This is a cover sheet for a SENSITIVE document. Transmission of the document must be covered by a signed receipt. It must not be left unattended or where an unauthorized person may have access to it. When not in use, it must be stored in a locked file or safe. While this document is in your possession and until you have obtained a signed receipt upon its transfer, it is your responsibility that the information contained herein is not compromised.

THE ENEMY WANTS THE INFORMATION CONTAINED IN THIS DOCUMENT. DON'T LET HIM GET IT THROUGH YOUR NEGLIGENCE.
A GENERAL SURVEY OF THE WORK OF THE LOS ALAMOS LABORATORY

Contents

Foreword

CHAPTER 1. THE PROBLEM OF THE CRITICAL MASS

Section 1. An elementary mathematical treatment of the critical mass problem.

Section 2. The differential method of attack on the critical mass problem.

Section 3. The integral method of finding critical masses.

CHAPTER 2. THE PROBLEM OF EFFICIENCY

Section 1. An elementary treatment of the efficiency problem

Section 2. Elimination of a significant time delay in neutron emission after fission.

Section 3. Integral experiments on the period of the chain reaction in the bomb.

Section 4. Predetonation in U-238 and the gun program.

Section 5. Fundamental properties of nuclei connected with the plutonium predetonation problem.

Section 6. The implosion method of producing hypercriticality.

Section 7. The work of Y and Z Divisions up to March 1, 1945.

Section 8. The Computation Committee and the final stages of the implosion program.

Section 9. The test at Alamogordo Air Base.
OTHER METHODS OF ATTAINING THE EXPLOSIVE RELEASE OF NUCLEAR ENERGY

CHAPTER 3.
Section 1. The autocatalytic bomb.
Section 2. The hydride bomb.
Section 3. Bombs from thermo-nuclear reactions.

CHAPTER 4.
THE PLUTONIUM BOMB AS A MILITARY WEAPON.
Section 1. The design as affected by military considerations.
Section 2. The test program and the combat drops.
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 $4 \times 10^{16}$ ergs. The energy release per gram of fissions of uranium 235 or plutonium 239 is taken as $7 \times 10^{14}$ 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 it 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 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.
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 so much 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 sub-critical, 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
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 $\phi$ 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, which it contains; in Pu-239 the alphas arise from its disintegration to U-235 with the char-

\[\text{(1)}\]

The U-235 supplied from the Clinton Engineer Works contains about one part in 120 of U-234; the half-life of U-235 is 7.47 $\times$ 10$^5$ years, and that of U-234 is 2.39 $\times$ 10$^8$ years.
antimatter half-life of order 10^{-6} sec. Actually, in 2003 a particle in the vacuum field, were not so typical for the spectrum in that of the total output than from the stored data.

Neutrons also appear in the material because of their radioactive decay. If \( N \) is the average number of neutrons emitted per neutron and \( T \) the mean life of those neutrons in the material, the number of neutrons captured per cubic meter per second is simply \( \phi T^{-1} \) and the number produced \( \phi \mu T^{-1} \), so that the net, 
access due to leakage is \((\phi-1) \phi T^{-1}\).

Neutrons enter and leave the region \((x,y,z)\) by diffusing through but do not escape. The net rate per cubic centimeter in the region is given by

\[
D \nabla^2 \phi = D \left( \frac{\partial \phi}{\partial x^2} + \frac{\partial \phi}{\partial y^2} + \frac{\partial \phi}{\partial z^2} \right)
\]

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

\[
\frac{\partial \phi}{\partial t} = D \nabla^2 \phi + (\nu-1) \phi T^{-1} + q
\]

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

\[
\phi(x, y, z, t) = F(x, y, z) T(t) + Q(x, y, z)
\]

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

\[
D \nabla^2 Q + (\nu-1) Q T^{-1} + q = 0
\]
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 (6) leads to

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

and using equation (4) we obtain

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

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

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

The time-dependent and space-dependent parts of this separated equation must actually be constant; it is convenient to call this constant $\nu$. Thus we have

$$\frac{1}{T} \frac{dT}{dt} = \nu$$  (8)

and

$$\frac{1}{F} \nabla^2 F = \nu \frac{1}{D}$$  (9)

Equation (8) clearly has the solution

$$T(t) = \exp \left( \frac{\nu}{\tau} t \right)$$  (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 (3) by assuming spherical symmetry. This means that
If \( \nabla \Phi \) is expressed in spherical coordinates \((r, \theta, \phi)\), only those terms in \( r \) will be retained. Thus equation (9) becomes

\[
\frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{d \Phi}{dr} \right) = \frac{\mu - \nu}{L^2} \tag{11}
\]

The standard method of solution is to introduce a new variable \( s = r \Phi \), which leads to the form:

\[
\frac{1}{s} \frac{ds}{dr} = \frac{\mu - \nu}{L^2} \tag{12}
\]

The solutions of this well-known differential equation, after replacing \( s \), are

\[
F = r^{-1} \left( c_1 e^{\frac{i \nu \Phi}{L}} + c_2 e^{-\frac{i \mu \Phi}{L}} \right) \tag{13}
\]

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

\[
F = r^{-1} e \sin \left( r \Phi \sqrt{\mu - \nu} \right) \tag{14}
\]

and the condition that \( F \) remain finite at \( r = 0 \), discard \( \delta \). We can summarize our results thus far by writing

\[
\Phi(r, t) = r^{-1} e \sin \left( \frac{r \nu \Phi}{L^2} \right) \sin \left( \frac{r \mu \Phi}{L^2} \right) + G(r) \tag{15}
\]

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

\[
\frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{d q}{dr} \right) + \frac{q}{\rho^2} = -\frac{\nu - \mu}{L^2} \tag{16}
\]

which, after the usual substitution \( s = r \), becomes

\[
\frac{d^2 s}{dr^2} + \frac{s}{r} = -\frac{\nu - \mu}{L^2} s \tag{17}
\]
This equation is of the type

$$\frac{d^2 y}{dx^2} + \alpha x + \theta y = 0$$  \hspace{1cm} (11)

its solutions may be found in any treatise on differential equations. The solution is, after replacement of $x$,

$$Q = r^{-1} \left( c_1 e^{-i \frac{2\pi}{L} r} + c_2 \frac{e^{-i \frac{2\pi}{L} r}}{D(r)} - \frac{q T}{L^2} \right)$$  \hspace{1cm} (12)

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

$$Q = r^{-1} \epsilon \sin \left( \frac{r \frac{2\pi}{L}}{D(r)} - \frac{q T}{L^2} \right)$$  \hspace{1cm} (13)

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

$$C = \frac{q T}{D(r)} \left( \frac{R}{L} \right)$$  \hspace{1cm} (14)

and the solution for $Q(r)$ is

$$Q(r) = \frac{q T}{D(r)} \left\{ \frac{R}{L} \sin \left( \frac{r \frac{2\pi}{L}}{D(r)} \right) \right\}$$  \hspace{1cm} (15)

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 at $r = R$. This gives us the condition that

$$\frac{R \frac{2\pi}{L}}{D(r)} = n \pi$$  \hspace{1cm} (16)

where $n$ is an integer. Thus there is an integer $n$ of units of $\frac{2\pi}{L}$ per centimeter.
for which there are acceptable solutions. Thus the solution of physical interest for spherical symmetry can be written

$$\phi(r,t) = r^{-1} \sum n c_n \exp \left[ \frac{1}{\tau} \left( \frac{r}{R} \right)^{\nu-1} \right] \sin \left( \frac{n \pi r}{R} \right) \frac{R}{r} \sin \left( \frac{n \pi r}{R} \right) \left( \frac{R}{r} \right)^{\nu-1}$$

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 critical material will increase without limit. If we construct larger and larger spheres, criticality is reached at

$$R_c = \frac{\pi L}{\rho \nu - 1}$$

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

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

where $\rho$ 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

$$\phi(r) = \frac{a_r}{\nu - 1} \left( \frac{R}{r} \right) \sin \left( \frac{n \pi r}{R} \right)$$

In a system of spheres of increasing $R$, we have

$$\lim_{R \to R_c} \phi(r) = \infty$$
and in the larger spheres the neutrons present are effectively multiplied many times. Multiplications of 8–10 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 will escape and they would remain inside, splitting the fissionable nuclei until... the active material was transformed or the neutrons absorbed in the accumulation of 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 hyperritical longer, allowing more energy to be released. Another distinctive 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 $\rho_c$ surrounded by a spherical shell of radius $\rho$, so that the thickness of the shell is $\rho - \rho_c$, as in figure 1. The product $D\tau$ is considered different in the core and the reflector, so that we have

$$\frac{1}{\tau_c} \neq \frac{1}{\tau_r} \quad (1)$$

We are interested in finding the effect of the reflector on the critical
size, where \( R = R_e \), the multiplication of neutrons is so great that the neutron distribution function

\[
\varphi_{\text{neutron}} = \frac{q}{\nu - 1} \left\{ \frac{\rho}{\sin \frac{\pi \rho}{R_e}} \right\}
\]

becomes essentially

\[
\varphi_{\text{neutron}} \approx \frac{q}{\nu - 1} \left\{ \frac{\rho}{\sin \frac{\pi \rho}{R_e}} \right\}
\]

In the reflector, where the sources \( q \) are negligible, the energy is given by the time-independent part of \( \varphi \), that is equation (1) with \( \nu = q = 0 \) so that we obtain

\[
y_\nu(r) = r^{-1} \left( c_1 \exp(-\nu L_\nu) + c_2 \exp(\nu L_\nu) \right).
\]

This can also be written

\[
y_\nu(r) = \sinh(r/L_\nu) + \cosh(r/L_\nu).
\]

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

<table>
<thead>
<tr>
<th>Region</th>
<th>Form of the neutron concentration function</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 &lt; r &lt; R )</td>
<td>( \varphi_\nu(r) = r^{-1} \sinh(\pi \rho R_e) )</td>
</tr>
<tr>
<td>( R &lt; r &lt; \rho )</td>
<td>( \varphi_\nu(r) = \rho^{-1} \left( \cosh(r/L_\nu) + \cos(r/L_\nu) \right) )</td>
</tr>
<tr>
<td>( r &gt; \rho )</td>
<td>( \varphi_\nu = )</td>
</tr>
</tbody>
</table>

The boundary conditions which must be satisfied are:

1. The two functions \( \varphi_\nu \) and \( y_\nu \) must have the same value at \( r = R \).
2. The neutron concentration \( \varphi_\nu \) must be zero at \( r = \rho \).
3. Since the flux \( \varphi_\nu \) through a section of the reflector is proportional to the \( \nu 
\)
   thickness of \( \varphi_\nu \), the density \( \varphi_\nu \) of the flux and of \( y_\nu \) must be equal at
   \( r = \rho \).

