Phase diagrams

Przemyslaw Fima

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Definition

- A **Phase Diagram** describes the state of a materials system in thermodynamic equilibrium as a function of temperature, pressure and composition.
- **Phase Diagrams** are maps of the equilibrium phases associated with various combinations of temperature, pressure, and composition.
- A **Phase Diagram** is a type of chart used to show conditions at which thermodynamically distinct phases can occur at equilibrium.

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Components and phases

- Components:

  The elements (or compounds) which are mixed initially

- Phases:

  The physically and chemically distinct material regions that result

  in other words:

  The phase is a homogeneous part of the space and the phase is limited by a phase boundary

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

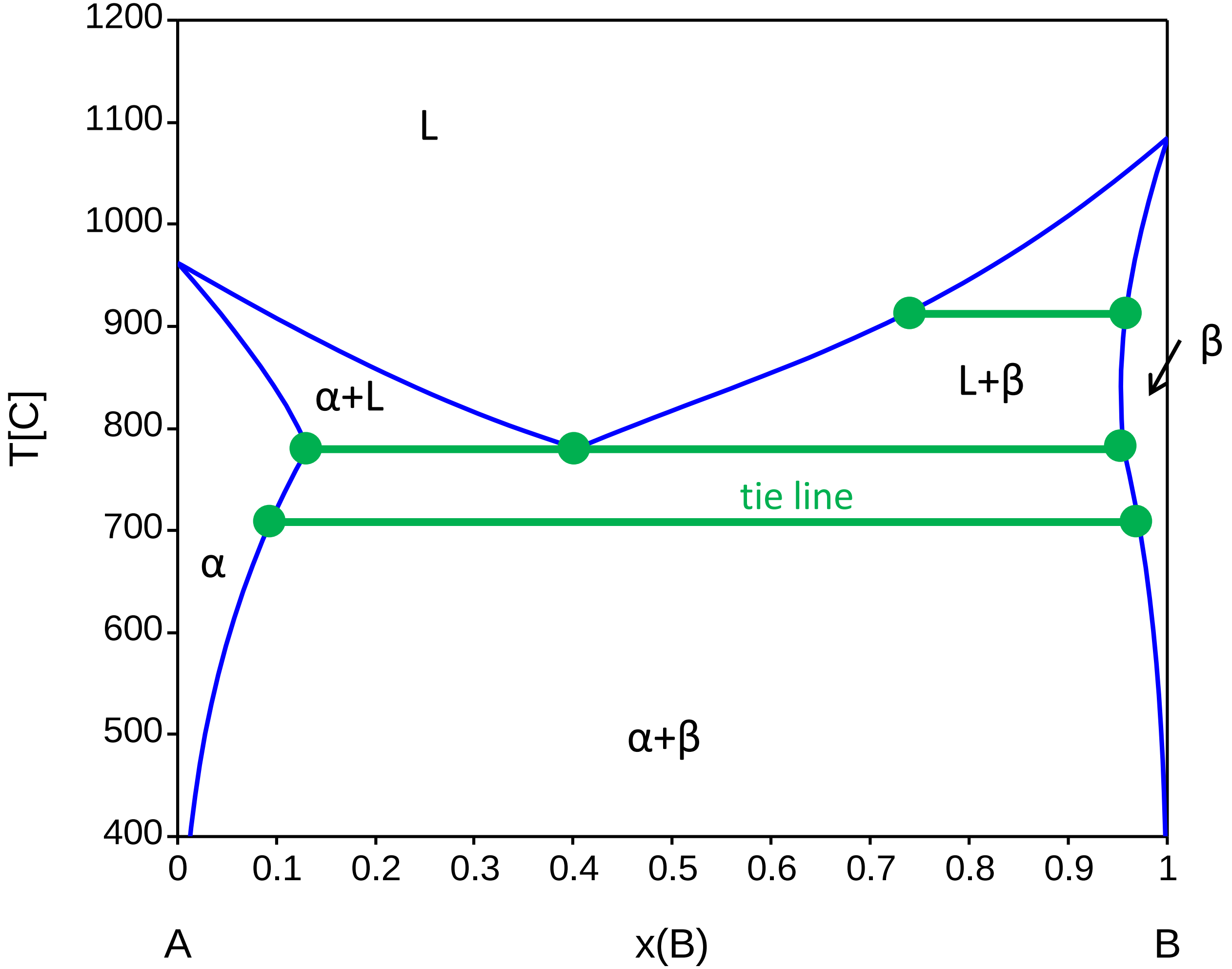
Thermodynamic equilibrium

- Condition for 2 phases to be in equilibrium

$$\mu_A^{\alpha} = \mu_A^{\beta}$$

$$\mu_B^{\alpha} = \mu_B^{\beta}$$

Thermodynamic equilibrium



$$\mu_A^L = \mu_A^\beta$$
$$\mu_B^L = \mu_B^\beta$$

$$\mu_A^\alpha = \mu_A^L = \mu_A^\beta$$
$$\mu_B^\alpha = \mu_B^L = \mu_B^\beta$$

$$\mu_A^\alpha = \mu_A^\beta$$
$$\mu_B^\alpha = \mu_B^\beta$$

What do we need phase diagrams for?

For example:

- to understand solidification processes
  - → microstructure → properties
- to characterize compounds and phases
  - Cu_5Zn_8, InSb, …
- to understand reactions
  - Soldering, surface layers, …

Number of metallic phase diagrams

(assuming: 80 metallic elements)

No. of components	No. of possible systems	Approx. No. of investigated systems
1	80	80
2	3 160	2500
3	82 160	3000
4	1 581 580	200
5	24 141 016	20
6	300 500 200	-
…	…	…

Where to look for phase diagrams?

- Collections of phase diagrams (printed):
  - T.B. Massalski et al. (Ed.) Binary Alloy Phase Diagrams, 2nd Edition (3 volumes) (ASM International 1990)
  - P. Villars, A. Prince, H. Okamoto (Ed.): Handbook of Ternary Alloy Phase Diagrams (10 Volumes) , ASM International (Materials Park, OH), 1992.
  - ASM Handbook Vol. 3 Alloy Phase Diagrams, ASM International 1992
- Collections of phase diagrams (online):
  - SGTE Free Binary Alloy Phase Diagrams (and many others) http://www.crct.polymtl.ca/fact/documentation/

Where to look for phase diagrams?

- Journals on phase diagrams:
  - Journal of Phase Equilibria and Diffusion (Springer)
  - CALPHAD – Computer Coupling of Phase Diagrams and Thermochemistry (Elsevier)

- Books on phase diagrams:
  - B. Predel, M. Hoch, M. Pool, ”Phase Diagrams and Heterogeneous Equilibria” Springer (2004)

Gibbs phase rule

$$P + F = C + 2$$

P = number of phases

C = number of components

F = degrees of freedom (number of variables that can be varied independently) **(T, p, X_i)**

If the pressure is kept constant:

$$P + F' = C + 1$$

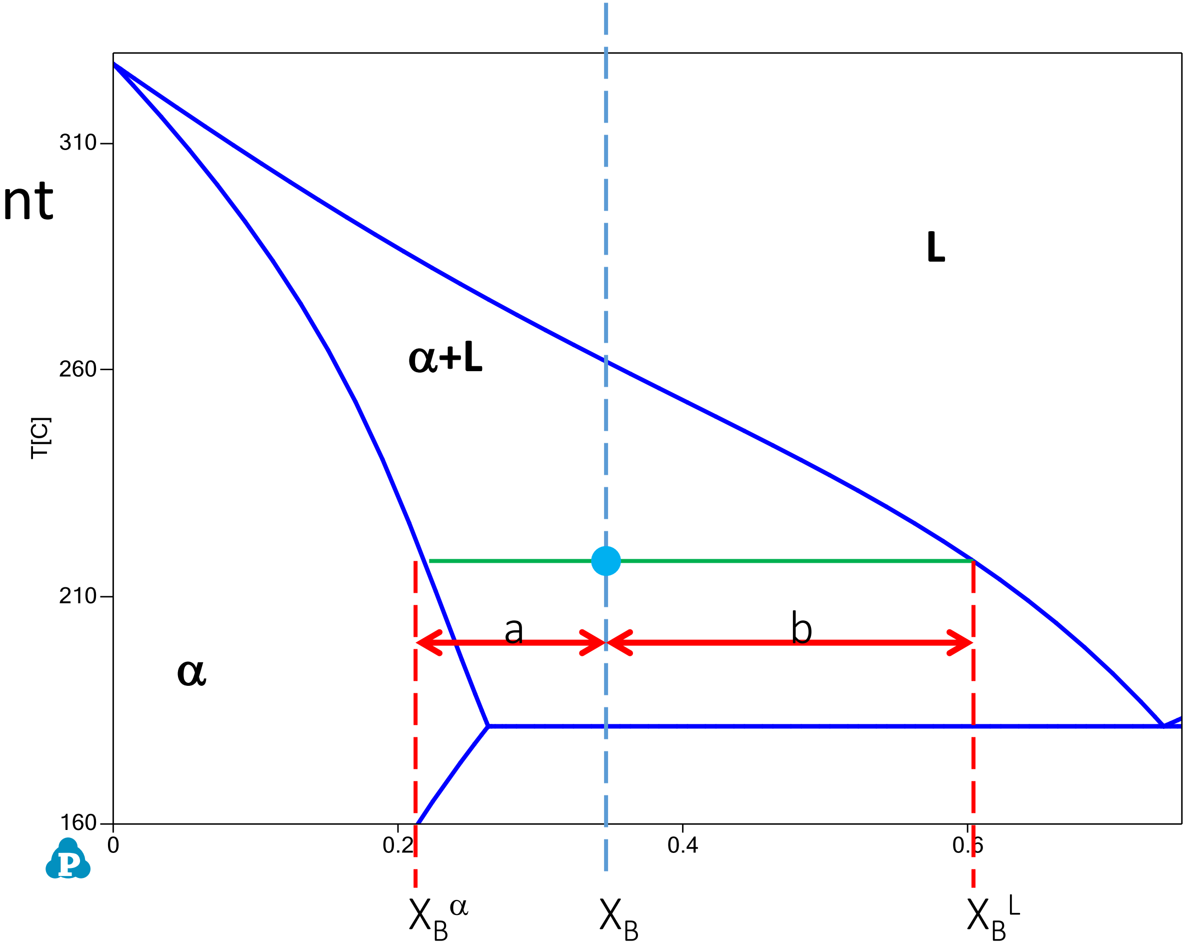
Lever rule

If we know T and X_B then we know:

- how many and what phases are present
- the composition of each phase
- the amount of each phase:

$F_\alpha = a / (a+b)$

$F_L = b / (a+b)$

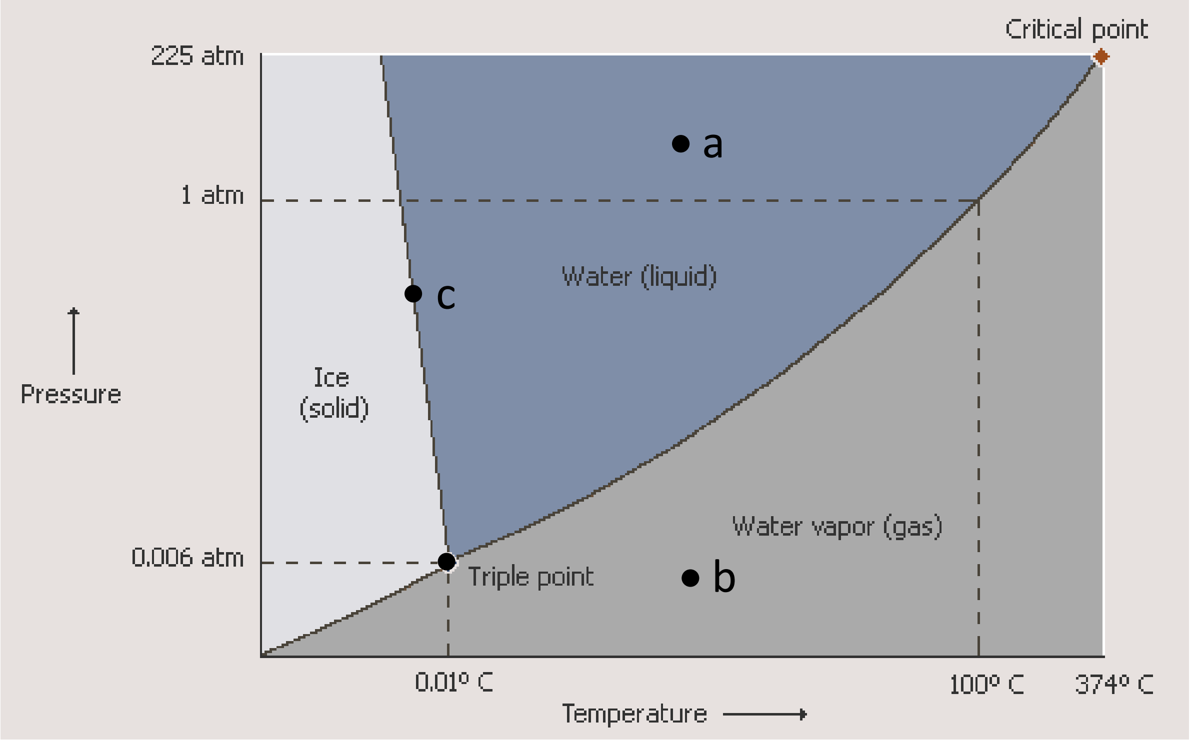


Definition of composition

- Molar (atomic) fraction $x_A = \frac{n_A}{\sum_i n_i}$ $\sum_i x_i = 1$
- Atomic percent $at\%\, A = x_A \cdot 100$
- Mass fraction $w_A = \frac{m_A}{\sum_i m_i}$ $\sum_i w_i = 1$
- Weight (mass) percent $wt\%\, A = w_A \cdot 100$

$$wt\%\, A = \frac{x_A \cdot M_A}{x_A \cdot M_A + x_B \cdot M_B} \cdot 100$$

Unary phase diagrams, example: H_2O



F = C - P + 2

a, b: C = 1, P = 1

F = 1 – 1 +2 = 2

c: C = 1, P = 2

F = 1 – 2 + 2 = 1

Triple pt.:

