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Plutonium Microstructures Part 2 Binary and Ternary Alloys

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Contents

Abstract	1
Introduction	1
Binary Alloys	3
Plutonium-Alkali Metals and Alkaline Earths	5
-Aluminum	6
-Americium	9
-Arsenic	10
-Beryllium	11
-Bismuth	13
-Boron	14
-Cadmium	15
-Carbon	16
-Cerium	18
-Chromium	22
-Cobalt	24
-Copper	28
-Dysprosium	31
-Erbium	33
-Gadolinium	34
-Gallium	36
-Germanium	40
-Gold	41
-Hafnium	43
-Holmium	45
-Hydrogen	47
-Indium	49
-Iron	53
-Lanthanum	56
-Lead	58
-Lutetium	61
-Magnesium	63
-Manganese	65
-Molybdenum	67
-Neodymium	69
-Neptunium	71
-Nickel	72
-Niobium	75
-Nitrogen	76
-Osmium	77
-Oxygen	80
-Palladium	82
-Phosphorus	84
-Platinum	85
-Praseodymium	87
-Rhenium	90
-Rhodium	92
-Ruthenium	94
-Samarium	97
-Scandium	99
-Silicon	102
-Silver	106
-Sulfur	109

-Tantalum	110
-Tellurium	111
-Terbium	112
-Thallium	114
-Thorium	116
-Thulium	119
-Tin	120
-Titanium	122
-Tungsten	124
-Uranium	125
-Vanadium	128
-Yttrium	130
-Zinc	132
-Zirconium	135
Ternary Alloys	139
Plutonium-Carbon-Thorium	141
-Cerium-Iron	143
-Cerium-Nickel	146
-Copper-Silver	148
-Platinum-Rhodium	149
-Silicon-Zirconium	151
-Titanium-Uranium	153
Acknowledgments	155
Appendices	157
A. Sources of Photomicrographs	157
B. Etchants	167
C. Pitting at Inclusions	168
D. Differing Hardnesses of Primary Constituents	169
E. Microcracking in Alpha Plutonium	170
F. Metastable Phases	171
G. The Grain Size of Alpha Plutonium	172
H. Banded Zeta Phase in Plutonium-Uranium Alloys	173
References	174

Plutonium Microstructures

Part 2

Binary and Ternary Alloys

Abstract

This report is the second of three parts that exhibit illustrations of inclusions in plutonium metal from inherent and tramp impurities, of intermetallic and nonmetallic constituents from alloy additions, and of the effects of thermal and mechanical treatments. This part includes illustrations of the microstructures in binary cast alloys and a few selected ternary alloys that result from measured additions of diluent elements, and of the microconstituents that are characteristic of phase fields in extended alloy systems. Microhardness data are given and the etchant used in the preparation of each sample is described.

Introduction

Part 2 of *Plutonium Microstructures* illustrates the characteristic microconstituents that are encountered when major additions (usually between 1 and 99 percent) of metallic or nonmetallic elements are made to plutonium. Most of the photomicrographs were taken during systematic studies of alloy systems with the purpose of developing phase diagrams. Some, however, were taken when alloy additions were made only to produce specific compounds. Each is numbered to show its location in the appropriate phase diagram.

As in Part 1, most of the photomicrographs were obtained from the data files at Lawrence Livermore and Los Alamos National Laboratories. An important contribution was also made by Battelle Pacific Northwest Laboratory from negative files of the Hanford Atomic Products Operation. It will be noticed that some fairly complete phase diagrams that were developed in the U.S. (e.g., for plutonium-copper) have relatively few micrographs for illustration—extensive files of photographs and negatives at both Argonne National Laboratory and Mound Laboratory of Monsanto Chemical Company, where plutonium-alloy research was also conducted, were found to have been recently destroyed. Negatives at Los Alamos from the period before 1960, when most of their alloy studies were made, had also been destroyed. Fortunately, however, file prints were available that could be copied. More recent contributions by Los Alamos, and those by both Lawrence Livermore and Battelle Pacific Northwest, were contact prints of original negatives. Sources of the photomicrographs are listed in Appendix A.

Photomicrographs representing systems that were mainly studied in England, France, Canada, or Russia may also be sparse, or in some cases lacking, because a retrenchment in funding at this time has made research abroad impractical or because of an anticipated political difficulty. These systems are here illustrated by examples from cursory studies of alloys that were made to verify published data.

The photomicrographs that were selected for publication were, of course, the best in technical quality of those that were available. Consequently, gaps were created when examples deemed unsuitable for publication were rejected. A dearth of photomicrographs was also found in systems where extraordinary difficulties were encountered in preparing bulk alloys. Data from carbon and oxygen alloys, for example, were obtained largely by high-temperature x-ray diffraction, or in some cases, x-ray diffraction of heat treated powders. Data concerning hydrogen alloys were obtained mostly from the interpretation of gas/metal reactions in an isolated system. Again, metallography did not make a major contribution.

Identification of constituents in the illustrations is considered to be well established. In the course of an alloy study, preliminary (and tentative) metallographic determinations of microconstituents are usually correlated with x-ray data obtained from either diffractometer traces or DeBye-Scherrer films of similar

samples or vice versa. Sometimes further refinement may be obtained by electron diffraction, by microprobe, spectrographic, or wet chemical analyses of samples selected for homogeneity, or in a few cases, perhaps, by single-crystal techniques. Such elaborate procedures as the latter are not, of course, applied to each sample. As a study progresses, identification of microconstituents in the metallography laboratory is most likely based upon the agreement of their characteristics with data accumulated from the coordinated sources referred to above, or with accepted phase diagrams.

Emphasis was placed on illustrating microstructures within phase fields with photomicrographs of "equilibrated" or, in a practical sense, heat-treated alloys. These examples are identified by photograph numbers in reversed contrast (e.g., **1**) and were assigned to appropriate fields without particular regard to nominal composition. While it was not always possible to find photomicrographs having only the constituents permitted by the phase rule, we believe that the examples presented do convey the information necessary to relate microstructures to their assigned locations.

Cast alloys, on the other hand, were placed according to their composition and are identified by photograph numbers having a white background (e.g., **1**). They illustrate microstructures that may be anticipated when alloys of their indicated compositions are made, and do not conform to equilibrium conditions.

Exceptions to the above may have been made when insignificant solid solubilities were known to exist. Alloys of the so-called refractory metals—tantalum, tungsten, vanadium, etc.—are examples. In these instances microconstituents in cast alloys resemble those in "equilibrated" alloys except, perhaps, in morphology.

In general, only the identity of constituents produced by alloying, their microhardnesses (expressed as Vickers Hardness Numbers, VHN), and the magnification accompany each photomicrograph. Temperatures are given in degrees Centigrade. Impurities were regarded as a necessary evil and their identity was not included. If an impurity is found to be of interest in maintaining quality of castings, it generally may be identified by referring to Part I and comparing with typical occurrences.

The etchant used to prepare each example may be found in Appendix A, where it is listed as a letter code. The formula may then be found by referring the code to Appendix B. As in all chemically active materials, preferential oxidation may have occurred accidentally or been induced deliberately. Where a microstructure has been enhanced by oxidation (e.g., photograph 7 of the gallium alloys or photograph 2 of the lead alloys), its presence is not regarded as an artifact. In contrast, phases in photographs 6 of the lead alloys, 2 of the silver alloys, and 1 and 3 of the silicon alloys acquired an objectionable layer of an oxidation product when adequate protection was not provided.

When conflicting data affected construction of a diagram, e.g., for the cerium alloys, the contradictions are discussed in connection with the diagram.

Anomalous behavior is discussed in Appendices C through H, which refer to photographs in the text.

Plutonium-Alkali Metals and Alkaline Earths

Available evidence indicates that the alkali metals (cesium, lithium, potassium, rubidium, and sodium) and the alkaline earths (barium, calcium, europium, and strontium) are virtually immiscible with plutonium both in the liquid and the solid states.^{1,2} Metallographic samples from these systems have consisted of a supernatant body of either alkali or alkaline earth more or less completely separated from an alpha plutonium substrate.

Definitive photomicrographs of such a composite were not found and probably have not been successfully prepared. Etched sections of the substrate were readily prepared and usually revealed a quite impure material. Since the impurity content of the plutonium nearly always appeared to have been increased, it may be assumed that tramp elements had been scavenged from the superstrate.

An unetched section from a plutonium-lanthanum composite illustrates the incomplete separation of two liquids prior to solidification. Although the plutonium-lanthanum system does not exhibit complete immiscibility (see Lanthanum), the gross microstructure under the miscibility gap is typical of the partition. The supernatant alkaline earth contains globules of plutonium-rich metal but the demarcation is sharp.

1 Immiscibility similar to that in plutonium-alkaline earth alloys. Photograph from the Pu-La system.³ (9×)

-Aluminum

All alloys are relatively stable and respond favorably to a variety of etchants.

FIG. 1. Plutonium-aluminum phase diagram.¹ The subscripts concerning PuAl_3 (ι) indicate polymorphic changes in the compound.

1 Cored Pu (δ) with some α Pu. (500 $\times$)

2 δ Pu (VHN 92). (250 $\times$)

3 δ and α Pu (dark). (250 $\times$)

4 Primary PuAl₂ (VHN 431) in δ Pu. (100 $\times$)

5 PuAl₂ (VHN 406) surrounded by peritectic PuAl (VHN 218) and Pu₃Al (dark, VHN 115). (100 $\times$)

6 The same structure as shown in 5 (500 $\times$)

7 Primary PuAl_3 in a eutectic mixture of PuAl_4 and Al. (100 $\times$)

8 Primary PuAl_4 (VHN 336) in a eutectic mixture of PuAl_4 and Al. The area adjacent to primary inclusion is depleted in Pu. (150 $\times$)

9 Massive PuAl_3 (VHN 510) and peritectic PuAl_4 (VHN 428) with Al from a eutectic mixture depleted in Pu. (500 $\times$)

10 PuAl_3 (dark, VHN 558) and PuAl_4 (VHN 498) from a microstructure similar to that shown in **9**. (100 $\times$)

11 The eutectic mixture of PuAl_4 (VHN 336) and Al (VHN 33) at 98 at.% Al. (150 $\times$)

12 Primary Al in eutectic mixture of PuAl_4 and Al. (500 $\times$)

-Americium

Only one photomicrograph was selected from several, all of which attested to the difficulty encountered in preparing these alloys for microscopy.

1

FIG. 2. Plutonium-amerium phase diagram.¹

1 Pu (α) in a Pu (δ) matrix. (500X)

-Arsenic

The following photomicrographs were obtained from a series of alloys that were prepared to identify intermetallic compounds. A phase diagram is not available. The samples are not etched, but contrast has been enhanced by preferential oxidation.

1 Primary PuAs (VHN 177) in Pu (α) in an alloy containing 10 at.% As. (125 $\times$)

2 Primary PuAs (av VHN 155) with excess Pu (α). A 47.5 at.% As alloy. (500 $\times$)

3 Primary PuAs with excess As. A 75 at.% As alloy. (500 $\times$)

-Beryllium

Since the solubility of beryllium in solid plutonium appears to be negligible, the microstructures of cast alloys are considered to be representative of the phase field of alpha plutonium and beryllium. The solubility of plutonium in solid beryllium was not determined but it, too, appears to be negligible. Since PuBe_{13} is a prolific emitter of neutrons, hand-polishing time was minimized; consequently, chipping of the brittle PuBe_{13} was not eliminated.

FIG. 3. Plutonium-beryllium phase diagram.¹

1 Primary PuBe_{13} (VHN 505) in $\text{Pu} (\alpha)$. (250 $\times$)

2 Primary PuBe_{13} in $\text{Pu} (\alpha)$. The brittle behavior of the constituent is apparent. (500 $\times$)

3 Massive PuBe_{13} (VHN 565) with some excess $\text{Pu} (\alpha)$. (500 $\times$)

4 Primary PuBe_{13} in a matrix of Be . (500 $\times$)

-Bismuth

Plutonium-bismuth alloys are quite reactive in air (ranking between lead and mercury). This is evidenced by the blackened areas of oxidation on the primary constituents. Neither constituent was identified because of the rapid deterioration. An areal analysis indicates that the compound is PuBi and the plutonium is presumed to be alpha.

[1]

FIG. 4. Plutonium-bismuth phase diagram.¹

[1] Tentatively identified as primary PuBi (VHN 120) in Pu (α). (320 $\times$)

-Boron

A phase diagram of the plutonium-boron system was not available. It seems well established, however, that the most plutonium-rich intermetallic compound is PuB_2 .¹ The following photomicrographs of nominal 10, 37.5, and 50 at.% boron alloys are consistent with this proposal. The constituent is brittle and fractures readily during coarse grinding.