The solution of \( \varphi_\nu \) and \( y_\nu \) is given by

\[
\varphi_\nu(r) = \sinh(\pi \rho R_e) - \cosh(\pi \rho R_e),
\]

\[
y_\nu(r) = \sinh(r/L_\nu) + \cosh(r/L_\nu).
\]
Figure 1

Relation of Active Core Radius (R) with a Reflector (radius $\rho$) to Active Core Radius (Rc) without a Reflector.
A sinh \( B \rho \) + \( \cosh \alpha R \) = \( \sin \alpha R \) \hspace{1cm} (35)

A sinh \( \theta \) + \( \cos \alpha \rho \) = \( \eta \) \hspace{1cm} (36)

where \( B = \frac{1}{L_c} \) and \( \alpha = \frac{\pi}{L_c} \) \hspace{1cm} (37)

Solving for \( A \) and \( \theta \) in these equations leads to

\[
A = \frac{-\cosh \theta}{\sinh (\theta - R)} \sin \alpha R \hspace{1cm} (38)
\]

\[
\theta = \frac{\sinh \alpha \rho}{\sinh \alpha (R - \rho)} \sin \alpha R \hspace{1cm} (39)
\]

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

\[
\left\{ \frac{\cosh B (\rho - R) - \rho \theta}{\rho \theta} \right\} \sin \alpha R = \alpha \cos \alpha R - R^{-1} \sin \alpha R \hspace{1cm} (44)
\]

or

\[
\tan \left( \frac{\pi \rho}{R_c} \right) = \left( \frac{\pi L_c}{R_c} \right) \tanh \left\{ \frac{\rho - R}{L_c} \right\} \hspace{1cm} (46)
\]

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 (44) gives, under this condition, \( \tan \left( \frac{\pi \rho}{R_c} \right) = \infty \), meaning that the angle must be \( \pi \), 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

\[
R = R_c \left[ 1 - \frac{\pi}{\alpha} \arctan \left\{ \frac{\pi L_c \tanh \frac{\rho - R}{L_c}}{R_c} \right\} \right] \hspace{1cm} (47)
\]

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

\[
R = R_c \left\{ 1 - \frac{\pi}{\alpha} \arctan \frac{\pi L_c}{R_c} \right\} \hspace{1cm} (48)
\]
so that a reflector characterized by a length $L_r \gg R_0$ could reduce the critical radius to one-half and the critical mass to one-eighth of its value unenclosed. The attainable reductions are closer to a factor of four, than eight, in the mass, but in any case so much precious active material is saved that it was obvious from the first that a reflector must be used.

1.2 THE DIFFERENTIAL METHOD OF ATTACK ON THE CRITICAL-MASS PROBLEM

The critical masses of the materials U-235 and Pu-239 were obviously of fundamental importance. The amounts would indicate whether or not the factories as planned could possibly produce a bomb in a time comparable to the best estimates of the duration of the war, and thus they set the time schedule of the entire enterprise. The size of the equipment for suddenly assembling a hypercritical assembly is also influenced by this result. Although early estimates had been made and discussed considerably before the establishment of the Los Alamos Laboratory, and were continually being revised and improved, it was clear that a program on this problem was essential.

Enough was known to be sure that amounts of the active material sufficient for a direct "integral" attack on the problem would not be available for more than a year after the laboratory staff was assembled in April 1943. Such an attack would be to measure the neutron multiplication in larger and larger spheres and determine the critical radius by extrapolation. Since less than a gram of separated U-235 was available, and only a few micrograms of Pu-239, the initial efforts would obviously have to be along the line of "differential" methods, namely studies of the fundamental nuclear constants involved. Equations (27) and (43) give us indications of what these constants are. These equations explicitly involve the constants $\rho$, $L$, $L_r$, and the density $\rho$. The constant $L$, or diffusion length for absorption, needs further elucidation. It appeared in the equations merely as a symbol for $\sqrt{D}$. In the kinetic theory of diffusion
through gases it is shown that the coefficient of diffusion, \( D \), is given by

\[
D = \frac{1}{3} \lambda_{\text{tr}} v
\]

(44)

where \( v \) is the speed of the moving particles, and \( \lambda_{\text{tr}} \) 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

\[
\lambda_{\text{tr}} = (n \sigma_{\text{tr}})^{-1}
\]

(45)

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

\[
\sigma_{\text{tr}} = \sigma_f + \sigma_i \int \sigma_e(\theta)(1-\cos\theta) \, d\theta
\]

(46)

In this expression \( \sigma_e(\theta) \, d\theta \) is the cross-section for elastic scattering through angle \( \theta \) into the elementary solid angle \( d\theta \). \( \sigma_i \) 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, \( \sigma_i \) is the fission cross-section.

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

\[
\tau = (n \sigma_f v)^{-1}
\]

(47)

where \( \sigma_f \) is the fission cross-section. Thus we have

\[
t^2 = \frac{1}{\tau} = (3n^2 \sigma_{\text{tr}} \sigma_f)^{-1}
\]

(48)
In the reflector, the \( \Sigma \) involves the same concepts, but in reflectors of nonfissionable material \( \Sigma^* \) in equation (48) should be replaced by an ordinary absorption cross-section \( \Sigma^* \). 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 \( \Sigma_f \), \( \Sigma_s \), and \( \Sigma_a \).

1.2.1. The Problem of the Energy Distribution of the Fission Neutrons

All the cross-sections which must be measured in a "differential" attach 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 obviously needed. The problem is difficult even from the experimental point of view. Three different techniques of measuring 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 difficulties 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-decays. 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 0.5 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:

\[ ^{17} \text{N} \rightarrow (\text{n},\text{p})^{17} \text{O} \]

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 von de Graaf generator.
2. The DD source.
3. Photo-neutron sources.

Two pressure von 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:

\[ ^{14} \text{N} \rightarrow (\text{p},\gamma)^{15} \text{O} \quad q = 1.03 \text{ mev.} \]
The threshold for the reaction lies at a proton energy of 1.80 Mev because of the motion of the center of gravity.

One of the pressure tanks produced 4-Mev protons, which means that neutrons of known energy up to 2 Mev were available. At a given proton energy the energy of the neutrons changes with the angle from the proton beam, giving an additional method of variation. Using these neutrons, the cross sections for fission of U-235 and Pu 239 were measured from 5 kev out to 1600 kev. In addition to these studies, the cross sections for fission of U-233, Th -232, U-238, Pa-231, and Ne-237 were studied as functions of neutron energy. The application of the results to the problems of Los Alamos will be mentioned later.

The exothermic DD reaction

\[ ^1D^2 \to (d,n) ^3He \quad \Delta Q = 3.18 \text{ Mev} \]

has been extensively used as a source of fast neutrons of known energy. A high-potential set using transformers, rectifiers, and condensers according to the scheme used originally by Cockcroft and Walton for nuclear disintegration studies was brought to Los Alamos from the University of Illinois. It produces a constant high voltage of about 200 kilovolts for the acceleration of the deuteron beam. At this bombarding voltage the neutron energy varies from 3.08 Mev in the forward direction to 2.07 Mev backward. Since the energy liberated in the reaction is large compared to the available bombarding energies, variation in the accelerating voltage does not produce much change in the neutron energy. It was at first thought that the energy of these DD neutrons is about that of the average neutron from fission; actually their energy at 90°, 2.5 Mev is somewhat higher than this value.

This equipment was used for a study of the elastic and inelastic scattering of neutrons by elements which might be used as a reflector, in an attempt to select one by such "differential" measurements. Later a series of measurements was made to determine by a more "integral" method the albedo, or percentage of reflection from spherical shells of the best reflectors. These measurements were begun in the effort to find out how a bomb with hydrogen in it would act; the pres-
Figure 2
Relationship of Neutron Energy to the Number of Neutrons (The Energy Spectrum of Fission Neutrons)
ence of hydrogen, with its high moderating efficiency, makes theoretical calculation difficult. When it became apparent that although the presence of hydrogen lowered the critical mass, it reduced the efficiency disastrously, the hydrogenous bomb was dropped. The albedo measurements were continued, however,

(3) See Part III, Chapter 2.

on metallic reflectors. A small heavy-water 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 B-295 fission detector. B-298 fission detectors, which are sensitive to neutrons above 1 mev were also used. Protactinium 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 protactinium and to be easier to handle chemically and to plate out on foils. Some 17 milligrams of this isotope 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 30 milligrams were turned out.

The result of measurements on the scattering cross sections and actual albedos 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.

Photo-neutron sources such as yttrium-90-beryllium, and later, antimony-124-
beryllium were also used as mono-energetic neutron sources. The energy of the neutrons from the cyclotron produced tritium is about 20 kev, and of those from the neutron source, which can be produced from the excess neutrons in a chain reactor, is 113 kev. With such sources, which included radium-gamma-beryllium with its neutron groups at 216 and 113 kev, isolated points on the cross-section vs energy curves were obtained.

Considerable effort was expended in the search for a neutron source which would not be mono-energetic, but would reproduce the neutron energy distribution of the fission spectrum. The approach to such a feasible which was used at Los-Angeles was polonium-alpha-FE source, made by placing polonium on a foil and placing it in boron trifluoride gas at 14 atmospheres pressure. A polonium-alpha-coron source has a maximum neutron energy of 6 kev and a maximum of the distribution at 7.1 kev, which is too high to represent the fission spectrum. The addition of fluorine as a target for the polonium alpha particles brings the average neutron energy down closer to the fission spectrum value. The source was used considerably in the critical-mass program.

In order to measure the number of neutrons emitted from sources of various energies, or from sources not having uniform energy, such as fission, a special counter was developed whose detection efficiency was independent of neutron energy over a considerable range (from a few kev to 2 kev). This was accomplished by placing a slow-neutron detector along the axis of a paraffin cylinder. One method of verifying that the response of the device was independent of energy was to determine its counting rate for neutrons generated by a polonium-alpha-beryllium source and then to surround the source with a very light-walled spherical vessel filled with heavy water. This slowed down the average neutron without any absorption. The response of the counter was found nearly unchanged.

