	85
Be	3.1
B	12
O	3650
F	37

The Chemical and Metallurgical Divisions of the Laboratory had the responsibility of producing U-235 metal in the proper form from the uranium tetrafluoride sent to the Laboratory from the Clinton Engineer Works, and were able to meet these tolerances rather easily.

DO
b(3)

of the summer of 1944, it was clear that the U-235 bomb could be assembled in this fashion, and the main developmental effort of the laboratory was focussed on the problems connected with securing a high efficiency and low predetonation probability in a bomb whose active material was Pu-239.

2.5 FUNDAMENTAL PROPERTIES OF NUCLEI CONNECTED WITH THE PLUTONIUM PREDETONATION PROBLEM

To a scientist interested in fundamental nuclear properties, the problems connected with the predetonation of the plutonium bomb were probably the most interesting ones solved by the atomic bomb project. The technological innovations brough forth by them were equally interesting and ranged from the development of cerium sulfide as a refractory material for crucibles to the invention of new high explosives of slow detonation velocity for the construction of explosive lenses.

In the latter part of 1942 it was realized in England and in this country that the predetonation problems in plutonium would be very serious if only because of the (α, n) reaction on impurities, and doubts were expressed whether the material could ever be used in an efficient fission bomb. The specific alpha activity is 2.46×10^9 α-particles per gram per second, greater than the specific α-activity of the Clinton U-235 by a factor of 2200. Theoretical calculations were made of the probability of the (α, n) reaction in the light-element impurities and showed that plutonium metal, made by chemical and metallurgical processes then unknown, would have to be extraordinarily pure. The theoretical predictions agreed very well with subsequent experiments on the (α, n) reaction caused by polonium. These experiments have been mentioned previously in the discussion of the (α, n) problem in U-235.

per gram per second. This emission would be attained if any one constituent in the following table exceeded the limit shown.

Element	Limit-ppm.
Li	1.3
Be	0.051
B	0.20
O	77
F	1.7

Realization of the severity of these limits initiated an extensive program in metallurgy, analytical and inorganic chemistry, and special refractories. The analytical work was divided between the Los Alamos Project and the Metallurgical Laboratory, with a consultant assigned to the task of maintaining liaison. Since beryllium and even oxygen, calcium, and magnesium would have to be avoided in the crucibles used for casting the metal, such refractories as cerium and molybdenum sulfides and uranium nitride were investigated under subcontracts at outlying universities, and many cerium sulfide crucibles were produced. Analytical methods were intensively studied in the effort to detect such small concentrations of impurities, and uranium or iron was used as a substitute for plutonium. Special difficulty was found in obtaining a sufficiently sensitive test for fluorine. Nevertheless by early summer of 1944 enough work had been done to indicate that the purity goals set could probably be attained. However, due to developments described below, the ultra-high purity program was dropped and the purity restrictions greatly relaxed.

In the summer of 1943 at Los Alamos, studies of the absorption of thermal and slow neutrons by fissionable atomic species were begun without a highly specific objective in mind, but on the sound basis that more fundamental information about the fission process had a high probability of being useful. To obtain mono-energetic neutrons the ion source in the cyclotron was modulated

the pile produced material will contain Pu-240. Investigations with the modulated cyclotron soon disclosed resonances similar to those observed in U-235, with a very large and prominent one at 0.13 electron volt. Experiments on the absorption cross section for fission compared to the total absorption cross section indicated an α of 0.49 in the thermal region.

The formation of Pu-239 and Pu-240 from U-238 placed in a bath of "pile" or essentially thermal neutrons can be described by the following differential equations.

$$dN_1/dt = k - \lambda_1 N_1 \qquad (9)$$

$$dN_2/dt = \alpha \lambda_1/(1+\alpha) - \lambda_2 N_2 \qquad (10)$$

N_1 = number of nuclei of Pu-239 per nucleus of U-238.

N_2 = number of nuclei of Pu-240 per nucleus of U-238.

k = $nv\sigma_r$(U-238), the flux times the radiative capture cross section of U-238.

λ_1 = $nv\sigma_t$(Pu-239), where σ_t represents the total absorption of Pu-239.

λ_2 = $nv\sigma_t$(Pu-240), where σ_t represents the total absorption of Pu-240.

and α has the meaning previously given. The equations take account of the possibility that Pu-240 may be destroyed as well as created by the neutron flux. It is convenient to express the postulated absorption by Pu-240 as a fraction of the absorption by Pu-239 and solve for special cases in addition to the general one. Thus let

$$\lambda_2 = x \lambda_1 \qquad (11)$$

then we have, in general

$$N_2/N_1 = \frac{\alpha}{1+\alpha}\left[\frac{1}{x}\,\frac{1-e^{-x\lambda_1 t}}{1-e^{-\lambda_1 t}} + \frac{e^{-x\lambda_1 t} - e^{-\lambda_1 t}}{(x-1)\,(1-e^{-\lambda_1 t})}\right] \qquad (12)$$

and as special solutions

$$x = 1 \quad N_2/N_1 = \frac{\alpha}{1+\alpha}\left[1 - \frac{\lambda_1 t}{1-e^{-\lambda_1 t}}\,e^{-\lambda_1 t}\right] \qquad (13)$$

$$x = 0 \qquad N_2/N_1 = \frac{\alpha}{1+\alpha}\left[\frac{\lambda_1 t}{1-e^{-\lambda_1 t}} - 1\right] \qquad (14)$$

Experience has shown that equation (14) gives a result sufficiently close to the findings, and thus it is indicated that the thermal neutron absorption coefficient of Pu-240 is small compared to that of Pu-239. If $nvt \ll 1$, equation (14) reduces to

$$\frac{\text{number of Pu-240 nuclei}}{\text{number of Pu-239 nuclei}} = \frac{\alpha}{1+\alpha} \cdot \frac{1}{2}\, nv\sigma_f(\text{U-239})t \qquad (15)$$

This means that the concentration of Pu-240 in Pu-239 increases as nvt. That is, the small amounts of Pu-239 which were produced at a very low nvt by cyclotron neutrons moderated and captured in uranyl nitrate will be very low in Pu-240/Pu-239 ratio, Clinton material will be higher, and Hanford plutonium f uranium irradiated for 100 days at fluxes of the order of 10^{13} will be relatively rich in Pu-240. In assaying the output of the Hanford plant, a rough measure of the time integral of the neutron flux to which the uranium has been subjected is the concentration of plutonium in the uranium at the time of chemical separation, which in the preceding equations we have called N_1. This concentration was measured at Hanford and repeated with each shipment. To an approximation comparable with equation (15), we have $N_1 = nv\sigma_f(\text{U-238})t$ and thus

$$\frac{N_2}{N_1} = \frac{\alpha}{4(1+\alpha)} \cdot \frac{\sigma_f(\text{U-239})}{\sigma_f(\text{U-238})} N_1 \qquad (16)$$

The coefficient of N_1 in actual practice is influenced among other things by the nonuniformity of the flux throughout the pile. By mass-spectroscopic analysis and another method mentioned below, the following empirical expression was obtained, analogous to equation (16).

(parts per million Pu-240 in Pu-239) = (parts per million Pu in U)·76 (17)

The concentrations of Pu in U at which Hanford separations took place varied

from 26.5 ppm in May 1945 to about 250 ppm by September 1945, so that batches of the extracted material contained from 0.2 per cent to 1.9 per cent Pu-240.

During the period July 1943 to July 1944, experiments by the physics group on the spontaneous fission of plutonium samples were underway. The first samples were of cyclotron-produced material and showed a small specific fission count of 0.01 fissions per gram per second. When material from the Clinton pile became available, it was inserted into the apparatus and showed a much greater specific activity of 0.05. A sample of plutonium was then irradiated in the Clinton pile and the specific fission activity jumped to 0.44 per gram per second. From the expected variation in Pu-240 content as discussed above, it was clear that it should be suspected of a very high spontaneous fission rate and of causing the effect. By July 1944, the cross sections of equation (15) and (16) were well-enough known to show that the increase in spontaneous fission activity was actually proportional to the calculated increase in Pu-240 content. The specific spontaneous fission activity of Pu-240 was found to be 450 per gram per second.

