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Fissile Material Conversion Times, Wastage and Significant Quantities: Lessons from the Manhattan Project

Introduction and Summary

Much of the discussion regarding the dangers of Iran's nuclear program related to the so-called breakout time i.e. the time that would be required for Iran to use its centrifuge enrichment facilities and its stocks of low enriched uranium to produce the highly enriched uranium (HEU) needed to manufacture nuclear weapons. For uranium to be enriched in a centrifuge, its chemical form must be uranium hexafluoride. It is well-known that for the HEU to be used in a nuclear weapon, it must first be converted into uranium metal and shaped into either a sphere or a cylinder depending on the nuclear weapon design.

Those who wished to downplay the Iranian nuclear threat claimed that the conversion time would be quite long. Iran itself published an estimate of six months.[2] While such an estimate would seem to be self-serving, a group of U.S. and Russian "technical experts" also published a six month estimate.[3] Others, while not being specific, clearly believed that the conversion time would be long.

However, an examination of the historical record shows that conversion times as long as six months are quite implausible. The Chinese began producing the HEU for its first nuclear test on January 14, 1964, yet only three and one half months later, on May 1 "the nuclear core for the bomb was ready."[4] The actual conversion time would have been much shorter, since most of this time would have been taken up enriching sufficient HEU for the test device.[5]

Further, the Chinese were in no particular hurry to test a nuclear weapon in contrast to a breakout from safeguards where time would be of the essence.[6] To gain a better idea of what the minimum time might be, it is necessary to look at the U.S. experience in World War II where every effort was being made to produce nuclear weapons as quickly as possible.

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[1] This paper is the product of the author's personal research and the analysis and views contained in it are solely his responsibility. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com

[2] "How long would an Iranian 'breakout' really take?," June 2014, nuclearenergy.ir

[3] "Iran's Nuclear and Missile Potential: A Joint Threat Assessment by U.S. and Russian Technical Experts," EastWest Institute, May 2009, p. 5. The Russian members of this group believed that the time could be even longer than six months.

[4] John Wilson Lewis and Xue Litai, *China Builds the Bomb*, Stanford University Press, 1988, p.136.

[5] Gregory S. Jones, "Critique of IISS Estimates of the Time Required for Iran to Produce the HEU Metal Core Required for a Nuclear Weapon, Addendum: Time Required to Produce the Non-Nuclear Components Needed For a Nuclear Weapon," Revised April 6, 2011, http://www.npolicy.org/article.php?aid=769

[6] For example, the Chinese produced a fully completed test device on August 19, 1964 but did not test it until October 16, 1964.

This paper contains a history of the Manhattan Project as it relates to the issue of fissile material conversion times. The production of the HEU for the Hiroshima weapon was the bottleneck delaying the production of the finished weapon. The HEU for this weapon was being produced at late as July 15, 1945, yet the HEU metal components (64.15 kilograms of approximately 82.5% enriched uranium) were ready on July 24, only nine days later. The HEU metal components would need to be mated to the rest of the weapon but this procedure would require only a few hours.

This history also provides insight into the process wastage i.e. how much extra fissile material a country would need to actually produce the required metal components given that in the manufacturing process some of the material would not windup in the final weapon's components.[7] The International Institute for Strategic Studies had claimed that Iran would need 50% more HEU than was used in the final nuclear core.[8] However the amount of HEU available to the Manhattan Project on July 15, 1945 indicates that such wastage could have been no more than 6%.

This history also provides insight into the time required to convert plutonium from the nitrate that is the product of a reprocessing plant into the metal sphere needed for a nuclear weapon. In the case of plutonium there was sufficient material for the weapon but there was a little-known last minute change from using a pure plutonium metal core to one that was a plutonium metal alloy.[9] The critical mass of this plutonium alloy was only determined on June 24, 1945, yet the core for the Alamogordo test was finished by July 1, only a week later. The increased size of this alloy core would have also required changes in other components of the weapon but the non-nuclear components of the test device were ready by July 12. The wastage for the three plutonium cores that were produced by the end of the war was no more than 3%.

