Written: March 1970
Distributed: August 1970

LA-4415
UC-4, CHEMISTRY
TID-4500

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

Plutonium Carbides

by

A. E. Ogard
J. A. Leary

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PLUTONIUM CARBIDES

by

A. E. Ogard and J. A. Leary

ABSTRACT

The preparation and properties of the plutonium carbides are reviewed.

I. INTRODUCTION

A. Preparation

Methods which have been used in the preparation of the plutonium carbides are direct arc melting of plutonium and graphite,¹⁻⁶ carbon reduction of PuO_2 at 1100 to 1450°C,^{1,7-12} sintering of mixtures of carbon powder and plutonium metal or plutonium hydride powder at temperatures up to 1400°C,^{7,13,14} and reaction of hydrocarbons with plutonium at 600 to 800°C.¹⁵ Each method of preparation has advantages. Arc melting produces a dense carbide that is essentially free of oxygen and nitrogen impurities. However, the composition is difficult to control and the product is inhomogeneous unless extensive heat treatment is performed. This is especially true of the monocarbide. Carbon reduction of PuO_2 is a consistent and economical procedure. It is difficult, though, to prepare single-phase PuC_{1-x} and impossible to eliminate completely all of the oxygen. Single-phase PuC_{1-x} of controlled carbon content can readily be prepared by sintering a mixture of graphite powder and plutonium hydride powder. An inert gas atmosphere glove box is necessary for this procedure because the plutonium hydride is pyrophoric. Even with the use of an inert gas atmosphere, most carbides made from powders contain up to 1000 ppm of oxygen.

B. Phase Relationships

The phase diagram of the plutonium-carbon system was first proposed by Mulford et al.¹ Figure 1 is basically the proposed diagram modified by more recent results.¹⁶ Four carbide compounds have been identified: the zeta-phase at Pu_3C_2 , a carbon deficient PuC_{1-x} ,

Fig. 1. Plutonium-carbon phase diagram.

Pu_2C_3 , and the high-temperature phase, PuC_2 .

The transformation temperatures of the six plutonium allotropes do not appear to be affected by the dissolution of carbon.^{1, 17} The melting point of plutonium is lowered by as much as 8° .^{1, 6} Above this eutectic the solubility of carbon in liquid plutonium can be expressed by the equation¹⁸

$$\log_{10} \text{ atom fraction carbon} = 0.50 - 2.3 \times 10^3/T \text{ (700-950}^\circ\text{K)}.$$

The structure of Pu_3C_2 has not been determined but appears to be related to that of PuC_{1-x} . X-ray powder diffraction patterns of the Pu_3C_2 phase have been described by several authors.^{1, 6, 19} Pu_3C_2 decomposes by a peritectoid reaction to $\epsilon\text{-Pu} + \text{PuC}_{1-x}$ in the range of 558 to 585°C .

Plutonium monocarbide has the fcc NaCl-type structure.²⁰ It is a nonstoichiometric compound that is deficient in carbon, and has a composition range of homogeneity as shown in Table I. The room-temperature lattice parameter increases from a value of 4.953 to 4.973 Å as the carbon content is increased from the hypo- to the hyperstoichiometric composition.^{1, 6, 7, 21, 22} The lattice parameter increases slowly with time owing to self-irradiation damage of the lattice.²²⁻²⁴ The high solubilities of oxygen and nitrogen in PuC_{1-x} , also cause wide variations in lattice dimensions.²⁵⁻²⁷ An antiferromagnetic transition occurs at $\sim 100^\circ\text{K}$ in PuC_{1-x} .²⁸ The monocarbide melts peritectically at $1658 \pm 5^\circ\text{C}$ to form liquid + Pu_2C_3 .^{1, 29}

The structure of Pu_2C_3 is body-centered cubic.³⁰ A small variation in lattice parameter has been found that suggests a small range of composition: 8.126 to 8.132 Å,¹ 8.129,⁷ 8.131 to 8.134,¹⁰ and 8.121 to 8.126.²¹ Volume fraction analysis of heat-treated $\text{PuC} + \text{Pu}_2\text{C}_3$ samples show a lower phase boundary of Pu_2C_3 at ~ 59 at. % carbon at temperatures above 855°C .¹⁹ The transition of $\text{Pu}_2\text{C}_3 + \text{C}$ to PuC_2 occurs at approximately 1650°C , and does not appear to be affected by the carbon concentration.¹⁶ Peritectic melting of Pu_2C_3 to liquid + PuC_2 occurs at $2020 \pm 40^\circ\text{C}$.^{1, 16, 31}

