

Carbon – Plutonium – Uranium

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Introduction

With a view to optimizing alloy composition for the preparation of plutonium-uranium carbide fuel and its operation in liquid-metal fast breeder reactors (LMFBR), information about phase relations in the corresponding ternary system C–Pu–U is of a great importance. But up to now this information has discrepancies and is not complete. It is presented in the literature as a partial reaction scheme [1963Ros1, 1981Udo, 1982Udo], liquidus and solidus temperatures and surfaces [1964Sta, 1965Far, 1967Rea, 1968Pot, 1969Lea, 1970Mar, 1976Ohs, 1982Udo], a series of isothermal sections [1963Ros1, 1963Ros2, 1970Mar, 1972Ker, 1975Hol, 1976Bro, 1981Udo, 1982Udo, 1984Hol] and temperature – composition sections [1981Udo, 1982Ogo, 1982Udo]. Phase content of the alloys and the crystal structures of the intermediate phases were studied by [1961Pas, 1963Nev, 1963Ros1, 1963Ros2, 1964Sta, 1967Rea, 1969Lea, 1976Bro, 2005Kut]. Thermodynamic properties were determined experimentally by [1964Sta, 1976Bro, 1976Ohs, 1977Fis]. The experimental methods used as well as the temperature and composition ranges studied are presented in Table 1. The literature related to the carbon-plutonium-uranium system was reviewed in [1968Pot, 1969Lea, 1970Mar, 1975Hol, 1978Kot, 1981Udo, 1982Udo, 1984Hol]. However, further amendment of character of the phase equilibria is necessary, in particular, the constitution of the liquidus and solidus surfaces, the reaction scheme and isothermal sections at different temperatures in the range of carbon content of more than 50 at. %.

Binary Systems

The C–Pu system is accepted from [Mas2]. Despite the fact that C–U system presented in [Mas2] is redrawn from [1967Sto] there is difference between them. The difference relates to the single-phase region between βUC and βUC_2 . In [Mas2] the δ phase leads to appearance of two phase regions: $1 + \delta$ and $\delta + (\text{C})$ either side of the δ phase. Actually, the phase designated by [Mas2] as δ represents the solid solution between βUC and βUC_2 with gradual change from the NaCl type of structure to the CaF_2 type of structure realized by a gradual change in the fraction of carbon atoms located in the tetrahedral interstices with respect to the octahedral sites. In accordance with [1967Sto], such a designation is consistent with the existence of a miscibility gap at lower temperatures. It was accepted by [2001Che] during thermodynamic modeling of the C–U system. The accepted phase diagram of the binary boundary system Pu–U is reported in the chapter “*Remarks on the Actinide Alloying Behavior*” in the present volume. It is based on the thermodynamic calculation by [1991Lei].

Solid Phases

Crystallographic data about the unary and binary phases are listed in Table 2. No ternary phases with crystal structures different from those inherent in the unary and binary phases were determined. In the forming Pu–U binary system, the existence of a continuous series of solid solutions between isostructural ϵ modification of plutonium and γ modification of uranium takes place (labelled as the μ phase). Also, four continuous series of solid solutions between isostructural binary C–Pu and C–U phases exist (the ν , θ , ρ and ρ' phases).

The (Pu,U)C phase, labelled ν , exists below the melting point of the PuC phase ($\sim 1654^\circ\text{C}$) across the whole range of plutonium and uranium mutual substitution. The experimental evidence of this is presented in [1963Nev, 1963Ros1, 1963Ros2, 1984Hol]. At higher temperatures, liquid-solid and liquid fields are located down to 50 at. % C along the C–Pu binary system. The ν phase is stoichiometric with respect to its carbon content over a composition range from 0 to about 35 at. % Pu. A further increase in the plutonium content induces a deviation from ideal stoichiometry towards greater metal-to-carbon ratios to form the defect ν phase. According to the crystallographic investigation carried out by [1963Ros2], plutonium

expands the unit cell of the monocarbide over the composition range over which it retains its stoichiometric character. In the region of the defect structure, the lattice parameter decreases with increasing plutonium content, the extent of the decrease being dependent upon the carbon content.

The $(\text{Pu,U})_2\text{C}_3$ phase, labelled θ , exists below the melting temperature (1833°C) of the U_2C_3 phase across the whole range of plutonium and uranium mutual substitution. This feature was observed experimentally at 1600°C by [1975Hol] and at 1700 and 1550°C by [1967Rea] with annealed alloys equilibrated with an excess of carbon. The upper and lower limits of the lattice parameter along UC_2 – PuC_2 are reported in Table 2. The θ phase seems to disappear at about 850°C from the C–U binary system.

According to experimental results of an earlier publication presented by H.Holleck in [1984Hol], the $(\text{Pu,U})\text{C}_2$ phase, labelled ρ , is a continuous series of solid solutions between the isostructural βPuC_2 and βUC_2 phases, and exists in the system over the temperature range from ~ 1797 to 2227°C . The KCN type of structure was attributed to the ρ phase, but from crystal structure data accepted in this assessment (Table 2), this is not possible because the βPuC_2 phase structure type is not clear. The ρ phase was also reported by [1978Kot] whereas this phase was questioned in the assessment of published experimental data given by [1981Udo]. This problem has not been resolved.

Complete solid solubility between the tetragonal αPuC_2 and the αUC_2 structures was observed by [1967Rea] and [1969Lea] from plutonium-uranium dicarbide samples equilibrated with excess carbon at high temperature and quenched. But all attempts to prepare the cubic PuC_2 – UC_2 solid solutions were unsuccessful. In view of the fact that the equilibrium structure of βPuC_2 is known to be cubic, the tetragonal $(\text{Pu,U})\text{C}_2$ phase (labelled as ρ' in Table 2) may represent a metastable phase at higher plutonium concentrations [1969Lea].

According to the results of experimental investigations available in the literature, solubilities of the third component in the Pu_3C_2 , η and $(\epsilon\text{Pu},\gamma\text{U})$ phases as well as in solid solutions based on the components were not reported.

Invariant Equilibria

The partial reaction scheme is presented in Fig. 1. It was compiled on the basis of [1963Ros1, 1981Udo, 1982Udo] with some amendments to maintain compatibility with the forming binary systems. The data of [1963Ros1] concerned phase equilibria at temperatures below 750°C while [1981Udo] and [1982Udo] deal with equilibria at higher temperatures, including the participation of the liquid phase. In order to agree with temperatures of invariant processes in the ternary and boundary binary systems, some invariant four-phase equilibria were changed: U_1 at 2250°C , P_1 at 2135°C , D_1 at $1767 \pm 10^\circ\text{C}$ and P_2 at 1750°C instead of a P, U, P and U types proposed by [1982Udo], respectively. Also, the ternary reaction at 594°C proposed by [1963Ros1] has been considered as peritectoid P_3 . According to the data of [1982Udo], the co-ordinates of the U_1 and P_1 points are as follows (in at.%): $66.67\text{C}-27.88\text{Pu}-5.45\text{U}$ and $60\text{C}-17.68\text{Pu}-22.32\text{U}$, respectively. The ternary reaction $\text{L} + \beta\text{UC} + \beta\text{UC}_2 \rightleftharpoons \text{Pu}_2\text{C}_3$ suggested by [1982Udo] at 2440°C which involves the βUC and the βUC_2 phases, cannot lead to a ternary reaction since βUC and βUC_2 form a continuous solid solution v on the binary edge. Consequently, this reaction was not taken into account in the reaction scheme. The corresponding invariant equilibria have been reported in Table 3.

Liquidus, Solidus and Solvus Surfaces

[1964Sta] have determined the values of liquidus and solidus temperatures of a $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}_{0.95}$ alloy as $2480 \pm 20^\circ\text{C}$ and about 2430°C , respectively, while the liquidus temperature of the $\text{Pu}_{0.05}\text{U}_{0.95}\text{C}_{0.98}$ alloy was reported to be about 2500°C . [1965Far] have corrected the last value to $2535 \pm 20^\circ\text{C}$ and reported the solidus temperature as $2520 \pm 25^\circ\text{C}$. [1967Rea] presented the melting points of alloy specimens in the range of compositions from 60 to about 100 at.% C. In the review of [1969Lea], the results of the experimental determination of liquidus and solidus temperatures of the alloys along the section $\text{Pu}:\text{U} = 1:1$ containing from 50 to 60 at.% C. [1976Ohs, 1982Udo] have presented the values of liquidus and solidus temperatures of alloys with 50 at.% C. On the basis of the above data, [1982Udo] assessed the constitution of the C–Pu–U system liquidus surface projection. They also compared their results with a schematic liquidus surface projection plotted by [1970Mar, 1982Udo] and noted that their own data possess a quantitative character.

The liquidus surface projection based on [1982Udo] with corrections according to the constitution of the binary systems accepted in this assessment, is shown in Fig. 2. [1982Udo] reported the existence of a monovariant curve which separates the UC and the βUC_2 phases. Since in the binary C–U these two phases form a continuous solid solution v , the corresponding monovariant curve on the liquidus surface has not been retained and the monovariant reaction $L + \text{UC} + \beta\text{UC}_2 \rightleftharpoons \text{U}_2\text{C}_3$ at 2240 °C has been deleted. The e_5e_8 monovariant curve (dashed line) joins the corresponding points in the C–Pu and C–U systems.

Isothermal Sections

Isothermal sections constructed by different authors on the basis of experimental investigations, with some corrections according to the accepted binary systems, are shown in Figs. 3 to 6. They correspond to the temperatures of 1600, 635, 570 and 400°C, respectively (the last three are in the range of compositions 0–50 at.% C).

The isothermal section at 1600°C (Fig. 3) is based on the calculation of [1975Hol], reported in the review of [1984Hol]. The upper limit of carbon content for the liquid phase field is shifted significantly in the direction of carbon corner. The position of the homogeneity range for the PuC phase is corrected. Two solid solutions, θ and v , take part in the phase equilibria. The carbon rich corner is still questionable and has been indicated with a question mark in Fig. 3. The αPuC_2 was not observed and a two-phase equilibrium $\text{Pu}_2\text{C}_3 + (\text{C})$ has been proposed [1975Hol, 1984Hol, 1982Udo]. [1969Lea] stipulates that αPuC_2 is metastable. More experimental investigations are needed.

The isothermal section at 635°C is presented in Fig. 4 according to the data of [1963Ros1] in the range of carbon contents up to 50 at.% C. The $L + \mu + v$ three-phase regions seem to be narrow by the mutual solubility of plutonium and uranium according to the two-phase $L + \mu$ regions in the Pu–U binary system. Consequently, the solubility of the liquid phase inside the ternary system along the Pu–U edge has been reduced compared with that suggested by [1963Ros1]. The unknown limits of the phase regions are indicated with dashed lines on the drawing (Fig. 4).

