

Aluminium – Silicon – Uranium

Peter Rogl, Henri Noël

Introduction

Due to their high potential as low-enriched uranium fuels ($< 20\%$ ^{235}U) in aluminium cladding, U_3Si and U_3Si_2 have directed research activities towards the metallurgy of the ternary system Al–Si–U. A first critical assessment of the Al–Si–U system has been made by [1998Ans]. Although many research groups dealt with the phase equilibria in the U rich part of the system [1961Pet, 1962Pet, 1963Svi, 1986Naz, 1989Ale1, 1991Pet], with the section $\text{UAl}_2\text{–USi}_{2-y}$ [1990Che, 1991Che] as well as with isothermal sections covering the whole composition range [1982Dwi, 1992Wei], there are several inconsistencies regarding phase relations, solution ranges and formation of ternary compounds (see discussion below). Some of the inconsistencies may have been inferred by the use of carbon containing uranium metal. Thus the authors of [1989Ale2] using high-purity electrolytic uranium (99.99 mass%) have demonstrated, that temperatures and reactions of ternary invariant equilibria reported by [1961Pet, 1962Pet] suffer from carbon impurity in uranium and in some aspects rather refer to the Al–C–Si–U quaternary system. Whereas [1977Zyg, 1990Che, 1991Che] reported on a ternary compound “UAlSi”, the investigations of [1982Dwi, 1986Naz, 1992Wei, 1994Wei] did not confirm its existence, but essentially agreed on a compound at or near $\text{U}_{-2}\text{AlSi}_{-2}$. The crystal structures of two further compounds U_3AlSi_3 and $\text{U}_3\text{Al}_2\text{Si}_3$ have been established by [1992Wei, 1994Wei].

The various experimental activities related to the constitution of the ternary Al–Si–U system are summarized in Table 1.

Binary Systems

The binary boundary system Al–Si has been accepted from [2004Gro]. The system Si–U is taken from the reinvestigation by [1992Rem], but the U rich part of the diagram up to 4 at.% Si is from [1965Str, 1991Pet]. The Al–U binary is based on a critical assessment by [1989Kas, 1990Kas], however, taking UAl_4 as a fully ordered, stoichiometric phase [2004Tou]. A listing of the crystallographic and melting data of the phases pertinent to the Al–Si–U system is given in Table 2.

Solid Phases

Although two research groups [1977Zyg] and [1990Che, 1991Che] independently corroborated the existence of the ternary compound UAlSi, investigations of the ternary isotherm by X-ray diffraction, metallography and EMPA [1982Dwi, 1992Wei, 1994Wei] did not reveal an equiatomic compound. Both [1977Zyg] and [1990Che, 1991Che] presented unit cell dimensions for “UAlSi”, however, did not agree on the crystal system: whereas [1977Zyg] reported a hexagonal unit cell with $a = 1077.8 \pm 8$, $c = 843.3 \pm 1.3$, [1990Che, 1991Che] arrived at a tetragonal system with $a = 679.6 \pm 0.3$, $c = 1080.5 \pm 0.3$. No further details were given, but [1977Zyg] presented an indexation for the powder pattern of presumably isotypic UAlGe ($a = 1005 \pm 2$, $c = 854 \pm 2$). In a re-evaluation of these powder data [1994Wei] demonstrated that the X-ray intensity pattern of “UAlGe” could be interpreted as a combination of a tetragonal main phase $\text{U}_3\text{Al}_2\text{Ge}_3$ with small amounts of $\text{U}(\text{Al},\text{Ge})_3$. $\text{U}_3\text{Al}_2\text{Si}_3$ is isotypic with $\text{U}_3\text{Al}_2\text{Ge}_3$ and its composition is close to equiatomic: it is thus conceivable that “UAlSi” of [1977Zyg, 1990Che, 1991Che] in fact should be better represented by $\text{U}_3\text{Al}_2\text{Si}_3$. As part of the section $\text{USi}_{2-y}\text{–UAl}_2$, the compound “UAlSi” was claimed to form in a peritectic reaction at 1355°C [1990Che, 1991Che].

Similarly, it was shown by [1994Wei] that the X-ray spectrum reported for the as-cast compound “ U_2AlSi_2 ” by [1982Dwi] could be reindexed on the basis of the tetragonal main phase $\text{U}_3\text{Al}_2\text{Si}_3$ with small amounts of $\text{U}(\text{Al},\text{Si})_2$ and U_3Si_2 . A small homogeneous range was reported for $\text{U}_3\text{Al}_2\text{Si}_3$ i.e. $\text{U}_{3+y}(\text{Al}_{1-x}\text{Si}_x)_{5-y}$ ranging in as cast alloys from $0.64 < x < 0.68$ and $0 < y < 0.04$ slightly deviating from the stoichiometric composition $\text{U}_3\text{Al}_2\text{Si}_3$ [1994Wei]. It should furthermore be noted that $\text{U}_3\text{Al}_2\text{Si}_3$ is a high-temperature

compound, which was found in as-cast alloys, but which decomposes in a rather sluggish reaction on annealing at 900°C for 100 h [1994Wei]. From experimental evidence it was thus concluded that the high temperature phase $\text{U}_3\text{Al}_2\text{Si}_3$ reported by [1994Wei] corresponds to as-cast “ U_2AlSi_2 ” of [1982Dwi], for which also the annealing experiments of [1982Dwi] attested a phase transformation at about 900°C. The crystal structure of $\text{U}_3\text{Al}_2\text{Si}_3$ was found to be a unique structure type deriving from anti- Cr_5B_3 type. From X-ray single crystal data a space group $I4/mcm$ was assigned [1994Wei], but detailed neutron powder and single crystal studies confirmed Al/Si atom order in the lower symmetric space group $I4$ [1997Rog, 2002Guk].

The compound U_3AlSi_3 was observed at 900°C at stoichiometric composition with full atom order [1992Wei].

The solubility of Al in U_3Si was determined by [1991Pet] to range between 1.94 and 3.2 at.% Al replacing silicon atoms in the lattice. Although [1961Pet, 1982Dwi, 1991Pet] claimed a non-negligible but minor solid solubility of Al in U_3Si_2 , EMPA and XPD revealed solubility of Al of up to 3 at.% Al at 900°C with Al atoms preferentially replacing the U atoms in the 2a-sites *i.e.* at the center of the CsCl type sublattice structure in U_3Si_2 [1992Wei]. Whereas agreement exists on negligible solid solubility at 900°C of Al in USi [1982Dwi, 1992Wei] as well as a small solid solubility of Al in the AlB_2 type based defect structures USi_{2-x} (5 at.% Al [1982Dwi]; < 2 at.% Al [1992Wei]), some controversies concern the solubility of Al in ThSi_2 type and GdSi_2 type USi_{2-x} . According to the reinvestigation of the Si–U binary by [1992Rem], the disilicide richest in Si is USi_{2-x} ($\text{USi}_{1.88}$) with the tetragonal defect- ThSi_2 type, followed at lower Si concentrations by the defect GdSi_2 type (orthorhombic distortion of ThSi_2 type) and at further reduction of Si content by two orthorhombic superstructures of defect AlB_2 type and finally by the simple hexagonal, defect AlB_2 type. In the investigation of [1982Dwi] the USi_{2-x} phase richest in Si (without specification of its structure type) was reported at 900°C to dissolve at least 16 at.% Al, whereas EMPA data of [1992Wei] showed a maximum solubility in $\text{USi}_{1.88}$ (ThSi_2 type) of only about 2 at.% Al. GdSi_2 type USi_{2-x} (not mentioned by [1982Dwi]!), however, was found from EMPA to dissolve at 900°C about 11 at.% Al [1992Wei]. The authors of [1990Che, 1991Che] reported a solubility of about 26 at.% Al in the ThSi_2 type structure, which, however, was shown to transform (second order transformation) into the GdSi_2 type. The understoichiometry of the USi_{2-x} solid solution was said to change on Al substitution from $\text{USi}_{1.97}$ to $\text{U}(\text{Si},\text{Al})_{1.84}$ for alloys with 8 at.% Al and the transformation temperature for the ThSi_2 type to GdSi_2 type transformation as a function of the Si/Al-substitution was given as follows: 215°C at 8 at.% Al, 350°C at 16.7 at.% Al, 290°C at 23 at.% Al, 190°C at 28.7 at.% Al [1990Che, 1991Che]. With respect to the location of the phase $\text{U}_3\text{Al}_2\text{Si}_3$ at 900°C [1994Wei], confirmed by a single crystal [2002Guk], the large solubility limit derived by [1990Che, 1991Che] seems to be doubtful.

Whilst [1982Dwi] reported a complete series of solid solutions at 900°C for the compounds UAl_3 and USi_3 , the investigations of [1992Wei] revealed difficulties to achieve equilibrium or alternatively were interpreted as the appearance of a miscibility gap at 900°C for the compositions $\text{U}(\text{Si}_{1-x}\text{Al}_x)_3$, $0.4 < x < 0.71$. Indications for the formation of a miscibility gap at 600°C were also reported by [1986Naz]. In all cases there is a clear indication for Al/Si-substitution. However, alloys “ UAl_2Si_2 ” made by [1977Zyg] ($a = 414.5$ pm) and [1985Ott] (three unit cell parameters were given for different samples of the same nominal composition: $a = 414.5, 416.3, 417.6$ pm) were claimed to be isotypic with the cubic Cu_3Au type structure. The phase composition was explained by filling the central position of the structure with Al/Si-atoms [1985Ott].

