Dr Smith goes to Los Alamos

Cyril Stanley Smith, Plutonium Metallurgy, and the Manhattan Project

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Long before the complex pressure-temperature phase diagram of plutonium (shown below) was determined, Cyril Stanley Smith's suggestion that adding small amounts of some impurity atoms to liquid plutonium might retard its undesirable transformation to the brittle alpha phase enabled the fabrication of the world's first nuclear device tested successfully in New Mexico on July 16, 1945.

A Top Secret Project Changes the World

The horrific destruction in Hiroshima and Nagasaki in August 1945 demonstrated the awesome power of nuclear weapons. At the Trinity Test site in New Mexico, where the world's first nuclear charge was exploded, the director of the Manhattan

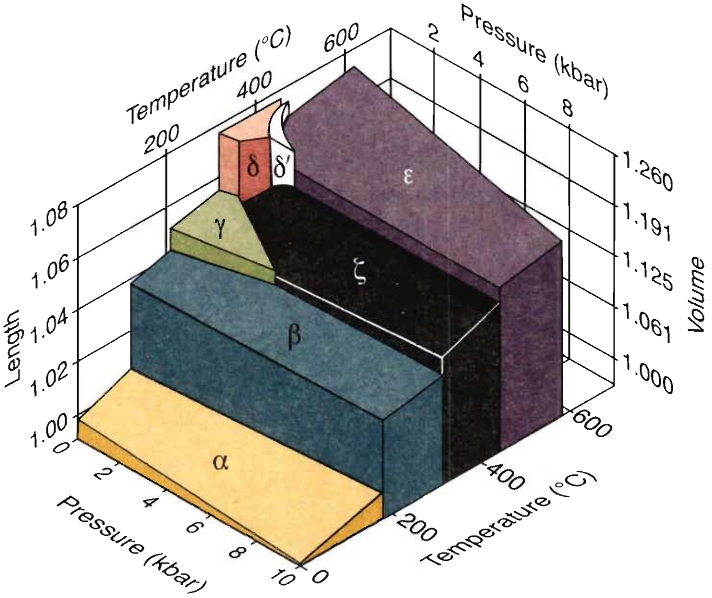


Figure from J R Morgan from *Proceedings of the 4th International Conference on Plutonium and Other Actinides* (1970), page 669, printed with permission of TMS.

Project, J Robert Oppenheimer, uttered the following poignant words: "We waited until the blast had passed, walked out of the shelter and then it was extremely solemn. We knew the world would not be the same. A few people laughed, a few people cried. Most people were silent. I remembered the line from the Hindu scripture, the *Bhagavad Gita*: *Vishnu* is trying to persuade prince *Arjuna* that he should do his duty and to impress him he takes on his multi-armed form and says, "Now I am become Death, the destroyer of worlds". I suppose we all thought that, one way or another." These words are particularly relevant today as we try to prevent the proliferation of nuclear weapons and the nexus of nuclear weapons and terrorism.

Keywords
Cyril Stanley Smith, plutonium, Manhattan project.

Nuclear weapons were first developed during World War II in the United States under a top-secret program called the Manhattan Project. These weapons were developed because of the fear that Nazi Germany was developing such weapons, but after Germany's surrender, they were used to end the war with Japan. University of California, Berkeley physicist J Robert Oppenheimer directed this project under the supervision of General Leslie Groves of the US Army Corps of Engineers. Many distinguished scientists from the United Kingdom, Canada, and refugees from fascist regimes in Europe assisted the Project. *Table* 1 summarizes some landmark events surrounding this project and *Figure* 1 shows some of its leaders.

The development of nuclear weapons, however, was not the only achievement of Oppenheimer and the Manhattan Project. At the peak of World War II, the mountains of Northern New Mexico saw a gathering of minds the likes of which the world had not

Figure 1. A few of the leaders of the Manhattan Project. From left: First director of Los Alamos National Laboratory, Robert Oppenheimer. Cyril Stanley Smith was in charge of metallurgy. He suggested adding impurity atoms to stabilize the δ-phase of plutonium. Seth Neddermeyer started the implosion program. Hans Bethe led the theorists in predicting critical masses and explosive yields. George Kistiakowsky developed the explosive lenses that enabled implosion.

1914	H G Wells coins the term "atomic bomb" in "The World Set Free"
1919	Rutherford discovers the proton
1930	Lawrence builds cyclotron
1931	Van de Graaf builds generator
1932	Chadwick discovers the neutron
1932	Crockroft and Walton split the atom
1934	Szilard files an "atomic bomb" patent in London
12/1938	Hahn/Strassmann discover fission in U
12/1938	Meitner/Frisch confirm fission
01/1939	Bohr reports Hahn's results in the USA
08/1939	Einstein writes to President Roosevelt on chain reactions and atom bombs
09/1939	Germany and USSR invade Poland
02/1941	Seaborg's team discovers Pu and shows Pu is more fissionable than U-235
06/1941	Germany invades the Soviet Union
12/1941	Japan attacks Pearl Harbor; Germany and Italy declare war on the US
01/1942	Roosevelt approves atom bomb project
09/1942	Groves is made the head of the Manhattan Project
11/1942	Groves selects Los Alamos for the laboratory (codename Project Y). Oppenheimer is chosen lab director.
12/1942	Fermi's team achieves self-sustained chain reaction in Chicago.
04/1943	Bomb design begins in Los Alamos
11/1943	Oak Ridge (X-10) produces Pu
03/1944	Bomb models tested at Los Alamos
06/1944	Allies launch Normandy invasion
07/1944	Pu gun bomb (Thin Man) abandoned
11/1944	Pu alloy survey program initiated
04/1945	Los Alamos receives Pu in kg quantities
05/1945	Germany surrenders to the Allies
07/1945	Pu implosion bomb successfully tested at Alamogordo, New Mexico
08/1945	U bomb (Little Boy) is dropped on Hiroshima on August 6
08/1945	Pu bomb (Fat Man) is dropped on Nagasaki on August 9
08/1945	Japan surrenders on August 14
08/1947	The Manhattan Engineering District is abolished.