C = 1, P = 3

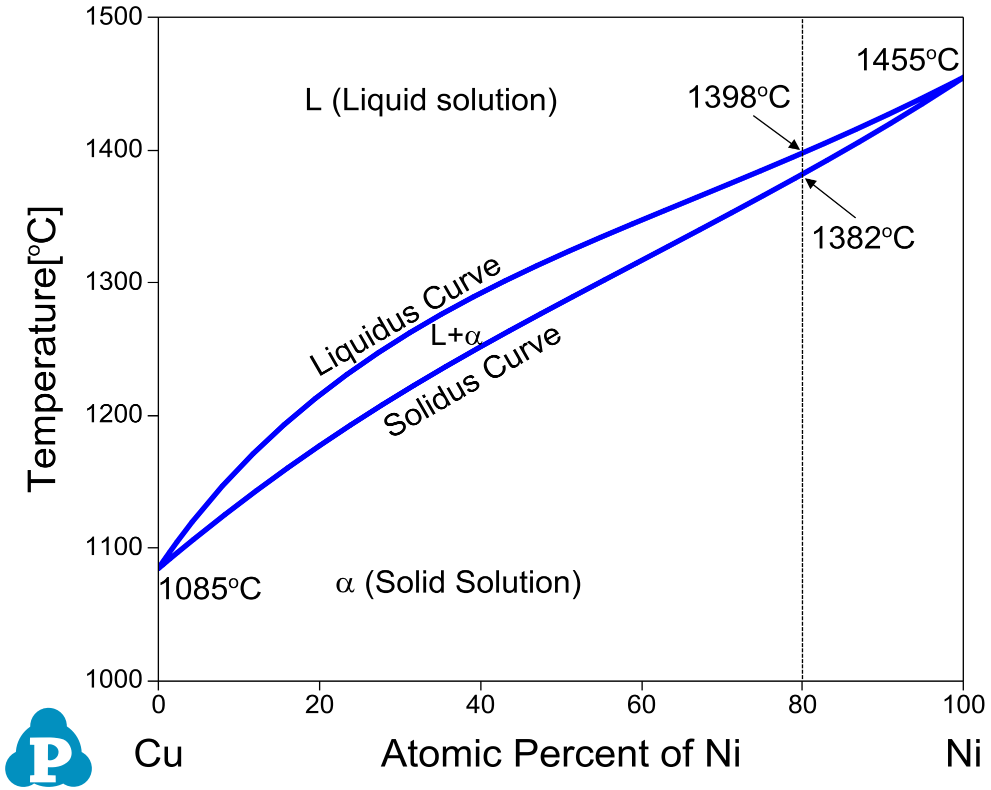
F = 1 – 3 + 2 = 0

Binary Phase Diagrams

- Isomorphous Systems
- Eutectic Systems
- Eutectoid Systems
- Peritectic Systems
- Peritectoid Systems
- Monotectic Systems
- Syntectic Systems
- Congruent transformations

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Isomorphous systems

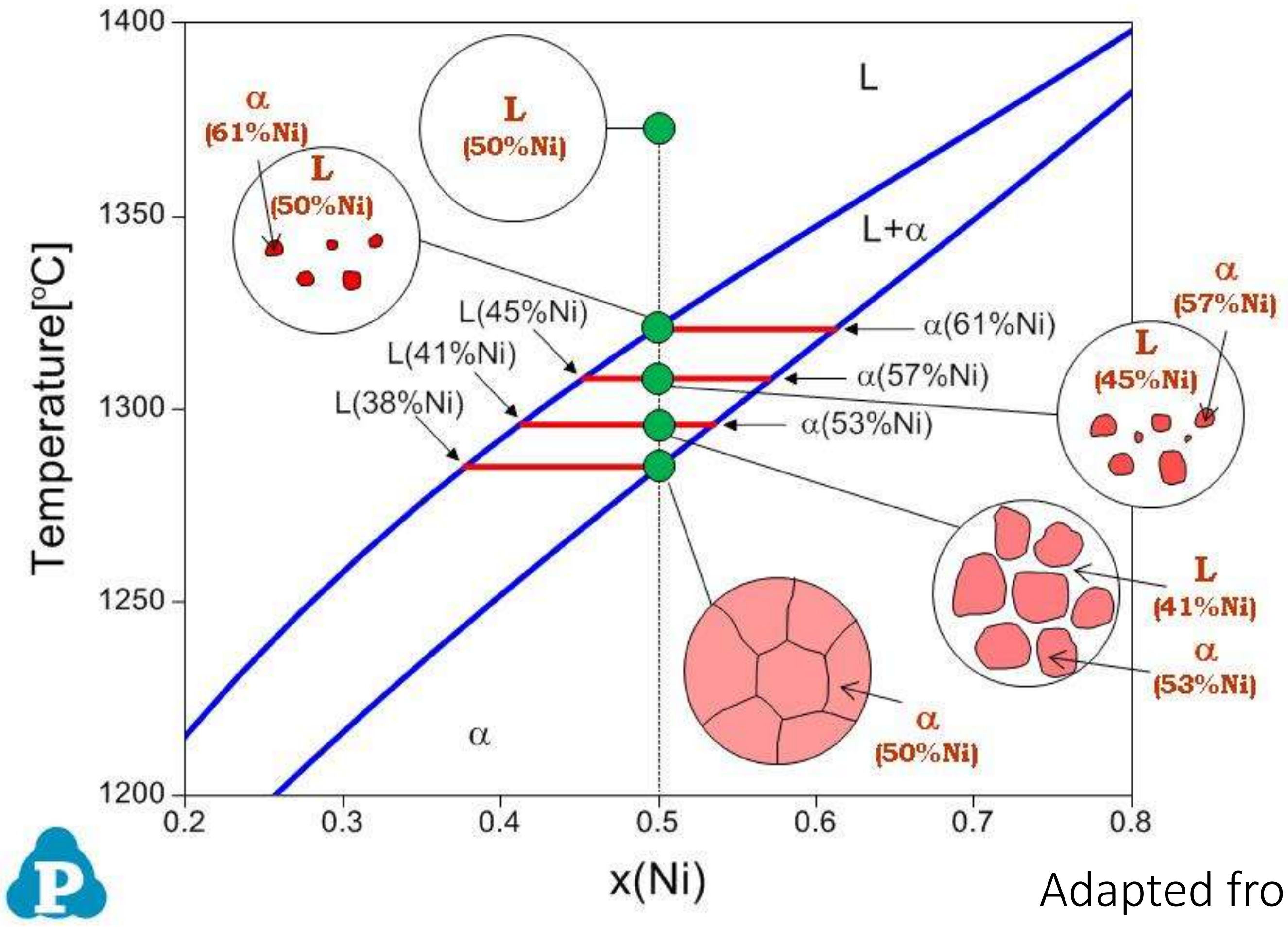


Information from this diagram:

- Two phases: α and L, but three phase fields: L, L+α, α
- Pure Ni melts at 1455°C
- Pure Cu melts at 1085°C
- Pure component melts at a fixed temperature, an alloy melts in a temperature range.
- Cu-80at%Ni starts to melt at 1382°C (solidus), and becomes complete liquid at 1398°C (liquidus)
- Liquid and solid coexist between the liquidus and solidus temperatures

Adapted from www.computherm.com

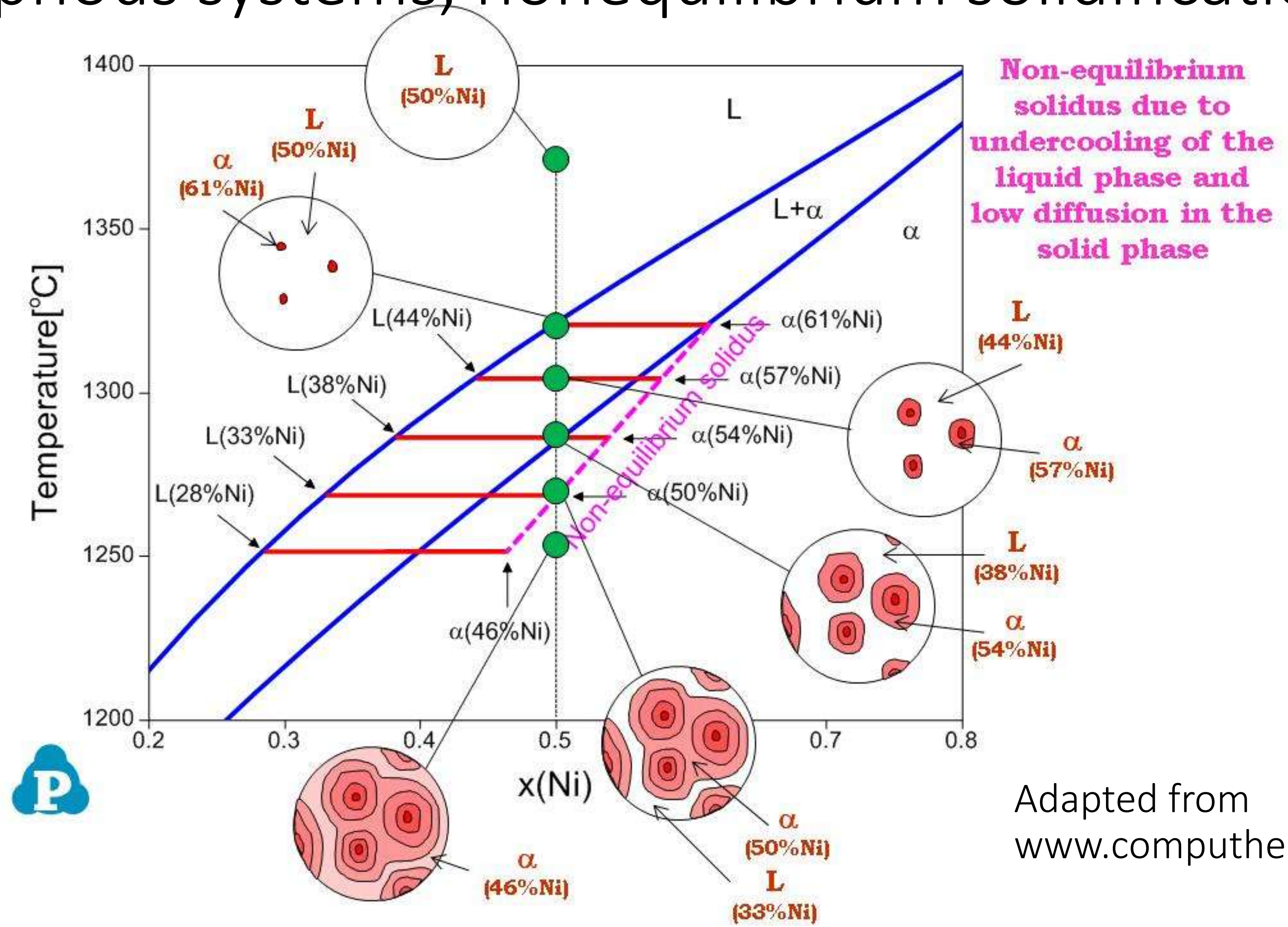
Isomorphous systems, Equilibrium solidification



Adapted from www.computherm.com

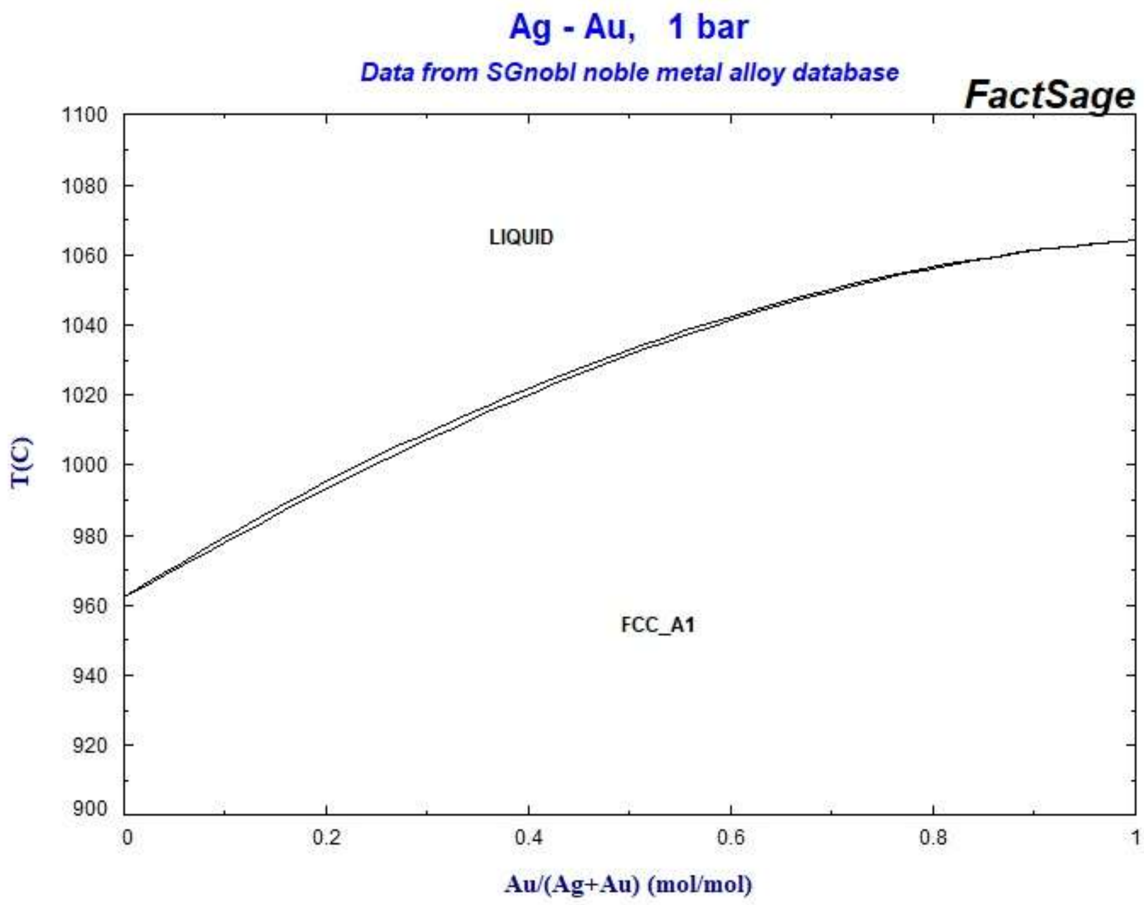
European Funds Knowledge Education Development | Institute of Metallurgy and Materials Science Polish Academy of Sciences | European Union European Social Fund

Isomorphous systems, nonequilibrium solidification



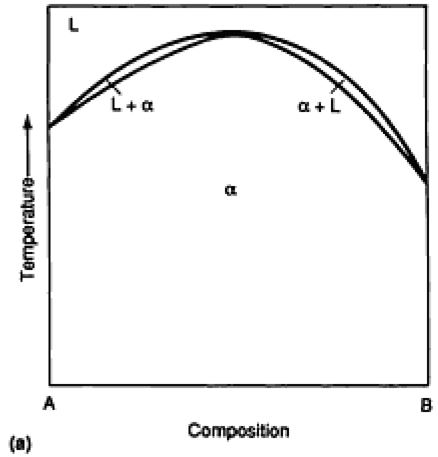
Adapted from www.computherm.com

Examples of isomorphous systems: Ag-Au

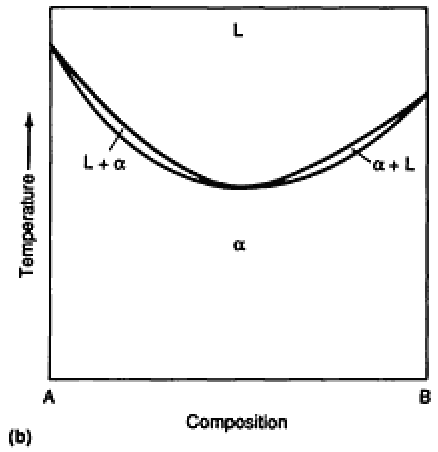


Special cases:

