The Los Alamos Primer

The following notes are based on a set of five lectures given by R. Serber during the first two weeks of April 1943, as an "indoctrination course" in connection with the starting of the Los Alamos Project. The notes were written up by E. U. Condon.

Everybody assembled in the big library reading room on the first floor of the Technical Area, the building where the theoretical physicists had their offices. We had a little blackboard set up in front and a lot of folding chairs spread around the room. Fifty people on hand, something like that. Scientific staff, a few visiting VIPs. There was hammering off in the background, carpenters and electricians working out of sight but all over the place. At one point during the lectures a leg came bursting through the beaverboard ceiling. One of the workmen misstepped and they had to pull him out.

1. Object

The object of the project is to produce a *practical military weapon* in the form of a bomb in which the energy is released

by a fast neutron chain reaction in one or more of the materials known to show nuclear fission.

I started lecturing. I started talking about the "bomb." After a couple of minutes Oppie[1] sent John Manley up to tell me not to use that word. Too many workmen around, Manley said. They were worried about security. I should use "gadget" instead. In the *Primer* Condon wrote it down both ways. But around Los Alamos after that we called the bomb we were building the "gadget."

Section 1 emphasizes that our purpose at Los Alamos was to build a *practical military weapon*—one small enough and light enough that an airplane could carry it.[2] There was no use making something that weighed one hundred tons. That was our concern.

We meant to build this weapon by utilizing the energy from nuclear fission. Fission had a history. For a long time before 1939, people were bombarding uranium with neutrons. Uranium was the heaviest element known up to 1939. People had the idea that the uranium they were bombarding was capturing neutrons and transmuting to heavier elements, elements beyond uranium on the periodic table, transuranics. I remember seminars in Berkeley in the 1930s when the chemists discussed the trouble they were having explaining the chemistry of these supposed transuranic elements. The chemistry didn't seem to be working out right. Then Otto Hahn and Fritz Strassmann, in Germany, working with the physicist Lise Meitner, found out that making transuranics wasn't what was

1. J. Robert Oppenheimer.

2. On Edward Teller's blackboard at Los Alamos I once saw a list of weapons—ideas for weapons—with their abilities and properties displayed. For the last one on the list, the largest, the method of delivery was listed as "Backyard." Since that particular design would probably kill everyone on Earth, there was no use carting it elsewhere.

usually happening at all. Instead, the uranium nucleus was actually splitting into two big pieces, and doing it with the release of a great deal of energy (and a couple of extra neutrons, as several people soon demonstrated). As soon as that was discovered, everybody realized the possibility both of making weapons and of getting power.

Finally, the reaction we were interested in was a *fast* neutron chain reaction, which I'll discuss later in these notes.

2. Energy of Fission Process

The direct energy release in the fission process is of the order of 170 Mev per atom. This is considerably more than 10^7 times the heat of reaction per atom in ordinary combustion processes.

In Section 2[3] we immediately come to the heart of the matter: that the energy released in the fission of the uranium nucleus is considerably greater than 10^7—that is, ten million times the energy

3. In Section 2 we begin using so-called scientific notation. Ordinary decimal notation is inconvenient when you're dealing with very large or very small numbers:

$$1{,}000{,}000 \times 10{,}000{,}000 = 10{,}000{,}000{,}000{,}000$$

Ten followed by twelve zeros, ten trillion, isn't an easy number to read. It's simpler and more convenient to tell how many zeros there are after the 1 instead of writing them all down. Thus we write 10^n to mean a 1 with *n* zeros after it. 10 is 10^1, 100 is 10^2, 1,000 is 10^3, and so on. Convert equation (1) to scientific notation (substituting a dot for the multiplication sign) and it looks like this:

$$10^6 \cdot 10^7 = 10^{13}$$

with the nice advantage that we can do multiplication by simply adding the superscripts, which in fact are powers of ten. We write 2,500,000 like this:

$$2.5 \cdot 10^6$$

released in a typical chemical combustion such as an explosion or a fire. All else follows from this fact. So we should try to understand where this large number comes from.

