Aluminium - Copper - Magnesium

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Introduction

This system was previously evaluated in this series by [91Eff]. Their evaluation has been used by two groups as the basis for thermodynamic assessments and phase diagram calculations [93Zuo, 96Zuo, 97Che] and [98Buh, 2000Jan]. Some experiments have been performed to support these calculations [95Hua, 95Kim, 95Soa, 98Fau] and [99Fau]. The equilibria in the Al-Cu-Mg system are complicated by the existence of six ternary phases. There is need for experiments to clarify the ternary equilibria involving the three Laves phases, $\lambda_{1\text{-}3}$, which have clearly been identified as three separate phases. The λ_1 phase with a Cu_2Mg type structure is a solution phase of the binary Cu_2Mg compound with replacement of the Cu atoms by Al along the 33.3 at.% Mg section. At a composition close to the $AlCu_3Mg_2$ formula, the λ_1 phase melts congruently at ~910°C. Further replacement of Cu by Al stabilizes the λ_2 phase with a $MgNi_2$ type structure and then the λ_3 phase with a $MgZn_2$ type structure. A variety of polytype structures with different atom layer stacking sequences have been observed between the $MgNi_2$ and $MgZn_2$ type phases. The $\lambda_{2\text{-}3}$ phases appear to be formed by peritectic reaction and each Laves phase is associated with a region in which it forms as the primary phase on solidification of melts. Four additional ternary compounds have also been studied extensively. The S phase is based on the Al_2CuMg composition, V on $Al_5Cu_6Mg_2$ and Q on $Al_7Cu_3Mg_6$. These three phases exist over very limited homogeneity ranges. The T phase has a broad range of homogeneity. A formula $(Al_xCu_{1-x})_{49}Mg_{32}$ is derived from the crystal structure [52Ber], but also some mutual replacement between Mg and Cu+Al takes place.

The liquidus projection, presented by [52Ura], does not include the monovariant curves associated with the $L+\lambda_1 \rightleftharpoons \lambda_2$ and $L+\lambda_2 \rightleftharpoons \lambda_3$ peritectic reactions. The Laves phase λ_1 is the predominant primary phase, but also the regions for primary solidification of (Al) and (Mg) are relatively large. Six pseudobinary reactions have been identified experimentally, and the pseudobinary reaction e_3 (Table 2b) has been suggested. The invariant reactions associated with the primary (Al) phase region are well characterized by numerous workers. The invariant reactions associated with the primary V, Q and T phase regions have been elucidated by Russian workers, summarized by [52Ura]. The liquidus surface across the Al_3Mg_2, T and $Al_{12}Mg_{17}$ phase regions is exceptionally flat and ranges in temperature from 420 to 475°C. [52Ura] gave a complete reaction scheme. The thermodynamic calculations referred to above in principle reproduce this reaction scheme, but differ in some details.

Binary Systems

Assessments of the Al-Cu system by [85Mur] and [Mas2] and of the Cu-Mg system by [84Nay] are accepted. The Al-Mg system is accepted from the assessment of [90Sau] except for the central composition region which had to be changed following new experimental results from [98Lia]. For the calculated figures and the reaction scheme the calculated diagrams of the COST 507 action [98Ans] were used; there some phases with small homogeneity range are simplified to stoichiometric phases, β_0 is neglected, η_1 and η_2 were considered as a single phase, η, and

also ζ_1 and ζ_2 were not distinguished and called ζ.

Solid Phases

There are four well-defined ternary phases, designated in the literature as Q, S, T and V phases. In addition the section at 33.3 at.% Mg contains a complex series of ternary Laves-Friauf phases that are designated as λ_1, λ_2, λ_3, 5L, 6L, 9L and 16L in this assessment, Table 1. The Q phase is based on the chemical formula $Al_7Cu_3Mg_6$ [47Str, 51Mir1] and has a very limited homogeneity range. The S phase has been extensively studied [36Lav1, 37Nis, 38Pet1, 38Pet2, 40Kuz, 41Obi, 43Per, 44Lit, 46Pet, 46Ura, 47Str, 49Mir]. It also has a limited homogeneity range, based on the chemical formula Al_2CuMg. Its structure was determined by [43Per] and confirmed by [49Mir]. The T phase has been equally thoroughly investigated [19Vog, 23Gay, 35Lav, 37Nis, 40Kuz, 43Gue, 44Lit, 46Pet, 46Ura, 48Str, 49Ura1, 49Ura2, 50Phr, 52Ber, 66Aul] and a variety of chemical formulae assigned to it. From the crystal structure determined by [52Ber], the formula $(Al_xCu_{1-x})_{49}Mg_{32}$ is adequate. The V phase has a small region of homogeneity centered on the $Al_5Cu_6Mg_2$ formulation [36Lav1, 36Lav2, 37Sch, 43Gue, 47Str, 48Str, 49Sam, 49Ura1, 51Mir3, 52Ura] although other chemical formulae have been quoted in the literature. Its structure was determined by [49Sam] with the ideal formula $Al_5Cu_6Mg_2$. The Laves-Friauf phases, although well studied, have not been integrated experimentally into the ternary equilibria in a satisfactory manner. The λ_1 phase with a Cu_2Mg type structure is based on the Cu_2Mg binary compound with a substitution of Al atoms for Cu to form a solid solution series. At a composition close to $AlCu_3Mg_2$, the λ_1 phase melts congruently [36Lav1, 52Ura]. With further replacement of Cu by Al on the 33.3 at.% Mg section, an $MgNi_2$ type phase is stable, λ_2. There is general agreement between [53Kle, 65Sli, 77Kom, 81Mel1] and [81Mel2] on the extent of the λ_2 phase region; earlier work did not detect λ_2 [34Lav, 43Gue, 49Ura1] or regarded it as stable at high temperature only [36Lav1]. The $MgZn_2$ type structure, λ_3, is formed with further substitution of Cu atoms by Al. The results from the different workers are summarized in Fig. 1. Polytype structures with variations in the layer stacking sequences have been studied by [62Kom, 77Kit, 77Kom] and [81Mel1]; they may be metastable phases. [98Che] proposed a "new intermetallic compound $Mg_{1.75}Cu_{1.0}Al_{0.4}$" at a composition, where [91Eff] and the calculations [97Che, 98Buh, 2000Jan] assume two phases, λ_1 and (Mg). The characteristics of this "new phase", however, clearly identify it as the λ_1 phase. Most probably the also present (Mg) phase was not detected in the X-ray patterns due to line broadening by cold deformation.

Pseudobinary Systems

A number of pseudobinary systems have been reported. The calculation [2000Jan] found 13 maxima of three-phase equilibria, but some of them are less than 1 K above an adjacent four-phase equilibrium and must be taken as tentative only. The (Mg)-λ_1 section is a pseudobinary eutectic [32Por, 33Bas, 34Por, 49Ura2], e_{13}, Table 2. The (Al)-S section contains a pseudobinary eutectic [37Nis, 46Ura, 48Bro, 52Han] e_{14}. The calculated temperatures [2000Jan] of both equilibria are far below those given by [46Ura] and accepted by [91Eff]. The sections Al_3Mg_2-T, e_{19}, and $Al_{12}Mg_{17}$-T, e_{16}, are also pseudobinary eutectic sections at Cu contents below the beginning of the primary Q phase region. [43Gue, 49Ura1, 49Ura2, 51Mir2] and [2000Jan] are in agreement on the nature of these two sections, Table 2. The investigation [51Mir2] of the region of primary solidification of Q led to the conclusion that the T phase is formed by peritectic reaction with Q at p_{13}, Fig. 2(a, b). A pseudobinary reaction was indicated by [46Ura] who found a maximum on the curve U_9U_{13} corresponding with the peritectic formation of S by reaction of liquid with a Laves phase. [49Ura1, 49Ura2] and [52Ura] refer to the cubic Cu_2Mg type phase λ_1 or to a composition AlCuMg. They take no account of the λ_2 and λ_3 Laves phases. The calculation of [2000Jan] gives λ_2 as the Laves phase participating in

this reaction, p_{10}, which is also favoured by [91Eff]. [38Pet1] regarded the $CuAl_2$-S section as a pseudobinary, but later work has disproved this assumption.

Invariant Equilibria

Table 2 lists the invariant reactions following from the thermodynamic calculation of [2000Jan] for the Al-Cu-Mg ternary system and may be read in conjunction with Fig. 2. The reaction scheme, following from this calculation is given in Fig. 3(a, b, c, d). In this calculation the phase β_0 is neglected, η_1 and η_2 as well as ζ_1 and ζ_2 were considered as single phases and called η and ζ, respectively. The ternary eutectic reaction E_5 has been widely studied, Table 3. The flat nature of the liquidus surface near to E_7 has led to a considerable scatter in quoted compositions and temperatures, Table 4. The reaction has normally been quoted as a ternary eutectic reaction and this is accepted. The transition reaction U_{16} has also been widely studied, Table 5. The work of [46Ura, 49Ura2] and [48Bro] rests on an examination of a greater number of alloys than other work and allowed a more precise determination of the liquid composition at U_{16}.Ternary eutectic reactions in Mg-rich alloys occur at E_6 and E_9. The reaction temperature at E_6 is 1 K [32Por, 33Bas, 34Por] or 2 K [49Ura2] below the binary Cu-Mg eutectic temperature. The ternary eutectic E_9, Table 6, was initially regarded as involving a Laves phase, but the work of [51Mir2] indicates that this eutectic involves the Q phase, which was not detected by the previous workers. Faudot et al. [98Fau, 99Fau] confirmed the eutectic, Table 6. The ternary eutectic reaction at E_9 was found by [49Ura2] at 525°C, what is much lower than calculated by [2000Jan], 544°C. The reaction at U_{13} was regarded as a transition reaction by [37Nis, 52Han], as calculated by [2000Jan], whereas [46Ura] and [49Ura2] considered it to be a ternary peritectic reaction, $L+\lambda_1+S \rightleftharpoons T$. [51Mir2] gives it as $L+\lambda_1+S \rightleftharpoons Q$. There is doubt about this reaction on two counts. The Q phase lies virtually on the L-λ_1 tie line [52Ura] and it is unlikely that the Laves phase is λ_1. For the reactions U_{15} and U_{18} [2000Jan] reproduced those given by [51Mir2] with 3 K deviation. For U_{18} Faudot et al. [98Fau] gave 427°C as calculated [98Buh, 2000Jan] but later [99Fau] they found it at 451°C with a more Al-rich liquid, Table 6. The transition reaction at U_{17} was given by [51Mir2] as $L+\lambda_1 \rightleftharpoons (Mg)+Q$, but the work of [81Mel2] indicates λ_3 as the reactant rather than λ_1, whereas [98Fau, 99Fau, 2000Jan] assume λ_2. The reactions in the Cu-rich corner have been little studied. In Table 2 are given those calculated by [2000Jan]. [49Ura2] assumed an eutectic instead of U_2 and a transition reaction instead of E_4. The temperatures of the invariant equilibrium in this area calculated by the two groups [97Che] and [98Buh, 2000Jan] deviate up to 20°C. The regions of primary solidification of the Laves phases λ_1, $\lambda_2$and λ_3 have not been experimentally defined, but the calculation [2000Jan] gives them as shown in Fig. 2 (a, b). [97Che] did not distinguish these Laves phases.

