Weapons of Mass Destruction-- 2015

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Abstract:

Millions of deaths and the end of civilizations can be inflicted by knife, machete, or fire, or even by the pen or the spoken word, but a *weapon of mass destruction* – WMD-- implies such a result more centrally imposed. Specifically, I class nuclear, , biological, and cyber weapons as WMD, relegating chemical, high-explosive, and incendiary weapons to a lesser category. Along another dimension, there are near-universal bans on states' use of biological weapons--BW, chemical weapons--CW, antipersonnel land mines, exploding anti-personnel bullets, and even on possession of BW; not all these treaties or agreements are honored by all. This talk will focus on nuclear weapons, their effects, development, deployment, delivery, control, and on efforts to limit or eliminate them—e.g., the Nonproliferation Treaty—NPT, Limited Test Ban Treaty—LTBT, Comprehensive Test Ban Treaty—CTBT, ABM Treaty limiting systems for intercepting ballistic missiles carrying nuclear weapons, Strategic Arms Limitation or Reduction Treaties—SALT or START, etc. But mostly on the technical aspects of nuclear weapons. A key tool to learning is simple search of my web site:

site:fas.org/RLG/ biological weapons Nixon

that yields 18 results, including http://www.fas.org/rlg/020821-terrorism.htm

First, a brief overview of my personalh involvement and views on WMD as a prelude to questions in the last half of the session.

I have worked since the 1950s on chemical and biological weapons, nuclear weapons, and to some extent on cyber weapons—CW, BW, NW, and CyW. Of course, millions or hundreds of millions of people can be killed and have been killed by relatively crude techniques such as knives, bullets, and fire, but a WMD implies a single agent that can kill a lot of people, variously and arbitrarily given as 50,000 or 0.5 million.

Chemical Weapons—CW.

Among CW, one can begin with industrial chemicals such as chlorine, used in warfare in WW I and up the line to more sophisticated nerve agents prepared for use in WW II and used since then, for instance, in the Iraq-Iran conflict. As military weapons, these are not very effective in killing troops prepared to fight, but even the threat of CW can reduce the effectiveness of a fighting force by a factor 10 or more, because of the protective garb and tactics. Much is known about the LD50 of various CW, but less about long-term debilitating effects of sub-lethal doses. In general, CW are an anti-population weapon. The United States and the UK had big CW programs, as did the Soviet Union and most other countries, with sophisticated means of delivering CW

against areas and relatively small point targets. These ranged from ground-carried nebulizers or aerosol generators to cluster munitions that would strike the ground and explode, dispersing CW. I won't discuss CW any further and do not regard it as a WMD in the same class as BW or NW. Exposure levels for CW are typically expressed as mg-minutes of agent per cubic meter of air. A lethal dose of sarin corresponds to an hour exposure at about 2 mg/m^3 of air—about 100 mg-min/m^3.

Biological Weapons—BW.

BW has a long history going back to the siege tool of spreading infection by catapulting corpses into a fortified enclosure. In the early days of the colonies or the United States, blankets infected with smallpox were given to the Native Americans, and many died as a result.

Many pathogens (living agents capable of causing disease) were weaponized by the great powers and tested. For military use, the ideal BW is one that is nonlethal but debilitating. And many of these have been identified. At the beginning of the modern age of molecular biology, the President's Science Advisory Committee considered BW and a special panel of the Committee was convened in response to a request from President Nixon, conveyed through his National Security Advisor, Henry A.Kissinger,

to study the pros and cons of BW. I was a member of that panel, which reported to Kissinger and Nixon the results of its analysis. Even less than CW, BW is not a military weapon, since it can readily be defended against. Unbroken skin is a pretty good barrier, so a reasonable defense against BW can be deployed with relatively simple masks to protect eyes, mouth, nose, and the respiratory system, combined with discipline in donning, removing, and disinfecting the protective gear. Laundry bleach diluted 100:1 is an excellent disinfectant.

But BW is a potent anti-population tool, as exemplified by the Black Death of the middle ages, the Spanish Flu of 1918-1919, and the potential impact of smallpox in a population with no immunity to smallpox since vaccination in the United States was terminated in 1972—a decision reviewed by the President's Science Advisory Committee (Nixon Administration) at that time, of which I was a member and from which I heartily dissented.

