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The Radioactive Signature of the Hydrogen Bomb

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It has long been supposed that the Teller–Ulam invention of February 1951, that made the construction of a full-scale fusion device feasible could be deduced from a careful analysis of the debris that scatters worldwide after an atmospheric test. This was part of the theme of an article in the January/February 1990 issue of the Bulletin of Atomic Scientists written by Daniel Hirsch and William G. Mathews.[1] Their conclusion, arrived at to a large degree through interviews with Hans Bethe, was that the H-bomb secret was given to the Soviets, not through the spy Klaus Fuchs, but rather by carrying out Mike, the first test of a fusion device based on the Teller–Ulam ideas. The Bulletin article and an extended version of that paper issued by the Los Angeles based Committee to Bridge the Gap[2] argue that the observation of the very high neutron fluencies in the explosion, which can be derived from the fallout composition, would lead a competent scientist to the trick. In the present paper it is proposed that this is not enough and a suggestion is given of what would complete the picture and together with the high fluencies more easily put the competent analyst on the right track. This suggestion is also supported by experimental data, not on Mike, but on a Chinese fusion explosion carried out in 1976.

The present paper is based on a paper written, but not published, in 1981, soon after the mass spectroscopy data on the 1976 Chinese explosion were first published.

INTRODUCTION

Until the fall of 1979 the construction principles of the full-scale hydrogen bomb were more or less unknown to people without classified information from the nuclear powers. The United States tested its first H-bomb, code-named Mike, on November 1, 1952 at the Eniwetak atoll in the Pacific, less than two years after the Teller–Ulam idea was conceived. It has been suggested by many that the Soviets managed to duplicate the success quite soon

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thereafter on 22 November 1955, partly by reading the Mike debris.[3] According to Hans Bethe[1] the British then in turn read the Soviet debris and tested their first fusion device successfully at Christmas Island in the Pacific on 15 May 1957.[5] The French probably did not collect and analyze foreign debris carefully enough. At least they didn't do it before the Partial Test Ban Treaty went into force in 1963, stopping US, USSR, and UK atmospheric tests and hindering continuing announcements of the H-bomb secret to the winds. For France eight years passed between its first fission bomb test in the Sahara on 13 February 1960 and its first successful thermonuclear test at Moruroa in the South Pacific on 24 August 1968.[5] Chinese progress was very rapid between their first fission test on 16 October 1964 and their first fusion test on 17 June 1967, both at their Lop Nor test site in Xinjiang (Sinkiang). Liu Xiyao, the administrative leader of the Chinese hydrogen bomb project, has said that China could not get "any secret scientific or technical data concerning hydrogen bomb development," but that it did benefit from analyzing the relevant reports published abroad.[6] He also said, however, that the Chinese at the outset of their thermonuclear program "commanded the necessary fundamentals that had been used to make hydrogen bombs in the United States, the Soviet Union and Great Britain."[6] This might imply that they had gotten the basic ideas from the Soviets before the termination of their nuclear assistance program. If the Chinese came up with a working scheme through some help, thinking on their own and analyzing foreign literature, it could very well be that their first full-scale fusion test, which was conducted in the atmosphere in June 1967, was of some final help for the French in designing their first working device tested in August of the following year.

Summarizing we can say that it is highly probable that the rapid proliferation of thermonuclear weapon technology in the fifties and the sixties was based on analyses of the messages carried by the worldwide disseminated test debris. It would thus be very interesting to understand what exactly is so informative in the fallout from a thermonuclear explosion.

This enigmatic question attracts even more curiosity if one reads citations from different authors who themselves took part in the US thermonuclear program in the 1940s and the 1950s. My own drive to solve the puzzle was born at a seminar given in 1974 by Carson Mark, leader of the theoretical division at Los Alamos between 1947 and 1973. When Stanislaw Ulam in his memoirs[7] describes how he came up with his clever idea for the construction of a functioning fusion device he writes:

> ...I thought of an iterative scheme. After I put my thoughts in order and made a semi-concrete sketch, I went to Carson Mark to discuss it.... The next morning I spoke to Teller.