The isothermal section at 570°C shown in Fig. 5 is reproduced on the basis of experimental work carried out by [1963Ros1] and [1963Ros2] over the composition range of up to 50 at.% C. The phase equilibria involving the Pu_3C_2 phase were added according to its existence at this temperature along the C–Pu binary system. The $\mu + \eta + v$ region has been considered in this assessment to be narrower than in [1963Ros1] according to the accepted Pu–U binary system (phase equilibria as dashed lines in Fig. 5).

The isothermal section at 400°C is presented in Fig. 6 according to the data of [1963Ros1] in the region up to 50 at.% C. Some discrepancies in the borders of the phase fields are observed as compared with the edges of the accepted Pu–U binary diagram. The new regions are indicated as dashed lines in the Fig. 6.

Isothermal sections were also investigated between 2300 and 2000°C by [1970Mar] as indicated by [1982Udo]. On the basis of the available literature data on phase equilibria in the ternary system and their own C–Pu and C–U binary phase diagrams, [1981Udo] and [1982Udo] have calculated the isothermal sections over the wide temperature range (1200 to 2435°C). They determined the positions of the phase boundaries for the phase equilibria $v / (v + \theta)$, $v / (v + \theta + \rho)$ and $v / (v + \rho)$ with specimens having the ratio Pu:U = 1.4. The isothermal section at 2000°C was calculated by [1984Hol] who proposed the existence of a solid solution ρ between βPuC_2 and βUC_2 . This result is in disagreement with the work done by [1982Udo] who suggested two separate phases βPuC_2 and βUC_2 involving two- and three-phase equilibria with carbon. Moreover, a deeper region for the Pu_2C_3 phase has been proposed in [1982Udo]. All the calculated isothermal sections available in the literature up to 2000°C need further experimental investigation.

Temperature – Composition Sections

The temperature – composition section PuC–UC was constructed by [1981Udo] using the experimental data about liquidus and solidus temperatures presented in [1964Sta], [1976Ohs] and in review [1978Kot], as well as data about the $v / (v + \gamma)$ boundary [1975Hol]. This section is shown in Fig. 7. Slight modifications were done according to the binaries and the liquidus surface accepted in this assessment. The liquidus and solidus

curves were also calculated in this section using thermodynamic assumption [1982Ogo]. This later work is in contradiction with [1981Udo] and was not retained in this assessment.

Other isopleths were also assessed by [1981Udo] and [1982Udo]: Pu_2C_3 - U_2C_3 , PuC_2 - UC_2 and $\text{Pu}_{0.5}\text{U}_{0.5}\text{C}$ - $\text{Pu}_{0.5}\text{U}_{0.5}\text{C}_{1.5}$. The isopleth U_2C_3 - Pu_2C_3 was not retained since the βUC_2 and UC phases form a series of solid solution leading to the non existence of the ternary reaction at 2240 °C. The two others isopleths are reproduced on Figs. 8 and 9 with corrections according to the binaries. In the UC_2 - PuC_2 section, the ternary reaction at 1750 °C has been modified due to the higher transition temperature between the βUC_2 and αUC_2 phases. Moreover, the phase equilibria occurring at temperatures lower than 1700°C have not been retained in this assessment owing to the absence of the αPuC_2 phase which exists in the binary edge.

Thermodynamics

Values of thermodynamic properties for the ν single-phase alloy $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$ were determined by [1975Tet] and [1977Fis]. The enthalpy was estimated over the range 25 to 2275°C by [1977Fis] using the enthalpy values reported by [1975Tet, 1977Fis] down to 627°C, and in the range 866 to 2148°C. The heat capacity values were deduced using thermodynamic calculations and are quite good in comparison to those reported by [1975Tet]. The values of S°_T and $-(G^\circ_T - H^\circ_{298})/T$ for the ν phase were calculated by [1977Fis] from 25 to 2275°C. All of these data are listed in Table 4. [1972Ker] determined the relationship between free energy of some alloys with compositions between 50 and 60 at.% C.

[1964Sta] estimated the vapor pressure of Pu and U over $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}_{0.95}$. Later, [1976Bro] measured the partial pressure of various species over $(\text{Pu},\text{U})\text{C} + (\text{Pu},\text{U})_2\text{C}_3$, $(\text{Pu},\text{U})\text{C}_2 + (\text{C})$, $(\text{Pu},\text{U})_2\text{C}_3 + (\text{C})$ specimens at 1600°C. All of the major experimental data of vapor pressure are reported in Table 5. The evaporation behavior of uranium-plutonium carbides has been studied in the high temperature phase fields $(\text{Pu},\text{U})\text{C}$, $(\text{Pu},\text{U})\text{C} + (\text{Pu},\text{U})_2\text{C}_3$, $(\text{Pu},\text{U})\text{C} + (\text{Pu},\text{U})\text{C}_2$ over the range of composition $(\text{Pu}_{0.2}\text{U}_{0.8})\text{C}_x$ with $1.014 \leq x \leq 1.30$ and temperature 1730-2230°C [1976Ohs]. A pressure-composition diagram has been deduced from the experimental data and is reported in Fig. 10. The $\log_{10}(p)$ values over $1/T$ are given in Table 5 for the single phase $(\text{Pu},\text{U})\text{C}$ and the two-phase region $(\text{Pu},\text{U})\text{C} + (\text{Pu},\text{U})_2\text{C}_3$. An increase in the heat of sublimation was observed for the different phase fields. For the $(\text{Pu},\text{U})\text{C}$ phase, this value varies from 361.57 kJ·mol⁻¹ to 432.2 kJ·mol⁻¹ for compounds $(\text{Pu}_{0.2}\text{U}_{0.8})\text{C}_x$ with $1.014 \leq x \leq 1.15$. In the two-phase region $(\text{Pu},\text{U})\text{C} + (\text{Pu},\text{U})_2\text{C}_3$, an increase from 382.5 to 455.2 kJ·mol⁻¹ for compounds $(\text{Pu}_{0.2}\text{U}_{0.8})\text{C}_x$ with $1.15 \leq x \leq 1.30$.

Notes on Materials Properties and Applications

Among the fuel materials that have been considered for LMFBR designs, plutonium-uranium carbide, in general, has material properties more conducive to achieving high performance than either the mixed-oxide or metal fuel [1975Bie, 1968Far]. The high density of the heavy metal and low density of the light atom of the carbide allow high breeding ratios. The high thermal conductivity in combination with a sufficiently high allowable fuel temperature permits high linear power. The adoption of the concept of the sodium-bonded fuel rod, in particular, will alleviate the problems of achieving high burnup. By providing sufficient room for the accommodation of fuel swelling, the cladding need not be required to restrain the swelling fuel as in the case with gas-bonded fuel rod designs [1969Sto]. It was found that the swelling rate strongly depends on the temperature for mixed carbides [1982Zim]. At high temperature, it decreases with increasing burnup due to a saturation of the fission gas bubble porosity. The swelling rate of carbide fuel under cladding restraint corresponds with the free swelling at relative low temperature. The irradiation-induced creep rate of carbide fuel seems to be considerably dependent on its porosity [1984Die]. The general information concerning investigations of the properties of C-Pu-U materials is listed in Table 6. [1961Pas] found that the electrical resistivity of a $(\text{Pu},\text{U})\text{C}$ solid solution which is of interest for a fast reactor is $1.5 \cdot 10^{-6} \Omega \text{ m}$. Coefficients of expansion of $\text{Pu}_{0.05}\text{U}_{0.95}\text{C}_{0.98}$ and $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}_{0.95}$, according to the data of [1964Sta], in the temperature range 25-1400°C are equal to $12.6 \cdot 10^{-6} \text{ }^\circ\text{C}^{-1}$ and $11.9 \cdot 10^{-6} \text{ }^\circ\text{C}^{-1}$,

respectively. Creep rates in the (Pu,U)C specimens tested by [1971Tok,1973Tok] were higher than those reported for UC tested under similar conditions.

Thermal diffusivity and thermal conductivity dependences of the $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$ solid solution in the temperature range from 407 to 1327°C obtained by [1989Ara] are presented in Figs. 11 and 12, respectively. The second one is normalized to 100% theoretical density. Both these dependencies gradually increase with the increasing temperature. Electrical resistivity of the $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$ solid solution depending on the temperature in the range from room temperature up to 727°C, normalized to 100% theoretical density, according to the data of [1989Ara], is shown in Fig. 13. A linear increase with the increasing temperature is observed.

Miscellaneous

In the reviews of [1966Bar1] and [1966Bar2], the results of the development of the technique of plutonium-uranium carbide synthesis are presented. The sintering behavior of $\text{Pu}_{0.55}\text{U}_{0.45}\text{C}$ pellets has been studied up to 1700°C using a dilatometer in an Ar-8% H_2 atmosphere. The mechanism for the initial stage of sintering was determined using a rate controlled sintering technique and it was found to be volume diffusion [2005Kut].

[1972Ker] investigated the phase relations at 1700°C and 1500°C on the two-phase $v + \theta$ samples with Pu : (U + Pu) ratios of 0.2 and 0.5 and proportion of the θ phase varied from 10 to 70%. The distribution coefficients k_U and k_{Pu} were measured where k represents the ratio (amount of U or Pu in v phase) / (amount of U or Pu in θ phase). 14 samples were analyzed and the values of k were found to be independent of temperature and the proportion of the two phases. [1976Bro] calculated the positions of the tie-lines in the $v + \theta$ two-phase region at 1500°C and 1950°C using ideal solution behavior. It was concluded that plutonium was concentrated in the θ phase. At the same time, [1976Ohs, 1982Udo] have determined the positions of the $v / (v + \theta)$, $v / (v + \theta + \rho)$ and $v / (v + \rho)$ phase boundaries in the temperature range from 1730 to 2230°C with specimens with a ratio of Pu:U = 1:4.