Some discrepancies concern the solubility limit of Si in UAl_2 : [1991Pet] deduced about 1 at.% in the range 1100° to 780°C in agreement with data reported by [1961Pet]. X-ray lattice parameter measurements by [1982Dwi], however, indicated a maximum solubility of 10 at.% Si at 700°C and of 16.5 at.% at 900°C. Also [1990Che, 1991Che] indicated 16 at.% Si solubility (dashed solvus line without temperature dependency between RT and 1000°C), whereas [1992Wei] arrived at about 10 at.% Si at 900°C. Studying the reaction in miniature fuel element plates (U_3Si , $\text{U}_3\text{Si}_2 + \text{Al}$; for U-densities up to 7 Mg U m^{-3} in the dispersion) under equilibrium conditions at 600°C [1986Naz] observed the formation of UAl_2 , UAl_3 , UAl_4 , U_2AlSi_2 and reported solubility limits of ~6 at.% Si in UAl_2 , of ~9 at.% Si in UAl_4 as well as indications for a miscibility gap within the solid solution of USi_3 – UAl_3 .

Crystallographic data concerning solid phases are compiled in Table 2.

Quasibinary Systems

The authors of [1961Pet] determined the phase relations within the quasibinary section $\text{UAl}_2\text{-U}_3\text{Si}_2$ using DTA, metallography, chemical and X-ray analyses. The diagram contains a eutectic transformation (max.) at 1360°C and 26 at.% Si (Fig. 1). The section $\text{USi}_{2-x}\text{-UAl}_2$ was reported by [1990Che, 1991Che] to be quasibinary, claiming a peritectic formation at 1355°C of a compound UAlSi (which has not been confirmed by [1982Dwi, 1992Wei]) and followed by a eutectic reaction at 1330°C and 40 at.% Al: $\text{L} \rightleftharpoons \text{UAlSi} + \text{UAl}_2$. Besides this controversy concerning UAlSi , the section is not perfectly quasibinary as it does not cut through congruently melting USi_{2-x} . Furthermore the solubility limit of Al in USi_{2-x} (at 26 at.% Al) is not in agreement with the limit given by [1982Dwi] at 16 at.% Al or by [1992Wei] at 11 at.% Al.

Invariant Equilibria

The reaction scheme of the $\text{U-UAl}_2\text{-U}_3\text{Si}_2$ partial system, as shown in Fig. 2 was taken from [1989Ale1, 1991Pet] adding the eutectoid decomposition of (βU) from [1962Pet] assuming a degenerate reaction, as the solubility of Al as well as of Si in βU and αU is very small at that temperature [Mas2]. This makes the temperature of 580°C given by [1962Pet] very improbable. A ternary eutectic reaction occurs at 976°C ; containing 10.9 at.% (1.5 mass%) Si and 3.69 at.% (0.49 mass%) Al. The intermetallic phases UAl_2 and U_3Si_2 are virtually stoichiometric at that temperature. U_3Si forms peritectoidally at 973°C from $(\gamma\text{U}) + \text{UAl}_2 + \text{U}_3\text{Si}_2$. At 765°C a transition reaction $(\gamma\text{U}) + \text{U}_3\text{Si} \rightleftharpoons (\beta\text{U}) + \text{UAl}_2$ occurs [1989Ale1, 1991Pet], superseding earlier data of [1963Svi] listing this reaction at 790°C . In the Al rich region [1976Mon] reported on an invariant reaction, $\text{L} + \text{UAl}_4 \rightleftharpoons \text{U}(\text{Al},\text{Si})_3 + (\text{Al})$, at 3 at.% Si, 5-10 at.% U, $\sim 600^\circ\text{C}$; and above 3 at.% Si, aluminium was said to be in equilibrium with $\text{U}(\text{Al},\text{Si})_3$ [1958Rou]. A ternary eutectic, $\text{L} \rightleftharpoons (\text{Al}) + (\text{Si}) + \text{U}(\text{Al},\text{Si})_3$, was suggested to be close to the Al-Si binary [1976Mon].

Table 3 contains all information pertinent to the ternary invariant reactions.

Liquidus Surface

Only a partial liquidus surface is established for the region $\text{U-UAl}_2\text{-U}_3\text{Si}_2$ including three fields of primary crystallization: (γU) , UAl_2 , U_3Si_2 (Fig. 3).

Isothermal Sections

Due to the strong interest in U_3Si , U_3Si_2 -fuel interaction with Al, three groups of authors supplied detailed information on the phase relations in the $\text{U-UAl}_2\text{-USi}_2$ concentration range: [1989Ale1, 1991Pet] reported 9 isothermal sections (at 1120, 980, 977, 975, 970, 950, 930, 780, 740°C), [1962Pet] reported 3 sections (at 950, 850, 650°C) and [1963Svi] reported 4 sections (at 900, 800, 770, 740°C) in the U corner up to 4 at.% Al and Si to determine homogeneity ranges of (αU) and (βU). Figures 4 and 5 summarize these results in terms of two isothermal sections at 780 and 950°C , taking the area near U_3Si from [1991Pet] and the U corner from [1963Svi, 1962Pet].

In a determination of the growth kinetics of $\text{U}(\text{Al},\text{Si})_2$, $\text{U}(\text{Al},\text{Si})_3$ and diffusion coefficient from diffusion couples $\text{U}_3\text{Si}+\text{Al}$ in the range from 510 to 670°C , [1991Rhe] observed $\text{U}(\text{Al},\text{Si})_2$ along the grain boundaries of U_3Si as the initial stage of reaction after 48 h anneal at 510°C , followed by $\text{U}(\text{Al},\text{Si})_3$ on the Al rich side of the diffusion couple. No evidence was found for the presence of the $\text{U}(\text{Al},\text{Si})_4$ phase in any of the diffusion couples: the composition of the phases were said to be $\text{U}(\text{Al}_{0.17}\text{Si}_{0.83})_2$ and $\text{U}(\text{Al}_{0.11}\text{Si}_{0.89})_3$ for the couple at 670°C [1991Rhe]. These findings are consistent with the phase triangulation as well as indicate large solid solubilities of Si in the phases UAl_2 and UAl_3 .

Two isothermal sections (at 900 and 400°C) over the whole concentration range were given by [1982Dwi], with one ternary compound $\text{U}_{-2}\text{AlSi}_{-2}$ (in high and low-temperature modification; $T_{\text{tr}} \approx 900^\circ\text{C}$). Figure 6 shows the phase equilibria in the isothermal section at 900°C based on the results of [1992Wei] with two ternary compounds: U_3AlSi_3 (W_3CoB_3 type) and $\text{U}_3\text{Al}_2\text{Si}_3$ (ordered anti Cr_5B_3 type), as well as the position of the low temperature phase $\text{U}_{-2}\text{AlSi}_{-2}$.

Temperature – Composition Sections

The isopleth $U_3Si - UAl_2$ is shown in Fig. 7.

Thermodynamics

Low-temperature specific heat data for $U_3Al_2Si_3$ ($2 < T < 70$ K) inferred a small gap of $\Delta = 54$ K in the magnon dispersion in close agreement with the gap of 29 K derived from electrical resistivity data: C_p/T (in $J \cdot K^{-2} \cdot mol^{-1}$) = $0.253 + 7.0 \cdot 10^{-4} T^2 + 17.9 \cdot T^{-0.5} \exp(-\Delta/T)$; $\Delta = 54$ K [2001Tro]. The slightly enhanced gamma-value points towards a medium-heavy fermion character.

Notes on Materials Properties and Applications

Additions of small amounts of Al to U_3Si greatly improved aqueous corrosion resistance [1975Mat]. Thermal stability of Al - “UAlSi” dispersion fuels (“UAlSi” = U - 3.5 mass% Si - 1.5 mass% Al which consists of a matrix of U_3Si containing 0.5 mass% Al in solution and particles of U_3Si_2 and UAl_2) with 55 mass% “UAlSi” and 75 mass% “UAlSi”, respectively, were examined in the temperature range from 250 to 400°C [1982Fer]. Whilst no metallurgical changes were observed after heating to 200°C, between 250 and 400°C the fuel particles reacted via grain boundary diffusion with the Al-matrix to form UAl_3 and UAl_4 [1982Fer]. Extruded rods of Al - “UAlSi” dispersion fuels were said to have an aqueous corrosion resistance similar to Al-U alloys [1980Fer]. Swelling due to irradiation with 0.5 and 2 MeV Ar-ions of an alloy U - 3.5 mass% Si - 1.5 mass% Al at 570-950 K was investigated by [1976Cai, 1975Fer, 1983Dom]. Postirradiation heating tests showed that U_3Si -fuel undergoes gross swelling at temperatures above 900°C [1975Mat]. The manufacture of miniature fuel element plates (U_3Si , $U_3Si_2 + Al$) was described for U-densities up to $7 \text{ Mg} \cdot \text{U} \cdot \text{m}^{-3}$ in the dispersion and the reaction behavior under equilibrium conditions at 600°C was determined [1986Naz]. After 33 days anneal at 600°C various uranium aluminides were detected (see section “Solid Phases”); minor swelling of the plates was obvious at 350°C and major swelling occurred at 550°C [1986Naz]. The exothermic reaction peak in DTA at about 630°C prior to clad melting was not interpreted; irradiation tests of U_3Si_2 -Al fuel show remarkable dimensional stability up to 97% burn-up [1986Naz]. Thermal conductivity of the fuel alloy U-1.5Al-3.5Si (mass%) was studied by [1975Feh]. Hot-hardness and microstructure of an U-350 ppm Si-800 ppm Al alloy was examined; the alloy content was dissolved in (β U) and subsequently precipitated in the (α U) phase; some dispersion hardening was observed [1965Far1]; dissolving Al, Si in liquid uranium and subsequent splat cooling failed to produce any precipitate particles, however on compaction at 600°C and extrusion at 500°C a precipitate with irregular shape (0.1-0.4 μm) was observed; aging of the splat cooled alloy for 100 h at 600°C produced considerable particle agglomeration [1965Far2]. The Vickers hardness of alloys containing 17% U and 2-3.5% Si was reported to be of the order of 350 - 300 $\text{MN} \cdot \text{m}^{-2}$ and rises to 450 - 500 $\text{MN} \cdot \text{m}^{-2}$ with 35% coldwork [1976Mon]. Diffusion of U in Al-Si alloys is much slower than in Al $D_0 = 0.07 \text{ S}$; $Q = 0.55 \text{ eV}$ [1976Mon].