Maximum →

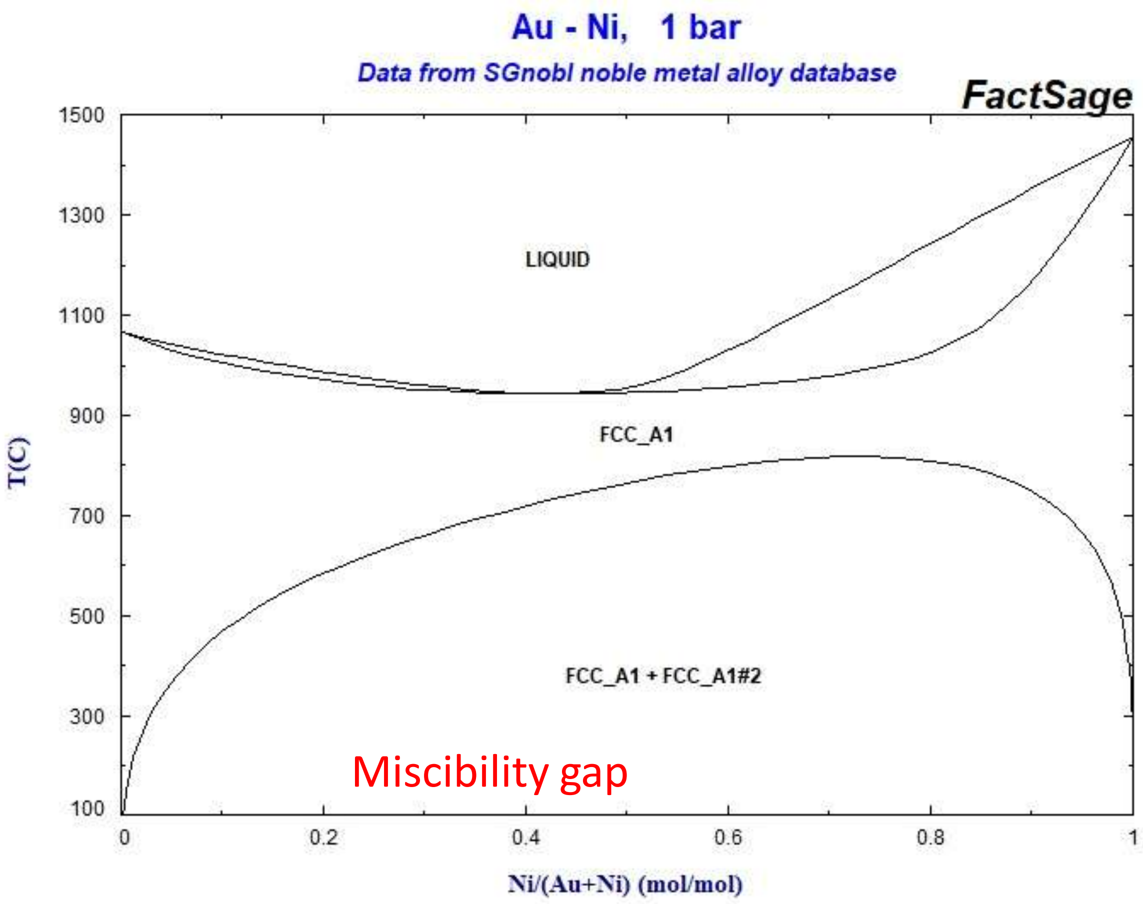


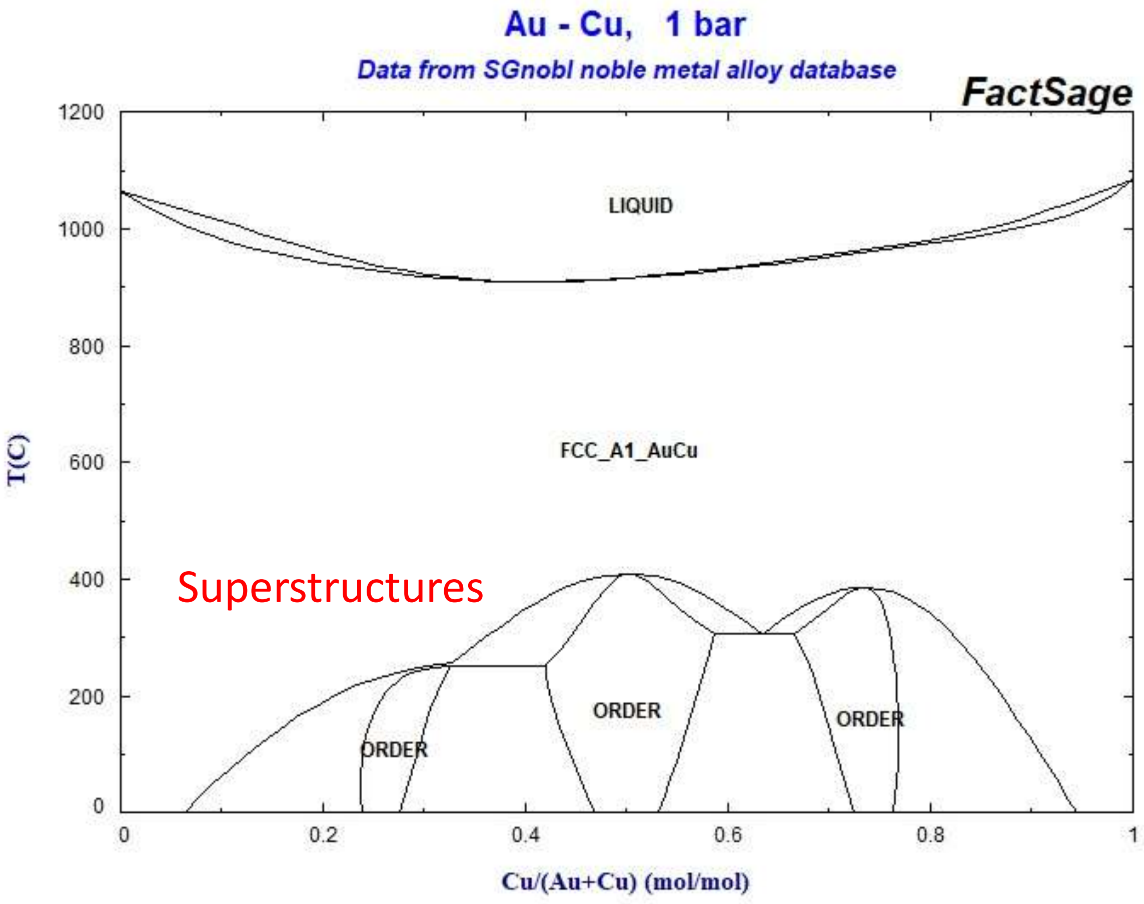
Minimum →



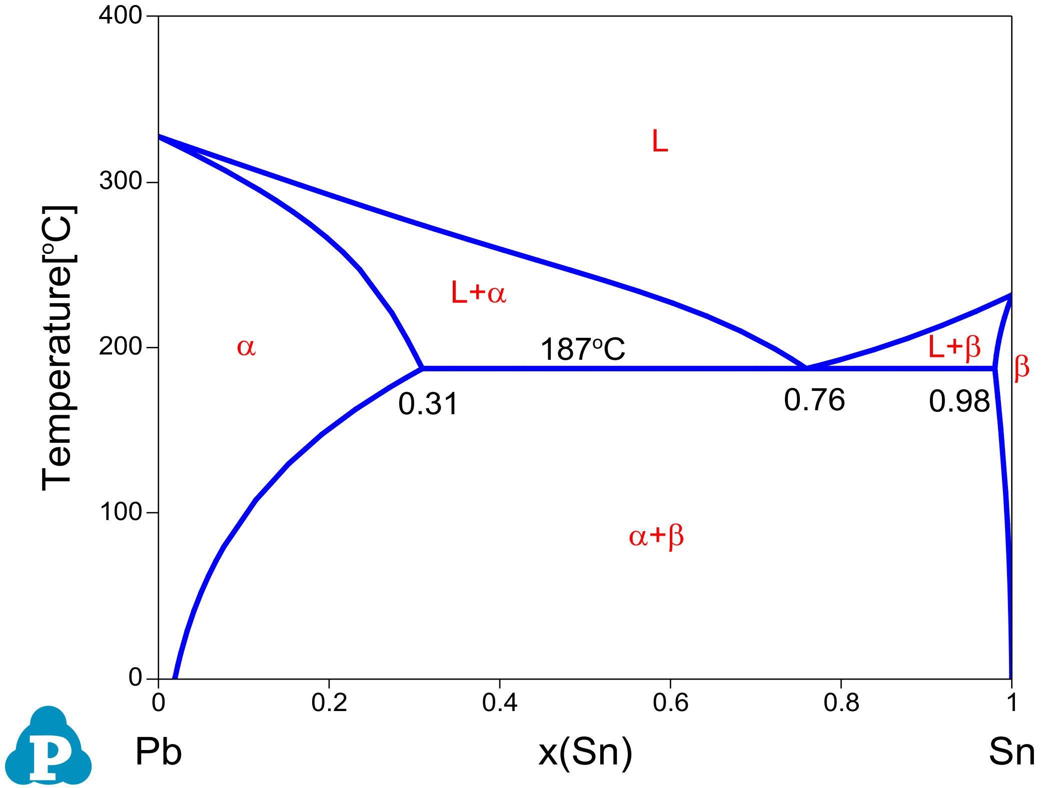
Source: ASM Handbook

Special cases of isomorphous systems: Au-Ni, Au-Cu





Eutectic systems

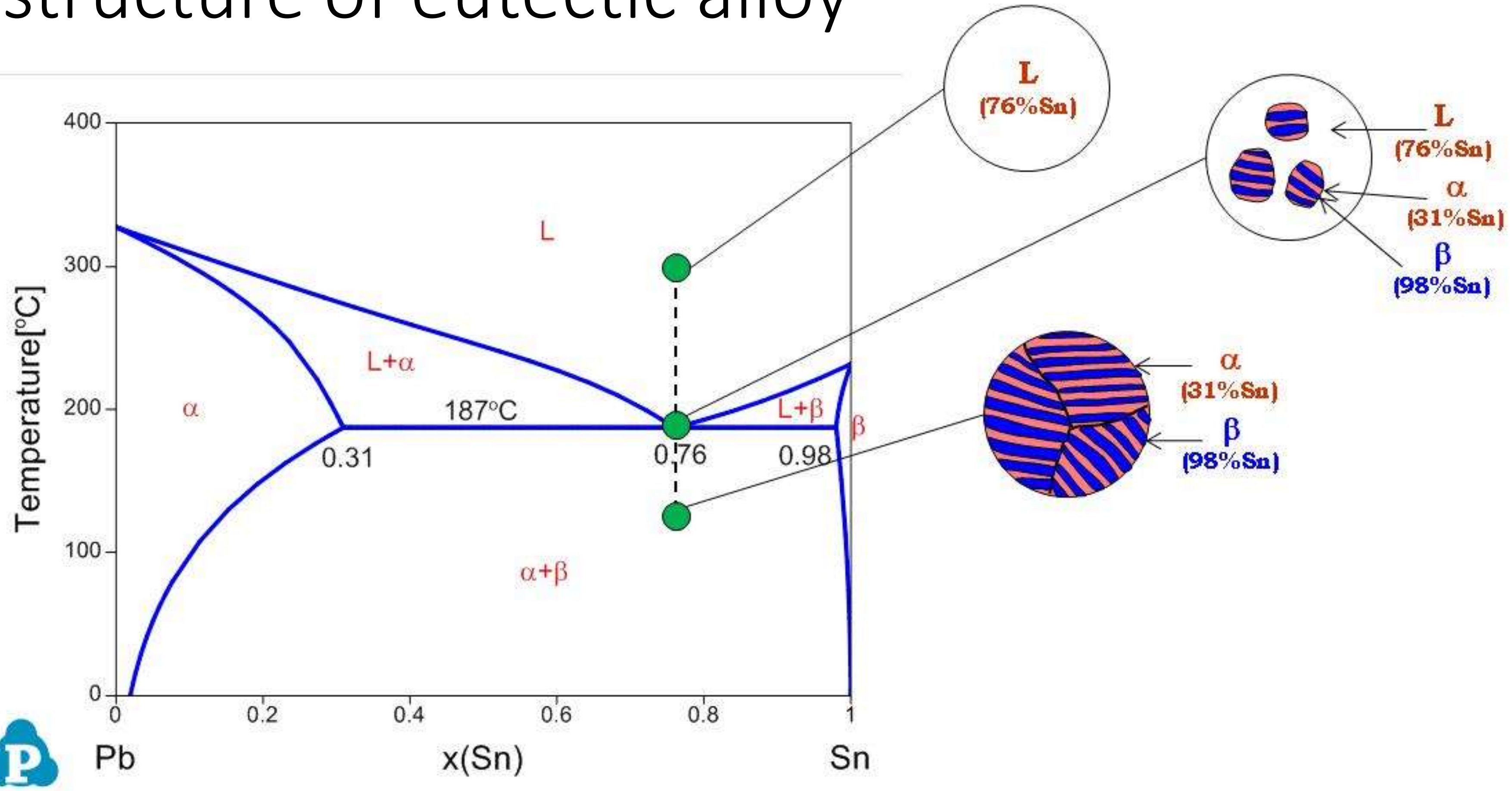


Information from this diagram:

- Eutectic reaction occurs at 187°C and 76 at% Sn: **L** ↔ α + β.
- Alloy (0.31<x_{Sn}<98%) starts to melt at eutectic reaction temperature 187°C and becomes complete liquid at liquidus.
- Alloy (x_{Sn}<0.31 or x_{Sn}>98%) starts to melt at solidus, and becomes complete liquid at liquidus.
- Solubility limit of Sn in α phase varies with temperature, maximum solubility of Sn in α phase is 31 at% at 187 °C.

Adapted from www.computherm.com

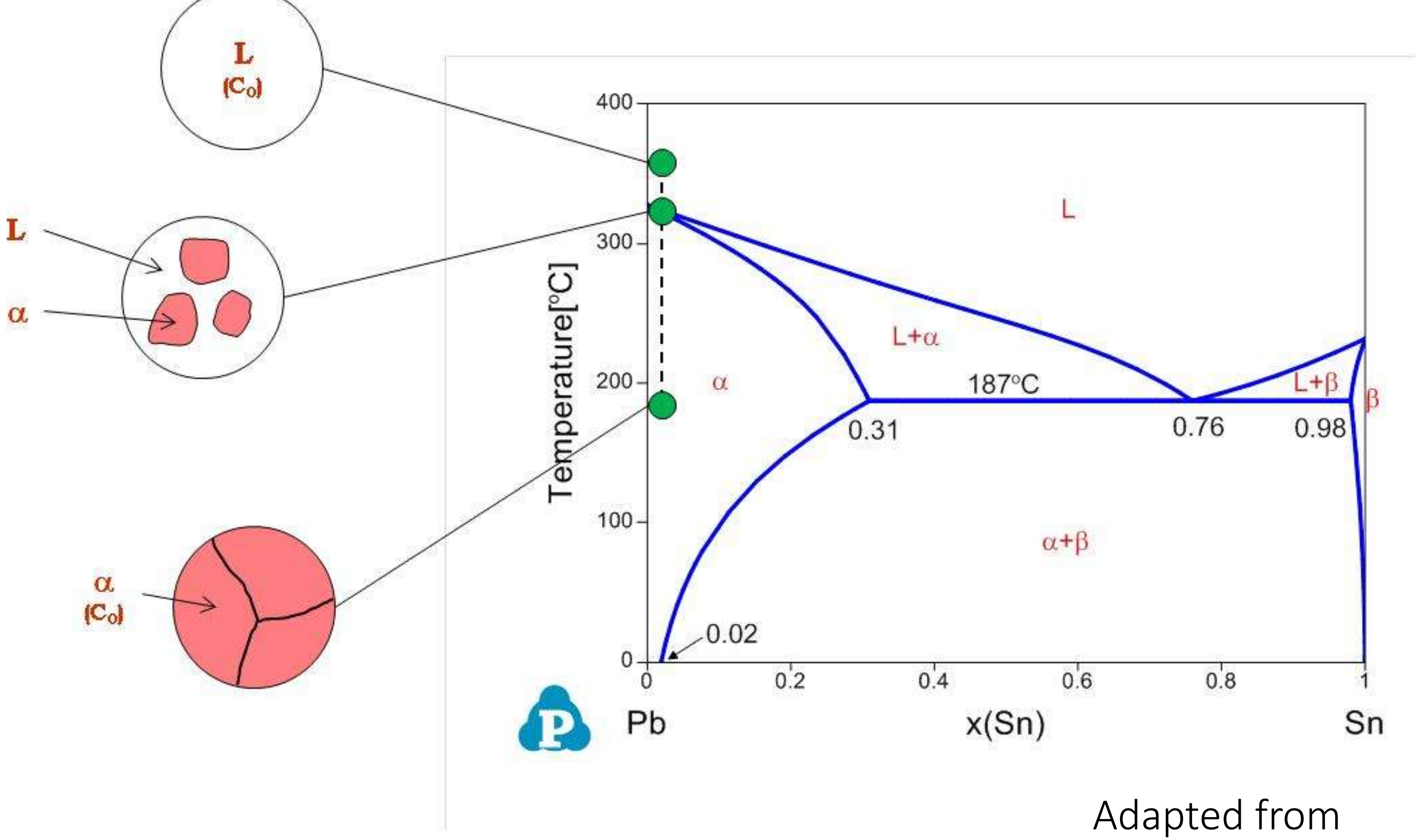
Microstructure of eutectic alloy



$$L(76\,\text{at\%}\,\text{Sn}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(31\,\text{at\%}\,\text{Sn}) + \beta(98\,\text{at\%}\,\text{Sn})$$