The neutron emission from this spontaneous fission greatly transcends the limit of 0.05 neutrons per gram per second which it was hoped to attain through chemical purification, since if the number of neutrons per fission is about 2.5, 21.4 will be emitted per gram-second, in material containing 1.9 per cent Pu-240. This result led to major changes in policy of the Los Alamos project, one of which was the abandonment in July 1944 of the vigorous program on plutonium purification. New and greatly relaxed chemical specifications were set so as to limit the (α, n) emission to 10 per cent of the spontaneous neutrons. The table of impurities for this, which should be compared to that previously given, is

Element	ppm to produce 10 per cent of spontaneous neutrons
Li	120
Be	4.3
B	17
O	5100
F	52

These limits are relatively easy to realize, and thus no difficult purification problem remained.

Plutonium arrived from the Hanford plant in the form of $Pu(NO_3)_4$, in concentrated aqueous solution. Specially constructed containers permitted discharge of the contents into purification trains set up at Los Alamos, where the nitrate was transformed into the tetrafluoride, and the reduction to metal carried out with calcium. In the late winter of 1944-45, after a fire had endangered the project by partially destroying one of the shops, it was realized that a fire-proof processing plant would have to be built for plutonium and polonium work. Plans were rapidly drawn up, and such a plant was constructed on a projection of the mesa to the eastward, at a distance of two to three miles from the main laboratory. The plant was ready to operate just at the time of the close of the war against Japan, and was given the code name "DP Site". Elaborate ventilation minimized the danger of inhaling dusts containing either plutonium or polonium.

A second consequence of the unavoidable high neutron emission was the abandonment of the gun method of assembly as a possibility for the plutonium bomb, and concentration of all effort for this bomb on the implosion method.

2.6 THE IMPLOSION METHOD OF PRODUCING HYPERCRITICALITY

is produced, i.e. by compression, the effect of this change on the overall reactivity and the critical mass is greatest if this change occurs in a region of high neutron flux, such as the center of the bomb. This is exactly where the high compression occurs, which is a further advantage of the implosion method.

The rewards of a successful technological development of implosion to produce hypercriticality were so clearly foreseen that work on a modest scale was begun at Los Alamos in the late spring of 1943. The first experiments were done in cylindrical symmetry, with a coating of high explosive around a cylindrical metal pipe. This involved the casting of high explosives and in the early days the Ordnance Division set up a small casting plant for shaped-charge production at the Anchor Ranch Site. Because of its high detonation velocity and consequently large impulse given to the metal liner, Composition B of RDX and TNT was used. The detonation was usually initiated at one point through a Primacord fuse. These early experiments showed that cylinders could be collapsed to solid rods and gave considerable promise. Methods of observing various stages in the implosion were developed during this period, with help from British scientists assigned to the project. Flash photography, using the light excited in argon from detonating high explosive, was used, also rotating prism cameras. Development work was begun on a flash X-ray method, in which an X-ray pulse of the order of a microsecond in duration was to be passed through the imploding material. The stage reached by the implosion at this moment was to be recorded by the response of a bank of Geiger counter tubes placed in a plane at right angles to the direction of propagation of the X-ray pulse. Such a technique would be limited to assemblies one or two inches in thickness.

During the progress of these investigations, it began to be realized by the theoretical physicists that attainment of hypercriticality by compression alone might be a relatively easy, although not the most efficient, implosion

method. Here the pressure produced would merely increase the density of a solid sphere, which under normal conditions was just subcritical. One advantage of this method seemed to be that it was relatively insensitive to the varitions from spherical symmetry in the collapsing detonation wave. As will be elaborated later, in the implosion of hollow metal liners, centrally directed jets had been observed which apparently formed at the points where detonation waves from different initiation points would be expected to meet. These jets would certainly be harmful to an efficient implosion, one bad feature being the likelihood of carrying reflector material into the center of the active material of the bomb. In a completely solid core such jet action seemed unlikely, except in radially directed flaws or cracks in the assembled material. A somewhat undesirable feature of the solid implosion was seen to be the relatively short time through which hypercriticality existed. For efficient performance, it was necessary to be certain that during the maximum of the hypercriticality sufficient neutrons would be present to insure inception of the chain reaction. This led to the development of the implosion initiator, also discussed later.

Throughout the development of the implosion program, the activities of the theoretical division, and specially of its calculating group, were of essential importance. With the help of British theoretical physicists, vigorous efforts were made to predict and understand the properties of matter under the extreme conditions of the implosion. An equation of state applicable to the enormous pressures and high temperatures was needed for the materials used, such as plutonium, uranium, aluminum, and high explosive. Existing data on the effect of high pressures on metals were sifted, and additional work on the compressibility of plutonium, uranium, and uranium trihydride was undertaken through a subcontract at Harvard University, where specimens prepared by the metallurgists at Los Alamos were used. Such data gave some of the constants

for a pressure region considerably below implosion conditions, i.e. the Harvard measurements extended up to 10^5 kilograms per square centimeter or 100,000 atmospheres. For conditions somewhat beyond the implosion region, an equation of state which could ignore the details of outer electronic orbits and use the Thomas-Fermi approximations was set up, so that estimates of the implosion conditions could be made by interpolation. Also the existing theories of the propagation of shock and detonation waves were critically analyzed and extended to the implosion conditions.

The basic relations in the hydrodynamics of the implosion problem are expressed in partial differential equations, and solutions of them by non-mechanical methods would have been impossible in the time available. Fortunately the Laboratory had acquired a set of International Business Machines, originally for calculations on problems of neutron diffusion. Considerable effort was expended in setting up the hydrodynamical problems in a form suitable for calculation by these machines, which then solved them mechanically. One of the many problems thus solved was the effect of substituting delta-phase plutonium for alpha-phase material in the solid implosion. The indication of a higher energy output contributed greatly to the decision to use the low density form.

During the period April 1943-December 1943, work on implosion development proceeded under the Ordnance Division at secondary priority. The gun programs occupied the main interest of the Laboratory. By the beginning of 1944, however, the theoretical advantages of the implosion method had become so apparent, and the preliminary development work was sufficiently promising so that the program became recognized as one of the major ones of the Laboratory. When the full import of the high spontaneous fission rate of Pu-240 was realized in July 1944, it became fully apparent that a successful implosion bomb was vital if fission bombs were to become of military value in the present

Figure 2

Organization of the Los Alamos Laboratory
March 1945.

[redacted] [redacted]

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3. TD CROSS-SECTION BRETSCHER
4. MEASUREMENTS WITH WATER CHAIN REACTOR ANDERSON

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2. X-RAY STUDIES PARRATT
3. MAGNETIC METHOD McMILLAN, E
4. ELECTRONICS HIGINBOTHAM
5. BETATRON KERST, NEDDER MEYER
6. RALA ROSSI, STAUB
7. ELECTRIC DETONATORS LOFGREN
8. LINER VELOCITY FROMAN
10. INITIATOR CRITCHFIELD
11. OPTICAL EQUIPMENT MACK
12. CORE AND REFLECTOR DESIGN HOLLOWAY MORRISON

O — ORDNANCE
PARSONS

1. U-235 GUN BIRCH
2. DELIVERY OF BOMB WALDMAN
3. FUZING BRODE
4. ENGINEERING AND DESIGN GALLOWAY
5. DAMAGE CALCULATIONS HIRSCHFELDER
6. BALLISTICS SHAPIRO
7. PRODUCTION AND PROCUREMENT LOCKRIDGE

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2. VAN DE GRAAF GENERATORS AND MASS SPECTROSCOPY J.H. WILLIAMS
3. D D SOURCE MANLEY
4. NUCLEAR PHYSICS E. SEGRE

T — THEORETICAL PHYSICS
H.A. BETHE

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2. CRITICAL MASSES SERBER, R
3. ALAMOGORDO TEST SHOT WEISSKOPF
4. HYDRIDES FEYNMAN
5. COMPUTING FLANDERS
6. IBM CALCULATIONS-NELSON
7. DAMAGE HIRSCHFELDER
8. NEUTRON DIFFUSION PLACZEK

X — EXPLOSIVES
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1. IMPLOSION RESEARCH BRADBURY
1B. TERMINAL OBSERVATIONS LINSCHITZ
1C. FLASH PHOTOGRAPHY-KOSKI
1D. ROTATING PRISM-HOFFMAN
1E. INSPECTION OF CASTINGS-TENNEY
2. DESIGN HENDERSON
3. MANUFACTURE ACKERMAN
3A. DEVELOPMENT HOPPER
3B. SPECIAL RESEARCH GURINSKY
3C. PRODUCTION POPHAM
3D. ENGINEERING WILDER
3E. MAINTENANCE CHAPPELL
4. MOLD DESIGN LONG, E
5. DETONATOR CIRCUIT FUSSELL
6. ASSEMBLY BRADBURY
7. DETONATORS GREISEN

[redacted] [redacted]

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considerable effort had been expended on it. [redacted]

[redacted] The method of X-ray detection, using Geiger counters, was more complex than the photography of an ion-cloud in a Wilson chamber as used in the betatron technique.