The authors of [1991Rhe] determined the growth kinetics of $U(Al,Si)_2$, $U(Al,Si)_3$ and the diffusion coefficient from diffusion couples $U_3Si + Al$ in the range from 510 to 670°C: the growth of the $U(Al,Si)_3$ interface phase followed a parabolic rate law and was concluded to be controlled by diffusion of Al atoms not by interfacial reactions; furthermore, an activation energy of $Q = 220 \text{ kJ} \cdot \text{mol}^{-1}$ was derived for the temperature range 510 to 670°C, which was said to be approximately equal to the activation energy for the Al diffusion through the $U(Al,Si)_3$ phase (Q was about three times higher than for the diffusion through UAl_3).

Miscellaneous

Magnetic susceptibility and magnetization data for polycrystalline $U_3Al_2Si_3$ showed ferromagnetic order below $T_C = 36 \text{ K}$ and $\mu_s = 0.45 \mu_B/U$; for the paramagnetic region $\mu_{\text{eff}} = 1.99 \mu_B/U$ and $\Theta_p = 11 \text{ K}$ were reported [1994Wei]. Hysteresis loop and susceptibility measurements on a Czochralsky grown single crystal specimen $U_3Al_2Si_3$ revealed a small magnetocrystalline anisotropy between b - and c -axis [1998Mih, 1999Mih]. Magneto-transport data at 0 and 8 Tesla revealed a pronounced maximum below T_C probably

caused by a reduction of effective conduction carriers or by a spin density wave type of spin-disorder scattering of electrons [2001Tro]. Nuclear and magnetic structure of $\text{U}_3\text{Al}_2\text{Si}_3$ were investigated by means of neutron powder [1997Rog, 1999Rog] as well as by single crystal diffractometry additionally employing polarized neutrons in the range from 7 K to 250 K and in external magnetic field up to 6 Tesla parallel $[\bar{1}10]$, $[100]$, $[001]$ [2002Guk]. Refinements of the nuclear structure at 70 K (above the magnetic ordering temperature defined by neutrons at $T_m \approx 33$ K) confirmed the fully ordered distribution of Al and Si atoms in the 8c sites of space group $I4$ ($R_F^2 = 0.054$). Thus isotypism was established with the $\text{U}_3\text{Ga}_2\text{Ge}_3$ type as a low symmetry derivative of the ordered anti type of Cr_5B_3 (space group $I4/mcm$). Refinement of the magnetic four-circle data collected at 7 K was performed in space group $I2$ ($I112$) keeping all atom positions as derived from the nuclear data at 70 K. Uranium moments are all parallel to the a, b plane, but equivalent pairs U3, U4 are non-collinear at an angle of 90° . Experiments with polarized neutrons at 7 K and in an external magnetic field of 6 Tesla along $[\bar{1}10]$, $[100]$, $[001]$ proved the non-collinear spin arrangement: $\Phi(\text{U3}) = 45^\circ$ (in direction $[110]$) and $\Phi(\text{U4}) = 135^\circ$ (in direction $[\bar{1}10]$), resulting in a ferromagnetic net component ($\mu(\text{U1}, \text{U2}) = 0.18(1) \mu_B$; $\mu(\text{U3}, \text{U4}) = 1.39(1) \mu_B$; $R_F^2 = 0.056$). A rather strong local anisotropy field prevents full alignment of the U spins to the external magnetic field of 6 T. However, moments U1 and U2 are small and align along the external magnetic field. Polarized neutron scattering as a microprobe for local anisotropy in the paramagnetic region provided the anisotropic magnetization parameters at 6 Tesla for the paramagnetic state up to 250 K. Size and direction of the uranium moments obtained confirm the strong local anisotropy field on the U3,4 atoms ($\Phi(\text{U3}) \sim 45^\circ$ and $\Phi(\text{U4}) \sim 135^\circ$) persisting even at 250 K [2002Guk]. Calculation of the band structure by the tight binding linear muffin-tin orbital method (TB-LMTO for a simple ferromagnetic order) and X-ray photoemission spectra (XPS) indicate predominantly itinerant 5f-electrons [2005Sza]. Figure 8 presents the magnetic phase diagram for $\text{U}_3\text{Al}_2\text{Si}_3$; the solid line is the phase boundary between the paramagnetic and the (non-collinear) ferromagnetic region. The inset shows the spin orientation for the three uranium atom sites.

Preliminary magnetic susceptibility and magnetization measurements on “ U_2AlSi_2 ” yielded weak ferromagnetism below $T_C = 27$ K and $\mu = 3 \cdot 10^{-2} \mu_B/\text{U}$ under 3T; for the paramagnetic region $\mu_{\text{eff}} = 3.15 \mu_B/\text{U}$ and $\Theta_p = -157$ K were found [1992Wei].

“ UAl_2Si_2 ” with the Cu_3Au type structure ($a = 414.5$ pm) showed superconductivity below $T_{sc} = 1.35$ K; coefficients of specific heat, $C_p = \gamma T + \beta T^3$, were given as $\gamma = 27.9 \text{ mJ} \cdot \text{mol}^{-1} \cdot \text{K}^{-2}$ and $\beta = 0.435 \text{ mJ} \cdot \text{mol}^{-1} \cdot \text{K}^{-4}$ [1985Ott].

The influence of silicon on the reprocessing of aluminium-uranium fuels was studied by [1968Pai] and instantaneous dissolution rates in nitric acid were related to the composition of the alloys *i.e.* to the Si content of the fuel. Analytical atomic spectrometric methods were optimized for detection of metal traces (including silicon) in Al-U samples [1989Arg].

[1993Kon] investigated the corrosion resistance of an alloy U-0.2Al-3.8Si (mass%) against water at 300°C under 90 MPa: the speed of corrosion was measured for various length of time from 10 to 3000 h. After 100 h the speed of corrosion for instance reached a value of saturation at $0.5 \text{ mg} \cdot \text{cm}^{-2} \cdot \text{h}^{-1}$.

References

- [1958Rou] Rough, F. A., Bauer, A.A., “Constitution of U and Th Alloys, Al-Si-U”, *Report No. BMI-1300, UC-25 Met. Cer.*, 81 (1958) (Review, 2)
- [1961Pet] Petzow, G., Kvernes, I., “The $\text{UAl}_2\text{-U}_3\text{Si}_2$ System” (in German), *Z. Metallkd.*, **52**(10), 693-695 (1961) (Experimental, Morphology, Phase Diagram, Phase Relations, 9)
- [1962Pet] Petzow, G., Kvernes, I., “On the Constitution of U-rich Alloys U-Si-Al” (in German), *Z. Metallkd.*, **53**(4), 248-256 (1962) (Experimental, Morphology, Phase Diagram, Phase Relations, 23)
- [1963Svi] Svistunova, Z.V., Ivanov, O.S., “The U Corner of the U-Al-Si Phase Diagram” in “*Stroenie Svoistva Splavov Urana, Toriya, Tsirkoniya*” (in Russian), Sb. Statei, Ivanov, O.S. (Ed.), Gosatomizdat, Moscow, 9-15 (1963) (Experimental, Phase Diagram, Phase Relations, 2)
- [1965Far1] Farkas, M.S., Storhok, V.W., Pardue, W.M., Martin, R.L., Stoltz, D.L., Veigel, N.D., Townley, C.W., Barnes, R.H., Wright, T.R., Chubb, W., Speidel, E.O., Rough, F.A., “Fuel