Adapted from www.computherm.com

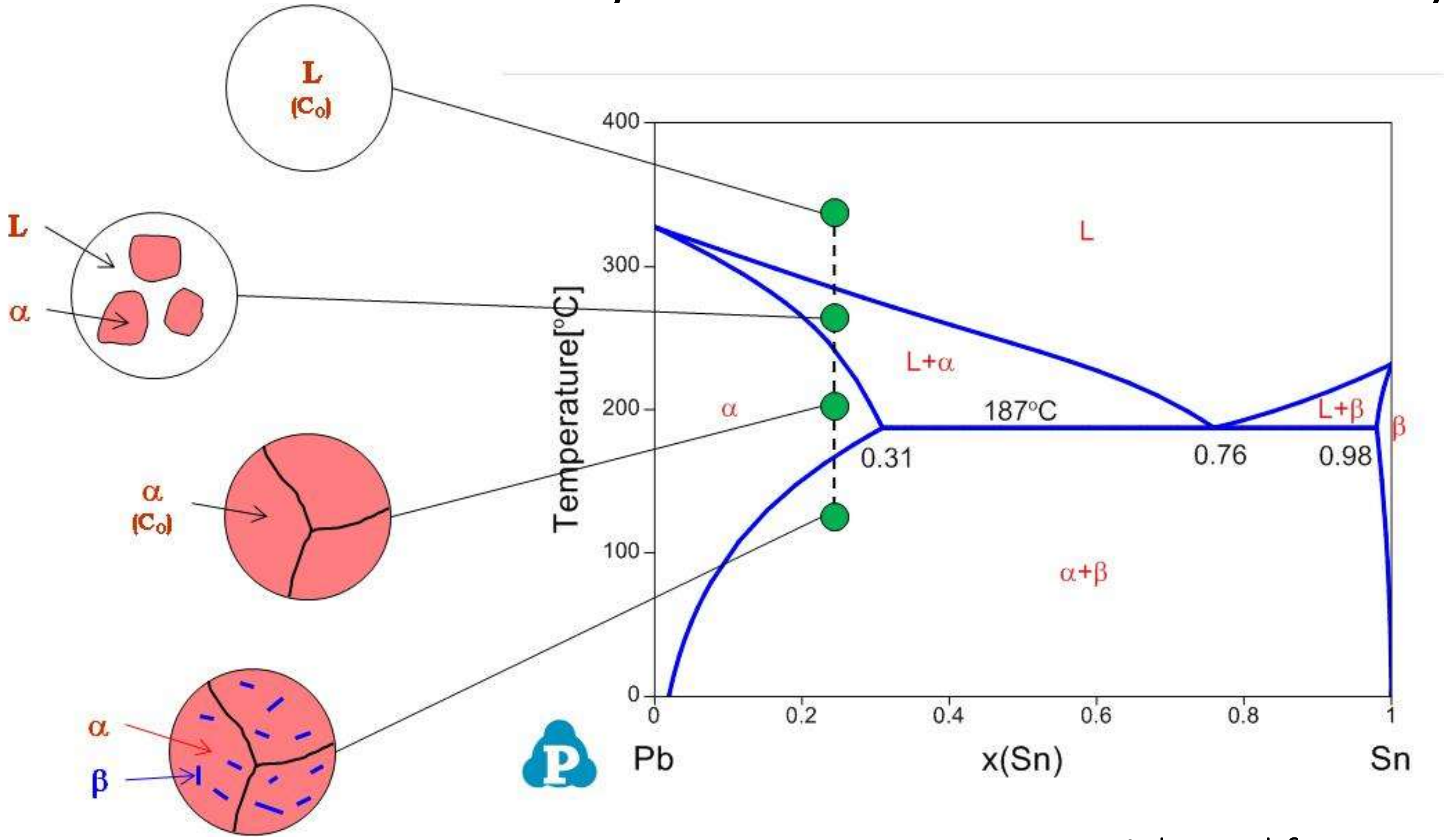
Microstructure of solid solution α



Adapted from www.computherm.com

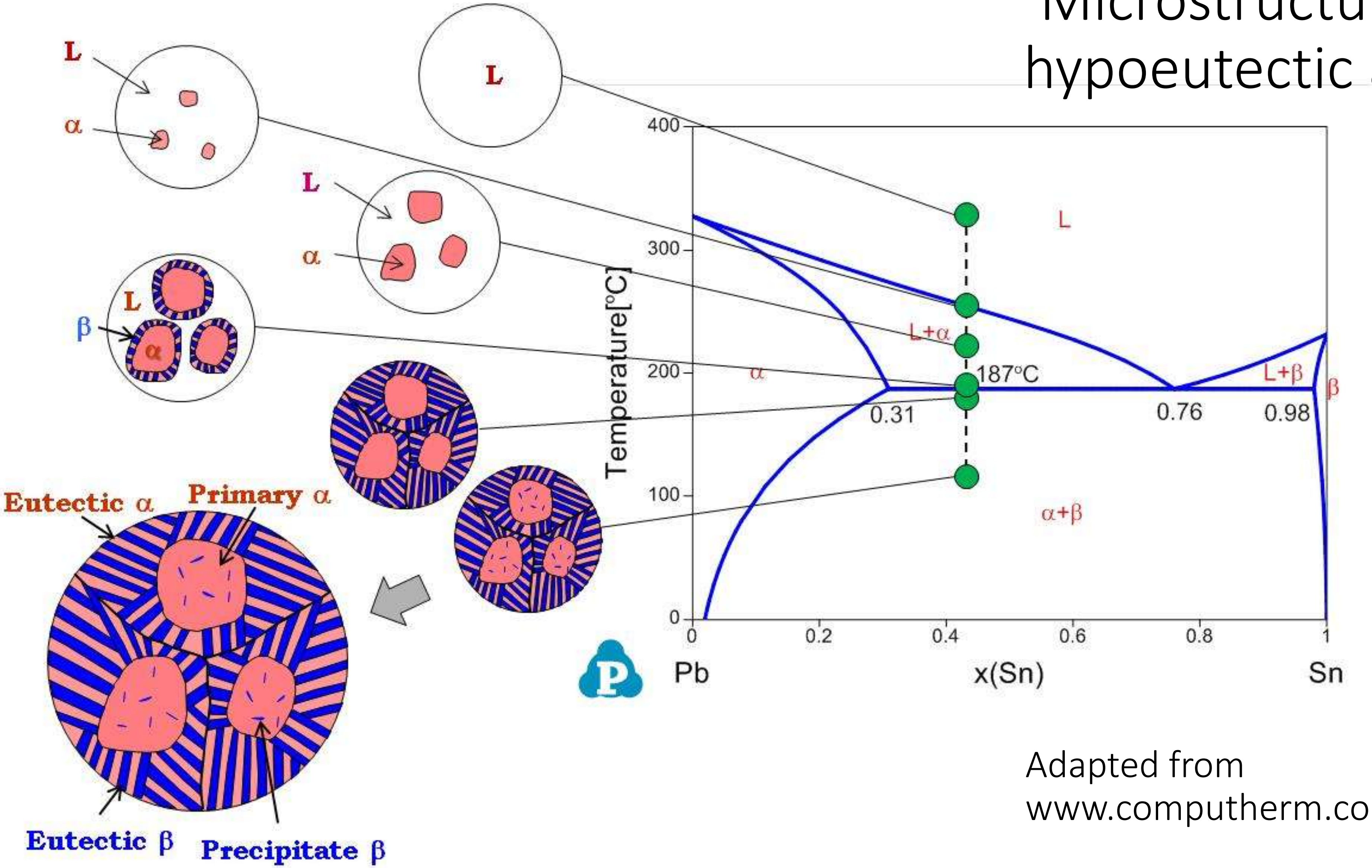
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Microstructure of an alloy which exceeds solubility limit