We can do so because the origin of the energy released in fission is exactly the same as the origin of the energy released when two atoms or molecules react chemically. It's the electrostatic energy between two similarly charged particles. Two similarly charged particles repel each other. There's an electrical force pushing them apart. Work has to be done to overcome that repulsion and push them together from a large distance, up to a point of separation we can call *R*.

To start with a simpler particle than an atom, let's look at two electrons pushed together. If you released them, they would fly apart with an amount of energy equal to the work that went into pushing them together. That energy *E* is given by the formula

$$E = \frac{e^2}{R} \tag{1}$$

where e is the electron charge, e^2 is e multiplied by itself, and R is the distance between the particles. The electrostatic energy thus ends

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This notation can be extended in turn to very small numbers by using a negative superscript, 10^{-n} which means 1 *divided by* 10 to the *n*. Thus, 10^{-1} is 1/10th, 10^{-2} is 1/100th, and so on. In decimal notation, $10^{-1} = 0.1$, $10^{-2} = 0.01$, $10^{-3} = 0.001$. To get

$$2.5 \cdot 10^{n}$$

you write 2.5 and move the decimal point *n* places to the right; to get

$$2.5 \cdot 10^{-n}$$

you write 2.5 and move the decimal point *n* places to the left.

up as kinetic energy, the energy of motion. In chemical reactions—the burning of hydrogen and oxygen in a rocket engine, for example—electrons bound in atoms or molecules change their positions, and the change in electrostatic energy is what appears as the energy of the chemical reaction.

Now let's consider the electrostatic energy in the uranium nucleus. The uranium nucleus contains 92 protons, each of which has the same charge as an electron, though of opposite sign—particles of opposite sign attract each other, those of the same sign repel. So the uranium nucleus has a charge 92 times as great as an electron; it's positive rather than negative, + rather than –, but since only the square of the charge is involved, that difference doesn't matter in equation (1). The numerator of (1) is thus 92^2 times bigger than for a chemical reaction. For our purposes, 92^2 is close enough to call 100^2. So the numerator for a uranium atom would be greater by a factor of 100^2, 100 times 100, or 10,000 (10^4).

The uranium nucleus is also much smaller than an atom. In an atom, the distance R is 10^{-8} cm (cm meaning centimeters). The radius of the uranium nucleus is 10^{-12} cm, which is 10^4 times smaller. The electrostatic energy for a uranium nucleus is therefore 10^4 for the numerator and another 10^4 for the denominator, for a total of 10^8 times greater than the electrostatic energy between atoms or molecules. When a uranium nucleus fissions, much of this energy is released as kinetic energy in the two fission fragments that fly apart. Suppose that the uranium nucleus broke in half. Each fragment would have half the charge. The numerator of equation (1) would be a quarter as big—a half times a half. Since the volume is proportional to the cube of the radius, the radius would be smaller by a factor of

$$1/\sqrt[3]{2} = 1/1.26$$

So each fragment would have an electrostatic energy of about a third of the total and the two fragments about two-thirds. That leaves a third left over for the reaction energy.

Thus we see that the energy of fission is about 10^8—one hundred million times—greater than the energy of a chemical reaction, confirming the statement that it's "considerably more than 10^7."