- and Fertile Materials - Uranium Metal and Alloys - Plutonium - Thorium and Its Alloys - Metal-Ceramic Fuels - Coated-Particle Fuel Materials - Uranium Oxides - Uranium and Thorium Carbides, Nitrides, and Sulfides - Mechanism of Corrosion of Fuels - B", *Reactor Mater.*, **8**(2), 57-73 (1965) (Assessment, Mechan. Prop., Phase Diagram, Phase Relations, 69)
- [1965Far2] Farkas, M.S., Storhok, V.W., Pardue, W.M., Martin, R.L., Stoltz, D.L., Veigel, N.D., Townley, C.W., Pfeifer, W.H., Wright, T.R., Barnes, R.H., Acuncius, D.S., Speidel, E.O., Chubb, W., Rough, F.A., "Fuel and Fertile Materials - Uranium Metal and Alloys - Plutonium - Thorium - Metal-Ceramic Fuels - Coated-Particle Fuel Materials - Uranium Oxide Fuel Materials - Uranium and Thorium Carbides, Nitrides, and Sulfides - Basic Studies of Irradiation Effects", *Reactor Mater.*, **8**(4), 175-195 (1965) (Assessment, Crys. Structure, Phase Diagram, Phase Relations, Thermodyn., Transport Phenomena, 86)
- [1965Str] Straatmann, J.A., Neumann, N.F., "Equilibrium Structures in the High Uranium-Silicon Alloy System", *USAEC Report MCW1486, Malinckrodt Chemical Works*, Oct. 23 1964, cited in *Reactor Mater.*, **8**(2), 57-73 (1965) (Experimental, Phase Diagram)
- [1968Pai] Paige, B.E., Rohde, K.L., "Effect of Metallurgical Composition of Aluminum-Uranium-Silicon Fuels On Chemical Reprocessing", *Nucl. Appl.*, **5**, 218-223 (1968) (Experimental, Phys. Prop., 10)
- [1975Mat] Matthews, R.B., Swanson, M.L., "Swelling of Uranium Silicide Fuel During Post-Irradiation Heating", *Nucl. Techn.*, **26**, 278-285 (1975) (Experimental, Phys. Prop., 10)
- [1975Feh] Fehrenbach, P.J., Cotnam, K.D., Morel, P.A., "In-Reactor Thermal Conductivity of U-Si-Al", *Chalk River Nucl. Lab. Report AECL-5104*, 1-38 (1975) (Experimental, Phys. Prop., 19)
- [1975Fer] Feraday, M.A., Fehrenbach, P.J., Cotnam, K.D., Morel, P.A., "Irradiation Behaviour of a Corrosion Resistant U-Si-Al Fuel Alloy, Fuel Mat.Branch", *Chalk River Nucl. Lab. Report AECL-5028*, 1-11 (1975) (Experimental, Phys. Prop., 13)
- [1976Cai] Caillibot, P.F., Hastings, I.J., "Simulation of In-Reactor Swelling in U-3.5 wt.% Si-1.5 wt.% Al by Ion Bombardment", *J. Nucl. Mater.*, **59**, 257-262 (1976) (Experimental, Phys. Prop., 16)
- [1976Mon] Mondolfo, L.F., "Aluminium Alloys: Structure and Properties", Butterworths, London, p. 615 (1976) (Review, 9)
- [1977Zyg] Zygmunt, A., "New Ternary Uranium Compounds", *Proc. 2nd-Int. Conf. Electron. Struct. Actinides*, 335-41 (1977) (Experimental, Crys. Structure, 7)
- [1980Fer] Feraday, M.A., Bélanger, L., Foo, M.T., Grolway, C.M., "The Development of Lower Enrichment Fuels for Canadian Research Reactors", *Fuel Mat. Branch, Chalk River Nucl. Lab. Report* (1980) 223-247 (Experimental, Phys. Prop., 9)
- [1982Dwi] Dwight, A.E., "A Study of the U-Al-Si System", *Argonne National Lab. Report ANL-82-14*, 1-40 (1982) (Experimental, Morphology, Phase Diagram, Phase Relations, Crys. Structure, 39)
- [1982Fer] Feraday, M.A., Foo, M.T., Davidson, R.D., Winegar, J.E., "The Thermal Stability of Al-USiAl Dispersion Fuels and Al-U Alloys", *Nucl. Techn.*, **58**, 233-241 (1982) (Experimental, Phys. Prop., 11)
- [1983Dom] Domagala, R.F., Wiencek, T.C., Thresh, H.R., "U-Si and U-Si-Al Dispersion Fuel Alloy Development for Research and Test Reactors", *Nucl. Techn.*, **62**, 353-360 (1983) (Experimental, Morphology, Phase Diagram, Phase Relations, Phys. Prop., 12)
- [1985Ott] Ott, H.R., Hulliger, F., Rudigier, H., "Superconductivity in Uranium Compounds with Cu₃Au Structure", *Phys. Rev.*, **B31**, 1329-1333 (1985) (Experimental, Crys. Structure, Electr. Prop., 19)
- [1986Naz] Nazaré, S., "New Low Enrichment Dispersion Fuels for Research Reactors Prepared by PM-Techniques", *Powder Metall. Int.*, **18**(3), 150-158 (1986) (Experimental, Phase Diagram, Phase Relations, Phys. Prop., 24)

- [1989Ale1] Alekseeva, Z.M., Petrov, Yu.I., Petrov, D.D., "Phase Equilibria in the U-U₃Si₂-UAl₂ System", *Atom. Ener.*, **67**(2), 645-649 (1989), translated from *Atom. Ener.*, **67**(2), 133-135, (1989) (Experimental, Phase Diagram, Phase Relations, 4)
- [1989Ale2] Alekseeva, Z.M., Petrov, Yu.I., Petrov, D.D., "Phase Equilibria in the U-U₃Si₂-UAl₂-UC System", *Atom. Energ.*, **67**(2), 649-652 (1989), translated from *Atom. Ener.*, **67**(2), 135-137, (1989) (Experimental, Phase Diagram, Phase Relations, 4)
- [1989Arg] Argekar, A.A., Thulasidas, S.K., Kulkarni, M.J., Bhide, M.K., Sampathkumar, R., Godbole, S.V., Adya, V.C., Dhawale, B.A., Rajeshwari, B., Goyal, N., Purohit, P.J., Page, A.G., Dalvi, A.G.I., Bangia, T.R., Sastry, M.D., Natarajan, P.R., "Trace Metal Characterization of the U-Al Matrix by Atomic Spectroscopy", *Nucl. Techn.*, **84**, 196-204 (1989) (Experimental, Phys. Prop., 19)
- [1989Kas] Kassner, M.E., Adler, P.H., Adamson, M.G., Peterson D.E., "Evaluation and Thermodynamic Analysis of Phase Equilibria in the U-Al System", *J. Nucl. Mater.*, **167** 160-168 (1989) (Experimental, Crys. Structure, Phase Diagram, Thermodyn., 49)
- [1990Kas] Kassner, M.E., Adamson, M.G., Adler, P.H., Peterson, D.E., *Bull. Alloy Phase Diagrams*, **11**(1), 82-89 (1990) (Experimental, Crys. Structure, Phase Diagram, Phase Relations, Review, 49)
- [1990Che] Chebotarev, N.T., Konovalov, L.I., Zhmak, V.A., "Investigation on the Crystal Structure and Phase Transformation of Alloys of the USi₂-UAl₂ Section of the Ternary System Uranium-Aluminium-Silicium", *Questions of Atomic Science and Technique. Ser. Mater. Sci. New. Mater.*, (3), 11-13 (1990) (Experimental, Crys. Structure, Phase Relations, Phase Diagram, 0)
- [1991Che] Chebotarev, N.T., Konovalov, L.E., Zhmak, V.A., "Investigation on the Crystal Structure and Phase Transformation of Alloys of the USi₂-UAl₂ Section of the Ternary System Uranium-Aluminium-Silicium" in "Phase Diagrams of Metallic Systems, 1990", (in Russian), Petrova, L.A. (Ed.), VINITI, Moscow, **35**(1), 363-364 (1991) (Abstract, Phase Diagram, Phase Relations, 1)
- [1991Pet] Petrov, Yu.I., Alekseeva, Z.M., Petrov, D.D., "Phase Equilibria in the U-U₃Si₂-UAl₂ System", *J. Nucl. Mater.*, **182**, 60-72 (1991) (Experimental, Phase Diagram, Phase Relations, 12)
- [1991Rhe] Rhee, C-K., Pyun, S-I., Kuk, I-H., "Phase Formation and Growth at Interface Between U₃Si and Aluminium", *J. Nucl. Mater.*, **184**, 161-166 (1991) (Experimental, Crys. Structure, Phys. Prop., 13)
- [1992Rem] Remschnig, K., Le Bihan, T., Noël, H., Rogl, P., "Structural Chemistry and Magnetic Behaviour of Binary Uranium Silicides", *J. Solid State Chem.* **97**, 391-399 (1992) (Experimental, Crys. Structure, Magn. Prop., 29)
- [1992Wei] Weitzer, F., Noël, H., Rogl, P., "Phase Relations and Magnetism in the Ternary System U-Al-Si", *Proc. 22^{èmes} Journées des Actinides*, Meribel, France, 35-36 (1992) (Experimental, Crys. Structure, 0)
- [1993Kon] Konovalov, L.I., Petrov, Yu.I., Petrov, D.D., Alekseeva, Z.M., "The Effect of Alloy Additives on Uranium Silicide Corrosion Resistance" (in Russian), *Izv. Ros. Akad. Nauk, Met.*, **6**, 200-203 (1993) (Experimental, Interface Phenomena, Morphology, 2)
- [1993LeB] Le Bihan, T., "Syntheses, Crystal Structures and Magnetic Properties of Ternary Silicides and Germanides with Uranium or Rare Earth Elements and Transition Metals of (V, Cr, Nb, Mo, Ta, W)" (in French), *Thesis*, University of Rennes, Rennes, France, pp. 1-194 (1993) (Experimental, Crys. Structure, Phase Relations, 64)
- [1994Wei] Weitzer, F., Potel, M., Noël, H., Rogl, P., "Crystal Structure and Magnetism of Novel Compounds U₃(M',M'')₅, M' = Al, Ga, M'' = Si, Ge", *J. Solid State Chem.*, **111**(2), 267-275 (1994) (Crys. Structure, Experimental, Magn. Prop., 9)
- [1996LeB] Le Bihan, T., Noel, H., Rogl, P., "Crystal Structure of the Uranium Monosilicide USi", *J. Alloys Compd.*, **240**, 128-133 (1996) (Experimental, Crys. Structure, Magn. Prop., 11)