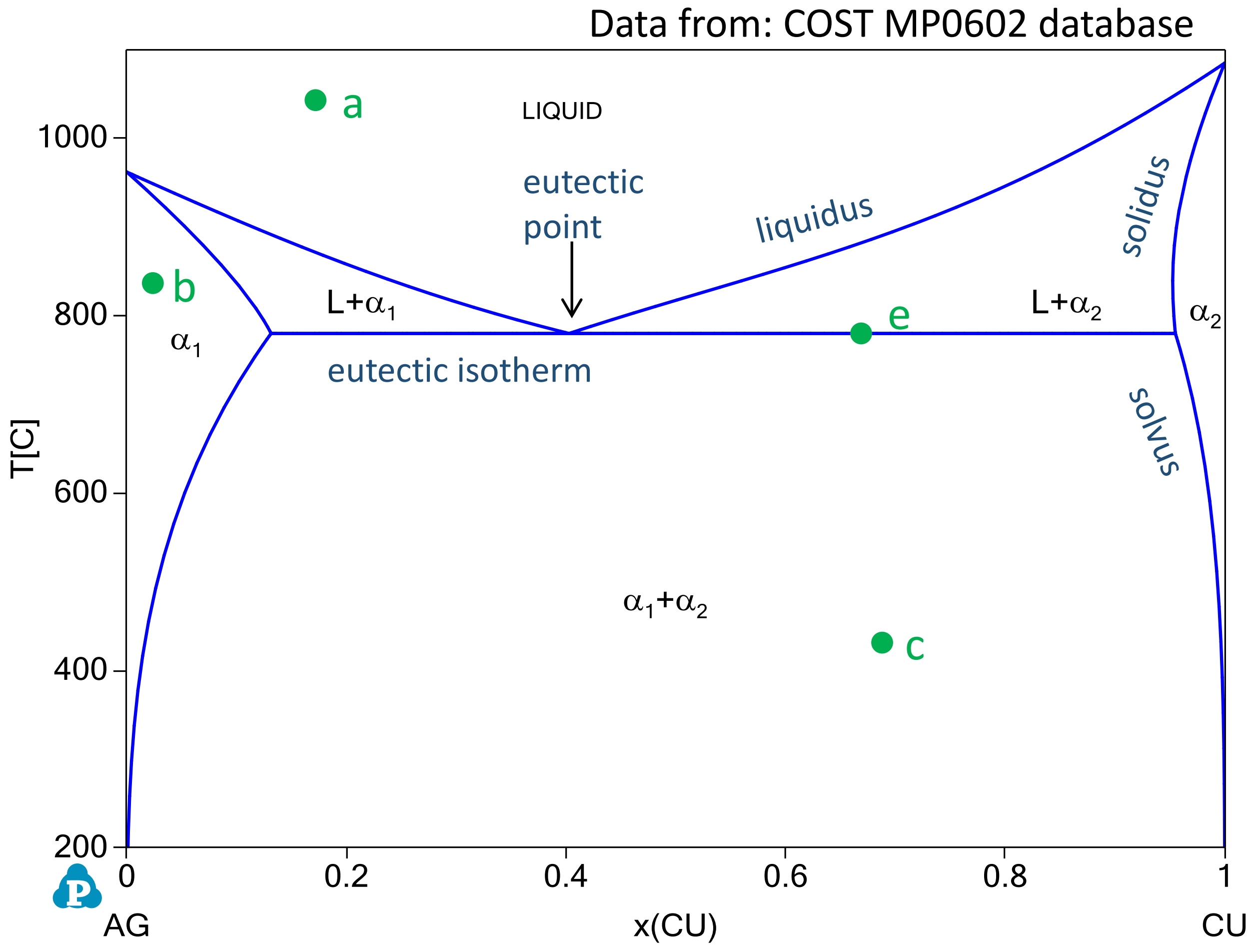
Adapted from
www.computherm.com

Microstructure of hypoeutectic alloy



Adapted from
www.computherm.com

Ag-Cu system



$$F = C - P + 2$$
$$P = \text{const.}$$
$$F' = C - P + 1$$

a, b: $C = 2, P = 1$

$F' = 2 - 1 + 1 = 2$

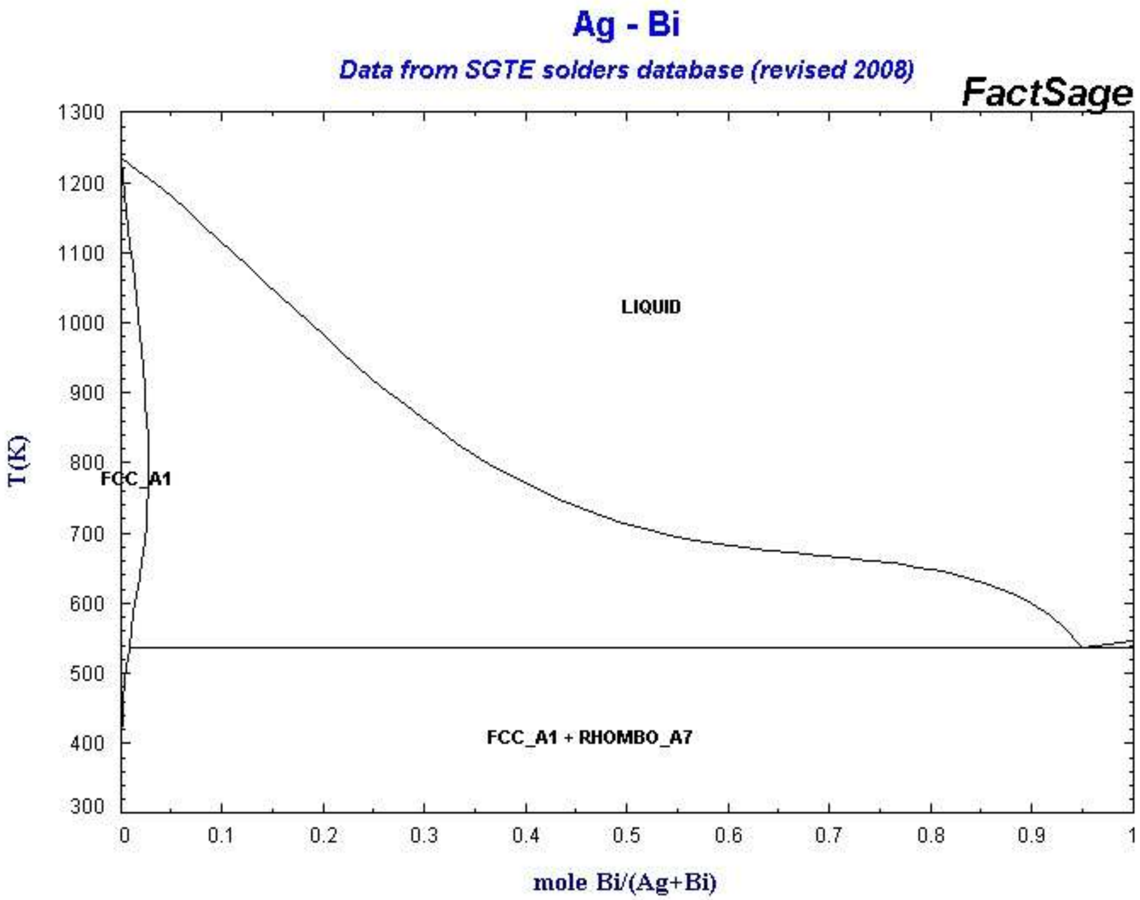
c: $C = 2, P = 2$

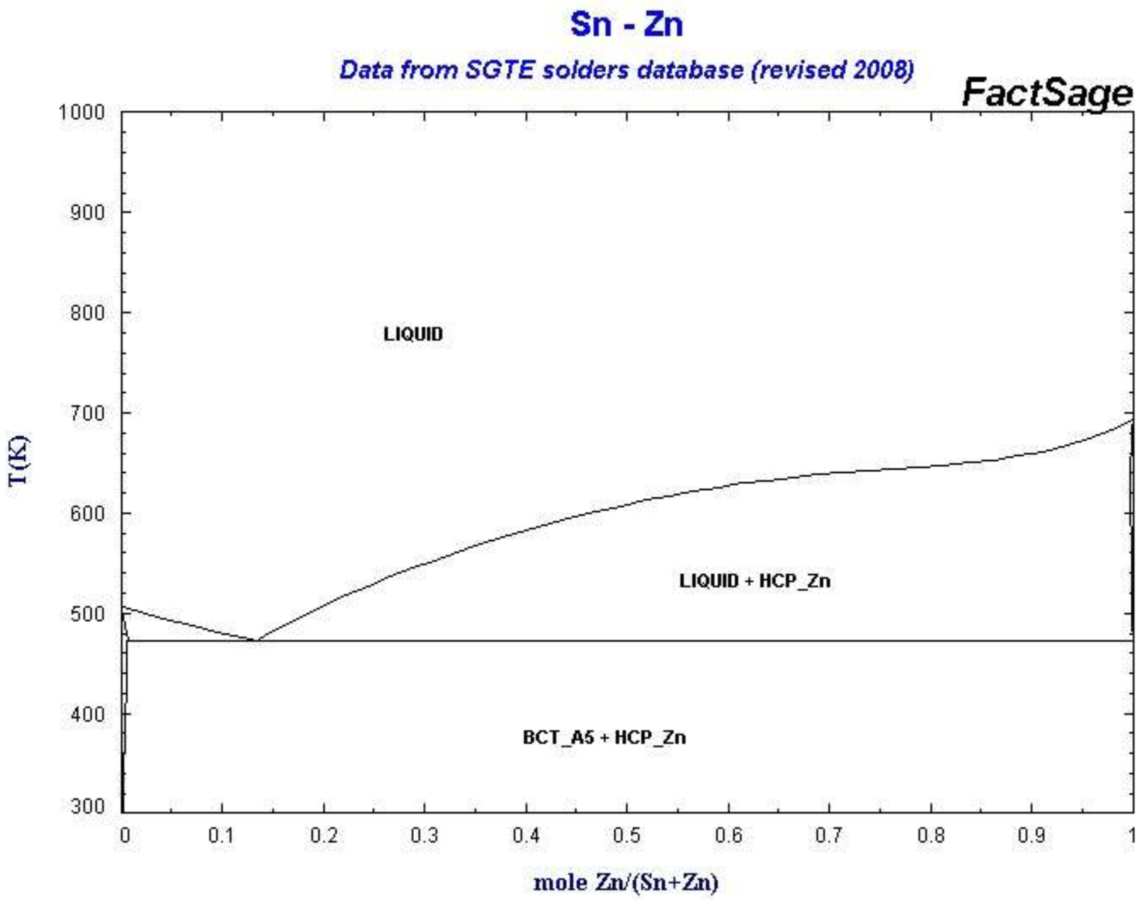
$F' = 2 - 2 + 1 = 1$

e: $C = 2, P = 3$

$F = 2 - 3 + 1 = 0$

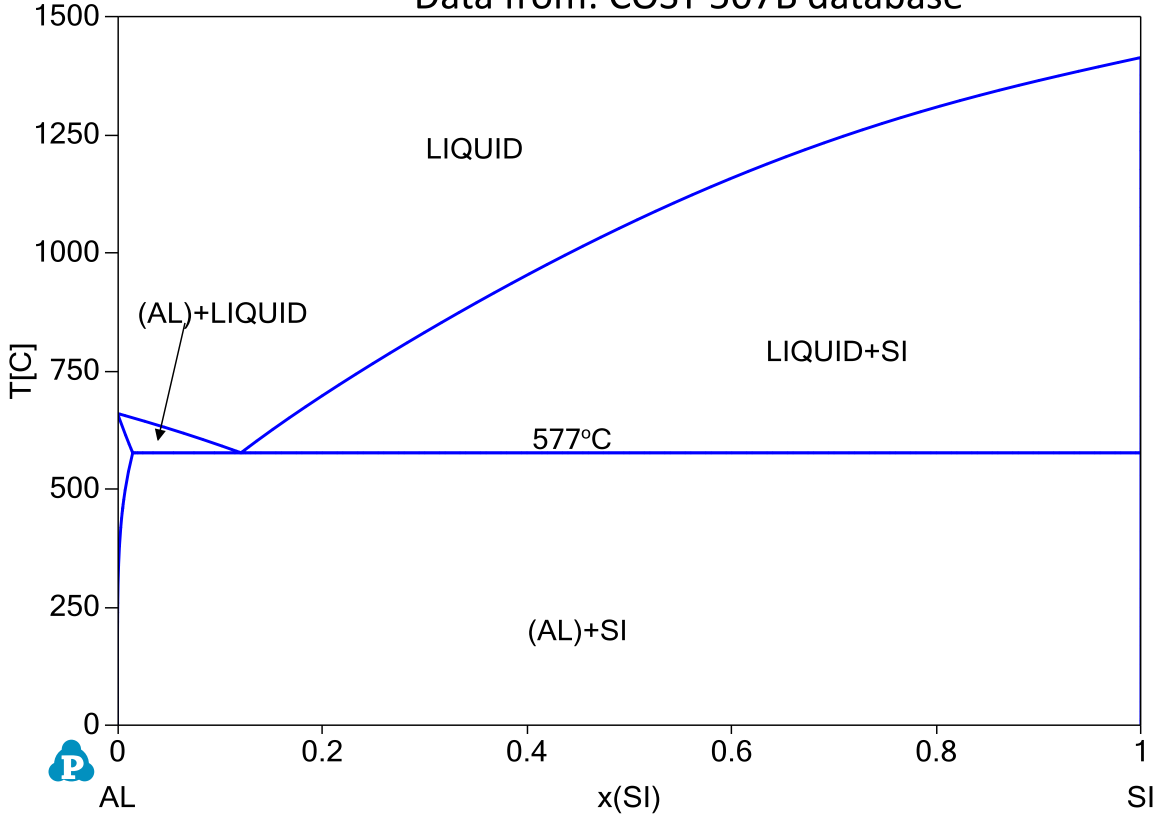
Examples of eutectic systems: Ag-Bi, Sn-Zn