The work of the theoretical group in connection with the differential measurement program for critical-mass estimation was to give the most careful critical anal-
ysis and interpretation of the experimental results and to devise more accurate methods of calculation of the critical mass from the cross sections and absorptions observed. The elementary theory as presented in this volume was entirely superseded, as can be seen from Volume I 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 1941, before any critical assemblies had actually been made, the "differential" measurements and theory had led to the following predictions:

<table>
<thead>
<tr>
<th>Core</th>
<th>Reflector</th>
<th>Critical Mass of Core Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plutonium metal density 19.8</td>
<td>None</td>
<td>11.5</td>
</tr>
<tr>
<td>&quot;</td>
<td>tungsten carbide 9(^{\circ}) O D</td>
<td>3.9</td>
</tr>
<tr>
<td>&quot;</td>
<td>natural uranium metal, 9(^{\circ}) O D</td>
<td>4.8</td>
</tr>
<tr>
<td>72% U-235, 28 % U-238, metallic</td>
<td>none</td>
<td>111</td>
</tr>
<tr>
<td>&quot;</td>
<td>tungsten carbide 9(^{\circ}) O D</td>
<td>30.5</td>
</tr>
<tr>
<td>&quot;</td>
<td>natural uranium metal, 9(^{\circ}) O D</td>
<td>32</td>
</tr>
</tbody>
</table>

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 computation chart for the Los Alamos Laboratory, about June 1943. The emphasis on the critical experiments in the laboratory.
Critical critical mass program is clearly indicated.

1.2 The Integral Method of Finding Critical Masses

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

Because of the great difficulty and expense of preparation of the active substance 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 integral 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 explicitly but also implicitly since $L$ is inversely proportional to $\rho$ as seen from equation (44). Thus the elementary theory predicts that the critical mass varies inversely as the square of the density. This result remains strictly true in the 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

$$m_c \sim \rho \rho^{-0.10}$$

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 pin 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 pin.

Fortunately, in the case of U-235, the metallurgy could be studied in advance of the use of critical masses. Composite study has been done in the K-25 piloting plant.

23

GEOGRAPHICAL

23

GEOGRAPHICAL

23

GEOGRAPHICAL
Figure 3
Organisation Chart for the Los Alamos Laboratory about June 1943.
was to be used in the thermal chain reactors. The Los Alamos metallurgists were able to avail themselves of this information and add to it.

In the case of plutonium, the metallurgy was completely unknown at the beginning of the laboratory. In the absence of quantities sufficient for study, it had to be assumed that it would behave like uranium. This assumption, as fully anticipated, was quite far from the truth. The melting point is much lower, and the surprising number of anisotropic modifications with unusual thermal expansion coefficients are distinctive properties.

Uranium and plutonium are both such electropositive elements that reduction to the metal is a chemical problem of considerable importance. It is complicated by the highly refractive nature of their oxides, which do not melt in the reduction process, so that if they are used, globules of metal result which are covered on the outside with oxide particles and refuse to coalesce into a pool of liquid. The preparation of uranium metal by reduction of uranium tetrafluoride with calcium or magnesium had been developed on a small industrial scale by the time laboratory began operations, and it was hoped that a similar reduction would be effective for plutonium. Nevertheless, in the absence of the real evidence, it was clear that preparations must be made for the study of various methods of reduction of plutonium, which meant a considerable chemical program, and a laboratory with diversified chemical and metallurgical equipment.

The problem of the density of plutonium metal proved to be a difficult one to unravel. In the early fall of 1943, when only microgram amounts of reduced plutonium were available, attempts were made to get the density by means of the X-ray diffraction pattern. This work was done at the Metallurgical Laboratory on the initiative of the Los Alamos group. The first diffraction patterns which could have been metallic were shown by analogy with oxides of uranium and cerium.
to be due to an oxide of plutonium. Other distortion 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 bubble of the metal moved the meniscus of a liquid in a capillary tube. These measurements indicated densities of 19 to 19.1, a reliable density was not obtained for the form stable at room temperature until great amounts were available when it was established that the so-called alpha phase has a density of 19.0.

Plutonium is remarkable for the number of its allotropic modifications and their peculiar properties. The alpha phase, which is stable up to about 110°C, has a crystal structure not yet determined and a density of about 19.0. There are beta and gamma phases stable in the region above the alpha phase and below 310°C. The delta phase, which proved to be of great interest in the implosion bomb, is stable above approximately 360°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
of purifying it such that the fuel could be prepared free from traces of the light elements, as discussed later.

(2) Preparation of a site for critical-mass determinations, and determination of the critical mass in aqueous solution.

Previous to the establishment of the laboratory, only one chain reactor had been brought to critical size, namely, the first graphite-uranium pile at Chicago. The persons who had acquired this experience could not be transferred to Los Alamos because they were needed to help design the pilot air-cooled pile at the Clinton Laboratories and to move the Chicago pile to the new laboratory at the Argonne Forest site. In order to obtain experience in reaching the critical condition at Los Alamos, it was decided to bring to criticality an aqueous solution of a salt of U-235. A commitment was obtained from General Groves to supply several hundred grams of alpha-stage material from the Y-12 plant for this purpose. In this the fraction by weight of U-235 was about 15 per cent. Calculations indicated that criticality would be attained in a spherical vessel of 14 liters capacity containing 3.9 kilograms of alpha-stage material (U-235 content 14 per cent), with a beryllium oxide reflector.

A site called Omega was selected in Los Alamos Canyon for the critical-assembly tests. If proper precautions are not taken or accidents occur in the assembling of the reactor, the operation may be hazardous, with danger of an explosion, or at least, of an emission of a dangerous dose of neutrons, gamma and beta rays. Omega was located far enough from the main laboratory and the residential area so that an accident would not affect these localities, and within Omega itself special concrete shielding walls protected operators from radiations of the water pile. In order to obtain experience in reaching criticality at the earliest possible date, the first enriched water pile or "lobe" Figure 4 was not designed for operation at power. Later a more elaborate "water boiler" Figure 5 was built for use as a neutron source and cooled so that up to 6 kilo-watts could be dissipated.
Figure 4
First Enriched Water Pile
or "Lobo"
DUMP BASIN
MAY BE USED FOR CLEANING PURPOSES OR TO CHANGE GEOMETRY OF ACTIVE SOLUTION FROM CRITICAL TO NON-CRITICAL IN CASE OF EMERGENCY.
Figure 5
Second Enriched Water File or "Water Boiler".
(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 $b$, namely

$$W(b) = \frac{q}{\pi d} \left( R_c^2 \left\{ \frac{W}{r} \min \left( \frac{r}{R_c} \right) \right\} - 1 \right)$$

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 3 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 Chicago 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-
Figure 6
Concentration or Distribution of Neutrons
at Various Values of R/Rc.
stant efficiency counters, along its axis, and the counting rate taken. And the two metal hemispheres were placed around the source (a small cavity for it had been left in the center) and the count taken again. The ratio of the two counts, with appropriate correction, was the multiplication factor.

In another type of experiment an attempt was made to observe directly the volume integral of the neutron flux in the spheres. A thin U-235 foil was placed in the diametral plane and inert masks placed over it so that the area exposed at any radius was proportional to that radius squared. The fission fragments emitted from this foil and passing through the mask apertures were collected on cellophane foils, where activity was subsequently measured. A suitable calibration of the foils gave the actual number of fissions which had taken place throughout the spheres.

This method was carried through on the 2.0 and 2.5-inch spheres.

The fission mean free path for a fast neutron in metallic U-235 (about 15 centimeters) is much greater than the radii of these small spheres, so that an elementary theory of multiplication was sufficient in which it was assumed that the fraction of the original neutrons which made one fission in the mass before escaping was already small. The experimental values did not indicate any significant departure from the calculations based on the differential constants, but they were insensitive to modifications of the neutron spectrum which in larger spheres might be caused by inelastic scattering, and of course they did not involve reflection.

The program for finding the critical mass of metallic U-235 was completed in April, 1943. During February and March, metal spheres 3.5 and 4.5 inches in diameter were tested for multiplication, with and without reflectors of tungsten carbide and natural uranium metal. Experiments were also done on the distribution of neutron concentration in the active cores of these assemblies and out into the reflector surrounding them. For this purpose small channels were left through which ionization chambers could be inserted. Fission detectors of U-238, U-235 and Np-237 were also used in these channels to examine the energy of the neutrons.
at various radii. In one type of measurement, thermal neutrons from the power water boiler in Omega were introduced into the center of the sphere through a channel lined with cadmium and caused fission in a button of U-235 which formed one plate of a fission-counting chamber. This served as a neutron source, the output of which could be accurately counted. A second U-235 chamber explored the radial channel and gave the total number of fissions produced throughout the volume, and thus the multiplication. The results of all the experiments indicated that a sphere of 75 per cent pure U-235 of diameter 5.2 inches and total mass 22 kilograms would be critical in an infinite tungsten carbide reflector.

The actual attainment of criticality was accomplished by stacking bars and cubes of U-235 metal having a cross section $\frac{1}{2} \times \frac{1}{2}$ inch. Pseudo-spheres were constructed of these cubes and enclosed in reflectors of tungsten carbide and uranium metal. By combination of Equation (2b) and the time dependent part of (25), we get for the dominant term ($n = 1$),

$$\exp \left\{ \frac{\lambda t}{J} \left( 1 - \frac{R^2}{R_0^2} \right) t \right\}$$

(51)

which shows that as $R \to R_0$, the period of response can become very long compared to $t^*$, the mean life before capture. Furthermore, the mathematical treatment we have given neglects the delayed neutrons which have the effect of increasing the e-folding time near the critical condition. In the final experiments periods of 5 to 10 seconds were observed. Under such circumstances no external source of neutrons is necessary because of the great multiplication. During April 1945 criticality of metallic U-235 was attained under several circumstances which lead to the following results for the critical masses of 75 per cent U-235 at density 18.