Mark, who obviously was very involved in the Teller–Ulam idea, somehow left the audience at the seminar with a feeling that it should be possible to find out the "H-bomb secret" from fallout analysis. As I was working at a laboratory doing fallout analysis, (mainly for the purpose of verifying the Partial Test Ban Treaty), I thought that maybe we have the answer in our archives. It became really challenging to try to solve this mystery.

In the October 1975 issue of *Scientific American* Herbert York, the first director of the Livermore National Laboratory in California, published an article with the title "The Debate Over the Hydrogen Bomb."[8] Its main thrust was to defend Robert Oppenheimer's and the US Atomic Energy Commission's General Advisory Committee's decision not to favor an all-out program to develop a superbomb in the dawn of the fifties. It argued that the very demonstration of a US functional thermonuclear device had pushed the Soviets to follow suit and it pointed out the possibility that the Soviets had gotten help from analysis of the Mike debris. York wrote:

> ...they had the powerful stimulus of knowing from our November 1952 test that there was some much better, probably novel way of designing hydrogen bombs.... A careful analysis of the radioactive fallout from the Mike explosion may well have provided them with useful information concerning how to go about it.

In 1976 an extended version of the article was published as a book, *The Advisors, Oppenheimer, Teller & the Superbomb*.[9] There, York also refers to Robert Oppenheimer and his view in 1952 that there might be a benefit to the United States in an indefinite postponement of the Mike test. Oppenheimer reportedly said in 1954 about this issue "We thought they would get a lot of information out of it". (In fact this citation had already been published in 1954 in the transcripts from the US Atomic Energy Commission's hearings on Oppenheimer's continuing right to a security clearance.[10]) Obviously it was clear even before the test what useful information would be written into the debris and freely broadcast around the world. The "message" can hardly then be based on some esoteric reactions or some very complicated function of the radionuclide composition. It must have been something rather obvious that they had in mind.

DECLASSIFICATION

In the wake of the Pentagon Papers affair in 1971 a large declassification program was instituted within the US Government. In the process a few mistakes were made and some sensitive nuclear-weapon related reports erroneously found their way to the public domain. This was especially so for two Livermore reports, UCRL-4725 "Weapons Development During June 1956" and UCRL-5280 "Weapons Development During June 1958," which reportedly contained a lot of detailed information on how to design thermonuclear weapons.

During the last years of the seventies several individuals started their own research into nuclear weaponry. There was for example Dimitri Rotow, who during visits to the public area of the library at Los Alamos found several of the sensitive but declassified reports. There was Howard Morland who in March 1979 tried to publish an article entitled "The H-bomb secret. How we got it—why we are telling it" in the liberal Wisconsin-based magazine *The Progressive*. This stirred up the US government who tried to bar publication in court. There was also Charles Hansen, who wrote a letter with a lot of bomb details, which several newspapers published in the midst of the *Progressive* case. The government gave up, and Morland's article was finally published in November 1979.[11]

This chain of events quite soon (September 1980) made the US Government declassify some basic facts on thermonuclear design, including the Teller–Ulam invention. It was then told that the imaginative Teller–Ulam idea was to use radiation from a fission explosion to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel. This and the concepts applied earlier for the classical Super are very thoroughly described by Hirsch and Mathews[1,2] and do not need to be repeated here. Let me only list the three major characteristics of the 1951 breakthrough.

- the thermonuclear fuel is compressed before ignition
- the energy is carried from the primary fission stage to the secondary fusion stage by bomb-thermal x-rays
- the primary and the secondary stages are physically separated.

These three concepts are described in a very condensed form in an issue of the journal *Los Alamos Science* commemorating the 40th anniversary of the laboratory in 1983: "The first megaton-yield explosions (hydrogen bombs) were based on the application of x-rays produced by a primary nuclear device to compress and ignite a physically distinct secondary nuclear assembly."[12]

HIGH COMPRESSION, A WELL KNOWN FACT

For Sweden it has been natural to spend some limited theoretical resources on the fusion bomb problem.[13] The purpose is to understand enough of the physics and principles of nuclear weapons to meet the national protection needs (it does, for example, have bearing on the protection against the electromagnetic pulse) and to support our efforts in the international disarmament arena. It soon became clear to us that an uncompressed fusion assembly cannot sustain thermonuclear burn due to the escape of too much bremsstrahlung (inverse Compton) radiation. A very high compression of the thermonuclear fuel was then the obvious theoretical solution, could one only find some way to accomplish it. Realizing the need for high compression did not, however, imply that the imaginative Teller–Ulam radiation implosion was reinvented here. This is one reason why I don't think that the evidence of very high compression in the Mike explosion is the most proliferating part of the radioactive signature that Oppenheimer, Mark, York, and others had in mind.