1 Primary PuB_2 in $\text{Pu} (\alpha)$. (250 $\times$)

2 Primary PuB_2 in $\text{Pu} (\alpha)$. (250 $\times$)

3 Primary PuB_2 in $\text{Pu} (\alpha)$. (250 $\times$)

-Cadmium

1

2

FIG. 5. Plutonium-cadmium phase diagram.¹

1 Primary PuCd_2 (VHN 250-265) in $\text{Pu}(\alpha)$. (500 $\times$)

2 Primary PuCd_2 (VHN 223), peritectic PuCd_4 , and Cd (VHN 32). (500 $\times$)

-Carbon

More than the usual difficulties were encountered in preparing plutonium-carbon alloys.⁴ Bulk alloys were rarely produced. Resistance heating was inadequate. Severe reaction with crucibles occurred. Carbon-rich material shattered in the arc. Alloys containing 45 at.% carbon shattered on quenching. Normal methods of thermal analysis fell short and high-temperature invariants were determined by visual observation of melting in powder samples. Of more concern here, metallographic samples corroded in the usual lubricants. Definitive photomicrographs of carbon-rich alloys were obtained by using a minimum of lubricant, finishing on an essentially dry wheel, and examining the section unetched. As a consequence, only a few examples of low-carbon alloys are present from what should have been a prolific system.

FIG. 6. Plutonium-carbon phase diagram.¹

1 Primary PuC (ζ variation, with about 40 at.% C) in Pu (α).⁴ The VHN varies from 175 to 500 depending on the C content. (500 $\times$)

2 Primary PuC (ζ variation, VHN 227) in Pu (α). (500 $\times$)

3 Primary spherical PuC (VHN 661) surrounded by ζ variation (VHN 195) in Pu (α). (500 $\times$)

4 Primary PuC (cored) in Pu (α). (500 $\times$)

5 Pu_2C_3 . The white phase is unmodified. The gray is from decomposition of PuC_2 . Black areas are presumed to be excess C. (100 $\times$)

-Cerium

Thermal analyses of plutonium-cerium alloys indicate a lowering of the liquidus to a eutectic reaction at 17 at.% cerium.⁵ A eutectic structure was not seen in metallographic samples. Rather, the primary structures in photographs 2, 3, and 4 are characteristic of a peritectic reaction; i.e., cerium-rich material is found in the interior of the cored (epsilon) dendrites. Similar structures are seen in the plutonium-gallium system.

FIG. 7. Plutonium-cerium phase diagram.¹

13 γ Ce. (100 $\times$)

-Chromium

A simple two-constituent system of the eutectic type. Metallographic evidence of a eutectic reaction was not seen.

3

FIG. 8. Plutonium-chromium phase diagram.¹

1 Cr solid solution (VHN 253) in α Pu.
(500 $\times$)

2 Cr solid solution (VHN 218) in α Pu.
(200 $\times$)

3 Primary Cr solid solution in Pu (α).
(100 $\times$)

-Cobalt

Alloys of plutonium and cobalt exhibit the phenomenon of retrograde melting. Primary epsilon melts on cooling and delta plutonium becomes primary. A greater proportion of the liquid phase is present as the temperature of the alloy approaches that of the eutectic horizontal. The effect is shown in photograph 1.

FIG. 9. Plutonium-cobalt phase diagram.¹

1 Primary Pu (α) in a eutectic mixture of Pu and Pu₃Co. Pu₃Co is the continuous phase in the mixture. (500 $\times$)

2 The eutectic mixture of Pu (α) and Pu₃Co. (500 $\times$)

3 Pu₆Co (VHN 149) in Pu (α). (500 $\times$)

4 Primary Pu₂Co, peritectic Pu₃Co, and eutectic mixture of Pu and Pu₃Co. (500 $\times$)

5 Pu₂Co (VHN 253) in Pu₃Co (VHN 162). (200 $\times$)

6 Primary Pu₂Co (VHN 247) and peritectic Pu₃Co (VHN 185) in eutectic mixture of Pu and Pu₃Co. (500 $\times$)

7 Pu_3Co (VHN 186) with some excess Pu_2Co . (500 $\times$)

8 PuCo_2 (VHN 609) surrounded by peritectic Pu_2Co (VHN 256). (500 $\times$)

9 Primary PuCo_2 (VHN 609) surrounded by peritectic PuCo_3 (VHN 521). Some eutectic mixture of PuCo_3 and $\text{Pu}_2\text{Co}_{17}$. (250 $\times$)

10 Primary PuCo_3 (VHN 450) in eutectic mixture of PuCo_3 and $\text{Pu}_2\text{Co}_{17}$. $\text{Pu}_2\text{Co}_{17}$ is the continuous phase. (250 $\times$)

11 PuCo_3 (VHN 692) in $\text{Pu}_2\text{Co}_{17}$ (VHN 405). $\text{Pu}_2\text{Co}_{17}$ is the continuous phase. (250 $\times$)

12 Primary Co solid solution (VHN 186) in $\text{Pu}_2\text{Co}_{17}$ (VHN 609). (Eutectic suppressed.) (250 $\times$)

13 Cobalt solid solution (VHN 212) in $\text{Pu}_2\text{Co}_{17}$ (VHN 756) and $\text{Pu}_2\text{Co}_{17}$ with rejected Co (VHN 568). (250 $\times$)

-Copper

FIG. 10. Plutonium-copper phase diagram.¹

1 PuCu₂ in Pu (α). Some PuCu₂ has been rejected. (250 $\times$)

2 Primary PuCu_2 in a partially divorced eutectic mixture of $\text{Pu} (\alpha)$ and PuCu_2 . (500 $\times$)

3 Primary PuCu_2 (VHN 260) in a coarse eutectic mixture of PuCu_2 and $\text{Pu} (\alpha)$. (500 $\times$)

4 Primary PuCu_2 (VHN 260) in a divorced eutectic mixture. (500 $\times$)

5 Primary $\text{Pu}_4\text{Cu}_{17}$, peritectic PuCu_4 , and PuCu_2 . (500 $\times$)

6 $\text{Pu}_4\text{Cu}_{17}$ (VHN 370-400). (250 $\times$)

7 Primary $\text{Pu}_4\text{Cu}_{17}$ in PuCu_6 . (250 $\times$)

8 Primary PuCu_6 in the eutectic mixture of PuCu_6 and Cu. (500 $\times$)

9 Primary Cu solid solution in the eutectic mixture of PuCu_6 and Cu. PuCu_6 is the continuous phase in the mixture. (500 $\times$)

-Dysprosium

A phase diagram for this system was not available; however, a quite extensive investigation of the alloy at Los Alamos indicated that it would display a limited solubility of dysprosium in solid plutonium, an extended solubility of plutonium in solid dysprosium, and an intermediate phase containing about 30 at.% dysprosium stable only at elevated temperatures.¹ The following microstructures are consistent with this.

1 An unidentified primary compound, presumed to be Pu_2Dy in $\text{Pu} (\alpha)$. A 15 at.% Dy alloy, cast. (500 $\times$)

2 Dy in $\text{Pu} (\alpha)$. A 15 at.% Dy alloy heat-treated at 450°. (500 $\times$)

3 Unidentified compound presumed to be Pu_2Dy . A 35 at.% Dy alloy heat-treated at 700°. (500 $\times$)

4 Dy solid solution. A 70 at.% Dy alloy, cast. (200 $\times$)

5 Dy solid solution. A 75 at.% Dy alloy heat-treated at 700°. (500×)

6 Dy solid solution. A 90 at.% Dy alloy, cast. (500×)

7 Dy solid solution. A 90 at.% Dy alloy heat-treated at 700°. (500×)

-Erbium

A phase diagram for this system was not available; however, limited investigation of the alloys at Los Alamos indicated that it would be similar to that of plutonium-dysprosium (see Dysprosium) and of other alloys with rare earth metals.¹ These alloys exhibit a limited solubility in solid plutonium, an extended solubility of plutonium in the rare earth, and, possibly, an intermediate phase containing about 30 at.% rare earth, stable only at elevated temperatures. Sufficient evidence for such a phase was not seen.

1 Presumed to be primary Er in Pu (α). A 15 at.% Er alloy, cast. (500 $\times$)

2 Er in γ Pu. A 15 at.% Er alloy heat-treated at 450°. (500 $\times$)

3 Er solid solution with excess Pu (white phase). An 80 at.% Er alloy heat-treated at 700°. (500 $\times$)

-Gadolinium

A phase diagram for this system was not available; however, an extensive exploration of the alloys at Los Alamos indicates that, similar to plutonium-dysprosium and other rare earth alloys with plutonium, limited solubility of gadolinium in solid plutonium and extended solubility of plutonium in solid gadolinium exists.¹ There is conflicting evidence for the presence of an intermediate phase: x-ray diffraction detected an unknown phase in 60 at.% alloys in both cast and heat-treated states (photographs 4 and 5) that may correspond to the high-temperature phase of the plutonium-dysprosium system. Morphology of microconstituents, however, indicates a continuous liquidus through the central part of the system.

1 Primary Gd in Pu (α , VHN 322). A 10 at.% Gd alloy, cast. (100 $\times$)

2 Gd in Pu (α). A 15 at.% alloy heat-treated at 400°. (500 $\times$)

3 Primary Gd (VHN 118) in Pu (α , VHN 118). A 20 at.% Gd alloy, cast. (100 $\times$)

4 Primary Gd (VHN 114, oxidized) in Pu (α). A 60 at.% Gd alloy, cast. (500 $\times$)

5 Gd solid solution in Pu (α). A 60 at.% Gd alloy heat-treated at 700°. (500 $\times$)

6 Primary Gd solid solution with minor Pu. A 70 at.% Gd alloy, cast. (500 $\times$)

7 Gd solid solution with minor Pu and impurities. A 75 at.% Gd alloy heat-treated at 600°. (500 $\times$)

8 Gd solid solution with rejected Pu at grain boundaries. A 75 at.% Gd alloy heat-treated at 910°. (500 $\times$)

9 Gd solid solution with impurity. An 80 at.% Gd alloy heat-treated at 700°. (500 $\times$)

10 Cored Gd solid solution. An 87.5 at.% Gd alloy, cast. (200 $\times$)

-Gallium

Alloys of plutonium containing between 3 and 8 at. % gallium are generally regarded as being of a stable allotropic, i.e., the conversion of delta to alpha (and Pu_3Ga) by application of pressure was reversible. A recent diagram⁶ suggests retained delta may be metastable at atmospheric pressure.

FIG. 11. Plutonium-gallium phase diagram.¹

1 Pu (α) in Pu (δ). (500 $\times$)

2 Pu (δ) (VHN 38) in a slowly cooled casting. (500 $\times$)

3 δ Pu (VHN 49). (250 $\times$)

4 Peritectoid Pu₃Ga in δ Pu. (1000 $\times$)

5 Pu₃Ga in δ Pu. (500 $\times$)

6 Unresolved Pu₃Ga in δ Pu, from decomposition of the η phase. (500 $\times$)

7 Pu₃Ga solid solution (VHN 149) from an inadequate quench of the η phase. (500 $\times$)

8 Pu₅Ga₃ in Pu₃Ga in a cast alloy. (500 $\times$)

9 Pu₃Ga₁ (VHN 329). (500 $\times$)

10 Primary PuGa (VHN 196) and Pu₅Ga₃ (VHN 376). (1000 $\times$)

11 Primary PuGa and Pu₅Ga₃. (500 $\times$)

12 Primary PuGa₂ (VHN 273) and peritectic PuGa (VHN 265). (500 $\times$)

[13] PuGa₂ (VHN 298) in PuGa (VHN 265). (500×)

[14] Primary PuGa₂ (VHN 318) and peritectic PuGa (VHN 191). (500×)

[15] Primary PuGa₂ (VHN 471). (100×)

[16] PuGa₂ (VHN 372) and PuGa₃. (500×)

[17] PuGa₃ (VHN 300). (100×)

[18] Primary PuGa₃ and peritectic PuGa₂. (100×)

-Germanium

A phase diagram for this system was not available. Both Pu_2Ge_3 and PuGe_3 appear to melt congruently, the latter followed by a eutectic reaction involving germanium. A eutectic structure was not seen in plutonium-rich alloys.

1 Pu_3Ge in unresolved δ , γ , and α Pu. A 5 at.% Ge alloy heat-treated at 450° . (500 $\times$)

2 Primary Pu_3Ge (VHN 393). Nominally 25 at.% Ge. (250 $\times$)

3 Primary Pu_2Ge_3 (VHN 531) and acicular Pu_2O_3 (hex. VHN 250) in a nominal 50 at.% alloy. (200 $\times$)

4 Primary PuGe_3 and eutectic mixture of PuGe_3 and Ge. Nominally 85 at.% Ge. (250 $\times$)

-Gold

The plutonium-gold alloys were studied in Russia, and also at Mound Laboratory, where the data were not preserved. Only a few examples were available.

[1]

[2]

FIG. 12. Plutonium-gold phase diagram.¹

1 Primary PuAu (VHN 229) in Pu (α). (500 $\times$)

2 Primary Au solid solution with interdentritic PuAu₅ (VHN 100). There is no evidence for the eutectic reaction shown by thermal analysis. (250 $\times$)

-Hafnium

FIG. 13. Plutonium-hafnium phase diagram: from Ref. 1 (top), and redrawn to show the 0-10 at.% alloys in more detail (bottom). A more recent study of the 0-10 at.% region was made at Los Alamos.⁷ Many changes were proposed, apparently from x-ray data since the microstructures are inconsistent with that version.