Table 1. A brief summary of events relevant to the Manhattan Project.

seen before: Oppenheimer, Alvarez, Bethe, Fermi, Feynman, Lawrence, Peierls, Rabi, Seaborg, Segré, Smith, Teller, Ulam, von Neumann, and Wigner are just a few of the scientists who contributed to the scientific legacy left by the Manhattan Project. One of the least known among them was Cyril Stanley Smith, a metallurgist from industry and the Metallurgy Division Leader during the Manhattan Project, who was essential to the project's success.

Smith reminisces thus [1], "The general public, reading the popular accounts of the wartime project cannot help but gain the impression that the bomb was designed and built by physicists. I don't think it can be otherwise; the solid middle structure is always less interesting than either the nature of the units or the outer fringes of assembly. Moreover, the physicists have been the most willing to explain in print what they did." He further adds, "Of course the nuclear bomb was a physical concept, stemming from physical theory and experiment of the most magnificent kind, but designs would have been nothing without fantastic chemistry, without stupendous achievements in engineering both chemical and mechanical, or if the metallurgists had not been able to fabricate fantastic materials into tricky shapes. Before any nuclear cross-section could be measured or before any critical assembly could be achieved, something had to be *made*."

Making this "something" was easier said than done. Barely two months before the Trinity Test, attempts to fabricate plutonium hemispheres at room temperature failed miserably because of the cracking in the hard and brittle α-phase of pure plutonium, the thermodynamically stable phase at room temperature. To overcome this problem the metallurgists unsuccessfully tried to form the hemispheres at 250-300°C and subsequently cooled them under an applied pressure. However, even under these processing conditions the plutonium still reverted to the α-phase and thermal stresses generated by large volume contraction triggered serious warping and cracking of the hemispheres.

It was Cyril Stanley Smith and his team of scientists and engineers that faced and solved the many problems involved in coaxing plutonium into a form that made fabrication of nuclear weapons possible, thereby ushering in the 'Plutonium Age'.

Implosion The explosively driven collapse of nuclear material. In our context, carefully crafted explosive elements surrounds a sphere of plutonium. Detonation of the explosives rapidly squeezes the plutonium inwards. In this process the density of plutonium increases several-fold, driving it supercritical and setting off a nuclear chain reaction.

Dawn of the Plutonium Age

The discovery, fabrication, and use of new and superior materials have shaped human civilization. In fact the rise and fall of great civilizations can frequently be attributed to their ability, or failure, to manipulate new materials into novel and ever more useful and/or lethal forms. Thus, materials give names to ages of civilization – Stone Age, Bronze Age, Iron Age, and Silicon Age. Viewed in this light, plutonium takes on similar status for it is only it and uranium (the isotopes 235 and 233) that are fissile and lend themselves to nuclear fission devices and the ready extraction of energy million-fold larger than the energy gained from chemical explosives. Cyril Stanley Smith commented that after Trinity, explosives were no longer the exclusive domains of organic chemists. It is interesting to note that after the war, Smith spent the rest of his professional life at the University of Chicago and the Massachusetts Institute of Technology, where he divided his time between metallurgy and the history of science and technology.

Element "49" During the Manhattan Project plutonium was simply called "49" to protect its secrecy. Number "4" is the last digit of plutonium's atomic number (94) and "9" the last digit in Pu-239, the isotope of choice for nuclear weapons.

Plutonium, element 94 in the periodic table, is an ancient element as old as the universe itself. Two isotopes of plutonium (Pu-239 and Pu-244) are 'natural' in origin. While nuclear processes occurring in uranium ore bodies produce natural Pu-239 (with a half life of 24,100 years), minute traces of Pu-244 (with a half life of 80 million years) exist in nature as remnants of primordial nucleosynthesis. Plutonium-239 is the most important isotope of plutonium. It has a high cross-section for fission with slow neutrons, and is the isotope that serves as nuclear fuel for both nuclear power and nuclear weapons. Virtually all plutonium currently in use is man-made in reactors by neutron capture in U-238 fuel, and requires a sophisticated technical infrastructure to make. Glenn Seaborg and colleagues first produced plutonium at the University of California Berkeley cyclotron in 1941. He named it after Pluto, then a recently discovered planet of our solar system, and in keeping with the sequence of Uranus and Neptune.

The properties of plutonium have remained a compelling mystery ever since its discovery. Cyril Stanley Smith facetiously remarked that they provide the ingredients for a first-class nightmare. Pure plutonium metal is difficult to handle because of its radiotoxicity and high reactivity. It exhibits bizarre properties: liquid plutonium expands like water on freezing; the density of its solid phases can fluctuate by as much as 25 percent with little provocation; solid plutonium can shatter like glass or be soft and malleable like aluminum. Its instability with temperature, pressure, chemical additions, and time (through its continuous radioactive decay) represents the greatest engineering challenge. Handling plutonium is also complicated by its spontaneous combustion at 150°C, and its ability to chemically react with nearly every other element in the periodic table. Plutonium also quickly corrodes containers in which it is processed or stored and breaks down plastics by radiolysis. Not surprisingly, G Chapline and J L Smith wrote in a plutonium update in *Los Alamos Science* in 2000 [2]: "After more than 50 years of plutonium research at Los Alamos, we might be expected to understand the strange properties of this metal. Instead, we are still stumped."