This conclusion is further supported by the fact that the high compression has not been kept secret. Due to the high compression and its resulting high neutron fluencies very high atomic-number elements were formed through multiple neutron capture in the natural uranium blanket enclosing the thermonuclear fuel. Already in 1955 the discovery in the Mike debris of the previously unknown elements einsteinium and fermium, with atomic numbers 99 and 100 respectively, was published.[14] The mass number of the fermium isotope was 255, which means that 17 neutrons had been successively captured by each uranium-238 target nucleus. Estimating the capture cross sections one finds that the neutron fluencies must have been of the order of moles per cm^2 (1 mole = $6.02 \cdot 10^{23}$ neutrons). In 1962 a fit of the Mike data to a theoretical calculation was published which arrived at a bomb-thermal neutron fluence of at least 2 mol cm^{-2} in Mike.[15]

The thermonuclear fuel in Mike was liquid deuterium, which has a density of 0.14 g cm^{-3} (the density of liquid hydrogen is 0.07 g cm^{-3}). The explosion yield was 10,400 kilotons,[16] and we can assume that about half of that, 5,000 kilotons, derived from fusion reactions. The D–D fusion reactions are:[17]

$$\mathrm{D + D \rightarrow He\text{-}3\ (0.82\ MeV) + \mathit{n}\ (2.45\ MeV)}$$

$$\mathrm{D + He\text{-}3 \rightarrow He\text{-}4\ (3.6\ MeV) + H\ (14.7\ MeV)}$$

$$\mathrm{D + D \rightarrow T\ (1.01\ MeV) + H\ (3.02\ MeV)}$$

$$\mathrm{D + T \rightarrow He\text{-}4\ (3.5\ MeV) + \mathit{n}\ (14.1\ MeV)}$$

At high enough temperatures the first and the second reaction pairs proceed at about the same rate and we can then form the sum reaction:[18]

$$\mathrm{3D \rightarrow He\text{-}4 + H + \mathit{n} + 21.6\ MeV}$$

One third of a neutron and an energy E of 7.2 MeV is thus liberated per fused deuterium nucleus. If we assume a spherical fuel volume of V cm^3 (with a surface of $S = (36\pi)^{1/3} \cdot V^{2/3}$ cm^2), a neutron fluence of Φ mol cm^{-2}, a compressed density of ρ g cm^{-3} and a fusion yield of y kilotons we get that

$$y = E \cdot \frac{\rho V}{2} \cdot \frac{N_0}{N} \qquad (1)$$

$$\Phi = \frac{1}{3} \cdot \frac{\rho V}{2} \cdot \frac{1}{S} \qquad (2)$$

where N_0 = Avogadro's number = $6.02 \cdot 10^{23}$ atoms mol^{-1} and N is $2.6 \cdot 10^{25}$ MeV kt^{-1}. By eliminating the volume we can solve the compressed density to be:

$$\rho = 36\sqrt{\frac{3\pi E N_0}{N}} \cdot \sqrt{\frac{\Phi^3}{y}} \qquad (3)$$

which with $\Phi = 2$ mol cm^{-2} and y = 5,000 kilotons as given above, yields a compressed density of 1.8 g cm^{-3}. This corresponds to a compression factor of 13. We have then assumed a complete burnout of the deuterium. If the burnout factor b is less than 1, we get a compression factor of $13/b$. A b value of 10–20 percent seems reasonable and this then implies a compression of about 100 times, which surely is very high.

That the fuel of a hydrogen bomb gets squeezed to an extreme compression could thus be worked out by anyone interested as early as 1955 or at least in 1962. But the Teller–Ulam invention kept its aura of mystery for 20 years more to come. And the reason was of course that the real element of new and imaginative thinking that Teller and Ulam provided was not the compression but rather the way to accomplish it through physical separation of the primary fission charge from the thermonuclear fuel and the process of radiation implosion.