Tetragonal PuC_2 exists at temperatures above 1650° .^{1, 13, 16, 31, 32} On cooling, the transformation

Table I

THE CARBON CONTENT OF PuC_{1-x}

Temperature	Reference	$\text{Pu}_2\text{C}_3 + \text{PuC}$ Boundary at. % Carbon	$\text{PuC} + \text{Pu}_3\text{C}_2$ Boundary at. % Carbon
300°C	2	45.4 - 45.8	..
400	21	45.4 - 46.8	..
555	19	43 - 44	46
575	2	41.1 - 43.2	..
570-586	6	43.5	46
600	22	40	49
610	19	42 - 43	46
634	22	38	49
1000	21	46.4	..

of PuC_2 to Pu_2C_3 is so rapid that difficulty is encountered in quenching in the PuC_2 phase. The peritectic melting point of PuC_2 to liquid + carbon is $2240 \pm 10^\circ\text{C}$.^{1, 16} Tetragonal PuC_2 is isostructural with tetragonal $\alpha\text{-UC}_2$; no evidence for the existence of a PuC_2 analog of cubic $\beta\text{-UC}_2$ has been reported.*

C. Physical Properties

The physical properties experimentally determined for the plutonium carbides are listed in Table II. It is important to note that the physical properties listed in Table II have not been determined as a function of the carbon concentration except the measurements of hardness.

A comparison of the free energies of formation expressed in Table II with the free energies of formation of the uranium carbides³³ indicates that plutonium carbides generally are less stable than the corresponding uranium carbides, but far more stable than originally reported.³⁴

It is difficult at this time to calculate the thermodynamic values at 238°K with any certainty. The heat content of PuC_{1-x} has been measured in a drop calorimeter.³⁵ These results were combined with reported equilibrium data and tabulated functions for plutonium and carbon to give the standard thermodynamic quantities at 298.15°K shown in Table III. Because the heat capacity of Pu_2C_3 has not been determined, only the heat of reaction is shown for the sesquicarbide. The results calculated for PuC_{1-x} from vaporization data³⁶⁻³⁹ do not agree internally, nor do they agree with those derived from the electromotive force measurements.⁴⁰ The absolute entropy of PuC_{1-x} from electromotive force results is in fairly good agreement with that of UC

*Recently, the Harwell workers reported evidence for the existence of cubic PuC_2 above 1800°C .