Published critical mass data show that the core of the Nagasaki weapon contained 6.15 kilograms of plutonium[10] and if 93.9% enriched HEU were used in this device, it would contain 20.5 kilograms. Using the Manhattan Project's actual upper limit for the wastage would produce estimates of the "significant quantities" (as defined by the International Atomic Energy Agency—IAEA) of only 6.3 kilograms of plutonium and 21.7 kilograms of HEU (20.4 kilograms of U-235). This confirms what others have stated, that even for the simple Nagasaki design, the IAEA's values for "significant quantities" (eight kilograms for plutonium and 25 kilograms of U-235) are too high.

[7] This fissile material is not lost. Since it is more valuable than gold, it is recovered from the process waste.
[8] *Iran's Nuclear, Chemical and Biological Capabilities, A net assessment*, an IISS strategic dossier, The International Institute for Strategic Studies, London, 2011.
[9] This episode is little-known, in part because when the standard histories of the Manhattan Project were written in the 1960s and 70s, it was still classified that plutonium metal alloy was the form used in weapons.
[10] This plutonium contained 1.0% Pu-240 and was an alloy containing 1.0% by weight of gallium.

Manhattan Project's Production of Nuclear Weapons

In December 1942, President Roosevelt approved a large scale effort to produce nuclear weapons. There were two way to produce the fissile material needed for such weapons. One required the production of HEU by enriching the U-235 content of uranium from its natural concentration of 0.7% to 80% or more. The other involved the production of plutonium (mainly Pu-239) by irradiating natural uranium in reactors and then chemically separating the resultant plutonium from the spent fuel. Since the U.S. development of nuclear weapons, all other countries aspiring to acquire nuclear weapons have initially focused their efforts on the production of only one or the other of these two fissile materials but the U.S., having abundant resources and facing the large uncertainties of being the first country to develop such weapons, pursued the production of both fissile materials simultaneously.

To produce HEU the Manhattan Project relied mainly on two methods, calutron and gaseous diffusion. In a calutron electrically charged uranium atoms are vaporized in a vacuum and sent on a curved path in a magnetic field. The mass difference between U-238 and U-235 leads to different paths and thereby enrichment of the uranium. To produce HEU would require two enrichment steps, Alpha and Beta. An Alpha calutron would take natural uranium and produce about 12% enriched uranium, the Beta calutron would take the 12% enriched uranium and produce HEU in the range of 70% to 90%. Over one thousand calutrons would be used by the Manhattan Project.

In the gaseous diffusion process uranium in the form of gaseous uranium hexafluoride would diffuse through a porous material. Each diffusion step would lead to a slight enrichment of the uranium so to produce HEU several thousand stages would be needed. When difficulties delayed both of these enrichment processes, thermal diffusion was used as well. This process produced relatively small amounts of enrichment by circulating gaseous uranium hexafluoride in the annulus formed by one pipe inside of a second pipe. The interior pipe was heated by steam, while the exterior of the second pipe was cooled with water.

To operate a nuclear reactor with natural uranium fuel to produce plutonium, a moderator of either graphite or heavy water must be used. The Manhattan Project used graphite reactors. It built a small experimental reactor, the X-10 in Tennessee and three large plutonium production reactors (B, D, and F) at Hanford in Washington State. Also built at Hanford were the precipitation based reprocessing plants need to separate and purify the plutonium.

The detonation of a nuclear weapon requires the generation of a supercritical mass of fissile material. There are two ways to produce this supercritical mass. One is the gun method where one subcritical mass of fissile material is fired as an artillery projectile into another subcritical mass of fissile material, producing the necessary supercritical mass and nuclear explosion. The other is the implosion method where a subcritical mass of fissile material is surrounded by high explosives. These explosives are detonated simultaneously compressing the fissile material. The reduced surface area of the compressed fissile material causes it to become supercritical. From the beginning it was recognized that of the two methods, implosion was the superior one as it would permit more efficient use of fissile material in nuclear weapons. However, in 1943 no one knew how to make this method work and it was decided to focus the main effort of research on

the gun method which involved the utilization of well-developed conventional artillery technology.