Plutonium is the most complex metal known to man. Its many unusual and fascinating properties continue to confound us today.

It was Cyril Stanley Smith's responsibility during the Manhattan Project to decipher this perplexing material. He had to first recruit qualified metallurgists, a difficult task given the large demand for metallurgists to produce steel for the war effort. Next, he had to procure equipment, raw materials, supplies, and have them installed before research could begin in July 1943. Furthermore, in addition to plutonium metallurgy, Smith's research responsibilities included most of the uranium research conducted at Los Alamos, providing fissile and non-fissile materials for experiments, and fabricating the bomb core, tamper (opaque radiation reflector material), and bomb case. In this paper, however, we restrict our discussions to some fascinating and groundbreaking, yet largely ignored, plutonium research at Los Alamos directed by Cyril Stanley Smith. In the process, we will introduce some of the unusual and fascinating properties of plutonium.

Cyril Stanley Smith and Challenges of Plutonium Metallurgy at Los Alamos

Los Alamos National Laboratory (Site-Y), in the remote mountains of Northern New Mexico, was the Manhattan Project's epicenter. Hanford (Site-W), Oak Ridge (Site-X), University of Chicago, University of California, Columbia University, and other institutions actively aided Los Alamos. The Project cost \$2 billion USD (~\$20 billion in constant Year 2004 dollars) and

The Manhattan project was a herculean collaborative effort of many distinguished scientists and renowned American Institutions of learning.

employed over 130,000 people at its peak. Its seminal accomplishment was the design, production, and detonation of three nuclear bombs in 1945. First, a plutonium bomb was tested on July 16 near Alamogordo, New Mexico at the Trinity Site. Next, an enriched uranium bomb code-named "Little Boy", was detonated over Hiroshima on August 6. Lastly, a plutonium bomb, code-named "Fat Man", was detonated over Nagasaki on August 9.

Although plutonium metallurgy was one of the most crucial, interesting, and demanding responsibilities of the scientists at Los Alamos, the challenges to the plutonium metallurgists were grossly underestimated in the initial planning and were not fully appreciated even later on. Imagine being in the shoes of a Manhattan Project metallurgist whose tasks are unclear, except that in less than two years you are to fabricate *ultrapure* specimens of some very precious but toxic, reactive, and radioactive metal – with properties of which you are mostly ignorant – into specific shapes. Further imagine you had access to only very tiny quantities of the metal to investigate those properties that would be used to build a gadget conjured up in the imagination of physicists. Despite these overwhelming odds, in the very short span of fifteen months, Smith's team engineered plutonium hemispheres to extraordinary and exacting specifications for the first nuclear bomb.

To unveil the strange properties of plutonium, Manhattan project scientists performed an astounding 1500 experiments with 51 grams of plutonium. After each experiment, the metallurgists recycled and purified every specimen.

The challenge of working with small quantities of plutonium is shown in *Figure* 2 [3]. Because only a very small amount of plutonium was initially available at Los Alamos for systematic studies, Smith assumed plutonium would behave like uranium, and hence used uranium as a surrogate or stand-in for initial plutonium research. Subsequent experiments invalidated his assumption and unveiled plutonium to be far more unusual, in fact the most complicated metal known. For example, the melting points of plutonium and uranium differ by about 500 degrees, and plutonium has six allotropic phases, more than any other metal. While most of the members of the plutonium metallurgy group at Los Alamos were chemists, Cyril Stanley Smith was an expert

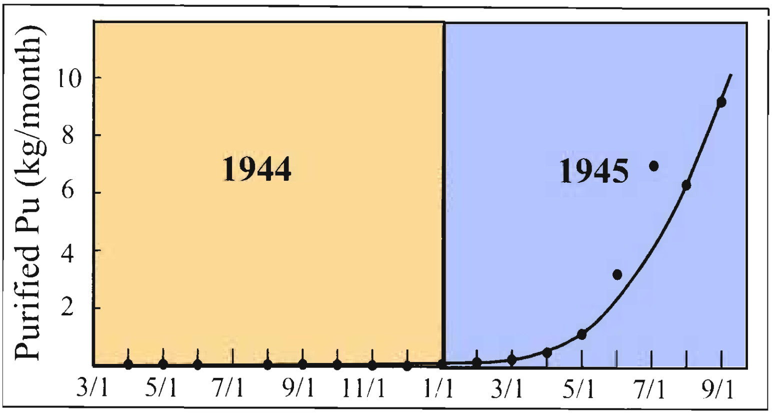


Figure 2. This curve shows the monthly delivery rate of pure plutonium metal to Los Alamos in 1944 and 1945. It reveals that much was accomplished with very little plutonium and in a very short time. Starting from tiny amounts in 1944, the delivery increased to kilogram quantities in May 1945 when the Hanford reactor became operational. At the end of August 1944, Oppenheimer wrote to Gen. Groves, "We have received 51 grams of this material. The material has been used for approximately 2500 experiments. The overall loss per experiment is about 1 percent." Recycling and purifying every metal specimen after each experiment allowed the metallurgists to obtain an enormous amount of data on plutonium [3].

on alloys because of his prior experience in the brass industry. This special knowledge helped Smith to strike upon the solution to the problem of fabricating complex plutonium shapes. Smith suggested deliberately adding impurity atoms such as gallium to plutonium, i.e. alloying, to avoid the brittle α-phase and retain the malleable δ-phase of plutonium at room temperature. His elegant solution is still used today. In hindsight, Smith's suggestion proved to be a critical breakthrough for the fabrication of the plutonium cores needed for the nuclear bombs.