This is $170 \cdot 10^6 \cdot 4.8 \cdot 10^{-10}/300 = 2.7 \cdot 10^{-4}$ erg/nucleus. Since the weight of 1 nucleus of 25 is $3.88 \cdot 10^{-22}$ gram/nucleus the energy release is

$$\mathbf{7 \cdot 10^{17}\ erg/gram}$$

The energy release in TNT is $4 \cdot 10^{10}$ erg/gram or $3.6 \cdot 10^{16}$ erg /ton. Hence

$$\mathbf{1\ kg\ of\ 25 \approx 20000\ tons\ of\ TNT}$$

To compare the energy released per gram of uranium versus a gram of a chemical explosive such as TNT, we have to remember that an atom of uranium weighs ten times as much as the atoms involved in the chemical reaction. So in a given weight of uranium there will only be a tenth as many atoms. We have to reduce our figure of 10^8 to 10^7 to compare equal weights of uranium and chemical explosive. That means that one kilogram of uranium, if it fissioned completely, would be equivalent to about 10^4 tons of explosives—10,000 tons, 10 kilotons, which is reasonably close to the actual figure at the end of Section 2 of 20,000 tons. (Twenty thousand may not look "reasonably close" to 10,000 if you're not used to thinking in terms of "orders of magnitude," which are factors of 10. Ten thousand and 20,000 are of the same order of magnitude, 10^4; one is $1 \cdot 10^4$ and the other is $2 \cdot 10^4$.)

Somehow the popular notion took hold long ago that Einstein's theory of relativity, in particular his famous equation $E = mc^2$, plays some essential role in the theory of fission. Albert Einstein had a part in alerting the United States government to the possibility of building an atomic bomb, but his theory of relativity is not required in discussing fission. The theory of fission is what physicists call a nonrelativistic theory, meaning that relativistic effects are too small to affect the dynamics of the fission process significantly.

Section 2 of the *Primer* gives a more exact calculation of the ratio of the energy released by the fission of a gram of uranium to the energy released by the explosion of a gram of TNT. To get the ratio of such quantities, you have to measure them in the same units. That complicates things, because in different branches of science it's convenient to use different units to measure the same quantity. A chemist is likely to measure energy in calories, while the standard unit of energy for the physicist is the erg. The erg is rather too small a unit to be convenient for everyday use. Utilities bill customers for kilowatt hours of electric energy; there are $3.6 \cdot 10^{13}$ ergs in a kilowatt hour. On the other hand, the erg is too large a unit to be convenient for an atomic physicist, who uses a smaller and different unit, the electron volt: the energy acquired by an electron falling through a potential difference of one volt. That's a convenient size; the energy that binds an electron in a hydrogen atom, for example, is just 14 ev—14 electron volts. The energy of typical chemical bonds is just a few ev. The nuclear physicist has borrowed the unit and uses it in larger multiples: *Kev,* meaning 1,000 ev (10^3); *Mev,* meaning 1,000,000 ev (10^6).

The *Primer* gives the energy released in fission as 170 Mev. To compare this number with the energy released by TNT, which is given in ergs per gram, you have to know how many electron volts there are in an erg. The simplest and most reliable way to answer this question is to go to a library and take down a reference book like the *Handbook of Chemistry and Physics*, which has elaborate tables giving the ratios of various units of measurement (thus 12 inches equals 1 foot, an inch equals 2.54 centimeters, an ounce equals 28 grams—these are the sort of ratios I mean). But at Los Alamos at this time, in April 1943, although we had a librarian—my wife Charlotte—and a library, we didn't yet have library books. So apparently I didn't answer the question the easy way. I figured out the ratio on the back of an envelope using the definition of an electron volt and some numbers I remembered. This is the mysterious little calculation that begins the second paragraph of Section 2:

$170 \cdot 10^6$ = energy in ev

times

$4.8 \cdot 10^{-10}$

which is the charge on the electron

/300

since a volt is 1/300th of the electrostatic unit of voltage

$= 2.7 \cdot 10^{-4}$ erg/nucleus

which is the equivalent in ergs to the energy in ev. My calculations indicated that the energy of fission of 1 kg of uranium equalled 20,000 tons of exploding TNT—the wiggly equal sign (≈) means "approximately equal to." When I referred to tons I meant short tons, by the way: 2,000 pounds, or 907 kilograms.