References

- [1961Pas] Pascard, R., “Preliminary Studies of the Plutonium-Carbon System and Solid Solutions Uranium Carbide - Plutonium Carbide” (in French), *Powder Metallurgy in Nuclear Technique, 4th Plansee Seminar “De Re Metallica”*, Juni 1961, Reutte, Tirol, Benesovsky, F., (Ed.), Metallwerk Plansee AG., Reutte, Tirol, **18**, 387-419 (1961) (Crys. Structure, Morphology, Phase Diagram, Phase Relations, Electr. Prop., 4)
- [1963Nev] Nevitt, M.V., Rosen, S., “The Monocarbides of Thorium, Uranium, Neptunium and Plutonium, and their Solid Solutions”, *Acta Crystallogr.*, **16**, A18 (1963) (Crys. Structure, Experimental)
- [1963Ros1] Rosen, S., Nevitt, M.V., Barker, J.J., “The U-Pu-C Ternary Phase Diagram Below 50 Atomic Percent Carbon”, *J. Nucl. Mater.*, **9**(2), 128-136 (1963) (Crys. Structure, Morphology, Phase Diagram, Phase Relations, Experimental, *, 7)
- [1963Ros2] Rosen, S., Nevitt, M.V., Mitchell, A.W., “The Uranium Monocarbide-Plutonium Monocarbide System”, *J. Nucl. Mater.*, **9**(2), 137-142 (1963) (Crys. Structure, Morphology, Phase Diagram, Phase Relations, Experimental, *, 6)
- [1964Sta] Stahl, D., Strasser, A., “Properties of Solid Solution Uranium-Plutonium Carbides” in *Carbides in Nuclear Energy*, Proc. Symp. Harwell, Nov. 1963, Vol. 1: Phys. Chem. Prop., Phase Diagrams, Russell, L.E., Bradbury, B.T., Harrison, J.D.L., Hedger, H.J., Mardon P.G., (Eds.), London, **1**, 373-391 (1964) (Crys. Structure, Morphology, Thermodyn., Experimental, Phys. Prop., 6)
- [1965Far] Farkas, M.S., Pardue, W.M., Martin, R.L., Stoltz, D.L., Kizer, D.E., Veigel, N.D., Townley, C.W., Pfeifer, W.H., Barnes, R.H., Wright, T.R., Chubb, W., Speidel, E.O., Berry, W.E., Lemmon, A.W., Rough, F.A., “Fuel and Fertile Materials - Uranium Metal and Alloys - Plutonium - Thorium - Metal-Ceramic Fuels - Coated-Particle Fuel Materials - Uranium Oxides - Carbide and Nitride Fuels - Mechanism of Corrosion of Fuel Alloys -

- Fuel-Water Reactions - Basic Studies”, *Reactor Mater.*, **8**(1), 1-17 (1965) (Crys. Structure, Phase Diagram, Phase Relations, Assessment, Review, Electr. Prop., 88)
- [1966Bar1] Barghusen, J.J., Nelson, P.A., “Production of Uranium, Thorium, and Plutonium and Their Compounds - Recovery of Uranium from Ores by Hydro-metallurgical Techniques - Production of Uranium Oxides - Production of Uranium Metal - Preparation and Properties of Plutonium Dioxide - Production”, *Reactor Fuel Proc.*, **9**(1), 51-64 (1966) (Phase Diagram, Phase Relations, Assessment, Phys. Prop., 69)
- [1966Bar2] Barghusen, J.J., Nelson, P.A., “Production of Uranium, Thorium, and Plutonium and Their Compounds - Production and Properties of Uranium Dioxide - Production of Plutonium Compounds - Production and Properties of Uranium and Plutonium Carbides - Production and Properties of Uranium and Plutonium”, *Reactor Fuel Proc.*, **9**(3), 177-183 (1966) (Crys. Structure, Phase Diagram, Phase Relations, Thermodyn., Assessment, 37)
- [1967Rea] Reavis, J.G., Shupe, M.W., Bjorklund, C.W., Leary, J.A., “Phase Relations in the High-Carbon Portion of the U-Pu-C System”, *Trans. Amer. Nucl. Soc.*, **10**, 111-112 (1967) (Crys. Structure, Phase Relations, Experimental, 5)
- [1967Sto] Storms, E.K., *The Refractory Carbides*, Academic Press, New York, 187 (1967) (Crys. Structure, Phase Diagram, Phase Relations, Review, #)
- [1968Far] Farkas, M.S., Daniel, N.E., Askey, D.F., Martin, R.L., Lozier, D.E., Smith, R.A., Veigel, N.D., Barnes, R.H., Wright, T.R., Chubb, W., Markworth, A.J., “Fuel and Fertile Materials - Uranium Metal and Alloys - Plutonium - Thorium - Metal-Ceramic Fuels - Coated-Particle Fuels - Uranium and Thorium Oxides - Carbide and Nitride Fuels - Basic Studies of Irradiation Effects in Fuel Materials”, *Reactor Mater.*, **11**(3), 145-156 (1968) (Phase Diagram, Phase Relations, Assessment, Transport Phenomena, 66)
- [1968Pot] Potter, P.E., “The Pu-U-C System”, *U.K. At. Energy Authority, AERE-R5922*, 1968 (1968) (Phase Relations, Experimental, Review) as quoted in [1982Udo] and [1984Hol]
- [1969Lea] Leary, J.A., “Present Status of the Uranium-Plutonium-Carbon Phase Diagram”, *Ceramic Nuclear Fuels*, Proc. Int. Symp., May, 1969, Washington, Kruger, O.L., Kaznoff, A.I., (Eds.), Am. Ceram. Soc., 4055 N. High St., Columbus, Ohio, 1969, 38-50 (1969) (Crys. Structure, Morphology, Phase Diagram, Phase Relations, Assessment, Experimental, *, 26)
- [1969Sto] Storrs, C.L., Menzel, G., “Economic Potential of High Performance (U, Pu) Carbide in an LMFBF”, *Trans. Amer. Nucl. Soc.*, **12**(2), 577 (1969) (Phase Relations, Theory, Phys. Prop., Transport Phenomena, 6)
- [1970Mar] Mardon, P.G., Potter, P.E., *U.K. At. Energy Authority, AERE-R6514*, 1970 (1970) (Phase Diagram, Phase Relations, Assessment, Experimental) as quoted in [1982Udo]
- [1971Tok] Tokar, M., Leary, J.A., “Compressive Creep and Hot Hardness of Uranium-Plutonium Carbide, (U,Pu)C”, *Amer. Ceram. Soc. Bul.*, **50**(4), 426 (1971) (Morphology, Abstract, Experimental, Mechan. Prop.)
- [1972Ker] de Keroulas, F., Calais, D., Marcon, J.-P., “Coefficient of Distribution of Uranium and Plutonium in the (UPu)C + (UPu)₂C₃ System” (in French), *J. Nucl. Mater.*, **44**, 64-70 (1972) (Morphology, Phase Relations, Thermodyn., Calculation, Experimental, 6)
- [1973Tok] Tokar, M., “Compressive Creep and Hot Hardness of U-Pu Carbides”, *J. Am. Ceram. Soc.*, **56**(4), 173-177 (1973) (Morphology, Experimental, Mechan. Prop., 22)
- [1975Bie] Bierman, S.R., Howes, B.W., Clayton, E.D., “The Criticality Implications of Pu-U Carbide and Pu-U Nitride Fuel Mixtures”, *Trans. Amer. Nucl. Soc.*, **21**, 237-238 (1975) (Experimental, Phys. Prop., 1)
- [1975Hol] Holleck, H., “Ternary Phase Equilibria in the Systems Actinide-Transition Metal-Carbon and Actinide-Transition Metal Nitrogen” in *Thermodynamics of Nuclear Materials*, Proc. Symp., 4th, Vienna, October 21-25, 1974, International Atomic Energy Agency, Vienna, Austria, **2**, 213-264 (1975) (Crys. Structure, Phase Diagram, Phase Relations, Thermodyn., Calculation, Experimental, Assessment, Review, #, 47)

- [1975Tet] Tetenbaum, M., Sheth, A., Olson, W., “A Review of the Thermodynamics of the U-C, Pu-C and U-Pu-C Systems”, *ANL-AFP-8*, June 1975 (1975) (Thermodyn., Calculation, Review) as quoted in [1977Fis]
- [1976Bro] Browning, P., Phillips, B.A., Potter, P.E., Rand, M.H., “Segregation and Vapour Pressure Studies in the Uranium-Plutonium-Carbon System” in *Plutonium and Other Actinides*, Proc. 5th Int. Conf., 1975, Blank, H., Lindner, R. (Eds.), North-Holland, Amsterdam, 257-265 (1976) (Thermodyn., Calculation, Experimental, 19)
- [1976Ohs] Ohse, R.W., Capone, F., “Evaporation Behaviour of the Ternary U-Pu Carbides” in *Plutonium and Other Actinides*, Proc. 5th Int. Conf., 1975, 245-256 (1976) (Phase Relations, Thermodyn., Experimental, 24)
- [1977Fis] Fischer, D.F., Leibowitz, L., “Enthalpy of U-Pu Carbide from 298 K to the Melting Point”, *J. Nucl. Mater.*, **67**, 244-248 (1977) (Thermodyn., Experimental, 4)
- [1978Kot] Kotel'nikov, R.B., Bashlykov, S.N., Kashtanov, A.I., Men'shikova, T.S., “*High-Temperature Nuclear Fuel*” (in Russian), Atomizdat, Moscow, 1-432 (1978) (Crys. Structure, Phase Diagram, Phase Relations, Thermodyn., Review, Mechan. Prop., Phys. Prop., *, 617)
- [1981Udo] Udovskiy, A.L., Alekseeva, Z.M., “Analysis of Phase Equilibria in the System Uranium-Plutonium-Carbon in the Temperature Interval 1335-1800°C”, in “*Phase Equilibria in Metallic Alloys*” (in Russian), Nauka, Moscow, 230-242 (1981) (Calculation, Phase Diagram, Phase Relations, Review, *, 15)
- [1982Ogo] Ogorodnikov, V.V., Ogorodnikova, A.A., “Calculation of the Phase Diagrams for Pseudo-binary Systems of Cubic Transition Metal Monocarbides”, *Russ. J. Phys. Chem. (Engl. Transl.)*, **56**(11), 1749-1751 (1982), translated from *Zh. Fiz. Khim.*, **56**(11), 2849-2852 (1982) (Phase Diagram, Phase Relations, Calculation, 13)
- [1982Udo] Udovskiy, A.L., Alekseeva, Z.M., “About Phase Equilibria Diagram of the Uranium-Plutonium-Carbon System in the 1200-2430°C Interval” (in Russian), *Dokl. Akad. Nauk SSSR*, **262**(2), 382-386 (1982) (Crys. Structure, Phase Diagram, Phase Relations, Assessment, Calculation, *, 15)
- [1982Zim] Zimmermann, H., “Investigation of Swelling of U-Pu Mixed Carbide”, *J. Nucl. Mater.*, **105**, 56-61 (1982) (Morphology, Experimental, Phys. Prop., 11)
- [1984Die] Dienst, W., “Swelling, Densification and Creep of (U, Pu)C Fuel under Irradiation”, *J. Nucl. Mater.*, **124**, 153-158 (1984) (Morphology, Experimental, Optical Prop., Phys. Prop., 13)
- [1984Hol] Holleck, H., “Ternary Carbide Systems of Actinoids” (in German) in “*Binary and Ternary Transition Metal Carbide and Nitride Systems*”, Petzow, G. (Ed.), Gebrueder Borntraeger Berlin, Stuttgart, 73-78 (1984) (Crys. Structure, Phase Diagram, Phase Relations, Assessment, Experimental, Review, *, 59)
- [1987Ben] Benedict, U., “Structural Data of the Actinide Elements and of their Binary Compounds with Non-Metallic Elements”, *J. Less-Common Met.*, **128**, 7-45 (1987) (Crys. Structure, Review, 118)
- [1989Ara] Arai, Ya., Ohmichi, T., Fukushima, S., Handa, M., “Thermal Conductivity of Near-Stoichiometric (U, Pu, Zr)C Solid Solutions”, *J. Nucl. Mater.*, **168**, 137-143 (1989) (Crys. Structure, Electr. Prop., Phys. Prop., 29)
- [1989Pet] Peterson, D.E., Foltyn, E.M., “The Pu-U System”, *Bull. Alloy Phase Diagrams*, **10**(2), 160-164 (1989) (Crys. Structure, Phase Relations, Phase Diagram, Review, Thermodyn., 23)
- [1991Lei] Leibowitz, L., Blomquist, R.A., Pelton, A.D., “Thermodynamic Modeling of the Phase Equilibria of the Plutonium-Uranium System”, *J. Nucl. Mater.*, **184**, 59-64 (1991) (Calculation, Thermodyn., 10)