There was one problem with the gun method. It produces a supercritical mass relatively slowly compared to the implosion method. If a stray neutron were to start a chain reaction too early, the weapon would predetonate and produce less (perhaps far less) than its design yield. The main source of neutrons was expected to be the result of the reaction of alpha particles (produced by the decay of U-235 or Pu-239) with light element impurities in the fissile material. For U-235 this was not much of a problem. With a 700 million year half-life, it produces alpha particles at a relatively low rate—resulting in a similarly low rate of neutron production.

For the plutonium gun weapon this problem was more serious. Pu-239 has a 24,000 year half-life and produces alpha particles at a 30,000 times higher rate than does U-235. To deal with this problem it was planned to build a special high velocity gun and at the same time to rigorously purify the plutonium so as to greatly reduce the amount of light element impurities. It was hoped that these two measures would be enough to make a plutonium gun nuclear weapon feasible.

In 1943 very little plutonium actually had been produced. Indeed plans to build large plutonium processing facilities at Hanford were based on less than one milligram of plutonium that had been produced in the Berkeley cyclotron. This plutonium was almost pure Pu-239.

In the spring of 1944 tens of grams of plutonium became available from the experimental X-10 reactor. Tests on this material showed that reactor produced plutonium (using nuclear reactors was the only way to produce large amounts of plutonium) would inevitably contain significant amounts of Pu-240. Further tests showed that this Pu-240 would produce large numbers of neutrons through spontaneous fission.[11] The number of neutrons so produced would greatly exceed the number produced by alpha particle reactions with light element impurities. As a result in July 1944 it was necessary to abandon the development of the plutonium gun weapon though the development of the HEU gun weapon continued. I will discuss the development of these two types of weapons separately.

HEU Weapons

With the abandonment of the plutonium gun weapon, the development of an HEU gun weapon was greatly simplified. The special high velocity gun being developed for plutonium was pushing the limits of artillery technology. However, the much lower rate of alpha particle production from HEU meant that the requirements for the gun system were relaxed and could be easily met using existing gun technology. Natural uranium metal could be used as a perfect stand-in for HEU and used to tested prototype gun weapons. By the end of 1944, there was no doubt that a gun type HEU nuclear weapon could be produced as soon as sufficient HEU was available.

An approximate curve of HEU production for the Manhattan Project published in the 1960s shows that the Hiroshima weapon contained about 50 kilograms of U-235 in uranium that was enriched somewhere between 63% and 89% i.e. between 79.4 kilograms and 56.2 kilograms of

[11] Pu-239 also undergoes spontaneous fission but the spontaneous fission rate of Pu-240 is 40,000 times higher.

total uranium respectively[12]. Information published in the 1980s indicated that the uranium was in the shape of a cylinder.[13]

Coster-Mullen has published more detailed information about the weapon which indicates that the Hiroshima weapon contained 64.15 kilograms of uranium (as we will see the enrichment was about 82.5% which would be about 52.9 kilograms of U-235).[14] Coster-Mullen has also published detailed information regarding the production of the HEU.[15]

The production of HEU started in June of 1944 using the calutron method but its production rate was very slow and only gradually improved. By the end of 1944 only 9.4 kilograms of 76% enriched uranium had been produced. There was a major problem finding the proper material to produce the gaseous diffusion barriers and the plant only started very limited operation in January 1945. In the first part of 1945 additional sections of the gaseous diffusion plant began operation and the amount and degree of enrichment increased. However, it was decided to limit the gaseous diffusion plant to less than 50% enrichment and have HEU produced only by the Beta calutrons. By February 1945 the thermal diffusion plant was also in operation. Although it only produced 0.87% enriched uranium, this 25% increase (compared to 0.71% in natural uranium) in the U-235 concentration lead to a similar increase in the HEU production rate.