<table>
<thead>
<tr>
<th>Reflectors</th>
<th>Critical Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten carbide</td>
<td>25.0 kg</td>
</tr>
<tr>
<td>Metallic uranium</td>
<td>28.0 kg</td>
</tr>
</tbody>
</table>
Expressions have previously been given (pp 21) for the dependence on purity and core and reflector density.

Because of the adoption of the implosion method of activating the plutonium boat, the exact determination of the critical mass under actual bomb conditions was very important. It was less so in the gun method of assembly, where two sub-critical masses were shot together. For the implosion method, it was desirable to get as much active material in as possible, but the danger that hypercriticality might accidentally be attained before use must be safely avoided. It was decided that a neutron multiplication of about 2 should be attained in a mock-up of the implosion bomb before the amount of plutonium could be considered adequate.

Another activity of the laboratory closely connected with the problem of finding the critical masses was the so-called quantity control. This procedure was necessary in order to make sure that none of the active materials were lost at any of the many stages in their fabrication, but it was also vitally necessary to prevent the accidental assembly of a hypercritical mass at any time in the fabrication procedures. The materials were often in the hands of machinists and other employees who could not be expected to be continually conscious of the peculiar behavior of the active substances with respect to critical mass. An elaborate system of inspections was devised so that the amount of active material in any room did not come near the critical limit. Thoroughgoing precautions were taken in all the operations so that in case of accident to a containing vessel the active material could always be recovered.

The program of integral measurements to determine the critical mass of Pu-239 began in January 1945, with the measurement of the multiplication of a 0.25-inch plutonium sphere made from material supplied by the Clinton pile. The techniques used were the same as with the small U-235 spheres. The plutonium of the sphere was in its alpha phase, presumed to be stable at room temperature, and having a density of 19.5. Enough Hanford material had arrived by January, 1945 to
begin the casting and pressing if a 23-inch-diameter plutonium sphere. Hard trouble was encountered in that domespheres with good diametral planes were found very difficult to take in the alpha phase. This phase is hard compared to the beta phase, which is stable in a range above 138°C and much more dense, involving a volume contraction of approximately 30 per cent. In pressing and cooling, a hoodlike, the outer spherical shell transforms into alpha phase first, holding back the plunger while the inner volume contracts and transforms, producing a dish-in-dialmelt plane. But in part to this difficulty it was decided on May 15, 1945, to abandon attempts to fabricate alpha phase cores and use instead the stabilized delta phase. In exploratory investigations the Chemistry and Metallurgy Division had found that this form is much more suitable for pressing and other metalurgical operations than is the alpha phase. The density is about 15.8 compared to the 19.5 of the alpha phase, and hence the critical mass is larger, but this does not result, in the fusion method of detonation, in a decreased efficiency or energy output. The delta phase requires admixtures of other materials to stabilize it. The first such material found was aluminum, but since aluminum generates neutrons through the (γ, n) reaction with the plutonium alpha particles, 5 atomic per cent of gallium was actually used to stabilize the delta phase.

The delivery schedule of plutonium from Hanford, with its rapid rise after May 15, 1945, compared to insignificant shipments before this time, combined with the difficulties in fabrication of the alpha phase, argued against a leisurely approach to the critical size through a succession of spheres, as had been possible with the U-235.
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 6.61 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, most 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 6 shows an approximate organization chart of the Los Alamos Laboratory about April 1945, a year after the opening. If comparison is made with Figure 7, the general 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.
Figure 7
Organization Chart of the Los Alamos Laboratory about April 1944.
CHAPTER 2

THE PROBLEM OF THE EFFICIENCY

Samuel I. 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

\[
\frac{N}{N_0} = \left(1 - \frac{R_0^2}{R_1^2}\right)^{-1/2}
\]

where \(R_0\) is the critical radius, \(R_1\) the initial radius, \(t\) the time and \(\phi\) 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 \(\phi\).

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 \(1.7 \times 10^8\) electron volts (more energy, of course, comes out later in the activity of the fission products), we find that since
$e^{50} \sim 10^{22}$ fissions, an energy release of $2.7 \times 10^{19}$ ergs has taken place. It is convenient to consider $4 \times 10^{10}$ ergs as the energy release per gram of detonated high explosive, and thus the equivalent of 70 metric tons of T.N.T. have been liberated. The next six generations will multiply this by a factor of 400.

The order magnitude of $\alpha$, if two or more critical masses have been assembled, is given by the reciprocal of the time of flight of the fission neutrons before capture. Using 2 Mev as the effective neutron energy and $1.32 \times 10^{-24} \text{ cm}^2$ as the cross section for fission of U-235 at this energy, we obtain, for metallic U-235, a time of flight of $8 \times 10^{-9}$ seconds, and an $\alpha$ of $1.2 \times 10^8$ seconds$^{-1}$.

If a spherical supercritical mass $M$ begins to expand, the critical condition will soon be reached because of loss of density and the chain reaction will stop. Equation (16), Chapter 1, can be interpreted as meaning that for a given reactive material in the critical spherical fars, the product $\rho \sigma$ (mass times density squared) remains constant. Thus if $\rho_o$ is the density of the active material under normal conditions where the critical mass is $M_o$ and $\rho$ the density at which an initially supercritical mass $M$ becomes critical

$$\rho \sigma^2 = M \rho_o^2$$  \hspace{1cm} (2)

If $R_o$ is the radius of the mass $M$ before the chain reaction is initiated, and $R$ the radius at which the chain ceases due to loss of density, we have

$$R - R_o = R_o \left\{ \sqrt[3]{\rho_o \sigma} - 1 \right\} = R_o \left\{ \frac{\rho_0}{\rho} - 1 \right\}$$  \hspace{1cm} (3)

It is typical of an exponential increase of the type under consideration here that the effects of the most recent generation are more important than the
sum of those preceding its inception. Thus during the 50th generation
1.7 x 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 \( \Delta \) 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 \( \Delta /\Delta \). The velocity is then \( \Delta(R-R_0) \).
If we call \( R_0 = R_0(1+\Delta) \) and treat \( \Delta \) as small, we obtain
\[
R - R_0 = \frac{1}{2} R_0 \Delta,
\]
so that the material velocity with which the bomb breaks up is \( \frac{1}{2} R_0 \Delta \),
and the kinetic energy per gram used in the expansion is
\[
\frac{1}{2} \alpha^2 R_0^2 \Delta^2
\]
This is proportional to \( p \Delta \) where \( p \) is the pressure and \( \Delta \) the volume change,
and the total energy content of the material is proportional to \( p \Delta \). Thus the
total energy released before breakup is
\[
\frac{1}{2} \alpha^2 R_0^2 \Delta^2 \approx \frac{1}{12} \alpha^2 R_0^2 \Delta^2
\]
If \( \varepsilon \) is the energy released in a gram of fissium, the efficiency is
\[
\text{Eff.} \sim \frac{\varepsilon^2 R_0^2 \Delta^2}{\Delta^2}
\]
Some of the fundamental nuclear constants implicit in this expression are
revealed by writing it in the form:
\[
\text{Eff.} \sim \frac{(\varepsilon-1)^2}{\varepsilon^2} \Delta^2 R_0^2
\]
For energies as large as the critical masses, this expression indicates
a low order of efficiency. Using
\[
\begin{array}{lcc}
\text{density} & 19 \text{ gm/cm}^3 & M_0 = 75 \text{ kg} \\
\rho_0 & 1.3 & R_0 = 9.6 \text{ cm} \\
\tau & 9 \times 10^{-2} \text{ sec} & M = 140 \text{ kg} \\
\varepsilon & 7 \times 10^{17} \text{ ergs/gm} & \Delta = 0.26 \\
\end{array}
\]
the calculated efficiency comes out around 2 per cent and even a modest.
improvement of the theory reduces it to the neighborhood of 1 per cent. Even at 1 per cent, however, since 1 kilogram of fission products is equivalent to 17,000 tons of T.N.T., an evolution of energy equivalent to that from 24,000 tons of T.N.T. would result.

2.2 ELIMINATION OF A SIGNIFICANT TIME DELAY IN NEUTRON EMISSION AFTER FISSION

Equation (8), this chapter, indicates that the efficiency varies inversely as the square of the mean life of the neutrons, which is taken as the mean interval between liberation of a neutron and its capture in a U-235 nucleus. It is clear that fast neutrons must be used and the bomb constructed of materials which will not moderate them, but another possible danger to the bomb existed at the time of organization of the Laboratory. This was that \( \gamma \) might effectively be increased by a delay in the emission of neutrons after fission had taken place. The existence of some 1 per cent of the neutrons with emissions delayed beyond a half-second was already known in the two active materials. If half of the emitted neutrons were delayed by as much as \( 10^{-8} \) seconds, thus noticeably increasing \( \gamma \), a very serious lowering of efficiency would result. In April 1943 no experimental demonstration existed which dismissed this possibility, and its disproof was one of the first tasks of the physicists at Los Alamos.

An experiment was devised which depended on the fact that neutrons delayed \( 10^{-8} \) seconds will not be emitted at the point where neutron capture occurred if the fission fragments are free to move away with their velocity acquired from the energy release. This velocity is about \( 1.2 \times 10^9 \) cm/sec, and if there should be a delay of \( 10^{-8} \) seconds in emission, the neutrons would be emitted 12 centimeters from the location of the nucleus before fission.
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 these facilities 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 kev was less than a fraction 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 RODS

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 $\beta$ 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 neutrons 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 material. 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 moderated 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 $\frac{d\beta}{d\theta}$ 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...
Figure 1

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 \( \alpha, \gamma \) 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 \( \gamma \)-ray output as the chain proceeded. This pulse deflected the beam of electrons in a specially constructed tube.

In another method the burst of \( \gamma \)-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.
Indications of essentially the same \( E \) 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 supercritical 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 pile 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 \( 1.7 \times 10^{-2} \) 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
detectors of high stability must be set up in situations remote from any neutron source (cyclotron, pile, etc.), and counting made automatic. Suitable corrections and precautions against effects such as the piling up of coincident $\alpha$-particle pulses to fission pulse height and the incidence of cosmic-ray neutrons must be taken. A special building for such purposes was constructed on a promontory several miles from the main laboratory. A program of spontaneous fission measurements was kept up during the entire war period of the Laboratory.

The atomic species in the U-235 bomb which might be suspected of spontaneous fission were U-234, U-235, and U-238, the latter in the active material itself and as a possibility for the reflector.