Diseases can be separated pretty well into those that are simply infectious from the pathogen initially distributed and those that have a high degree of contagion, spreading from one human host to another as in the case of influenza, smallpox, and, especially measles and the common cold. Some diseases are largely nonlethal, but

even among influenzas, the mortality (deaths per person infected) can vary from well below one per cent to 50%.

Against both BW and CW, one can have personal protective measures (PPM) or collective protection—CP—in which a small overpressure is maintained in an enclosure by a blower bringing in air through a filter or of a device adequate to screen-out or destroy the poison or pathogen.

President Nixon astonished the world by issuing a statement 11/25/1969 banning U.S. use, possession, or research on offensive BW. Many were critical of this saying that Nixon had thereby abandoned any possibility of obtaining the agreement of the Soviet Union to a treaty to the same ends, but they were proved wrong when the Soviet Union promptly signed up. Unfortunately, the USSR apparently believed that the United States was not sincere in its actions, and although the U.S. promptly terminated all of its BW programs known to the government, the Soviet Union (and later Russia) did not, until much later. A major loose end was the lack of proscription of "toxins"—chemicals of biological origin, of which one example is botulinum toxin. On 02/14/1970, President Nixon renounced also toxins, bringing them under the same control as living BW agents1.

[1] http://ndupress.ndu.edu/Portals/68/Documents/casestudies/CSWMD_CaseStudy-1.pdf

That is the last I will talk about BW, although I have written about it.

Nuclear Weapons—NW.

There is an enormous history of technical aspects of nuclear weapons, including the basic phenomena involved in their operation, their effects, stockpiles, delivery systems, and means of commanding and controlling nuclear weaponry, including agreements and treaties. Many of these topics are treated in papers and speeches on my website, www.fas.org/RLG/, and especially in my books with Georges Charpak and Venance Journé, most recently in English Megawatts and Megatons, 2001/2002. In French there is an expanded version of Megawatts and Megatons2, but untranslated into English.

Technical history of nuclear weapons. The scientific concept of nuclear weaponry really got its start with Leo Szilard who read an account of a speech by Lord Rutherford in September, 1933 that "anyone who looked for a source of power in the transformation of the atoms was talking moonshine." Szilard, living in London, was well aware of Chadwick's discovery of the neutron in 1932 and had carried out some

[2] *De Tchernobyl en tchernobyls*, by G. Charpak, R.L. Garwin, and V. Journé, Odile Jacob, September 2005

experiments himself, with others, especially chemists. Goaded by Rutherford's dismissive comment3, Szilard filed a patent application in London for a system that employed an element that gave more than one neutron out per neutron in, on average, so that there could be an exponentially growing "chain reaction" with a sufficiently large amount of this material to minimize neutron escape probability. Szilard's experiments began at the light end of the periodic table and ended without showing a hopeful candidate.

In the meantime, Enrico Fermi's group at Rome ran with the neutron activation of all of the elements of the periodic table, and in December 1938 Fermi received the Nobel Prize in Stockholm for his discovery of transuranic elements and for the efficacy of slow neutrons in causing nuclear reactions.

Artificial nuclear reactions were first observed by the use of alpha-particle bombardment of target nuclei, but Fermi's group showed that neutrons produced by alpha particles incident on beryllium could be much more widely effective, because a neutron is not repelled by the Coulomb barrier—that is by the positive charge on a nucleus, as are other elementary particles that can be accelerated in cyclotrons or electrostatic accelerators. The Fermi group early on made a crucial discovery that

[3] http://www.fas.org/rlg/04_07_2014LeoSzilardinPhysicsandInformation.pdf

immersing the neutron source on the target in water or surrounding them with paraffin wax or other material containing large amounts of hydrogen increased the effectiveness of the neutron by as much as a factor 100, essentially because repeated "elastic" collisions of the neutron with the hydrogen (billiard-ball collisions) slowed the neutron from the initial energy of millions of electrons volts (MeV) to "thermal energies" of 1/40 eV, and the slow neutrons spent much more time in the vicinity of the nucleus than did the fast neutrons and thus were correspondingly more effective in causing transmutation.