By mid-April 1945 about 30 kilograms of HEU enriched to an average of about 80% had been produced which was sufficient to directly determine the critical mass of HEU. Published data gives the critical mass as 27.8 kilograms of 78.7% enriched uranium in a thick uranium reflector.[16] By early July 1945 the non-nuclear components of the Hiroshima weapon along with the 38.5 kilograms of HEU in the projectile component were finished and loaded on to the cruiser Indianapolis. With the successful nuclear test at Alamogordo on July 16, the Indianapolis departed San Francisco and delivered these weapon components to Tinian on July 26.

But there was not yet sufficient HEU for the additional 25.6 kilograms required for the target component needed to complete the weapon. From the production data it is clear that 64.15 kilograms of HEU were not produced until around July 8. Hawkins implies that the production for the Hiroshima weapon continued until July 15 at which time 67.8 kilograms of HEU with an average enrichment of 82.5% had been produced. Yet by July 24, only nine days later, the final HEU components of the Hiroshima weapon were completed.

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[12] David Hawkins, "Manhattan District History, Project Y, The Los Alamos Project," Volume I, Inception Until August 1945, LAMS-2532, written 1946, distributed December 1, 1961, p.308.

[13] For example, see: George D. Kerr, "Findings of a Recent Oak Ridge National Laboratory Review of Dosimetry for the Japanese Atom-Bomb Survivors," *Reevaluations of Dosimetric Factors: Hiroshima and Nagasaki*, Proceedings of a symposium held at Germantown, Maryland, September 15-16, 1981, Technical Information Center, U.S. Department of Energy, 1982, p.66.

[14] John Coster-Mullen, *Atom Bombs, The Top Secret Inside Story of Little Boy and Fat Man*, 2009. At one place Coster-Mullen incorrectly states that this is 64.15 kilograms of U-235 but as we will see, this is significantly more than all of the U-235 in HEU produced up to that point.

[15] *Ibid.*, p. 266. This production data was originally published in the Oak Ridge document: A.L. Compare and W.L. Griffith, "The U.S. Calutron Program for Uranium Enrichment: History, Technology, Operations and Production," ORNL-5928, October 1991. This production data was provided to Coster-Mullen by Dr. Robert Norris of the Federation of American Scientists.

[16] H.C. Paxton, "Los Alamos Critical-Mass Data," LAMS-3067, Los Alamos Scientific Laboratory, April 1964, p. 14.

On July 26 the parts of the HEU target were flown to Tinian in three separate aircraft. They arrived during the night of July 28-29 and by July 31, only two days later, the weapon was ready for combat use.[17] Due to weather, it was not dropped on Hiroshima until August 6.

As was noted, the average enrichment of the HEU produced up to July 15 was 82.5%. If the weapon was produced excluding the 3.7 kilograms with the lowest enrichment then the average HEU enrichment in the weapon would have been 83.0%. If it were produced excluding the 3.7 kilograms of HEU with the highest enrichment, then the HEU in the weapon would have had an average enrichment of 82.1%. Therefore the average enrichment of the HEU in the Hiroshima weapon was between 82.1% and 83.0% with the mid-range of 82.5%. This enrichment is significantly less than the at least 90% figure often cited as being necessary for a nuclear weapon.

After the Hiroshima weapon had been used, the Nagasaki weapon was used on August 9 and a second plutonium weapon would have been used in August had the war not ended. On July 30 General Groves provided a schedule for nuclear weapon production for the rest of 1945.[18] Groves expected there would be three to four weapons available in September, one of which would be a U-235 weapon. Since the rate of HEU production was insufficient to produce an additional 64.15 kilograms of HEU by September it is clear that additional HEU weapons would have used the implosion method.

In October there would have been another three to four weapons available, one of which would have been an HEU implosion weapon. Groves indicates that the yield of the implosion HEU weapons in September and October would have been only two-thirds that of the plutonium implosion weapons. It was expected that in November at least five weapons would be available and that the yield of the HEU implosion weapons would be equal to that of the plutonium implosion weapons. In December seven weapons would have been available with increasing numbers in 1946. Clearly, had the war not ended, Japan would have faced a sustained and increasing nuclear bombardment. Only four Japanese cities had been set aside for nuclear attack so it is not totally clear what other targets would have been struck.