- [1997Rog] Rogl, P., André, G., Weitzer, F., Potel, M., Noël, H., “Nuclear and Magnetic Structure of $U_3Ga_2Ge_3$, a Neutron Powder Diffraction Study”, *J. Solid State Chem.*, **131**, 72-77(1997) (Crys. Structure, Experimental, Magn. Prop., 10)
- [1998Ans] Ansara, I., Grieb, B., Legendre, B., Alekseeva, Z.M., “Aluminium-Silicon-Uranium“, MSIT Ternary Evaluation Program, in *MSIT Workplace*, Effenberg, G. (Ed.), MSI, Materials Science International Services GmbH, Stuttgart; Document ID: 10.16089.1.20, (1993) (Crys. Structure, Phase Diagram, Assessment, 11)
- [1998Mih] Mihalik, M., Rogl, P.F., Menovsky, A.A., “Search for Magnetocrystalline Anisotropy in $U_3M_2M'_3$ ”, *Acta Phys. Slovaca*, **48**(6), 815-818 (1998) (Crys. Structure, Experimental, Magn. Prop., 3)
- [1998Noe] Noël, H., Queneau, V., Durand, J.P., Colomb, P., “Characterization of a New Binary Uranium Silicide U_5Si_4 ”, in “*Abstract of a Paper at Int. Conf. on Strongly Correlated Electron Systems - SCES98*”, Paris, pp. 92 (1998) (Experimental, Crys. Structure, 0)
- [1999Mih] Mihalik, M., Rogl, P.F., Menovsky, A.A., “Magnetic Properties of $U_3M_2M'_3$ ”, *Physica B (Amsterdam)*, **259-261**, 258-259 (1999) (Crys. Structure, Experimental, Magn. Prop., 3)
- [1999Rog] Rogl, P., André, G., Boureé, F., Noël, H., “Magnetic Structures of $U_3M_2M'_3$, M = Al, Ga; M' = Si, Ge: a Neutron Powder Diffraction Study”, *J. Nucl. Mater.*, **191**, 291-300 (1999) (Crys. Structure, Experimental, Magn. Prop., 12)
- [2001Tro] Troc, R., Rogl, P., Tran, V.H., Czopnik, A., “Magnetotransport and Heat Capacity in Ternary Compounds $U_3M_2M'_3$, M = Al, Ga; M' = Si, Ge.”, *J. Solid State Chem.*, **158**, 227-235 (2001) (Electr. Prop., Magn. Prop., Thermodyn., 13)
- [2002Guk] Gukasov, A.G., Rogl, P., Brown, P.J., Mihalik, M., Menovsky, A., “Site Susceptibility Tensors and Magnetic Structure of $U_3Al_2Si_3$: a Polarized Neutron Diffraction Study”, *J. Phys.: Condens. Matter.*, **14**(38), 8841-8851 (2002) (Crys. Structure, Experimental, Magn. Prop., 10)
- [2004Gro] Groebner, J., “Al-Cu (Aluminium-Copper)”, MSIT Binary Evaluation Program, in *MSIT Workplace*, Effenberg, G. (Ed.), MSI, Materials Science International Services GmbH, Stuttgart; Document ID 20.14887.1.20, (2004) (Phase Diagram, Crys. Structure, Assessment, 68)
- [2004Tou] Tougait, O., Noël, H., “Stoichiometry of UAl_4 ”, *Intermetallics*, **12**, 219-223 (2004) (Experimental, Crys. Structure, 17)
- [2005Sza] Szajek, A., Morkowski, J.A., Bajorek, A., Chelkowska, G., Tro, R., “X-Ray Photoemission Spectra and Electronic Band Structure of the Ternary Compounds $U_3M_2M'_3$, M = Al, Ga, M' = Si, Ge”, *J. Alloys Compd.*, **386**, 75-81 (2005) (Electronic Structure, Experimental, Magn. Prop., Optical Prop., 18)
- [2006Noe] Noël, H., “The Crystal Structure of U_5Si_4 ”, Research at Univ. Rennes, France (2006) (Experimental, Crys. Structure)

Table 1: Investigation of the Al-Si-U Phase Relations, Structures and Thermodynamics

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1961Pet]	12 samples prepared from 99.99% pure Al, Si and reactor-grade U (containing ca 150 ppm C) via argon arc melting. Samples were annealed in vacuum at 950°C (200 h), 850°C (340 h), 650°C (500 h) and quenched; thermal analyses, DTA; chemical analyses; metallography of as cast and annealed alloys; X-ray powder diffraction.	Quasibinary eutectic section UAl_2 - U_3Si_2 ; eutectic at 26 at.% Si and 1360°C.
[1962Pet]	About 150 samples prepared from 99.99% pure Al, Si and reactor-grade U (containing ca 150 ppm C) via argon arc melting. Samples were annealed in vacuum at 950°C (200 h), 850°C (340 h), 650°C (500 h) and quenched; thermal analyses, DTA; chemical analyses; metallography of as cast and annealed alloys; X-ray powder diffraction; micro-hardness, chemical and thermal etching.	Investigation of the region $\text{U-U}_3\text{Si}_2$ - UAl_2 : liquidus surface and solidus; isothermal sections at 650°C, 850°C, 950°C; Isopleths $\text{U-U}_3\text{Si}_2$, UAl_2 - U_3Si_2 , U-UAl_2 ; isopleths at 3 at.% Al up to 40 at.% Si; at 6 at.% Si up to 55 at.% Al; at 30 at.% Al up to 25 at.% Si; isopleth from 64U36Si to 60Al40U. Scheil diagram.
[1963Svi]	Purity of starting materials: 99.87% U, 99.99% Al, Si. Samples were annealed in evacuated quartz ampoules at 740°C (84 h), 770°C (72 h), 800°C (60 h), 900°C (48 h); chemical analyses; metallography (chemical etching) of as cast and annealed alloys; X-ray powder diffraction.	Investigation of the U rich corner up to U-4 at.% Si-4 at.% Al on three series of alloys with constant ratios Si:Al = 3:1, 1:1 and 1:3. Determination of liquidus and solidus lines; isothermal sections at 740°C, 770°C, 800°C, 900°C. Scheil diagram.
[1977Zyg]	Samples UAlSi and UAl_2Si_2 were prepared from 99.99% pure Al, Si and 99.8% U via argon arc melting. Samples were annealed in Ta containers, sealed in evacuated quartz ampoules at 850-900°C for 170 h; X-ray powder diffraction.	Identification of hexagonal compound (crystal structure unknown). Indexation of the powder pattern of presumably isotypic UAlGe was reported.
[1982Dwi]	About 260 samples prepared from 99.99% pure Al, Si and reactor-grade U (containing ca 100 ppm C) via argon arc melting. Samples were annealed in vacuum at temperatures between 700 and 1040°C and water quenched; thermal analyses, DTA; metallography of as cast and annealed alloys (chemical etching); X-ray powder diffraction;	Investigation of the ternary system (<80 at.% Al and <75 at.% Si). Determination of isothermal sections at 400 and 900°C. Lattice parameter data for solutions $\text{U}(\text{Al},\text{Si})_2$ and $\text{U}(\text{Al},\text{Si})_{2-x}$. One or two ternary compounds near U_2AlSi_2 (unknown crystal structure).

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1986Naz]	U ₃ Si, U ₃ Si ₂ prepared by arc melting in inert gas. Preparation of fuel plates (U ₃ Si, U ₃ Si ₂ + Al) for U-densities up to 7 Mg·U·m ⁻³ in the dispersion containing 75 mass% fuel < 44 to 150 μm particle size, rest < 44 μm particles. Homogenization at 600°C for 33 days in evacuated pyrex tubes, quench. Metallography, EMPA, X-ray powder diffraction at RT, DTA.	Investigation of chemical reaction with Al. Dimensional thermal stability and stability under irradiation.
[1990Che] [1991Che]	Purity of starting materials: 99.8% U, 99.999% Al, Si. annealed at 1000°C for 5 h under He. DTA; metallography of as cast and annealed alloys; X-ray powder diffraction at RT and high temperatures.	Determination of concentration section UAl ₂ -USi _{2-y} from RT to 1800°C. Lattice parameter data for solutions U(Si,Al) _{2-x} and U(Al,Si) _{2-x} . Peritectic formation of UAlSi at 1355°C.
[1991Pet]	Purity of starting materials: electrolytic 99.98%U, 99.999% Al, Si. Samples were prepared via argon arc melting subsequently were wrapped in Zr foil, delta annealed in evacuated quartz capsules at 800°C for 100 h. Then they were annealed for 5 h at successively higher temperatures (10 K intervals) from 880°C to 980°C. DTA (80 K·min ⁻¹); metallography of as cast and annealed alloys; X-ray powder diffraction.	Investigation of the region U-U ₃ Si ₂ -UAl ₂ : isothermal sections at 1120, 980, 977, 975, 970, 950, 930, 780, 740°C. Isopleths U ₃ Si-UAl ₂ ; isopleth at 75 at.% U up to 25 at.% Al; Scheil diagram.
[1991Rhe]	Preparation of alloy U-3.9 mass% Si in vacuum induction furnace followed by casting and heat treatment at 800°C, 3 days. Depleted U < 0.1% impurities, 99.999% Si. Diffusion couples prepared from 5x5x20 mm ³ U ₃ Si-block dipped into Al-melt at 750°C, sealed in evacuated quartz, anneal 510-670°C up to 300 h, air cooling. X-ray diffraction, metallography, EMPA.	Determination of growth kinetics of U(Al,Si) ₂ , U(Al,Si) ₃ and diffusion coefficient from diffusion couples U ₃ Si+Al. Phase relations.
[1992Wei] [1994Wei]	About 60 samples prepared from 99.99% pure Al, Si and nuclear grade U-platelets (E. Merck) via argon arc melting. Samples were wrapped in Mo foil, annealed in evacuated quartz capsules at 800°C for 150 h (900°C for 100 h, respectively) and water quenched; EMPA, metallography of as cast and annealed alloys (chemical etching); X-ray powder diffraction.	Investigation of the isothermal sections at 900, 800°C. Crystal structure and lattice parameter data.