Liquidus Surface

A liquidus projection, Fig. 2b, is taken from the calculation of [2000Jan]. It should be compared with the projection, Fig. 2a. The liquidus isotherms reproduce fairly well those assessed by [91Eff]. The primary (Al) region has been widely studied with general agreement on the form of the liquidus. The isotherms for the region of primary solidification of the series of Cu-rich Cu-Al phases are uncertain.

Isothermal Sections

The calculated 400°C isothermal section, Fig. 4, agrees with Fig. 4 of [91Eff] except the broadening of the homogeneity range of λ_1 near 25 at.% Al, which in calculation needs to model an anomality in the Gibbs energy description at that composition, but there is no other evidence for an anomality. The phase Al_3Mg_2 is simplified as a stoichiometric phase

The solubility of Cu and Mg in Al-rich alloys at 460°C was determined by [44Lit] and [47Str], Fig. 5. [44Lit] also produced data for 375°C. The results of [32Dix] agree with the solubilities given in Fig. 5. [46Pet] found lower Mg solubilities but used fewer alloys. [55Zam] published solubility curves with a series of cusps that cannot be reconciled with the alloy constitution. The calculated solvus isotherms of [86Cha] and [2000Jan], Fig. 6, are in good agreement with [44Lit] and [47Str]. [57Rog] reported on the solubility of Al and Mg in Cu, Fig. 7. No comparable work has appeared. In this area the calculation is less reliable, as it cannot be based on adjacent experimental data. More extensive isothermal sections were determined by [46Pet] at 400°C in the region from Al to S and T. [49Mir] reported on the S phase region at 420°C, [49Ura1] on the T and λ_1 phase region at 400°C, [51Mir1] on the Q phase region at 400°C, [52Ura] on an almost complete isothermal section at 400°C and [81Mel2] on the region from 33.3 to 100 at.% Mg at 400°C. [44Lit] and [47Str] studied the 460°C isothermal section from Al to θ, S, Q and T phases.

Miscellaneous

[72Pre] studied the enthalpy of formation of alloys on the 33.3 at.% Mg section. Substitution of Cu by Al increases the stability of the λ_1 phase although there is a decrease of stability at a valency electron concentration of 1.5 (76.9Cu, 17.3Mg). [87Hoc] calculated the enthalpy of a ternary alloy containing 33.3% "Al_2Mg"; agreement with [72Pre] is fair. [85Kuz] applied a thermodynamic model to predict the ternary solidus from the ternary liquidus and the binary solidus-liquidus for Al-rich alloys. [73Dav] used quasi-chemical regular solution theory to calculate the monovariant curve e_2E_5 of Fig. 2a. With the introduction of a ternary interaction parameter the calculated ternary eutectic point E_5, Table 3, shows reasonable agreement with the assessed composition. [87Lac] calculated the Al-rich region of the phase diagram using an extended Redlich-Kister formalism. Excellent agreement was obtained with the assessed liquidus, Fig. 2b. [85Far] calculated the composition of the ternary eutectic E_5, Fig. 2a and Table 2, assuming both ideal solution behaviour and regular solution behaviour. The calculated eutectic compositions, 34.4 Cu, 8.8 mass% Mg for ideal solutions and 30.3 Cu, 7.5 mass% Mg for regular solutions, approximate to the assessed values. The calculated eutectic temperatures are surprisingly low at 273 and 271°C, respectively. Recently two groups [97Che] and [98Buh, 2000Jan] calculated the whole ternary system, describing the Gibbs energies of all phases involved by the compound energy formalism. Both calculations show very similar results, only in the Cu-rich part there is some disagreement of the invariant temperatures (up to 20°C). The first group also calculated solidification paths using the model of Scheil [93Zuo, 96Zuo].

[86Che] measured the enthalpy of fusion of the ternary eutectic E_5 as 365 J/g. [86Not] measured the enthalpy of formation of the S phase as -63.2 $\pm$4.0 kJ/mol of Al_2CuMg. [95Kim] measured the enthalpy of mixing of ternary liquids by a high temperature calorimeter at 986 K along three lines with constant Al/Mg ratios up to 40 at.% Cu and along Al/Cu = 13/7 up to 27 at.% Mg. [95Soa] measured the chemical potential of Mg in ternary melts by an isopiestic method.

[40Kuz] and [46Kuz] measured lattice spacings of the (Al) phase along sections from Al with various Cu:Mg ratios. [51Poo] measured the lattice spacings of the (Al) phase along sections from 99 Al, 1 at.% Mg to 99.5 Al, 0.5 at.% Cu and from 98 Al, 2 at.% Mg to 99 Al, 1 at.% Cu, Table 7.

The crystal structure of a metastable variant of S on aging Al alloys was studied by [50Bag]. Aging studies of single crystals of an alloy containing 1.2 at.% Cu, 1.2 at.% Mg [78Ale] showed S particles to be coherent with the Al matrix. The effect of aging on mechanical properties of Al-rich alloys have been reported by [39Han, 41Mec] and [48Sha]. More recent studies on metastable precipitates in (Al) are from [90Gar] and [91Jin].

[59Pal] prepared thin film Al-rich ternary alloys by evaporation on to Al substrates. The

constitution is claimed to correspond with bulk samples. There is a growing literature on the formation of a non-equilibrium icosahedral quasicrystalline phase by rapid solidification of alloys in the T phase region. [86Cas] tentatively outlined the phase region that produces quasicrystals on rapid solidification as containing 10 to 13.5 at.% Cu, 35 to 37 at.% Mg. This composition range is on the low Mg side of the equilibrium T phase region. Annealing a rapidly solidified alloy with 1 Cu, 5 at.% Mg for 100 h at 190°C gave both the icosahedral phase and the equilibrium T phase at the grain boundaries of the Al matrix. For anneals of 24 h at 250°C only the T phase was observed at the grain boundary [86Cas, 87Cas] with precipitation of the S phase in the Al matrix. [87San1] and [87San2] rapidly solidified an alloy corresponding to Al_6CuMg_4. This composition lies in the T phase region. DSC measurements gave a melting point of 474.9°C which is in good agreement with the assessed temperature of the pseudobinary reaction p_6, L+Q ⇌T, Fig. 3(a, b, c, d). A polymorphic transformation of the T phase, reported at 356.5°C, has not been noted by other workers. [88She] rapidly solidified an alloy containing 51Al, 12.5Cu, 36.5 at.% Mg and found it to be a single phase icosahedral quasicrystal. This composition is within the phase region given by [86Cas]. A wider, but less exact, delineation of the icosahedral quasicrystal phase region was given by [88Shi]. They quote the composition as typically Al_5CuMg_4, as proposed by [37Nis] for the stable T phase. [88San] rapidly solidified the composition Al_6CuMg_4 and carried out a detailed X-ray study of the quasicrystalline phase and its transformation to the crystalline T phase by annealing for 1 h at 340°C. [89She] used high resolution X-ray diffraction to study atomic distribution in quasicrystalline phases as well as differential scanning calorimetry (DSC) to get thermodynamic properties. [91Wit] prepared and studied an icosahedral alloy with composition $Al_{51}Cu_{12.5}Mg_{36.5}$ by electrical resistivity measurements and DSC.

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Table 1: Solid Phases

Phase/ Temperature Range (°C)	Pearson Symbol/ Prototype	Lattice Parameters (pm)	Comments
(Al)	cF4 Cu	a = 404.88	at 24°C [V-C]
(Cu)	cF4 Cu	a = 361.48	at 25°C [V-C]
(Mg)	hP2 Mg	a = 320.94 c = 521.01	at 25°C [V-C]
Θ, Al_2Cu < 591	tI12 Al_2Cu	a = 606.3 c = 487.2	[85Mur]
η_1, AlCu(h) 624-560	oP16	a = 410 b = 1202.4 c = 865	[85Mur]
η_2, AlCu(r) < 569	mC20 AlCu(r)	a = 1206.6 b = 410.5 c = 691.3 β = 55.04°	[85Mur]
ζ_1, ~Al_4Cu_5 590-530	hP42	a = 810 c = 1000 or 1237?	[85Mur]
ζ_2, Al_4Cu_5 < 570	monocl.	a = 707 b = 408 c = 1002 β = 90.63°	[85Mur]
ϵ_1, Al_4Cu_5 958-848	cubic (?)	-	[85Mur]
ϵ_2, $AlCu_{1+x}$ 850-560	hP4 AsNi	a = 414.6 c = 506.3	$0.47 \leq x \leq 0.78$ [85Mur] (55 to 61 at.% Cu)
δ, Al_3Cu_2	rhomboh.	a = 869 α = 89.78°	[85Mur]