Groves did not state why the HEU implosion weapons in September and October would have had lower yields. The most likely reason is that these weapons would still have used uranium with an enrichment of less than 90% and the improved yields from November on would have been the result of using HEU with a higher enrichment. Critical mass data has been published for 93.9% enriched HEU in a Nagasaki weapon.[19] The critical mass is 21.5 kilograms. Since the plutonium in the Nagasaki weapon was 95.2% of critical, a similar HEU loading would be 20.5 kilograms. (See discussion in plutonium weapon section).

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[17] These two days were taken up preparing mundane items such as batteries. Implosion weapons developed in the early 1950s inserted the fissile core in flight, meaning that the time required to mate the core to the weapon was only a matter of hours.

[18] "Memorandum to the Chief of Staff by General Groves," July 30, 1945, Manhattan Engineering District Papers, Box 3, Folder 5B, p.2, Record Group 77, Modern Military Records, National Archives, Washington D.C.

[19] H.C. Paxton, "Los Alamos Critical-Mass Data," LAMS-3067, Los Alamos Scientific Laboratory, April 1964, p.26. As will be discussed in the section on plutonium weapons, the Nagasaki weapon had a uranium reflector with a 9 inch outer diameter, surrounded by aluminum with as 18.5 inch outer diameter.

Plutonium Weapons

In August 1944, Los Alamos was reorganized to attack the problem of creating the implosion weapons needed to utilize plutonium. By February 1945, less than seven months later, a design for such a weapon had been selected.[20] It would take until July 1945 before this design could be converted into an actual weapon.

The small X-10 reactor had produced tens of grams of plutonium by the spring of 1944 but to produce the kilograms of plutonium needed for weapons, the three plutonium production reactors (the B, D and F) at Hanford would need to start operation. The B reactor went critical in September 1944 but it soon became clear that the reactor could not operate at anywhere near its intended power level. The problem turned out to be caused by a fission product (Xe-135) which has an unusually large neutron capture cross section.

The design for the reactor as called for by the Manhattan Project physicists specified 900 fuel channels but fortunately the DuPont engineers who built the reactor had conservatively included 2,004 fuel channels. The initial operation of the reactor in September had utilized only 900 fuel channels but by increasing the number of fuel channels in increments to the full 2,004 it was possible for the reactor to achieve sustained fuel power operation though this did not occur until December.[21] The D reactor went critical in December and thanks to the work at the B reactor, the D reactor was able to achieve sustained full power operation only a few weeks after it went critical. The F reactor went into sustained full power operation in February 1945.[22] The fuel in each reactor would have to be irradiated for at least several months to allow the concentration of plutonium to build up. After the fuel was discharged from the reactor, the radioactivity would have to be allowed to decay for two months before the plutonium could be extracted. Never-the-less it was only a matter of time before the quantities of plutonium needed for weapons could be produced.

Once the plutonium arrived at Los Alamos it would have to be fashioned into metallic hemispheres but producing these metallic hemispheres would turn out to be a key problem due to the unusual metallurgical properties of plutonium. A major part of these metallurgical problems was due to the allotropes of plutonium.

Many elements form allotropes, which are different crystal structures of the same substance. For example both graphite and diamonds are nothing but pure carbon but due to different crystal structures they have very different properties. Many metals form allotropes but unlike carbon, which is very difficult to change from one allotropic form to another, metals can easily change allotropic forms as the temperature is increased or decreased. Each metallic allotrope is stable over a certain temperature range. By convention metallic allotropes are designated by Greek letters with alpha being the lowest temperature form, beta the next highest and so on.