- [2001Che] Chevalier, P.Y., Fischer, E., “Thermodynamic Modelling of the C-U and B-U Binary Systems”, *J. Nucl. Mater.*, **288**, 100-129 (2001) (Phase Relations, Thermodyn., Calculation, Assessment, 97)
- [2005Kut] Kutty, T.R.G., Khan, K.B., Kutty, P.S., Basak, C.B., Sengupta, A.K., Mehrotra, R.S., Majumdar, S., Kamath, H.S., “Densification Behaviour and Sintering Kinetics of (U_{0.45}Pu_{0.55})C Pellets”, *J. Nucl. Mater.*, **340**, 113-118 (2005) (Crys. Structure, Experimental, Kinetics, 20)

Table 1: Investigations of the C-Pu-U Phase Relations, Structures and Thermodynamics

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1963Nev]	X-ray diffraction studies, optical metallography	50 at.% C
[1963Ros1]	Metallography, X-ray diffraction Debye-Scherrer studies, melting point beginning measurements, chemical analysis	< 635°C, 0-50 at.% C
[1963Ros2]	Metallography, X-ray diffraction Debye-Scherrer studies, chemical analysis	< 635°C, ~ 50 at.% C
[1964Sta]	Metallography, X-ray diffraction studies, chemical etching, microprobe analysis, Knudsen effusion cell method, melting points determination (black body technique)	Pu _{0.2} U _{0.8} C _{0.95} Pu _{0.05} U _{0.95} C _{0.98}
[1965Far]	Liquidus and solidus temperatures measurements (black body technique)	Pu _{0.05} U _{0.95} C _{0.98}
[1967Rea]	High-temperature DTA, X-ray powder diffraction, metallographic techniques	≤ 2425°C, ≥ 60 at.% C
[1968Pot]	Liquidus and solidus temperatures measurements	2000-2200°C; 50 to 60 at.% C, Pu:U = 1:1
[1969Lea]	X-ray powder diffraction, DTA	50 to 66.67 at.% C
[1970Mar]	Thermal analysis, metallography, X-ray diffraction	Whole range of compositions
[1972Ker]	Microprobe analysis	1500°C, 1700°C, 50 to 60 at.% C
[1976Bro]	Chemical analysis, mechanical polishing, chemical etching, X-ray Debye-Scherrer studies, EMPA, Knudsen effusion mass spectrometry	(Pu,U)C + (Pu,U) ₂ C ₃ phase region
[1976Ohs]	Liquidus and solidus temperatures measurements, vapor pressure measurements	~ 50 at.% C; Pu:U = 1:4
[1977Fis]	Induction-heated drop calorimetry	766-2148°C, Pu _{0.2} U _{0.8} C
[1989Ara]	X-ray diffraction, chemical analysis, density measurements	≤ 1327°C, Pu _{0.2} U _{0.8} C

Table 2: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(C) $\leq 3827 \pm 50$ (S.P.)	<i>hP4</i> <i>P6₃/mmc</i> C (graphite)	$a = 246.12$ $c = 670.9$	at 25°C [Mas2] sublimation point Negligible solubility of U [2001Che]
(δ' Pu) 483 - 463	<i>tI2</i> <i>I4/mmm</i> In	$a = 333.9$ $c = 444.6$	pure, 477°C [1989Pet], dissolves about 1.3 at.% U at 440°C [1991Lei]; exists down to 437°C in the Pu-U binary [1991Lei]
(δ Pu) 463 - 320	<i>cF4</i> <i>Fm$\bar{3}m$</i> Cu	$a = 463.70$	pure, 320°C [1989Pet], dissolves about 1.6 at.% U at 318°C [1991Lei]
(γ Pu) 320 - 215	<i>oF8</i> <i>Fddd</i> γ Pu	$a = 315.87$ $b = 576.82$ $c = 1016.2$	pure, 235°C, [1989Pet], dissolves about 1.6 at.% U at 278°C [1991Lei], negligible solubility of C [Mas2]
(β Pu) 215 - 125	<i>mC34</i> <i>C2/m</i> β Pu	$a = 928.4$ $b = 1046.3$ $c = 785.9$ $\beta = 92.13^\circ$	pure, 190°C [1989Pet], dissolves about 2.7 at.% U at 278°C [1991Lei], negligible solubility of C [Mas2]
(α Pu) < 125	<i>mP16</i> <i>P2₁/m</i> α Pu	$a = 618.3$ $b = 482.2$ $c = 1096.3$ $\beta = 101.79^\circ$	pure, 21°C [1989Pet], negligible solubility of U and C. [1991Lei, Mas2]
(β U) 776 - 668	<i>tP30</i> <i>P4₂/mnm</i> β U	$a = 1075.9$ $c = 565.6$	pure, 720°C, [1989Pet] dissolves about 24 at.% Pu at 702°C [1991Lei], the solubility of C is very small [2001Che]
(α U) (r) < 668	<i>oC4</i> <i>Cmcm</i> α U	$a = 285.37$ $b = 586.95$ $c = 495.48$	pure, at 25°C [1989Pet] dissolves about 24 at.% Pu at 702°C [1991Lei], the solubility of C is very small [2001Che]
μ , (ϵ Pu, γ U)	<i>cI2</i> <i>Im$\bar{3}m$</i> W		continuous solid solution which exists between 1135 and 454°C [1991Lei]
(ϵ Pu) 640 - 483		$a = 363.8$	pure, 500°C [1989Pet] dissolves 100 at.% U [1991Lei]
(γ U) 1135 - 776		$a = 352.4$	pure, 805°C [Mas2] dissolves 100 at.% Pu [1991Lei]
Pu ₃ C ₂ ≤ 575	-	-	40 at.% C [Mas2]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
v, (Pu,U)C	$cF8$ $Fm\bar{3}m$ NaCl	$a = 496.47$	continuous solid solution called v in the $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$ specimen sintered at 1750°C [1989Ara]
PuC $\lesssim 1654$		$a = 497.25$	~ 44 to ~ 48 at.% C [Mas2] sometimes labelled as “ PuC_{1-x} ” (the structure defect by carbon content)
βUC < 2515		$a = 495.97$ $a = 495.63$	[V-C2] stoichiometric [2001Che] 48 at.% C [2001Che] from 47 to 66 at.% C. Miscibility gap (critical point at 2050°C, 43.8 at.% C) [2001Che]
θ , (Pu,U) $_2\text{C}_3$	$cI40$ $I\bar{4}3d$ Pu_2C_3	$a = 808.8$ to 813.3	continuous solid solution called θ ; $(\text{Pu}_{1-x}\text{U}_x)_2\text{C}_3$, $0 \leq x \leq 1$, $T = 1700^\circ\text{C}$, specimen with excess carbon [1967Rea]
Pu_2C_3 $\lesssim 2050$		$a = 812.58 \pm 3$	~ 59 to ~ 60 at.% C [Mas2] [V-C2]
U_2C_3 < 1833		$a = 808.89$	60 at.% C [Mas2] [1969Lea]
ρ , (Pu,U) C_2		$a = 352.0$ to 360.6 $c = 598.5$ to 610.6	continuous solid solution called ρ $T = 2227$ to $\sim 1797^\circ\text{C}$ [1984Hol] $(\text{Pu}_{1-x}\text{U}_x)\text{C}_2$, $0 \leq x \leq 1$, $T = 1700^\circ\text{C}$, specimen with excess carbon [1967Rea]
βPuC_2 $\sim 2350 - 1660$	c^{**}	$a = 569.6$	66.7 at.% C [Mas2]
βUC_2 2435 - 1763	$cF12$ $Fm\bar{3}m$ $\text{CaF}_2?$	$a = 545.0$	[2001Che] actually, “ βUC_2 ” phase represents the UC phase in equilibrium with graphite [2001Che]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
ρ' , (Pu,U)C ₂	<i>tI6</i> <i>I4/mmm</i> CaC ₂	$a = 357.5$ $c = 605$ $a = 355$ $c = 603$	continuous solid solution called ρ' reported as metastable in [1969Lea] Pu _{1-x} U _x C ₂ , $x = 0.4$, quenched from high temperature in the presence of excess carbon [1969Lea] Pu _{1-x} U _x C ₂ , $x = 0.7$, quenched from high temperature in the presence of excess carbon [1969Lea]
α PuC ₂ < 1660		$a = 363$ $c = 609.4$	66.7 at.% C [Mas2] [1987Ben]
α UC ₂ 1780 - 1478		$a = 351.90$ $c = 597.87$ $a = 352.41$ $c = 599.62$	U rich [2001Che] C rich [2001Che]
ζ , PuU ≤ 628	<i>t**</i>	$a = 1069.2$ $a = 1065.1$	~26.4 to ~77 at.% U at 25°C, 35 at.% U [1969Lea] at 25°C, 70 at.% U [1969Lea] $c/a \approx 1$
η , PuU 702 - 278	<i>tP52</i>	$a = 1057$ $c = 1076$	~4 to ~78 at.% U at 25 at.% U [1969Lea]