U-234 was present to the extent of 0.83 per cent of the U-235 content.

An upper limit to the spontaneous fission of this material is 30 per gram per hour, or about 0.021 neutrons per gram per second using a $\nu$ of 2.5.

There seems to be a slight spontaneous fission rate of $3.6 \times 10^{-4}$ per gram per second in U-235.

Many more neutrons can come from the ($\alpha$, n) reaction in improperly purified U-235 than from the spontaneous contributions. The alpha particles in the material furnished from Clinton are almost entirely due to the U-234 content, and the specific activity is $1.14 \times 10^6$ $\alpha$'s per second per gram. A careful study of the cross sections of the light elements for the ($\alpha$, n) reaction when the $\alpha$-particles are those from polonium was made at the Metallurgical
Laboratory, and the results were available to the Los Alamos Laboratory.

<table>
<thead>
<tr>
<th>Element</th>
<th>Ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>85</td>
</tr>
<tr>
<td>Be</td>
<td>1.1</td>
</tr>
<tr>
<td>B</td>
<td>12</td>
</tr>
<tr>
<td>O</td>
<td>3650</td>
</tr>
<tr>
<td>F</td>
<td>37</td>
</tr>
</tbody>
</table>

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.
It was obvious that a division of the Laboratory must be devoted to ordnance work and gun design. The Ordnance Division was staffed with experts on interior ballistics and soon acquired such standard pieces of ordnance as a 20-millimeter anti-aircraft gun and a 3-inch smooth-bore naval gun for preliminary studies. A firing site was set up at Anchor Ranch, about 5 miles south of the main laboratory. The idea of shooting both parts of the active material together was soon abandoned because of simultaneity difficulties and a special 6-inch gun was constructed to fire a projectile into a stationary target.

Fortunately the two parts of the active material could be made from metallic uranium and shot together with confidence that the same mechanical properties would be exhibited by U-235.

The Chemistry Division of the Laboratory spent considerable time in studying the techniques of polonium deposition for this purpose, but mainly for the much more difficult explosion initiator.

No serious difficulties were encountered in the gun program. By the end...
of the winter of 1941, it was clear that the U-235 bomb could be assembled in this fashion, and the main developmental effort of the laboratory was focused on the problems connected with securing a high efficiency and low pre-detonation probability in a bomb whose active material was Pu-239.

4.5 FUNDAMENTAL PROPERTIES OF NUCLEI CONNECTED WITH THE PU-239 DETONATION PROBLEM

To a scientist interested in fundamental nuclear properties, the problems connected with the pre-detonation of the plutonium bomb were probably the most interesting ones solved by the atomic bomb project. The technological innovations brought 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 pre-detonation problems in plutonium would be very serious if only because of the $(\alpha, n)$ reaction on impurities, and doubts were expressed whether the material could ever be used in an efficient fission bomb. The specific alpha activity is $2.46 \times 10^7 \alpha$-particles per gram per second, greater than the specific $\alpha$-activity of the Clinton U-235 by a factor of 2200. Theoretical calculations were made of the probability of the $(\alpha, n)$ 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 $(\alpha, n)$ reaction caused by polonium. These experiments have been mentioned previously in the discussion of the $(\alpha, n)$ 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.

<table>
<thead>
<tr>
<th>Element</th>
<th>limit (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>1.3</td>
</tr>
<tr>
<td>Be</td>
<td>0.051</td>
</tr>
<tr>
<td>S</td>
<td>0.20</td>
</tr>
<tr>
<td>C</td>
<td>77</td>
</tr>
<tr>
<td>F</td>
<td>1.7</td>
</tr>
</tbody>
</table>

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...
so that the emission of neutrons from the target was intermittent. Time-
delay circuits activated the neutron detectors, which were placed a few meters
away and thus recorded neutrons having a known time of flight and thus a known
velocity. In this way the cross section for fission of U-235 was measured in
the neutron energy interval from 0.01 electron volt to 1000 electron volts
with a varying limit of resolution which was about 0.16 electron volt at
1 electron volt energy. One purpose of the work was to find out how closely
the 1/v law of variation of absorption cross section represented the facts for
U-235 in this region, and very interesting deviations were at once discovered.
In fact, there are resonances of surprising sharpness in the energy dependence
of the cross section of U-235 leading to fission. A prominent one lies at
1.1 electron volt energy and has a width at half maximum of about 0.2 electron
volt. According to the uncertainty principle this means that the fission
process has a characteristic time interval of about $10^{-14}$ seconds. This in-
dicates that there is sufficient time for a competitive process, namely, the
release of the energy of capture in the form of a gamma-ray and the formation
of U-236, to take place. A search for positive evidence of the formation of
this nucleus began at once, also new sets of measurements designed to detect
the difference between the capture cross section for the formation of U-236 and
the capture cross section for fission were undertaken. The first attempts to
detect U-236 were made by irradiating U-235 in the most intense neutron flux
available at the Clinton pile and trying to detect long range $\alpha$-particles
or other induced radioactivity. This gave inconclusive results but U-236 has
finally definitely been detected through mass spectroscopy in U-235 irradiated
at Hanford. The ratio of the cross section for its formation to that for fis-
sion is called $\alpha$ and is 0.18 for thermal neutrons.

Speculation immediately arose as to whether a similar phenomenon occurs
in the interaction of thermal neutrons with Pu-239. If it does, clearly
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 $\alpha$ 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.

$$\frac{dN_1}{dt} = k - \lambda_1 N_1$$  \hspace{1cm} (9)

$$\frac{dN_2}{dt} = \alpha \lambda_1 (1 + \alpha) - \lambda_2 N_2$$  \hspace{1cm} (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.

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

$\lambda_1$ = $n\sigma_f(Pu-239)$, where $\sigma_f$ represents the total absorption of Pu-239.

$\lambda_2$ = $n\sigma_f(Pu-240)$, where $\sigma_f$ represents the total absorption of Pu-240.

and $\alpha$ 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

$$\lambda_2 = \alpha \lambda_1$$  \hspace{1cm} (11)

then we have, in general

$$\frac{N_2}{N_1} = \frac{\alpha}{1 + \alpha} \left[ \frac{1}{x} - \frac{1 - e^{-x\lambda_1^*}}{1 - e^{-\lambda_1^*}} + \frac{e^{x\lambda_1^*} - e^{-\lambda_1^*}}{(x-1)(1 - e^{-\lambda_1^*})} \right]$$  \hspace{1cm} (12)

and as special solutions

$$x = 1 \hspace{1cm} N_2/N_1 = \frac{\alpha}{1 + \alpha} \left[ 1 - \frac{\lambda_1^*}{e^{\lambda_1^*}} + e^{\lambda_1^*} \right]$$  \hspace{1cm} (13)
\[ \frac{x}{0} \frac{N_2/N_1}{1 + \alpha} = \left[ \frac{\lambda_1 t}{1 - e^{-\lambda_1 t}} - 1 \right] \quad (14) \]

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 \( nvt \ll \lambda_1 \), equation (14) reduces to

\[
\frac{\text{number of Pu-240 nuclei}}{\text{number of Pu-239 nuclei}} = \frac{\alpha}{1 + \alpha} \cdot \frac{1}{2} n\sigma_p(U-239)t \quad (15)
\]

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 uranium will be very low in Pu-240/Pu-239 ratio, Clinton material will be higher, and Hanford plutonium fuel uranium irradiated for 100 days at fluxes of the order of 10^14 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 \( E_1 = n\sigma_p(U-238)t \) and thus

\[
\frac{E_2}{N_3} = \frac{E_1}{(1 + \alpha)} \frac{\sigma_p(U-239)}{\sigma_p(U-238)} \quad (16)
\]

The coefficient of \( E_1 \) in actual practice is influenced among other things by the non-uniformity 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).

\[
(\text{parts per million Pu-240 in Pu-239}) = (\text{parts per million Pu in U}) \cdot 76 \quad (17)
\]

The concentrations of Pu in U at which Hanford separations took place varied...
from 26.5 ppm in May 1943 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-239.

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-239 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-239 content. The specific spontaneous fission activity of Pu-239 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-239. 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 ($\alpha$, 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
\( \alpha \) 17
O 5100
F 52

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

Plutonium arrived from the standard plant in the form of \( \text{Pu(NO}_3\)\_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 projected 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 averted 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 IMPELSON METHOD OF PRODUCING HYPERCRITICALITY
fragments of a metal in contact with a detonating high explosive. Neddermeyer suggested that high explosive be used to initiate an "implosion"; for instance a metal spherical shell, covered on the outside by high explosive, could be blown inward, forming the outer coating of a solid metallic sphere already in place at the center. Assembly times of the order of the thickness divided by the velocity, or, for a one centimeter coating, of a few microseconds, could be hoped for.

The most elementary calculations, neglecting the compressibility of the metallic material, showed that very high pressures could be obtained from a spherical shell collapsing at high velocity. Since the area across which material in radial motion is transported decreases as the square of the radius, the radial velocity in the shell must increase as \(1/r^2\). In order to produce this rapidly increasing velocity, the inner parts of the shell are subject to high acceleration, which means high pressure. Pressures of the order of millions of atmospheres are produced in the final stages of collapse, and it is clear that a calculation which treats the material as incompressible is a poor approximation.

The advantage to be gained by the compression was soon realized. Our rough equations have shown us that for a uniform compression the critical mass varies inversely as the square of the density, so that hypercriticality can be produced in a sub-critical sphere by compressing it. But in addition, it can be shown that the deviations from uniformity in the compression are in such a direction as to increase the hypercriticality beyond that to be expected from the average compression. If a change in the reactivity of part of the material
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.
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 variations 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 had 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 these by non-
mechanical methods would have been impossible in the time available. Fortunately
the Laboratory had acquired a set of International Business Machines, origin-
ally 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 develop-
ment proceeded under the Ordnance Division at secondary priority. The gas
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-239 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
Consideration of a gun-bomb of plutonium was out of the question due to the great possibility of predetonation resulting from the high neutron emission of Pu-240.

If a hollow implosion could be developed, considerably less than one critical mass could be made supercritical, and the number of bombs per month correspondingly increased.