[20] Richard G. Hewlett and Oscar E. Anderson Jr., *A History of the United States Atomic Energy Commission, Volume I, 1939/1946, The New World*, WASH 1214, U.S. Atomic Energy Commission, 1972, p.318.
[21] "Hanford Engineer Works monthly report, October 1944, HW-7-870-Del and Hanford Engineer Works monthly report, December 1944, HW-7-1141-Del.
[22] Hanford Engineer Works monthly report, February 1945, HW-7-1388-Del.

For example, Table 1 shows the three allotropic forms of uranium.[23] Alpha phase uranium is stable below 662 ^{o}C. At the transition point from alpha to beta phase the density of uranium drops by about 0.5%. At 772 ^{o}C uranium changes from beta to gamma phase and the density of uranium drops by 0.7%. Uranium melts at 1,100 ^{o}C. The phase change from alpha to beta limits metallic uranium reactor fuel to temperatures lower than 662 ^{o}C. The physical properties of uranium also vary with allotropic form with gamma phase being the most easily worked of the three phases.

Table 1
Allotropic Forms of Uranium

Phase	Temperature Range ^{o}C	Density, g/cm^3
alpha	Below 662	18.4*
beta	662 to 772	18.2* to 18.1**
gamma	772 to 1,100	17.9** to 17.6***

*At 662 ^{o}C
** At 772 ^{o}C
***At 1,100 ^{o}C

Before plutonium was known, no other metal had more than three allotropic forms but plutonium has six. One of these (delta prime) only exists over a narrow temperature range and only in very pure plutonium. As a result it was unknown in 1944-1945. The other five allotropic forms were known. All six forms are shown in table 2.[24] Plutonium phase changes are accompanied by large changes in density. The transition from alpha to beta phase, which occurs at the relatively low temperature of 122 ^{o}C, results in an 11% density change. What is worse alpha phase plutonium is brittle behaving more like a ceramic than a metal. Delta phase plutonium has physical properties similar to such easily worked metals as copper or aluminum.

Table 2
Allotropic Forms of Plutonium

Phase	Temperature Range ^{o}C	Density, g/cm^3
alpha	Below 122	19.9
beta	122 to 205	17.7
gamma	205 to 318	17.1
delta	318 to 452	15.9
delta prime	452 to 476	16.0
epsilon	476 to 640	16.5

To deal with this problem, the Manhattan Project took a two prong approach.[25] To make suitable alpha phase metal, the plutonium was worked in its gamma phase form and then cooled to room

[23] Manson Benedict, Thomas H. Pigford, and Hans Wolfgang Levi, *Nuclear Chemical Engineering*, Second Edition, McGraw-Hill Book Company, 1981, p.223.
[24] *Ibid.* p.431.
[25] Edward F. Hammel, "The Taming of '49': Big science in little time," *Los Alamos Science*, Number 26, 2000, p.48.

temperature under pressure to inhibit phase transformation. This method was successful with the small quantities that were available at the end of 1944 but it was still unclear as to whether it would work with the kilogram quantities needed for a weapon.

It was also known from metallurgy that higher temperature allotropic forms of a metal can be stabilized at room temperature by alloying the metal with small amounts of another metal. Research was performed to see if delta phase plutonium could be stabilized at room temperature. This research was also successful as it was found that small amounts of aluminum could stabilize delta phase plutonium over a broad range of temperatures.

There was one potential problem with the plutonium-aluminum alloy. Aluminum is light enough that the alpha particles from plutonium decay would cause significant production of neutrons, posing a predetonation threat. It was only after the design of the implosion weapon was finalized in February 1945, that the limit on the acceptable number of neutrons could be established. By the end of March it was recognized that the number of neutrons produced by the plutonium-aluminum alloy would be too high and it had to be abandoned as a potential nuclear weapon material. It was decided that alpha phase plutonium would be used in the weapon.

In early April research was performed on a plutonium-gallium alloy. Since gallium was the next element down from aluminum in the periodic table, it was hoped that such an alloy might also have a stable delta phase at room temperature. The heavier gallium would produce far fewer neutrons than would aluminum. It was confirmed that a plutonium-gallium alloy has a stable delta phase over a wide range of temperatures but little other work was done on this alloy since it had been decided that the weapon would use pure alpha phase plutonium metal.