In fact, although Fermi had produced transuranics, the radioactive evidence of their existence did not come from transuranics in large part, but from the breakup of the rare isotope of uranium (U-235, 0.7% of natural uranium) by "fission" into two nuclei of mass adding up almost to that of the 235 atomic mass units (amu). The fission products normally intensely radioactive because they have far more neutrons per proton than is stable for a nucleus of intermediate mass. Cesium (Cs) and barium (Ba) are representative of the light and heavy fission fragments.

The act of fission is accompanied by the emission of more than two neutrons on average (about 2.5 from thermal-neutron fission of U-235), which are typically boiled off the fission fragments during a fraction of a picosecond, although about 0.65% of

the neutrons are emitted in the course of the radioactive decay of the fission fragments long after they have come to rest—over an interval of 1-100 s.

The Fermi group had been causing fission, reproduced all over the world for four years or more, without any recognition of the fact, until shortly after the Nobel Prize a group of German radiochemists determined that some of the radioactivity produced by neutron capture in uranium was chemically identical to barium, and Lise Meitner and Otto Frisch attributed it to the breakup of the nucleus, which could be understood by the “liquid drop” model of nuclei.

The LDM estimates the “surface tension” of the nuclear material, the oscillation frequencies of the drop, and the probability of fission when even a slow neutron is absorbed and contributes on the order of 8 MeV in excitation to the nuclear matter.

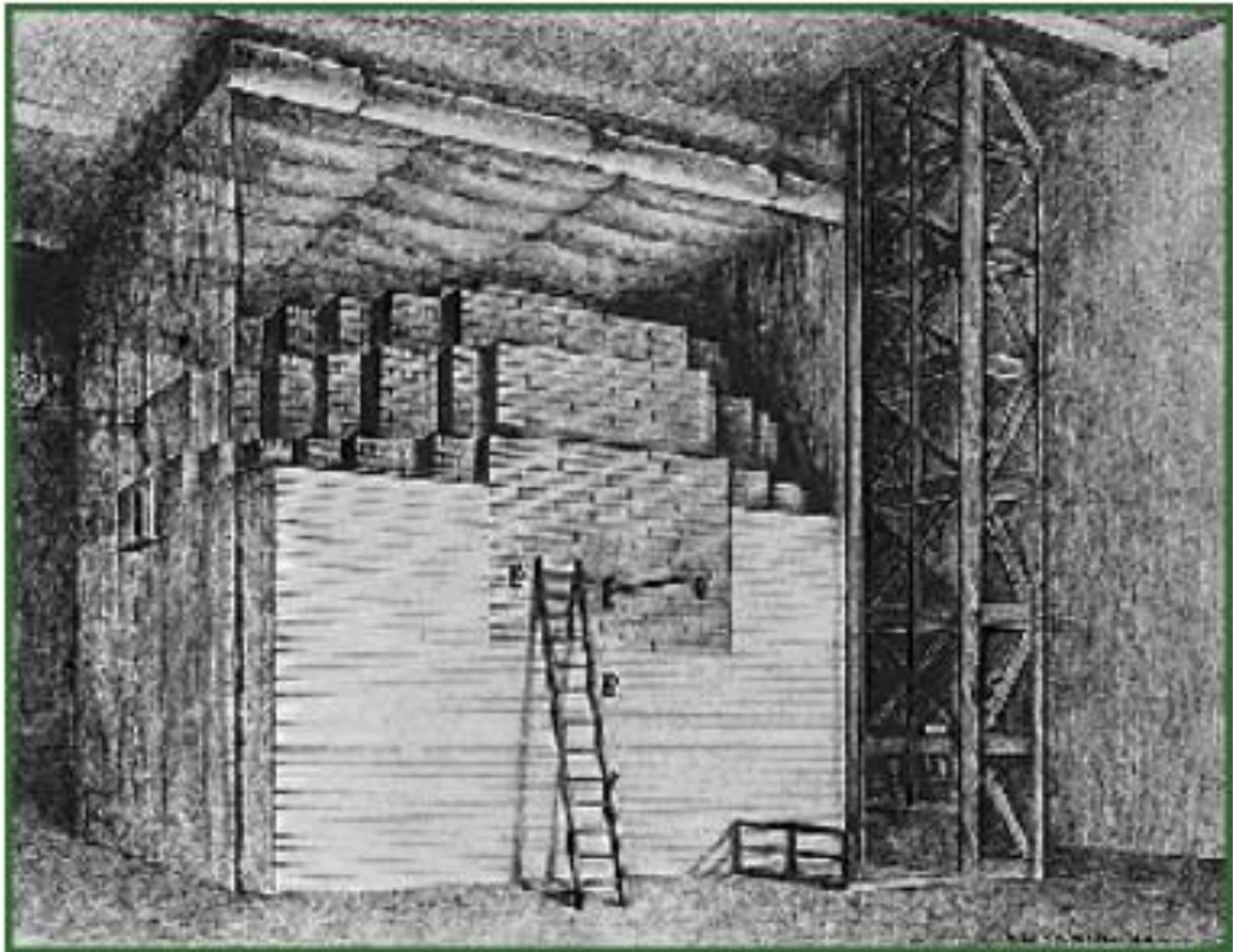
In early December 1938 Fermi had traveled with his wife, Laura, and children, Nella and Giulio, to Stockholm to receive the Nobel Prize, secretly having accepted a job as Professor of Physics at Columbia University in order to escape fascist Italy, which had just passed the “race laws” under which the Fermi children would not have access to universities because Laura’s family was Jewish. Laura’s father, Italian Admiral Augusto Capon felt secure remaining Rome because he had served with great