In Section 2 I refer to the rarer form of uranium, the form we were interested in, as "25." This simple code was commonly used in the Manhattan Project; 25 meant U^{235}, 28 meant U^{238}, 49 meant one kind of plutonium, Pu^{239}. Uranium is element 92, plutonium element 94, the numbers referring to the number of protons in their nuclei. The sum of both protons and neutrons in the nuclei of atoms gives what is loosely referred to as the atomic weight (it's not really a weight). Every kind of uranium has 92 protons, every kind of plutonium has 94 protons, but different kinds differ in their numbers of neutrons. These different kinds are called "isotopes." The common isotope of uranium has atomic number 92 and atomic weight 238 (indicating 146 neutrons: 238 total nucleons — 92 protons = 146). A much rarer isotope, the one we were interested in, has atomic number 92 but atomic weight 235. The isotope of plutonium we were interested in has atomic number 94 and atomic weight 239. The code we used simply took the last digit of the atomic number and put it together with the last digit of the atomic weight: 92^{238} became 28, 94^{239} became 49, and 92^{235}, as here in Section 2, became 25. Since our work on the atomic bomb was a military secret, we weren't supposed to say the words "uranium" and "plutonium" aloud. That's why we used the code.

Twenty thousand tons is a pretty impressive figure for one kilogram of anything. Seven times 10^{17} ergs per gram is nearly 20,000 kilowatt hours. So one pound of uranium, 454 grams, would release

9 million kilowatt hours, for which my local electric utility, Consolidated Edison, would charge me more than one and a quarter million dollars.

3. Fast Neutron Chain Reaction

Release of this energy in a large scale way is a possibility because of the fact that in each fission process, which requires a neutron to produce it, two neutrons are released. Consider a very great mass of active material, so great that no neutrons are lost through the surface and assume the material so pure that no neutrons are lost in other ways than by fission. One neutron released in the mass would become 2 after the first fission, each of these would produce 2 after they each had produced fission so in the nth generation of neutrons there would be 2^n neutrons available.

Having established roughly how much energy might be available from fissioning a quantity of uranium, I next began discussing how to get this energy out.

Massive energy release from fission depends on developing a chain reaction—a geometric progression of fission events, one triggering two, two triggering four, four triggering eight, and so on. That phenomenon depends in turn on the propensity of what the *Primer* calls "active materials"—U^{235} and Pu^{239}, for example—to eject more neutrons per fission on the average than they absorb when they're bombarded with neutrons. Enrico Fermi, Frederic Joliot, Leo Szilard, and others found secondary neutrons from fission in experiments they conducted independently, within days of each other early in 1939, in Paris and New York. This first paragraph of Section 3 assumes an ideal arrangement of material where no neutrons are lost through the surface or to impurities. Fission of U^{235} releases 2.2 secondary neutrons on the average; 2 is a reasonable order-of-magnitude rounding of that number.

Since in 1 kg. of 25 there are $5 \cdot 10^{25}$ nuclei it would require about n=80 generations ($2^{80} \approx 5 \cdot 10^{25}$) to fish the whole kilogram.

The second paragraph of Section 3 is notable for a mistake. There are not $5 \cdot 10^{25}$ nuclei in a kilogram of uranium. There are $2.58 \cdot 10^{24}$. Uranium metal has a density of 19 grams per cubic centimeter; $5 \cdot 10^{25}$ is 19 times $2.58 \cdot 10^{24}$ and is thus the number of nuclei in 1,000 cubic centimeters, not 1,000 grams. On the other hand, 2^{80} is not $5 \cdot 10^{25}$ but $1.2 \cdot 10^{24}$. So 80 generations is still the right answer (81 if you want to be cranky about it). Since fission occurs in about 10^{-8} seconds, those 80 generations would pass in .8 microseconds: it would take less than a millionth of a second to fission a kilogram of uranium.