Engineers and physicists have divergent working philosophies. Working as a team, they were able to fuse conventional metallurgical wisdom with sublime physics to usher in the Nuclear Age.

Plutonium – The Baffling Saga of a Maverick Metal

Plutonium metal continues to hold many undiscovered scientific mysteries. It captivates and baffles physicists, materials scientists, and chemists alike. Engineers, on the other hand, must solve the problems of their day within specified time frames using the methods and materials available to them. Why, then, did the bomb designers in the Manhattan Project choose plutonium, despite its inherent complexities and crippling uncertainties? The answer lies in the 1938 discovery that splitting the nucleus through a process called fission unleashes millions of electron volts (eV) of energy per atom. In comparison, conventional sources that burn fuels or detonate explosives, release only a few eV per atom of chemical energy from the electrons orbiting their nuclei. Thus, nuclear fission offers over a million-fold advantage compared to conventional explosives.

Plutonium deteriorates with time, a process called 'aging' both from the outside inward and from the inside outward. Understanding aging process is crucial to extend the lifetime and reliability of nuclear weapons for many decades, rather than months.

The Manhattan Project began as the Uranium Project because it was found that U-235, the isotope that constitutes only 0.7 % of natural uranium, was fissile. The immediate challenge was to enrich uranium for the bomb in U-235 by taking advantage of the slight mass difference with U-238, the predominant natural uranium isotope. The process selected was gaseous diffusion enrichment, which required an enormous industrial infrastructure. Oppenheimer and Groves were concerned that sufficient quantities for a uranium bomb (the one eventually used in Hiroshima) would not be available. Plutonium provided an alternative path to the bomb. Moreover, physicists postulated that Pu-239, the element with 94 protons and 145 neutrons would perhaps offer optimal fissile properties. Today, plutonium is the heart of all modern nuclear weapons.

Plutonium is the sixth member of the actinide series in the periodic table. It is very reactive with air and exhibits a complex chemistry – it is strongly reducing in solution, its five different oxidation states allow it to form multiple compounds. Oxidation tarnishes a freshly machined plutonium surface in minutes. Internally, plutonium decays through self-irradiation, damaging its crystalline lattice and causing the accumulation of decay products such as helium, uranium, americium and neptunium. Thus, plutonium deteriorates with time, a process called 'aging', both from the outside inward and from the inside outward. Smith's team had to devise special coatings to protect the plutonium core from corroding.

Allotropy The ability of a substance to assume two or more different crystal structures. Every such structure is stable in different temperature and/or pressure ranges. For example, diamond and the graphite used in pencils are allotropes of carbon soot.

We will focus on plutonium properties such as its multiple allotropy, peculiar preference for low symmetry crystal

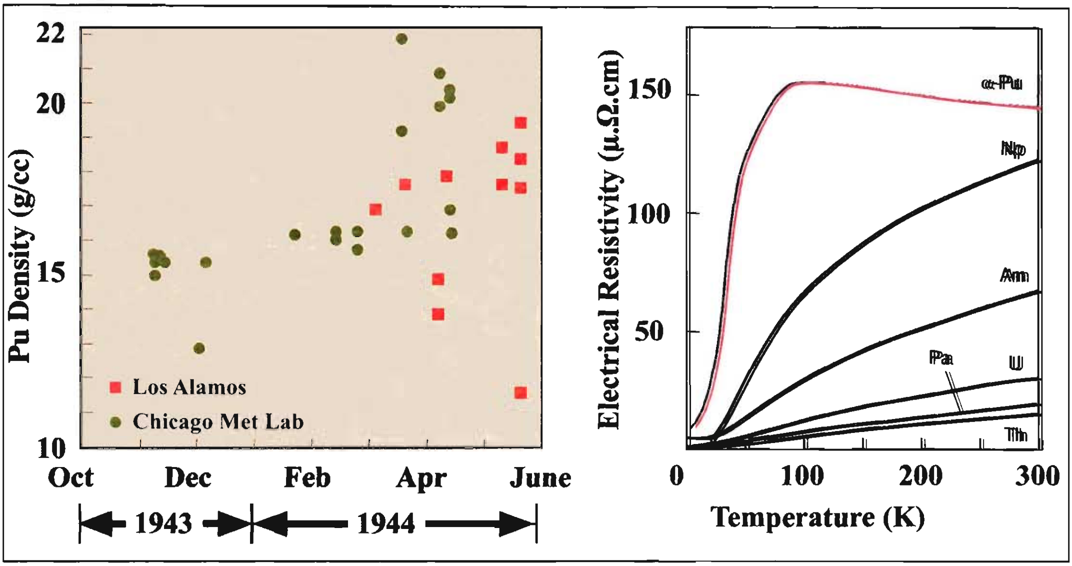


Figure 3. (a) Large variations in measured plutonium densities initially puzzled the Manhattan Project Metallurgists. In mid 1944 this was conclusively attributed to the high allotropy of plutonium, i.e. plutonium was found to possess five crystal structures between room temperature and its melting point – each having a different density. A sixth structure was found later and a seventh by the application of hydrostatic pressure. (b) Cooling below room temperature reveals other abnormal properties – for example, contrary to most metals, plutonium's already abnormally large electrical resistivity at room temperature increases as the temperature decreases to 100K.

structures, and abnormal density changes with temperature because Smith's team considered these the most relevant properties to understand for achieving their goal. *Figures* 3-5 illustrate some of these oddities of plutonium [2].