distinction in WW II. Nevertheless, when the Nazis entered Rome on October 16, 1943, Admiral Capon, with 1000 other Jews, was shipped to Auschwitz where he died on October 23.

Szilard was already a hanger-on at the Columbia University Physics Department and when news of fission reached New York in early January, 1939. Szilard pressed Fermi to explore fission not in detail as a physical phenomenon, but to explore the possibility of the neutron chain reaction and, especially, of using the chain reaction to create nuclear weapons.

You are probably familiar with the "Einstein letter" to President Franklin D. Roosevelt of August 2, 1939, actually written by Leo Szilard, who recognized that Einstein's name would provide authority that Szilard's would not. A small team at Columbia University continued to work with Fermi on the "exponential pile", which was moved in mid-1942 to the University of Chicago, where a full-size proof of principle, CP-1, was built containing 400 tons of graphite as moderator, with 6 tons of uranium metal and 34 tons of uranium oxide in lumps or cans to allow the fast neutrons to slow in the moderator without being captured by the 99.3% U-238 in the natural uranium with which the pile was loaded. The 3-D arrangement was probably due to Szilard; Fermi had originally proposed a 2-D arrangement of alternating layers

of uranium and graphite. Criticality was achieved on December 2, 1942, and work began immediately on the design of the plutonium production reactors in Hanford.



Drawing of CP-1

Although the capture of neutrons on U-238 was an impediment to achieving a self-sustaining neutron chain reaction with natural uranium, the result of that capture was U-239 which decayed into neptunium (Np-239) and then into plutonium (Pu-239) within a couple of days, to the extent that a gram of Pu-239 was produced in a pile that had a "thermal power output" of 1 MW. It was realized first by Louis Turner, a Princeton physics professor, that Pu-239 should be as good a material as U-235 for the "fast-neutron chain reaction" involved in a nuclear explosive, and it was clear that "only" chemical separation would be required to obtain the plutonium from fuel irradiated in a production reactor. Scale up from CP-1 to the first production at Hanford was enormous—a factor 100 million, from 2 W to 200 MW thermal power output. The Hanford reactor thus produced about 0.2 kg of plutonium per day, and it turned out that the bare-sphere critical mass of Pu-239 is 10 kg for alpha-phase metal of density 19.6. Using a neutron reflector of natural uranium of beryllium (Be) can reduce the critical mass by a factor two, and in fact, the plutonium bomb tested at Alamogordo, NM, 07/16/45 and used to destroy Nagasaki on 08/09/45 used about 6 kg.