γ_0, Al_4Cu_9(h) 1022-780	-	-	[85Mur]
γ_1, Al_4Cu_9(r) < 873	cP52 Al_4Cu_9	a = 870.68	[85Mur]
β_0, $AlCu_3$(h_2) 1037-964	-	-	[85Mur]
β, $AlCu_3$(h_1) 1049-567	cI2 W	a = 295.64	[85Mur]
$CuMg_2$	oF48 $CuMg_2$	a = 905.0 b = 1824.7 c = 528.3	[84Nay]
Al_3Mg_2	cF1168 ~Cd_2Na	a = 2823.9	[82Mur]
$Al_{12}Mg_{17}$	cI58 ~αMn	a = 1054.38	[82Mur]
X, $Al_{30}Mg_{23}$	hR53 -	a = 1282.54 c = 2174.78	[81Sch, V-C]
Y, $Al_{52}Mg_{48}$	-	-	[81Sch], does not exist after [98Lia]
λ_1, $(Al_xCu_{1-x})_2M$ Cu_2Mg	cF24 Cu_2Mg	 a = 701.3 a = 711.7	$0 \leq x \leq 0.35$ [36Lav1] at x = 0 at x = 0.35
*Q, $Al_7Cu_3Mg_6$	cI96	a = 1208.7	[51Mir1]
*S, Al_2CuMg	oC16 BRe_3	a = 401 b = 925 c = 715	[43Per]
*T, $(Al_xCu_{1-x})_{49}Mg_{32}$	cI162 $Mg_{32}(Al,Zn)_{49}$	a = 1428 to 1435	[52Ber] composition dependent
*V, $Al_5Cu_6Mg_2$	cP39 Mg_2Zn_{11}	a = 827	[49Sam]
*λ_2, $(Al_{1-x}Cu_x)_2Mg$ 870-650?	hP24 $MgNi_2$	a = 509.8 to 510.2 c = 1664 to 1676	$0.35 \leq x \leq 0.54$ [36Lav1]

*λ_3, $(Al_{1-x}Cu_x)_2Mg$	hP12 $MgZn_2$	a = 507 to 512 c = 829 to 839	$0.35 \leq x \leq 0.60$ [36Lav1]
*5L, $(Al,Cu)_2Mg$	hP30	a = 514 c = 2105	stacking variation of Laves phases observed by electron diffraction [62Kom]
*6L, $(Al,Cu)_2Mg$	hP36	a = 510 c = 2500 a = 514 c = 2530	stacking variation of Laves phases observed by electron diffraction [77Kit] [77Kom]
*9L, $(Al,Cu)_2Mg$	hR18	a = 1297 α = 22°50	[62Kom], stacking variation of Laves phases observed by electron diffraction [77Kom]
*16L, $(Al,Cu)_2Mg$	hP96	a = 510 c = 6670 a = 514 c = 6740	stacking variation of Laves phases observed by electron diffraction [77Kit] [77Kom]

Table 2a: Invariant Four-Phase Equilibria

T (°C) Reaction	Type	Phase	Composition (at.%)		
			Al	Cu	Mg
876.4 $\gamma_0 + \varepsilon_1 \rightleftharpoons L + \gamma_1$	U_1	γ_0 ε_1 L γ_1	34.2 36.8 39.2 35.0	65.8 62.8 56.4 65.0	0.0 0.4 4.4 0.0
827.6 $\varepsilon_1 \rightleftharpoons L + \gamma_1 + \varepsilon_2$	E_1	ε_1 L γ_1 ε_2	39.7 43.4 36.1 42.0	59.9 52.4 63.9 58.0	0.4 4.2 0.0 0.0
804.0 $L \rightleftharpoons \gamma_0 + \gamma_1 + \lambda_1$	E_2	L γ_0 γ_1 λ_1	25.1 31.8 32.7 16.3	59.6 68.2 67.3 50.6	15.3 0.0 0.0 33.1
803 $L \rightleftharpoons \beta + \gamma_0 + \lambda_1$	E_3	L β γ_0 λ_1	21.8 27.5 31.3 14.2	62.8 71.4 68.7 52.8	15.4 1.1 0.0 33.0
782.8 $L + \beta \rightleftharpoons (Cu) + \lambda_1$	U_2	L β (Cu) λ_1	12.9 20.7 17.8 8.6	70.2 78.3 81.1 58.7	16.9 1.0 1.1 32.7
782.1 $\gamma_0 + \lambda_1 \rightleftharpoons \beta + \gamma_1$	U_3	γ_0 λ_1 β γ_1	31.2 14.0 27.2 31.4	68.8 53.0 71.7 68.6	0.0 33.0 1.1 0
739.9 $L + \gamma_1 \rightleftharpoons \varepsilon_2 + \lambda_1$	U_4	L γ_1 ε_2 λ_1	38.7 36.3 42.5 23.4	48.4 63.7 57.5 43.4	12.9 0.0 0.0 33.2

692	D_1	ε_2	42.8	57.2	0.0
$\varepsilon_2 + \gamma_1 \rightleftharpoons \delta, \lambda_1$		γ_1	36.3	63.7	0.0
		δ	40.0	60.0	0.0
		λ_1	23.4	43.3	33.2
666.5	P_1	L	48.4	39.3	12.3
$L + \varepsilon_2 + \lambda_1 \rightleftharpoons V$		ε_2	44.5	55.5	0.0
		λ_1	28.0	38.9	33.1
		V	38.5	46.1	15.4
623.5	U_5	ε_2	43.9	56.1	0.0
$\varepsilon_2 + \lambda_1 \rightleftharpoons \delta + V$		λ_1	25.5	41.3	33.2
		δ	40.0	60.0	0.0
		V	38.5	46.1	15.4
599.0	U_6	L	57.6	33.5	8.9
$L + \varepsilon_2 \rightleftharpoons \eta + V$		ε_2	45.8	54.2	0.0
		η	49.0	51.0	0.0
		V	38.5	46.1	15.4
582.7	D_2	ε_2	44.4	55.6	0.0
$\varepsilon_2 \rightleftharpoons \delta + \zeta, V$		δ	40.0	60.0	0.0
		ζ	45.0	55.0	0.0
		V	38.5	46.1	15.4
579.3	D_3	ε_2	45.7	54.3	0.0
$\varepsilon_2 \rightleftharpoons \eta + \zeta, V$		η	48.9	51.1	0.0
		ζ	45.0	55.0	0.0
		V	38.5	46.1	15.4
564.6	E_4	β	22.8	76.9	0.3
$\beta \rightleftharpoons (Cu) + \gamma_1 + \lambda_1$		(Cu)	20.4	79.3	0.3
		γ_1	29.6	70.4	0.0
		λ_1	10.2	56.7	33.1
557.8	U_7	L	60.1	27.2	12.7
$L + \lambda_1 \rightleftharpoons \lambda_2 + V$		λ_1	32.8	34.3	32.9
		λ_2	36.5	31.0	32.5
		V	38.5	46.1	15.4
555.3	U_8	L	62.0	29.1	8.9
$L + \eta \rightleftharpoons \theta + V$		η	49.6	50.4	0.0
		θ	67.0	33.0	0.0
		V	38.5	46.1	15.4

554.3	U_9	L	60.5	27.0	12.5
$L + \lambda_2 \rightleftharpoons S + V$		λ_2	36.6	30.9	32.5
		S	50.0	25.0	25.0
		V	38.5	46.1	15.4
543.9	U_{10}	L	62.2	26.9	10.9
$L + V \rightleftharpoons \theta + S$		θ	7.0	33.0	0.0
		S	50.0	25.0	25.0
		V	38.5	46.1	15.4
533.6	U_{11}	L	59.0	10.8	30.2
$L + \lambda_2 \rightleftharpoons \lambda_3 + S$		λ_2	39.1	27.9	33.0
		λ_3	40.4	26.3	33.3
		S	50.0	25.0	25.0
527.0	U_{12}	L	46.8	7.7	45.5
$L + \lambda_3 \rightleftharpoons \lambda_2 + Q$		λ_3	40.1	26.5	33.4
		λ_2	38.5	28.3	33.2
		Q	43.8	18.7	37.5
513.1	U_{13}	L	59.0	8.3	32.7
$L + \lambda_3 \rightleftharpoons Q + S$		λ_3	41.0	25.6	33.3
		Q	43.8	18.7	37.5
		S	50.0	25.0	25.0
501.9	E_5	L	73.9	15.5	10.6
$L \rightleftharpoons \theta + (Al) + S$		θ	67.8	32.2	0.0
		(Al)	95.7	1.7	2.6
		S	50.0	25.0	25.0
497.3	U_{14}	L	18.6	7.1	74.3
$L + \lambda_1 \rightleftharpoons \lambda_2 + (Mg)$		λ_1	31.0	35.5	33.5
		λ_2	34.6	32.0	33.4
		(Mg)	3.8	0.0	96.2
481.2	E_6	L	1.1	16.6	82.3
$L \rightleftharpoons \lambda_1 + CuMg_2 + (Mg)$		λ_1	19.2	47.1	33.7
		$CuMg_2$	0.0	33.3	66.7
		(Mg)	0.1	0.1	99.8
477.0	U_{15}	L	64.8	5.4	29.8
$L + Q \rightleftharpoons T + S$		Q	43.8	18.7	37.5
		T	52.1	8.2	39.7
		S	50.0	25.0	25.0

469.2 L + S ⇌ T + (Al)	U_{16}	L S T (Al)	67.0 50.0 52.4 89.2	4.9 25.0 8.1 0.3	28.1 25.0 39.5 10.5
456.6 L + λ_2 ⇌ Q + (Mg)	U_{17}	L λ_2 Q (Mg)	26.0 37.1 43.8 7.3	4.2 29.5 18.7 0.0	69.8 33.4 37.5 92.7
447.6 L ⇌ T + Al_3Mg_2 +(Al)	E_7	L T Al_3Mg_2 (Al)	63.5 55.4 61.1 83.6	0.5 4.1 0.0 0.0	36.0 40.5 38.9 16.4
447.6 L ⇌ T + Al_3Mg_2 + $Al_{12}Mg_{17}$	E_8	L T Al_3Mg_2 $Al_{12}Mg_{17}$	57.4 55.1 61.1 51.9	0.3 3.4 0.0 0.0	42.3 41.5 38.9 48.1
426.8 L + T ⇌ Q + $Al_{12}Mg_{17}$	U_{18}	L T Q $Al_{12}Mg_{17}$	31.6 48.1 43.8 40.3	1.8 9.0 18.7 0.0	66.6 42.9 37.5 59.7
424.9 L ⇌ (Mg) + Q + $Al_{12}Mg_{17}$	E_9	L (Mg) Q $Al_{12}Mg_{17}$	31.1 11.1 43.8 40.0	1.7 0.0 18.7 0.0	67.2 88.9 37.5 60.0
412.1 Q + $Al_{12}Mg_{17}$ ⇌ T + (Mg)	U_{19}	Q $Al_{12}Mg_{17}$ T (Mg)	43.8 40.2 48.1 10.5	18.7 0.0 9.2 0.0	37.5 59.8 42.7 89.5
409.8 Al_3Mg_2 + $Al_{12}Mg_{17}$ ⇌ ⇌ $Al_{30}Mg_{23}$, T	D_4	Al_2Mg_3 $Al_{12}Mg_{17}$ $Al_{30}Mg_{23}$ T	61.1 50.6 56.6 55.2	0.0 0.0 0.0 3.4	38.9 49.4 43.4 41.4
250.1 $Al_{30}Mg_{23}$ ⇌ ⇌ Al_3Mg_2 + $Al_{12}Mg_{17}$, T	D_5	$Al_{30}Mg_{23}$ Al_2Mg_3 $Al_{12}Mg_{17}$ T	56.6 61.1 46.4 55.8	0.0 0.0 0.0 3.5	43.4 38.9 53.6 40.7