Table 3: Invariant Equilibria

Reaction	T [°C]	Type	Phase	Composition (at.%)		
				C	Pu	U
$L + (C) \rightleftharpoons \beta UC_2 + \beta PuC_2$	2250	U ₁	L (C) βPuC_2	66.67 ~ 100 ~ 66.67	27.88 ~ 0.00 ~ 33.33	5.45 ~ 0.00 0.00
$L + \beta UC_2 + \beta PuC_2 \rightleftharpoons \theta$	2135	P ₁	L βPuC_2 θ	60.00 ~ 66.67 ~ 60.00	17.68 ~ 33.33 ~ 40.00	22.32 0.00 0.00
$\beta PuC_2 + \beta UC_2 \rightleftharpoons \theta, \alpha UC_2$	1767±10	D ₁	βPuC_2 θ αUC_2	~ 66.67 ~ 60.00 ~ 66.67	~ 33.33 ~ 40.00 0.00	0.00 0.00 ~ 33.33
$\alpha UC_2 \rightleftharpoons \beta UC_2 + \beta PuC_2 + (C)$	1750	E ₁	βPuC_2 (C) αUC_2	~ 66.67 ~ 100 ~ 66.67	~ 33.33 ~ 0.00 0.00	0.00 ~ 0.00 ~ 33.33
$\alpha UC_2 + \beta PuC_2 \rightleftharpoons \theta + (C)$	1725	U ₂	αUC_2 βPuC_2 θ (C)	~ 66.67 ~ 66.67 ~ 60.00 ~ 100	0.00 ~ 33.33 ~ 40.00 ~ 0.00	~ 33.33 0.00 0.00 ~ 0.00

Reaction	T [°C]	Type	Phase	Composition (at.%)		
				C	Pu	U
$(\gamma\text{U}) + (\beta\text{U}) + \mu \rightleftharpoons \eta$	712	P_2	(γU)	~ 0	~ 0	~ 100
			(βU)	~ 0	~ 0	~ 100
$(\beta\text{U}) + \eta \rightleftharpoons \zeta + \mu$	594	D_2	(βU)	~ 0.00	~ 0.00	~ 100
$(\beta\text{U}) \rightleftharpoons (\alpha\text{U}) + \zeta + \mu$	549	E_2	(βU)	~ 0.00	~ 0.00	~ 100
			(αU)	~ 0.00	~ 0.00	~ 100
$\eta + \mu \rightleftharpoons (\beta\text{Pu}) + \zeta$	283	U_3	(βPu)	~ 0.00	~ 100	~ 0.00

Table 4: Thermodynamic Properties of Single Phases

Phase	Temperature Range [°C]	Property, per mole of atoms [J, mol, K]	Comments
$\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$	25 - 1627	$H(T) - H(298) = -20.0288 \cdot 10^3 + 58.0823 \cdot T + 59.7601 \cdot 10^{-5} T^2 + 95.6713 \cdot 10^{-8} T^3 + 78.7303 \cdot 10^4 / T$	[1975Tet], v phase
	766 - 2148	$H(T) - H(298) = -48.3832 \cdot 10^3 + 121.652 \cdot T - 42.9571 \cdot 10^{-3} T^2 + 10.2309 \cdot 10^{-6} T^3$	[1977Fis] drop calorimeter, v phase
	25 - 2275	$H(T) - H(298) = -12.4866 \cdot 10^3 + 32.5225 \cdot T + 37.2021 \cdot 10^{-3} T^2 + 20.8151 \cdot 10^{-6} T^3 + 43.8487 \cdot 10^{-10} T^4$	[1977Fis] deduced by extrapolation, v phase
	25	$C_p^\circ = 49.62$	calculated value from [1975Tet], v phase
	25	$S^\circ = 61.92$	calculated value from [1977Fis], v phase
	25	$-(G_T^\circ - H_{298}^\circ) / T = 61.92$	calculated value from [1977Fis], v phase

Table 5: Vapor Pressure Measurements

Phases	Temperature [°C]	Pressure [bar]	Comments
$\text{Pu}_{0.2}\text{U}_{0.8}\text{C}_{0.95}$	2347	$p_{\text{Pu}} = 2.49 \cdot 10^{-6}$ $p_{\text{U}} = 8.81 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 10 min
	2327	$p_{\text{Pu}} = 3.16 \cdot 10^{-6}$; $3.46 \cdot 10^{-6}$ $p_{\text{U}} = 3.30 \cdot 10^{-4}$; $4.66 \cdot 10^{-4}$	[1964Sta] Knudsen effusion time of the test: 20 min; 10 min
	2237	$p_{\text{Pu}} = 1.35 \cdot 10^{-5}$ $p_{\text{U}} = 1.73 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 45 min
	2227	$p_{\text{Pu}} = 2.98 \cdot 10^{-6}$; $4.12 \cdot 10^{-7}$ $p_{\text{U}} = 3.59 \cdot 10^{-5}$; $6.18 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 25 min
	2217	$p_{\text{Pu}} = 4.13 \cdot 10^{-7}$ $p_{\text{U}} = 3.59 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 25 min
	2127	$p_{\text{Pu}} = 5.32 \cdot 10^{-6}$; $2.35 \cdot 10^{-6}$; $5.53 \cdot 10^{-8}$ $p_{\text{U}} = 2.89 \cdot 10^{-6}$; $5.02 \cdot 10^{-6}$; $4.40 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 60 min; 45 min; 30 min
	2117	$p_{\text{Pu}} = 5.57 \cdot 10^{-8}$ $p_{\text{U}} = 9.07 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 45 min
	2022	$p_{\text{Pu}} = 3.45 \cdot 10^{-4}$ $p_{\text{U}} = 4.94 \cdot 10^{-4}$	[1964Sta] Knudsen effusion time of the test: 60 min
	2012	$p_{\text{Pu}} = 1.66 \cdot 10^{-8}$; $2.08 \cdot 10^{-4}$ $p_{\text{U}} = 4.74 \cdot 10^{-5}$; $4.83 \cdot 10^{-4}$	[1964Sta] Knudsen effusion time of the test: 60 min
	1997	$p_{\text{Pu}} = 4.65 \cdot 10^{-8}$ $p_{\text{U}} = 3.85 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 60 min
	1912	$p_{\text{Pu}} = 3.43 \cdot 10^{-4}$ $p_{\text{U}} = 1.74 \cdot 10^{-4}$	[1964Sta] Knudsen effusion time of the test: 90 min
	1897	$p_{\text{Pu}} = 6.60 \cdot 10^{-4}$ $p_{\text{U}} = 5.83 \cdot 10^{-5}$	[1964Sta] Knudsen effusion time of the test: 90 min
	1797	$p_{\text{Pu}} = 1.22 \cdot 10^{-3}$ $p_{\text{U}} = 2.21 \cdot 10^{-4}$	[1964Sta] Knudsen effusion time of the test: 120 min
	1782	$p_{\text{Pu}} = 1.22 \cdot 10^{-4}$ $p_{\text{U}} = 1.27 \cdot 10^{-4}$	[1964Sta] Knudsen effusion time of the test: 120 min
$\text{Pu}_{0.17}\text{U}_{0.83}\text{C}_{1.5} + (\text{C})$	1589 - 1995	$\log_{10}(p_{\text{Pu}}) = -20.300/T + 3.541$	[1976Bro] Knudsen effusion, all the expressions are given with T in K
$\text{Pu}_{0.335}\text{U}_{0.665}\text{C}_{1.5} + (\text{C})$	1610 - 1984	$\log_{10}(p_{\text{Pu}}) = -20.500/T + 3.841$	[1976Bro] Knudsen effusion, all the expressions are given with T in K
$\text{Pu}_{0.59}\text{U}_{0.41}\text{C}_{1.5} + (\text{C})$	1559 - 1845	$\log_{10}(p_{\text{Pu}}) = -21.429/T + 4.681$	[1976Bro] Knudsen effusion, all the expressions are given with T in K

Phases	Temperature [°C]	Pressure [bar]	Comments
$\text{Pu}_{0.19}\text{U}_{0.81}\text{C}_{1.5} + \text{Pu}_{0.43}\text{U}_{0.57}\text{C}_{1.5}$	1500	$\log_{10}(p_{\text{Pu}}) = -6.58$	[1976Bro] Knudsen effusion
$\text{Pu}_{0.34}\text{U}_{0.66}\text{C} + \text{Pu}_{0.66}\text{U}_{0.34}\text{C}_{1.5}$	1500	$\log_{10}(p_{\text{Pu}}) = -6.12$	[1976Bro] Knudsen effusion
$(\text{Pu}_{0.2}\text{U}_{0.8})\text{C}_{1.014}$ to $(\text{Pu}_{0.2}\text{U}_{0.8})\text{C}_{1.15}$	1730 - 2230	$\log_{10}(p_{\text{Pu}}) = 4.28 - 18700/T$ to $5.66 - 22600/T$	[1976Ohs] Knudsen effusion and mass spectrometry; (Pu,U)C single phase region
$(\text{Pu}_{0.2}\text{U}_{0.8})\text{C}_{1.15}$ to $(\text{Pu}_{0.2}\text{U}_{0.8})\text{C}_{1.30}$	1730 - 2230	$\log_{10}(p_{\text{Pu}}) = 4.32 - 20000/T$ to $5.96 - 23800/T$	[1976Ohs] Knudsen effusion and mass spectrometry; (Pu,U)C + (Pu,U) ₂ C ₃ two-phase field

Table 6: Investigations of the C–Pu–U Materials Properties

Reference	Method/Experimental Technique	Type of Property
[1961Pas]	Electrical resistivity measurements	Electrical resistivity of a solid solution (Pu,U)C
[1964Sta]	Dilatometry	Coefficient of expansion of $\text{Pu}_{0.05}\text{U}_{0.95}\text{C}_{0.98}$ and $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}_{0.95}$
[1971Tok]	Compressive creep and hot hardness studies, ceramographic examination	Compressive creep of $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$ specimens (1300-1500°C); hot hardness of $\text{Pu}_{0.2-1}\text{U}_{0.8-0}\text{C}$ specimens
[1973Tok]	Compressive creep and hot hardness tests, optical pyrometry	$\text{Pu}_{0.21}\text{U}_{0.79}\text{C}_{1.02}$ specimen at 1300, 1400 and 1500°C
[1982Zim]	Immersion density measurements	Swelling of the (Pu,U)C in the temperature range 300-1750°C
[1984Die]	Irradiation tests	Swelling, irradiation-induced denazification Irradiation-induced creep of the (Pu,U)C fuel
[1989Ara]	Laser flash, dc four probes techniques	Thermal diffusivity, electrical resistivity, thermal conductivity