TABLE II
REPORTED PHYSICAL PROPERTIES OF PLUTONIUM CARBIDES

Property	Pu ₃ C ₂	PuC _{1-x}	PuC _{1.5}	PuC ₂
Average Coefficient of Thermal Expansion ($\alpha \times 10^{-6}/^{\circ}\text{C}$)	~ 11 [2]	10.8 ± 0.2 [2, 41, 42, 14] (25-900 ^o C)	15.5 ± 0.7 [41, 43] (20-800 ^o C)	...
Thermal Conductivity (cal/cm-sec- ^o C)	...	$0.0155 + 38.5 \times 10^{-6}T$ [44] (200 - 400 ^o C)	...	...
Thermal Diffusivity (m ² sec ⁻¹)	...	$2.4 - 3.5 \times 10^{-6}$ [45] (400 - 1330 ^o C)	...	...
Resistivity (μ ohm cm)	...	230 - 270 [7, 44, 46, 47] (25 - 900 ^o C)	500 [48] (25 ^o C)	...
Thermal Electric Power (microvolt/ ^o K)	...	0 - 17.5 [46, 47] (60 - 1200 ^o K)	0 - 23 - 20 [48] (0 - 100 - 200 ^o K)	...
Hardness (DPHN)	100 $\pm$ 50 [1, 19]	500 - 900 [19]	~ 1100 [19]	...
Lattice Parameter, Å	...	4.953 - 4.973 [1, 6, 7, 21, 22]	8.121 - 8.134 [1, 7, 10, 21]	a = 3.63 [32] c = 6.09
Theoretical Density (g/cm ³)	...	13.5 $\pm$ 0.1	12.7 $\pm$ 0.1	10.9
Magnetic Susceptibility	...	Maximum at $\sim 20^{\circ}\text{K}$ [49]	...	...
Vapor Pressure of Pu over a Mixture of the Carbide and the next higher Carbide	...	- 19,160/T + 5.30 [36] (1366 - 1835 ^o K)	- 20,330/T + 4.39 [36] (1541 - 1989 ^o K)	- 17,920/T + 2.779 [50] (2000 - 2400 ^o K)
log p (atm)	...	- 18,091/T + 4.686 [37] (1761 - 1907 ^o K)	...	- 18,732/T + 3.618 [37] (2017 - 2472 ^o K)
	...	- 18,990/T + 5.164 [38] (1533 - 1799 ^o K)	- 20,450/T + 4.385 [38] (1745 - 1928 ^o K)	- 19,250/T + 3.764 [38] (1934 - 2140 ^o K)
	...	- 51,100/T + 22.3 [39] (1773 - 1838 ^o K)	...	...
Free Energy of Formation, ΔG_f (kcal/mole)	...	- 17.2 + 0.0023 T [40] (971 - 1060 ^o K)	- 26.2 + 0.0072 T [40] (974 - 1091 ^o K)	...
	...	- 11.053 - 0.00064 T [36] (1366 - 1835 ^o K)	- 13.310 - 0.00239 T [36] (1541 - 1989 ^o K)	- 3.300 - 0.0092 T [50] (2000 - 2400 ^o K)
	...	- 5.610 - 0.00361 T [37] (1761 - 1907 ^o K)	- 18.0 [37] (2023 ^o K)	- 4.350 - 0.00677 T [37] (2017 - 2472 ^o K)
	...	- 10.939 - 0.00089 T [38] (1533 - 1799 ^o K)	- 13.397 - 0.00259 T [38] (1745 - 1928 ^o K)	- 7.400 - 0.00569 T [38] (1934 - 2140 ^o K)
H _T - H ₂₉₈ (cal/mole)	...	- 5035 + 13.08 T + 5.718 $\times 10^{-4}T^2$ + 3.232 $\times 10^5T^{-1}$ [35] (425 - 1300 ^o K)	...	...
Heat Capacity, C _p (cal/mole/ ^o K)	...	13.08 + 11.44 $\times 10^{-4}T$ - 3.232 $\times 10^5T^{-2}$ [35] (425 - 1300 ^o K)	...	...

Bracket [] indicate References.

Table III

STANDARD THERMODYNAMIC PROPERTIES OF PLUTONIUM CARBIDES
AT 298.15°K

Compound	$-\Delta H_{298}^{\circ}$, kcal/mole	ΔS_{298}° , e. u.	S_{298}° , e. u.	Reference
PuC_{1-x}	10.04	3.49	18.2	42
"	4.6	6.46	21.2	43
"	18.2	0.55	15.3	44
"	10.5	2.8 ± 2.0	17.2	45
Pu_2C_3	21.2			42
"	11.4			43
"	48.1			44
"	25.4	4.9 ± 2.0	20.2	45

(14.2 e. u.). Similarly, the heat of formation of Pu_2C_3 obtained by electromotive force measurements is approximately the same as that of U_2C_3 . It is surprising that the heat capacity of PuC_{1-x} is less than that of UC, in view of the fact that U and UO_2 have lower heat capacities than plutonium metal and PuO_2 .⁵¹⁻⁵⁴ Thermal conductivity measurements⁴⁴ and thermal conductivities calculated from thermal diffusivity data⁴⁵ differ by a factor of approximately 2. The sample used for diffusivity measurements did, however, contain ~10% Pu_2C_3 . Obviously, the thermochemical data on plutonium carbides must be considered as provisional.

Plutonium monocarbide containing ~10% Pu_2C_3 impurity has been found to react with the nickel in stainless steel when heated in contact at 1050°C for 120 hours.¹⁴ It is unlikely that PuC_{1-x} that contains significant amounts of free plutonium metal will be compatible with nickel, cobalt, or iron base alloys, because low melting binary eutectics are formed. Less reaction has been found between Pu_2C_3 and the refractory metals. The amount of reaction zone decreased in the order niobium > molybdenum > tantalum > tungsten.