1 δ Pu (dark, VHN 60) in ζ (white, VHN 136). The pre-treatment structure was retained. (200 $\times$)

2 Pu (δ , white) and θ (oxidized, VHN 185). (1000 $\times$)

3 α Hf in β Pu. The δ -Pu "equilibrium" structure was not retained. (500 $\times$)

4 θ phase (VHN 173). (1000 $\times$)

5 Primary Hf solid solution in Pu (δ). (500 $\times$)

-Holmium

A phase diagram was not available for this system. Microstructures of the examples from a cursory investigation indicate that it would be similar to those of plutonium and dysprosium, gadolinium, and other rare earths. Limited solubility of holmium in solid plutonium exists as well as an extended solubility of plutonium in holmium. There is, however, no evidence for the presence of an intermediate phase such as that found in dysprosium alloys.

1 Primary Ho in Pu (cored δ and α). A 5 at.% Ho alloy, cast. (50 $\times$)

2 Primary Ho in Pu (δ and α). A 15 at.% Ho alloy, cast. (500 $\times$)

3 Ho (VHN 72) in Pu (δ , VHN 75). A 15 at.% alloy heat-treated at 600°. (500 $\times$)

4 Primary Ho (α) in Pu (α). A 60 at.% Ho alloy, cast. (1000 $\times$)

[5] Primary Ho with some interdendritic Pu. A 70 at.% alloy, cast. (500 $\times$)

6 α Ho (VHN 85) with excess Pu. A 70 at.% Ho alloy heat-treated at 500°. (500 $\times$)

[7] Primary solid solution of Pu in Ho (α). A 75 at.% Ho alloy, cast. (500 $\times$)

8. Solid solution of Pu in Ho (α , VHN 83). A 75 at.% Ho alloy heat-treated at 600°. (500 $\times$)

-Hydrogen

The phase relations in this system were largely determined from pressure-temperature-composition relations of plutonium and hydrogen in a closed system. Only a few incidental photomicrographs were available. (See also Hydrogen-Rich Inclusions in Part I, pp. 10 and 11.) The compound, PuH_2 , is known to exist over a range of compositions; however, a variation in properties has not been apparent in photomicrographs.

1
2

FIG. 14. Plutonium-hydrogen phase diagram.¹

1 Primary PuH_{-2} (VHN 116) in Pu (α , VHN 270). (200 $\times$)

2 Primary PuH_{-2} (VHN 132) in Pu (α , VHN 280). (125 $\times$)

-Indium

Photograph 4 illustrates the result of an inadequate quenching rate by which eta was not retained. The constituents that were present in the specimen at 940°, we feel, are apparent.

FIG. 15. Plutonium-indium phase diagram.¹

1 Primary Pu₃In in Pu (δ). (100×)

2 Pu₃In (VHN 125). (100×)

3 Pu₃In in PuIn. (500 ×)

4 Proeutectoid ξ and eutectoid PuIn in Pu₃In from the decomposition of η. (500×)

5 η (metastable) retained in a cast alloy. (500 ×)

6 Pu₃In (gray) and PuIn. (500×)

7 PuIn (VHN 75). (50 $\times$)

8 PuIn containing precipitated Pu_3In_5 with eutectic mixture of PuIn and Pu_3In_5 . (100 $\times$)

9 Primary PuIn (VHN 110) in the eutectic mixture of PuIn and Pu_3In_5 . (500 $\times$)

10 PuIn and Pu_3In_5 (with remainder of eutectic). (500 $\times$)

11 PuIn_3 (VHN 160-270) in Pu_3In_5 (VHN 260-370). (500 $\times$)

12 PuIn_3 , apparently with excess In. (500 $\times$)

[13] PuIn_3 in In solid solution. (250 $\times$)

-Iron

Plutonium-iron alloys exhibit the phenomenon of retrograde melting in compositions up to about 9 at.% iron. The eutectic reaction involves delta plutonium and Pu_6Fe (compare with cobalt alloys) and occurs at 10 at.% iron.

FIG. 16. Plutonium-iron phase diagram.¹

1 Primary Pu (α) in the eutectic mixture of Pu and Pu_6Fe . (500 $\times$)

2 The Pu- Pu_6Fe eutectic mixture. Pu_6Fe is the continuous phase. (500 $\times$)

3 Primary Pu_6Fe (VHN 236) in the eutectic mixture of Pu and Pu_6Fe . (500 $\times$)

4 Primary Pu_6Fe in the eutectic mixture. (500 $\times$)

5 Primary PuFe_2 (VHN 530) and peritectic Pu_6Fe (VHN 230) in the eutectic mixture. (500 $\times$)

6 Primary PuFe_2 (VHN 560), peritectic Pu_6Fe , and some unresolved eutectic mixture. (100 $\times$)

7 Primary PuFe_2 and peritectic Pu_6Fe .
(250 $\times$)

8 Primary iron solid solution in a eutectic
mixture of PuFe_2 and Fe. (500 $\times$)

-Lanthanum

Because of the large difference in their densities, partition of L_1 and L_2 occurs rapidly in molten plutonium-lanthanum alloys. Unless special precautions are taken, any alloy containing more than 4 at.% and less than 76 at.% lanthanum will segregate into two compositions, La-rich (L_2) supernatant on L_1 . Because of this difficulty, the locations of photomicrographs from this region conform to these extremes rather than to nominal compositions. Photographs 3 and 4 illustrate substrate and superstrate, respectively.

FIG. 17. Plutonium-lanthanum phase diagram.¹

1 The eutectic structure – La (α) in a Pu (α) matrix. (500 $\times$)

2 Globules corresponding to L_2 in L_1 . (100 $\times$)

3 A globule from L_1 . La (α , VHN 69) in Pu (α , VHN 226). The impurity resembles PuO but is not identified. (500 $\times$)

4 The superstrate. Pu (α) in La (α , oxidized). (500 $\times$)

5 Primary solid solution of Pu in La (VHN 35). (500 $\times$)

6 Solid solution of Pu in La. (500 $\times$)

1 Primary Pu_5Pb_3 (VHN 312), peritectic Pu_3Pb (VHN 162), and $\text{Pu}(\alpha)$. (100 $\times$)

2 Primary Pu_5Pb_3 (VHN 322), peritectic Pu_3Pb (VHN 182), and $\text{Pu}(\alpha)$ (VHN 240). (100 $\times$)

3 Pu_3Pb in αPu . (100 $\times$)

4 Primary Pu_5Pb_4 (VHN 1.3), peritectic Pu_5Pb_3 , and peritectic Pu_3Pb . (250 $\times$)

5 Primary Pu_5Pb_4 (VHN 198) with some peritectic Pu_5Pb_3 . (100 $\times$)

6 Primary Pu_4Pb_5 (oxidized) and peritectic PuPb_2 (VHN 102). (100 $\times$)

7 Primary PuPb_2 (VHN 113) in a eutectic mixture of PuPb_2 and PuPb_3 . (100 $\times$)

8 The eutectic mixture of PuPb_2 and PuPb_3 (VHN 107). PuPb_2 is the continuous phase. (100 $\times$)

9 Primary PuPb_3 (VHN 99) in the eutectic mixture of PuPb_3 and Pb. The Pb contains imbedded abrasive. (50 $\times$)

-Lutetium

A phase diagram was not available. Microstructures from a cursory investigation at Los Alamos indicate that it would be similar to those of plutonium and dysprosium, gadolinium, and other rare earths. There appears, however, to be appreciable solubility of lutetium in solid plutonium (note the presence of delta plutonium in photographs 4 and 5). Extended solubility of plutonium in solid lutetium exists, but the intermediate phase that was present in the plutonium-dysprosium system was not seen.

1 Primary Lu in Pu (δ). A 10 at.% Lu alloy, cast. (500 $\times$)

2 Primary Lu in Pu (α). A 15 at.% Lu alloy, cast. (500 $\times$)

3 Lu in Pu (δ , VHN 61). A 15 at.% Lu alloy heat-treated at 600°. (500 $\times$)

4 Lu in Pu (δ). A 15 at.% alloy heat-treated at 450°. (500 $\times$)

5 Primary solid solution of Pu in Lu (VHN 126) with excess Pu in grain boundaries. A 70 at.% Lu alloy, cast. (500 $\times$)

6 Excess Pu in Lu solid solution. A 70 at.% Lu alloy heat-treated at 600°. (100 $\times$)

7 Primary Lu solid solution (cored) with Pu in grain boundaries. An 80 at.% Lu alloy, cast. (500 $\times$)

-Magnesium

The diagram shown was chosen because it involved solid-state reactions. Photomicrographs of the plutonium-rich substrate were not available. A subsequent investigation of the miscibility gap places the monotectic at about 0.4 at. % magnesium and 638°, and the eutectic at 89.5 at. % and 523°.

FIG. 19. Plutonium-magnesium phase diagram (revised from Ref. 1).

1 The eutectic mixture of Pu and Mg. (250 $\times$)

2 The eutectic mixture of Pu and Mg. Mg solid solution is the continuous phase. (500 $\times$)

3 $\text{PuMg}_{2.5}$ in Mg. This is the hexagonal η phase. (250 $\times$)

4 Primary Mg solid solution (cored) in the eutectic mixture. (250 $\times$)

-Manganese

The manganese alloys were systematically studied in Russia and only a few exploratory samples were available at Los Alamos.

FIG. 20. Plutonium-manganese phase diagram.¹

1. Primary Pu (α) in the eutectic mixture of Pu and PuMn₂. (500 $\times$)

2. Primary PuMn₂ (VHN 445) in a partially divorced eutectic mixture. (500 $\times$)

3. Primary PuMn₂ (VHN 426) in a partially divorced eutectic mixture. (500 $\times$)

-Molybdenum

FIG. 21. Plutonium-molybdenum phase diagram.¹⁰

1 Primary Mo solid solution in Pu (mixed allotropes). (500 $\times$)

2 Primary Mo solid solution (VHN 169) in Pu (mixed allotropes). (100 $\times$)

-Neodymium

FIG. 22. Plutonium-neodymium phase diagram.¹

[1] Divorced eutectic of Nd in Pu (α). (500×)

2 Nd in Pu (α). (500 $\times$)

3 Primary Nd in Pu (α). (500 $\times$)

4 Nd in Pu (α). (500 $\times$)

5 Primary Nd in Pu (α). (500 $\times$)

6 Primary solid solution of Pu in Nd. (500 $\times$)

7 Solid solution of Pu in Nd (VHN 45). (100 $\times$)

-Neptunium

FIG. 23. Plutonium-neptunium phase diagram.¹

1. Np (α) solid solution. (100 $\times$)

-Nickel

FIG. 24. Plutonium-nickel phase diagram.¹

1 Pu (α). (1000 $\times$)

2 Pu (α) pro-eutectoid structure. (250 $\times$)

3 The eutectic mixture of Pu and PuNi. Pu (α) is the continuous phase. (500 $\times$)

4 Primary PuNi (av VHN 250) in the eutectic mixture. (500 $\times$)

5 Primary PuNi₂ (av VHN 580) and peritectic PuNi. (250 $\times$)

6 PuNi₄ (av VHN 225). (100 $\times$)

[7] Primary PuNi_3 (av VHN 525), peritectic PuNi_3 , and peritectic PuNi_3 (av VHN 485). (500 $\times$)

[8] Primary PuNi_3 , peritectic $\text{Pu}_2\text{Ni}_{17}$ (av VHN 500), and the eutectic mixture of $\text{Pu}_2\text{Ni}_{17}$ and Ni. (500 $\times$)

[9] PuNi_3 in $\text{Pu}_2\text{Ni}_{17}$. (500 $\times$)

[10] Primary Ni solid solution in the eutectic mixture of $\text{Pu}_2\text{Ni}_{17}$ and Ni. (100 $\times$)

-Niobium

FIG. 25. Plutonium-niobium phase diagram.¹

¹ Primary Nb solid solution in Pu (α). (500 ×)

-Nitrogen

A phase diagram was not available for this system. Technical interest has been in its compounds, of which one is known. Otherwise, interest has been in identifying it as an impurity constituent.

[1] PuN (av VHN 580), sintered. (500 $\times$)

-Osmium

Phase relations in plutonium-osmium alloys were studied in Russia. Only a few exploratory alloys were produced and examined in the United States.

FIG. 26. Plutonium-osmium phase diagram.¹

7 Pu_3Os in ζ . (100 $\times$)

8 Pu_3Os in ζ (pseudo-eutectic). (200 $\times$)

9 Primary PuOs_2 , peritectic Pu_5Os_3 , and eutectic mixture of Pu and Pu_3Os . (150 $\times$)

10 Primary PuOs_2 and peritectic Pu_5Os_3 . (150 $\times$)

[1] Pu in Pu_2O_3 (probably β -hexagonal, VHN 205). (500 $\times$)

[2] Pu_2O_3 (probably α -cubic, av VHN 430). (500 $\times$)

[3] PuO_2 (VHN 552) with Ta (from crucible, which may act as a stabilizer for PuO_2). (500 $\times$)

-Palladium

Phase relations in plutonium-palladium alloys were studied in Russia. Only a few exploratory alloys were made and examined in the United States.