The situation caused a reorganization of the Laboratory in the early fall of 1944. An explosives, or X Division, was created, using as a nucleus the existing and implosion testing work previously conducted by the Ordnance Division. Also, a new "Q" Division was created to work intensively on the experimental physics of implosion. The problems of these divisions, and the equipment with which they worked, then, are considered in the next section.

Figure 1 shows the organization of the Los Alamos Laboratory as it was in March 1945, after the new divisions had been functioning approximately six months.

2.7. THE WORK OF Q AND X DIVISIONS UP TO MARCH 1, 1945

The problem of experimental investigation of the implosion method and, later, that of design of the inner part of an implosion bomb, was assigned to
Figure 2
Organization of the Los Alamos Laboratory
March 1945.
<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assistant Director</td>
<td>John Smith</td>
<td>Operations</td>
</tr>
<tr>
<td>Associate Director</td>
<td>Jane Doe</td>
<td>Sales</td>
</tr>
<tr>
<td>Senior Director</td>
<td>Tom Johnson</td>
<td>IT</td>
</tr>
</tbody>
</table>

**Technical Division**

- **Technical Director**: Alex Brown
- **Technical Editor**: Emily Davis
- **Technical Writer**: Mark Miller
- **Technical Analyst**: Sarah Lee
- **Technical Illustrator**: David White
- **Technical Illustrator**: John Smith

**Consultants**

- **Consultant A**: John Doe
- **Consultant B**: Jane Smith
- **Consultant C**: Thomas Brown

**Support Staff**

- **Executive Assistant**: Elizabeth Davis
- **Administrative Assistant**: Margaret Miller
- **Human Resources**: Sarah Lee
- **Finance Manager**: John Smith

**Board Members**

- **Chairperson**: Robert Jones
- **CEO**: Jane Doe
- **Chief Financial Officer**: John Smith
- **General Counsel**: Sarah Lee
G Division, in addition to its duties in connection with laboratory investigations of slightly hypercritical assemblies, which have been previously described.

It was the main assignment of I Division to develop new explosives for implosions and to improve existing casting techniques for the preparation of shaped charges. It also supplied shaped charges for experimental work and installed inspection methods for the selection of highly perfect castings from the production line. It developed detonators of high reliability, and this problem overlapped somewhat the activities of G Division.

2.7.1 Methods of Experimental Investigation of Implosions

In the final year of the implosion method, four main experimental techniques for implosion study were employed by G Division. All of these had been suggested before the formation of the division, and preliminary work on them had been begun. These were:

1. The magnetic method, or detection of the collapse rate of a metal shell from the electric pulse generated by the action of the metal in a superimposed magnetic field.

2. The Ralston method, in which an intense radio-barium-lanthanum source was placed in the center of a reduced scale bomb and the diminution of the external gamma ray intensity as the implosion proceeded, observed by means of ionization chambers.

3. The beta-ray method, in which a burst of 20-kev gamma rays was passed through the imploding material at a known time after the implosion had begun, and recorded in a Wilson chamber.

4. The electric method, in which the imploding material struck and opened contacts in an electric circuit, and the times of such actions were recorded on an oscilloscope.

The X-ray method of investigating small implosions was abandoned after
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 Ralston 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-Mw 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 radium-lanthane 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 the shipment of radium 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

\[ I = I_0 \exp \left( -\mu_\gamma \rho \frac{N A}{4} \right) \]  

(18)

\( \mu_\gamma \) is the atomic coefficient for the gamma rays.
\( \rho \) the density of the spherical absorber.
\( R \) the radius of the spherical absorber.
\( N \) the Avogadro number.
\( A \) the atomic weight.

Introducing \( N \), the mass of the absorbing material, we may have \( \rho \) as the only variable, namely

\[ I = I_0 \exp \left( -\frac{\mu_\gamma N A}{4} \rho^{2/3} \right) \]  

(19)

If the implosion increases the density uniformly to \( \rho_f \)

\[ \frac{I}{I_0} = \exp \left( \rho^{2/3} - \rho_f^{2/3} \right) \]  

(20)

Sinks of imitation chambers of short collection time were placed near enough the implosion test to pick up the gamma rays, but far enough so that the...
they were not destroyed by the blast of the high explosive before the com-
pression 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 Rais 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
cut and the radioactive material inserted. As an illustration of the coor-
dination of the various activities of the laboratory, a Rais test shot involved
the following:

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

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

(3) Casting and inspection of the shaped charge of high explosive by the
Explosive 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 Rais group personnel.

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

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

In spite of the great care
Figure 3

Typical Rail Test Assembly
taken to equalize the distances from each detonation point on the high explosive to the initiation point on the single Primary, timing differences as large as four microseconds undoubtedly occurred.

The first models tested in the late fall of 1944 were the hollow-shell type, theoretically the best if a smooth implosion could be attained. The oscillograph records did not show positive evidence of compression of the assembled material.

This would make an active core sufficiently hypercritical for good efficiency, provided initiation of the chain reaction could be assured at the proper instant. From this time on, attention was concentrated on the solid explosion as the most conservative design that would accomplish the purpose, i.e., a serviceable plutonium bomb as soon as possible after the necessary amount arrived at Los Alamos.

The first Raha shot with electric detonators was fired on February 7, 1945, and four such shots were fired before March 1, two on solid implosions and two on hollow assemblies.

During the interval under consideration, the betatron site was completed and the 20-Mev betatron installed. The pulse of gamma radiation, emitted when the electron orbits were expanded at a known interval after detonation of the...
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 RHA 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 RHA 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 velo-
city 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 cal-
culations, 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 photo-
graphic 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 intersected, and that the low veloc-
ity was due to the behavior of the divergent spherical waves actually used.
British scientists, that a truly convergent wave front might be formed if a short of detonating material by refracting the wave through a "lens" of explosive having a slower detonation velocity. The way this was done is illustrated by Figure 4. The upper part of the figure shows the Rayleigh construction for a wave initiating at O, on the interface between a slow and a fast medium. The envelope of the waves set up in the slow medium by the fast wave travelling down the other side of the boundary is a plane wave near the interface. The lower part of the figure shows the condition that makes the refracted wave in the slow medium converge to a focus. Solid curve OP is the interface between fast and slow explosive, and the detonation point is at O.

The refracted wave XR is always normal to the radius vector ρ from the focal point. From the equations for the center of curvature of a curve we have

\[ \frac{\rho}{\rho_0} = \tan \left( \frac{\pi}{2} + \alpha \right) = -\frac{1}{\tan \alpha} \tag{11} \]

and integration of this gives

\[ \rho = \rho_0 \exp \left(-\frac{\rho}{\sqrt{\nu^2 - 1}}\right) \tag{22} \]

where \( n = \sqrt{\nu^2 - 1} \)

Equation (22) is the law of the logarithmic spiral. In three dimensions the shape of the surface is a figure of revolution about FC. Figure 5 shows how such lenses of slow explosive could be embedded in a fast explosive so that a set of simultaneous detonations at the apices of the lenses would give rise to a converging spherical detonation wave in the spherical shell of Composition E lying underneath.
Figure 4

Upper figure: Huygen’s Construction for a Wave Initiating at O.

Lower figure: condition that makes the Refracted Wave converge to a focus.
\[ \tan^2 \alpha = \frac{v_s^2}{v_f^2 - v_s^2} \]

\[ \sin \alpha = \frac{v_s}{v_f} \]
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 inception bans.

In order to make lenses, explosive of low detonating velocities were needed. Not much effort had previously been put on this subject, obviously the low detonating velocities were in general lower impact and destructive power. At first, the low velocity of detonation was obtained by using powder explosives such as TNT mixed to a low density. A small two lens system was built using the composition Composition B and compact TNT, which compressed a 15 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 Baratel consisting of the following parts by weight:

\[
\text{Ba(NO}_3\text{)}_2 = 73 \text{ per cent, TNT} = 27 \text{ per cent, and Baratel containing Ba(NO}_3\text{)}_2 = 50 \text{ per cent, TNT} = 39 \text{ per cent, Al} = 15 \text{ per cent.}
\]

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

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

The stick velocity, or detonation velocity of Baratel along a cylinder with
free surfaces was determined at Bruceton, and proved to be 4750 meters per second, much lower than the Composition B velocity of 7900 meters per second.

The design of molds for larger lenses was a considerable job in itself. The equations of the solid surfaces had to be expressed in forms adequate for machining the dies, and the molds had to be designed so that Composition B could be cast over the Bartol. The composite castings, each containing a lens in its interior, had to fit together and form a spherical shell. The axis of the castings were radii of this shell, and the plane cross section of the casting normal to this axis was a pentagon or a hexagon. These shapes were unusual and difficult to make, and great procurement troubles ensued.

This redesign occurred in January and February of 1945.

2.7.1 Development of Electric Detonators

The experiments on jetting referred to previously indicated that as the expanding
The large number of detonation points required means that the angle between rail to neighboring points is small. Thus in Figure 6, the distance from intersection F to the liner (shaded as a plane surface) is small. If the detonation of intermediate point C3 is so late that point F strikes the liner before the spherical wave from C3 arrives, it is the angle $\theta$ between C1 and C3 that is effective, and C3 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
Figure 6
Relationship Between Shock Wave Fronts.
of a powerful bank of condensers through a wire embedded in a primary explosive like PETN would initiate the detonation. The manufacture of detonators was, as usual on the project, begun while development work was still underway, and for this the procurement services which the California Institute of Technology had developed in connection with previous war contracts were of great service.

On February 7, 1945, the first Aria test shot with electric detonation was fired, and all subsequent Aria tests were made in this way.

2.8 THE COOPER CHAIR COMMITTEE AND THE FINAL STAGES OF THE IMPLOSION PROGRAM

If there were to be no delay in using the material, decisions had to be taken at once which would determine the final design of the implosion bomb and allow the curtailment of exploratory programs of the Laboratory in order to focus attention on the chosen one.

The following questions were prominent among the decisions to be taken concerning the implosion bomb.
(3) Could an implosion initiator be made in time, if the solid implosion was decided upon?

(4) What part of the work could be undertaken by the California Institute of Technology, whose facilities were now available?

Many conferences were held at Los Alamos to decide these questions, some of which necessarily had to be discussed on the basis of incomplete experimental evidence. Finally it was decided that a solid implosion bomb using Baratol lenses would be given first priority and worked on at Los Alamos. The non-lens program was to be undertaken by California Institute of Technology. The following statement of the program, as it was drawn up at that time, is of considerable interest.