D. Irradiation

Plutonium carbides by themselves are not normally considered as potential power reactor fuels, and very little irradiation experience has been obtained. A few irradiations of arc-cast PuC_{1-x} powder and vibratory compacted PuC_x have been reported.⁵⁵ Burn-ups of $\sim 3 \times 10^{19}$ fissions/cm³ of the arc-cast specimens and up to 12.9×10^{20} of the vibratory compacted PuC_{1-x} have been obtained. Most specimens cracked during irradiations and one specimen of vibratory compacted PuC_x of

6.22 wt% carbon reacted disastrously with the 304 stainless steel cladding after 12.9×10^{20} fissions/cm³. The fission gas release, where measurable, was low, ~0.24%.

II. REFERENCES

1. R. N. R. Mulford, F. H. Ellinger, G. S. Hendrix, and E. D. Albrecht, "The Plutonium-Carbon System," Plutonium 1960, Ed. by E. Grison, W. B. H. Lord, and R. D. Fowler, Cleaver-Hume Press Ltd., London (1961) p. 301.
2. A. E. Ogard, C. C. Land, and J. A. Leary, "The Thermal Expansion of PuC and PuC-UC Solid Solution," LA-2768 (1962).
3. T. D. Chikalla, "Lattice Constants and Phase Relations of Arc-Melted Plutonium-Carbon Alloys," HW-74024 (1962).
4. O. L. Kruger, "Preparation and Some Properties of Arc-Cast Plutonium Monocarbide," J. Nucl. Mater. 7, 142 (1962).
5. M. Palfreyman and L. E. Russell, in Powder Metallurgy in the Nuclear Age, Plansee Proceedings 1961, Ed. by F. Benesovsky, Metallwerk Plansee AG., Reutte/Tyrol (1962) p. 417.
6. S. Rosen, M. V. Nevitt, and A. W. Mitchell, "Metallographic and X-ray Observations of Pu-C Alloys," J. Nucl. Mater. 10, 90 (1963).
7. R. Pascard, "Études préliminaires sur le système plutonium-carbone et les solutions solides carbure d'uranium-carbure de plutonium," in Powder Metallurgy in the Nuclear Age, Plansee Proceedings 1961, Ed. by F. Benesovsky, Metallwerk Plansee AG., Reutte/Tyrol (1962) p. 387.
8. A. E. Ogard, W. C. Pritchard, R. M. Douglass, and J. A. Leary, "The Powder Metallurgy of Plutonium Fuel Materials," Ibid, 364.
9. A. E. Ogard, W. C. Pritchard, R. M. Douglass, and J. A. Leary, "The Preparation of Uranium Monocarbide-Plutonium Monocarbide Solid Solutions, Plutonium Sesquicarbide and Plutonium Monocarbide," J. Inorg. Nucl. Chem. 24, 29 (1962).
10. R. E. Skavdahl, "The Reactions Between PuO_2 and Carbon," Trans. Am. Nucl. Soc. 6, 393 (1963).
11. R. Ainsley, B. R. Harder, M. Hodge, R. C. Swden, D. B. White, and D. C. Wood, "Carbides as Reactor Fuels: Preparation from Oxides and Sintering Characteristics," AERE-R-4327 (1963).
12. H. Bairot, I. Lafontaine, and A. Pizzolo, "Description of the Belgonucleaire-C. E. N. Work on Plutonium Bearing Carbides," in Carbides in Nuclear Energy, Vol. 2, Ed. by L. E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 467.