At the end of April, kilogram quantities of plutonium began to be available from Hanford. For the next few weeks attempts were made to manufacture four 2 inch diameter (about 1 kilogram each) spheres of alpha phase plutonium. However these attempts failed. Despite being cooled under pressure, all four spheres cracked due to the phase transformation to alpha phase.

In the latter part of May there was then a decision to use a plutonium-gallium alloy instead. However, virtually nothing was known about this alloy. It was only at the beginning of June that long-term surveillance of this alloy could begin to demonstrate that it would remain stable for at least several weeks. (As it turned out the alloy is stable for centuries.) It was only on June 24 that the critical mass of this plutonium-gallium alloy could be determined[26] yet by July 1, only seven days later, the two plutonium alloy hemispheres had been produced for the Trinity nuclear test which occurred on July 16.

Much information has been published on the Trinity/Nagasaki design. It is known that the weapon used 13.5 pounds (about 6.1 kilograms of plutonium).[27] The British, at the start of their nuclear weapon program, produced a general description of the entire weapon, based on their Manhattan Project experience. This document has been publically released.[28] It indicated that

[26] Richard G. Hewlett and Oscar E. Anderson Jr., *A History of the United States Atomic Energy Commission, Volume I, 1939/1946, The New World*, WASH 1214, U.S. Atomic Energy Commission, 1972, p.375.
[27] Terrence R. Fehner and F. G. Gosling, "The Manhattan Project," U.S. Department of Energy, April 2012, p.6.
[28] UK Public Record Office File AVIA 65 "Implosion." Written by William G. Penney, July 1, 1947.

the weapon used natural uranium tamper with an outer diameter of nine inches and the tamper was surrounded by an aluminum liner with an outer diameter of 18.5 inches. Several sources have indicated that critical mass data for the Trinity/Nagasaki weapon has been published by the U.S.[29]

With this information it is not hard to find this published data.[30] The weapon used 6.15 kilograms of delta phase plutonium containing 1.0% by weight of gallium. The core was 95.2% of a critical mass in this configuration. The plutonium was 1.0% plutonium 240 with a density of 15.6 g/cm^3. The plutonium core contained a 0.83 inch diameter central void to provide space for the initiator. From this information it is easy to calculate that the plutonium core was 3.6 inches in diameter and that the uranium tamper was 2.7 inches thick and weighed about 110 kilograms. The aluminum shell was 4.75 inches thick and weighed about 130 kilograms.

The change from a pure plutonium core to one using a plutonium-gallium alloy would have required changing the uranium tamper as well. Pure alpha phase plutonium in a several inch thick uranium reflector would have a critical mass of around 5 kilograms instead of the 6.15 kilograms of plutonium-gallium alloy. This reduced plutonium mass combined with the higher density of alpha phase plutonium means that the plutonium core would have had a diameter of only about 3.1 inches, a full half an inch smaller than that of the core actually used. This means that a quarter inch would have to have been removed from the inside of the uranium reflector to make room for the larger plutonium-gallium alloy core. Though this would have been discovered only on June 24 when the size of the plutonium-gallium alloy core was determined, the Trinity device was shipped on July 12 only three weeks later.

The fissile core for the Nagasaki weapon was finished by July 14.[31] It was flown to Tinian and arrived on July 28.[32] On August 2 three B-29s arrived at Tinian each carrying a complete non-nuclear implosion assembly for a Nagasaki type weapon.[33] Though all the components for the weapon had arrived by August 2, no effort was made to ready the weapon until after the Hiroshima weapon had been dropped on August 6. One of the three implosion assemblies without a plutonium core was dropped near Tinian on August 8 as a non-nuclear test. On August 9 the Nagasaki weapon was used in combat.