Before the chain reaction with natural uranium was established as feasible, and the plutonium route opened to nuclear weapons, the initial concept in Germany, the UK, and the United States was a U-235 weapon, which would require "isotopic separation"

or enrichment from the U-235 content of 0.71% in natural uranium (NU) to something of the order of 90% U-235 in the weapon-grade highly enriched uranium—HEU. In the 1930s, physicists and chemists had done isotope enrichment of chlorine, mercury, and, especially hydrogen by various chemical or physical means, all relying (except for the separation of deuterium from hydrogen) on the relatively small mass difference between the isotopes, which in the case of uranium amounts to about 1%, or 3 amu. Almost all the approaches utilize the gas UF6, solid at room temperature but a vapor slightly above room temperature, which has the initial virtue that natural fluorine is monoisotopic, with a mass of 19 amu.

The massive uranium enrichment facilities built at Oak Ridge, TN, during WW II employed two processes—gaseous diffusion and electromagnetic (Calutron) enrichment. The thermal velocity of a UF6 bearing U-235 is about ½% (the square root of the mass ratio) larger than that of a U-238, so a nickel-bearing porous barrier served to provide an enrichment per stage of about 0.5%. Two hundred stages would thus provide a factor 2 or e (2.71828…) enrichment, so that on the order of 2000 stages would be required. Many large low-pressure compressors were used between stages to bring the gas back up to pressure, and the output from a stage was routed into the “cascade” which had a feed point, a “tails” delivery point, and a “product” delivery point.

The electromagnetic separation approach used a beam of ions not unlike that in an old-fashioned TV tube (electrons) for which the magnetic rigidity of a beam accelerated to a given energy differs, again by 0.5%. But because many “spots” can be resolved on the (one dimensional) TV tube, a “pocket” or collector for the product U-235 can be placed at one point and one for the tails (U-238) at another, so that only a single stage of separation would be necessary, in principle. However, to obtain an atom of U-235, 140 atoms of NU would need to be ionized and accelerated, so that the system would be very inefficient. In fact, if all ions are accelerated to 100 kV there would be in investment in acceleration alone of about 14 MeV per U-235 separated.

Although thermodynamically the energy to separate U-235 almost entirely from U-238 in NU should take less than 1 eV per atom of U (about 100 eV per product atom of U-235), the overall power required for the gaseous diffusion plant amounted to about 5 MeV per atom of U-235 in the product HEU—one of the least efficient processes known to me.

Other approaches to enrichment were also a matter of research, including chemical rate differences and centrifuge enrichment, but the Manhattan Project (as the overall

secret effort was called after September 1942) really had the wrong concept of the centrifuge.

The real invention of the gas centrifuge for uranium separation was due to G. Zippe, an Austrian swept up by the Soviet Union and put to work on uranium enrichment. Zippe's genius resulted in the centrifuge used almost universally today for enrichment of uranium for use in power reactors or nuclear weapons worldwide, at a commodity cost of about $100 per kilogram separative work unit-- $100/kg-SWU[4].

[4] https://www.fas.org/rlg/SWU_Calculations_version_3_1.xls for an active Excel spreadsheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**SWU per kg for various enrichment parameters.**						SWU_Calculations (version 3).xls				R.L. Garwin, 12/19/2007			
2	Row													
3	3	Xp	Xw	Xf	P	W/P	F/P	Vp	Vw	Vf	ΔSWU/	ΔSWU/	ΔSWU/	
4	4	(product)	(waste)	(feed)	kg	kg W/kg P	kg F/kg P	----------value function--------			kg product	kg U-235	P kg of	
5	5	% U-235	% U-235	% U-235	kg of product			---------- (2x-1) ln [x/(1-x)] ------				in product	product.	
6	6													
7	7	95.000	0.250	0.711	1.00	204.53	205.53	2.65	5.96	4.87	220.75	232.37	232.37	
8	8	90.000	0.250	0.711	1.00	193.69	194.69	1.76	5.96	4.87	208.03	231.15	231.15	
9	9	80.000	0.250	0.711	1.00	171.99	172.99	0.83	5.96	4.87	183.46	229.32	229.32	
10	10	19.900	0.250	0.711	1.00	41.62	42.62	0.84	5.96	4.87	41.35	207.77	207.77	
11	11	90.000	0.400	0.711	1.00	287.10	288.10	1.76	5.47	4.87	170.42	189.36	189.36	
12	12	3.500	0.400	0.711	1.00	8.97	9.97	3.08	5.47	4.87	3.64	103.89	103.89	
13	13	90.000	0.400	3.500	1.00	27.90	28.90	1.76	5.47	3.08	65.33	72.58	72.58	
14	14	3.500	0.360	0.710	1.00	7.97	8.97	3.08	5.58	4.87	3.89	111.22	111.22	
15	15	4.400	0.250	0.711	1.00	8.00	9.00	2.81	5.96	4.87	6.66	151.41	151.41	
16	16	3.500	0.400	0.710	1.00	9.00	10.00	3.08	5.47	4.87	3.64	104.02	104.02	
17	17	95.000	0.500	0.711	1.00	446.87	447.87	2.65	5.24	4.87	163.79	172.41	172.41	
18	18	95.000	0.500	19.900	1.00	3.87	4.87	2.65	5.24	0.84	18.85	19.84	19.84	
19	19	19.900	0.711	4.400	1.00	4.20	5.20	0.84	4.87	2.81	6.69	33.62	33.62	
20	20	90.000	0.400	3.500	1.00	27.90	28.90	1.76	5.47	3.08	65.33	72.58	72.58	
21														
22	**Enter your desired set** of enrichment parameters in Columns B-D for Xp, Xw, and Xf-- the U-235 conentrations in %, and in Col. E the kg of product.													