The so-called Rala method, perhaps the most daring in that it involved the practical use of a fission product whose recovery in other than small activities from irradiated uranium had not yet been accomplished, actually gave the most valuable data. Soon after the initial successful operation of the air cooled graphite pile at Clinton Laboratories in November 1943, the Los Alamos Project requested that Clinton Laboratories undertake the preparation of radio-lanthanum gamma ray sources of high specific activity. The fission yield of the mass 140 chain in which radio-barium and its daughter radio-lanthanum lie is about 5.4 per cent so that they are relatively common fission products. The 1.7-Mev gamma ray from the 40-day lanthanum 140 is the product desired. When the radio-lanthanum is kept in equilibrium with its parent, 12.5-day barium 140, the specific activity of the combination is essentially 75 millicuries per microgram, or one curie per 13 micrograms. Thus sources of thousands of curies strength are possible in fractions of a gram, even of impure material. The carrying out of this request at the Clinton Laboratories involved construction of a special extraction or "hot" laboratory, and finally a second such plant, using more permanent equipment designed by chemical engineers for the dissolving of highly radioactive irradiated uranium slugs and the recovery of the barium fraction from the solution. Once the material was prepared, it had to be transported, heavily shielded in lead, 1200 miles to Los Alamos in a time short compared to 12.5 days. This was done

in special trucks driven day and night by relays of drivers.

At Los Alamos, techniques had to be devised by the chemists to separate the radio-lanthanum from the barium and introduce it into the center of a mock-up of the implosion bomb. This had to be accomplished without health hazard, so that the services of the health group at Los Alamos were needed to monitor the operation. Three or four such separations were sometimes made from one shipment of radio-barium so that several implosion tests could be carried out.

The elementary law of absorption, neglecting scattering, for a gamma ray source at the center of a homogeneous sphere is

$$I = I_0 \exp \left\{ - \mu_a \rho \, NR/A \right\} \tag{18}$$

μ_a is the atomic coefficient for the gamma rays

ρ the density of the spherical absorber

R the radius of the spherical absorber

N the Avogadro number

A the atomic weight

Introducing M, the mass of the absorbing material, we may have ρ as the only variable, namely

$$I = I_0 \exp \left(-\mu_a \frac{N}{A} \sqrt[3]{\frac{3M}{4}} \, \rho^{2/3} \right) \tag{19}$$

If the implosion increases the density uniformly to ρ_f

$$\frac{I_f}{I} = \exp \left(\rho^{2/3} - \rho_f^{2/3} \right) \tag{20}$$

Banks of ionization chambers of short collection time were placed near enough the implosion test to pick up the gamma rays, but far enough so that

they were not destroyed by the blast of the high explosive before the compression of the core was completed. The ionization current in these chambers as a function of time was recorded on the sweep of an oscillograph.

The dimensions of a typical RaLa test of the solid implosion are shown in Figure 3. The core of active material, destined to be plutonium in the bomb, was simulated by cadmium. A conical plug, not shown, could be pulled out and the radioactive material inserted. As an illustration of the coordination of the various activities of the Laboratory, a RaLa test shot involved the following:

(1) Production of the RaLa under subcontract at Clinton Laboratories, Tennessee.

(2) Preparation of the test site with explosion-proof shelters, etc. (In the first RaLa experiments the electronic apparatus was housed in two Army tanks.)

(3) Casting and inspection of the shaped charge of high explosive by the Explosives Division.

(4) Preparation of radio-lanthanum from the radio-barium by the chemical group.

(5) Fabrication of the metal parts inside the high explosive by the Los Alamos shops.

(6) Filling and testing of four banks of ionization chambers.

(7) Calibration of the electronic circuits by the RaLa group personnel.

(8) Monitoring the site after the explosion for radio-activity (done by the Health Group).

The first ten RaLa implosions were carried out without benefit of electric detonation, and without explosive lenses.

[redacted] In spite of the great care

Figure 3

Typical Rela Test Assembly

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(b)(3)

produced a circle of less ionization in the center of the chamber, and the diameter of this circle could be measured before the implosion and at a known interval afterward, thus giving the average compression.

The magnetic method, which eventually proved capable of giving, in some respects, more detailed information than any of the others, was under vigorous development during the interval under consideration. Attempts were made to coordinate it with the betatron and RaLa investigations, because it was capable of giving a fiducial time pip showing exactly when motion of the metallic parts of the core began under the impinging detonation wave. At first the circuits for the magnetic method interfered, or appeared to interfere, with the control circuits appropriate to the main experiment, but continued effort finally made the magnetic measurements a valuable auxiliary of the betatron and RaLa tests.

A detailed magnetic record gives information on the reverberations of the shock waves through the metallic core that cannot be obtained any other way.

All these changes in the collapse velocity of the outer surface are in the magnetic record with the time intervals between them also evident.

The electric method during the period under consideration, gave very valuable information, essentially of a detailed or "differential" type. The projection velocity of metal liners in contact with detonating high explosive

was measured for various thicknesses of high explosive and various values of the ratio of outer radius to inner radius of the spherical shell of metal. The rate of advance of the shock wave in the various metals was also measured by embedding the pins, or contact points of the circuit, in the solid materials. The constants thus obtained were at once introduced into the theoretical calculations, so that the theory, although becoming more empirical, came to represent the experimental results more and more closely.

Certain experimental techniques for investigating implosions were left in the Explosives Division, such as flash photography of imploding cylinders and hemispheres, investigation of the recovered spheres after implosion, and observations of the simultaneity of arrival of a detonation wave at a surface by means of a rotating prism camera which swept the image across the photographic plate. These will be mentioned in the subsequent discussion.

2.7-2 The Development of Explosive Lenses

By the winter of 1943-44, the implosion program had advanced far enough to get into trouble.

The flash photography and pin loop experiments, together with theoretical investigations, showed that the jets occurred at those places where detonation waves from two different detonation points interacted, and that the low velocity was due to the behavior of the divergent spherical waves actually used

Figure.4

Upper figure Huygben's Construction for a Wave Initiating at O.

Lower figure condition that makes the Refracted Wave converge to a focus.

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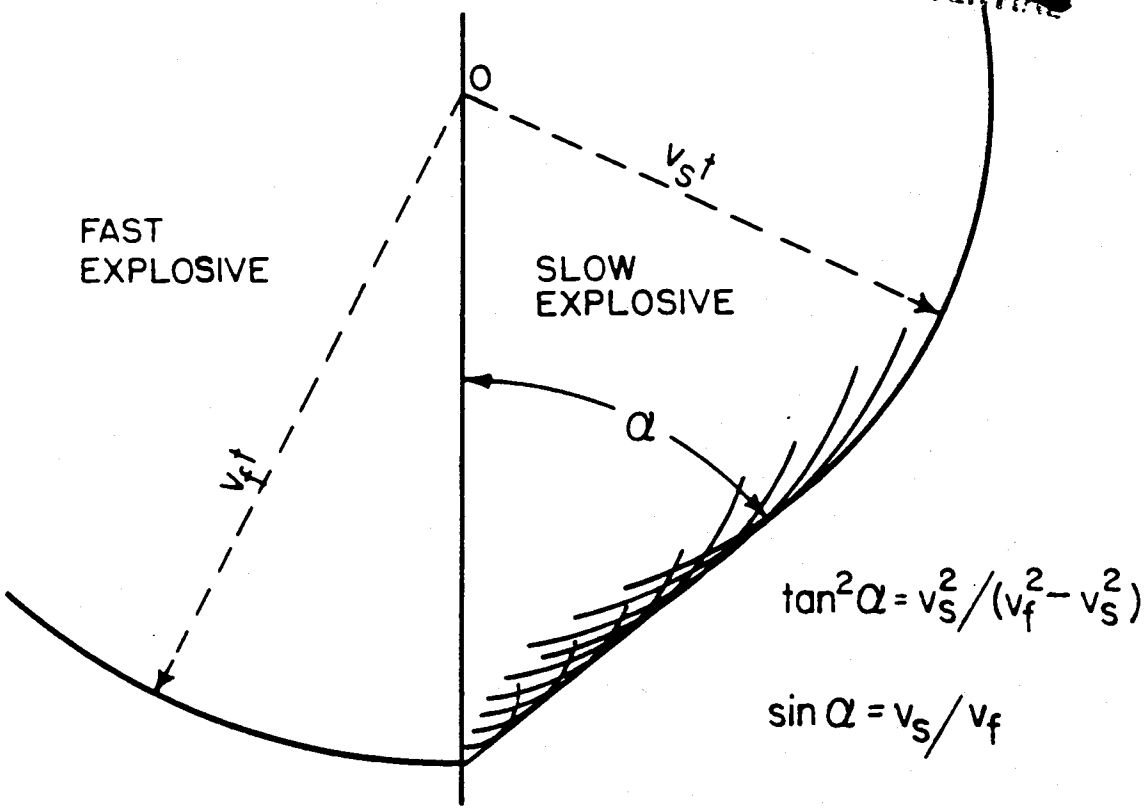