THE PROLIFERATING SIGNATURE

Understanding the heart of the Teller–Ulam idea, it is not too difficult to work backwards and realize what there is in the debris to tell you the trick. In a classical Super with the fission trigger as close to the thermonuclear fuel as possible the trigger material, plutonium-239 or possibly uranium-235 or both, will be exposed to about the same neutron flux as the natural uranium blanket. A fluence of 2 mol cm^{-2} of bomb-thermal neutrons, like in Mike, onto plutonium-239, which has a fission cross section s of 2 to 10 barns (one barn = 10^{-24} cm^2) in the energy region of interest, will burn the plutonium to a very high degree. Even disregarding the plutonium loss in the fission process of the primary and the loss in other reaction channels like capture and $(n,2n)$, as much as 91–100 percent ($= 1 - \exp[-\Phi \cdot s \cdot 0.6]$) will be consumed.

Virtually all plutonium of a primary in a position equivalent to the uranium mantle would thus disappear. If one then can show that the debris from a thermonuclear explosion does in fact contain significant amounts of trigger plutonium this will be evidence that the primary has not been close to the thermonuclear burn. It must instead have been physically separated and/or very well shielded from the secondary fusion stage.

It is not enough, however, just to measure the plutonium-239 activity. There are two major problems. First, most of the plutonium in the debris derives from neutron capture in the uranium-238. Uranium-239 is formed, which decays with a halflife of 23.5 minutes to neptunium-239, which in turn, with a halflife of 2.36 days, decays to plutonium-239 (figure 1). One has to accurately know how much plutonium is formed this way. The measurements therefore has to be done within the first few weeks before the neptunium decays away. Second, plutonium-239 in itself is difficult to measure as its alpha energy is too close to the alpha energy of plutonium-240, which is also present. One has to rely on mass spectroscopy to resolve them, and for most laboratories that is a technique that is not easily available (at least not for very small samples).

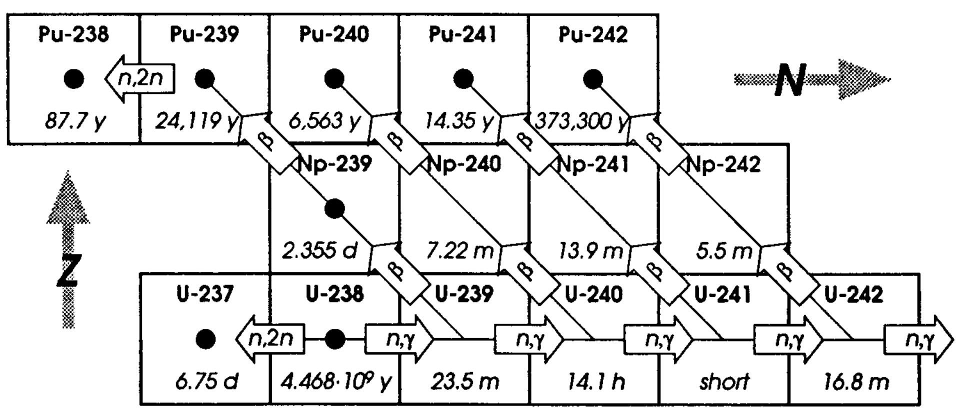

Figure 1: The production of plutonium isotopes through single and multiple neutron capture (n,γ), in the uranium-238 mantle and two subsequent beta decays (β). The gradually decreasing abundances at increasing masses can be used to estimate the bomb-thermal neutron fluence in the uranium. The figure also indicates the ($n,2n$) reactions in the plutonium-239 trigger and in the uranium-238 mantle, that are discussed at the end of the paper. Halflives are given according to the latest available Nuclear Data Sheets. Uranium-238 and the radionuclides measured in the debris are marked with a filled circle.