13. J.L. Drummond, B.J. McDonald, U.M. Ockenden, and G.A. Welch, "The Preparation and Properties of Some Plutonium Compounds. Part VII. Plutonium Carbides," *J. Chem. Soc.* IV, 4785 (1957).
14. F.G. Reshetnikov, V.V. Artamonov, M.G. Gurvich, V.I. Kutaitsev, V.G. Kuznetsova, V.I. Bagrova, O.A. Alekseev, N.T. Chebotarev, and N.I. Kuzin, "Preparation and Studies of Some Properties of Plutonium Monocarbides," in *Plutonium 1965*, Ed. by A.E. Kay and M.B. Waldron, Chapman and Hall, London (1967) p. 757.
15. F. Brown, F.S. Dennerd, P. Ellis, P.T. Good, and R. Lapage, "The Preparation of Pu-, U-, and Mixed (Pu, U)-Carbides by the Metal-Hydrocarbon Gas Reaction," in *Carbides in Nuclear Energy*, Vol. 2, Ed. by L.E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 692.
16. J.G. Reavis, M.W. Shupe, C.W. Bjorklund, and J.A. Leary, "Phase Relations in the High-Carbon Portion of the U-Pu-C System," *Trans. Am. Nucl. Soc.* 10, 111 (1967).
17. R.P. Elliott and A.C. Larson, "Delta-Prime Plutonium," *The Metal Plutonium*, Ed. by A.S. Coffinberry and W.N. Miner, University of Chicago Press, Chicago (1961) p. 265.
18. D.F. Bowersox and J.A. Leary, "The Solubility of Carbon, Tantalum, Tungsten, and Rhenium in Liquid Plutonium," *J. Nucl. Mater.* 21, 219 (1967).
19. K.A. Johnson, "Metallographic Preparation and Observations of Some Plutonium-Carbon Alloys," LA-3191-MS (1965).
20. W.H. Zachariasen, "The Crystal Structure of Plutonium Nitride and Plutonium Carbide," *The Transuranium Elements, National Nuclear Energy Series, IV-14B*, Ed. by G.T. Seaborg, J.J. Katz, and W.M. Manning, McGraw-Hill Book Co., Inc. New York (1949) p. 1448.
21. O.L. Kruger, "Phase Studies on Arc-Melted Plutonium-Carbon Alloys Near the Monocarbide Composition," *J. Am. Ceram. Soc.* 46, 80 (1963).
22. J.B. Burnham, R.E. Skavdahl, and T.D. Chikalla, "Plutonium Bearing Refractory Carbides," *Carbides in Nuclear Energy*, Vol. 1, Ed. by L.E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 51.
23. K. Mendelssohn, E. King, J.A. Lee, M.H. Rand, C.S. Griffin, and R.S. Street, "Self-Irradiation Damage in Transuranic Elements and Compounds," *Plutonium 1965*, Ed. by A.E. Kay and M.B. Waldron, Chapman and Hall, London (1967) p. 189.
24. C.W. Bjorklund, R.M. Douglass, and R.L. Nance, "X-ray Powder Diffraction," LA-3820-MS, (1967).
25. F. Anselin, G. Dean, R. Lorenzelli, and R. Pascard, "On the System (U, Pu) (CNO) as Applied to Sintered Carbides, Carbonitrides, and Oxycarbides," *Carbides in Nuclear Energy*, Vol. 1, Ed. by L.E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 113.
26. R.N.R. Mulford, F.H. Ellinger, and K.A. Johnson, "The Plutonium-Carbon-Oxygen System," *J. Nucl. Mater.* 17, 324 (1965).
27. P.E. Potter, "The Ternary System: Plutonium-Carbon-Oxygen," *Thermodynamics of Nuclear Materials with Emphasis on Solution Systems*, IAEA, Vienna (1967) p. 337.
28. J.L. Green, G.P. Arnold, J.A. Leary, and N.G. Nereson, "A Low Temperature Magnetic Transition in Plutonium Monocarbide," *J. Nucl. Mater.* 23, 231 (1967).
29. O.L. Kruger, "Constitution and Properties of Plutonium Monocarbide," *Compounds of Interest in Nuclear Reactor Technology*, Ed. by J.T. Waber and P. Chioti, American Institute of Mining, Metallurgical and Petroleum Engineers, Inc. (1964) p. 387.
30. W.H. Zachariasen, "Crystal Chemical Studies of the 5f-Series of Elements. XV. The Crystal Structure of Plutonium Sesquicarbide," *Acta Cryst.* 5, 17 (1952).
31. J.T. Dalton, "Equilibria in the System Uranium-Plutonium-Carbon," *Carbides in Nuclear Energy*, Vol. 1, Ed. by L.E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 77.
32. D.M. Chackraburty and N.C. Jayadevan, "Crystal Chemistry of Higher Carbides of Plutonium" *Acta Cryst.* 18, 811 (1965).
33. E.K. Storms, *The Refractory Carbides*, Academic Press, New York and London (1967).
34. E.J. Huber, Jr., and C.E. Holley, Jr., "The Thermodynamic Properties of the Actinide Carbides Including New Measurements of the Heats of Formation of Some Thorium, Uranium, and Plutonium Carbides," *Thermodynamics of Nuclear Materials*, IAEA, Vienna (1962) p. 581.
35. O.I. Kruger and H. Savage, "Heat Capacity of Plutonium Monocarbide from 400° to 1300°K," *J. Chem. Phys.* 40, 3324 (1964).