In these notes I use the verb "to fission." In the *Primer* we used the verb "to fish." That's some indication of how new our work was. Otto Frisch and Lise Meitner named the new nuclear reaction they confirmed in 1939 "fission," borrowing the word from biology. We hadn't settled on a verb form of the noun yet. "To fish" didn't stick. Today we say "to fission," but we kept the pronunciation: it's "*fishin'*," not "*fizj-un*."

While this is going on the energy release is making the material very hot, developing great pressure and hence tending to cause an explosion.

The statements in Section 2 tend to be laconic. If the reaction proceeded at 10 percent efficiency, it would heat the uranium initially, in less than a millionth of a second, to a temperature of about

10^{10} degrees Celsius—about 10 billion degrees. The pressure develops accordingly, and the explosion is correspondingly powerful.

In an actual finite setup, some neutrons are lost by diffusion out through the surface. There will be therefore a certain size of say a sphere for which the surface losses of neutrons are just sufficient to stop the chain reaction. This radius depends on the density. As the reaction proceeds the material tends to expand, increasing the required minimum size faster than the actual size increases.

The whole question of whether an effective explosion is made depends on whether the reaction is stopped by this tendency before an appreciable fraction of the active material has fished.

As the sphere expands, the density of the material within it drops, which simply means that the atoms are further apart. The distance a neutron moves between nuclear collisions increases and as a result more neutrons escape through the surface before making another fission. As the expansion proceeds, more and more neutrons escape, until the loss is enough to stop the chain reaction. This process is described in more detail in Section 13.

Note that the energy released per fission is large compared to the total binding energy of the electrons in any atom. In consequence, even if but ½% of the available energy is released the material is very highly ionized and the temperature is raised to the order of $40 \cdot 10^6$ degrees. If 1% is released the mean speed of the nuclear particles is of the order of 10^8 cm/sec. Expansion of a few centimeters will stop the reaction, so the whole reaction must occur in about $5 \cdot 10^{-8}$ sec otherwise the material will have blown out enough to stop it.

Now the speed of a 1 Mev neutron is about $1.4 \cdot 10^9$ cm/sec and the mean free path between fissions is about 13 cm so the mean time between fissions is about 10^{-8} sec. Since only the last few generations will release enough energy to produce much expansion, it is just possible for the reaction to occur to an interesting extent before it is stopped by the spreading of the active material.

It should be realized that at temperatures of tens of millions of degrees the uranium is no longer a metal but has been converted to a gas, a gas at tremendous pressure which will expand very rapidly. We can estimate the velocity of expansion for 1 percent energy release from the relation

$$E = \tfrac{1}{2}Mv^2 \qquad (2)$$

where *E* is energy, *M* mass and *v* velocity. Using the figures for the energy released per fission and for the mass of a uranium atom given in Section 2, we do a little calculation:

$$\begin{aligned} E &= 1\% \text{ of fission energy} \\ &= .01 \cdot 2.7 \times 10^{-4} = 2.7 \cdot 10^{-6} \text{ ergs} \\ M &= 3.88 \cdot 10^{-22} \text{ gm} \\ v^2 &= 2E/M = 1.4 \cdot 10^{16} \\ v &= 1.2 \cdot 10^{8} \text{ cm/sec} \qquad (3) \end{aligned}$$

and we find that the velocity of the nuclear particles would indeed be about 10^8 cm/sec. This estimate assumes that all the energy is transformed into energy of expansion, which is not literally true but is an adequate assumption for an order-of-magnitude estimate. In any event, the velocity of expansion can't be *greater* than the number we've derived. That I based my calculations on the assumption of releasing only 1 percent of the fission energy indicates that in 1943 we would have been satisfied with quite low efficiencies.

In these paragraphs we also run into the technical term "mean free path." Since the concepts of mean free path and cross section are essential to the rest of the discussion, they need to be explained. Both concern the likelihood that a neutron will encounter and fission a uranium atom. (For a more detailed technical discussion, see endnote 1.)

