Phase	Unit Cell Type	Unit Cell Dimensions, A	Number of Molecules	Density, g/cm^3 X-Ray	Density, g/cm^3 Other	Space Group	Remarks
Alpha	Orthorhombic	a = 2.852 b = 5.865 c = 4.945	4	19.12		Cmcm	
Beta	Tetragonal	a = 10.759 ± 0.001 c = 5.656 ± 0.001	30	18.11		P_4/mnm	Data for 720 C
Gamma	Bcc	a = 3.524	2	18.06		I_{m3m}	Data for 805 C

References

(1) Dahl, A. I., and Cleaves, H. E., "The Freezing Point of Uranium", J. Research Natl. Bur. Standards, 43, 513-17 (1949).

(2) Baumrucker, J. E., and Chiswick, H. H., unpublished information (March, 1953).

(3) Jacob, C. W., and Warren, B. E., "The Crystalline Structure of Uranium", J. Am. Chem. Soc., 59, 2588 (1937).

(4) Lukesh, Joseph S., "Note on the Structure of Uranium", Acta Cryst., 2, 420 (1949).

(5) Tucker, C. W., Jr., "The Crystal Structures of Metallic Uranium", Trans. Am. Soc. Metals, 42, 762-70 (1950).

(6) Tucker, C. W., Jr., "The Crystal Structure of the Beta Phase of Uranium", Acta Cryst., 4, 425-31 (1951).

(7) Thewlis, J., "X-ray Powder Study of Beta-Uranium", Acta Cryst., 5, 790-794 (1952).

(8) Tucker, C. W., Jr., and Senio, Peter, "An Improved Determination of the Crystal Structure of Beta Uranium", Acta Cryst., 6, 753-760 (1953).

(9) Wilson, A. S., and Rundle, R. E., "The Structures of Uranium Metal", Acta Cryst., 2, 126-127 (1949).

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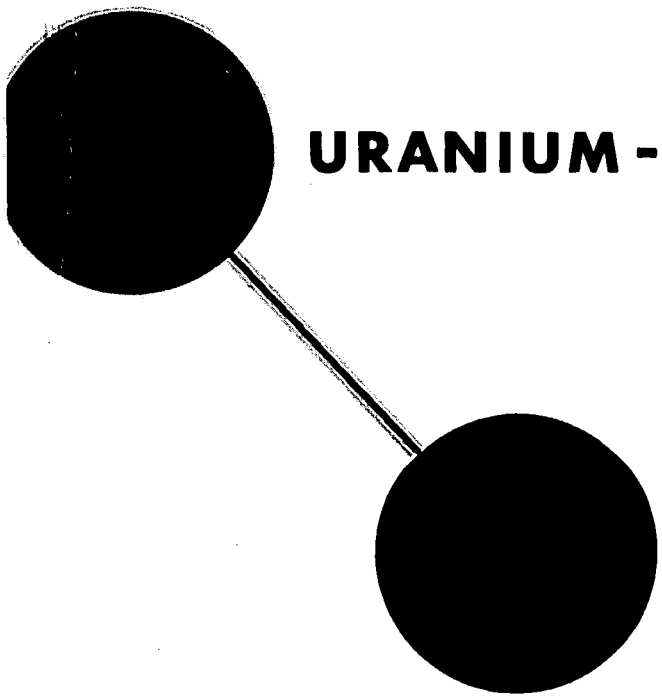
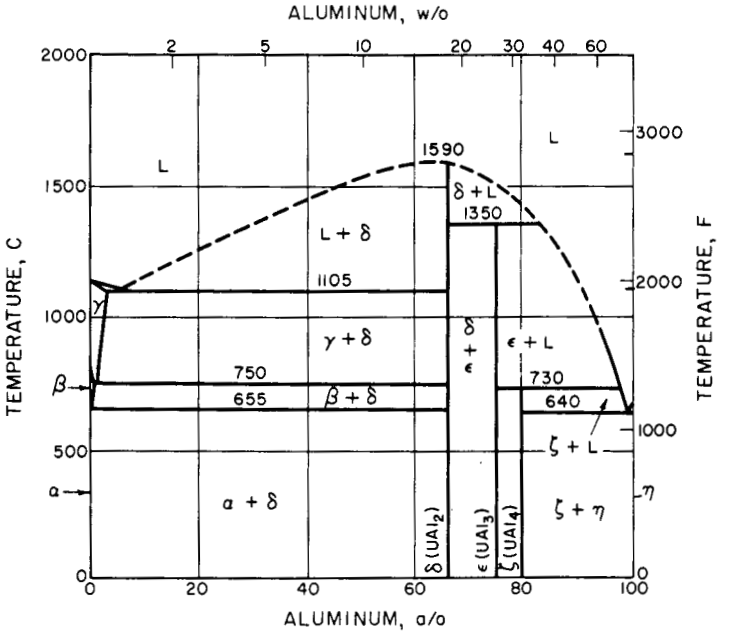