Table 2: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(Al) < 660.5	<i>cF4</i> <i>Fm$\bar{3}m$</i> Cu	$a = 404.88$	pure Al [Mas2, V-C2]
(Si) < 1414	<i>cF8</i> <i>Fd$\bar{3}m$</i> C _{diamond}	$a = 543.06$	[Mas2]
(γ U) 1135 to 774.8	<i>cI2</i> <i>Im$\bar{3}m$</i> W	$a = 353.35$	[Mas2] refined at 787°C
(β U) 774.8 to 667.7	<i>tP30</i> <i>P4₂/mnm</i> β U	$a = 1075.89$ $c = 565.31$	[Mas2]
(α U) < 667.7	<i>oC4</i> <i>Cmcm</i> α U	$a = 285.37$ $b = 586.95$ $c = 495.48$	[Mas2]
U(Al _{1-x} Si _x) ₂ UAl ₂ < 1620	<i>cF24</i> <i>Fd$\bar{3}m$</i> MgCu ₂	$a = 776.6$ $a = 772.5$ $a = 771.3$ $a = 769.8$	$0 \leq x \leq 0.17$ at 900°C; $0 \leq x \leq 0.10$ at 700°C; linear variation of $a(x)$ [1982Dwi]; at $x = 0$ [1982Dwi] at $x = 0.10$ [1982Dwi] in alloy 40U40Al20Si, 900°C [1992Wei] at $x = 0.17$ [1982Dwi]
U(Al _{1-x} Si _x) ₃ UAl ₃ < 1350 USi ₃ < 1510	<i>cP4</i> <i>Pm$\bar{3}m$</i> Cu ₃ Au	$a = 426.51$ $a = 403.53$	$0 \leq x \leq 1$ at 900°C; nonlinear variation of $a(x)$ [1982Dwi]; miscibility gap at $T < 900^\circ\text{C}$? at $x = 0$ [V-C2] at $x = 1$ [V-C2]
UAl ₄ < 731	<i>oI20</i> <i>Imma</i> UAl ₄	$a = 440.14$ $b = 625.52$ $c = 1372.79$	[1990Kas] [2004Tou]
USi ₂ < 450?	<i>tI12</i> <i>I4₁/amd</i> ThSi ₂	$a = 392.2$ $c = 1415.4$	(metastable) [1992Rem]
U(Si _{1-x} Al _x) _{2-y} α_1 , USi _{2-y} (USi _{1.88}) < 1710	<i>tI12</i> <i>I4₁/amd</i> defect ThSi ₂	$a = 394.23$ $c = 1371.2$	$0 \leq x \leq 0.05$; $y = 0.12$ at 900°C [1992Wei] at $x = 0$; $y = 0.12$; 65 at.% Si

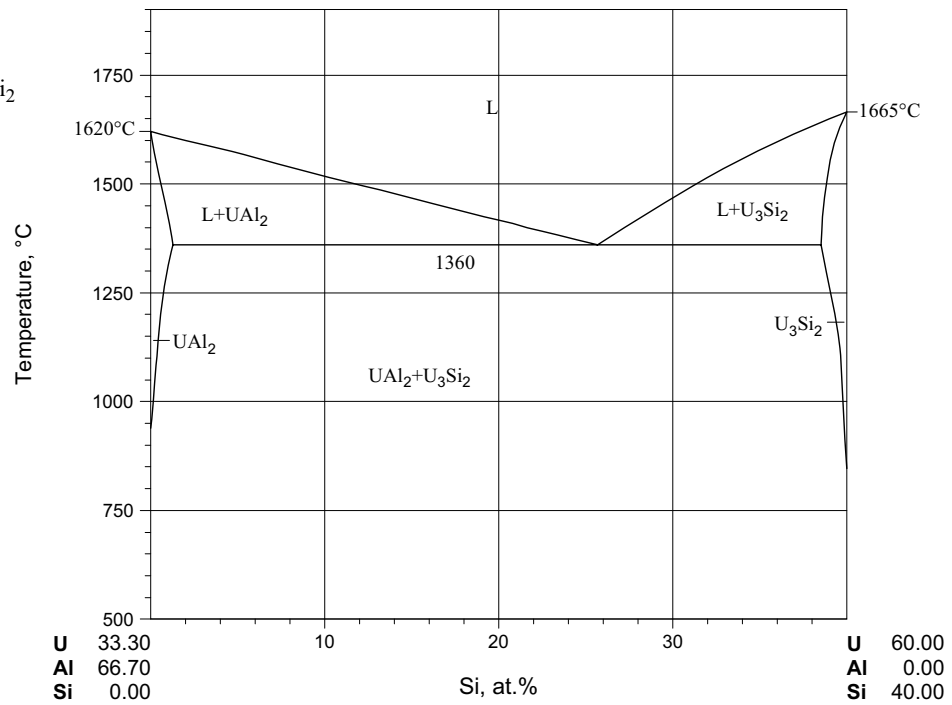
Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
α_2 , $\text{U}(\text{Si}_{1-x}\text{Al}_x)_{2-y}$ USi_{2-y}	<i>oI12</i> <i>Imma</i> defect GdSi_2	$a = 395.45$ $b = 393.02$ $c = 1365.2$	$0 \leq x \leq 0.17$; $y = 0.22$ at 900°C [1992Wei] at $x = 0$; $y = 0.22$; 64 at.% Si [1992Rem]
		$a = 402.88$ $b = 392.02$ $c = 1359.2$	at $x = 0.17$; $y = 0.22$; 64 at.% Si [1992Wei]
α_3 , $\text{USi}_{2-y}(\text{U}_3\text{Si}_5\text{-o2})$	<i>oP6</i> <i>Pmmm</i> (?) distorted AlB_2	$a = 389.3$ $b = 671.7$ $c = 404.2$	at ~ 63 at.% Si [1992Rem]
α_4 , $\text{USi}_{2-y}(\text{U}_3\text{Si}_5\text{-o1})$	<i>oP6</i> <i>Pmmm</i> distorted AlB_2	$a = 386.4$ $b = 666.0$ $c = 407.3$	at 63 at.% Si [1992Rem]
α_5 , $\text{USi}_{2-y}(\text{U}_3\text{Si}_5\text{-hex}$ or $\text{USi}_{1.67})$ < 1770	<i>hP3</i> <i>P6/mmm</i> defect AlB_2	$a = 384.75$ $c = 407.40$	[1992Rem]
USi < 1580	<i>tI138</i> <i>I4/mmm</i> USi	$a = 1058.7$ $c = 2431.0$	[1992Rem, 1993LeB, 1996LeB]
USi	<i>oP8</i> <i>Pnma</i> FeB	$a = 758.5$ $b = 390.3$ $c = 566.3$	probably impurity (O) stabilized [1992Rem, 1993LeB]
U_5Si_4 < 1100	<i>hP18</i> <i>P6/mmm</i> U_5Si_4	$a = 1046.7$ $c = 391.2$	[1998Noe] single crystal study [2006Noe]
$(\text{U}_{1-x}\text{Al}_x)_3\text{Si}_2$ U_3Si_2 < 1665	<i>tP10</i> <i>P4/mbm</i> U_3Si_2	$a = 732.99$ $c = 390.04$	$0 \leq x \leq 0.05$ at 900°C ; [1992Wei] at $x = 0$
		$a = 729.60$ $c = 393.92$	at $x = 0.05$
$\gamma\text{U}_3\text{Si}$ 930 - 759	<i>cP4</i> <i>Pm3m</i> Cu_3Au	$a = 434.6$	[V-C2, 1965Str]
$\beta\text{U}_3\text{Si}$ 762 - -153	<i>tI16</i> <i>I4/mcm</i> $\beta\text{U}_3\text{Si}$	$a = 603.28$ $c = 869.07$	[V-C2, 1965Str]
$\alpha\text{U}_3\text{Si}$ < -153	<i>oF32</i> <i>Fmmm</i> $\alpha\text{U}_3\text{Si}$	$a = 865.4$ $b = 854.9$ $c = 852.3$	[V-C2, 1965Str] at -193°C

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
* τ_1 , U_3AlSi_3	<i>oC28</i> <i>Cmcm</i> W_3CoB_3	$a = 399.63$ $b = 1049.7$ $c = 1348.1$	[1992Wei]
* τ_2 , $\text{U}_3\text{Al}_2\text{Si}_3$ $\geq 900^\circ\text{C}$	<i>tI32</i> <i>I4</i> $\text{U}_3\text{Al}_2\text{Ge}_3$	$a = 761.83$ $c = 1077.51$ $a = 764.95$ $c = 1082.21$	[1992Wei, 1994Wei] single crystal $\text{U}_3\text{Al}_{1.76}\text{Si}_{3.24}$ $R_F^2 = 0.057$ from alloy $\text{U}_{45.5}\text{Al}_{22.9}\text{Si}_{31.6}$ [1994Wei]
* τ_3 , $\text{U}_{\sim 2}\text{Al}_{\sim 1}\text{Si}_{\sim 2}$ $\leq 900^\circ\text{C}$	unknown	-	[1982Dwi] at $\text{U}_{\sim 37}\text{Al}_{\sim 24}\text{Si}_{\sim 39}$ in at.% [1992Wei]