1 [2]

FIG. 28. Plutonium-palladium phase diagram.¹

1 The eutectic mixture of Pu (α) and Pu_5Pd_4 . (500 $\times$)

2 Primary Pu_5Pd_4 in a divorced eutectic mixture of Pu (α) and Pu_5Pd_4 . (125 $\times$)

-Phosphorus

A phase diagram was not available. The single example is from an alloy prepared to obtain the intermetallic compound PuP.

[1] PuP (VHN 234) in Pu. From a nominal 50 at.% alloy; the Pu phase was not identified. (500 $\times$)

-Platinum

Only a few examples from a cursory investigation were available.

FIG. 29. Plutonium-platinum phase diagram.¹¹

1 Primary Pu_5Pt_3 in the eutectic mixture of $\text{Pu}(\alpha)$ and Pu_3Pt_3 . (250 $\times$)

2 Pu_5Pt_3 and $\text{Pu}(\alpha)$. (250 $\times$)

-Praseodymium

FIG. 30. Plutonium-praseodymium phase diagram.¹

1 Primary Pu (α) with Pr from a divorced eutectic mixture. (500 $\times$)

2 Similar to 1. A well-defined eutectic structure was not seen. (500 $\times$)

3 Primary Pr in Pu (α). (500 $\times$)

4 Primary Pr in Pu (α). (100 $\times$)

5 Primary Pr in Pu (α). (500 $\times$)

6 Primary Pr solid solution with grain-boundary Pu. (500 $\times$)

7 Solid solution of Pu in Pr (α , VHN 66).
(500 $\times$)

8 Solid solution of Pu in Pr (α). (500 $\times$)

9 Solid solution of Pu in Pr (α , VHN 60).
(100 $\times$)

10 Solid solution of Pu in Pr (α , VHN 53).
(500 $\times$)

11 Solid solution of Pu in Pr (α , VHN 62).
(500 $\times$)

-Rhenium

A cursory examination of rhenium alloys identified one intermetallic compound (PuRe_2) and established the presence of a eutectic reaction between epsilon plutonium and PuRe_2 .¹¹ This tentative diagram¹¹ proposes that PuRe_2 is the only compound and is the product of a peritectic reaction.

FIG. 31. Plutonium-rhenium phase diagram.¹¹

[1] Primary Pu(α) in the eutectic mixture of Pu and PuRe₂. (500×)

[2] Primary PuRe₂ (VHN 790-870) and primary Pu in a eutectic mixture of Pu(α) and PuRe₂. This structure is the result of an incomplete reaction and gravity segregation. (500×)

-Rhodium

This system was studied mostly in Russia; only two examples from a cursory investigation were available from United States studies.

FIG. 32. Plutonium-rhodium phase diagram.¹¹

1 Primary Pu_2Rh in the eutectic mixture (divorced) of $\text{Pu}(\alpha)$ and Pu_2Rh . (250 $\times$)

2 Primary Pu_2Rh (VHN 790-870) with some eutectic mixture (PuO inclusions). (500 $\times$)

-Ruthenium

FIG. 33. Plutonium-ruthenium phase diagram.¹

1. Primary $\text{Pu}(\epsilon)$ in a pseudo-eutectic mixture of Pu and Pu_3Ru (500 $\times$)

2. Pu_3Ru (VHIN 247) in $\text{Pu}(\alpha)$ (500 $\times$)

3 Acicular Pu (α) in Pu₁₀Ru (VHN 193). (200 ×)

4 The eutectic mixture of Pu₃Ru and Pu. (1000 ×)

5 Pu₃Ru (VHN 185) in Pu₁₀Ru (VHN 135). (500 ×)

6 Pu₃Ru in Pu (α). (500 ×)

7 Primary Pu₃Ru₃ (VHN 185), peritectic Pu₃Ru, and the eutectic mixture of Pu and Pu₃Ru. (1000 ×)

8 Pu₃Ru (VHN 207) in a eutectoid mixture of Pu (α) and Pu₃Ru from the decomposition of Pu₃Ru₃. (250 ×)

9 Primary Pu_5Ru_3 (VHN 163), peritectic Pu_3Ru , and the eutectic mixture of Pu and Pu_3Ru . (500 $\times$)

10 Primary PuRu (VHN 198) in Pu_5Ru_3 (VHN 308). There is no evidence of a divorced eutectic structure. (250 $\times$)

11 Primary PuRu (VHN 166) with PuRu and Pu_3Ru eutectic mixture. (500 $\times$)

12 PuRu (VHN 175) with some remaining Pu_5Ru_3 . (200 $\times$)

13 Primary PuRu_2 (VHN 393) in the eutectic mixture of PuRu_2 and Ru. (500 $\times$)

14 Primary Ru solid solution (VHN 290) in PuRu_2 (VHN 393). (100 $\times$)

-Samarium

FIG. 34. Plutonium-samarium phase diagram.¹ (DHCP denotes double hexagonal close-packed structure.)

1. Primary Pu (α) in the eutectic mixture of Pu and Sm. (200 $\times$)

2. The eutectic mixture of Pu and Sm. (100 $\times$)

3. Primary Sm solid solution in a totally divorced eutectic. (100 $\times$)

4. Primary Sm solid solution with grain-boundary Pu (α). The Pu is decorated with PuO₂. (100 $\times$)

5. Solid solution of Pu in Sm (VHN 74) and Pu (α). (100 $\times$)

6. Solid solution of Pu in Sm (VHN 52) with excess. Pu. (100 $\times$)

-Scandium

FIG. 35. Plutonium-scandium phase diagram.¹

1 δ Pu (cored δ) with some α . From primary ϵ . (100 $\times$)

2 δ Pu. (500 $\times$)

3 ζ phase in δ Pu. (500 $\times$)

4 Major phase— ζ (VHN 85); minor phase—Pu (δ). (500 $\times$)

5 ζ (VHN 100). (500 $\times$)

6 Peritectoid ζ in δ Pu. (1000 $\times$)

7 ζ (minor) in Sc solid solution. (100 $\times$)

8 α Sc solid solution. (100 $\times$)

9 α Sc solid solution. (100 $\times$)

10 α Sc solid solution. (100 $\times$)

-Silicon

FIG. 36. Plutonium-silicon phase diagram.¹

1 Pu₅Si₃ (VHN 484) in Pu (δ). (100×)

2 The eutectic mixture of Pu and Pu₅Si₃. (500×)

3 Primary Pu₅Si₃ in the (divorced) eutectic mixture of Pu (δ) and Pu₅Si₃. (500×)

4 Primary Pu₅Si₃ (VHN 341-495). The eutectic structure is completely divorced. The Pu consists of mixed phases, unresolved. (250×)

5 Primary Pu₅Si₃ in the partially divorced eutectic mixture. The Pu matrix is δ. (250×)

6 Primary Pu₅Si₃ (VHN 370) in the partially divorced eutectic mixture. The Pu matrix is δ. (250×)

7 Primary Pu_5Si_3 (VHN 370) in the eutectic mixture of Pu and Pu_5Si_3 . (125 $\times$)

8 Primary Pu_5Si_3 in the eutectic mixture. (200 $\times$)

9 Primary PuSi (VHN 710), peritectic Pu_3Si_2 (VHN 661), and peritectic Pu_5Si_3 (VHN 435). (500 $\times$)

10 Primary PuSi. The minor phase is not identified. (500 $\times$)

11 Primary PuSi in the eutectic mixture of PuSi and $\sim\text{Pu}_3\text{Si}_5$. (500 $\times$)

12 The eutectic mixture of PuSi (white) and $\sim\text{Pu}_3\text{Si}_5$. Pu_3Si_5 is the continuous phase. (500 $\times$)

[13] Primary $\sim\text{Pu}_3\text{Si}_5$. The compound is brittle and friable. (100 $\times$)

[14] Primary $\sim\text{PuSi}_2$ and interdendritic eutectic mixture of $\sim\text{PuSi}_2$ and Si. (500 $\times$)

[15] The $\sim\text{PuSi}_2$ and Si eutectic mixture. Si is the continuous phase. (500 $\times$)

[16] Primary Si solid solution in the eutectic mixture of $\sim\text{PuSi}_2$ and Si. (500 $\times$)

-Silver

Alloys of plutonium and silver are quite reactive in air and did not yield satisfactory photomicrographs when etched electrolytically. The darkening of the silver-rich phase from L_2 in photographs 1 and 2, and $\text{PuAg}_{3.6}$ in photographs 5 and 8, is caused by air oxidation of mechanically polished surfaces.

[1] [2]

[3] [4] [5] [6] [7] [8]

FIG. 37. Plutonium-silver phase diagram.¹²

[1] Globules from L_2 in a matrix corresponding to L_1 . (100 $\times$)

[2] Globules from L_1 in the superstrate. Globules from L_2 and PuAg_2 in the Pu-rich substrate. (100 $\times$)

[3] Primary PuAg_2 with globules corresponding to L_2 from the monotectic reaction. (100 $\times$)

[4] Primary $\text{PuAg}_{3.6}$ in PuAg_2 . (100 $\times$)

[5] Massive $\text{PuAg}_{3.6}$ with intergranular porosity. (500 $\times$)

[6] Primary $\text{PuAg}_{3.6}$ in eutectic mixture of $\text{PuAg}_{3.6}$ and Ag. (500 $\times$)

The eutectic mixture of PuAg_{3.6} and Ag. PuAg_{3.6} is the continuous phase. (500×)

Primary Ag solid solution in a eutectic mixture of PuAg_{3.6} (VHN 180) and Ag. (500×)

-Sulfur

A phase diagram was not available for this system. The single example was from an alloy made to produce the compound PuS.

1 Primary PuS in Pu (α). (500 $\times$)

-Tantalum

Primary tantalum solid solution in plutonium (alpha) is characteristic of all compositions.

FIG. 38. Plutonium-tantalum phase diagram.¹

1 Primary Ta solid solution in Pu (α). (100 $\times$)

-Tellurium

A phase diagram was not available for this system. The only example available was from a sample prepared to investigate the compound PuTe.¹ Only the identity of the major phase (gray, PuTe) was recorded. Assuming the white phase (VHN 128) is plutonium, it appears to be partly reacted and in a eutectic mixture with PuTe.

1 Primary PuTe in an unidentified matrix phase. (500×)

-Terbium

A phase diagram was not available for this system. The alloys are similar to those of plutonium and other rare earths, i.e., exhibiting a very limited solubility of terbium in solid plutonium, an intermediate phase containing ~60 at.% terbium, and extended solubility of plutonium in solid terbium.

1 ζ phase with Pu (α). A 40 at.% Tb (nominal) alloy, cast. (200×)

2 ζ in Pu (α). A 50 at.% (nominal) alloy heat-treated at 600°. (200×)

3 ζ and Pu in a 70 at.% Tb thermal-analysis specimen. (200×)

4 ζ (VHN 74) and Pu in a 70 at.% Tb alloy heat-treated at 500°. (200×)

5 Tb (α) solid solution and ζ in an 85 at.% alloy, cast. (100 $\times$)

6 Tb (α) solid solution and ζ in an 85 at.% Tb alloy heat-treated at 700°. (200 $\times$)

7 Tb (α) solid solution in a 95 at.% Tb alloy, cast. (100 $\times$)

-Thallium

A phase diagram was not available. Only a few alloys were examined at Los Alamos. The plutonium-rich phase in photographs 2 through 5 is readily oxidized and darkened, whereas the thallium-rich phase appears to be quite inert to ambient oxygen.