Plutonium is more than twice as dense as iron, and heating changes its density dramatically. At specific temperatures, plutonium spontaneously transforms into a new crystal structure causing its density to change discontinuously. Plutonium's instability is legendary among metallurgists – its goes through six distinct crystallographic phases when heated to its melting point at ambient pressure. Plutonium's ground state is the low symmetry monoclinic, α-phase with 16 atoms in the unit cell instead of the usual cubic structures found in most metals. This structure was not deciphered during the Manhattan Project. Smith listed it as orthorhombic like uranium, but added "doubtful" to

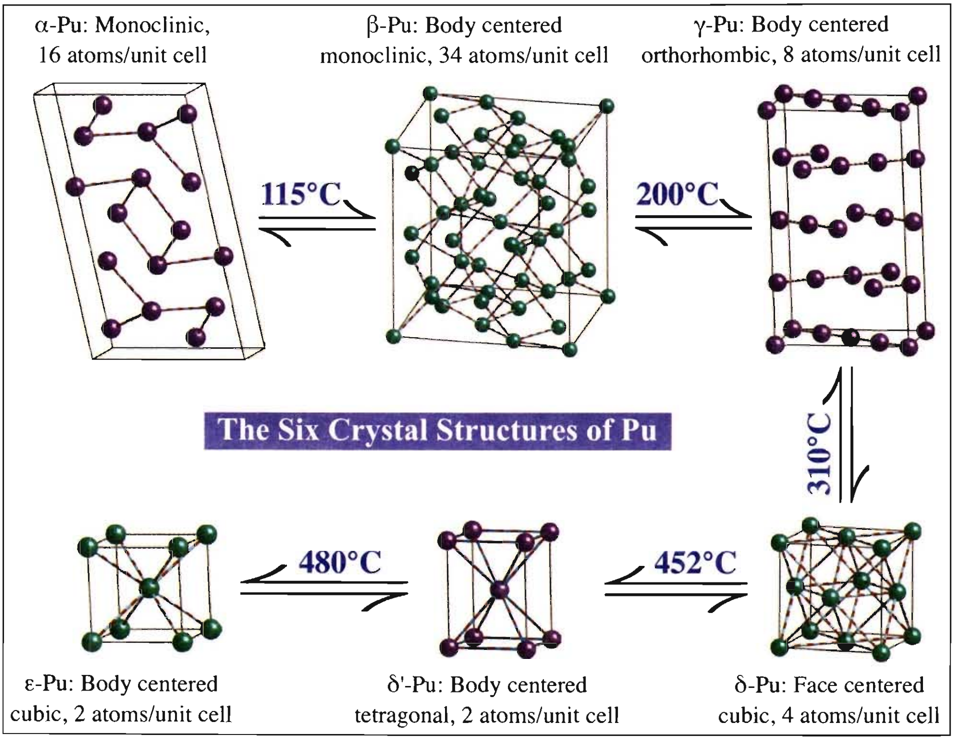
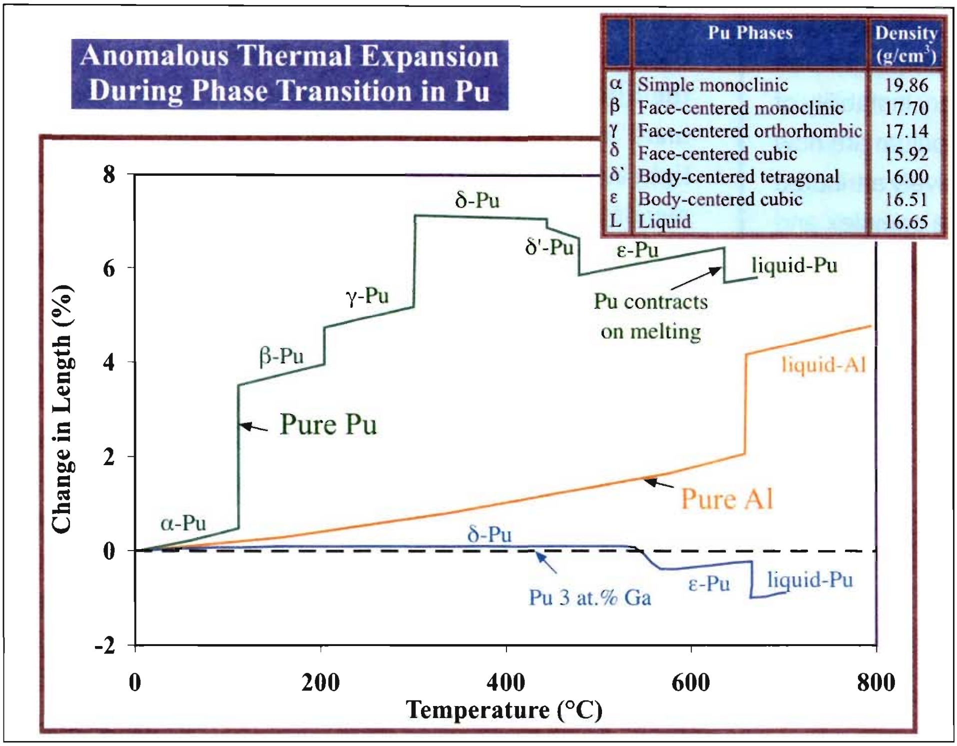


Figure 4. Allotropy of Plutonium. Starting from α-Pu and moving clockwise, we see the six allotropes of plutonium in the order in which they appear as the metal is heated at ambient pressures. The bonds are drawn between nearest neighbor atoms and serve as guides to the eye. Plutonium has an additional high-pressure allotrope that is not discussed in this article.

this determination [1]. After the war, the world's greatest crystallographer, Willie Zachariasen, indexed the incredibly complex monoclinic structure [4] during his summer visits to Los Alamos. It is interesting to see that while the α-phase expands five times faster than iron, plutonium in face-centered-cubic δ-phase contracts slightly upon heating. Surprisingly, the close-packed δ-phase also has the lowest density. Further, like ice, plutonium contracts on melting. Thankfully, for reasons discussed below, the δ-phase can be retained to relatively low temperatures by adding suitable alloying elements.