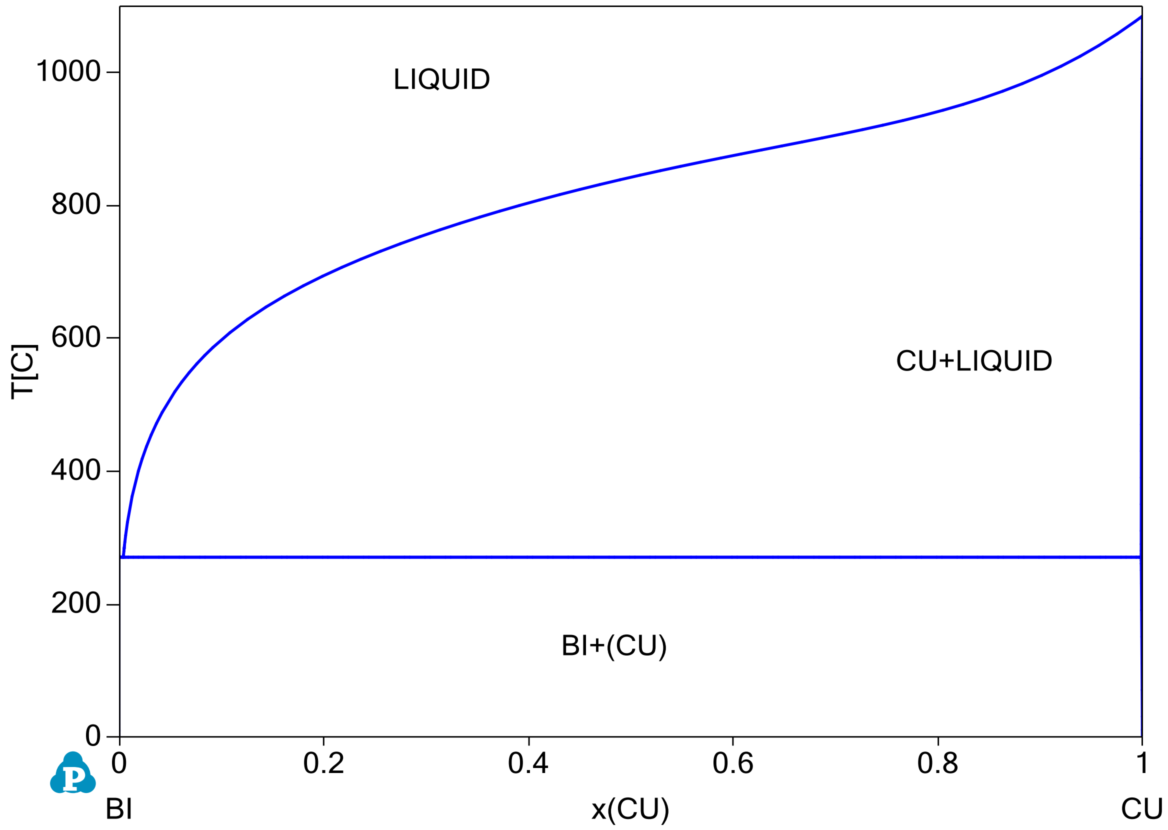


Examples of eutectic systems: Al-Si, Bi-Cu

Data from: COST 507B database

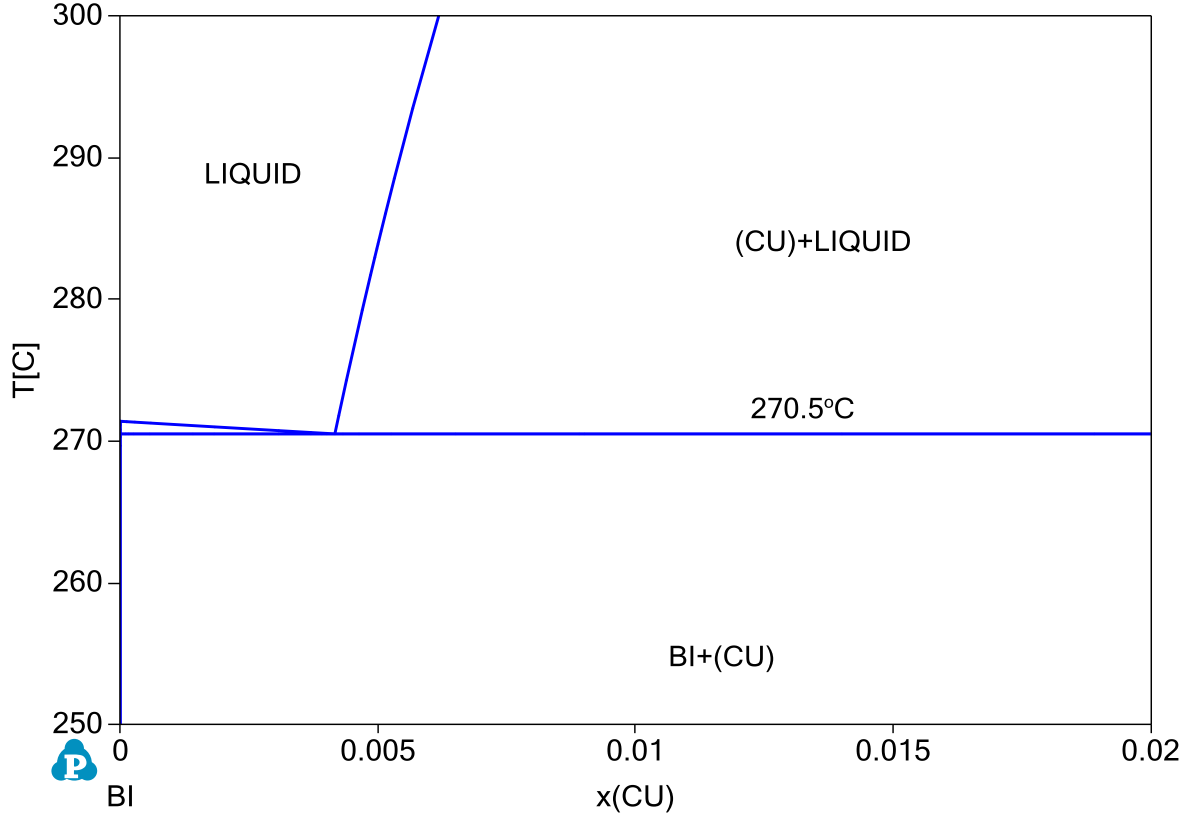


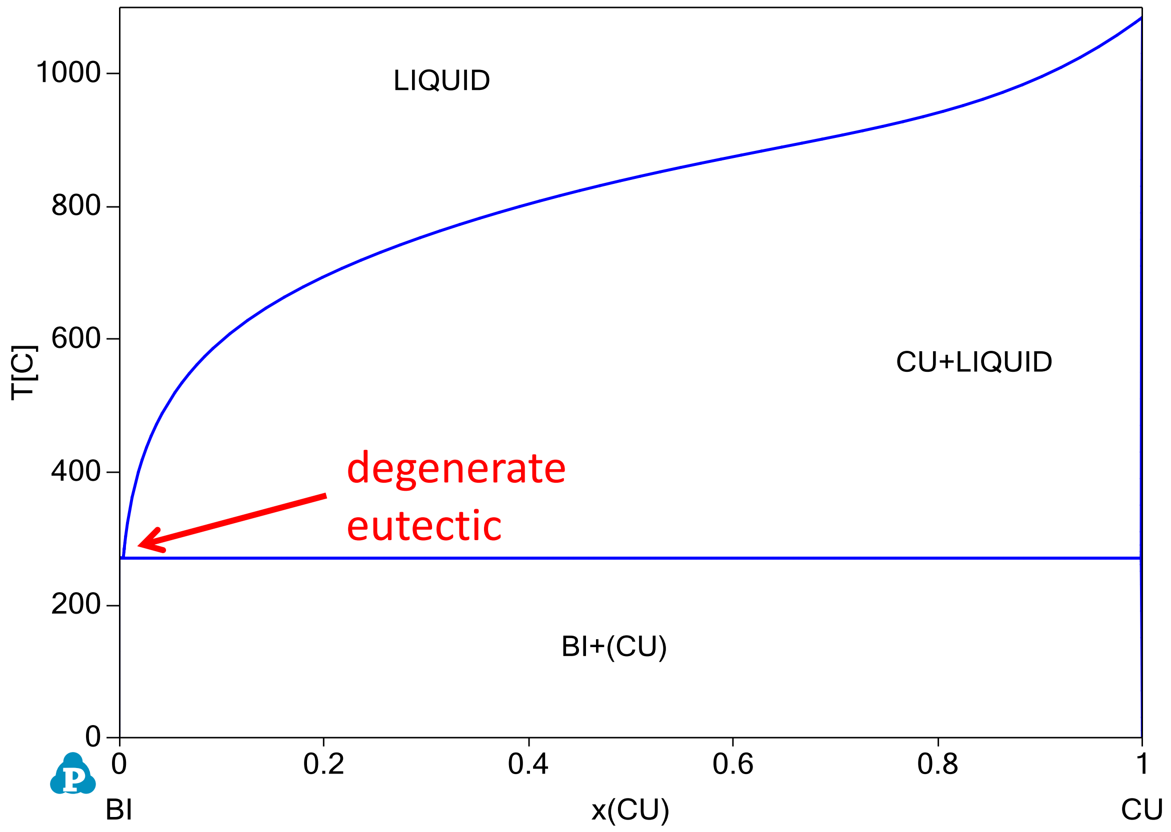
Data from: COST MP0602 database



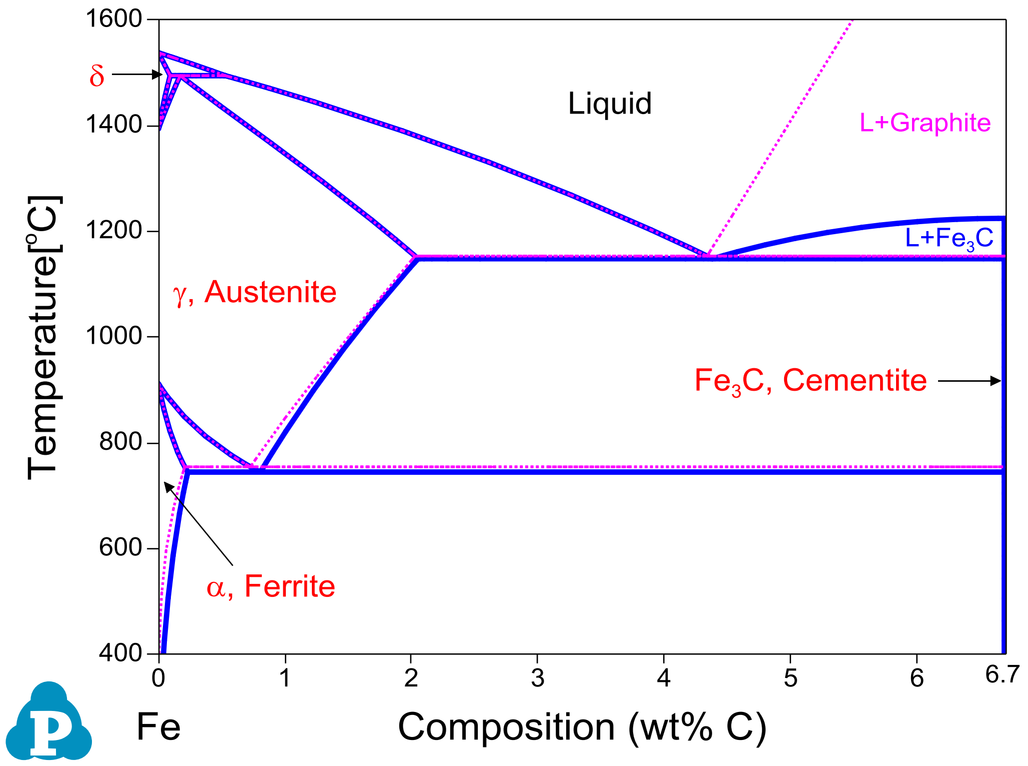
Examples of eutectic systems: Bi-Cu

Data from: COST MP0602 database





Eutectoid systems



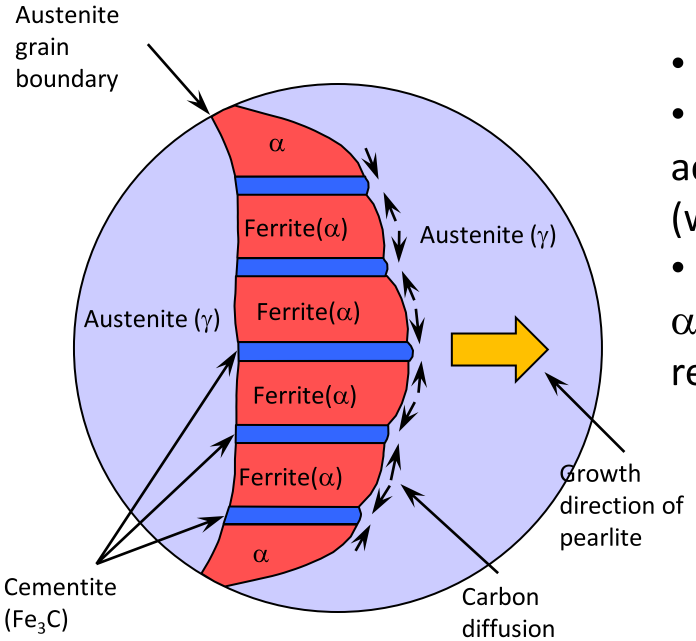
Information from this diagram:

- Fe-C stable phase boundaries are represented by pink dot lines, and Fe-Fe_3C metastable phase boundaries are represented by blue solid lines.
- Fe_3C phase is a line compound (6.7 wt% of Carbon) without any solubility.
- Carbon is an interstitial impurity in iron and forms a solid solution with the α, γ, δ phases.
- Eutectoid reaction is a solid state reaction with no liquid involved: $\gamma \leftrightarrow \alpha + \mathbf{Fe_3C}$.

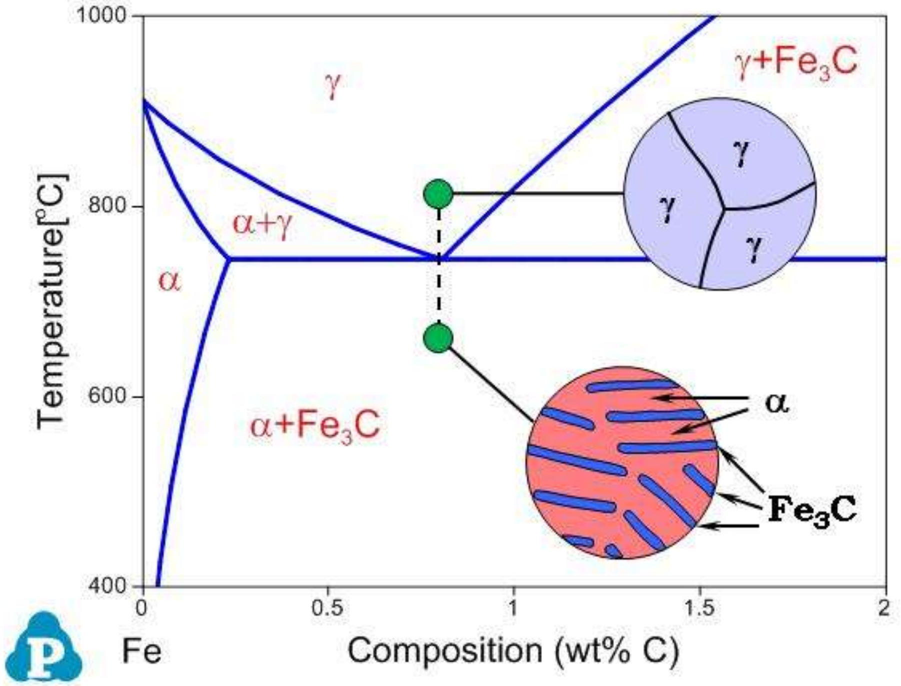
Adapted from www.computherm.com

Fe-Fe_3C system, formation of pearlite

Due to the eutectoid reaction: $\gamma \leftrightarrow \alpha + Fe_3C$, pearlite structure is formed.
Pearlite: alternating layers of α and Fe_3C phases, not a single phase.

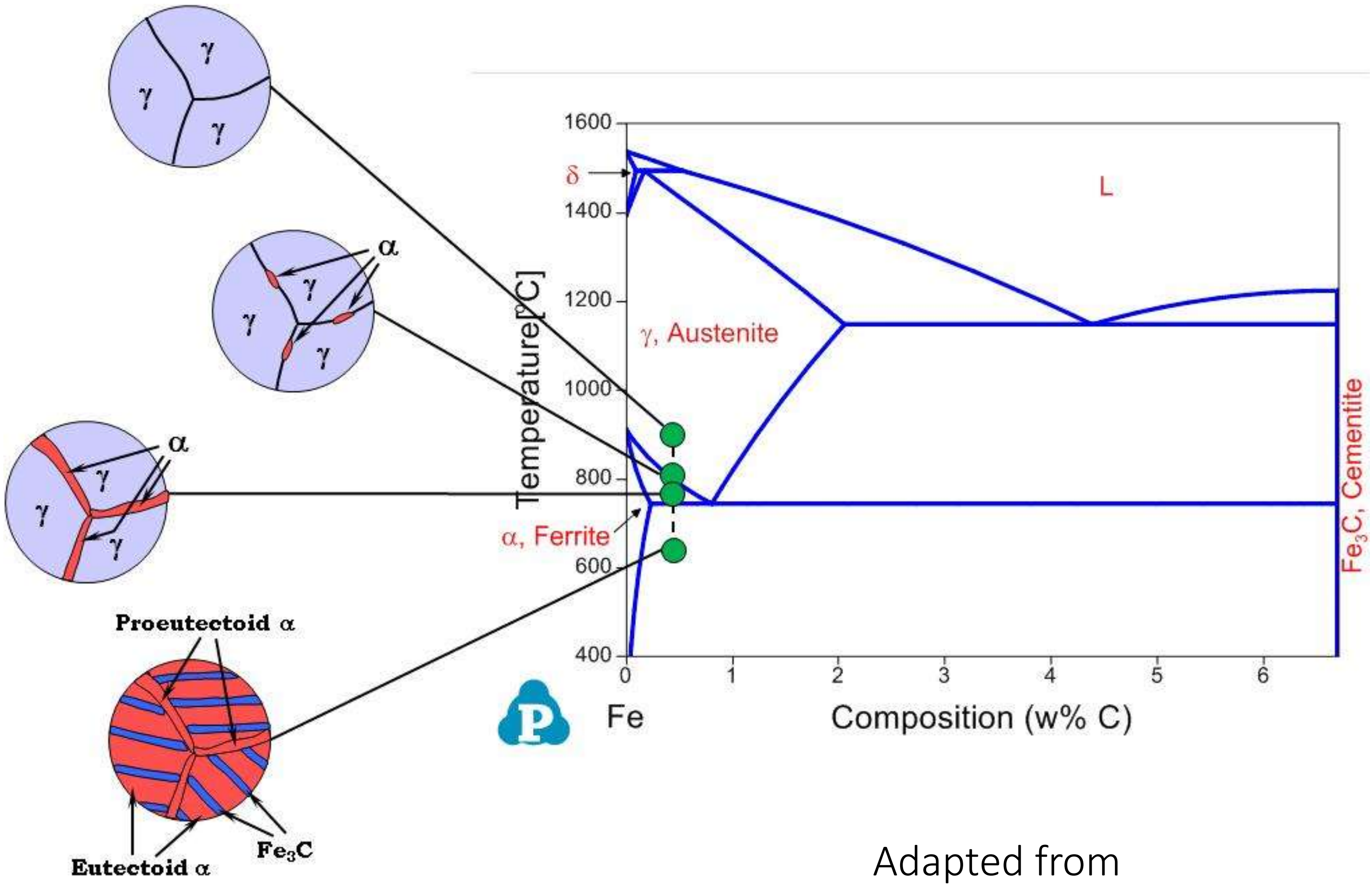


- Nucleating at γ grain boundaries.
- Growth by diffusion of carbon to achieve the compositions of α and Fe_3C (with structure changes).
- According to lever rule, the amount of α is much larger than that of Fe_3C, resulting in a much thicker α lamellae.