URANIUM - BINARY SYSTEMS

URANIUM-ALUMINUM



The Constitutional Diagram

There is virtually complete agreement on the uranium-aluminum system. The diagram shown is that of Gordon and Kaufmann[1], modified to include the UAl_4 intermetallic compound reported by Borie[2] and Allen[3].

Minor differences exist between this diagram and that of Allen[3]. These differences consist of small variations in the liquidus and in the various reaction isotherms. For example, at the uranium end of the system, Allen[3] reports values of 1123, 757, and 672 C for the eutectic and eutectoid isotherms. These values correspond to 1105, 750, and 655 C, respectively, in the diagram shown here. The work of Saller[4] is in agreement with the diagram shown. Thermal-analysis techniques resulted in slightly higher values for the aluminum-rich liquidus with UAl_3, as reported by Storhok and Bauer[5]:

755 C	17 w/o uranium
855 C	20 w/o uranium
954 C	24.5 w/o uranium
1068 C	30.9 w/o uranium
1190 C	41.7 w/o uranium
1265 C	51.2 w/o uranium

Some details of the solubility of aluminum in uranium have been reported by Allen[3]:

980 C	0.5 w/o aluminum
800 C	0.2 w/o aluminum
700 C	0.11 w/o aluminum
650 C	<0.1 w/o aluminum

Similar values, perhaps slightly lower, can be scaled from diagram in the gamma-uranium region.

Crystallography

The crystallography of the intermetallic compounds is summarized in the tabulation below. The data shown for UAl_2 and UAl_3 are from the work of Rundle and Wilson[6]. The structure of UAl_3 is confirmed by Maskrey and Frost[7], although they report a lattice dimension of a = 4.27 A. They also report that the atom positions of UAl_3 are surely those of the $AuCu_3$ ordered structure. On the basis of intensity data, it appears that a high degree of order exists in UAl_3.

Borie studied UAl_4 (once identified as UAl_5[1]) by both X-ray and neutron diffraction.[2] Chemical analyses and density measurements were somewhat inconsistent with the UAl_4 stoichiometry and structure. However, this inconsistency is explained on the basis of a defect lattice where some of the uranium sites are unoccupied or are occupied by aluminum atoms. Analysis of the structure revealed that it can be described as plates of the cubic UAl_3 structure held together by extra aluminum atoms[2].

Phase	Unit Cell Type	Unit Cell Dimensions, A	Number of Molecules	Density, g/cm^3 X-Ray	Density, g/cm^3 Other	Space Group	Remarks
Delta (UAl_2)	Fcc	a = 7.811	8	8.14	8.2	Fd3m	C15-type Cu_2Mg structure
Epsilon (UAl_3)	Simple cubic	a = 4.287	1	6.8		Pm3m	Ordered, $AuCu_3$-type structure
Zeta (UAl_4)	Orthorhombic	a = 4.41 b = 6.27 c = 13.71	4		5.7 ± 0.3	Ima or Imma	

References

(1) Gordon, P., and Kaufmann, A. R., "The Alloy Systems Uranium-Aluminum and Uranium-Iron", J. Metals, 2, (1) 182 (1950).

(2) Borie, B. S., Jr., "Crystal Structure of UAl_4", J. Metals, 3 (9), 800-802 (1951).

(3) Allen, N. P., United Kingdom, unpublished information (1947).

(4) Saller, H. A., Battelle Memorial Institute, "Preparation and Properties of Aluminum-Uranium Alloys", TID-65, 9-19 (July, 1948). Classified.

(5) Storhok, V. W., and Bauer, A. A., private communication (1958).

(6) Rundle, R. E., and Wilson, A. S., "The Structures of Some Metal Compounds of Uranium" (AECD-2388), Acta. Cryst., 2, 148-50 (1949).