Table 2b: Invariant Maxima of Two- and Three-Phase Equilibria

T (°C) Reaction	Type	Phase	Composition (at.%)		
			Al	Cu	Mg
909.3 L ⇌ λ_1	-	L λ_1	16.1 16.1	50.5 50.5	33.4 33.4
804.4 L ⇌ γ_0 + λ_1	e_3	L γ_0 λ_1	24.2 31.6 15.8	60.4 68.4 51.1	15.4 0.0 33.1
804.0 L ⇌ γ_1 + λ_1	e_4	L γ_1 λ_1	25.1 32.7 16.3	59.6 67.3 50.6	15.3 0.0 33.1
800.4 L ⇌ β + λ_1	e_5	L β λ_1	20.9 26.9 13.7	63.5 72.0 53.3	15.6 1.1 33.0
601.6 L+ λ_1 ⇌ λ_2	p_8	L λ_1 λ_2	51.5 33.9 37.0	16.4 32.9 29.9	32.1 33.2 33.1
566.5 L ⇌ λ_1 + $CuMg_2$	e_{10}	L λ_1 $CuMg_2$	0.2 9.3 0.0	33.9 56.6 33.3	65.9 34.1 66.7
565.6 L + λ_2 ⇌ S	p_{10}	L λ_2 S	60.8 37.5 50.0	20.9 29.8 25.0	18.3 32.7 25.0
537.8 L + λ_2 ⇌ λ_3	p_{11}	L λ_2 λ_3	54.4 38.8 40.3	9.7 28.1 26.4	35.9 33.1 33.3
528.2 L ⇌ λ_1 + (Mg)	e_{13}	L λ_1 (Mg)	7.8 26.3 1.1	10.7 40.1 0.0	81.5 33.6 98.9

527.5 L + λ_3 ⇌ Q	p_{12}	L λ_3 Q	49.1 40.3 43.8	7.9 26.3 18.7	43.0 33.4 37.5
505.2 L ⇌ (Al) + S	e_{14}	L (Al) S	73.5 95.1 50.0	12.6 1.2 25.0	13.9 3.7 25.0
495.0 L + Q ⇌ T	p_{13}	L Q T	53.5 43.8 51.1	4.8 18.7 8.3	41.7 37.5 40.6
457.2 L ⇌ $Al_{12}Mg_{17}$ + T	e_{16}	L $Al_{12}Mg_{17}$ T	48.0 47.1 52.4	0.9 0.0 5.4	51.1 52.9 42.2
449.3 L ⇌ Al_3Mg_2 + T	e_{19}	L Al_3Mg_2 T	60.5 61.1 55.3	0.4 0.0 3.8	39.1 38.9 40.9

Table 3: Reported data for the invariant reaction E5.

Temperature (°C)	Liquid composition (mass%)		Reference	Comment
	Cu	Mg		
500	26.8	6.2	[37Nis]	-
500	29.7	7.2	[46Ura, 49Ura2]	-
507	33.0	6.1	[48Bro]	-
-	29.0	6.5	[50Phr]	scaled from figure
506.5	33.1	6.8	[52Han]	-
506	33.0	7.0	[67Coo]	unidirect. solidificat.
506	33.1	6.25	[72Gar]	unidirect. solidificat.
507	33.0	7.1	[73Dav]	-
507	34.0	7.6	[73Dav]	calculated
507	30.0	6.0	[76Mon]	-
506±1	-	-	[80Bir]	d.s.c
506.6	33.4	7.2	[87Lac]	calculated
503	32.0	7.2	[95Hua]	DTA
503±2	33.4	6.95	[97Che]	calculated
503	30.4	8.0	[98Buh]	calculated
501.9	30.4	8.0	[2000Jan]	calculated

Table 4: Reported data for the invariant reaction E7.

Temperature (°C)	Liquid Composition (mass%)		Reference
	Cu	Mg	
451	~0.0	35.0	[19Vog]
447	3	32	[37Nis]
445	1.5	33	[46Ura, 49Ura2]
451	~2.7	~32	[48Bro]
450	~3.5	~32	[52Han]
-	4	31.5	[50Phr]
~450	2.8	32	[51Mir2]
443	3.4	34	[87Lac]
448±5	1.34	34.2	[97Che]
448	1.5	33.3	[98Buh]
447.6	1.3	33.4	[2000Jan]

Table 5: Reported data for the invariant reaction U16.

Temperature (°C)	Liquid Composition (mass%)		Reference	Comment
	Cu	Mg		
471	10	27	[19Vog]	-
465	11	25	[37Nis]	-
465	10	25.6	[46Ura]	-
462	10	25.6	[49Ura2]	-
467	10	26	[48Bro]	-
465	9.3	26.5	[51Mir2]	-
472.3	11.3	25.7	[52Han]	scaled from figure
467	10	26	[76Mon]	-
468	11.4	25.5	[87Lac]	assessment
467±4	10.7	26.1	[97Che]	calculated
469	11.1	24.6	[98Buh]	calculated
409.2	11.2	24.4	[2000Jan]	calculated

Table 6: Reported data for the Mg-rich invariant reactions E9, U17 and U18.

Temperature (°C)	Liquid Composition (mass%)		Reference	Invariant Reaction
	Cu	Mg		
412	17	56.5	[33Bas,	L
419-420	6	62.2	34Por]	⇌(Mg)+$Al_{11}Mg_{17}$+λ
423	4.6	67	[40Han]	L
425	6	63	[49Ura2]	⇌(Mg)+$Al_{11}Mg_{17}$+λ
423.6	5.4	62.6	[51Mir2]	L
426	4.4	63.2	[97Che]	⇌(Mg)+$Al_{11}Mg_{17}$+λ
425	4.2	63.3	[98Buh]	L
427	5	63	[98Fau]	⇌(Mg)+$Al_{12}Mg_{17}$+Q
424.9	4.3	63.3	[99Fau]	L
			[2000Jan]	⇌(Mg)+$Al_{12}Mg_{17}$+Q
				L
				⇌(Mg)+$Al_{12}Mg_{17}$+Q
				L
				⇌(Mg)+$Al_{12}Mg_{17}$+Q
				L
				⇌(Mg)+$Al_{12}Mg_{17}$+Q
				L
				⇌(Mg)+$Al_{12}Mg_{17}$+Q
452.0	11.3	62.7	[97Che]	L+λ_2 ⇌ (Mg)+Q
457	10.0	63.7	[98Buh]	L+λ_2 ⇌ (Mg)+Q
447	10	64	[99Fau]	L+λ_2 ⇌ (Mg)+Q
456.6	9.9	63.7	[2000Jan]	L+λ_2 ⇌ (Mg)+Q
444.0	6.0	52.9	[97Che]	L+T ⇌ $Al_{12}Mg_{17}$+Q
428	4.4	62.3	[98Buh]	L+T ⇌ $Al_{12}Mg_{17}$+Q
425	4.4	62.6	[98Fau]	L+T ⇌ $Al_{12}Mg_{17}$+Q
451	9.6	64.0	[99Fau]	L+T ⇌ $Al_{12}Mg_{17}$+Q
426.8	4.4	62.6	[2000Jan]	L+T ⇌ $Al_{12}Mg_{17}$+Q

Table 7: Lattice Parameters, a,of the (Al) phase [51Poo] at 25°C

Analysed Composition		Observed	Intended Composition		Corrected
at.% Mg	at.% Cu	a, pm	at.% Mg	at.% Cu	a, pm
0.189	0.367	404.80	0.25	0.375	404.81
0.456	0.247	404.97	0.50	0.25	404.99
0.655	0.119	405.10	0.75	0.125	405.14
0.202	0.880	404.58	0.25	0.875	404.60
0.414	0.750	404.72	0.50	0.75	404.76
0.637	0.628	404.90	0.75	0.625	404.95
0.927	0.500	405.07	1.00	0.5	405.10
1.247	0.362	405.24	1.25	0.375	405.24
1.311	0.246	405.32	1.50	0.25	405.40
1.608	0.127	405.50	1.75	0.125	405.56
0.356	0.302	404.91	0.375	0.313	404.91
0.578	0.179	405.05	0.625	0.188	405.07
1.058	0.422	405.12	1.125	0.438	405.14
0.570	0.659	404.77	0.625	0.688	404.78
0.804	0.521	404.90	0.875	0.563	404.91