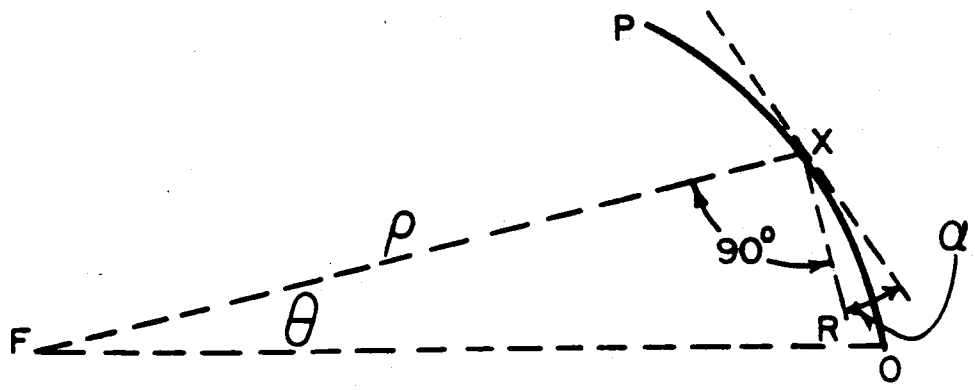

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Figure 5

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b(3)

From the very first, the idea of producing a smooth explosion with such lenses seemed inherently right, and although many technical difficulties appeared in carrying it out, and the question of dropping the effort came up more than once, the decision was always to press on with the development, and lenses were actually used in the test and combat implosion bombs.

In order to make lenses, explosives with low detonating velocities were needed. Not much effort had previously been put on this subject, obviously ex[illegible] low detonating velocity means in general lower brisance and destructive power. At first, the low velocity of detonation was obtained by using powdered explosives such as TNT tamped to a low density. A small two lens system was built using the components, Composition B and tamped TNT, which compressed a 1½ inch diameter iron sphere to a density of about 1.3 times normal, the compression being measured by flash X-ray photographs. Such slow explosives were too impermanent in characteristics for large scale and combat purposes and efforts were made to find explosives with good mechanical properties. A number of explosives containing barium nitrate were known to have promising properties, notably Baratol consisting of the following parts by weight: $Ba(NO_3)_2$ - 73 per cent, TNT - 27 per cent; and Haromal, containing $Ba(NO_3)_2$ - 50 per cent, TNT - 35 per cent, Al - 15 per cent.

In collaboration with the Explosives Research Laboratory at Bruceton, a study was made of these explosives, also, since lower density decreases the velocity, sintering and aerating of explosives was tried, also mixtures containing organic materials such as Durez synthetic resin.

Because of various disadvantages, such as lack of mechanical stability, lack of uniformity, difficulty of casting, etc., the completion of a satisfactory barium nitrate mixture was eventually laid aside to be considered in the future.

The stick velocity, or detonation velocity of Baratol along a cylinder with

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Not reviewed [illegible]

[redacted]

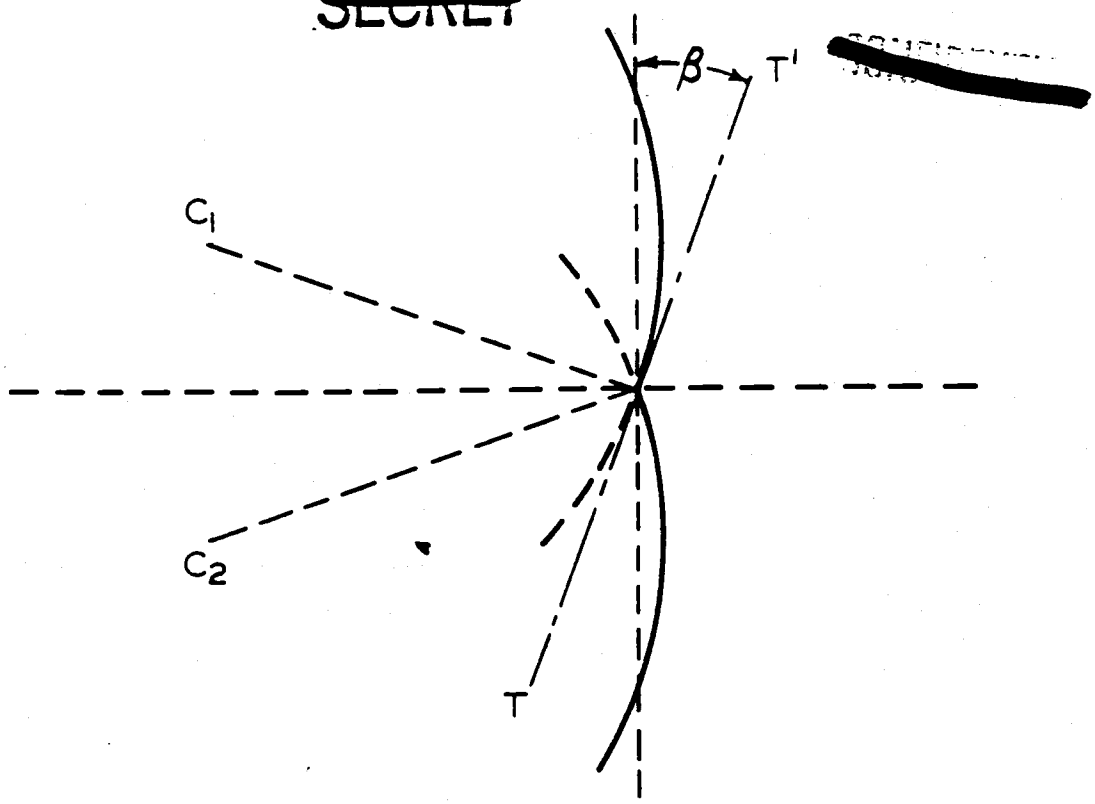
The large number of detonation points required means that the angle between radii to neighboring points is small. Thus in Figure 8, the distance from intersection P to the liner (showed as a plane surface) is small. If the detonation of intermediate point C_3 is so late that point P strikes the liner before the spherical wave from C_3 arrives, it is the angle β between C_1 and C_2 that is effective, and C_3 does not assist in taking the sharp corners off the front impinging on the liner.

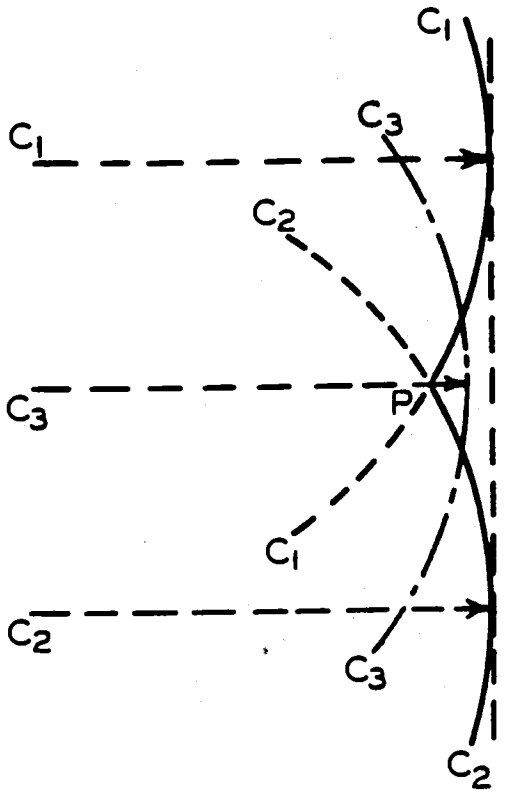
With the help of a subcontract at the California Institute of Technology, work in the "Gadget" Division was begun on electric detonation in the fall of 1944. The general idea was that the discharg

[redacted]

Figure 6

Relationship Between Shock Wave Fronts.