1 Pu₃Tl in Pu (α). A nominal 1 at.% alloy heat-treated at 450°. (500×)

2 Pu₃Tl in Pu (δ). A 10 at.% Tl alloy. (500×)

3 Primary Pu₃Tl (VHN 75-106) in Pu (δ). A 20 at.% Tl alloy, cast. (500×)

4 Primary Pu₃Tl in a eutectic mixture tentatively identified as Pu₃Tl and PuTl₃. A 65 at.% Tl alloy. (Estimated to be 500×)

5 Primary PuTi_3 . The matrix is probably Ti.
A 78 at.% Ti alloy, cast. (Estimated to be 500 $\times$)

-Thorium

FIG. 39. Plutonium-thorium phase diagram.¹

[1] Cored Pu (δ , VHN 71) with unresolved γ and α . (100 $\times$)

2 Pu (α) with rejected Pu₂Th. (250×)

3 The eutectic mixture of Pu (δ) and Pu₂Th. (500×)

4 Primary Pu₂Th in plutonium (δ, VHN 54). (1000×)

5 Primary Th solid solution and peritectic Pu₂Th in divorced eutectic that is essentially Pu (δ). (500×)

6 Peritectic surrounding of primary Th solid solution by Pu₂Th. Remnants of Pu₂Th in a divorced eutectic mixture. (500×)

7 α Th solid solution (VHN 105) in Pu₂Th (VHN 166). (500×)

8 Primary Th solid solution (α) and peritectic Pu_2Th in Pu (δ) from a divorced eutectic. (500 $\times$)

9 Th solid solution (α , VHN 128) in Pu_2Th (VHN 198). (500 $\times$)

10 Th solid solution (α , VHN 121), the second phase is presumed to Pu_2Th . (100 $\times$)

11 Th (α) solid solution (VHN 121). Rejected Pu_2Th at grain boundaries. (100 $\times$)

-Thulium

A phase diagram was not available for this system. Data from a cursory examination of plutonium-thulium alloys indicate that the system is similar to that of plutonium-gadolinium alloys, exhibiting restricted solubility of thulium in solid plutonium and extended solubility of plutonium in solid thulium.¹

1 Tm solid solution (VHN 86) in Pu (δ). A 15 at.% Tm alloy heat-treated at 600°. (500 $\times$)

2 Tm solid solution (VHN 105) in δ and α Pu. A nominal 60 at.% Tm alloy, cast. (1000 $\times$)

3 Tm solid solution in Pu (δ). A nominal 60 at.% Tm alloy heat-treated at 600°. (500 $\times$)

4 A solid solution of Pu in Tm. An 80 at.% Tm alloy heat-treated at 600°. (500 $\times$)

-Tin

A phase diagram was not available for this system. The intermetallic compounds were determined by a rigorous electron-microprobe analysis of a diffusion couple.¹³ The photomicrographs exhibited are, however, from a cursory examination of a few alloys at Los Alamos.¹ The alloys are moderately reactive in air and many are best examined unetched.

1 Primary Pu₃Sn (VHN 144) in unidentifed Pu (a 5 at.% Sn alloy). (100X)

2 Primary Pu₃Sn and a remnant of a eutectic mixture (presumed to be Pu and Pu₃Sn). A 10 at.% Sn alloy, cast. (500X)

3 Pu₅Sn₃ (dark gray) and Pu₃Sn (light gray) in Pu. The black areas are voids. An ~65 at.% alloy, cast. (100X)

4 PuSn₂ (VHN 140-151) in Sn. A 78 at.% Sn alloy. (250X)

5 PuSn_2 in Sn. A 90 at.% Sn alloy heat-treated at 500°. (250 $\times$)

-Titanium

FIG. 40. Plutonium-titanium phase diagram.¹

1 Ti solid solution (α , VHN 500; see Appendix D) in Pu matrix. (500 $\times$)

2 Ti solid solution (α) in Pu matrix. (500 $\times$)

3 Primary Ti solid solution (α , VHN 137) in β and γ Pu. (500 $\times$)

4 Primary Ti solid solution (α , VHN 425) in Pu (α) in a slowly cooled specimen. (100 $\times$)

5 Primary Ti solid solution (α , VHN 575) and rejected Ti (VHN 208). The Pu matrix is a mixture of β and γ . (500 $\times$)

6 Ti solid solution (α , VHN 182). (500 $\times$)

-Tungsten

1

FIG. 41. Plutonium-tungsten phase diagram.¹

1 Primary W solid solution in Pu (α). (100×)

-Uranium

The zeta phase—the most prominent in the system—has a variable hardness, varying from VHN 200 to 450 with increasing uranium content. The harder material is generally obtained in a badly fractured state. This condition, with the increase in reactivity that occurs at high temperature, makes heat treatment difficult to carry out without excessive oxidation.

FIG. 42. Plutonium-uranium phase diagram.

1 Unresolved ζ in Pu (α). (250 $\times$)

2 ζ (VHN 310) and Pu (α , VHN 270). Pu is the continuous phase. (250 $\times$)

3 Eutectoid ζ (VHN 167) in Pu (β , VHN 127) from the decomposition of η . (250 $\times$)

4 ζ phase, from η . (500 $\times$)

5 Unresolved ζ and η from η . (500 $\times$)

6 η phase (minor) in ζ . (500 $\times$)

7 η phase (minor) in ζ . The ζ phase is brittle and has fractured. (500 $\times$)

8 The ζ phase (VHN 224) shows typical fracturing. (100 $\times$)

9 ζ phase (VHN 369). (500 $\times$)

10 U (α solid solution) in ζ . (500 $\times$)

11 U solid solution (α , VHN 160). (100 $\times$)

12 ζ in U solid solution (α). (500 $\times$)

-Vanadium

[1]

[2]

FIG. 43. Plutonium-vanadium phase diagram.¹

1 Primary V solid solution in Pu (α , VHN 234). (100 $\times$)

2 Primary V solid solution (VHN 142) in Pu (α , VHN 196). (100 $\times$)

-Yttrium

r

Phase relations in plutonium-yttrium alloys were studied in Russia and confirmed by work at Mound Laboratory and at Los Alamos.

FIG. 44. Plutonium-yttrium phase diagram.¹

1 Primary Y solid solution in Pu (α , VHN 326). (100 $\times$)

2 Primary Y solid solution in Pu (α , VHN 240). (500 $\times$)

3 Y solid solution in Pu (α , VHN 192). (500 $\times$)

4 Primary Y solid solution (VHN 133) with interdendritic Pu (α). (500 $\times$)

5 Primary solid solution of Pu in Y (VHN 125) with Pu and unidentified inclusions resembling PuO. (500 $\times$)

6 Solid solution of Pu in Y solid solution (VHN 100). (500 $\times$)

-Zinc

FIG. 45. Plutonium-zinc phase diagram.¹

Fig. 46 with interdendritic α . (250X)

2 ϵ Pu with eutectoid PuZn_2 in Pu (α) at grain boundaries. (500 $\times$)

3 Pu (δ). (100 $\times$)

4 Primary PuZn_2 in Pu (δ , VHN 59). (1000 $\times$)

5 Primary PuZn_2 (VHN 175) in Pu (δ , VHN 67). (500 $\times$)

6 Primary PuZn_2 (VHN 372) in the eutectic mixture of PuZn_2 and Pu_2Zn_9 (VHN 400). Pu_2Zn_9 is the continuous phase. (250 $\times$)

7 Primary Pu_2Zn_9 (VHN 380) in the eutectic mixture. (200 $\times$)

8 Pu_2Zn_9 (VHN 386). (50 $\times$)

9 Primary $\text{Pu}_3\text{Zn}_{22}$ (VHN 436) and peritectic Pu_2Zn_9 (VHN 403). (100 $\times$)

10 Primary $\text{Pu}_2\text{Zn}_{17}$ (VHN 281), peritectic $\text{Pu}_3\text{Zn}_{22}$ (VHN 307), and peritectic Pu_2Zn_9 (VHN 309). (100 $\times$)

11 $\text{Pu}_2\text{Zn}_{17}$ (VHN 375). Some $\text{Pu}_3\text{Zn}_{22}$ appears at the bottom and lower right. (200 $\times$)

12 Constitutional lines $\text{Pu}_2\text{Zn}_{17}$, K, K' (indistinguishable from $\text{Pu}_2\text{Zn}_{17}$). A series of peritectic constitutional lines. (200 $\times$)

13 Primary λ (VHN 337) in Zn. (100 $\times$)

-Zirconium

FIG. 46. Plutonium-zirconium phase diagram.¹

1 Primary Zr solid solution (α) in Pu (δ). (250 $\times$)

2 Remnants of Zr in Pu (δ , VHN 86). (500 $\times$)

3 δ Pu in β Pu. (500 $\times$)

4 δ Pu in θ (VHN 142). (1000 $\times$)

5 Primary Zr in Pu (δ) and θ . (500 $\times$)

6 Pu (δ , stained) after ϵ . (250 $\times$)

7 Zr solid solution (α) in Pu (δ) and θ . (500 $\times$)

8 Primary Zr solid solution in Pu (δ). (500 $\times$)

9 Pu solid solution (δ) after ϵ . Rejected α Zr present. (150 $\times$)

10 Primary Zr solid solution (VHN 439) in Pu (δ , VHN 95). (250 $\times$)

11 Primary Zr solid solution (VHN 512) in Pu (δ , VHN 72). (250 $\times$)

12 Zr (α solid solution, white) and δ Pu (dark). (200 $\times$)

13 Primary Zr solid solution (VHN 490). (Acicular Zr solid solution, VHN 690; see Appendix D.) (500 $\times$)

14 Solid solution of Pu in Zr (α , VHN 131). (100 $\times$)

Binary Alloys

Ternary Alloys

Plutonium-Carbon-Thorium

Neither a diagram nor a liquidus surface was available.

1 Pu₂C₃ in PuC₂. A 32Pu-67C-1Th* alloy heat-treated at 1720°. (200×)

2 Pu₂C₃. Same alloy as in **1**, heat-treated at 1470°. (500×)

3 ThC₂ in Pu₂C₃. A 28Pu-67C-5Th alloy heat-treated at 1680°. (200×)

4 Pu₂C₃. Same alloy as in **3**, heat-treated at 1470°. (200×)

* In atomic percents.

5 ThC₂ and Pu₂C₃ (not differentiated). A
23Pu-67C-10Th alloy heat-treated at 1700°.
(200×)

-Cerium-Iron

FIG. 27. Liquidus surface of the plutonium-cerium-iron phase diagram.¹

1 Primary Ce (α , VHN 39) with coprecipitated Ce and MFe_2 in Pu (δ , VHN 50) matrix. (500 $\times$)

2 Primary Ce with coprecipitated Ce and MFe_2 in Pu_6Fe matrix. (1000 $\times$)

3 Primary Ce, coprecipitated Ce and MFe_2 , then Pu- Pu_6Fe eutectic. (500 $\times$)

4 Primary MFe_2 , coprecipitated Ce- MFe_2 and Pu- MFe_2 , then Pu- Pu_6Fe eutectic. (500 $\times$)

5 Primary Ce (α), coprecipitated Ce- MFe_2 and Pu- MFe_2 , then Pu- Pu_6Fe eutectic. (500 $\times$)

6 Primary MFe_2 with coprecipitated MFe_2 -Ce and MFe_2 -Pu (δ) in Pu_6Fe (VHN 218) matrix. (1000 $\times$)

[7] Primary Pu (δ , VHN 57), coprecipitated Pu-MFe₂ and Pu₆Fe (VHN 159). (500 $\times$)

[8] Primary Pu (δ), coprecipitated Pu-MFe₂ and Pu₆Fe. (500 $\times$)

[9] Coprecipitated Pu (δ) and Ce (α), Pu-MFe₂ (questionable), Pu₆Fe, and Pu-Pu₆Fe eutectic. (500 $\times$)

[10] Primary Pu (δ , VHN 65), Pu₆Fe (VHN 193), and Pu-Pu₆Fe eutectic. (500 $\times$)

-Cerium-Nickel

FIG. 48. Plutonium-cerium-nickel liquidus surface.¹

1 Primary MNi (VHN 206) with coprecipitated MNi and Pu. (100 $\times$)

2 Coprecipitated MNi and Pu (α). (500 $\times$)

3 Primary Pu (δ , VHN 47) with coprecipitated Pu and MNi (VHN 133). (500 $\times$)

4 Primary Ce with coprecipitated Ce and Ce_3Ni_2 . (250 $\times$)

-Copper-Silver

No diagram was available. Only one example in which a thorough investigation of constituents had been carried out was found in this alloy series.¹⁴

[1] Primary Pu_2AgCu_5 in a eutectic mixture containing 6 at.% Pu, 78.3 at.% Ag, and 15.7 at.% Cu. (100 $\times$)

-Platinum-Rhodium

FIG. 49. Plutonium-platinum-rhodium liquidus surface (partial only).¹⁵

1 Primary PuM_3 in coprecipitated PuM_3 and M solid solution. (1000 $\times$)

2 Primary PuM_3 in coprecipitated PuM_3 and M solid solution. (1000 $\times$)

3 Primary M solid solution in coprecipitated PuM_3 and M solid solution. (1000 $\times$)

4 PuM_3 (VHN 850). (100 $\times$)

5 Primary PuM_5 in coprecipitated PuM_5 and M solid solution. (1000 $\times$)

6 Coprecipitated PuM_3 and M solid solution. (1000 $\times$)

-Silicon-Zirconium

Only a few exploratory alloys were made. Without thermal data on which to base a tentative liquidus surface, we show only the location of the four alloys within the composition triangle.

FIG. 50. Plutonium-silicon-zirconium alloys.