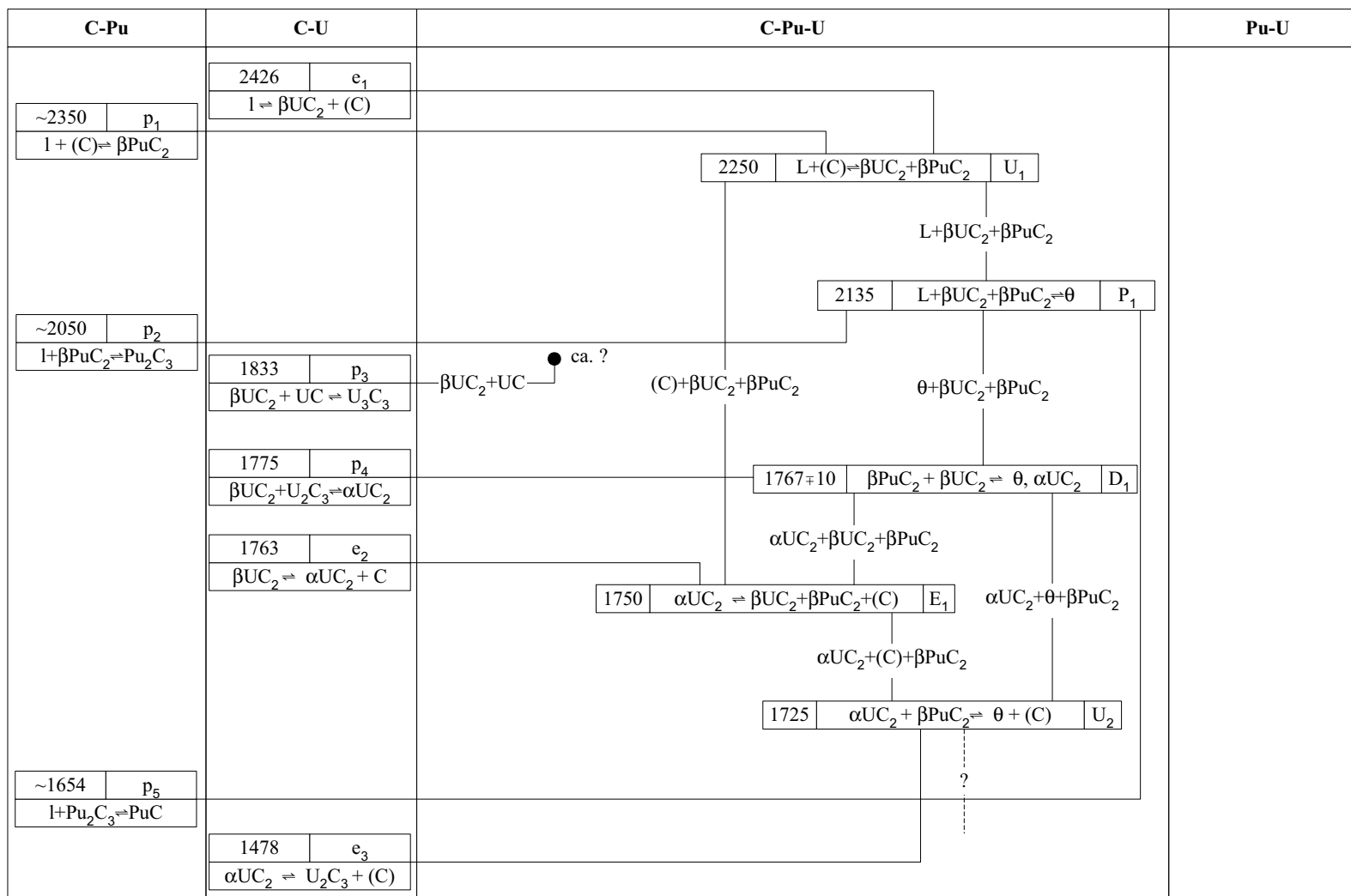


Fig. 1a: C-Pu-U. Partial reaction scheme

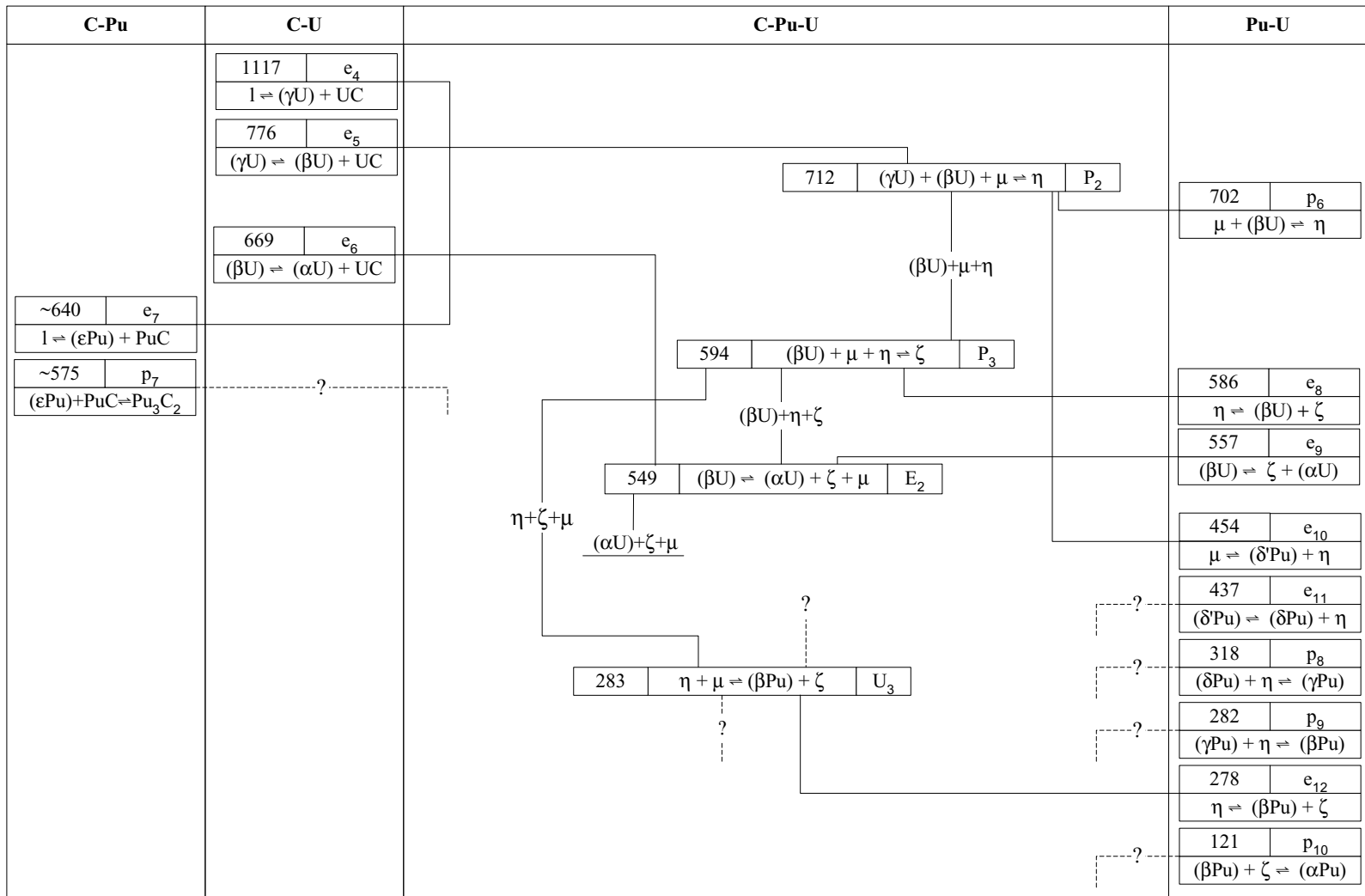


Fig. 1b: C-Pu-U. Partial reaction scheme

Fig. 2: C-Pu-U.
Liquidus surface
projection

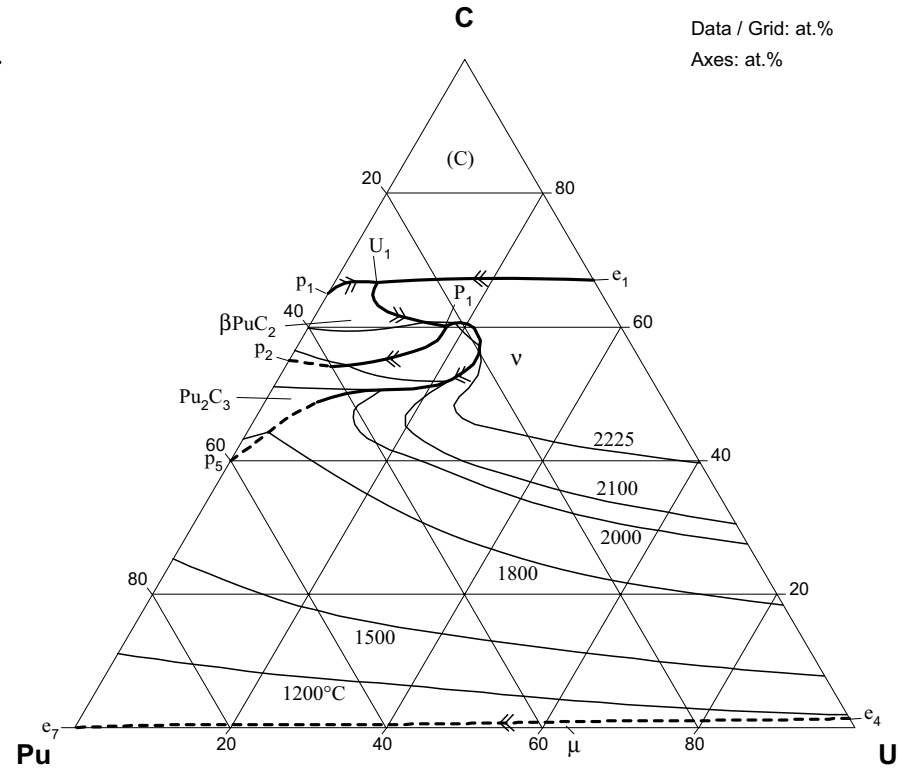


Fig. 3: C-Pu-U.
Isothermal section at
1600°C

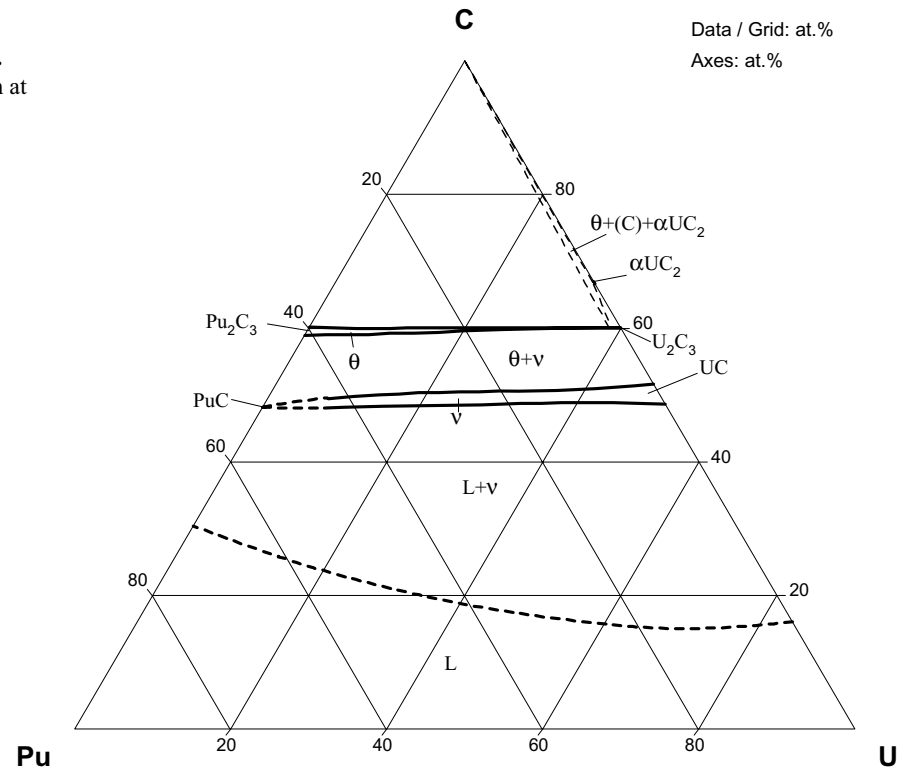


Fig. 4: C-Pu-U.
Partial isothermal
section at 635°C

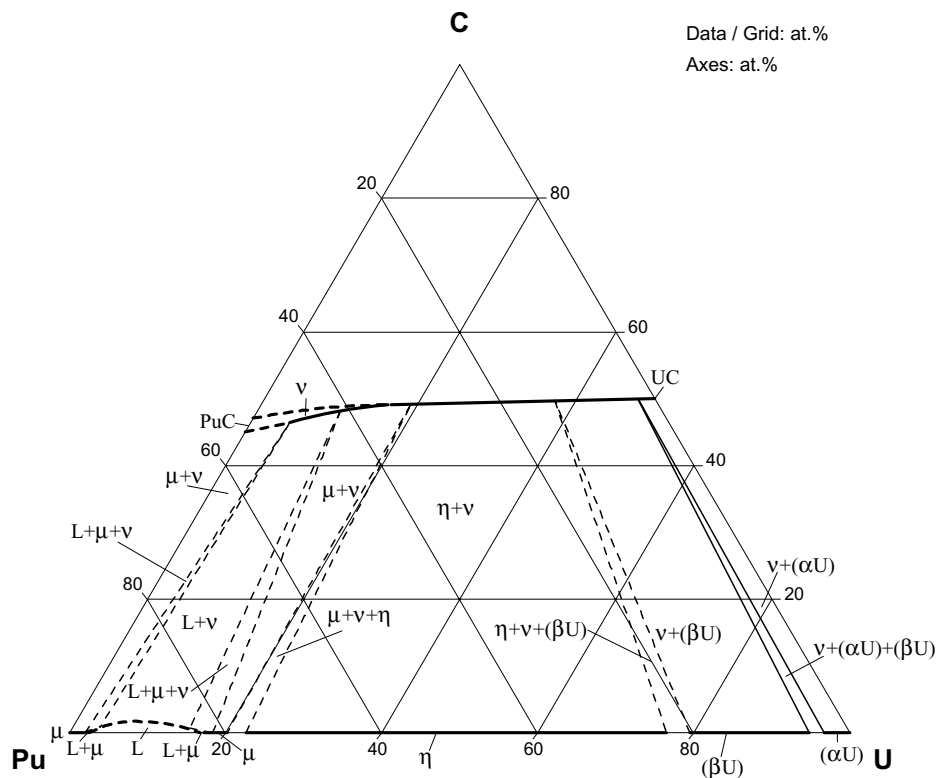


Fig. 5: C-Pu-U.
Partial isothermal
section at 570°C

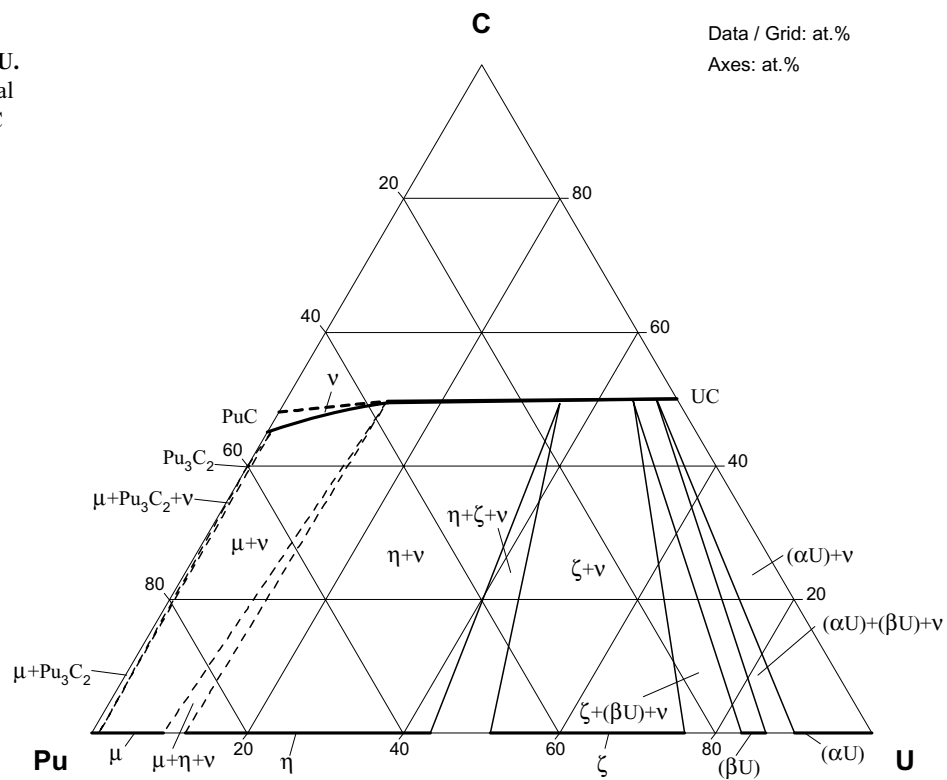