A CHINESE TELLER–ULAM TELL-TALE SIGN

The Swedish surveillance program for airborne radionuclides has been in regular operation since the mid 1950s. Its purpose has changed during the years but for the last three decades its focus has been on verification of the Partial Test Ban Treaty. Detecting venting underground nuclear explosions is thus its prime goal, although much work has also been done on the atmospheric tests; in the 1970s mainly the Chinese ones at Lop Nor. The program comprises eight ground-level filtering stations and equipment on some fighter aircraft to allow high-altitude sampling. All samples are measured at a central gamma spectroscopy laboratory employing large and high-resolution germanium detectors. Almost no alpha counting is carried out in house and no mass spectroscopy at all.

Good enough data on the 1952 Mike explosion are not available in Sweden. Instead detailed gamma spectroscopic data collected by us on debris from a Chinese thermonuclear explosion in the 1970s, combined with corresponding mass spectroscopy results gathered elsewhere, are used to test the hypothesis of the present paper. (As shown below these data also confirm a high neutron fluence in the Chinese explosion and thus the prerequisites for the argumentation.)

At 2pm local time on 17 November 1976 the People's Republic of China carried out its 21st nuclear explosions test at Lop Nor in Xinjiang. It was an atmospheric test of a fusion device with a yield of 4,000 kilotons.[19] Eight days after the explosion our aircraft sampling system collected the first debris and one day later we got an unusually strong sample (corresponding to $1.55 \cdot 10^{11}$ fissions) at an altitude of 14 kilometers. This sample was very carefully analyzed and the results have been reported elsewhere.[20] It was typical for the samples from this explosion that they were unfractionated, i.e. that they closely resembled the original nuclide composition produced in the explosion. A total of 35 different gamma-emitting and three alpha-emitting radionuclides were quantified (counting plutonium-239 and plutonium-240 as one). Judging from the fisson product mass distribution the average fissioning neutron energy was about 10 MeV, and this shows that the exposed uranium-238 must have been very close to the burning fusion fuel. The number of plutonium-239 nuclei from the neutron capture chain in the strongest sample was determined from the analysis of neptunium-239 to be $(42.5 \pm 1.7) \cdot 10^9$ atoms. With $(7.87 \pm 0.06) \cdot 10^9$ atoms of zirconium-95 in the sample this yields a capture plutonium-239 to zirconium-95 ratio of 5.40 ± 0.22.

The Environmental Measurements Laboratory (EML) in New York for many years did high altitude sampling by means of aircraft along the American west coast (project Airstream). At the April 1977 mission many samples were collected that were completely dominated by debris from the November 1976 explosion. These samples were analyzed for some fission products and for individual plutonium isotopes, i.e. the plutonium fractions were analyzed by mass spectroscopy.[21,22] If these results for the nine strongest samples are corrected for the small plutonium background from older explosions (about 2-percent correction) as taken from a mission in August 1976[23] (transformed to the spring of 1977 via a stratospheric half-residence time of 10 months) we arrive at a total plutonium-239 to zirconium-95 ratio of 6.46 ± 0.31. The trigger plutonium to zirconium-95 ratio can now be calculated as the difference $(6.46 \pm 0.31) - (5.40 \pm 0.22) = (1.06 \pm 0.38)$. The trigger remnants thus constitute (16 ± 6) percent of the total plutonium in the debris, which must be considered to be a significant part. (As this is the result of a small difference between two larger numbers the treatment of errors has been extremely careful.)

According to the mass spectroscopy results reported by EML[22] the plutonium-240 to plutonium-239 atom ratio was 0.224 ± 0.002 in the debris from the 17 November 1976 explosion. In Mike the corresponding ratio was 0.363 ± 0.004[24] and we can thus conclude that the bomb-thermal neutron fluence in the uranium mass (or part of it) of the Chinese device was $0.224/0.363 = 62$ percent of that in Mike, i.e. at least 1.2 mol cm^{-2}. This is still high enough to completely burn a central plutonium trigger.