On August 1 the next plutonium core was completed.[34] It was going to be shipped from Los Alamos on August 12 or 13 for combat use on August 17 or 18 but on August 10 President Truman delayed this shipment since Japan had begun serious surrender negotiations.[35] With

[29] For example, Victor Gilinsky, Marvin Miller, and Harmon Hubbard, "A Fresh Examination of the Proliferation Dangers of Light Water Reactors," Nonproliferation Policy Education Center, October 22, 2004, p.59.
[30] H.C. Paxton, "Los Alamos Critical-Mass Data," LAMS-3067, Los Alamos Scientific Laboratory, April 1964, p. 45.
[31] Edward F. Hammel, "The Taming of '49': Big science in little time," *Los Alamos Science*, Number 26, 2000, p.55.
[32] John Coster-Mullen, *Atom Bombs, The Top Secret Inside Story of Little Boy and Fat Man*, 2009, p.264.
[33] *Ibid.*
[34] Edward F. Hammel, "The Taming of '49': Big science in little time," *Los Alamos Science*, Number 26, 2000, p.55.
[35] John Coster-Mullen, *Atom Bombs, The Top Secret Inside Story of Little Boy and Fat Man*, 2009, p.296.

Japan's surrender this plutonium core was not sent overseas. In October the non-nuclear implosion assembly was returned from Tinian and found to be in good condition.

As was discussed in the HEU weapon section, if the war had continued two to three additional Nagasaki type weapons per month would have been available in September and October with increasing numbers of weapons in the subsequent months. Los Alamos suggested increasing the number of weapons by using a core that combined plutonium and uranium but General Groves rejected the suggestion fearing delaying the availability of additional weapons.[36]

A graph has been published showing the cumulative weekly deliveries of plutonium to Los Alamos.[37] The 6.15 kilograms of plutonium required by the Trinity test were available at the end of May but as we have seen the last minute change from pure plutonium metal to a plutonium-gallium metal alloy delayed the completion of the core for this weapon until July 1. By August 1 three plutonium-gallium alloy cores had been produced requiring 18.45 kilograms cumulatively. Yet by August 1 only about 19 kilograms of plutonium has been delivered which shows that as in the case of HEU, the amount of wastage of plutonium during the manufacturing process was quite small, less than 3%. Also since the week before only about 17 kilograms had cumulatively been delivered, the third core must have been manufactured in less than one week.

IAEA Conversion Times and Significant Quantities

This analysis demonstrates the basis for the published IAEA conversion times of one to three weeks.[38] Further the IAEA has said that for pure plutonium and uranium compounds, the time will tend to be at the low end of the range.

An important element in IAEA safeguards are the "significant quantities" which the IAEA defines as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes…"[39] For plutonium the IAEA's estimate of the significant quantity is 8 kilograms of plutonium and for HEU it is 25 kilograms of U-235, meaning that for 93.9% enriched HEU, the significant quantity is 26.6 kilograms.

As was discussed above, published critical mass data showed that the core of the Nagasaki weapon contained 6.15 kilograms of plutonium and if 93.9% enriched HEU were used in this device, it would contain 20.5 kilograms. Using the Manhattan Project's actual upper limits for the wastage produces estimates of the significant quantities as only 6.3 kilograms of plutonium and 21.7 kilograms of HEU (20.4 kilograms of U-235). This confirms what others have stated, that even for the simple Nagasaki design, the IAEA's significant quantities are too high.[40]

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[36] "Memorandum to the Chief of Staff by General Groves," July 30, 1945, Manhattan Engineering District Papers, Box 3, Folder 5B, p.3, Record Group 77, Modern Military Records, National Archives, Washington D.C.
[37] Thomas Widner *et al.* "Draft Final Report of the Los Alamos Historical Document Retrieval and Assessment (LAHDRA) Project," June 2009, p.4-5.
[38] IAEA Safeguards Glossary,2001 Edition, International Atomic Energy Agency, Vienna, 2002, p.22.
[39] *Ibid*, p.23. This is to say that wastage is included.
[40] Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," National Resources Defense Council, August 22, 1994.