Fig. 6: C-Pu-U.
Partial isothermal
section at 400°C

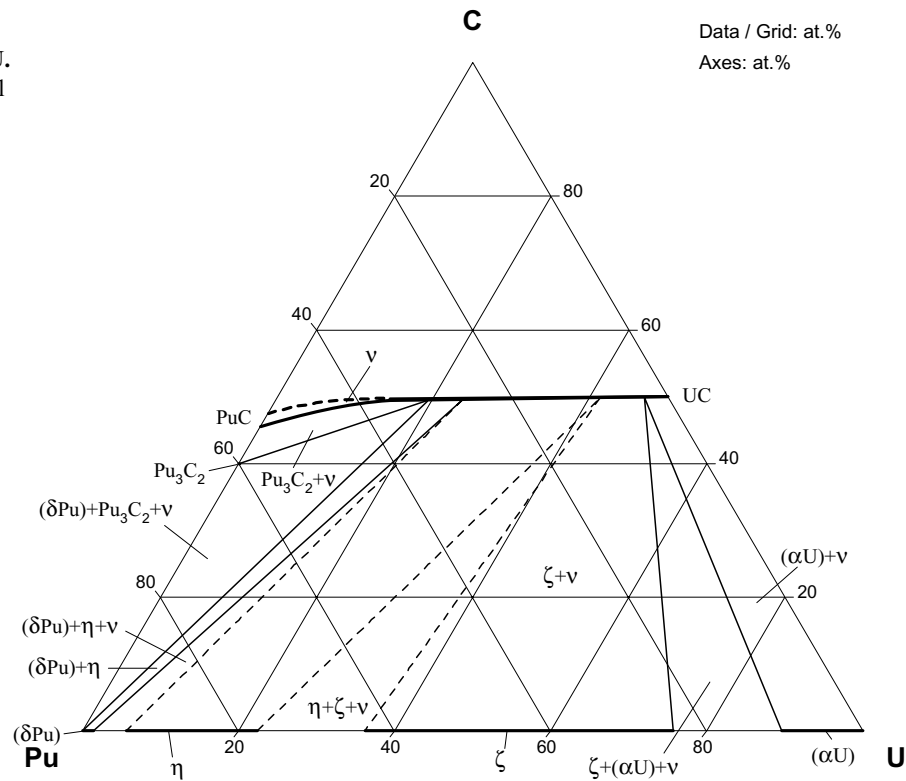


Fig. 7: C-Pu-U.
Temperature -
composition section
PuC-UC

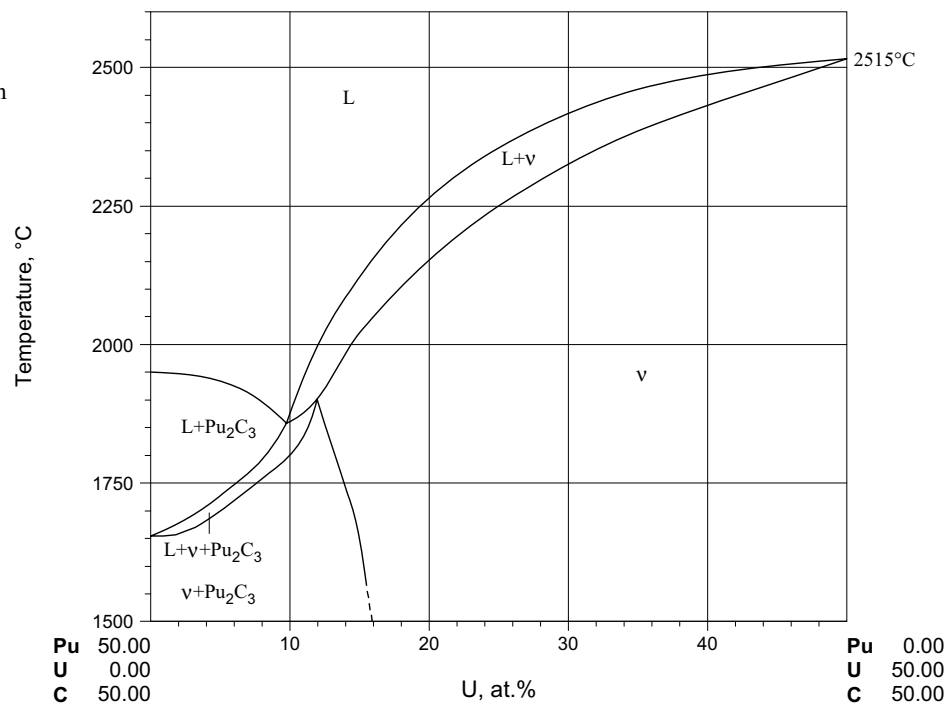


Fig. 8: C-Pu-U.
Temperature -
composition section
 $\text{PuC}_2\text{-UC}_2$

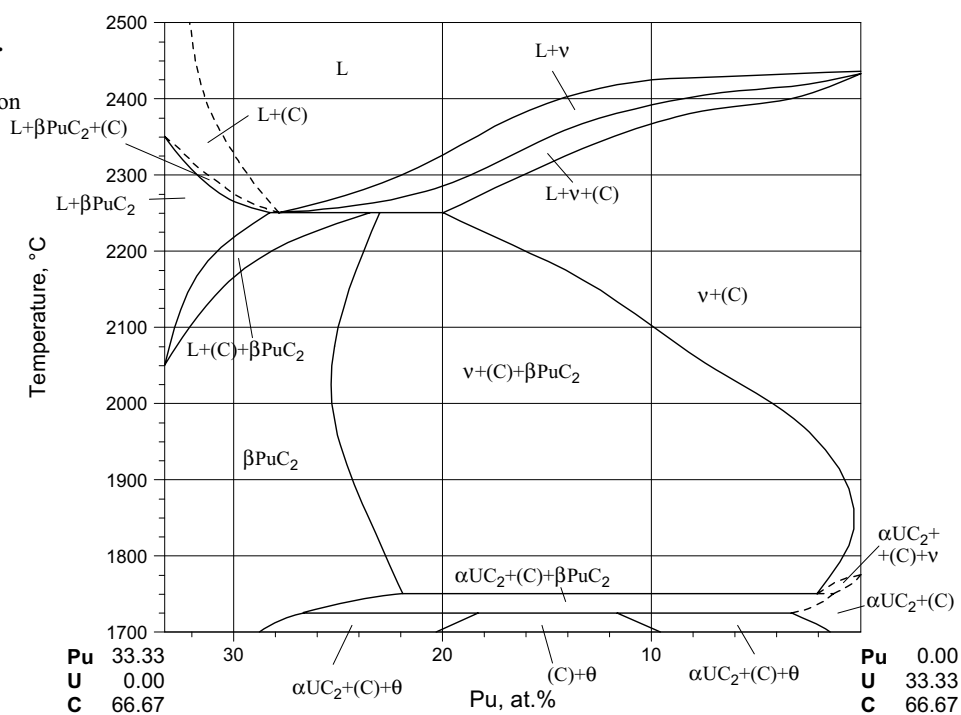


Fig. 9: C-Pu-U.
Temperature -
composition section
 $(\text{Pu,U})\text{C-(Pu,U)}_2\text{C}_3$

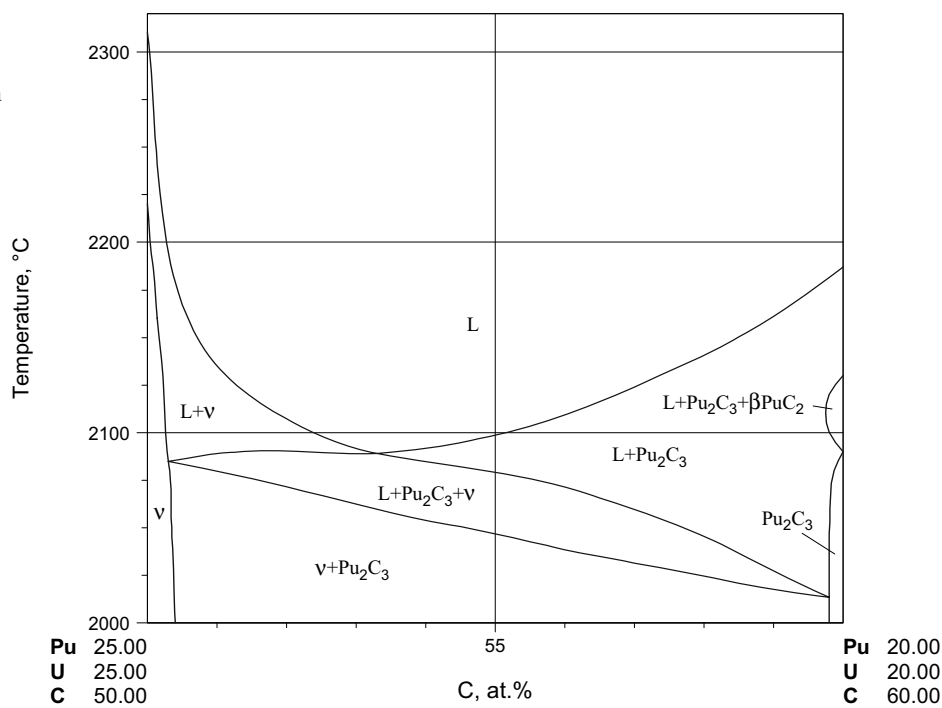


Fig. 10: C–Pu–U.
Pressure-composition
diagram showing the
boundary between the
(Pu,U)C and the