1 Primary Pu_5Si_3 and Zr in mixed phases of Pu (VHN 107). (500 $\times$)

2 Primary Pu_5Si_3 and Zr in predominantly δ Pu (VHN 91). (500 $\times$)

3 Primary Pu_5Si_3 (VHN 532) and Zr (VHN 636) in δ Pu (VHN 69). (250 $\times$)

4 Primary Pu_5Si_3 (VHN 505) and Zr in mixed phases of Pu (VHN 114). (250 $\times$)

-Titanium-Uranium

FIG. 51. Tentative (partial) plutonium-titanium-uranium liquidus surface.¹

1 ζ (VHN 467) with minor U_2Ti . (See Pu-U binary system.) (200 $\times$)

2 ζ (VHN 502) with unresolved U_2Ti . (500 $\times$)

3 ζ and U_2Ti (not resolved) from eutectoid decomposition of η . (1000 $\times$)

4 U_2Ti and ζ in the eutectoid mixture of U_2Ti and ζ . (1000 $\times$)

5 U_2Ti (VHN 416) and ζ (VHN 458) with the eutectoid mixture. (1000 $\times$)

6 Remnants of U_2Ti in an unresolved eutectoid mixture. (500 $\times$)

7 U_2Ti (VHN 430) in the eutectoid mixture of U_2Ti and ζ . (1000 $\times$)

8 Alloy similar to **7**, after heat treatment at 800°. (1000 $\times$)

Appendix A

Sources of Photomicrographs

Photograph No.	Source	Specimen No.	Negative No.	Composition (at.%)	Condition	Etchant ^a	Magnification (×)
Binary alloys							
Alkali Metals and Alkaline Earth alloys							
1	Los Alamos ^b	11477	34101	35 (Li)	Cast	Unetched	10
Aluminum alloys							
1	Los Alamos	3007	5025	2.7	Cast	A	500
2	"	6322	13790	2.5	HT 450°	A	250
3	"	1269	6448	4	Cast	O	500
4	"	3741	7336	40	"	A	100
5	"	3527	10773	50	HT 550°	A	100
6	"	3527	10782	50	HT 550°	A	500
7	"	213	2181	80	Cast	A	100
8	"	3501	6687	97.2	"	E	150
9	"	2370	5042	80	"	A	500
10	"	2370	5171	80	HT 950°	G	100
11	"	3501	6694	97.2	Cast	E	150
12	"	3223	5662	97.3	"	F	500
Americium alloys							
1	Los Alamos	10403	27189	1.5	Cast	D	500
Arsenic alloys							
1	Los Alamos	2278	4624	10	Cast	Unetched ^d	125
2	"	10607	28910	47.5	"	Unetched	500
3	"	2340	5237	75	"	Unetched	500
Beryllium alloys							
1	Los Alamos	708	1717	25	Cast	A	250
2	"	880	2261/2	37	"	A	500
3	"	773	2201	94	"	I	500
4	"	651	2185/6	95	"	L	500
Bismuth alloys							
1	Los Alamos	10240	26-B13	35	Cast	Unetched	320
Boron alloys							
1	Los Alamos	5298	10968	10	Cast	D	250
2	HAPO ^c	4540	R-6386	37.5	"	Unetched	250
3	"	4513	R-6314	50	"	Unetched	250
Cadmium alloys							
1	Los Alamos	6655	15391/2	2	Cast	D	500
2	LIN ^e	1279	4	68.5	"	V	500
Carbon alloys							
1	Los Alamos	3331	9430	5	Cast	A	500
2	"	6522	15088	15	"	A	500
3	"	6521	15078	15.3	"	A	500
4	"	11453	33848	56.4	"	NR ^f	500
5	"	11607	34517	60	HT 2020	P	100
Cerium alloys							
1	Los Alamos	4737	10449	3	HT 550	A	500
2	"	4739	9938	5	Cast	A	500
3	"	4747	9967	9	"	D	500
4	"	4754	9994	13	"	D	500

5	"	11836C	37100	22.5	"	X	500
6	"	11836A	37126	22.5	HT 600°	X	500
7	"	3506	6595	50	Cast	A	500
8	"	6280	14077	50	HT 630°	A	500
9	"	4866	11417	65	HT 550°	O	100
10	"	6618	15407	80	Cast	O	500
11	"	5251	11415	84	"	O	500
12	"	5257	12373	86	HT 550°	O	500
13	"	4792	10439	94	Cast	O	100
Chromium alloys							
1	Los Alamos	4837	10972/3	10	HT 540°	D	500
2	"	1882	3872	50	HT 600°	Unetched	200
3	"	1883	3525	80	Cast	A	100
Cobalt alloys							
1	Los Alamos	3359	6170	8	Cast	A	500
2	"	3409	6117	12	"	A	500
3	"	3367	6140	12	HT 350°	B	500
4	"	3371	6083	20	Cast	A	500
5	"	3449	6943	22.2	HT 400°	D	200
6	"	3284	5785	25	Cast	A	500
7	"	7511	18856	25	HT 425°	A	500
8	"	3245	5736	40	Cast	A	500
9	"	3428	6862	70	"	A	250
10	"	3429	6864/5	80	Cast	A	250
11	"	3468	6900	85	HT 900°	A	250
12	"	3474	6827	95	Cast	K	250
13	"	3474	6907	95	HT 900°	A	250
Copper alloys							
1	Los Alamos	6579	14904	3.4	HT 450°	A	250
2	"	3089	5422	10	Cast	A	500
3	"	4775	10258	25	"	D	500
4	"	4735	9928	50	"	D	500
5	LLNL	373	1421	80	"	D	500
6	"	361	1359	80.9	"	D	250
7	"	218	2164	NR	"	D	250
8	"	185	1990	69	"	NR	500
9	Los Alamos	6674	15015	93	"	U	500
Dysprosium alloys							
1	Los Alamos	10137B	25943	15	Cast	D	500
2	"	10137A	26161	15	HT 450°	D	500
3	"	11544	34941	35	HT 700°	X	500
4	"	11545	34331	70	Cast	D	200
5	"	11540	34487	75	HT 700°	X	500
6	"	11536B	34468	90	Cast	X	500
7	"	11536A	34541	90	HT 700°	X	500
Erbium alloys							
1	Los Alamos	10166B	26005	15	Cast	D	500
2	"	10166A	26613	15	HT 450°	D	500
3	"	10288	27270	80	HT 700°	Unetched	500
Gadolinium alloys							
1	Los Alamos	11831	37886	10	TA spec. ⁸	L	100
2	"	10242A	26727	15	HT 400°	D	500
3	"	11835	37914	20	TA spec.	D	100
4	"	11804	40334	60	Cast	X	500
5	"	12004A	41101	60	HT 700°	X	500

6	"	12305	40351	70	Cast	X	500
7	"	11532	40165	75	HT 600 ^o	X	500
8	"	11532	45503	75	HT 910 ^o	NR	500
9	"	10104	27417	80	HT 700 ^o	V	500
10	"	12654	41527	87.5	Cast	X	200
Gallium alloys							
1	Los Alamos	2365	4847	3	Cast	A	500
2	LLNL	1762	9833	3	"	D	500
3	"	1899	467	3	HT 460 ^o	V	250
4	Los Alamos	7107	16856	18	HT 560	B	1000
5	"	7127	16858	20	HT 560 ^o	B	500
6	"	7127	16844	20	HT 685 ^o	B	500
7	"	6977	16832	24	HT 700 ^o	B	500
8	"	6984	15692	32	Cast	I	500
9	"	6986	16838	36	HT 700 ^o	I	500
10	"	6916	16354	42	Cast	I	1000
11	"	7105	16352	48	"	I	500
12	"	6899	16343	50	"	D	500
13	"	7459	17358	55	HT 600	A	500
14	"	6901	16346	60	Cast	D	500
15	"	7191	16879	67	"	I	100
16	"	6928	16815	70	HT 600	I	100
17	"	10422	29245	75	Cast	Unetched	100
18	"	10799	30524	85	"	NR	100
Germanium alloys							
1	Los Alamos	7172	17362	5	HT 450 ^o	A	500
2	"	3031	5097	25	Cast	Unetched	250
3	"	3032	5201	50	"	Unetched	200
4	"	3073	5230	85	"	Unetched	250
Gold alloys							
1	Los Alamos	3088	5419	10	Cast	B	500
2	"	2139	3919	99.4	"	H	250
Hafnium alloys							
1	Los Alamos	11974	39130	3.5	HT 250	I	200
2	"	11839	38855	5	HT 325	I	1000
3	"	11764	35437	5	HT 450 ^o	X	500
4	"	11814	38154	6	HT 250	I	1000
5	"	11763	35316	10	Cast	A	500
Holmium alloys							
1	Los Alamos	10213	26173	5	Cast	NR	50
2	"	10140	25970	15	"	D	500
3	"	10140	26714	15	HT 600	D	500
4	"	10690	35487	60	Cast	I	1000
5	"	11691	35805	70	"	X	500
6	"	11691A	52070	70	HT 500	X	500
7	"	11693	35503	75	Cast	X	500
8	"	11693	52073	75	HT 600	X	500
Hydrogen alloys							
1	Los Alamos	2183	4568	5	Cast	Unetched	200
2	"	2184	4574	5	"	A	125
Indium alloys							
1	Los Alamos	9890	25017	10	Cast (1A)	D	100
2	"	10129	26617	24	HT 700	D	100
3	"	9801	24671	30	HT 800	D	500
4	"	9810	25072	30	HT 940	D	500

5	"	9977	25252	38	Cast	D	500
6	"	9959	25207	38	HT 860°	D	500
7	"	9797	25228	50	HT 1050°	D	50
8	"	9963	25260	48	HT 875°	D	100
9	"	9980	25247	52	Cast	D	500
10	"	9946	25203	58	HT 980°	D	500
11	"	9903	25047	66	HT 800°	D	500
12	"	9902	25054	75	HT 800°	D	500
13	LLNL	1199	5924	99.8	Cast	S	250
Iron alloys							
1	LLNL	3155	5471	8	Cast	A	500
2	"	673	3014	10	"	D	500
3	Los Alamos	3233	5679	10	"	A	500
5	LLNL	1145	5685	15	"	D	500
6	Los Alamos	3486	6545	14.3	"	A	500
6	"	3149	5456	50	"	A	100
7	LLNL	1645	9048	66.7	"	D	250
8	Los Alamos	3150	5460	85	"	A	500
Lanthanum alloys							
1	Los Alamos	11501	34103	5	Cast	L	500
2	"	11477	34113	35	"	L	100
3	"	3509	6589	50	"	A	500
4	"	10391	27263	80	"	L	500
5	"	10387	27255	95	"	L	500
6	"	10266	26690	95	HT 600°	L	500
Lead alloys							
1	LLNL	600	2573	10	Cast	Unetched	100
2	"	605	2596	20	"	D	100
3	"	993	4753	20	HT 750°	D	100
4	"	1041	5060	37.5	Cast	Unetched	250
5	"	1025	4964	41	"	Unetched	100
6	"	597	2560	60	"	Unetched	100
7	"	645	2821	67	"	Unetched	100
8	"	637	2780	69	"	Unetched	100
9	"	593	2541	80	"	Unetched	50
Lutetium alloys							
1	Los Alamos	7860	24716	10	Cast	D	500
2	"	10184B	26059	15	"	D	500
3	"	10184B	26716	15	HT 600	D	500
4	"	10184A	26188	15	HT 450	D	500
5	"	10327	26881	70	Cast	L	500
6	"	10327	27441	70	HT 600	L	100
7	"	10185	26063	80	Cast	L	500
Magnesium alloys							
1	LLNL	975	4601	90	Cast	L	250
2	"	974	4592	86.2	"	J	500
3	"	975	4606	90	HT 410	L	250
4	"	1070	5270	86	Cast	L	250
Manganese alloys							
1	Los Alamos	3171	5582	5	Cast	B	500
2	"	3172	5585	10	Cast (IA)	A	500
3	"	3160	5476	50	"	B	500
Molybdenum alloys							
1	LLNL	1463	7784	5	Cast	D	500
2	"	1432	7582	25	"	D	100

Neodymium alloys

1	Los Alamos	10497	27460	2	Cast	D	500
2	"	10497B	28136	2	HT 600 ^a	D	500
3	"	10155A	25946	15	Cast	D	500
4	"	10155	26738	15	HT 600 ^c	D	500
5	"	3510	6599	50	Cast	A	500
6	"	10375	27107	70	"	L	500
7	"	10380	27315	95	HT 800 ^b	L	100

Neptunium alloys

1	LLNL	361	12	80	Cast	I	100
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Nickel alloys

1	Los Alamos	1122	5507	1.8	HT 450 ^c	D	1000
2	"	1128	5583	1.8	HT 450 ^c	D	250
3	"	6185	13023	14	Cast	A	500
4	"	3899	8264	25	"	A	500
5	"	589	1070	66	"	A	250
6	"	6677	15048	80	"	A	100
7	"	555	NR	84	"	A	500
8	"	556	NR	86.5	"	A	500
9	"	492	NR	87.5	HT 800 ^c	A	500
10	"	546	NR	95	Cast	Y	100