In order to define the task of making actual nuclear explosives out of the U-235 scheduled to arrive from Oak Ridge and the Pu that would be produced if the reactor at Chicago proved a success, scientists convened a summer study in June 1942 at the University of California at Berkeley, chaired by J. Robert Oppenheimer, a Professor of Physics at Berkeley and also at Caltech (Pasadena, CA). The group of about a dozen theoretical physicists at Berkeley spent perhaps a day on defining solutions to

the problem of maintaining the fissile material subcritical in transport but then quickly bringing it to a (neutron-chain-reaction) supercritical state. If the degree of criticality is defined by the number of fissions in the successive generation, divided by the number of fissions in the previous generation, its value must be maintained below 1.0 (and in fact below 0,9935) because the system in transit must be subcritical when delayed neutrons are taken into account, even though only prompt neutrons contribute to useful yield in a nuclear explosive.

The considerations involved are well recorded in a monograph by Robert Serber, a participant at the Berkeley summer study and one of the first denizens at Los Alamos when the Laboratory was established there in March 1943 as "Site Y" of the Manhattan Project. Serber had the responsibility of briefing the Laboratory personnel as they arrived from all over the country (and from England) on what the program was about. Edward Condon at Los Alamos took notes which were to become the famous "Los Alamos Primer (LA-1), the first official document of the Manhattan Project at Los Alamos. This was classified for a long time, then declassified, then reclassified, but is now available in a version later annotated by Bob Serber, from the University of California Press. As you may know, Bob Serber was a professor here at Columbia for many years after leaving Berkeley in 1950 over the "loyalty oath", but that is another story.

The baseline approach from the 1942 Berkeley summer study was to use “gun assembly” of about 60 kg of HEU or correspondingly less (perhaps about 10 kg) of Pu-239 in order to move quickly from the subcritical configuration to one of maximum supercriticality. The system was to be provided with a neutron generator so that when the two portions of fissile material were fully assembled, a copious stream of neutrons would initiate the chain reaction before mechanical disassembly could occur. Of course, after many e-foldings of neutron population, the internal energy would be so high that the system would blow itself apart before all of the fissile material was consumed in the chain reaction. In fact, the Hiroshima bomb, gun-assembled 60-kg of U-235, which at 100% fission would have a full yield of about 1000 kT (kilotons of TNT equivalent), actually had a yield of about 11-15 kT, so about 1% efficiency. This was predicted, although with some uncertainty, by the Bethe-Feynman formula, worked out at Los Alamos.