Why is plutonium so complex? In his first plutonium article in the open literature in 1954, Cyril Stanley Smith wrote [5]: "In 1945 the theory of metals was (indeed in 1954 it still is) unable to explain any of these structures or properties. Since plutonium is a member of a new rare earth series (commencing with actinium or thorium depending on valence), there are many electron energy levels of nearly identical energy and the electron state is



	Pu Phases	Density (g/cm^3)
α	Simple monoclinic	19.86
β	Face-centered monoclinic	17.70
γ	Face-centered orthorhombic	17.14
δ	Face-centered cubic	15.92
δ`	Body-centered tetragonal	16.00
ε	Body-centered cubic	16.51
L	Liquid	16.65

Figure 5. Thermal expansion of pure plutonium, pure aluminum, and Pu alloyed with 3 atomic percent gallium are compared between 0 °C to 800 °C. An abrupt jump in a curve indicates a phase transition, while smooth segments represents thermal expansion or contraction of a material in the labeled crystal structure. The crystal structure and density of each phase in pure plutonium is shown in the inset table. (a) Pure Plutonium: At ambient pressure, pure plutonium easily transforms to six different crystallographic phases with increasing temperature. Volume changes during phase transition and thermal expansion of pure plutonium are large. Like ice, and unlike most metals, plutonium contracts on melting. (b) Pure Aluminum: Compared to plutonium, aluminum is predictable and uninteresting. Like most metals, it expands on heating while in its solid state and also upon melting. (c) Pu-3 atomic % Ga Alloy: Liquid plutonium alloy expands as it solidifies to both body-centered-cubic ε and face-centered-cubic δ phases. Upon further cooling to room temperature this alloy, unlike pure plutonium, remains in the metastable δ-phase instead of transforming to γ, β, and α phases and contract slightly. This stabilization of the malleable and ductile δ-phase over a wide temperature range is key to the easy fabrication of plutonium parts.

easily affected by external factors." How correct he was! The peculiar properties of plutonium and its instability are now recognized to result from its complex electronic structure because of plutonium's position near the middle of the actinide (which it is now called instead of a new rare earth) series. In

The peculiar properties and legendary instability of plutonium are now conclusively attributed to its complex and unusual electronic structure.

solids, the valence electrons of the isolated atomic states occupy the conduction band and govern bonding. The actinides mark the filling of the 5*f* atomic sub-shell much like the rare earths mark the filling of the 4*f* sub-shell. Yet, the 5*f* electrons of the light actinides behave more like the *d* electrons of the transition metals than the 4*f* electrons of the rare earths. Moreover, the 7*s*, 6*d*, and 5*f* electrons, all of nearly equivalent energies, form overlapping (hybridized) bands. The dominant band controls the bonding and resulting properties.

As one moves across the actinide series, it is precisely at plutonium that the 5*f* electrons change from being itinerant and bonding (as are the *d* electrons in transition metals) to being localized and chemically inert (as are the 4*f* electrons in the rare earths). Sitting at this knife-edge transition from itinerancy to localization accounts for plutonium's instability. It is the peculiar characteristics of the dominant 5*f*-electrons that favor the low-symmetry ground state structure of plutonium. We still do not understand the basic physics of the high-symmetry δ-phase (for example, its peculiar negative thermal expansion) and why adding gallium retains this phase to room temperature.

Fortunately, Smith made this discovery based on his intuitive metallurgical know-how and did not wait for a proper basic physics understanding. In 1954, Smith also concluded in retrospect [5], "The most valuable aspect from the point of view of a metallurgist is the fact that throughout the project physicists and metallurgists through enforced close association learned to appreciate the value of each others' special knowledge and viewpoint. This is in some degree responsible for the increased activity in the physics of metals that has been evident in the last decade". His observation has proven correct, as the metallurgists who followed in Smith's footsteps at Los Alamos had to turn to the physicists time and again to try to understand why plutonium does not follow conventional metallurgical wisdom. On the flip side, physicists benefited from the practical knowledge of the metallurgists to be able to frame their basic questions correctly.

Teaching a New Dog an Old Trick: Or the Art of Fabricating Plutonium Parts and Making Certain They Last Long Enough

As a rule of thumb, a material's practical utility is limited by our ability to fabricate it into useful parts. Metallurgists use a combination of processes like casting, pressing, machining, and assembling for fabrication. Unlike most metals, plutonium is easy to cast because it expands upon solidification. However, this gift of nature is soon lost because of the enormous volume changes that occur in the solid phases during cooling (as shown in *Figure* 5 [6]). Consequently, it is virtually impossible to cast pure plutonium without cracking. However, as shown in *Figure* 5, the addition of a few atomic percent gallium retains the benefit of expansion upon solidification, followed by virtually no dimensional changes on cooling. Cyril Stanley Smith and his colleagues took advantage of this behavior to cast acceptable, crack-free plutonium cores for the Trinity and Nagasaki bombs.