(7) Maskrey, J. T., and Frost, B. R. T., "The System Uranium-Lead" (AERE M/R 1027), J. Inst. Metals (12), 171-180 (1953).

URANIUM-ANTIMONY

There is evidence of a number of intermetallic compounds in the uranium antimony system.[1, 2, 3] The following solubilities of uranium in liquid antimony have been reported[4]:

Temperature, C	650	700	750	800	850	900
Solubility, w/o	0.1	0.3	0.5	0.8	1.8	2.9

Crystallography

The crystallography of USb, U_3Sb_2, and USb_2 compounds is reported by Ferro[1,2] as shown below.

Phase	Unit Cell Type	Unit Cell Dimensions, A	Number of Molecules	Density, g/cm^3 X-Ray	Density, g/cm^3 Other	Space Group	Remarks
USb	Fcc	a = 6.191	4				NaCl structure; isomorphous with UN, UP, and UAs
U_3Sb_4	Cubic	a = 9.095					
USb_2	Tetragonal	a = 4.272 c = 8.741					

References

(1) Ferro, R., Atti accad. nazl. Lincei. Rend., Classe sci. fis., mat. e nat., 13, 53-61 (1952).

(2) Ferro, R., Atti accad. nazl. Lincei. Rend., Classe sci. fis., mat. e nat., 13, 151-157 (1952).

(3) Katz, J. J., and Rabinowitch, E., The Chemistry of Uranium, Part I, McGraw-Hill Book Company, Inc., New York (1951), pp 241-2.

(4) Hayes, E. E., and Gordon, P., TID-65, 130-141 (July, 1948). Classified.

URANIUM-ARSENIC

There is evidence supporting three intermetallic compounds in the uranium-arsenic system, but little else is known about these alloys.

Crystallography

The crystallography of UAs and UAs_2 compounds is summarized below. The data for UAs are those of Rundle[1]. Ferro[2] reports that UAs is similar in structure to USb, UN, UP, and UBi.

On the basis of X-ray studies, Iandelli[3,4] reports the existence of UAs, U_3As_4, and UAs_2.

Katz and Rabinowitch[5] have surveyed information on this system.

Phase	Unit Cell Type	Unit Cell Dimensions, A	Number of Molecules	Density, g/cm^3 X-Ray	Density, g/cm^3 Other	Remarks
UAs	Fcc	a = 5.767 ± 0.01	4	10.77		NaCl structure, isomorphous with rare-earth arsenides of La, Ce, Pr, Nd
UAs_2	Tetragonal	a = 3.954 c = 8.116	2	9.8		Isomorphous with UP_2

References

(1) Rundle, R. E., and Baenziger, N. C., unpublished information (1944).

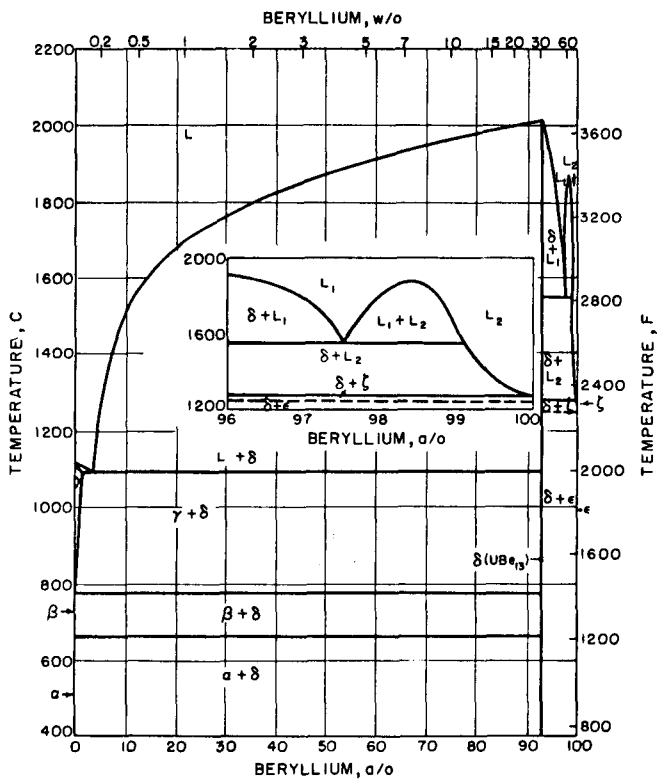
(2) Ferro, R., Atti. accad. nazl. Lincei. Rend., Classe sci. fis., mat. e nat., 13, 53-61 (1952).