Los Alamos was the designated site for making nuclear explosives from the fissile material arriving from Oak Ridge or Hanford—U-235 and Pu-239 respectively. But when the plutonium began to arrive in tiny amounts from Hanford, early in 1944 it needed to be investigated for its “spontaneous” neutron generation rate. Because the Pu-239 half-life is 27,000 years, compared with the 730 My half-life of U-235, a tiny

amount of beryllium or oxygen in the Pu could cause unacceptable neutron generation rate from the (alpha,n) reaction, and lead to premature initiation of the neutron chain and thus to a "fizzle." Much effort was expended at Chicago to purify Pu metal these light elements, but when the Hanford Pu was investigated at Los Alamos by Emilio Segre, it turned out to have unacceptably high neutron generation rate that was quickly attributed to Pu-240 content, formed by neutron capture on the Pu-239 itself. This was minimized by short exposure of the natural uranium fuel slugs in the reactor, but still the Hanford Pu could not be used for gun assembly in the "Thin Man" Pu gun. The U-235 gun assembly was dubbed "Little Boy."

In the Los Alamos Primer another assembly mechanism is sketched, using a surrounding shell of high explosive to more rapidly assemble pieces of Pu, but when at Los Alamos the gun assembly means for plutonium proved to be impossible, there were major concerns about the symmetry of the explosive assembly approach. The UK contingent had brought with them the design of high-explosive "lenses" to convert a number of detonation points on the high explosive (32 in the Nagasaki bomb) from spherically expanding detonation waves to a single spherical contracting detonation wave, but there were still imperfections in the use of this "implosion" technique to assemble surrogate materials such as steel, lead, or the like—stand-ins for plutonium in tests. The problem was resolved by an observation perhaps due to

John von Neumann and Edward Teller that the explosive assembly of plutonium metal would lead to significant compression of the metal, so that even a solid sphere could be driven under explosive influence from subcritical to substantially supercritical.

At the Metallurgical Laboratory at Chicago, the scientists from the beginning decided that everyone within the program should have full access to all of the ideas and progress, and that was carried over to Los Alamos under the leadership of Robert Oppenheimer, despite initial objections by the overall head of the Manhattan Project, Brigadier General (BGen) Leslie R. Groves. Robert Christie proposed the solid sphere plutonium core, which then took the name of "Christie Gadget," and was the approach used in the Alamogordo test and the identical Nagasaki bomb, Fat Man.

The two bombs, Little Boy and Fat Man were delivered August 6 and 9 against Hiroshima and Nagasaki from the North field at Tinian Island. They were assembled at Tinian by a contingent from Los Alamos headed by Norman Ramsey, Professor of Physics at Harvard University for a long time after the war. Luis Alvarez, Professor of Physics at Berkeley and part of the Los Alamos assembly team on Tinian had the idea, for the Nagasaki drop, to attach to some parachute-borne "yield gauges" a letter to R. Sagane, known to three of the scientists on Tinian, explaining that these were the first two of many nuclear weapons that would be used against Japan, and that Sagane

should bring this to the attention of the Emperor. Apparently this was done, and perhaps was instrumental in obtaining the prompt and unconditional surrender of Japan.

Both the HEU gun-assembled weapon and the Pu implosion weapon had switchable neutron generators in the form of hundreds of curies of Po-210 (137-day half-life) adjacent to beryllium metal, but with a thin layer of nickel coating the Po alpha source so that the alpha particles from the radioactive decay (37 billion per second per Ci) could not provide neutrons by the (alpha,*n*) reaction until the Ni film was disrupted by the passage of a shock wave.

After the surrender of Japan, there was little urgency for additional nuclear weapons until the Cold War developed with the Soviet Union, which picked up the pace of weapon development at Los Alamos. One problem with the early nuclear weapons was that they were not "one-point safe" in the sense that accidental detonation of the explosive by lightning or a bullet would have given a nuclear yield. Initially a portion of the nuclear weapon was kept separate and armed by a person carrying it to the rest of the assembly once the aircraft neared the target, but this was clearly not practical for a widely dispersed nuclear weapons delivery capability.

The story of one-point safety, insensitive high explosive, and the like, is too long to tell here.

External initiators.

The continuous resupply of 137-day Po-210 for internal initiators and the requirement for access to the very core of the nuclear weapon caused major design, maintenance, and logistical problems. Accordingly, Norris Bradbury, the Director of the Los Alamos Laboratory following Robert Oppenheimer in 1945, in 1951, as I recall, convened a small meeting in his office (at which I was present) at which Edward McMillan of the Berkeley Radiation Laboratory took the responsibility to provide external initiators in the form of betatrons that would be packaged with the implosion weapon, that would at the appropriate time of maximum criticality fire an intense burst of high-voltage x-rays into the core of the nuclear weapon, thus producing photofission neutrons that would initiate the chain reaction.