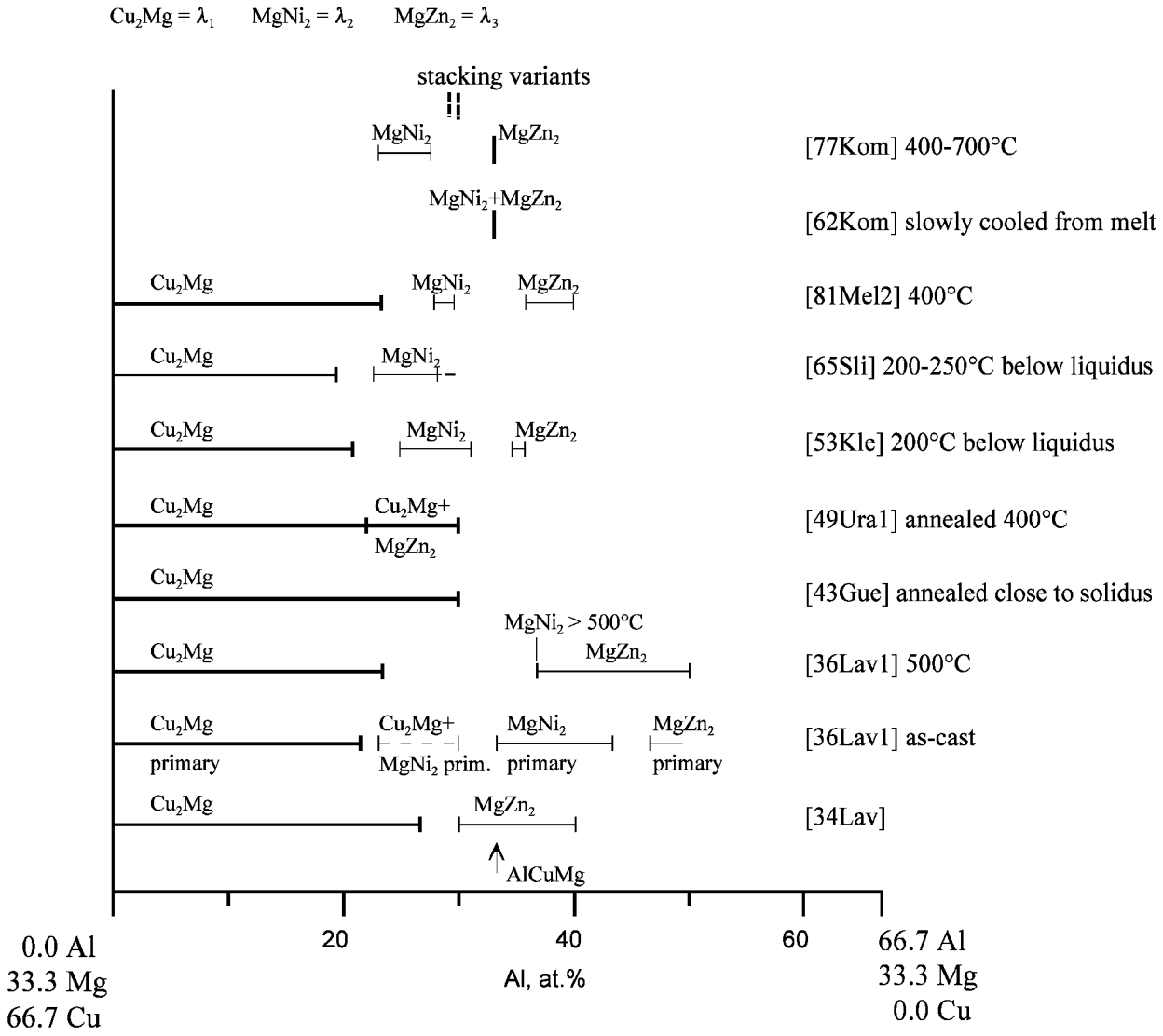

Fig. 1: Phases detected along the 33.3 at.% Mg section

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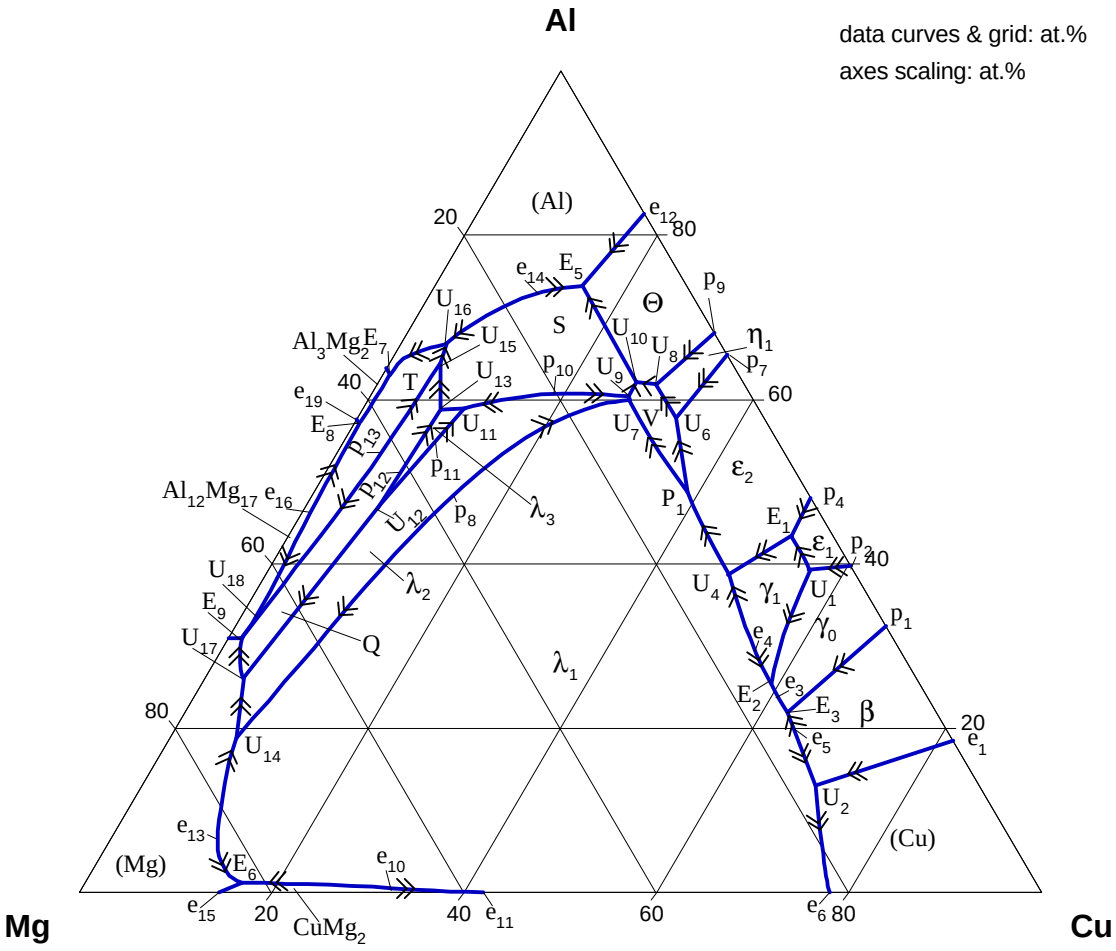