(3) Iandelli, A., "Uranium Arsenides II. Crystal Structure of UAs_2 and UP_2", Atti. accad. nazl. Lincei. Rend., Classe sci. fis., mat. e nat., 13, 144-51 (1952).

(4) Iandelli, A., "Uranium Arsenides I", Atti. accad. nazl. Lincei. Rend., Classe sci. fis., mat. e nat., 13, 138-143 (1952).

(5) Katz, J. J., and Rabinowitch, E., The Chemistry of Uranium, Part I, McGraw-Hill Book Company, Inc., New York (1951), pp 241-2.

URANIUM-BERYLLIUM



The Constitutional Diagram

The diagram shown here is the work of Buzzard and co-workers(1). It represents the results of much difficult and trying work, since the atomic-weight ratio of uranium to beryllium is very high. The work was further complicated by the high volatility of beryllium at elevated temperatures. In general, the less elaborate work of other investigators is in agreement with this diagram. No confirmation exists for the tentatively proposed high-temperature modification in beryllium, which is designated as zeta (ζ) in the diagram. Details of the monotectic reaction are amplified in the inset of the diagram.

Buzzard reports that the eutectic between uranium and UBe_{13} occurs at a composition of less than 5 a/o beryllium (0.2 w/o). He also reports that the solubility of beryllium in uranium is small and that of the solubility of uranium in beryllium has not been detected.(1)

The National Physical Laboratory reports that the solid solubility of beryllium in uranium is between 2.8 and 8.4 a/o beryllium. The beryllium-rich eutectic contains about 0.06 a/o uranium(4).

Crystallography

Data for UBe_{13} are summarized in the accompanying tabulation[2,3]. There is no doubt that the unit cell is complex, although first studies tended to indicate a simple cubic structure with a lattice constant of about 5 A. Baenziger and Rundle[2] studied a whole series of MBe_{13} compounds where M was uranium, thorium, cerium, and zirconium. Study of rotation and Weissenberg diagrams of single crystals of $ZrBe_{13}$ revealed the more complex structure. On closer inspection, they found that the (531) reflection, which requires the larger unit, could be seen on powder diagrams. Their data were calculated from back-reflection data obtained with a symmetrical, self-focusing powder camera[2].

Koehler and co-workers[3] studied single crystals of UBe_{13} by both X-ray- and neutron-diffraction methods. Their work is in complete agreement with that of Baenziger and Rundle[2].

	Unit Cell			Density, g/cm^3			
Phase	Type	Dimensions, A	Number of Molecules	X-Ray	Other	Space Group	Remarks
Delta (UBe_{13})	Fcc	a = 10.2568 ● 0.0001	8	4.373	4.420 ± 0.002 at 26 C	Fm3c	Isomorphous with $NaZn_{13}$, $ThBe_{13}$, $CeBe_{13}$, and $ZrBe_{13}$