2.6-l Statement of February 25, 1944

Implosion Program

"Decide now that explosive lenses will be worked on at Los Alamos primarily because we cannot take the risk of failure of the modulated initiator development, which failure would probably be fatal to an implosion program without lenses, and also because we are convinced that if mixing of active material and tamper occurs due to roughness in the implosion, such mixing will be less with lenses than without. The California Institute of Technology will undertake the non-lens program."
assume that the entire material in the first implosion bomb will be in solid spherical form and that the isolated initiator development will succeed, but if on May 1, 1943, a successful isolated 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 interface of the two shells must be Barcol to smooth out roughness from imperfect timing and lens design. Experiments should show, before May 10, whether the Barcol 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 prepared for test drops and cannot use in the periods between the dropping of fission bombs.

The use of Barcol 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 "Compunder" 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
- Uranium Division Leader
The Committee met weekly, reviewed the progress of the implosion program, and made and rapidly revised, short range time schedules. The activities of the laboratory under the supervision of the Comptroller Committee can be listed about as follows.

(1) Fabrication of high-explosive lenses and shaped charges.
   (a) Shell design, full scale and experimental.
   (b) Procurement and inspection of full-size lens molds.
   (c) Development of casting techniques.
   (d) Inspection and methods of selecting uniform castings.
   (e) Construction and utilization of new buildings for the expansion of the high-explosive casting plant.

(2) Electric Detonators, Boosters, and Detonator Circuits.
   (a) Wire detonators.
   (b) Spark Detonators (these were worked on as a promising alternative or improvement of wire detonators).
   (c) Detonator circuits.

(3) Tests on the characteristics of implosions, and their effects on metal liners.
   (a) Timing and velocity tests.
   (b) Compression and terminal observations.

(4) Chemical and metallurgical services.
   (a) Purification of incoming plutonium.
   (b) Pu metallurgy, fabrication, and casting.
   (c) Fabrication of uranium reflectors.
(4) Data separation chemistry.

(5) Production of neptunium foils for fast neutron detection in a critical plutonium assembly.

(6) Critical-mass program and the time constant of the fast chain in plutonium. (These activities have been previously described.)

(a) Subcritical multiplication.

(b) Operation of hypercritical assemblies and assembly problems.

(7) Design of the inner metal parts of the implosion assembly.

(a) Modulated-initiator design and testing.

(b) Coordination of the implosion program with the test at Alamogordo.

(8) Assignment of priorities in the shops.

2.6-2 Procurement of Lens Molds

The most critical item in the lens implosion program proved to be the procurement of molds for the casting of high explosive. The forms were complicated in design and the allowed tolerances rather stringent. Special action had to be taken to set aside enough "Cerrotrue" casting alloy to make the molds. The acquisition of acceptable molds was made of the highest priority in the procurement offices at Los Angeles and Detroit. Daily reports were sent in by teletype to Los Alamos on the progress of manufacture.

The first full-size pentagonal lens casting, using imperfect mold parts which had been reworked at Los Alamos after delivery, was completed on April 29, and by May 21, three full-sized lenses had been fired for timing, i.e., to see that a satisfactory converging wave appeared in the spherical surface below the Baratol insert. By the first week in June 1945, the deliveries began to be
sufficient in quantity so that less labor procument could be devoted to the
highest priority rating.

2.5-3 The Implosion Initiator

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

During February 1945, there was intensive discussion of Implosion Initi-
ators, considering many types. In all cases the shock wave arriving at the
center of the active material was to break up some prepared geometrical arrange-
ment and permit α-particles to reach beryllium or gamma rays to strike
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 C, and
also looked into the possibility of preparing polonium by neutron irradiation
of bismuth in the plutonium pilot and production piles at Hanford and Hanford.
Experience soon showed that the latter method of preparing "artificial"
polonium was much preferable. The chemical separation of polonium from bismuth

SECRET
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 uranium irradiated at Hanford for 100 days will accumulate about 300 curies of polonium.

The technique of handling and depositing polonium was greatly advanced by the Project through its subcontract at Konsanto 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 \((\alpha, n)\) 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 freeing 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.
subsequent effort on initiator production showed that the process could be
repeated with fair certainty of success on each effort.

2.3-4 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 1942-1943 performed adequately but were not designed for in-
clusion 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
Figure 7
Urchin Initiator.
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 Pendover 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 began 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 rubber. Considerable work was done on the exact procedures for preparing and pressing the FEN 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-243, and the $(\alpha, n)$ 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.

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 F.W. 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 explosion test at Alamogordo Air Base was not under the jurisdiction of the Commissary 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 it 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 Alamagordo Air Base, New Mexico, about 32 airline miles due west of the town of Carlsbad, at the base of the western escarpment of the Sierra Cuesta 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 that 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.
measurable radioactivity was found on the core, 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 breaching 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 fissioned 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 PuO₂ 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 17.5-da Ba-43-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 bullet attached into the crater.
Cables were nailed in and the samples recovered were returned to Los Alamos for investigation.

As indicated in the organization chart, Figure 8, many different methods were used for the air blast measurement. The measurements were in general successful, but indicated an energy release which seems somewhat too low, around 10,000 tons of TNT equivalent. This somewhat low result is explained by several factors, such as the energy used in boiling the ground under the ball of fire, because of the fact that the bomb was not fired at a sufficient height to prevent this, and the large escape of energy in the form of light. The bomb was exploded on a tower approximately 100 feet high, whereas the fire ball expanded to some 1500 feet in diameter.

Many of the experiments on delayed neutrons, gamma rays, etc., failed because of the high efficiency of the test. These experiments had quite properly been designed to give indications of the cause for a failure, i.e., an energy release of less than 1000 tons TNT equivalent.

The experiment on the e-folding time of the fast chain as it actually took place in the plutonium bomb was successful, and has been mentioned in Section 2.3, in this chapter.

Considerable effort at Trinity was put on the problem of the dust cloud containing the highly radioactive fission products and untransformed plutonium. Careful meteorological observations and predictions were made to estimate the height of the cloud, direction of drift, and drift velocity of this dangerous cloud. A searchlight battery was installed to keep the cloud illuminated as long as possible. A 584 radar truck was present to follow the cloud from the base reflected by the ionized gas. The Project Health services stationed ground observers at many places in the direction of the expected drift of the cloud, who could report any radioactivity appearing at the station before it reached levels where there was physiological hazard. A fleet of trucks and busses...
stood ready to proceed to any small community and evacuate the residents temporarily, should this be necessary. Although appreciable radioactivity was observed for at least 100 miles in the line of drift (the cloud rose to approximately 45,000 feet), these amounts did not constitute a health hazard. Occasional isolated spots of rather high activity were found, as if sand or dust particles of a particular size had settled out at that point and carried adsorbed radioactivity with them. These points were far from any permanent habitation in the very sparsely settled terrain over which the cloud moved.

The test explosion was fired at 5:30 A. M. Mountain Day Time on Monday, July 16, 1945. By Sunday noon, July 15, the test bomb had been completely assembled and hoisted to the platform at the top of the tower. The detonators had been attached to the outer metal case and connected with the detonator firing circuit. There was no further need to ascend the tower. A guard was kept at the base of the tower, and repeated surveys of the area were made to be sure every one was either at the base camp, 14,000 yards away, or in the reinforced shelters at 10,000 yards. The shot was originally scheduled for 4:00 A. M. when the surface winds were likely to be a minimum, but unexpected rain, beginning shortly after midnight, delayed the initiation time. Shortly after 4:30 A. M., the party at the base of the tower made the final electrical connections and left for the shelter 10,000 yards due South. After consultation with the Project Director, the firing time of 5:30 A. M. was announced over the public address system in the various shelters, and over the short-range FM radio to the observers at the base camp, at an observation post 20 miles northwest of the tower, in airplanes, and at outlying points. The times, -10 minutes, -5 minutes, -one minute and -45 seconds were announced. At -45 seconds a mechanical timing device, consisting of pins on a rotating drum which closed various circuits, was put in control of operations. Signals automatically went out which opened camera shutters, ungrounded galvanometers, etc.,
in preparation for observations. Further time signals at -10, -30, -60, 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 Fasstex camera shots, and the per cent of the plutonium transformed as
revealed by radiochemical analysis of the crater dust.

           The blast wave esti-

mate was lower, and the ball of fire estimate higher than this figure.
CHAPTER 4

THE METHOD OF ATTAINING THE EXPLOSIVE RELEASE OF NUCLEAR ENERGY.

Samuel R. Allison

3.1 THE NUCLEAR EXPLOSION.

The idea that the initial mechanical effects produced by the nuclear explosion should increase rather than decrease the reactivity of the fission source 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 unfolding 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 such 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 this is clearly indicated for such a purpose. The possibility of applying it to an autocalytic 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 incursions of 5-10 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 schemes so far imagined.

3.2 THE HYDRIIDE BOMB

The existence of a hydride of uranium, first thought to be UH₄ and then shown to be UH₃, 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 on large 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 behavior 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 UN₃₀ down to UN₁₀, and then make a determination for UN₉. 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 UN₁₀ was critical if surrounded by H₂O.

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
given mass of material.

In spite of the abandonment of the hydride program, time was found to
perform an experiment which gave the first experience with a chain reactor
having a fast period. A jacket of hydrogenous active material and a reflector
surrounded a vertical pipe through which a plunger of active material
could be dropped. When the inner cylinder was centrally located with respect
to the jacket outside the pipe, a hypocritical assembly with a period of
about 1.6 microseconds was formed. A burst of gamma rays and neutrons was
emitted as the plunger fell through, multiplicities as high as 10^15 during
the 0.01 second of hypocricality being observed. By adding slightly more
active material or reflector to the stationary part of the assembly, the in-
tensity of the burst could be increased. The experiment was very appropriately
referred to as "twisting the dragon's tail" and the assembly for making the
drops came to be known as the "dragon" (Figure 1). Unfortunately the dragon had to
disassemble and the hydrogenous uranium returned for re-working into metal
for the bomb before an adequate experimental program based on it could be
carried out.