Figure 2a: Liquidus univariant lines and primary phases

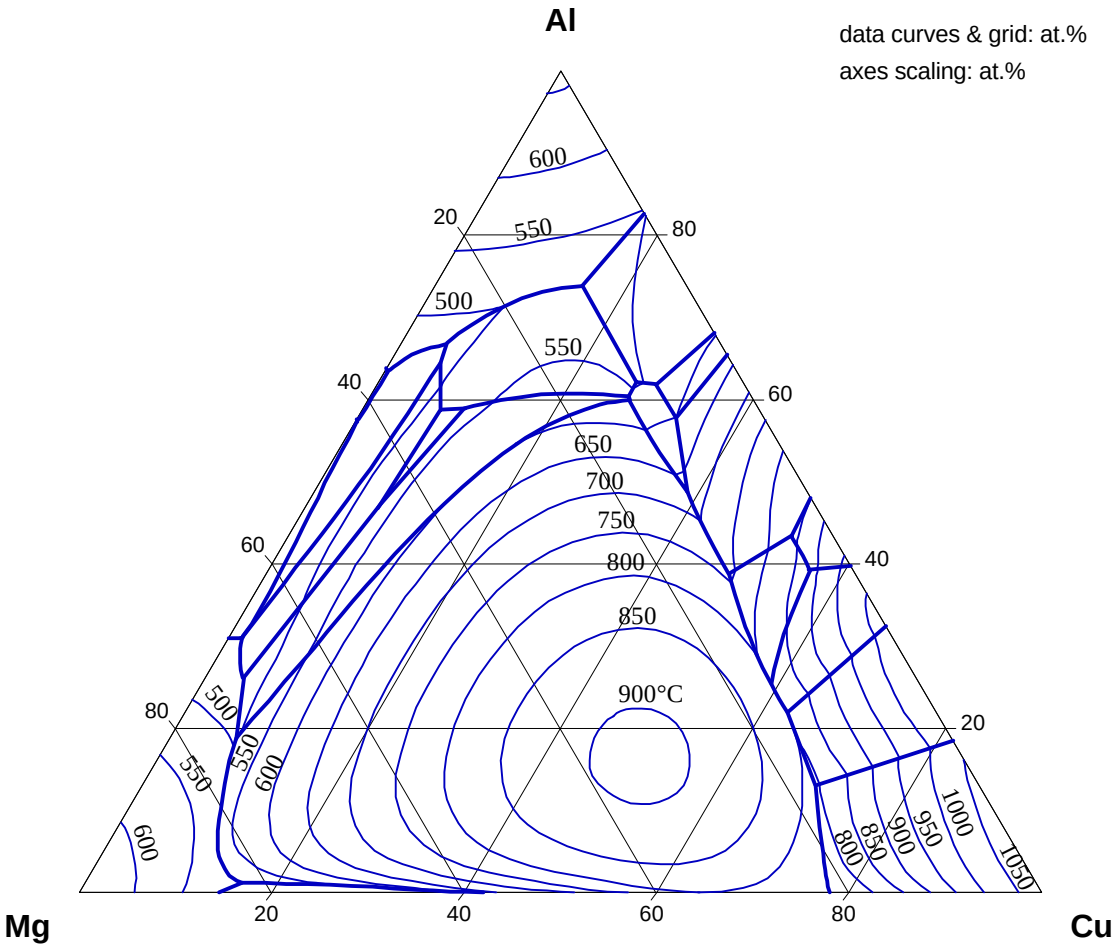

Figure 2b: Liquidus projection with liquidus isotherms

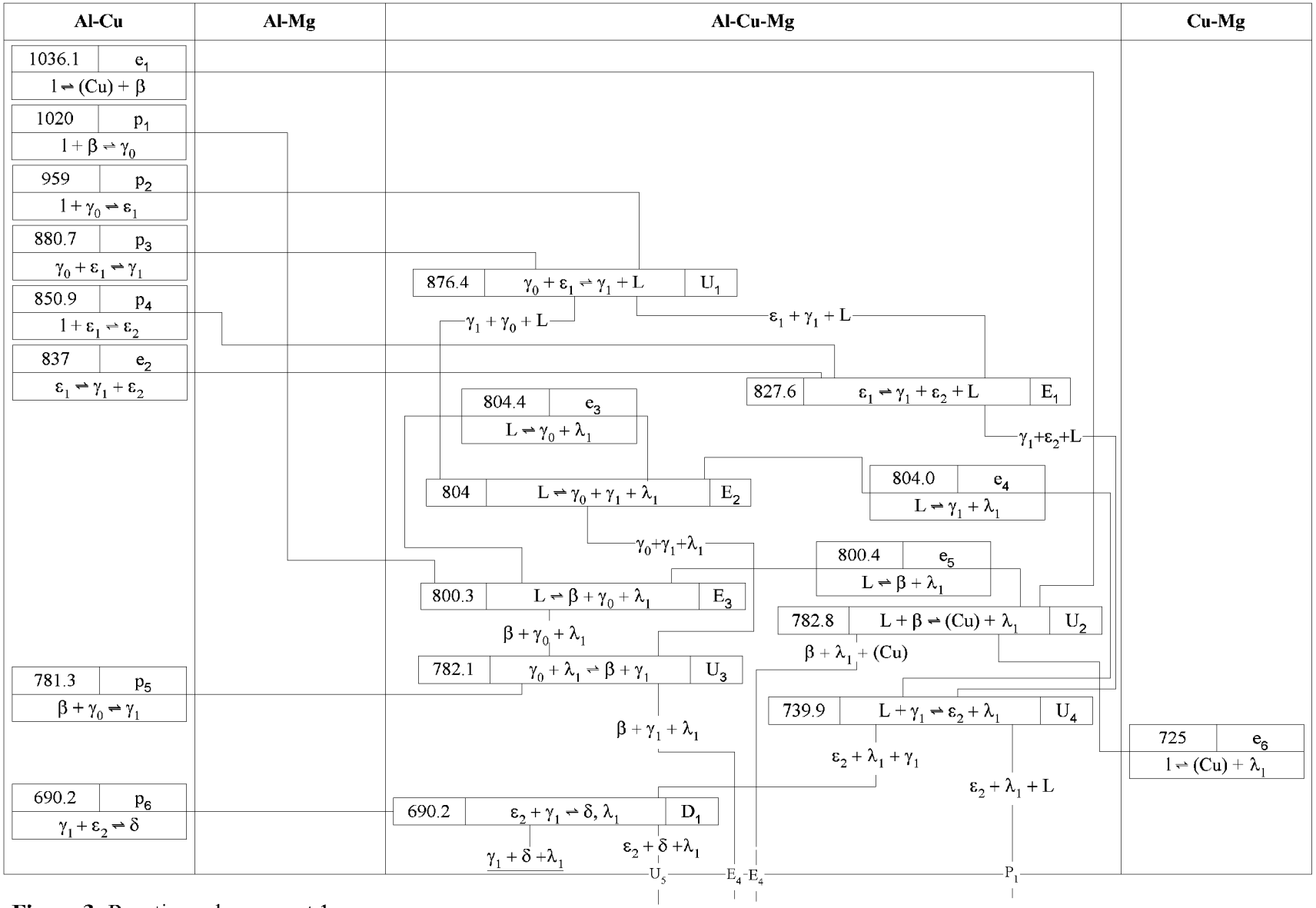

Figure 3: Reaction scheme, part 1.

Fig. 3a : Reaction scheme, part 1.

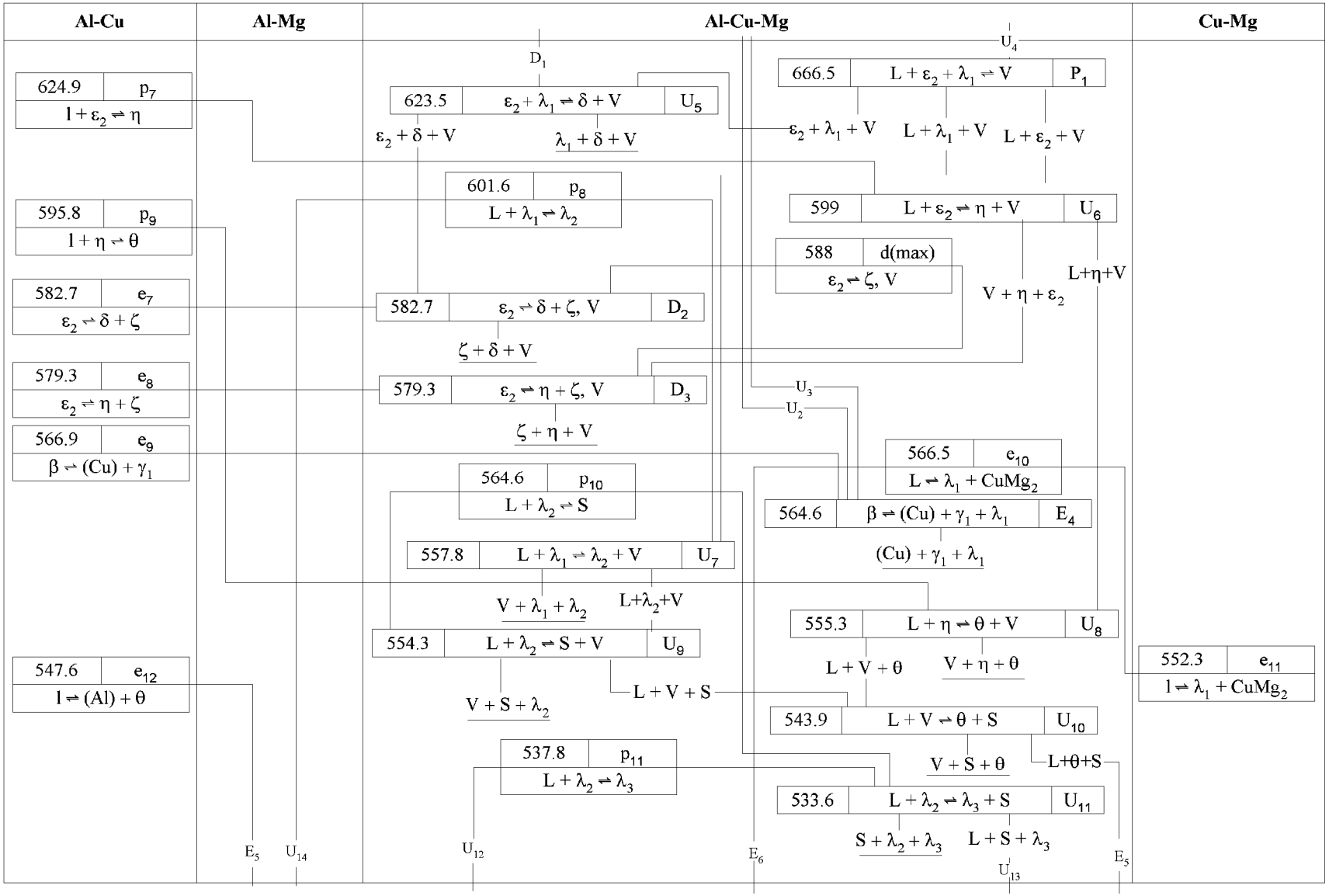

Figure 3: Reaction scheme, part 2

Fig. 3b : Reaction scheme, part 2.

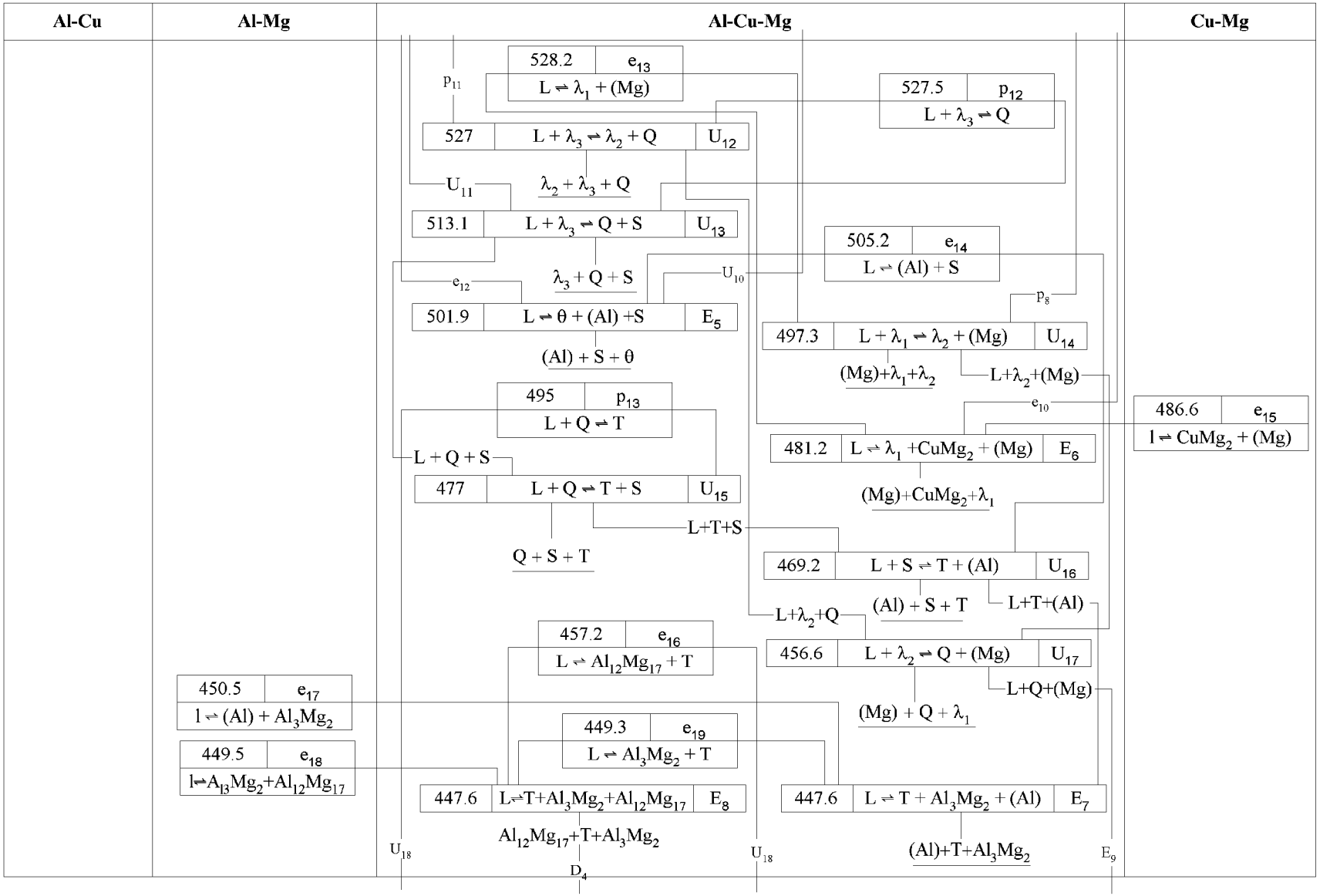

Figure 3: Reaction scheme, part 3

Fig. 3c : Reaction scheme, part 3.