Table 3: Invariant Equilibria

Reaction	T [°C]	Type	Phase	Composition (at.%)		
				Al	Si	U
$\text{l} \rightleftharpoons \text{U}_3\text{Si}_2 + \text{UAl}_2$	1360	e_1	l U_3Si_2 UAl_2	24 ~1 ~66	26 ~39 ~1	50 ~60 ~33
$\text{L} \rightleftharpoons (\gamma\text{U}) + \text{U}_3\text{Si}_2 + \text{UAl}_2$	976	E_1	L (γU) U_3Si_2 UAl_2	~3.6 3.5 ~0.5 ~66.7	10-11 1.8 ~39.5 ~0	~85 94.7 ~60 ~33.3
$(\gamma\text{U}) + \text{U}_3\text{Si}_2 + \text{UAl}_2 \rightleftharpoons \text{U}_3\text{Si}$	973	P_1	U_3Si (γU) U_3Si_2 UAl_2	3 3.5 ~0.5 ~66.7	22 1.8 ~39.5 ~0	75 94.7 ~60 ~33.3
$(\gamma\text{U}) + \text{U}_3\text{Si} \rightleftharpoons (\beta\text{U}) + \text{UAl}_2$	765	U_1	U_3Si (γU) (βU) UAl_2	~2.5 ~1.2 ~0.4 ~66.7	~22.5 ~0.5 ~1.2 ~0	75 ~98.3 ~98.4 ~33.3
$(\beta\text{U}) \rightleftharpoons (\alpha\text{U}) + \text{U}_3\text{Si} + \text{UAl}_2$	665	D_1	-	-	-	-
$\text{L} + \text{UAl}_4 \rightleftharpoons \text{U}(\text{Al},\text{Si})_3 + (\text{Al})$	~600	U_2	L	87-92	3	~5-10
$\text{L} \rightleftharpoons (\text{Al}) + (\text{Si}) + \text{U}(\text{Al},\text{Si})_3$?	E_2	-	-	-	-