36. W.M. Olson and R.N.R. Mulford, "Thermodynamics of the Plutonium Carbides," Thermodynamics of Nuclear Materials with Emphasis on Solution Systems, IAEA, Vienna (1967) p. 467.
37. P.S. Harris, B.A. Phillips, M.H. Rand, and M. Tetenbaum, "The Volatility of Plutonium Carbides, Part I," AERE-R-5353 (1967).
38. R.A. Kent, "Mass Spectrometric Studies of Plutonium Compounds at High Temperatures: The Plutonium Carbon System," International Conference on Mass Spectroscopy, Kyoto, Japan (1969).
39. M. Palfreyman and P.E. Potter, "The Volatility of Plutonium Carbide," Carbides in Nuclear Energy, Vol. 1, Ed. by L.E. Russell, et al., Macmillan and Co. Ltd., London (1964) p. 336.
40. G.M. Campbell, L.J. Mullins, and J.A. Leary, "Thermodynamic Properties of Plutonium Compounds by Electromotive Force Techniques," Thermodynamics of Nuclear Materials with Emphasis on Solution Systems, IAEA, Vienna (1967) p. 88.
41. P.G. Pallmer, "Thermal Expansion of Plutonium Carbides," HW-72245 (1962).
42. M.H. Rand and R.S. Street, "Anomalous Thermal Expansions in the Plutonium Monocarbide Region," Carbides in Nuclear Energy, Vol. 1, Ed. by L.E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 108.
43. M.H. Rand and R.S. Street, "High Temperature X-ray Diffraction Studies, Part 3, Plutonium Nitride and Plutonium Sesquicarbide," AERE-M-973 (1962).
44. J.A. Leary, R.L. Thomas, A.E. Ogard, and G.C. Wonn, "Thermal Conductivity and Electrical Resistivity of UC, (U, Pu)C, and PuC," Carbides in Nuclear Energy, Vol. 1, Ed. by L.E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 365.
45. J.B. Moser and O.L. Kruger, "Thermal Diffusivity of Actinide Compounds," Thermal Conductivity, Proceedings of Seventh Conference, National Bureau of Standards Special Publication 302 (1968).
46. P. Costa and R. Lallement, "Resistivite et Pouvoir Thermoelectriques des Carbuers de Thorium, d'Uranium et de Plutonium," Phys. Letters 7, 21 (1963).
47. O.L. Kruger and J.B. Moser, "Electrical Properties and Electronic Configuration of the Monocarbide, Monophosphide, and Monosulfide of Plutonium," J. Chem. Phys. 46, 891 (1967).
48. P. Costa, R. Lallement, F. Anselin, and D. Rossignol, "Magnetic Transitions in Uranium and Plutonium Mononitrides, Monocarbides, and Sesquicarbides," Compounds of Interest in Nuclear Reactor Technology, Ed. by J.T. Waber and P. Chioti, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc. (1964) p. 83.
49. D.J. Lam, M.V. Nevitt, J.W. Ross, and A.W. Mitchell, "The Magnetic Susceptibility of the Monocarbides of Uranium and Plutonium," Plutonium 1965, Ed. by A.E. Kay and M.B. Waldron, Chapman and Hall, London (1967) p. 274.
50. R.N.R. Mulford, J.O. Ford, and J.G. Hoffman, "The Volatility of Plutonium Carbide," Thermodynamics of Nuclear Materials, IAEA, Vienna (1962) p. 517.
51. G.E. Moore and K.K. Kelley, "High-Temperature Heat Contents of Uranium, Uranium Dioxide and Uranium Trioxide," J. Am. Chem. Soc. 69, 2105 (1947).
52. A.E. Kay and R.G. Loasby, "The Specific Heat of Plutonium at High Temperatures," Phil. Mag. 9, 37 (1964).
53. "Heat Capacity of PuO₂," MLM-1402, (1967).
54. A.E. Ogard and J.A. Leary, "High Temperature Heat Content and Heat Capacity of Uranium Dioxide and Uranium Dioxide-Plutonium Dioxide Solid Solutions," Thermodynamics of Nuclear Materials with Emphasis on Solution Systems, IAEA, Vienna (1967) p. 651.
55. L.A. Neimark, J.H. Kittel, C.C. Crothers, "Irradiation of Pu-C and (U, Pu)-C," Carbides in Nuclear Energy, Vol. 2, Ed. by L.E. Russell et al., Macmillan and Co. Ltd., London (1964) p. 864.