One kiloton of fission in a large thermonuclear explosion with a uranium-238 blanket produces $1.45 \cdot 10^{23} \cdot 5.07/100$ atoms of zirconium-95 (and $1.45 \cdot 10^{23} \cdot 3.50/100$ atoms of strontium-90).[25] From this and the plutonium/zirconium ratio given above we can deduce that there were 3.09 ± 1.01 grams of trigger plutonium left per kiloton of fission in the Chinese 17 November 1976 explosion. An estimate of the total amounts of fission products formed in this explosion has been made by EML from integrations of the stratospheric inventory.[26] They arrive at 260 ± 25 kilocuries of strontium-90, which can be translated into $2{,}500 \pm 200$ kilotons fission and subsequently into 7.7 ± 2.6

kilograms of trigger plutonium left after the shot.[27]

A similar way to get an idea of the H-bomb secret, which needs no mass spectroscopy but is less quantitative, is to compare the amounts of $(n,2n)$ reaction products in the uranium blanket and in the plutonium primary. These reactions occur only above a threshold neutron energy of about 6 MeV in both uranium-238 and plutonium-239. The cross section curves are furthermore fairly uniform (although it is about four times higher for uranium). This means that an analysis of the uranium-237/plutonium-238 ratio in a sample through gamma and alpha counting will yield a measure of the uranium-238/plutonium-239 mass ratio in the unexploded device—all under the assumption that the plutonium is exposed to the same neutron flux as the uranium, i.e. under the assumption of the old Super concept.

For the 1976 Chinese explosion the analysis in this way showed a uranium/plutonium mass ratio exceeding 1,000 (our strong sample contained $(28.5 \pm 1.7)\cdot 10^9$ atoms of uranium-237 and $(6.0 \pm 1.8)\cdot 10^6$ atoms of plutonium-238). Assuming a plutonium trigger of some kilograms would then imply a tamper mass of many tons, which is fairly unreasonable.

We can thus conclude, along the lines discussed above, that the primary can not have been in close contact with the thermonuclear burn region. The primary must instead have been quite separated from the fusion stage. If one now asks how the energy transport between the primary and the secondary has been arranged it seems much more natural that the radiation implosion idea will be borne than if one only knows that the fuel was highly compressed. I believe that showing a significant amount of surviving plutonium from the primary and/or unexpectedly low amounts of plutonium-238 were/was the route(s) along which the H-bomb secret was really given away.

NOTES AND REFERENCES

1. Daniel Hirsch and William G. Mathews, "The H-Bomb: Who Really Gave Away The Secret," Bulletin of the Atomic Scientists, 46, January/February 1990, p.23.

2. Daniel O. Hirsch and William G. Mathews, "Fuchs and Fallout: New Insights into the history of the H-Bomb," report issued by the Committee to Bridge the Gap, Los Angeles, California, 1990.

3. This is denied by Andrei Sakharov, the creator of the Soviet H-bomb, in his memoirs (see note 4), where he writes that they did collect samples from Mike in November 1952, but that it was lost due to a chemist who "emotionally upset over some personal matter absentmindedly poured the concentrate down the drain." It was, however, after

this, in 1953–54, that Sakharov and his colleagues came up with what he calls the "third idea" and which he describes as "new and quite original." The "third idea" was the concept tested in their first high-yield thermonuclear explosion on 22 November 1955. From the similarities in the US and Soviet developments it is tempting to believe that the "third idea" was something very close to the Teller–Ulam invention.

4. Andrei Sakharov, *Memoirs* (New York: Alfred A. Knopf, 1990), pp.158,182.

5. Ivo Zander and Rolf Araskog. "Nuclear Explosions 1945–1972. Basic Data," report A 4505-A1 issued by the National Defence Research Institute, Stockholm Sweden, 1973.

6. John Wilson Lewis and Xue Litai, *China Builds the Bomb* (Stanford, California: Stanford University Press, 1988) p.199.

7. Stanislaw M. Ulam, *Adventures of a Mathematician* (New York: Charles Scribner's Sons, 1976), pp.219–220.

8. Herbert F. York. "The Debate over the Hydrogen Bomb," *Scientific American*, October 1975, p.106.

9. Herbert F. York, *The Advisors, Oppenheimer, Teller & the Superbomb* (San Francisco, California: W.H. Freeman and Company, 1976), p.100.

10. "In the Matter of J. Robert Oppenheimer" transcript of hearing before personnel security board of the AEC, US Government Printing Office, 1954.