β
T'
C1
C2
T


C1
C3
C1
C2
C3
P
C1
C2
C3
C2

Assume that the active material in the first implosion bomb will be in solid spherical form and that the modulated initiator development will succeed, but if on May 1, 1945, a successful modulated initiator seems impracticable, be prepared to shift to a hollow implosion design. Prepare all mold parts to cast the inner charges in two shells of equal thickness, and assume, until experiment proves the contrary, that the innermost of the two shells must be Baronal to smooth out roughness from imperfect timing and lens design. Experiments should show, before May 10, whether the Baronal pad is necessary. If not, both parts of the inner charge can be made of Composition B."

A few weeks after this decision had been taken, the lens program at Los Alamos had made such satisfactory progress that the attempts at California Institute of Technology to make a non-lens fission bomb were practically abandoned. However, a large number of practice bombs, called "pumpkins", were produced for test drops and combat use in the periods between the dropping of fission bombs.

DO
b(3

The use of Baronal was dropped soon after the final program was initiated.

In order to carry out the final implosion program, which involved coordination of many activities of the Laboratory, the Director appointed the "Cowpuncher" Committee to supervise the program to its completion in the test at Alamogordo Air Base. The committee included

The Director of the Laboratory

Theoretical Division Leader

Explosives Division Leader

Ordnance Division Leader

sufficient in quantity so that land hold procurement could be removed from the highest priority rating.

2.9-3 The Implosion Initiator

One of the most crucial programs which the Newmember Committee had to supervise was the development of an initiator, which would spray neutrons into the active material at the optimum moment in the period of hypercriticality. The period during which the chain reaction must be initiated in a solid implosion is relatively short, and lasts only a few microseconds.

DOE b(3)

During February 1945, there was intensive discussion of implosion initiators, considering many types. In all cases the shock wave arriving at the center of the active material was to break up some prepared geometrical arrangement and permit α-particles to reach beryllium or gamma rays to eject neutrons from beryllium. The polonium-beryllium type was finally adopted, and the remaining question was the design of the geometry which was to be broken up by the shock wave.

Fortunately, the need of the project for polonium had been anticipated from the very beginning. The Research Laboratories of the Monsanto Chemical Company were asked to undertake the preparation of intense polonium sources. They acquired a considerable amount of uranium residues containing Radium D, and also looked into the possibility of preparing polonium by neutron irradiation of bismuth in the plutonium pilot and production piles at Clinton and Hanford. Experience soon showed that the latter method of preparing "artificial" polonium was much preferable. The chemical separation of polonium from bismuth

is more straightforward than the separation of Ra D from pitchblend residues and the subsequent milking off of polonium. The amounts which can be produced are indicated by the fact that 62 kilograms of bismuth irradiated at Hanford for 100 days will accumulate about 500 curies of polonium.

The technique of handling and depositing polonium was greatly advanced by the Project through its subcontract at Monsanto and the work of the chemists at Los Alamos itself. In order to have a low neutron background before the shock wave mixed polonium and beryllium, preparation of polonium deposits free from light element impurities which could give rise to the (α, n) reaction was essential.

During March and April 1945 a vigorous experimental program was underway in G Division for the testing of various initiators. Unfortunately no test which gave exactly the information needed could be devised.

It was impossible to verify that any one of the designs actually emitted in these crucial microseconds, since the total number of neutrons was far too few to detect. Terminal observations could verify that the initiator was emitting at the required rate a few minutes after the implosion.

The time set for freezing the design of an initiator for the solid implosion was May 1, 1945. By that time, although no conclusive experiments had been made, the experiments that were possible indicated that such an initiator was feasible.

The subsequent effort on initiator production showed that the process could be repeated with fair certainty of success on each effort.

2.8-4 Detonator and Detonator Circuit Design and Procurement

The design and procurement of a circuit to fire the electric detonators was also a critical Cowpuncher item. The experimental circuits supplied during the winter of 1944-1945 performed adequately but were not designed for inclusion in the bomb itself, and a carefully engineered and tested circuit had to be developed. The contracts for the manufacture of the circuit were placed

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Figure 7

Urchin Initiator.

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with the Raytheon Company, and the design was developed under consultation with a special group in the Explosives Division. The condensers for storing the charge which deflagrated the wires in the detonators and the mountings of the condensers had to be designed to withstand the accelerations of the airplane and the falling bomb. Severe shake tests were applied to the circuits produced, and also low-temperature tests to insure functioning after being kept at 30,000 feet altitude for several hours. Two hand-made Raytheon detonator circuits of the final design had been received by May 2, but production difficulties delayed shipment in quantity and by July 1, only 15 circuits had arrived at Los Alamos. Although these were ample for the Alamogordo test and the combat drop, the shortage of such circuits delayed the practice bombing at Wendover Field during the spring of 1945.

The detonators themselves had to be rugged and sure to function.

A design for the detonator (Y 1773) was completed on May 14 and manufacture of parts begun at various outlying points. At first, the detonators showed an alarming failure rate due to various causes, among them failure of the insulators, which often cracked under the stresses of assembly. The problem was finally solved by making the insulator parts of molded nylon. Considerable work was done on the exact procedures for preparing and pressing the PETN which was detonated by the deflagrating wire. During the work on wire detonators, development work on spark-gap detonators was kept in progress at Los Alamos and at California Institute of Technology. One of the advantages of a successful spark gap detonator would be the smaller amount of capacity needed to make it function. A disadvantage would be the possibility of the detonating spark jumping from a static charge accumulated during handling of the bomb. The wire detonators were actually used in the test and combat

shots.

2.8-5 Insertion of Boron Plastic Absorber

Early in June 1945, the Theoretical Division called attention to the danger of predetonation from neutrons slowed down in the explosive around the active material. The inner parts of the plutonium bomb were continually emitting neutrons from the background of the initiator, the spontaneous fission of Pu-240, and the (α, n) reactions.

However, once the high explosive is detonated, the temperature rises to some 3000° C, and the exploded material no longer slows down the neutrons to an energy at which their absorption in diffusing inward is certain. The sudden increase in these "hot" neutrons in the plutonium may detonate the fission chain before the correct moment of hypercriticality has been reached.

It was considered worthwhile to include a "hot"-neutron absorbing shell between the high explosive and the plutonium.

The first such hemisphere of proper dimensions for the bomb was produced by the metallurgists on June 29, and by the time of the Alamogordo test shot five such hemispheres were ready.

2.8-6 Final Dates

A trapdoor, or channel had been left so that after arrival at Alamogordo Air Base the plutonium, with the initiator embedded in it, could be inserted in the center of the bomb by temporarily removing one of the lenses. At 11 P. M. on July 12, the assembly was loaded in a truck and the convoyed journey to the test site begun. On the afternoon of July 13, the plutonium was inserted into the assembly, and on July 14, the bomb was hoisted up to the top of the firing tower, and the rest of the test was left to the organization set up for this purpose at the test site.

2.9 THE TEST AT ALAMOGORDO AIR BASE

The preparation for the solid plutonium implosion test at Alamogordo Air Base was not under the jurisdiction of the Compuncher Committee; a separate temporary organization of the Los Alamos Laboratory was created for this purpose called "Trinity", the code name of the site and test. The organization for

Trinity is indicated in Figure 8. The main objectives in the test were to obtain some measure of the energy release in the explosion, to make measurements of the air blast, and to carry out experiments which would reveal the cause of failure, if the test was unsuccessful. There were, of course, other experiments of technical and scientific interest.

The site for the test was chosen in the summer of 1944, a semi-desert tract in the bombing range of the Alamogordo Air Base, New Mexico, about 32 airline miles due west of the town of Carizozzo, at the base of the western escarpment of the Sierra Oscura Mountains.

The original plan was that an implosion with active material would be made in a vessel of some sort which would not burst from the effect of the high explosive alone, and thus the active material could be recovered in case of failure. In the fall of 1944, a large steel cylindrical container, known as "Jumbo" was designed, and it was eventually constructed, shipped to Trinity, and erected. By the spring of 1945, however, the probability of successful performance was high enough so that it was concluded that Jumbo need not be used. The presence of the steel casing of some 200 tons weight around the implosion would have made much more difficult any measurements of the energy released, or any blast measurements which could be used to estimate the effect of the bomb in combat.