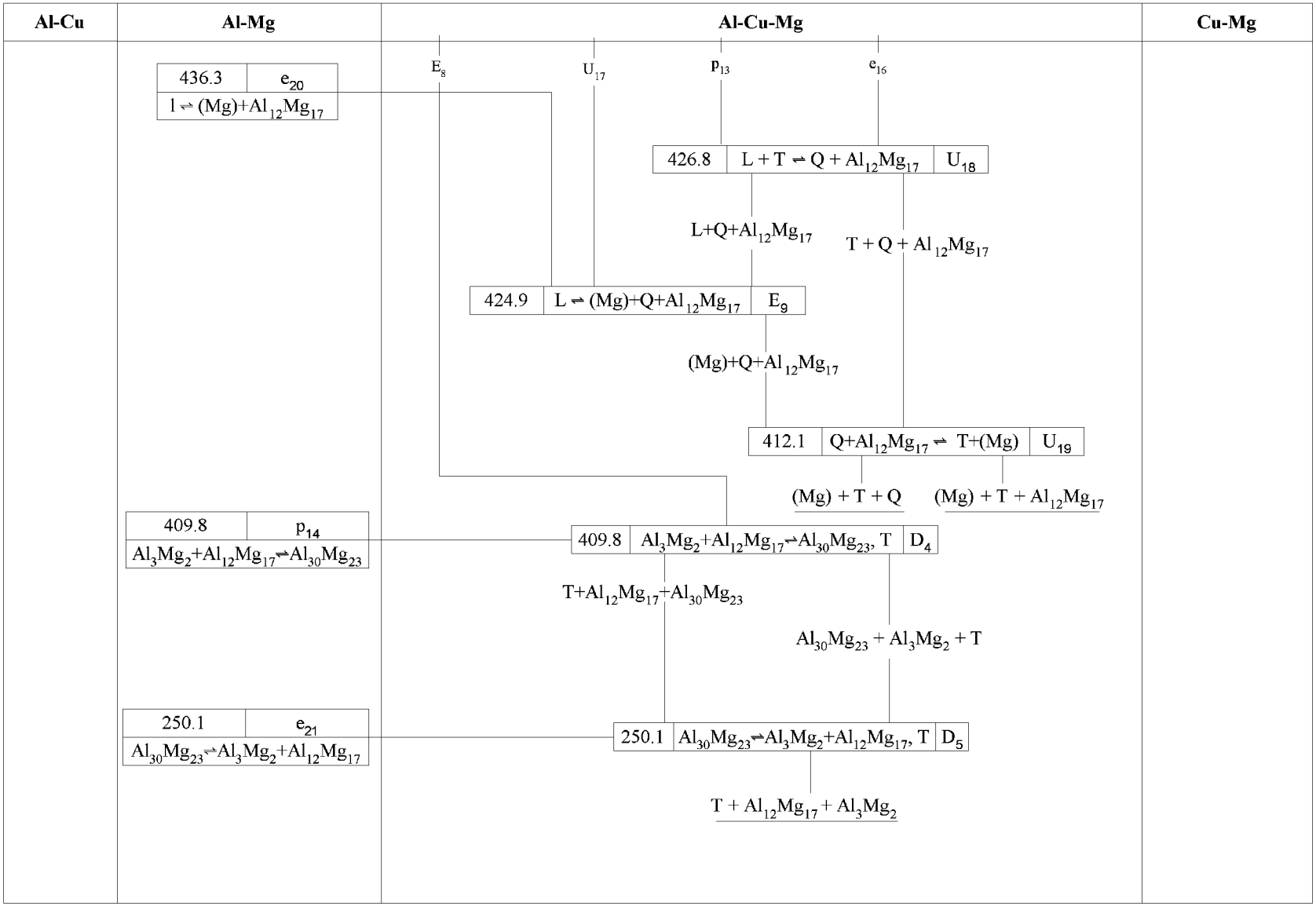

Figure 3: Reaction scheme, part 4

Fig. 3d : Reaction scheme, part 4.