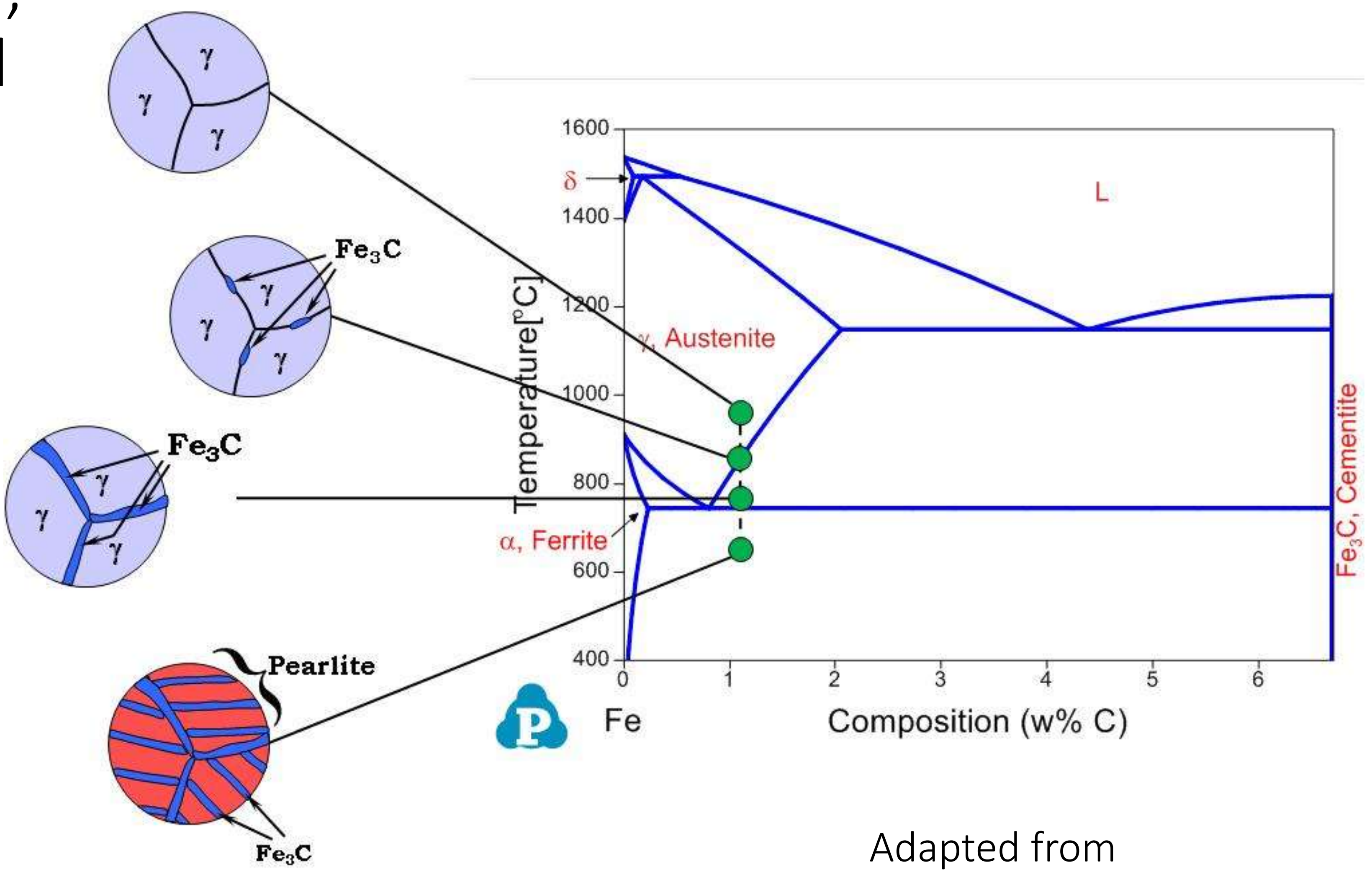
Adapted from www.computherm.com

Fe-Fe_3C system proeutectoid microstructure



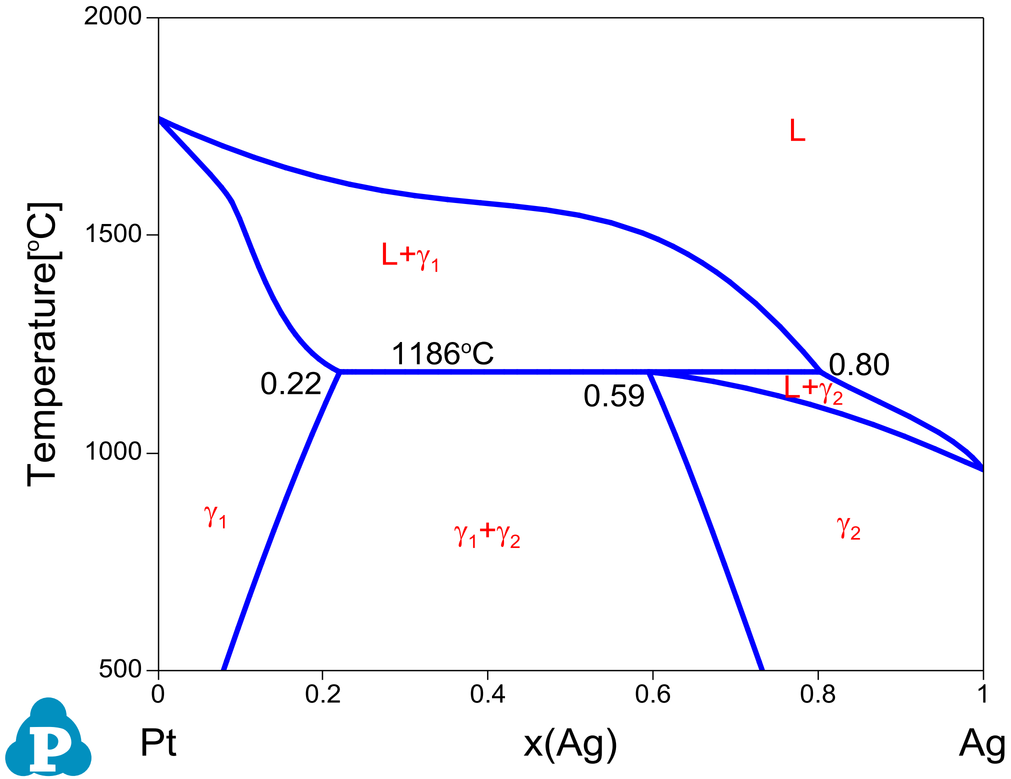
Adapted from www.computherm.com

Fe-Fe_3C system, hypereutectoid microstructure



Adapted from www.computherm.com

Peritectic systems

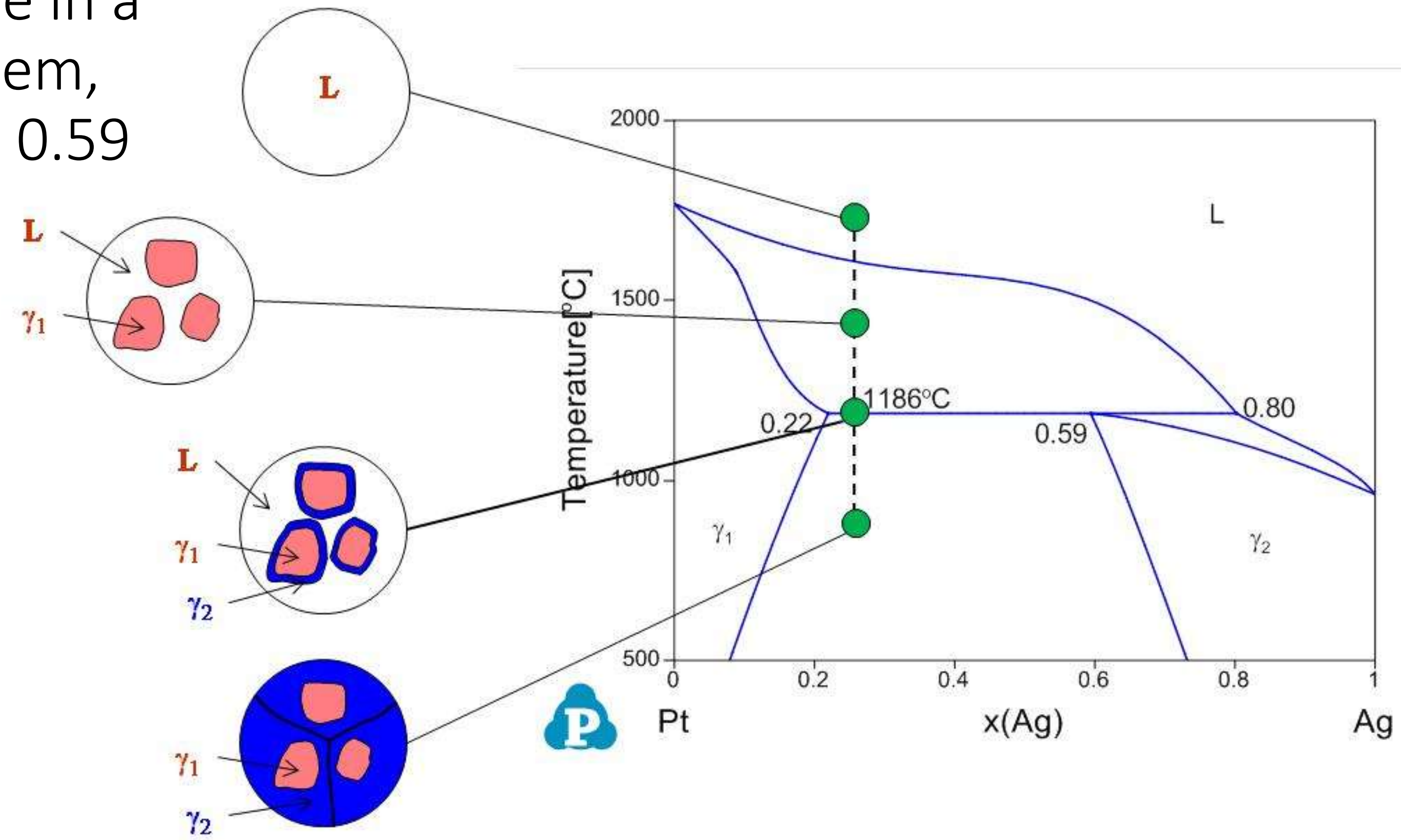


Information from this diagram:

- Peritectic reaction occurs at 1186°C, Liquid containing 80 at% Ag reacts with γ_1 containing 22 at% Ag: $\mathbf{L} + \gamma_1 \leftrightarrow \gamma_2$.
- Alloy (22%<x_{Ag}<59%) starts to melt at peritectic reaction temperature 1186°C and becomes complete liquid at liquidus.
- Alloy (x_{Ag}<22% or x_{Ag}>59%) starts to melt at solidus, and becomes complete liquid at liquidus.

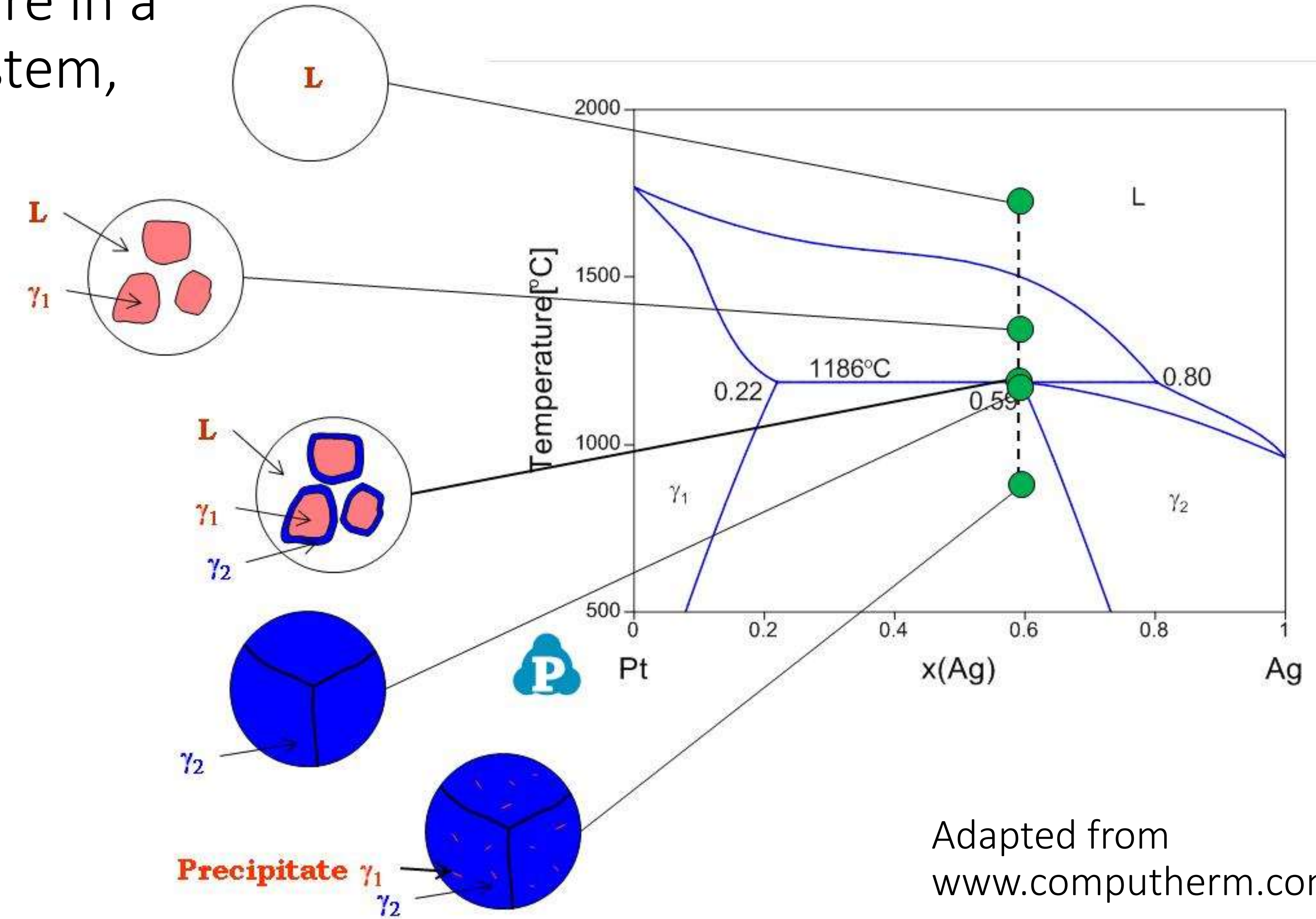
Adapted from www.computherm.com

Microstructure in a peritectic system, 0.22 < x(Ag) < 0.59



Adapted from www.computherm.com

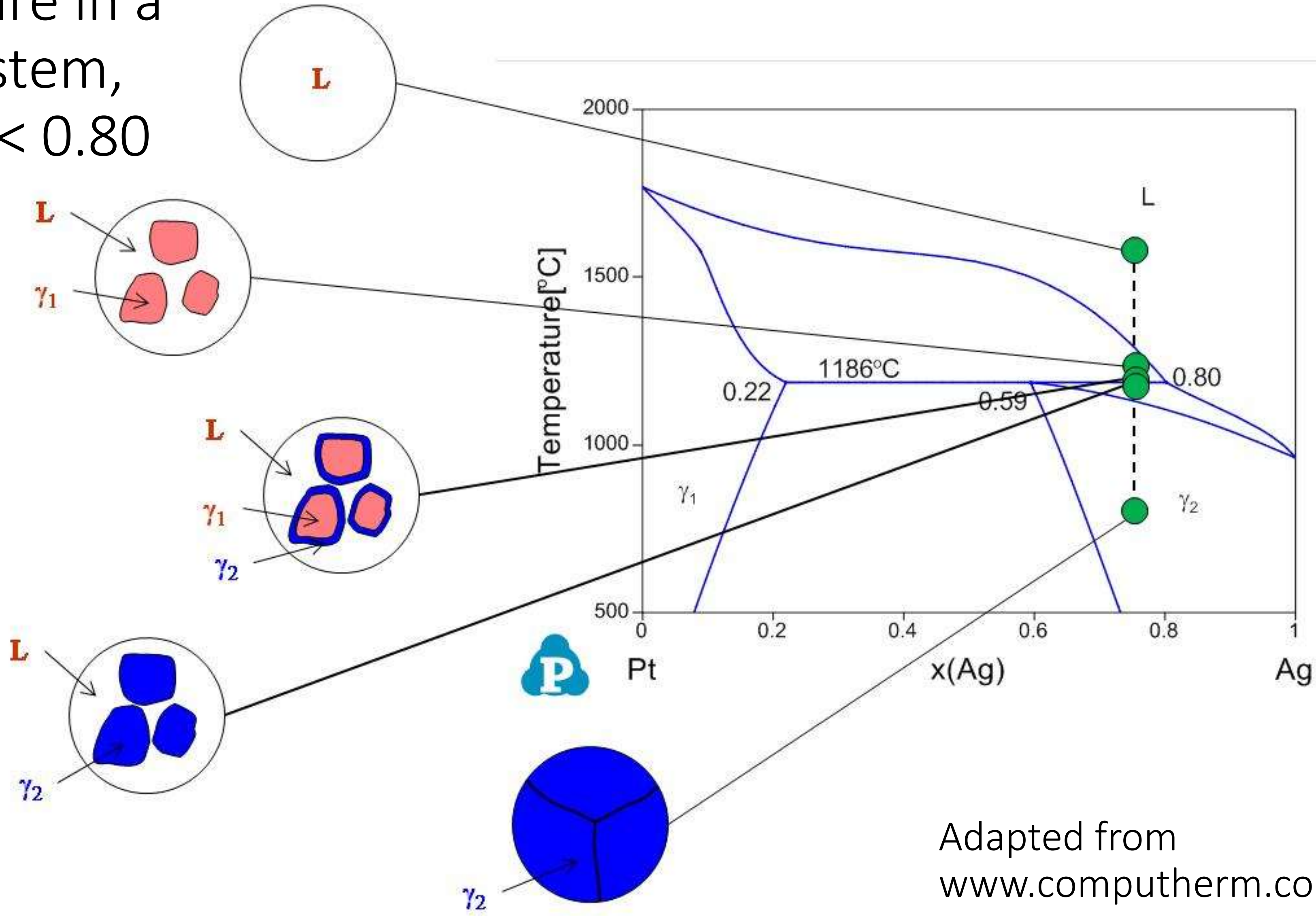
Microstructure in a peritectic system, x(Ag) = 0.59