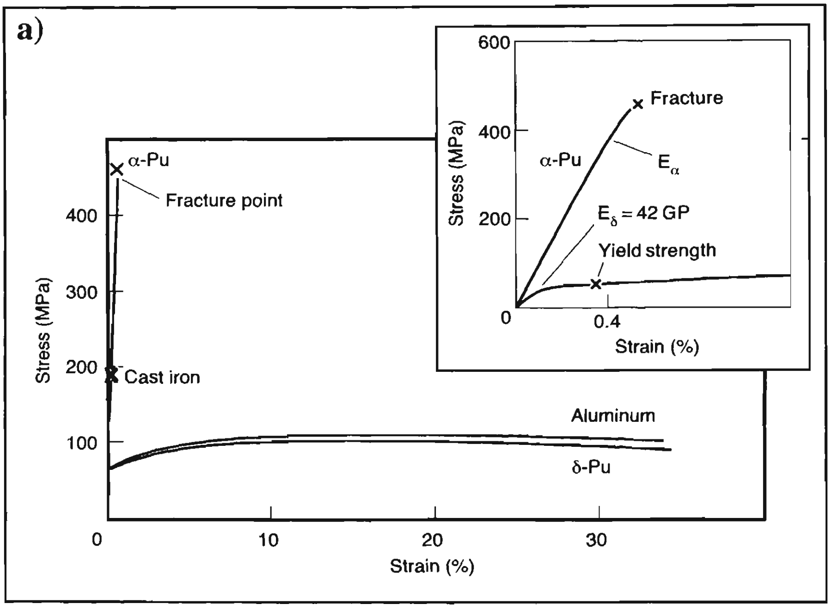
Mechanical properties are important for fabrication and performance. The casting benefits of plutonium-gallium alloys also carried over to its mechanical behavior. As shown in *Figure* 6a, the addition of gallium changes the mechanical properties of plutonium from brittle to ductile [7]. Again, Smith and colleagues took advantage of this benefit in pressing the plutonium cores to final shape and in knowing that they would not fail in a brittle manner if mechanically stressed because the δ-phase is very tolerant to flaws – like pure aluminum and unlike glass.

Cyril Stanley Smith and colleagues began a massive alloy survey program in November 1944 to determine which element addition provided the most stable material for the plutonium cores. Edward Hammel, one of Smith's colleagues, recently described how they tried dozens of alloying additions, including multiple combinations of elements [8]. The physicists scorned all of these additions because they viewed any addition that did not fission as an impurity. Smith and his colleagues, however, insisted because without these additions, the core could not be fabricated.

Brittle Fracture In brittle fracture, no plastic deformation takes place before fracture. α-plutonium and cast iron, like glass, fail via brittle fracture.

Ductile Fracture In ductile fracture, extensive plastic deformation takes place before fracture. δ-plutonium, aluminum and many other metals fail via ductile fracture.

Ductility – This physical property is related to malleability. Ductility is the ability of a material to sustain large plastic deformations before fracture (in metals, such as being drawn into a wire). Gold, copper, and aluminum are very ductile metals.



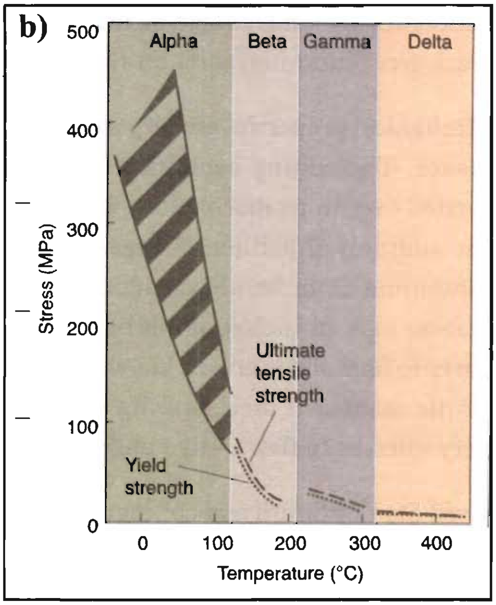


Figure 6. Stress-strain behavior of pure plutonium and its alloy with gallium under tension. (a) Room temperature, uniaxial stress-strain response of α-phase of pure plutonium, δ-phase of Pu-1.7 atomic % Ga alloy, and pure aluminum are compared with each other. The α-phase of pure plutonium behaves like a brittle glass and its fracture strength and its elastic limit match. In contrast, Pu-1.7 atomic % Ga alloy work-hardens and fails gracefully via ductile fracture like aluminum and most metals. The inset figure is a magnified view of the small strain region. (b) Tensile test results for unalloyed, *polycrystalline plutonium showing the dependence of strength on temperature for some plutonium phases. The δ-phase has a small, constant strength over its entire stability range, while the strengths of the α- and β-phases are large and sensitive to temperature. The ε-phase, not shown here, has very low and time dependent strength because of high diffusion rates in its more open body-centered cubic structure. For α-plutonium, a band of strengths are shown since the yield and ultimate strengths show wide scatter. For other phases, the upper and lower curves denote the ultimate tensile and yield strengths. This data was collated from diverse sources, different purity samples, and various testing speeds (Adapted from H R Gardner, Plutonium Handbook, The American Nuclear Society, p.68, 1980.)*

Yet, they had to keep the amount as low as possible and also not use low-Z (atomic number) elements because the alpha particles generated by plutonium's radioactive decay interact with such elements to produce extraneous neutrons that would interfere with the timing of the nuclear chain reaction. The final selection of the Pu-3 atomic% Ga alloy was not made until May 1945 when pure plutonium was finally abandoned because of disastrous fabrication results.

In parallel to the alloy survey program, the Manhattan Project metallurgists also studied the "long-term" stability of the alloy with time and temperature. Smith recognized that the alloy retained to room temperature was most likely not thermodynamically stable, but rather metastable. In fact, several tests at low temperatures indicated that the alloy transformed to the α-phase. However, stability tests at room temperature demonstrated that the Pu-3 atomic% Ga alloy did not transform over the period of a couple of months – long enough to consider it adequate for the purpose at hand [8]. Subsequent phase diagram work at Los Alamos implied that this alloy was, indeed, thermodynamically stable at room temperature. Following the US – Soviet thaw in 1955 with the Atoms for Peace Program and Conference in Geneva, we found that Soviet work indicated that the δ-phase was metastable, instead. This disagreement finally resolved in Russia's favor more than 40 years later when the end of the Cold War allowed Los Alamos and Russian scientists to compare the details of their experiments [9]. Today, we are concerned about long-term stability of Pu-Ga alloys because of the interest in extending the lifetimes of nuclear weapons for many decades, rather than months. In addition to metallurgical stability, we are concerned about the long-term effects of self-irradiation damage in plutonium and its alloys.