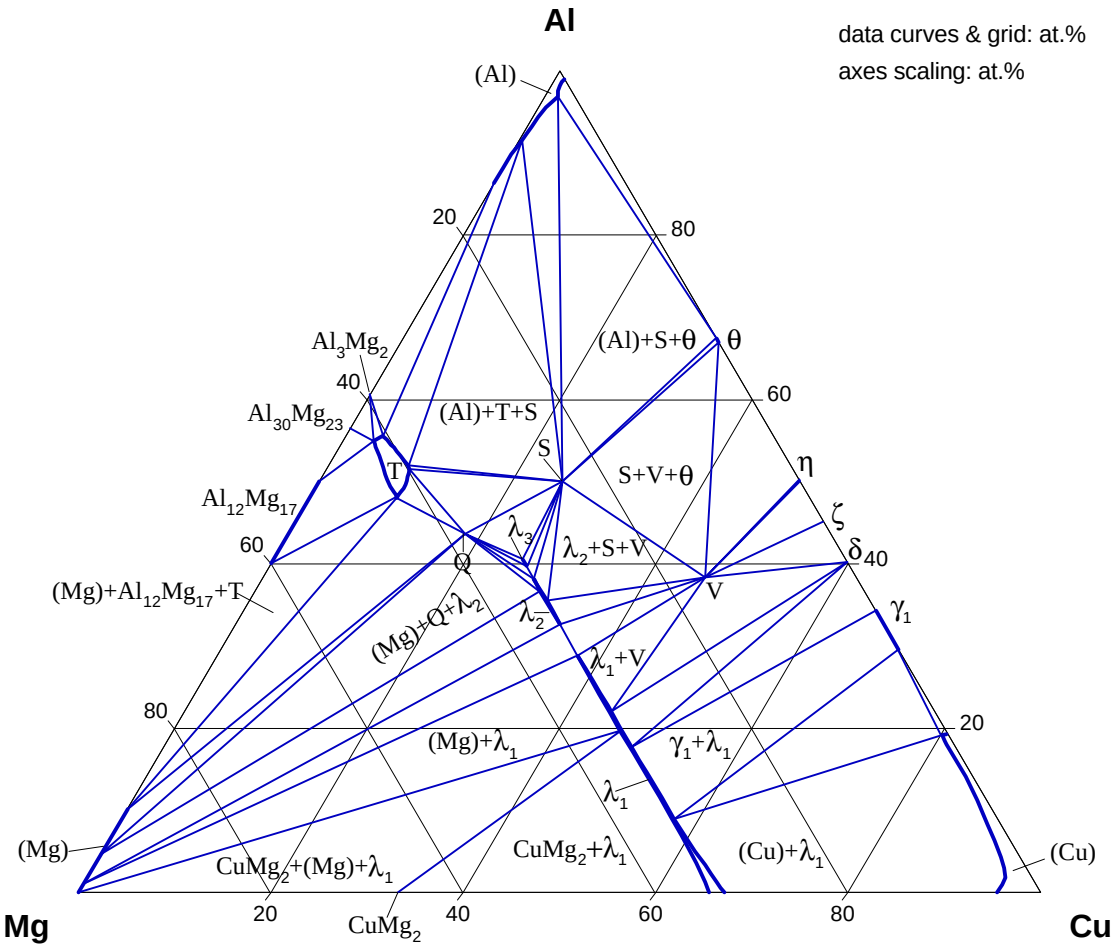

Figure 4: Calculated isothemal section at 400°C

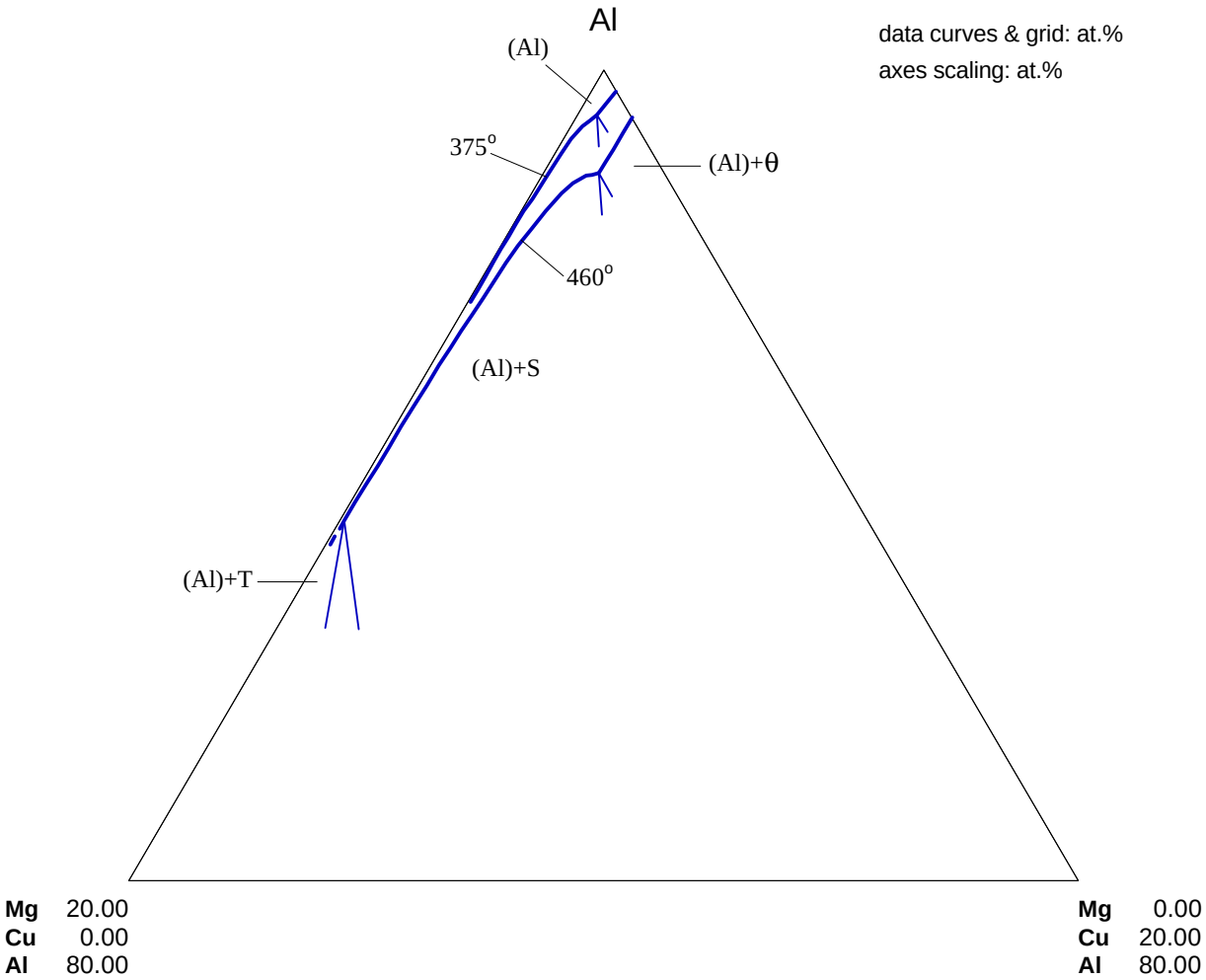

Fig. 5: Isothermal sections in the Al-rich corner at 460 and 375°C

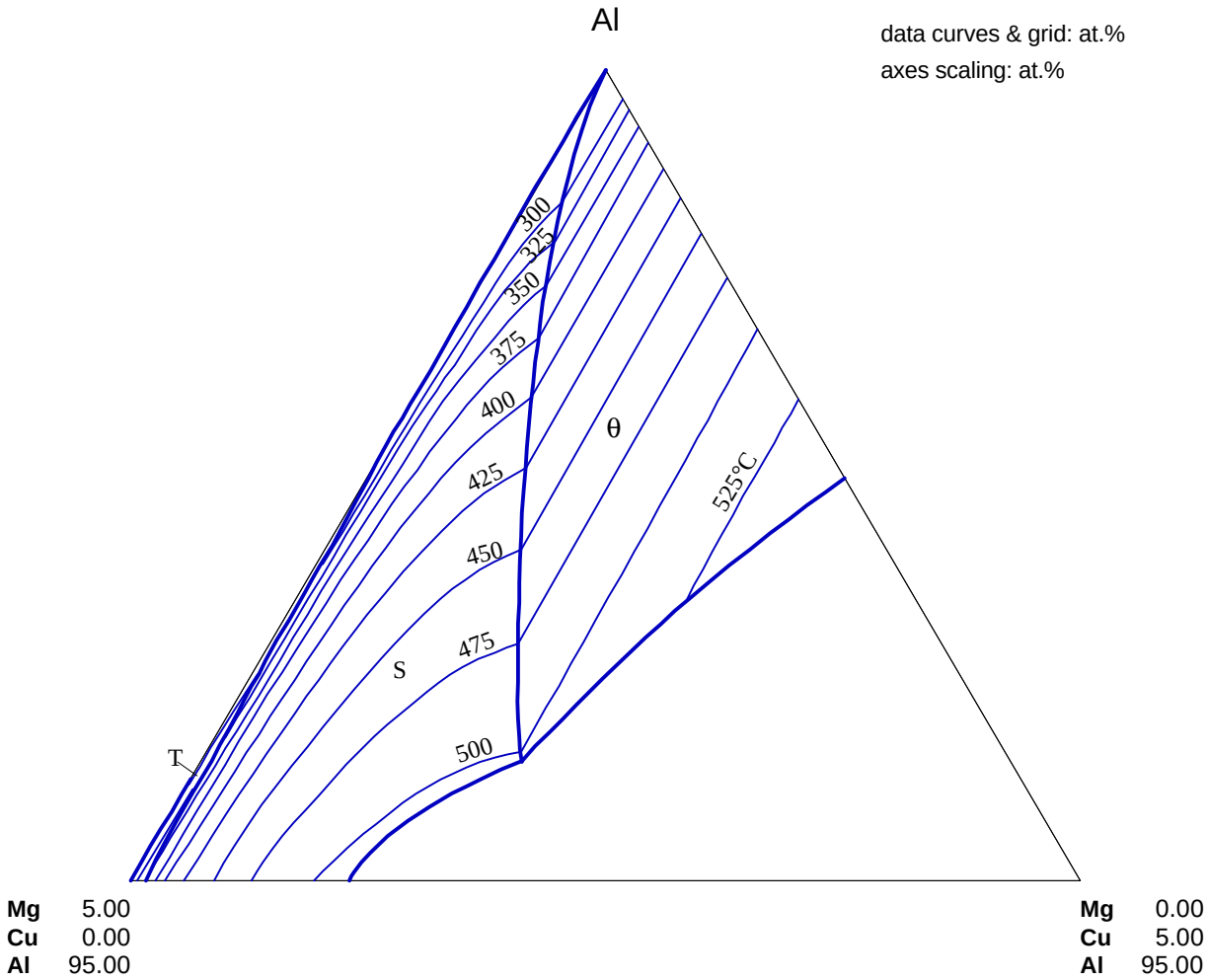

Figure 6: Isotherms of the (Al)-solvus and phases in equilibrium with (Al)

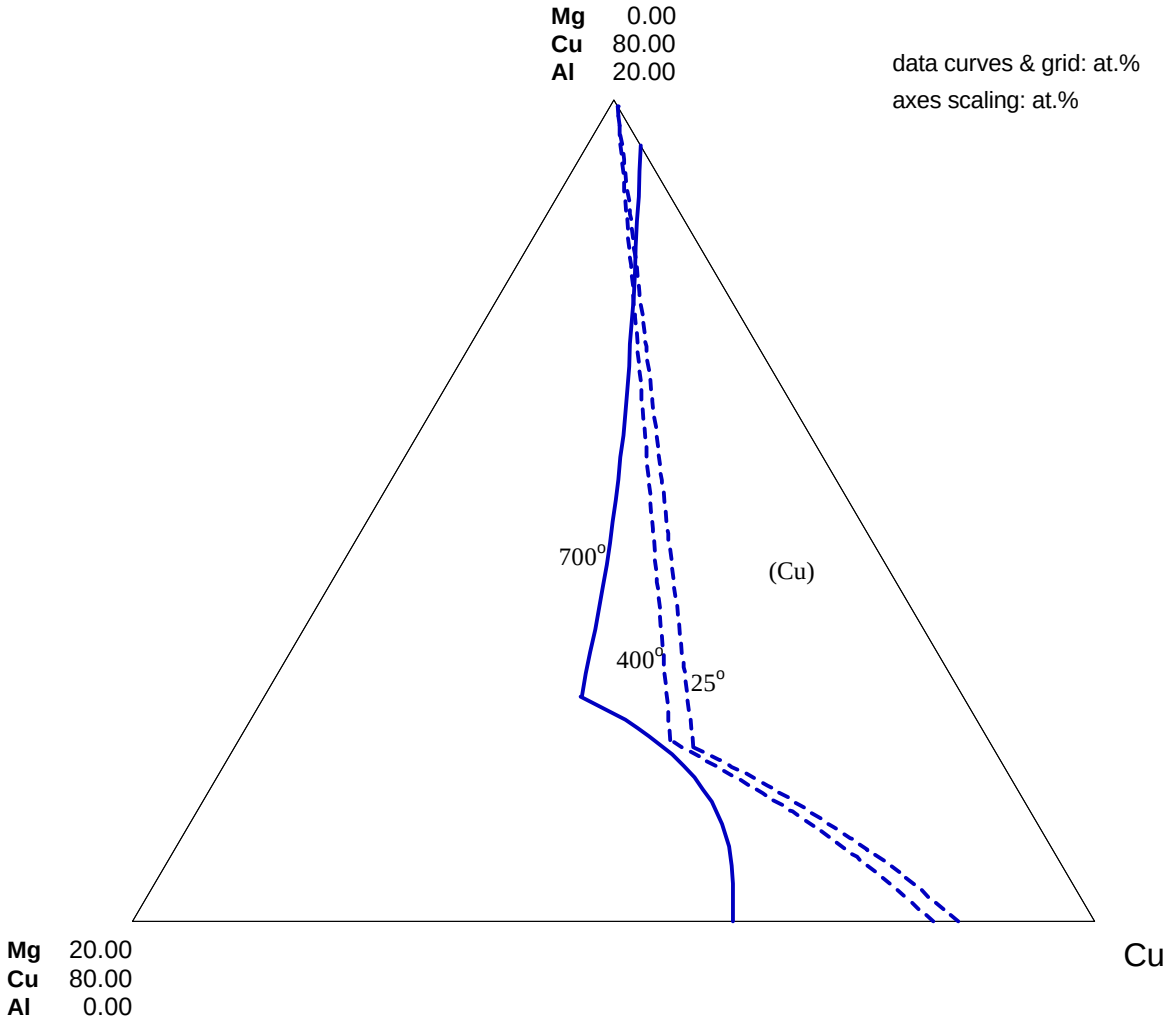

Fig. 7: Solubility of Al and Mg in (Cu) [57Rog]