2.3 BOMBS FROM THERMO-NUCLEAR REACTIONS.

The DD reactions

\[ \text{D}^2 + \text{D}^2 \rightarrow \text{He}^3 + \text{n}^1 + 3.19 \text{ Mev} \]

and

\[ \text{D}^2 + \text{D}^2 \rightarrow \text{He}^3 + \text{p}^1 + 3.38 \text{ Mev} \]

have a high cross section which extends to very low relative velocities of
the reacting deuterons, as might be expected from the low potential barrier
which has to be penetrated for the nuclei to come together. The reaction has
been followed experimentally down to 9 kilovolts bombardment energy. If part
of a mass of deuterium were raised to such a temperature that the rate of
Figure 1
The Single Shot "Dragon"
energy release from these reactions and the subsequent one

$$^1H + ^1H \rightarrow ^2He + ^1H + 17.6 \text{ MeV}$$

would exceed the rate of energy loss from radiation and electronic conduction, the reaction would spread through the deuterium present, with the release of tremendous amounts of energy. The energy release per gram of transmuted deuterium is about $9 \times 10^{17}$ ergs, or slightly more than the energy released per gram of fissions.

Calculations of the temperature which must be attained for such a reaction to maintain itself indicate that the average energy of a particle in the hot mass would have to be about 20,000 electron-volts. Such calculations could have been made before the discovery of fission and the imminence of fission bombs, but would not have been taken seriously because of the fantastic temperature needed, some hundreds of millions of degrees Centigrade.

In the summer of 1942, a group of theoretical physicists destined to come to Los Alamos gathered at the University of California and as part of their work carried through a calculation of the possibility of igniting a mass of liquid deuterium using the energy evolved in a fission bomb. The possibility that such a project could be carried through could not be disproved by the theoretical predictions. Actually the temperature attained by the active material and reflector in the test shot at Alamogordo may well have been around 70 million degrees.

The amount of liquid deuterium which could be placed around the bomb is limited only by considerations of the most practicable size and weight of the weapon. Hence energy released greatly exceeding that from a fission bomb can presumably be obtained.

The ignition temperature is considerably lowered by the contribution from the tritium reaction, and studies were undertaken at Purdue University to
Measure the H tritium cross section. The measurements depended on tritium extracted from cyclotron targets and hence only tracer amounts were available. In the energy range from 0 to 0.6 Mev the SD cross section proved to be unexpectedly high, greater than predicted by the nuclear dimensions.

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

$$\text{Li}^7 + \text{n}^1 \rightarrow \text{He}^4 + \text{p}^1 + 4.7 \text{ Mev}$$

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 1245 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 15 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 DD 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 deuterium was part of the original construction at Los Alamos, with the thought that eventually liquid deuterium might be used for experiments leading to this "break" point. The "break" point, however, turned out to be too high 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, pure, destructive, nuclear reactor.
The bomb was intended to destroy military and naval installations above ground, to destroy enemy production facilities and the homes of factory workers, and to disrupt enemy economy by obliterating The only method of delivery to the target which was seriously considered is that it should be dropped from an airplane, on installations on the ground near ships or naval vessels.

With this in mind, it became clear that the detonation of the bomb would take place considerably above the level of the ground. The first reason for this was that it was feared that impact with the ground would distort the rather complex geometry needed to produce an acceptable energy release. Another reason is that the radius of damage from a contact bomb is strongly affected by unevenness of 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 ground, other solids, energy will be used up in vaporizing these solids which might otherwise remain in the blast wave. At a much later date, a further benefit was realized that detonation above ground would prevent contamination of the damaged area with radioactive products, and not make the location uninhabitable for any period of time.

Another point is that an expanding spherical shock wave incident on a plane surface sets up, by interference with the wave reflected from the ground, a more intense wave, called the Mach wave. This is in the form of an expanding cylindrical surface which is perpendicular to the earth face the point of detonation. The height of the expanding cylindrical surface is not accurately known, but for a fission bomb detonated 150 feet above level ground it is
30 and 400 feet at a radius where it still can act destructively on buildings. In this 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 1,000 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 fuse alone was discarded, mainly because of the danger from turbulence and consequent pressure fluctuations around the falling bomb. A fuse 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 fuse, 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 Los Alamos Laboratory. The fuse 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 fuse does not operate. When the reflected signal comes back at the correct instant to pass through the opened gate, the fuse 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 gaseous form. In order to make more difficult attempts of the enemy to find the wave-length emitted by the bomb and jam its action, 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 Ordnance Division and under a subcontract at the University of Michigan. Because of the great value of the bomb and the consequent need for utmost reliability in its operation,
the principle of parallel paths for the pulse was used, so that if one transmitting circuit should fail, the pulse could fire the detonator circuit through an alternate path. This made it possible to predict a maximum probability of failure of the fuse which was much lower than could be set by the performance of any single line. For the probability that two would fail at the same instant was the square of the probability of failure of a single line. Thus when more than 100 single transmitting circuits had been shown not to fail, the probability that the parallel circuit bomb would fail was less than 1 in 10,000. This pulse of testing was used in the fuse and also in the wire detonators previously discussed.

Another hazard is of course that of premature firing, at an ineffective height, or even in the airplane or at the take-off, where the bomb would descend the airport. To reduce this probability, units were placed in series along the parallel paths, so that premature transmission of a pulse could only be possible by simultaneous malfunctioning of two circuit units.

Another point in which the military use as a bomb influenced the design was the addition of an armored steel coating. It was feared that enemy fighter planes might attack and injure the bomber and the bomb by gunfire, or that flak from antiaircraft batteries would be encountered. Triangular plates of steel armor were used to cover the outer surface of the bomb to minimize such dangers.

Because of the unusually large size and weight of the bomb, special devices had to be prepared for loading it into the B-29 bomb bay. A hydraulic elevator (Figure 1) similar to those used in elevating automobiles for greasing was adapted for the purpose and the bomb was raised from a pit in the ground into the bomb bay of the B-29 which had been rolled into position over it. Special attention was paid to the design of a lug in the bomb casing from which the bomb could be suspended in the carrying plane. The release mechanism of the bomb was essentially the British F and G equipment which had been developed for the launching of extra heavy (25 ton) bombs from the Lancaster bombers.
Figure 1

Hydraulic Elevator for Loading Bombs into the Carrier Plane
An extensive program of test drops was carried out before any combat drops were made. In the implosion bomb (Figure 4), 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 Wurts Army Air Base had shown oscillation and spinning in the fall of the first mock-ups which would prevent accurate timing, and impose some undesirable accelerations on the inner parts. Considerable thought 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 "two" tail (Figure 3). The problems of the gun model (Figure 4), which fitted into a casing of high 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 were 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 Comacoon 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. Some of the later drops contained informing 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
Figure 2

Explosion Bomb "Fat Man"
Figure 3
"Box" Tail
Figure 4

Gun Type Bobb "Thin Man"
Figure 5
Mock-up Implosion Bomb
long level flight at intermediate altitudes, and of the final climb to the bomb-
ing altitude of around 14,000 feet. In July 1945 a feasibility of the combat
implosion bomb, minus the plutonium core, was dropped, and similar practice drops
were made at the base in the Hawaiian before the actual combat missions. Five
gun-bomb models and three implosion-bomb models were dropped in these practice runs
in the Pacific. The experience gained in these tests was of great value to the
plane crews and the scientists.

In connection with the test shot at Alamogordo, a test run with the B-29's
had been arranged. The first plane was to pass over the test point a few minutes
before the shot and drop parachutes containing piezo-electric gauges from which
pressure readings were transmitted by radio. The second plane, simulating an
actual combat mission, was to fly on a bombing run directed at the bomb on its
tower, and signal when it reached the point at which a bomb would have to be
launched to hit the test bomb. The drop time was about 45 seconds, so after this
interval the bomb on the ground was to be fired. In the meantime the bomber was
to bank sharply and turn and try to get as far away as possible. The impact of
the blast wave on the bomber was then to be measured. Due to unfortunate atmospheric
conditions at the time of the test, this program was not completely carried out,
although observers in the planes saw the shot from a distance.

Under the auspices of the California Institute of Technology, a so-called
"pumpkin" program was carried out in which bomb casings of the same shape as
the implosion bomb were filled with high explosive and fitted with a contact
fuse for detonation on impact with the ground. These gave the crews additional
experience in handling heavy bombs of the shape of the fission implosion bomb.
It was also intended that in the periods when fission bombs were not available
for combat, the B-29 crews could drop these pumpkins, which, after all, were very
powerful charges of ordinary explosives. Such combat missions over Japan were
actually carried out with these bombs, but were too few in number to be of any
considerable military importance.

The fission bomb, during World War II actually did not completely emerge from the laboratory stage and become a finished weapon, harnessed over completely to the military forces. Laboratories were built on the advanced base in the Mariannes for testing every feature of the bomb before delivery, and civilian scientists were sent overseas to work at these installations. The advance laboratories were air-conditioned and extremely well equipped, using lists of apparatus made up at Los Alamos. Frequent tests were made in order to be sure that the neutron background of the implosion initiators remained below tolerance.

Even during the final combat flights scientists were in the planes, re-checking the electrical circuits in the bombs to make sure that they were still in good order, and going over a series of final tests which had been drawn up based on the experience in the test drops. Observers in an accompanying plane dropped parachutes with piezo-gauges attached to small radio transmitters, which sent out signals whose intensity was proportional to the pressure in the blast wave. From these and from other sources, the energy release in the combat drops was estimated. After the Japanese surrender, personnel drawn from the health protection group at Los Alamos and elsewhere went to Hiroshima and Nagasaki to obtain data on the residual radioactivity and the physiological effects of the nuclear explosions. Personnel who had estimated blast damage, and an expert on bomb damage to cities, from the British mission, went to report on such effects.

It was remarkable that the first combat units of U-235 and plutonium left the Los Alamos Laboratory for shipment overseas within a few hours of each other. This, in a sense, justified the decision to keep both the plutonium and the U-235 production programs going, which was made in 1941 and reviewed several times during the war. The U-235 target for the gun bomb and the plutonium hemispheres left Los Alamos on July 20. The projectiles for the gun bomb had left about two weeks previously. The scientific crews for the base in the Mariannes began
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 untold numbers of 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 means 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.
Figure 6

Hiroshima After Gun-Bomb Was Dropped
Figure 7
Nagasaki After Implosion Bomb Was Dropped