References

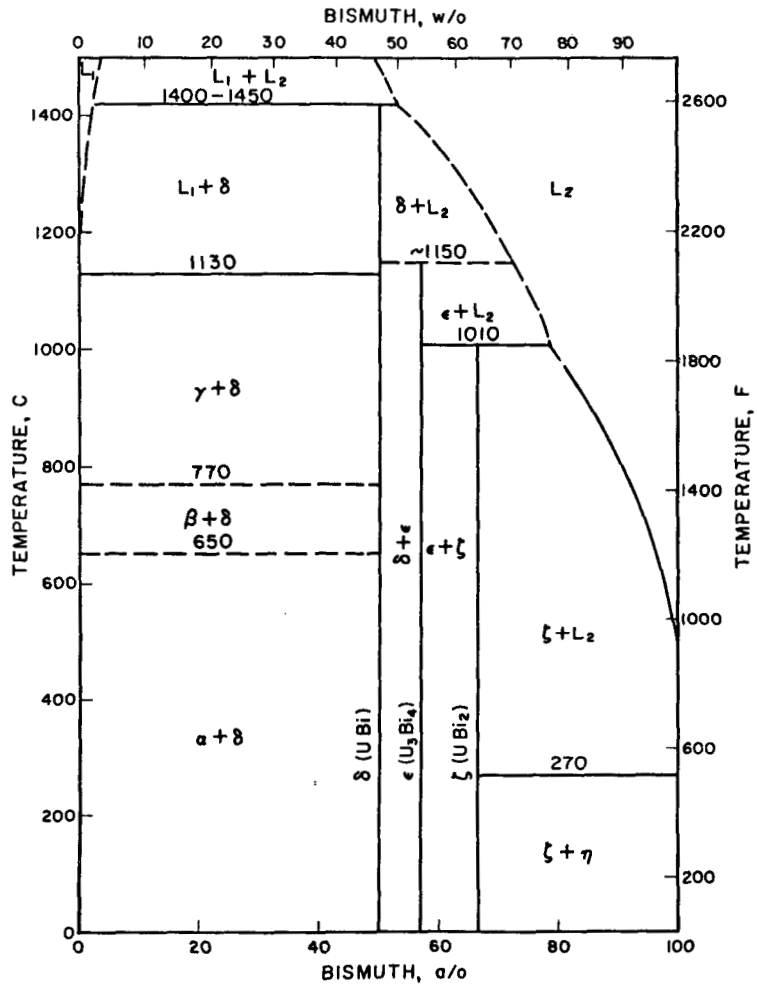
(1) Buzzard, R. W., Sterling, J. T., Buzzard, E. A., and Darr, J. H. (AECD-3417), J. Res. Natl. Bur. Standards, 50, 63-67 (2), (1953).

(2) Baenziger, N. C., and Rundle, R. E., "The MBe_{13} Compounds" (AECD-2506), Acta Cryst., 2, 258 (1949).

(3) Koehler, W. C., Singer, Joseph, and Coffinberry, A. S., "X-Ray and Neutron Diffraction Studies of the MBe_{13} Intermetallic Compounds" (AECD-3298), Acta Cryst., 5, 394 (1952).

(4) National Physical Laboratory, United Kingdom, unpublished information (October, 1948).

URANIUM-BISMUTH



The Constitutional Diagram

The original study of the uranium-bismuth system was performed by Ahmann and Baldwin[1]. Their data indicated the existence of two compounds, UBi and UBi_2, and their diagram, although incomplete, had all the major features of the system as it is now interpreted. The work of Teitel[2] and Ferro[3] brought about revision of the system as it is shown here and identified the compounds as UBi, U_3Bi_4, and UBi_2.

Determinations of the solubility of uranium in bismuth by Greenwood[6], who used filtration, by Cotterill[7], who used thermal analysis, and by Bareis[8], who used filtration and flotation techniques, are substantially in agreement with the diagram as shown. Greenwood[6] found the solubility obeyed the relationship $\log_{10}$ (uranium, w/o) = $3.00 - \frac{2440}{T}$, where T is the absolute temperature, and obtained the following values:

Temperature, C	515	546	602	668	722	760	796	816	898	960
Solubility, w/o	0.7	0.9	1.3	2.7	3.5	5.1	6.7	9.3	13.9	19.6

The values of Bareis[8] agree well with those of Greenwood, but since they cover a different temperature range, the values are given below:

Temperature, C	271	300	350	400	450	500	550	600	650	700
Solubility, w/o	0.031	0.051	0.108	0.21	0.36	0.60	0.97	1.47	2.18	3.1

Crystallography

Data on the crystallography of the intermetallic compounds in this system are summarized in the tabulation below.

The structure of UBi is from the work of Teitel[2] and was determined by means of neutron-diffraction experiments. Both Ferro[3] and Brewer[4] have reported the UBi structure to be face-centered cubic and give lattice constants of a = 6.356 A and a = 6.364 A, respectively.

The data for U_3Bi_4 and for UBi_2 are from the work of Ferro[3,5].

Phase	Unit Cell: Type	Unit Cell: Dimensions, A	Unit Cell: Number of Molecules	Density, g/cm^3: X-Ray	Density, g/cm^3: Other	Space Group	Remarks
Delta (UBi)	Bc tetragonal	a = 11.12 c = 10.55	24	13.6			
Epsilon (U_3Bi_4)	Cubic	a = 9.350	4	12.59			
Zeta (UBi_2)	Tetragonal	a = 4.445 c = 8.908	2	12.38		P4/nmm	C38-type structure

References

(1) Ahmann, D. H., and Baldwin, R. R., "The Uranium-Bismuth System", CT-2961 (November 12, 1945).