11. Howard Morland. "The H-bomb secret. How we got it—why we're telling it." *The Progressive*, November 1979.

12. C. Paul Robinson, "The Weapons Program, Overview," *Los Alamos Science*, 7, p.110, Winter/Spring 1983.

13. Sweden has no intention to develop nuclear weapons. In 1968 Sweden signed the Nonproliferation Treaty.

14. A. Ghiorso, S.G. Thompson, G.H. Higgins, G.T. Seaborg, M.H. Studier, P.R. Fields, S.M. Fried, H. Diamond, J.F. Mech, G.L. Pyle, J.R. Huizenga, A. Hirsch, W.M. Manning, C.I. Browne, H.L Smith, and R.W. Spence. "New Elements Einsteinium and Fermium, Atomic Numbers 99 and 100," *Phys. Rev.* **99**, 1955, p.1048.

15. David W. Dorn. "Mike Results—Implications for Spontaneous Fission," *Phys. Rev.* **126**, 1962, p.693.

16. "Announced United States Nuclear Tests, July 1945 through December 1985," report NVO-209 Rev 6 issued by US Department of Energy Nevada Operations Office, 1986.

17. S. Glasstone and R.H. Lovberg, *Controlled Thermo-nuclear Reactions*, (New York: Robert E. Krieger Publ. Company, 1975).

18. Such high temperatures (above several hundred million degrees) are probably not reached even in a thermonuclear explosion. That means that the second reaction, D + He-3 → T + H, will not proceed fast enough. The cross section for the He-3 + n → T + H reaction is, however, quite high (0.1–1 barn) for MeV neutrons and as the triton will be immediately consumed in a D–T reaction the effective sum reaction will be the same. The total sum reaction given for a D–D plasma, 3D → He-4 + H + n + 21.6 MeV, will thus still hold.

19. USERDA Weekly Announcements, **2**, 1976, p.46.

20. L.-E. De Geer, R. Arntsing, I. Vintersved, J. Sisefsky, S. Jakobsson, and J.-Å. Engström. "Particulate Radioactivity, Mainly from Nuclear Explosions, in Air and Precipitation in Sweden mid-year 1975 to mid-year 1977," report C 40089-T2(A1) issued by the National Defence Research Establishment Sweden 1978. Reprinted in report EML-349 issued by the Environmental Measurements Laboratory, New York, 1979.

21. R. Leifer, L. Toonkel, and R. Larsen. "Project Airstream, Radioactivity in the Lower Stratosphere," p.II-7 in report EML-342 issued by the Environmental Measurements Laboratory, New York, 1978.

22. R. Leifer and L. Toonkel. "Plutonium isotopic analysis of stratospheric samples from April 1977," p.I-407 in report EML-390 issued by the Environmental Measurements Laboratory, New York, 1981.

23. R. Leifer, L. Toonkel, and M. Schonberg. "Project Airstream," p.II-7 in report HASL-321 issued by the Health and Safety Laboratory, New York, 1977.

24. H. Diamond, P.R. Fields, C.S. Stevens, M.H. Studier, S.M. Fried, M.G. Ingram, D.C. Hess, G.L. Pyle, J.F. Mech, W.M. Manning, A. Ghiorso, S.G. Thompson, G.H. Higgins, G.T. Seaborg, C.I. Browne, H.L. Smith, and R.W Spence. "Heavy Isotope Abundancies in Mike Thermonuclear Device," *Phys. Rev.* **119**, p.2000, 1960.

25. N. Harley, I. Fisenne, L.D.Y. Ong, and J. Harley, "Fission Yield and Fission Product Decay," p.251 in report HASL-164 issued by the Health and Safety Laboratory, New York, 1965.

26. R. Leifer, R. Larsen, and L. Toonkel. "Updating Stratospheric Inventories to July 1978," p.I-109 in report EML-363 issued by the Environmental Measurements Laboratory, New York, 1979.

27. According to conventional knowledge that fission devices contain about 3–5 kilograms of plutonium 7.7 ± 2.6 kilograms left in the debris might seem too much. The very careful analysis, however, shows this, and there can only be two explanations: 1) the Chinese do not follow conventional wisdom or 2) 7.7 ± 2.6 kilograms, where 2.6 kilograms is the one sigma estimated error, does in this case mean something significantly less than 7.7 kilograms. The probability that this is close to zero is, however, very low.