A preliminary explosion was carried out at Trinity for calibration purposes, using 100 tons of TNT. This shot was fired on May 6, and calibration measurements on the air blast, earth shock, damage, were carried out, together with practice in photography. In order to obtain experience in measuring radioactivity on the ground after the shock, an irradiated uranium slug was shipped down from Hanford, dissolved in nitric acid and the solution piped into the stack of TNT boxes before the shot. The highly active fission products were mostly carried upward in the ascending cloud after the explosion, but

Figure 8

The Organization of the "Trinity" Implosion Test at Alamogordo.

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DIRECTOR OF THE ALAMOGORDO IMPLOSION TEST

K.T. BAINBRIDGE

CONSULTANTS TO THE DIRECTOR

PHYSICS	FERMI, WEISSKOPF
DAMAGE	HIRSCHFELDER
SAFETY	KERSHAW
EARTH SHOCK	LEET
BLAST	PENNEY
STRUCTURAL DESIGN	CARLSON
METEOROLOGY	CHURCH

ASSEMBLY OF THE TEST BOMB

BRADBURY, KISTIAKOWSKI

INITIATOR, CORE, REFLECTOR AND ALUMINUM LINER

HOLLOWAY, MORRISON

FIRING CIRCUITS	FUSSELL, HORNIG
DETONATORS	GREISEN, LOFGREN
UNIT ASSEMBLY	BRADBURY

TECHNICAL DIVISIONS

1 SERVICES	2 AIR BLAST & EARTH SHOCK	3 PHYSICS	4 METEOROLOGY	5 SPECTROSCOPY & PHOTOGRAPHY	6 AIR BLAST	7 MEDICAL GROUP
J.H. WILLIAMS	J.H. MANLEY	R.R. WILSON	HUBBARD	J. MACK	B. WALDMAN	NOLAN
1A CONSTRUCTION KEILLER	2A PIEZO GAUGES WALKER	3A MEASUREMENT OF ALPHA WILSON, ROSSI	4A RADAR CURTIS			7A INSTRUMENTS WATTS
1B TIMING Mc KIBBEN TITTERTON	2B CONDENSER GAUGES BRIGHT	3B DELAYED NEUTRONS RICHARDS	4B BALLOONS ALDERSON			7B MONITORS BARNETT
1C PROCUREMENT VAN GEMERT	2C EXCESS VELOCITY BARSCHALL	3C DELAYED GAMMAS SEGRE	4C RADIOSONDE TUDER			
1D TRANSPORT GREENE SWANK	2D IMPULSE GAUGE JORGENSEN	3D GAMMA RAYS MOON	4D BASE WEATHER BLADES			
1E RADIO COMMUNICATIONS STOKER	2E MAXIMUM PRESSURE GAUGE SHEARD	3E EFFICIENCY BY PERCENT CONVERSION ANDERSON				
1F BALLOONS GEARY						

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measureable radioactivity was found on the ground, and an estimate of what to be expected from the test fission bomb was possible.

One of the methods proposed for finding the efficiency of the fission bomb in the test was to collect radioactive residues, and measure the ratio of certain fission products to plutonium. From laboratory experiments on the branching ratio of the measured product, the fraction of the plutonium which had been transformed by fission could be estimated. In preparation for this work, the Metallurgical Laboratory was approached in the late winter of 1945, and asked to make some measurements on the fission yields in plutonium when the fission was caused by fast neutrons as in a fission bomb. The previous measurements on fission yields had been made on fissions induced by thermal neutrons. Experiments of this type were made by enclosing plutonium in a shell of uranium metal and placing the combination in a chain-reacting pile.

It was estimated that the most reliable efficiencies would be obtained by the use of fission products whose oxides were highly refractory like ZrO_2 and which did not have any gaseous ancestors in the fission chain. Furthermore, the period must be long enough to allow recovery from the crater, and careful chemical separation and counting. The fission products which gave the best yield results were 275-da cerium and 67-hour molybdenum. Measurements on 17-hour zirconium were somewhat less reliable, since it was found that the chemical methods used did not entirely separate zirconium from the neptunium produced. Measurements on the 12.5-da Ba-40-hour La combination showed low results on yield, as expected, since a gaseous xenon is known to exist in this chain.

After the test shot on July 16, the group assigned to the measurement of efficiency by residual activity approached the crater in tanks which had special lead protection against gamma rays installed. The tanks proceeded as far in as was safe and then fired rockets with cables attached into the crater. The

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in preparation for observations. Further time signals at -40, -30, -20, and -10 seconds were announced over the radio and the public address system. Announcements of -5, -4, -3, -2, -1, and 0 seconds were made over the public address system. The terrific flash of light as the bomb exploded at 0 time and the subsequent effects have been described many times.

Evidence of the energy released came mainly from three observations, the intensity and duration of the pressure wave in the atmosphere at a known distance, the rate of growth and ultimate size of the ball of fire as revealed in the Fastex camera shots, and the per cent of the plutonium transformed as revealed by radiochemical analysis of the crater dust. [redacted] The blast wave estimate was lower, and the ball of fire estimate higher than this figure.

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CHAPTER 3

THEIR METHODS OF ATTAINING THE EXPLOSIVE RELEASE OF NUCLEAR ENERGY.

Samuel K. Allison

3.1 THE AUTOCATALYTIC BOMB.

The idea that the initial mechanical effects produced by the nuclear explosion should increase rather than decrease the reactivity of the fission bomb is older than the founding of the Los Alamos Laboratory. Clearly a very high efficiency and a simplification of the initiation procedure might be possible in a bomb in which the e-folding time of the chain decreased markedly after the reaction got under way.

One of the most widely discussed possibilities was the so-called boron-bubble bomb. Its action would depend on the fact that the effective absorption cross section of a very potent neutron absorber is not its nuclear cross section times the number of nuclei present unless it is spread out in layers thin enough to prevent self-absorption. Thus if the mechanical effects of the early stages of the nuclear explosion would collect an absorber in which much surface was exposed into a small compact lump, it would greatly increase the reactivity by virtually eliminating the competitive absorption of the substance.

Boron-10 has the largest known absorption cross section for fast neutrons and thus is clearly indicated for such a purpose. The possibility of applying it to an autocatalytic bomb was one of the reasons favoring the decision to separate the boron isotopes on a commercial scale of operation.

The density of particles (nuclei and electrons) in elementary boron is about five times less than that in uranium metal. It can be shown that under such circumstances inclusions of B-10 in the active material would be highly compressed as soon as the heat liberated had vaporized the material and highly ionized the gas produced. The reaction time is too short for the boron to spread through the mass by diffusion before the explosion is over.

Such a scheme requires several critical masses of active material (at least five, for appreciable efficiency) which would be held below criticality by the competitive absorption of the boron. A small increment of active material would be shot in to start the reaction, and when the boron was compressed, the reactivity would jump to a high level.

Although considerable time and effort were spent in calculations on this and other autocatalytic possibilities, they never seemed attractive enough to become a main program of the laboratory. The initial amount of the active material required was too great and the calculated efficiency for any reasonable amount was too low. There always remained, however, the possibility that a new idea would arise which would obviate the bad features of the assemblies so far imagined.

3.2 THE HYDRIDE BOMB.

The existence of a hydride of uranium, first thought to be UH_4 and then shown to be UH_3, was discovered in 1943 at Iowa State College, where work under the Manhattan District was in progress. The hydride is pyrophoric if finely divided, and has a density of about 11. The availability of this substance stimulated thought and experiment on the general question of the use of hydrogen or deuterium mixed with the active material in a bomb.

The most attractive feature of such schemes was the lowering of the critical mass, and the possibility of an early use of a nuclear bomb before amounts

of active material sufficient for the all-metal bomb were available. In aqueous solution amounts of the order of half a kilogram of the active materials can become critical, but such aggregates are in no sense bombs, if only in that thermal neutrons constitute a link in the chain. If considerably less hydrogen is used, the hope was that the critical mass might be reduced from that of the metallic bomb without reducing the effective neutron energy to such a point that the e-folding time of the chain is so slow that negligible efficiency results.

Calculations of the behaviour of a hydrogenous bomb are much more difficult and uncertain than those for purely metallic assemblies. In order to check them and to obtain experience with solid critical assemblies, a program of finding hydride critical masses by the integral method was carried out at Omega Site in the late fall of 1944. This was before enough U-235 had arrived to reach criticality in encased metal spheres. In order to vary the size of the assemblies in small steps, the materials were made into cubes, one-half inch on an edge. The original program was to study the critical sizes of hydrogenous combinations from approximately UH_{30} down to UH_{10}, and then make a determination for UH_3. For the higher hydrogen concentrations the natural hydride had to be mixed with a hydrogenous plastic, after which it was compressed into the required shape.