Niobium alloys

1	Los Alamos	3190	5571	50	Cast	A	500
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Nitrogen alloys

1	Los Alamos	11107	35111	70	Sintered	NR	500
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Osmium alloys

1	Los Alamos	12687	41442	1.5	Cast	I	500
2	"	12691	41701	2	HT 500	I	200
3	LLNL	1182	5854	2.5	Cast	D	500
4	Los Alamos	12622B	41063	3	"	I	500
5	"	12622A	41459	3	HT 400	I	500
6	"	12780	42299	6	HT 400 ^c	D	500
7	"	12690	43821	7	HT 275	NR	100
8	"	13024	43894	9	Cast	I	200
9	HAPO	4637	R6632	NR	"	Unetched	150
10	"	4642	R6525	50	"	NR	150

Oxygen alloys

1	Los Alamos	3716	7343	74.5	Cast	Unetched	500
2	"	3259	7404	61.5	"	"	500
3	"	3756	7357	65.5	"	"	500

Palladium alloys

1	Los Alamos	3567	7533	5	Cast	D	500
2	"	2280	4628	10	"	Unetched	125

Phosphorus alloys

1	Los Alamos	3187	5234	50	Cast	Unetched	500
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Platinum alloys

1	HAPO	3687	R5244	14	Cast	M	250
2	"	3888	R5176	23.5	HT 450	Unetched	250

Praseodymium alloys

1	Los Alamos	10374	27121	1	Cast	D	500
2	"	10484	27448	3	"	D	500
3	"	10147	25940	15	"	Unetched	500
4	"	10285	26765	20	"	D	100
5	"	10350	26981	50	"	I	500
6	"	10365	27072	65	"	I	500

7	"	10148	26832	80	HT 600 ^c	L	500
8	"	10502	27487	85	Cast	L	500
9	"	10256	26778	85	HT 600 ⁿ	L	100
10	"	10541	27797	90	Cast	L	500
11	"	10544	28131	90	HT 600 ^c	L	500
Rhenium alloys							
1	Los Alamos	3954	8798	5	Cast	D	500
2	"	3976	8581	25	"	D	500
Rhodium alloys							
1	HAPCO	3227	R3536	20	Cast	NR	250
2	"	4474	R6204	37	NR	Cathodic	500
Ruthenium alloys							
1	Los Alamos	3685	7623	2	Cast	B	500
2	"	3701	7987	0.5	HT 275 ⁿ	A	500
3	"	12690	41482	3.6	Cast	L	200
4	"	3850	7993	10	"	D	1000
5	"	3492	7602	10	HT 275 ⁿ	A	500
6	"	3492	6916	10	HT 375 ⁿ	A	500
7	"	3696	7689	20	Cast	D	1000
8	"	3696	7789	20	HT 500 ^c	D	250
9	"	3686	7629	30	Cast	D	250
10	"	3860	8340	45	"	D	250
11	"	3661	7555	30	"	D	500
12	"	12587	41597	50	HT 250 ⁿ	L	200
13	"	3699	7700	75	Cast	D	500
14	"	3700	7716	90	"	D	100
Samarium alloys							
1	Los Alamos	11755	35405	1	Cast	A	200
2	"	11756	35385	2	"	A	100
3	"	10481	27725	30	"	L	100
4	"	10444	27372	60	"	L	100
5	"	10619	32731	65	HT 600 ^c	L	100
6	"	10291	26924	90	HT 600 ^c	L	100
Scandium alloys							
1	Los Alamos	10259	26667	5	Cast	D	100
2	"	10548	28963	70	HT 600 ⁿ	D	500
3	"	10440	30193	30	HT 650 ⁿ	L	500
4	"	10802	30911	35	HT 700 ⁿ	L	500
5	"	10729	30170	40	Cast	D	500
	"	10729B	27685	40	"	D	1000
	"	10656	29493	55	HT 850 ⁿ	D	100
8	"	10657	29497	60	HT 850 ⁿ	D	100
9	"	11294	33084	80	HT 1155 ⁿ	L	100
10	"	10516	27636	90	HT 800 ⁿ	D	100
Silicon alloys							
1	Los Alamos	2383	5625	3	HT 550 ⁿ	A	100
2	"	740	1717	3.4	Cast	Unetched	500
3	"	2211	4538	10	"	A	500
4	ENI	195	658	15	Cast	D	250
5	"	224	770	20	"	D	250
6	"	2226	4743	25	"	A	200
7	"	2261	4595	35	"	A	125
8	"	2328	5206	35	"	A	200
9	"	9455	23579	40	"	A	500
10	"	9615	24052	50	"	S	500

11	"	9642	24090	55	"	N	500
12	"	9642	24089	55	"	N	500
13	"	9380	24842	63	"	N	100
14	"	9607	24056	67	"	N	500
15	"	9641	24098	65	"	N	500
16	"	10399	27205	90	"	"	500
Silver alloys							
1	Los Alamos	6904	16400	3	Cast	Unetched	100
2	UNL	1466	7837	10	Cast (TA)	Cathodic	100
3	"	1454	7726	65	"	"	100
4	"	1458	7759	70	"	"	100
5	"	184	1969	78	Cast	Unetched	500
6	"	1461	7776	80	"	Cathodic	500
7	"	1475	7882	90	"	"	500
8	"	3653	7135	90	"	Unetched	500
Sulfur alloys							
1	Los Alamos	9263	19904	50	Cast	Unetched	500
Tantalum alloys							
1	UNL	1382	7258	25	Cast	D	100
Tellurium alloys							
1	Los Alamos	2287	4648	50	Cast	Unetched	500
Terbium alloys							
1	Los Alamos	11689	34704	40	Cast	NR	200
2	"	11676	34900	50	HT 600	A	200
3	"	11692	35480	70	Cast	A	200
4	"	11674	52000	70	HT 500	I	200
5	"	11590B	34800	85	Cast	NR	100
6	"	11590A	34800	85	HT 700	I	200
7	"	11593	34800	95	Cast	NR	100
Thallium alloys							
1	Los Alamos	7756	20884	1	HT 450	D	500
2	"	7761	20907	10	HT 450	D	1000
3	"	10786	30400	30	Cast	D	500
4	"	10793	51006	65	"	Unetched	NR
5	"	10797	52006	78	"	"	NR
Thorium alloys							
1	Los Alamos	4622	9600	2	Cast	A	100
2	"	3857	9600	2	HT 605	A	250
3	"	3952	8529	7	Cast	A	500
4	"	3664	7575	5	"	A	1000
5	"	5265	11338	25	"	D	500
6	"	1251	6315	33.3	"	D	500
7	"	5267	11692	33.3	HT 585	A	500
8	"	5269	11347	50	Cast	D	500
9	"	5269	11723	50	HT 585	A	500
10	"	2333	7501	75	Cast	D	100
11	"	2333	7569	75	HT 900	D	100
Thulium alloys							
1	Los Alamos	10169	26719	15	HT 600	D	500
2	"	10330	26916	50-70	Cast	D	1000
3	"	10330B	27436	50-70	HT 600	D	500
4	"	10170	26797	80	HT 600	I	500
Tin alloys							
1	Los Alamos	3259	5799	5	Cast	A	100
2	"	3244	5730	10	"	A	500

3	LLNL	1049	5113	54	"	Unetched	100
4	Los Alamos	9378	22724	78	"	O	250
5	"	9140	22770	90	HT 500°	O	250
Titanium alloys							
1	Los Alamos	3000	5736	3	Cast	A	500
2	"	623	1653	10	HT 600°	A	500
3	"	6717	15523	30	Cast	D	500
4	"	5358	12345	35	Cast (TA)	A	100
5	"	620	1106	75	Cast	A	500
6	"	6494	14457	95	"	P	500
Tungsten alloys							
1	LLNL	1564	8597	35	Cast	D	100
Uranium alloys							
1	LLNL	1920	648	5	HT 575°	Q	250
2	"	39	1048	15	HT 575°	Q	250
3	Los Alamos	780	2367	25	HT 250°	A	250
4	"	911	2417	27.5	Cast (TA)	A	500
5	LLNL	1889	442	32	"	S	500
6	"	1857	93	40	HT 400°	NR	500
7	"	1908	586	50	HT 475°	Q	500
8	Los Alamos	704	1510	45	HT 600°	A	100
9	"	714	1557	60	Cast	A	500
10	"	745	2531	75	HT 300°	A	500
11	"	811	1955	85	Cast	A	100
12	"	1168	8610	86	HT 400°	A	500
Vanadium alloys							
1	Los Alamos	3730	7875	10	Cast	B	100
2	"	636	1196	90	"	A	100
Yttrium alloys							
1	Los Alamos	10263	26634	5	Cast	D	100
2	"	10278A	26893	15	"	D	500
3	"	10278B	27036	15	HT 600°	D	500
4	"	10279	26664	80	Cast	L	500
5	"	10512	27610	85	"	Unetched	500
6	"	10554	27889	95	"	"	500
Zinc alloys							
1	Los Alamos	6913	16554	2	Cast	B	250
2	"	6460	16309	2	HT 250	D	500
3	"	6460	14407	3	Cast	D	100
4	"	4766	10204	10	"	D	1000
5	"	4770	10221	30	"	D	500
6	"	6625	14984	70	Cast (TA)	D	250
7	"	7714	19479	78	Cast	R	200
8	LLNL	470	1894	82	Cast (TA)	R	50
9	"	526	2187	85	Cast	R	100
10	"	481	1947	88	"	R	100
11	Los Alamos	7714	19507	88.9	HT 627	R	200
12	LLNL	515	2145	95	Cast	R	500
13	"	529	2197	99.5	"	R	100
Zirconium alloys							
1	HAPO	4851	87253	5	Cast	Unetched	250
2	Los Alamos	3720	7421	5	HT 525	A	500
3	"	12244	41168	5	HT 450	D	500
4	"	12397	41427	7.5	HT 250	L	1000
5	LLNL	1651	9090	22.6	Cast	D	500

6	"	1652	9094	22.6	HT 500°	D	250
7	"	1655	9109	22.6	HT 230°	D	500
8	"	203	686	30	Cast	D	500
9	HAPO	4654	86639	40	NR	--	150
10	Los Alamos	633	1179	50	Cast	A	250
11	"	687	1128	75	"	A	250
12	"	13030	43689	85	HT 700°	X	200
13	"	688	1432	90	Cast	A	500
14	"	13031	43694	90	HT 700°	X	100

Ternary alloys

Carbon-Thorium-Plutonium alloys

1	Los Alamos	11599B	34698	67C-1Th-32Pu	HT 1720°	Z	500
2	"	11599A	34711	67C-1Th-32Pu	HT 1470°	NR	500
3	"	11601B	34714	67C-5Th-28Pu	HT 1680°	AA	200
4	"	11601A	34705	67C-5Th-28Pu	HT 1470°	AA	200
5	"	11604	34746	67C-10Th-23Pu	HT 1700°	NR	200

Cerium-Iron-Plutonium alloys

1	Los Alamos	4601	9374	45Ce-10Fe-45Pu	HT 408°	BB	500
2	"	4588	9279	22Ce-11Fe-67Pu	Cast	A	1000
3	"	4767	10177	42.5Ce-15Fe-42.5Pu	"	A	500
4	"	4937	11763	20Ce-20Fe-60Pu	"	A	500
5	"	4934	11293	20Ce-10Fe-70Pu	"	A	500
6	"	4810	10476	15Ce-15Fe-70Pu	"	A	500
7	"	4594	9613	14Ce-5Fe-81Pu	"	A	500
8	"	4773	10173	13Ce-12Fe-75Pu	"	A	500
9	"	4600	9631	10Ce-14-76Pu	"	A	500
10	"	4753	10135	6Ce-11Fe-83Pu	"	A	500

Cerium-Nickel-Plutonium alloys

1	Los Alamos	7745	20002	3Ce-17Ni-80Pu	Cast (TA)	D	100
2	"	7751	20006	5Ce-15Ni-80Pu	"	D	500
3	"	5322	11786	25Ce-15Ni-60Pu	"	A	500
4	"	6230	13523	55Ce-20Ni-25Pu	Cast	BB	250

Copper-Silver-Plutonium alloys

1	U NI	186	1956	2.5Cu-72.7Ag-24.8Pu	Cast	C	100
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Platinum-Rhodium-Plutonium alloys

1	Los Alamos	16175	61659	10Pt-72Rh-18Pu	Cast	W	1000
2	"	16176	61664	30Pt-52Rh-18Pu	"	W	1000
3	"	16115	61201	43Pt-43Rh-14Pu	"	W	1000
4	"	15997	60731	60Pt-15Rh-25Pu	"	W	100
5	"	16056	61100	72Pt-11Rh-17Pu	"	W	1000
6	"	16111	61194	75Pt-13Rh-12Pu	"	W	1000

Silicon-Zirconium-Plutonium alloys

1	U NI	289	1067	35Si-12Zr-83Pu	Cast	NR	500
2	"	294	1094	55Si-18Zr-77Pu	"	"	500
3	"	184	613	25Si-8Zr-67Pu	"	"	250
4	"	248	877	27Si-4Zr-69Pu	"	"	250

Titanium-Uranium-Plutonium alloys

1	Los Alamos	3558	6971	4Ti-72U-24Pu	HT 400	D	200
2	"	3558	6946	4Ti-72U-24Pu	HT 1300	A	500
3	"	3559	7082	8Ti-69U-23Pu	Cast	D	1000
4	"	3559	6977	8Ti-69U-23Pu	HT 800	D	1000
5	"	3560	7100	12Ti-66U-22Pu	HT 800°	D	1000
6	"	3560	6948	12Ti-66U-22Pu	HT 1300	D	500
7	"	3547	7047	20Ti-60U-20Pu	Cast	A	1000
8	"	3547	7079	20Ti-60U-20Pu	HT 800	A	1000

Appendices

D. Differing Hardnesses of Primary Constituents

D-1	Los Alamos	4843	10802	Pu/Ta interface	Cast	D	100
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E. Microcracking in Alpha Plutonium

E-1	LLNL	1554	496-1	Pu	Cast	Unetched	100
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F. Metastable Phases

F-1	LLNL	1526	8358	5 Zr	NR	NR	NR
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F-2	Los Alamos	3570	7235	10 U	HT 275 ^c	B	250
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G. The Grain Size of Alpha Plutonium

G-1	LLNL	1552	495-3	Pu	Cast	D	100
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G-2		204	2118	Pu	"	NR	100
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H. The Banded Zeta Phase in Plutonium-Uranium Alloys

H-1	LLNL	1162	5765	15 U	Cast	D	500
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^a See Appendix B for formulas

^b Los Alamos National Laboratory, Los Alamos, NM.