(2) Teitel, R. J., "Uranium-Bismuth System", Trans. A.I.M.E., 209, 131-6 (1957).

(3) Ferro, Ricardo, "Alloys of Uranium With Bismuth II", Atti accad. nazl. Lincei. Rend., Classe sci. fis., mat. e nat., 14, 89-94 (1953).

(4) Brewer, L., Edwards, R. K., and Templeton, D. H., "The Crystal Structure of UBi", AECU-653 (November 15, 1949).

(5) Ferro, Ricardo, "Alloys of Uranium With Bismuth", Atti. accad. nazl. Lincei. Rend., Classe sci. fis., mat. e nat., 13, 401-5 (1952).

(6) Greenwood, G. W., "The Solubilities of Uranium and Thorium in Liquid Bismuth", A.E.R.E. M/R 2234 (June, 1957).

(7) Cotterill, P., United Kingdom, unpublished information (April, 1957).

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URANIUM-BORON

Although the diagram has not been completed some data are available on the general characteristics of the uranium-boron system. The system contains three intermetallic compounds: UB_2, UB_4, and UB_{12}[1]. The portion of the diagram between pure uranium and UB_2 has been studied[2] and determined to be of simple eutectic form with the eutectic temperature between 1120 and 1128 C. The melting point of UB_2 is 2440 C. UB_4 exhibits a higher melting temperature[3] and forms a eutectic with UB_2 well above 1565 C.

The compound UB_{12} is reported to be too unstable for refractory use[3] and it does not exist at as such high temperatures as do UB_2 and UB_4.

Crystallography

The crystallography of UB_2, UB_4, and UB_{12} is summarized below. The lattice constants for UB_2 are reported by Daane and Baenziger[1]. Similar results are reported by Brewer[3], but the lattice constants are given as a = 3.136 ± 0.006 A and c = 3.988 ± 0.008 A.

The lattice constants of UB_4 are taken from the work of Brewer[3]. Similar but slightly lower values are reported by Bertaut[4]. Both Bertaut[4] and Zalkin[5] report the space group of UB_4 to be P4/mbm.

The data for UB_{12} are the work of Andrieux and Blum[6]. Additional discussion of the uranium borides can be found in The Chemistry of Uranium[7].

Phase	Unit Cell Type	Unit Cell Dimensions, A	Number of Molecules	Density, g/cm^3 X-Ray	Density, g/cm^3 Other	Space Group	Remarks
UB_2	Hexagonal	a = 3.12 c = 3.96	1	12.82	12.8		Axial ratio suggests it may be isomorphous with AlB_2
UB_4	Tetragonal	a = 7.075 ● 0.004 c = 3.979 ± 0.002	4			P4/mbm	Isomorphous with ThB_4 and CeB_4
UB_{12}	Fcc	a = 7.473	4	5.825		Fm3m	

References

(1) Daane, Adrian, and Baenziger, N. C., unpublished information (July 18, 1949).

(2) Howlett, B. W., and Marriott, B., Associated Electrical Industries Research Laboratory, United Kingdom, unpublished information (March, 1957).

(3) Brewer, L., Sawyer, D. L., Templeton, D. H., and Dauben, C. H., "The Borides of Uranium and Thorium" (AECD-2823), J. Chem. Phys., 18, 391 (1950).

(4) Bertaut, F., and Blum, P., "The Structure of the Borides of Uranium", Compt. rend., 229, 666-667 (1949).

(5) Zalkin, A., and Templeton, D. H., "The Crystal Structure of CeB_4, ThB_4, and UB_4", Acta Cryst., 6, 269-272 (1953); J. Chem. Phys., 18, 391 (1950).

(6) Andrieux, J. L., and Blum, P., Compt. rend., 229, 210 (1949).

(7) Katz, J. J., and Rabinowitch, Eugene, The Chemistry of Uranium, Part I, McGraw-Hill Book Company, Inc., New York (1951), p 214.

URANIUM-CALCIUM

There are very few data on the uranium-calcium system. However, in attempts to prepare calcium alloys, Ahmann[1] found no reaction between uranium and calcium after as much as 24 hr at 800 C.

Crystallography

There are no compounds in the uranium-calcium system.

Reference

(1) Ahmann, D. H., "Note on Attempts to Prepare Magnesium and Calcium Alloys of Uranium", CT-2959 (December 5, 1945).