The surface reactions of plutonium were also a constant concern to Cyril Stanley Smith. Plutonium reacts strongly with oxygen, particularly in humid conditions or in the presence of hydrogen. The Pu-Ga alloy turned out to have significant advantages here also – cutting the corrosion rate to 4% of that of pure plutonium

A Peril and a Hope

The article by Alice Kimball Smith, 'Los Alamos: Focus of an Age', *Bulletin of Atomic Scientists*, June 1970 presents a somewhat nostalgic view of what made living at Los Alamos during World War II a special time in the lives of those involved in building the first atomic bombs. The author mentions the beauty of the area and the chance for scientists to have unlimited funding. It describes the opportunity for scientists to live in a community that included many great scientists and the permanent friendships that developed. She spends a considerable portion of the article discussing the scientists' later efforts for a nuclear test ban and disarmament, hinting that those activities may be a sign of feelings of guilt. The author speaks not only as a historian, but also from experience, having lived at Los Alamos during the Manhattan Project.

[8]. However, protective coatings were still required to cut corrosion even more and to make plutonium safe to handle outside of protective enclosures. Smith tells the story of the electroplated hemispheres for the Trinity test developing tiny blisters because of some retained electrolyte. He proposed the insertion of some rings of crinkled gold foil, and got to do this first-hand as a member of the final assembly team on July 15, 1945, the day before the test. He wrote [1]: "I put the proper amount of gold foil between the two hemispheres of plutonium. My fingers were the last to touch those portentous bits of warm metal. The feeling remains with me to this day, thirty-six years later."

Concluding Remarks

Cyril Stanley Smith's metallurgical team, within a short span of time, overcame innumerable difficulties to prepare nuclear materials in sufficient quantities and at high purities, fabricated them into useful components of exacting specifications, and protected the device from all external elements until its detonation. Along the way, they also solved serious problems in peripheral materials like uranium, beryllium, high explosives, and others. Their achievement is one of the enduring legacies of the Manhattan Project and a fascinating case study in the history of metallurgy.

We must also not forget that many of the pioneering studies on the properties of plutonium alloys were conducted by empiricism and intuition. Recent years have witnessed a huge increase of interest in plutonium, and many successes in developing a thorough and rigorous scientific understanding of this material [2]. Although state-of-the-art techniques of solid-state-physics and first-principles computational modeling are applied today to its study, the future of plutonium science will be shaped by the penetrating insight of motivated scientists following the example of Cyril Stanley Smith.

Finally, we also note that the Manhattan Project not only changed the world, but it also changed each of the individuals that

Suggested Reading

[1] **Cyril Stanley Smith, Some Recollections of Metallurgy at Los Alamos, 1943-45, *Journal of Nuclear Materials*, Vol.100, No.1, pp.3-10, 1981.**

[2] **Necia Grant Cooper, Challenges in Plutonium Science, *Los Alamos Science*, Vol.26, Volumes I and II, 2000.**

[3] **Edward F Hammel, Taming of "49" – Big Science in Little Time, *Los Alamos Science*, Vol.26, No.1, pp.48-55, 2000.**

[4] **W H Zachariasen and F H Ellinger, The Crystal Structure of Alpha-Plutonium Metal, *Acta Crystallographica*, Vol. 16, pp. 777-783, 1963.**

[5] **Cyril Stanley Smith, Metallurgy at Los Alamos: 1943 – 1945, *Metal Progress*, Vol. 65, No. 5, pp.81-89, 1954.**

[6] **Siegfried S Hecker, Plutonium and its Alloys – From Atoms to Microstructure, *Los Alamos Science*, Vol.26, No.2, pp.290-335, 2000.**

[7] **Siegfried S Hecker and Michael F Stevens, Mechanical Behavior of Plutonium and its Alloys, *Los Alamos Science*, Vol.26, No.2, pp.336-355, 2000.**

[8] **Edward F Hammel: *Plutonium Metallurgy at Los Alamos, 1943-1945*, Los Alamos Historical Society, 2000.**

[9] **Siegfried S Hecker and Lidia F Timofeeva, A Tale of Two Diagrams, *Los Alamos Science*, Vol.26, No. 2, pp. 244-251, 2000.**

participated. Cyril Stanley Smith wrote [4] "Working at Los Alamos in wartime was an exciting and moving experience. The knowledge of the broad problems that would face mankind if the bomb was successful, the excitement of discovering the properties of a brand new element, the pressure and the isolation of the work, the personal association with many of the leading scientists of the day, the background of the fantastically beautiful New Mexico landscape – all combined to make the period unforgettable."

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Members of the Research Institutes at Chicago at a New Year's Eve Party circa 1960. Among the guests are Mario-Goppert Mayer, Harold Urey, Cyril Stanley Smith, Riccardo-Levi-Setti, Yoichro Nambu, and S Chandrasekhar.

In 1945 Prof Cyril Stanley Smith was appointed as the founder Director for the Institute for the Study of Metals at the University of Chicago. There he developed his ideas of metallurgy being in alliance with materials science. Indeed this was one of the first truly interdisciplinary centres for materials science and the forerunner of many similar laboratories in later years.