The small critical masses which were anticipated were actually observed, i.e. it was found that 3.6 kilograms of 72 per cent pure U-235 in the mixture UH_{10} was critical if surrounded by BeO.

However, by the fall of 1944 the theoretical evidence pointed so strongly to very low efficiencies for a hydrogenous bomb that it was decided to abandon the program. The efficiency of a hydride bomb rises more slowly with the mass of U-235 used than does that of the metal bomb, and for efficiencies over a few tenths of a percent it is better to remove the hydrogen from a

measure the TT reaction cross section. The measurements depended on tritium extracted from cyclotron targets and hence only tracer amounts were available. In the energy range from 0.1 to 1.0 Mev the TT cross section proved to be unexpectedly high, greater than indicated by the nuclear dimensions.

Tritium can be produced in chain reacting piles, by using their excess neutrons in the reaction

$$_3Li^6 + {}_0n^1 \longrightarrow {}_2He^4 + {}_1H^3 + 4.7 \text{ Mev}$$

and the production in amounts of a few cubic centimeters was undertaken at the Clinton Laboratories at the request of the Los Alamos Laboratory. Lithium fluoride was introduced into the pile after being thoroughly outgassed, and the accumulated helium and tritium pumped off when the fluoride was subsequently heated. The tritium was purified by passing the evolved gas through hot palladium. In the early spring of 1945 amounts of tritium corresponding to about 1 cubic centimeter at S.T.P. began to arrive. An acceleration tube operating at voltages from 10 to 40 kilovolts had been prepared at Los Alamos with the aid of members of the British Mission, and it had been tried out with the DD reaction. The TD measurements confirmed the cyclotron results in that the cross section seems to be on the order of 100 times that for DD in the significant energy range.

Thus it seems that if tritium were prepared in nuclear reactors and put into liquid deuterium as a booster, the ignition temperature of deuterium could probably be reduced to a point where the mixture could be ignited from a fission bomb, and the reaction would spread to a much larger amount of pure deuterium.

A cryogenic laboratory with facilities for the production of liquid hydrogen was part of the original construction at Los Alamos, with the thought that eventually liquid deuterium might be produced for experiments leading to this "super" bomb. The "super" program, however, proved to be too much for the

laboratory to handle at high priority, and furthermore the idea of using artificially prepared tritium as a booster was not in the picture during the early days. It was judged that all effort should be spent on the production of fission bombs as being the only real possibility for shortening the war.

Calculations on the problem were kept going, however, and a fairly complete theory of its action, including its efficiency and time scale, were prepared. It was judged that although the certainty of successful operation was not as well established as was that of a fission bomb at the time of opening the Los Alamos Laboratory, nevertheless, especially with the tritium booster, no one was willing to state that the project could not be carried through. It was hoped that the international situation would not deteriorate to such an extent that it would be necessary to build such a terrific, purely destructive, nuclear reactor.

CHAPTER 4

THE FISSION BOMB AS A MILITARY WEAPON

S. K. Allison

4.1 THE DESIGN AS AFFECTED BY MILITARY CONSIDERATIONS

The bomb was intended to destroy military and naval installations w above ground, to destroy capacity to produce military equipment by attac and the homes of factory workers, and to disorganize economy by oblitera The only method of delivery to the target which was seriously considered it should be dropped from an airplane, on installations on the ground rat on ships or naval vessels.

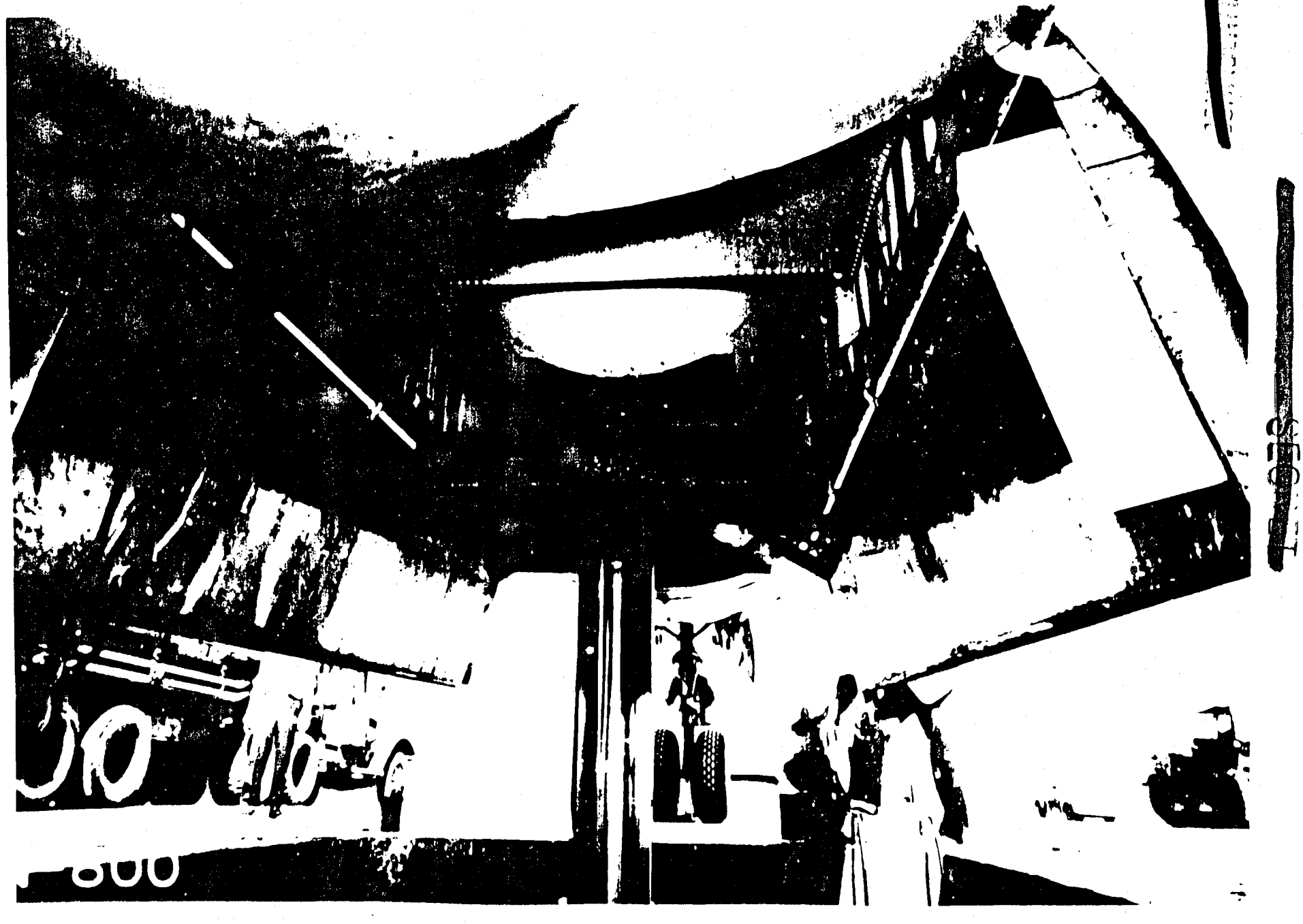
With this in mind, it became clear that the detonation of the bomb sh take place considerably above the level of the ground. The first reason f was that it was feared that impact with the ground would distort the rathe geometry needed to produce an acceptable energy release. Another reason is the radius of damage from a contact bomb is strongly affected by unevenness terrain; a slight rise will cast a protective shadow. Furthermore, if the fire is not allowed to come to its full expansion before it touches the gro other solids, energy will be used up in vaporizing these solids which might gone into the blast wave. At a much later date, a further benefit was real that detonation above ground would prevent contamination of the damaged are radioactive products, and not make the location uninhabitable for many year cessation of hostilities. Another point is that an expanding spherical sho incident on a plane surface sets up, by interference with the wave reflecte the ground, a more intense wave, called the Mach wave. This is in the form expanding cylinder whose axis is the perpendicular to the earth from the po detonation. The height of the expanding cylindrical surface is not accurat known, but for a fission bomb detonated 1850 feet above level ground it is

30 and 100 feet, at a radius where it still can act destructively on buildings. In this Mach wave the pressure and impulse transmitted to a vertical obstacle are roughly twice that in the primary wave from the detonation point. There is also a very strong wind following the passage of the Mach wave.