The *mean free path* is a number derived by measurement: the distance a neutron traveling through a mass of material such as uranium moves, on the average, before colliding with a nucleus of that material.

Cross section is the area of the nucleus, πR^2 ($3 \cdot 10^{-24}$ cm^2). This is the area that the neutron has to hit, the *geometrical cross section*. When a neutron strikes a uranium nucleus, it's temporarily absorbed to make a nucleus with one extra neutron. Then one of several things can happen. A certain fraction of the time, the combined nucleus fissions, with a corresponding release of energy and ejection of secondary neutrons. A certain fraction of the time a neutron is emitted with lower energy than the original neutron, a process called inelastic scattering.

The *fission cross section* is the fraction that leads to fission times the geometrical cross section (that is, times πR^2). The *inelastic cross section* is the fraction that leads to inelastic scattering times the geometrical cross section. The sum of these numbers adds up to the geometrical cross section.

But this description is not quite exact. I've been discussing a purely geometrical picture of the nucleus. There is a quantum mechanical effect which causes the path of a neutron that just misses the edge of a nucleus to be bent. The neutron comes out with unchanged energy but in a different direction. This is called elastic scattering and the cross section for its occurrence is called the *elastic cross section*. The *total cross section*, the sum of the fission, inelastic and elastic cross sections, will thus be somewhat bigger than the geometrical cross section.

Slow neutrons cannot play an essential role in an explosion process since they require about a microsecond to be slowed down in hydrogenic materials and the explosion is all over before they are slowed down.

The last paragraph in Section 3, concerning slow neutrons, will be clearer after we look at figure 1 in Section 4 of the *Primer*. Let's skip it for now and return to it then.

4. Fission Cross-sections

The materials in question are U_{92}^{235} =25, U_{92}^{238} =28 and element 94^{239} =49 and some others of lesser interest.

Ordinary uranium as it occurs in nature contains about 1/140 of 25, the rest being 28 except for a very small amount of 24.

When I reread the first sentence of Section 4 I was struck by the phrase "element 94^{239} =49" where the structure of the sentence seemed to demand "Pu =49." I checked and discovered that the word "plutonium" is never used in the *Primer*. Glenn Seaborg proposed the name in 1942. I wonder if I was aware of it yet in April 1943.

The second paragraph of Section 4 conceals a very great effort of human enterprise. In order to make an atomic bomb with uranium the United States had to separate the 1/140th part of

U^{235} from the 139 parts of U^{238} in natural uranium when the only difference between the two for purposes of separating them was their mass. Most of the two billion dollars that the wartime program to develop the atomic bomb—the Manhattan Project—spent was invested in building the vast machinery necessary to separate uranium. One system, gaseous diffusion, converted natural uranium to a gas and then relied on the two isotopes' differing rates of diffusion across a porous barrier to accomplish the separation, but the difference is so slight it required a cascade of several thousand barrier tanks, the largest of them 1,000 gallons in volume, to enrich the product to bomb grade. The building that held the gaseous-diffusion plant at Oak Ridge, Tennessee, was correspondingly large—a U-shaped structure with each leg of the U nearly half a mile long. Another system, electromagnetic separation, relied on the fact that an electrically charged atom traveling through a magnetic field moves in a circle at a radius determined by its mass. Ions of a vaporous uranium compound projected through a strong magnetic field inside a curved vacuum tank separate into two beams, with lighter U^{235} atoms following a narrower arc than heavier U^{238} atoms. Metal pockets set at the end of the thousands of tanks built at Oak Ridge collected each beam of isotopes separately in the form of metal flakes. The system was notoriously inefficient, but it got the job done. Most of the uranium used in the Hiroshima bomb was separated this way.

Another great effort was required to produce plutonium. This element does not occur naturally but has to be manufactured in a nuclear reactor. In the reactor, fission neutrons are slowed down in graphite (carbon) and some of them are captured in U^{238} to produce the isotope U^{239} (since a neutron is added, the atomic weight