Another approach committed at that time proved to be better in the long run, and that was to have electrostatic acceleration of tritons or deuterons, in the d-t reaction producing 14.7-Mev neutrons that would penetrate to the weapon core and initiate the

chain reaction. This is the approach used today in essentially all U.S. nuclear weapons.

Boosting and two-stage fission-fusion weapons.

Edward Teller from the 1942 Berkeley summer study joined the Los Alamos program, but with the intent of working on thermonuclear weapons, in which the energy release came not from the initially room-temperature exponential growth of neutrons and fission in a supercritical mass of U-235 or Pu-239, but from an initially intensely hot mixture of mass of deuterium (or deuterium-tritium mixture). Rather than about 150 MeV of prompt energy release from a fission, the *d-t* reaction gives 17.6 MeV as the product He-4 and n fly apart. Teller never had more than a couple of people working with him at Los Alamos on this because it was clear that the only way to get sufficient temperature was with a successful fission bomb, and sensible people realized that would be enough to end the war. But after 1945 Teller continued to push on fusion weapons, and a major experiment in the GREENHOUSE series in the Pacific was committed for 1951—GREENHOUSE GEORGE, an experiment on burning thermonuclear fuel. Unfortunately, nothing more can be said about GEORGE except that it was highly successful. In the same series, GREENHOUSE ITEM was a test of an implosion weapon containing *d-t* mixture at the center of the fissile core—

not to produce a significant amount of energy but to “boost” the number of neutrons present in the core at that time, and with each of those neutrons provoking a fission in the highly supercritical assembly, to increase the fission yield. This was a major step forward and is used in essentially all U.S. nuclear weapons to this day.

But Teller’s dream of a weapon fueled with the unlimited energy supply of deuterium from water was unrealized and probably unrealizable until in February 1951 the Los Alamos mathematician Stan Ulam came to Teller with a proposal that nuclear weapons could be built with an auxiliary external nuclear explosion to compress a main charge. Edward Teller was dismissive of the prospect, because he had long formulated an unwritten “theorem” that if you couldn’t get deuterium to burn at normal liquid density (about 0.17 g/cc) compressing it 100-fold or 1000-fold would do no good, because the rate of energy gain from fusion reactions would go up as the square of the density (per unit volume) but the rate of energy loss from the hot ions by collision with electrons and electrons with collision with photons would go up similarly. So an unfavorable balance would be preserved.

But when he decided actually to put some numbers on paper, Teller discovered that he had made a logical error and that the ultimate loss to photons of the radiation field was limited by the equilibrium energy density of such photons. The energy content at a

given temperature per unit volume of photons was independent of the compression, but the available fusion energy would go linearly as compression (per unit volume) and the rate of generation as the square of the compression. So there was much to be gained by compression.

Two-stage thermonuclear weapons by radiation implosion.

When I arrived at Los Alamos for the second summer in May 1951, Teller asked me to design an experiment that would incontrovertibly demonstrate the effectiveness of this "radiation implosion" approach to burning thermonuclear fuel. I decided that the best and quickest way to demonstrate was at full size and provided the initial design of the IVY MIKE experiment. From the date of my paper at Los Alamos, July 25, 1951, to the actual detonation at Eniwetok on November 1, 1952 was 15 months.

So here I make the transition to my presentation ten years ago at the American Philosophical Society in Philadelphia, on the same platform with a (recorded) speech by Robert Oppenheimer that had been made to the same group 60 years earlier. And then we will go to questions.

But first a caution. Although the principles of nuclear weapons have not changed since the early 1950s, the evolution of technology and the spread of knowledge has made the acquisition of nuclear weapons much easier. “Two nuclear weapons for $2 billion” (the cost of the Manhattan project by 1945) has nothing to do with the investment required now, if HEU or plutonium compound from the nuclear power industry is available. Hence the major concern with preventing the proliferation of nuclear weapons.