^c Heat-treated.

^d Preferentially oxidized

^e Hanford Atomic Products Operation (Hanford Engineering Development Laboratory), Richland, WA.

^f Not recorded.

^g Thermal analysis specimen

Appendix B

Etchants

Etchant	Formula (parts by volume unless otherwise indicated)	Method
A	7 tetraphosphoric acid, 57 2-ethoxyethanol, 36 water	Electrolytic
B	2 tetraphosphoric acid, 5 2-ethoxyethanol, 3 water	"
C	12 tetraphosphoric acid, 55 2-ethoxyethanol, 33 water	"
D	8 phosphoric acid, 5 ethanol, 5 glycerine	"
E	1 hydrofluoric acid, 99 water	Swab
F	2 hydrofluoric acid, 98 water	"
G	1 hydrofluoric acid, 1 nitric acid, 98 glycerine	"
H	5 g potassium cyanide, 95 water	Electrolytic
I	1 acetic acid, 1 nitric acid, 1 glycerine	Swab
J	1 nitric acid, 99 ethanol	"
K	2 nitric acid, 98 ethanol	—
L	10 nitric acid, 90 ethanol	Electrolytic and Swab
M	1 nitric acid, 75 ethylene glycol, 24 water	electrolytic
N	10 nitric acid, 90 glycerine	"
O	1 nitric acid, 3 acetic acid, 5 glycerine	"
P	1 nitric acid, 1 hydrofluoric acid, 98 water	Swab
Q	25 g chromic acid, 153 acetic acid, 7 water	Electrolytic
R	5 hydrochloric acid, 95 ethanol	Swab
S	5 hydrochloric acid, 1 g picric acid, 94 ethanol, (Villega)	"
T	10 g citric acid, 8 ml 25% potassium nitrate in water, 92 water	Electrolytic
U	3 hydrogen peroxide, 20 ammonium hydroxide, 20 water	Swab
V	10 nitric acid, 90 ethylene glycol	Electrolytic
W	50 hydrochloric acid, 50 saturated sodium chloride in water	"
X	10 phosphoric acid, 5 lactic acid, 20 acetic acid, 5 nitric acid (with or without 1 sulphuric acid)	Electrolytic and Swab
Y	50 phosphoric acid, 100 water	Electrolytic
Z	1 nitric acid, 2 hydrofluoric acid, 2 water	Swab
AA	6 sulphuric acid, 50 lactic acid, 15 water	"
BB	1 nitric acid, 1 acetic acid, 1 glycerine	Electrolytic

Appendix C

Pitting at Inclusions

This annoying effect, shown in photograph 6 of the indium alloys and photograph 5 of the iron alloys, is frequently encountered in mechanically polished delta plutonium. It makes it difficult to photograph an interface between an inclusion and its matrix, and, at low magnifications, only a dark halo is seen. It initiates as a depression with deep scratches adjacent to an inclusion—scratches that cannot be removed by continued polishing. *The effect appears to be caused by the flow of abrasive-laden vehicle around the inclusion and can be minimized through vibratory polishing.*

Electropolishing further deepens the pit, probably through the action of a galvanic cell, or by the disruption of the saturated electrolyte layer by bubble formation on the inclusion.

Appendix D

Differing Hardnesses of Primary Constituents

The phenomenon was first seen in cast material as a distinct difference in both the hardness and morphology of primary inclusions, the harder material being platelike rather than massive. Both, however, yield a diluent x-ray pattern. It is illustrated under zirconium alloys in photographs 11 and 13 but is also seen in titanium, hafnium, niobium, and tantalum alloys. The origin of the hard platelets is best seen in a partially reacted melt (photograph D-1). A skin of the diluent has loosened and begun to float away. The inclusions disperse and remain after melting has been completed and through subsequent heat treatments. It appears that the material is an interstitial solid solution of the diluent and an impurity gettered from the melt¹⁶ or ambient atmosphere.

The phenomenon was also related to a "plating" effect observed in high-temperature diffractometry in which the diluent pattern becomes superimposed on the desired plutonium pattern.¹⁷ A clear pattern of the diluent may be obtained, but having slightly altered cell constants.

D-1 The interface of a Pu melt with Ta.
(100×)

Appendix E

Microcracking in Alpha Plutonium

Microcracking is a phenomenon common to "high-purity" alpha plutonium metal having less than ~ 500 ppm (by weight) of impurities. This material is appreciably harder than less pure metal and exhibits a maximum volume change of transformation. Undergoing a change from a highly ductile to a brittle material, accompanied by a negative volume change of about 8.9% in the beta to alpha transformation, is generally held responsible for bulk microcracking.

Although regarded as high-purity, this grade of material is not free of internal discontinuities, notably carbide inclusions and oxide skins, or dross. Either are effective as stress risers to initiate cracking, although they may not always be apparent since the points of origin may be hidden. Cracking then proceeds from these discontinuities, which are themselves often torn apart, apparently along crystallographic planes.

[E-1] Microcracking in cast Pu (α). (100 $\times$)

Appendix F

Metastable Phases

Delta is the only elevated-temperature allotrope of plutonium that has been stabilized (see Gallium) to room temperature by alloying, namely, by additions of either aluminum, americium, cerium, or gallium. Metastable delta has been observed in binary alloys of plutonium with erbium, hafnium, indium, lutetium, rhenium, thallium, zinc, and zirconium. In addition to the preceding, delta has also been observed with gamma, beta, and alpha in alloys of plutonium with germanium, silicon, thorium, and titanium.

The gamma allotrope has been observed in zirconium alloys (photograph F-1) and in the combinations above. Beta has been observed in uranium alloys and, again, in the combinations above.

F-1 γ Pu. A 5 at.% Zr alloy, treatment not known. (Magnification not known)

F-2 β Pu. A 10 at.% U alloy heat-treated at 275°. (250 $\times$)

Appendix G

The Grain Size of Alpha Plutonium

The grain size of annealed delta-phase alloys may readily be determined. Grain boundaries can be revealed by a variety of etchants, and the grains can then be compared with standard charts or their sizes described by area counts or line intercepts. Epsilon grain structure has been observed but a representative photomicrograph was not available. Individual gamma grains have not been revealed. Delta prime grains have not been retained to room temperature. Beta grain structures have been well defined (photograph 1-2).

Grains in alpha plutonium are best observed in polarized light (photograph G-2). A thin layer of epitaxial oxide, produced by anodizing at a higher voltage than that used to electropolish,¹⁸ enhances optical activity. The structure that will be observed appears to be highly distorted or fragmented (photograph G-2). Indeed, a study of alpha plutonium by x-ray micrography indicates that the apparent "grains" are aggregates of subgrains generally less than 10 μm in width disoriented by more than 1° .¹⁹ Similarly, x-ray diffraction patterns of stress-relieved filings may have their lines broadened to the extent that suggests the diffracting entities are smaller than those observed in polarized light.

G-1 α Pu grains in bright field. (100 $\times$)

G-2 α Pu grains observed in polarized light. (100 $\times$)

Appendix H

The Banded Zeta Phase in Plutonium-Uranium Alloys

The zeta phase, probably the most prominent feature of the plutonium-uranium system, also occurs with beta plutonium as a product of the eutectoid decomposition of eta (see Uranium). It is this two-phase region that gives rise to an anomalous behavior.

The microstructure of a slowly cooled cast alloy containing 15 at.% uranium is shown in photograph H-1. It consists of alpha plutonium and zeta. The zeta now exhibits a banded structure that was identified as a single phase.²⁰ An electron-beam microprobe analysis of a similar structure in a 15 at.% alloy revealed that the zeta had partitioned into alternating bands containing approximately 7 and 22 at.% uranium.²¹ A concurrent diffraction pattern of the material corresponded to that reported in Ref. 20; however, the investigators felt that their data represented two discrete phases. Unfortunately, this anomaly has not been resolved at this time.

H-1 Pu (α) islands in ζ . (500 $\times$)

References

1. F. H. Ellinger, W. N. Miner, D. R. O'Boyle, and F. W. Schonfeld, *Constitution of Plutonium Alloys*, Los Alamos National Laboratory, Los Alamos, NM, LA-3870 (1968).
2. D. H. Wood and E. M. Cramer, "The Plutonium-Europium System," *J. Less Common Metals* **19** (1969).
3. F. H. Ellinger, C. C. Land, and K. A. Johnson, "The Plutonium-Lanthanum System," *Trans. Met. Soc. AIME* **239** (1967).
4. R. N. R. Mulford, F. H. Ellinger, G. S. Hendrix, and E. D. Albrecht, "The Plutonium-Carbon System," *Plutonium 1960* (Cleaver Hume Press, London, 1961).
5. F. H. Ellinger, C. C. Land, and E. M. Cramer, "Plutonium-Cerium Phase Diagram," *Extractive and Physical Metallurgy of Plutonium and Its Alloys* (Interscience Publishers, 1960).
6. *Bulletin of Alloy Phase Diagrams* **2** (4), (1982), American Society for Metals, Metals Park, OH, ASM-NBS Data Program for Alloy Phase Diagrams.
7. F. H. Ellinger and C. C. Land, "The Constitution of Plutonium-Rich Plutonium-Hafnium Alloys," *J. Nucl. Mater.* **28**, 291 (1968).
8. D. H. Wood, E. M. Cramer, P. L. Wallace, and W. J. Ramsey, "Phase Relations in the Plutonium-Lead System," *J. Nucl. Mater.* **32**, 193 (1969).
9. W. Knoch, J. B. Knighton, and R. K. Steunenberg, "Contribution to the Plutonium-Magnesium Phase Diagram," *Nucl. Metall.* **15**, 535 (1969).
10. *Handbook of Binary Phase Diagrams*, General Electric Corp., Res. Eng. Div., Schenectady, NY (1982), vol. 3, Update 7.
11. *Handbook of Binary Phase Diagrams*, General Electric Corp., Res. Eng. Div., Schenectady, NY (1980), vol. 3.
12. D. H. Wood, E. M. Cramer, and P. L. Wallace, *An Investigation of the Plutonium-Silver System, Plutonium and Other Actinides*, vol. 2 (Metallurgical Society of AIME, New York, NY, 1970), p. 707.
13. P. L. Wallace and M. R. Harvey, "An Electron Probe Microanalysis of the Plutonium-Tin Alloy System," *J. Nucl. Mater.* **54**, 171 (1974).
14. P. L. Wallace, Lawrence Livermore National Laboratory, Livermore, CA, unpublished work, 1983.
15. C. C. Land, D. E. Peterson, and R. B. Roof, "Phase Relations of the Pu-Pt, Pu-Rh, and Pu-Pt-Rh Systems," *J. Nucl. Mater.* **75**, 262 (1978).
16. C. O. Matthews, Los Alamos National Laboratory, Los Alamos, NM, unpublished work, 1954.
17. R. O. Elliott, Los Alamos National Laboratory, Los Alamos, NM, personal communication, circa 1958.
18. K. J. Ingham and E. M. Cramer, "The Metallographic Preparation of Plutonium and its Alloys at Los Alamos," *Proceedings of the AIC Metallographic Group* (1958).
19. E. Cramer, *X-Ray Micrography of Alpha Plutonium*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-7651 (1964).
20. F. H. Ellinger, R. O. Elliott, and E. M. Cramer, "The Plutonium-Uranium System," *J. Nucl. Mater.* **1** (3), 236 (1959).
21. P. L. Wallace and M. R. Harvey, *Phase Analysis of a 15 Atom Percent Uranium Alloy*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-18922. (See also D. H. Riesenberget al., Rocky Flats Plant, Rocky Flats, CO, RFP 1721, 1980.)

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