Fig. 1: Al-Si-U.
The quasibinary
section UAl_2 - U_3Si_2



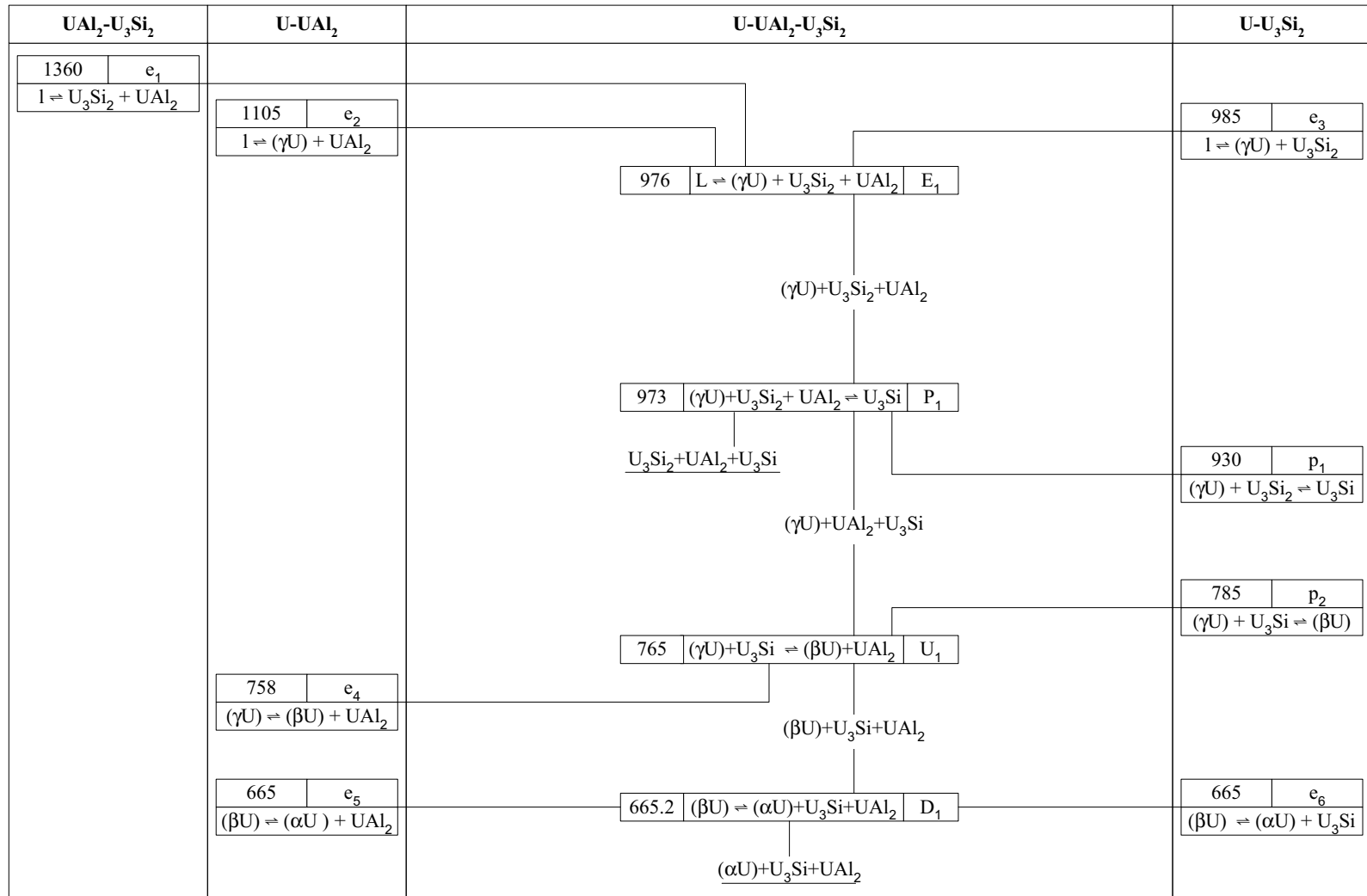


Fig. 2: Al-Si-U. Reaction scheme

Fig. 3: Al-Si-U.
Liquidus surface for
the region
U-UAl₂-U₃Si₂

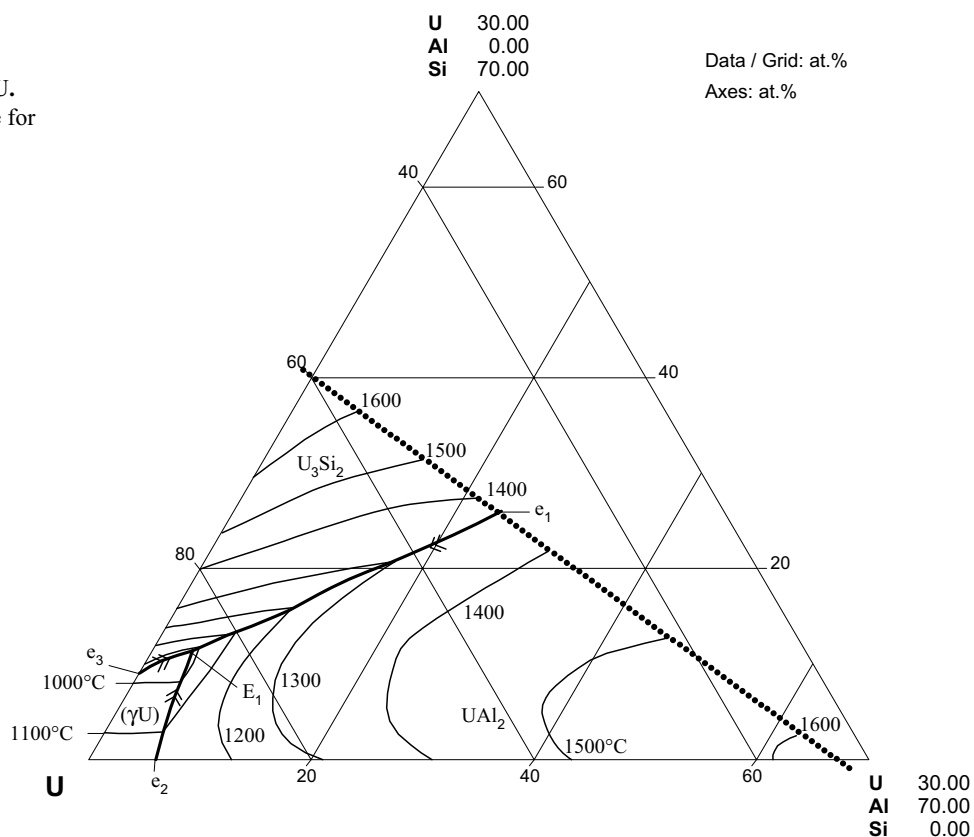


Fig. 4: Al-Si-U.
Isothermal section for
the region
U-UAl₂-U₃Si₂ at
780°C

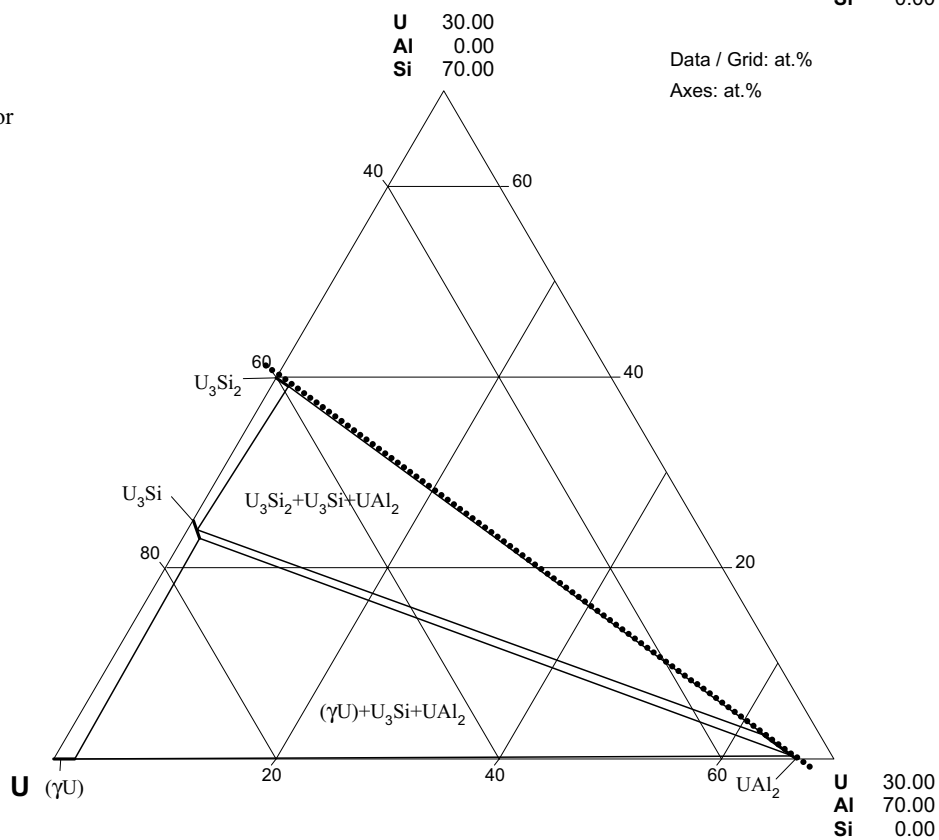


Fig. 5: Al-Si-U.
Isothermal section for
the region
U-UAl₂-U₃Si₂ at
950°C

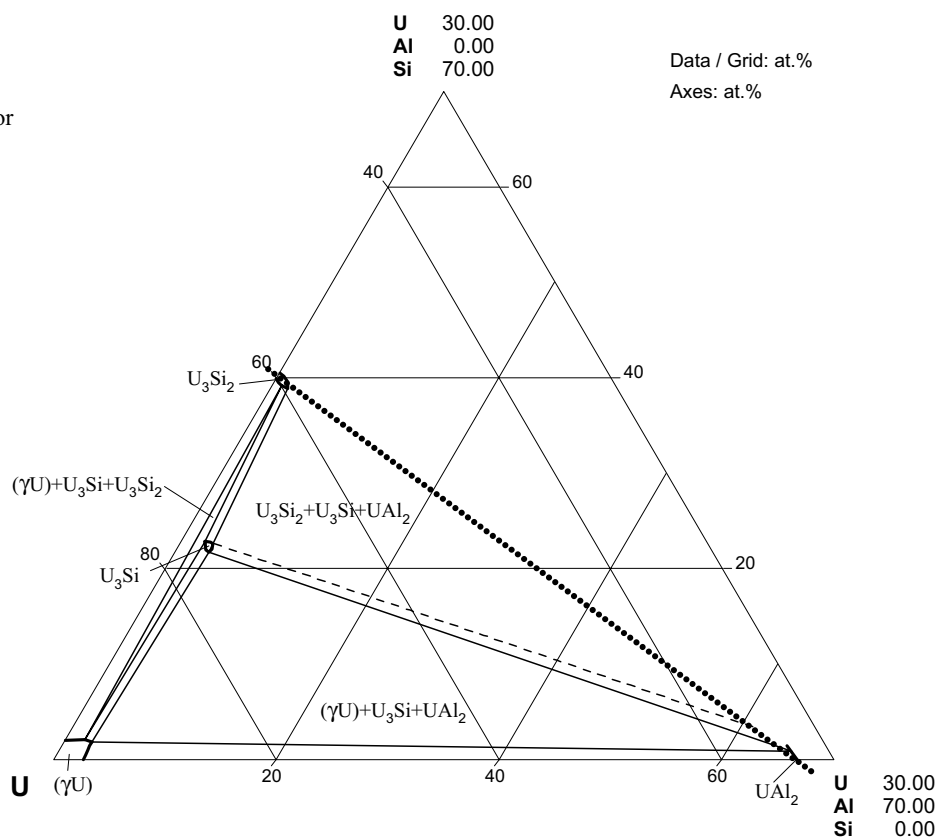


Fig. 6: Al-Si-U.
Isothermal section at 900°C; the position of the low-temperature compound τ_3 near $\text{U}_{-2}\text{AlSi}_{-2}$ is labelled by a filled square

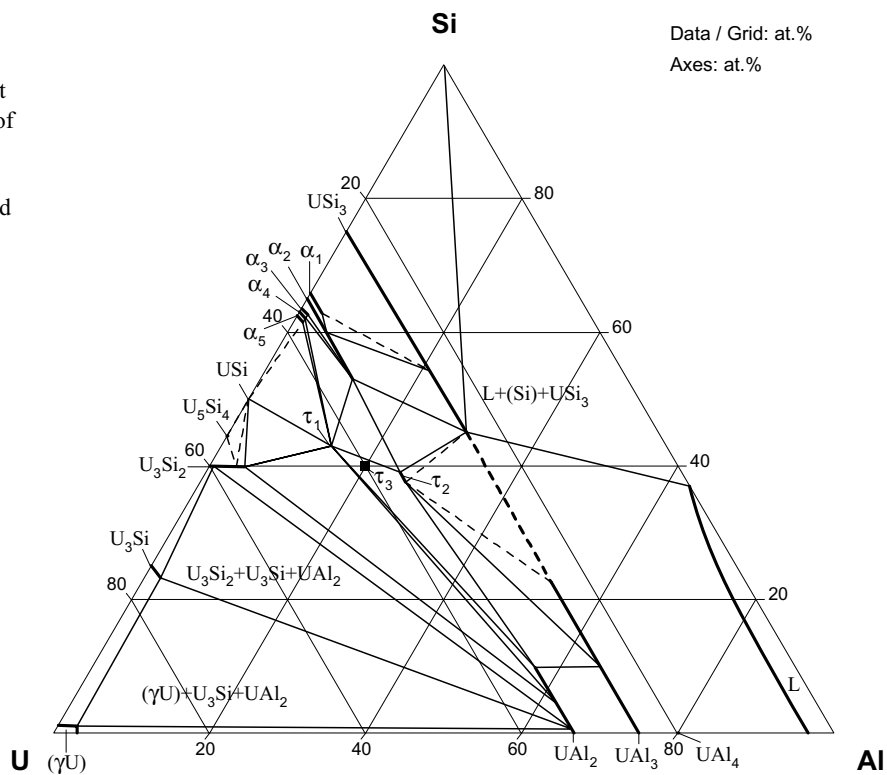


Fig. 7: Al-Si-U.
Isopleth $U_3Si - UAl_2$

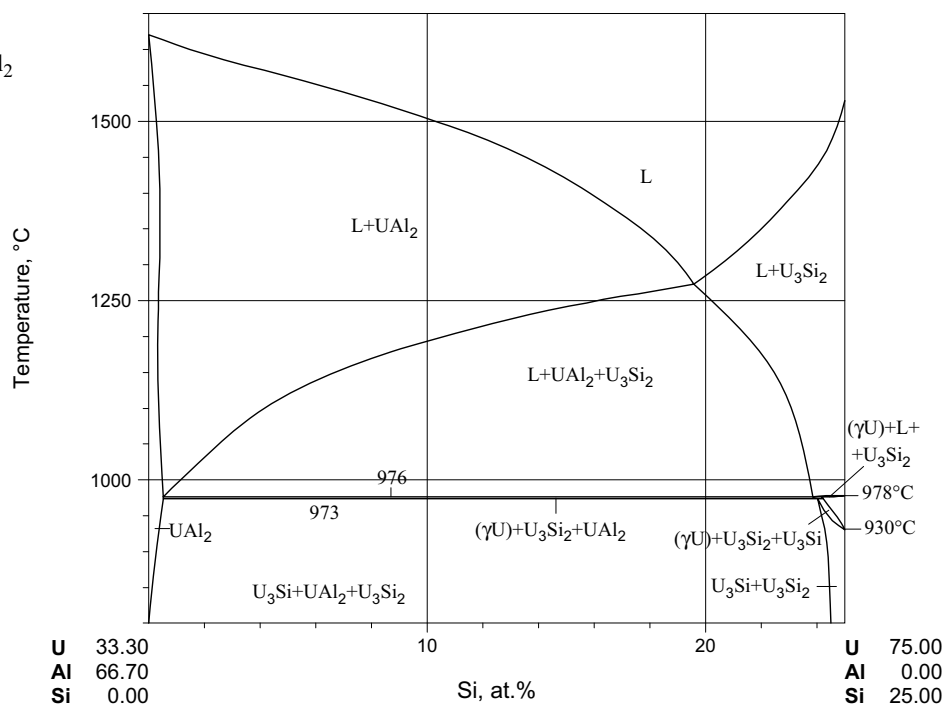


Fig. 8: Al-Si-U.
Magnetic phase diagram for $U_3Al_2Si_3$; the solid line is the phase boundary between the paramagnetic and the (non-collinear) ferromagnetic region. The inset shows the spin distribution and spin orientation for the three uranium atom sites