The estimate of the proper height for detonation varied greatly from time to time, some estimates being as low as 250 feet, some as high as 3000 feet. The mechanism planned in the bomb for this purpose obviously had to be flexible enough to allow adjustment within such limits when the final altitude was decided upon. Initiation by a barometric fuze alone was discarded, mainly because of the danger from turbulence and consequent pressure fluctuations around the falling bomb. A fuze whose action depended on the reflection of short wave radio signals from the ground was decided upon. Some experience with this sort of device had been gained in the development of the radio proximity fuze, carried out by the Office of Scientific Research and Development under the auspices of the Navy. Several men who had had experience in this work were shifted to the Los Alamos Laboratory. The fuze finally developed sends out a radio signal which is picked up in the falling bomb after reflection from the earth. If the reflected signal comes back too late, it finds an electrical gate closed in the receiving circuit so that the fuze does not operate. When the reflected signal comes back at the correct instant to pass through the opened gate, the fuze operates and transmits the amplified pulse to the detonator firing circuit in the implosion bomb or the firing circuit which touches off the powder in gun model. In order to make more difficult attempts of the enemy to find the wave-length emitted by the bomb and jam its actio the bomb emits signals only a short time before the correct height is reached. The height at which the emission of signals is initiated is controlled by a barometric switch. The development of the circuit was undertaken at Los Alamos in the Ordnanc Division and under a subcontract at the University of Michigan. Because of the gre value of the bomb and the consequent need for utmost reliability in its operation,

Figure 1

Hydraulic Elevator for Loading
Bombs into the Carrier Plane



H. M. S. O., OPERATION H.O. 79, SHOWING LIFT RAISING CRADLE AND F.d.

4.2 THE TEST PROGRAM AND THE COMBAT DROPS

An extensive program of test drops was carried out before any combat drops were made. In the implosion bomb (Figure 2), the design which was necessary to contain the necessary parts was not one which gave a high ballistic coefficient to the falling object. Initial drop tests at Muroc Army Air Base had shown oscillation and spinning in the fall of the first mock-ups which would prevent accurate aiming, and impose some undesirable accelerations on the inner parts. Considerable trought and effort was placed on the design of tail fins for the bomb which would produce streamlined flight, and this problem was eventually solved with a "box" tail (Figure 3). The problems of the gun model (Figure 4), which fitted into a casing of higher ballistic coefficient, and gave nearly perfect drops, caused much less concern.

The testing program, after a few initial trials, got underway in the latter part of the winter of 1945 at the Army Air Field at Wendover, Utah. In order to obtain experience in drops to sea level, test flights were made to the Salton Sea in central-southern California and drops made on the adjacent lowlands. At Wendover, a special squadron of modified B-29's trained themselves in all the operations likely to become a part of the combat missions.

The latter part of the test schedule was supervised by a Weapons Committee, which was set up at the same time as the Cowpuncher Committee. The work of the Weapons Committee was to plan in detail the drop tests, coordinate the tests with those undertaken directly by the California Institute of Technology, to select scientific crews for the final assembly and the combat drops in the Pacific, and to schedule their departures from Los Alamos.

In the test schedule many mock-up gun bombs and implosion bombs (Figure 5) were loaded, transported and dropped on various types of terrain and in water. S of the later drops contained informer circuits which sent out signals indicating what detonators had actually fired. The Salton Sea drops were some six hundred miles from the takeoff at Wendover, so the crews had the experience of taking off

[redacted]

[redacted]

Figure 2

Implosion Bomb "Fat Man"

[redacted]

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Figure 3

"Box" Tail

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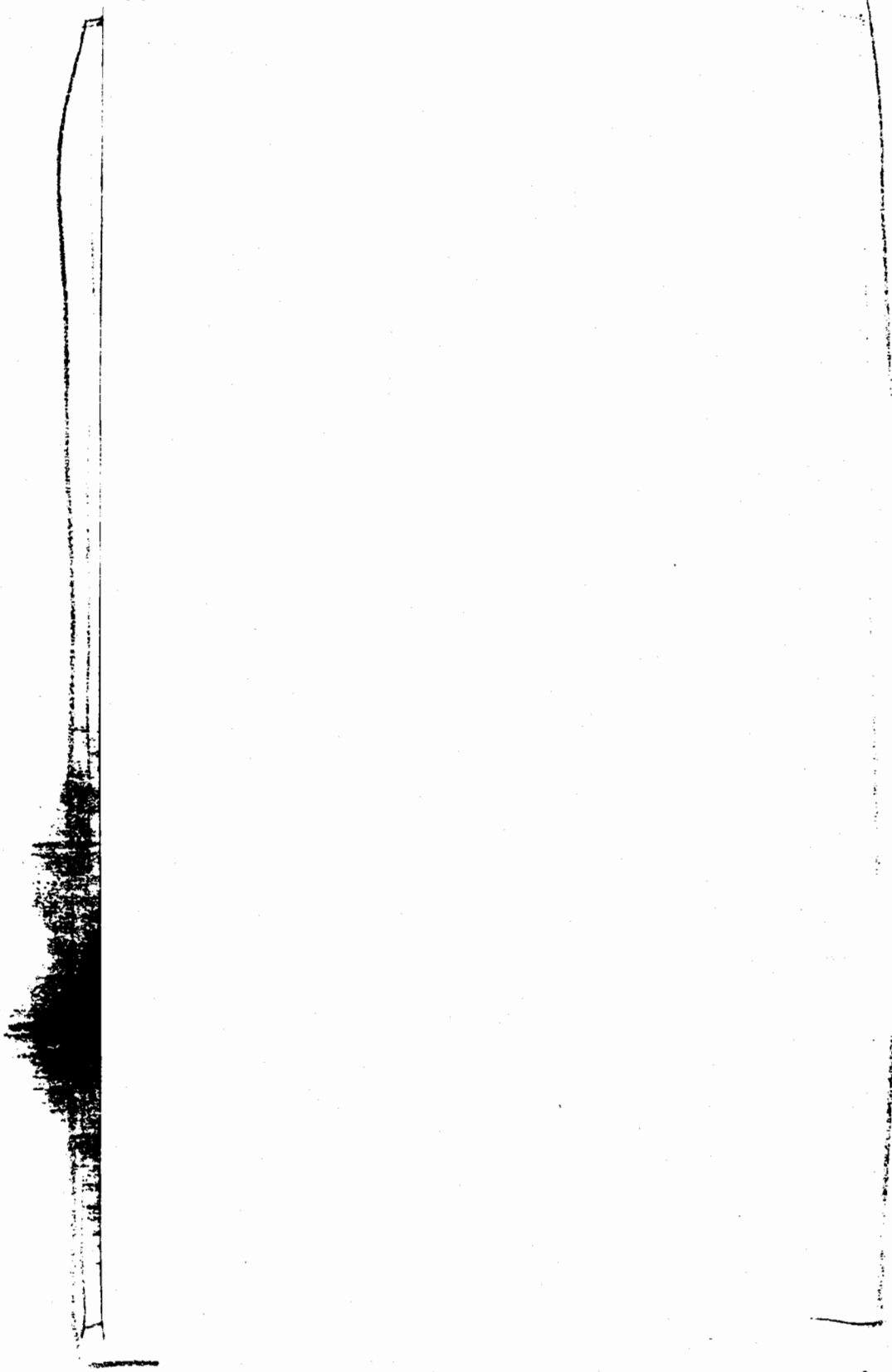

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[redacted]

[redacted]

Figure 5

Mock-up Implosion Bomb

[redacted]

[redacted]

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leaving Los Alamos late in June 1945.

On August 6, the U-235 gun fission bomb was dropped on Hiroshima (Figure 6). It detonated reasonably close to the prescribed height of 1850 feet, released 8000 tons TNT equivalent energy, made at least 60 per cent of the city uninhabitable, and caused uncountable deaths and casualties. On August 9, a plutonium implosion fission bomb was dropped on Nagasaki (Figure 7). It detonated at about 1640 feet elevation and released 30,000 tons TNT equivalent, obliterating the northern wing of the city. It seems that these two disasters finally made the hopeless military position of the Japanese evident to their leaders, and the unconditional surrender quickly followed on August 16, 1945.

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Figure 6

Hiroshima After Gun-Bomb Was Dropped

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Figure 7

Nagasaki After Implosion Bomb Was Dropped

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