(Pu,U)C + (Pu,U)₂C₃
phase fields

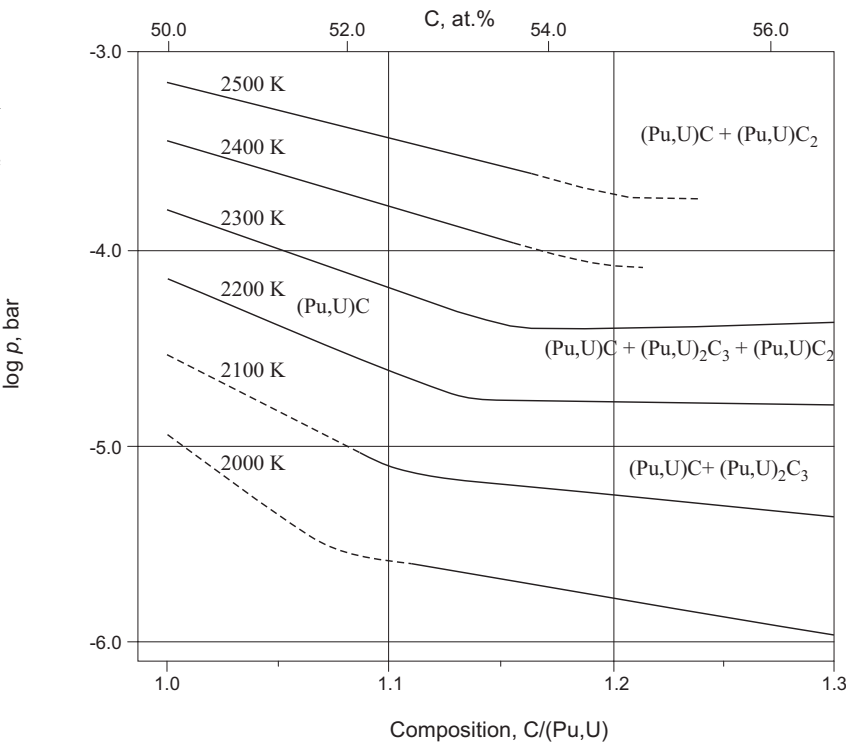


Fig. 11: C–Pu–U.
Thermal diffusivity of
the Pu_{0.2}U_{0.8}C solid
solution

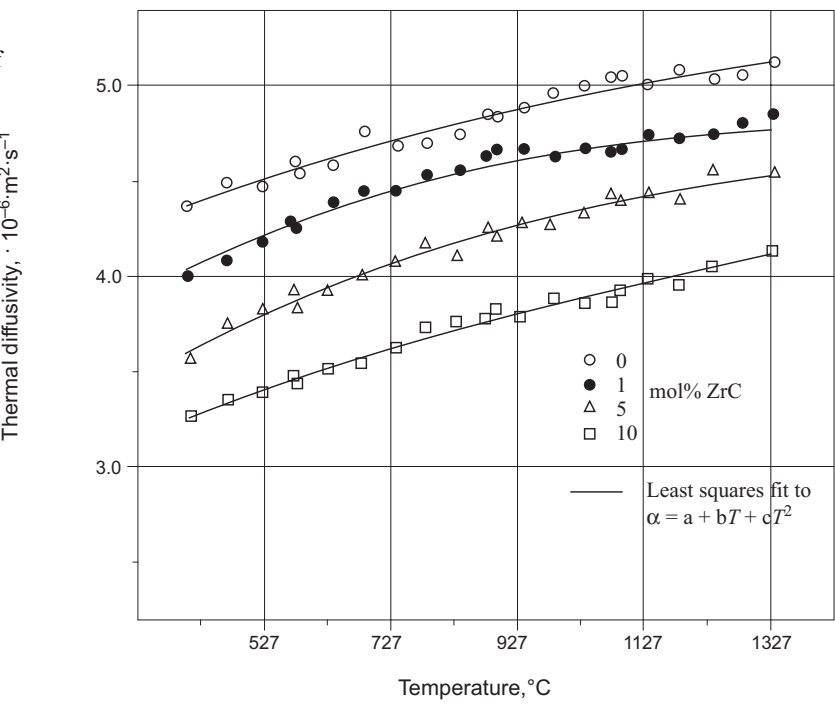


Fig. 12: C-Pu-U.
Thermal conductivity
of the $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$
solid solution
normalized to 100%
theoretical density

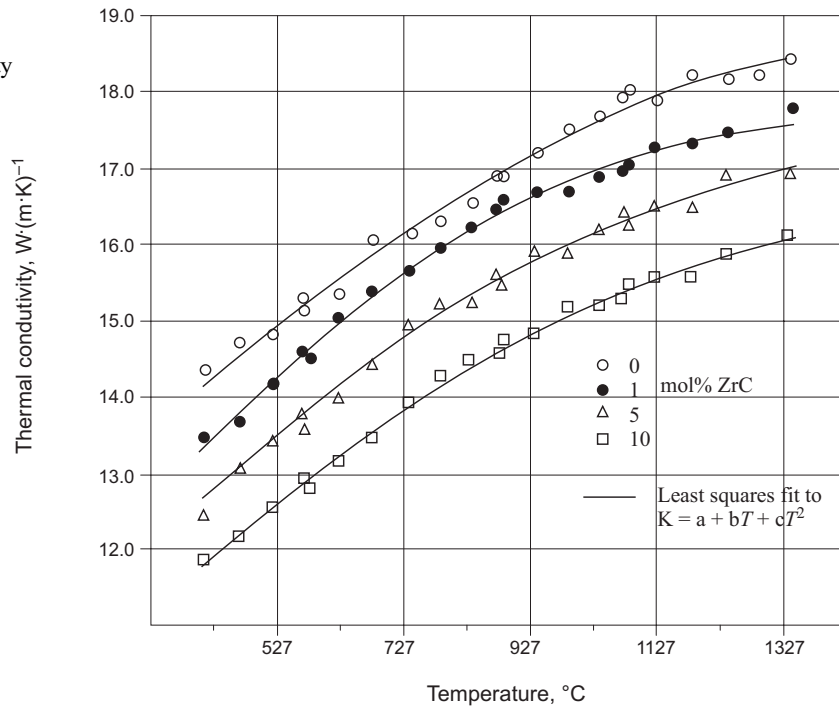


Fig. 13: C-Pu-U.
Electrical resistivity
of the $\text{Pu}_{0.2}\text{U}_{0.8}\text{C}$
solid solution
normalized to 100%
theoretical density