Adapted from www.computherm.com

Project co-financed by the European Union within the European Social Funds

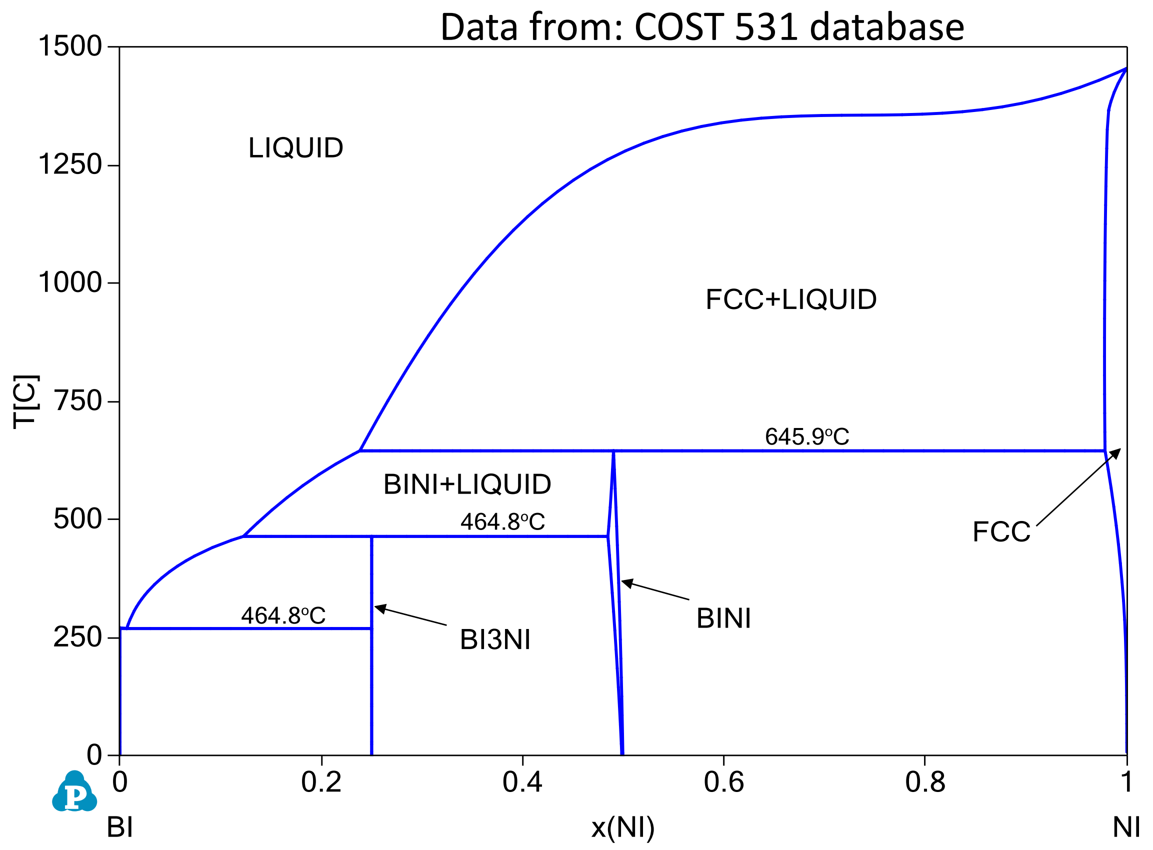
Microstructure in a peritectic system, 0.59 < x(Ag) < 0.80



Adapted from
www.computherm.com

International Interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

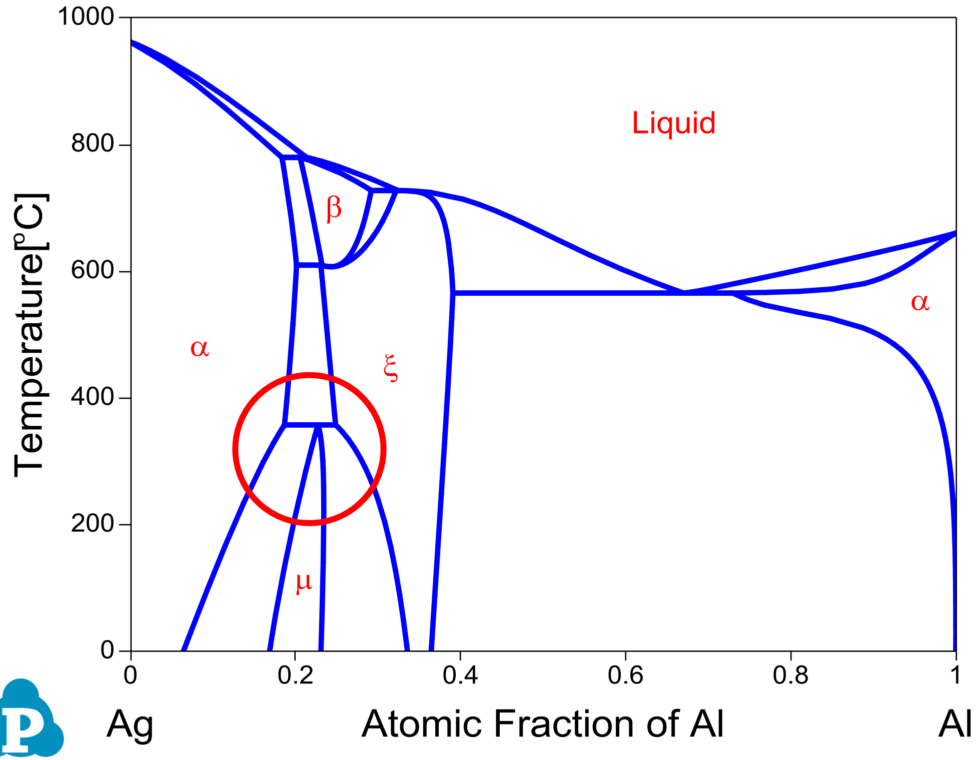
Bi-Ni system (another example)



Information from this diagram:

- Two peritectic reactions and eutectic reaction
- Peritectic reaction L + FCC ↔ BINI occurs at 645.9°C.
- Peritectic reaction L + BINI ↔ BI3NI occurs at 464.8°C.
- Eutectic reaction L ↔ BINI + RHOMBO ocurs at 269°C.
- Incongruent melting of phases Bi3Ni and BiNi.

Peritectoid systems

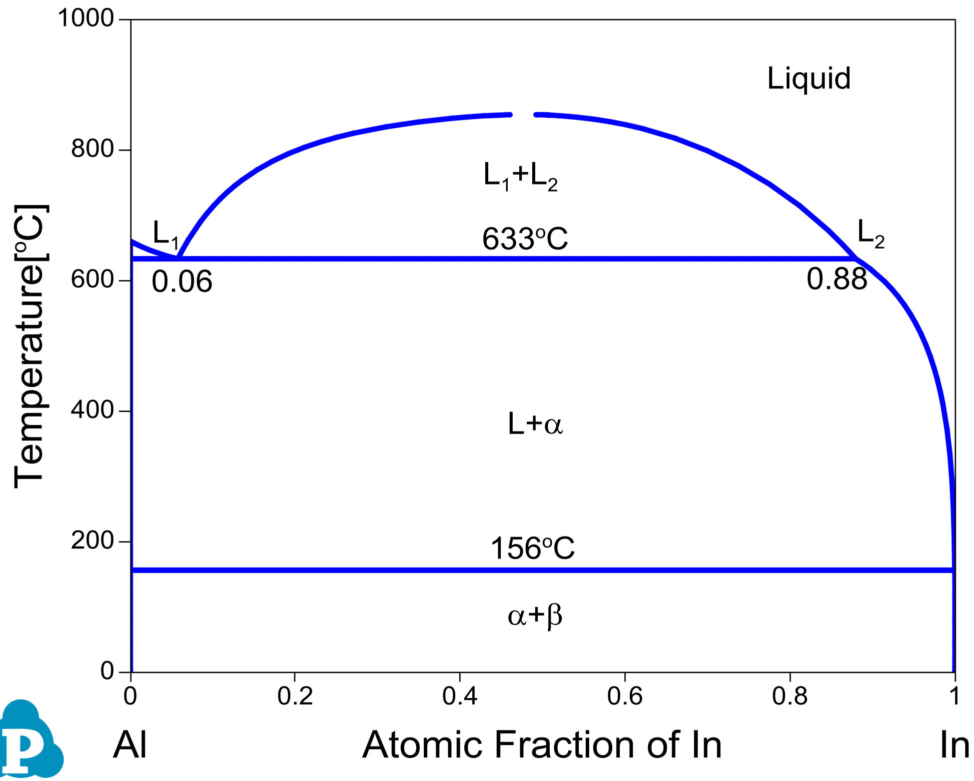


Information from this diagram:

- Peritectoid reaction is a solid state reaction without any liquid involved.
- Peritectoid reaction occurs at 358°C and 18.6 - 24.8 at% Al: $\alpha + \xi \leftrightarrow \mu$.

Adapted from www.computherm.com

Monotectic systems

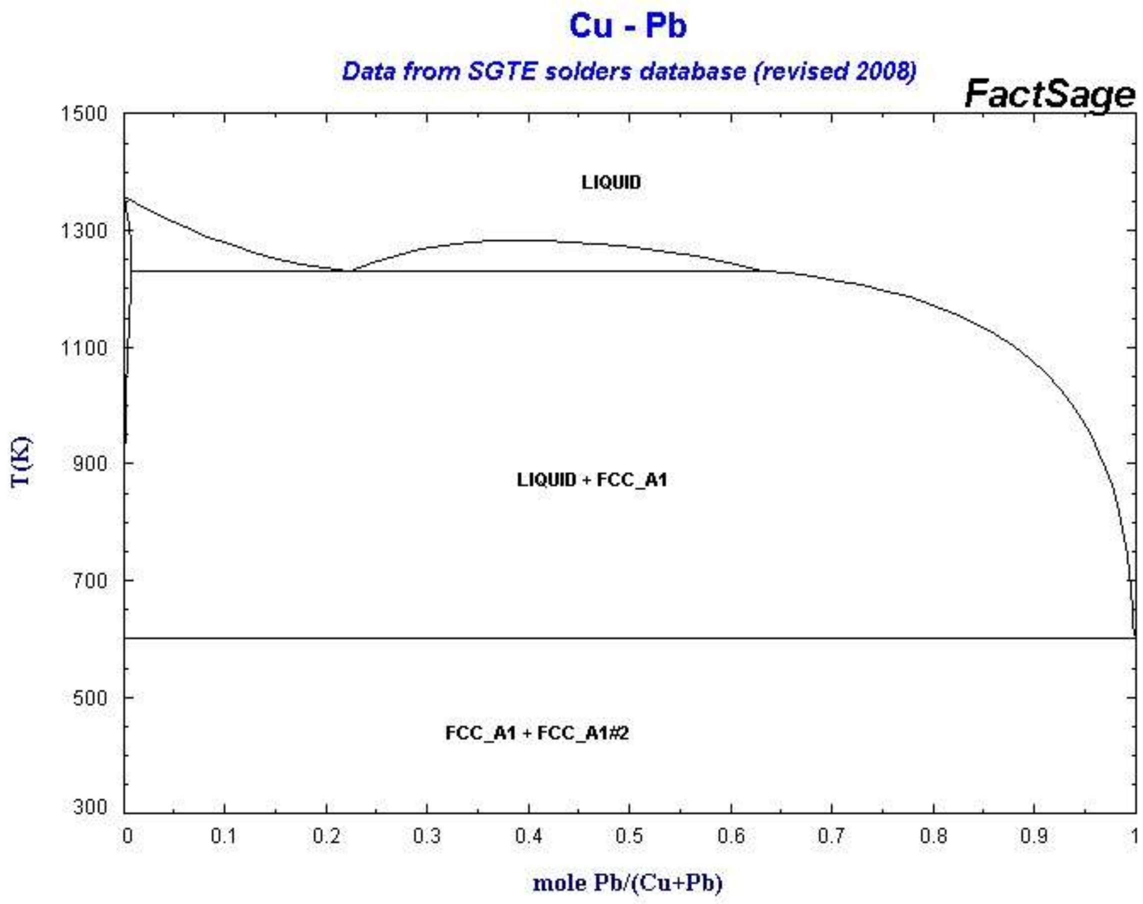


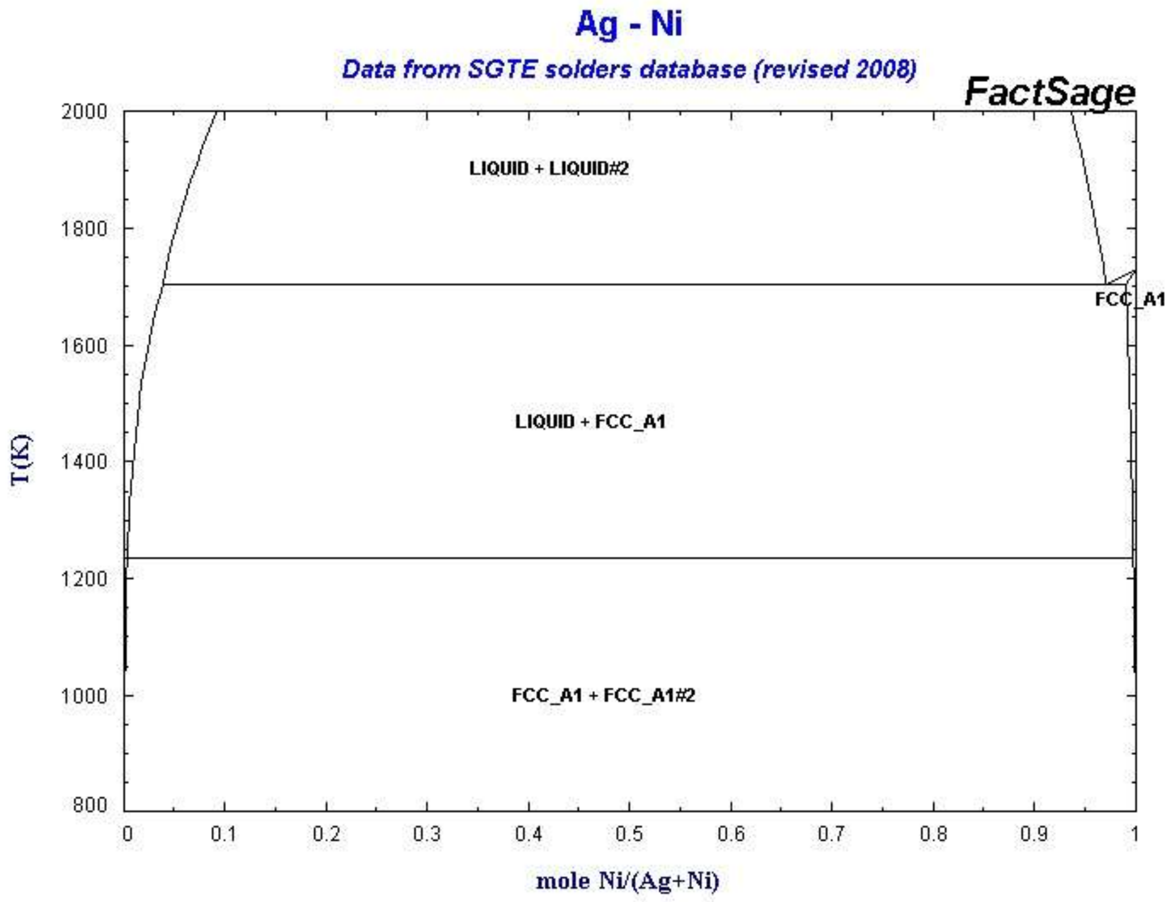
Information from this diagram:

- Monotectic reaction occurs at 663°C and 6 at% In: $\mathbf{L_1} \leftrightarrow \alpha + \mathbf{L_2}$.
- Alloys of all compositions start to melt at eutectic temperature 156°C: $L \leftrightarrow \alpha + \beta$.
- Alloy (x_{In}<6at% or x_{In}>88at%) becomes complete liquid at liquidus.
- Alloy (6at%<x_{In}<88at%) becomes complete liquid mixture (two liquids with different compositions) at 663°C.

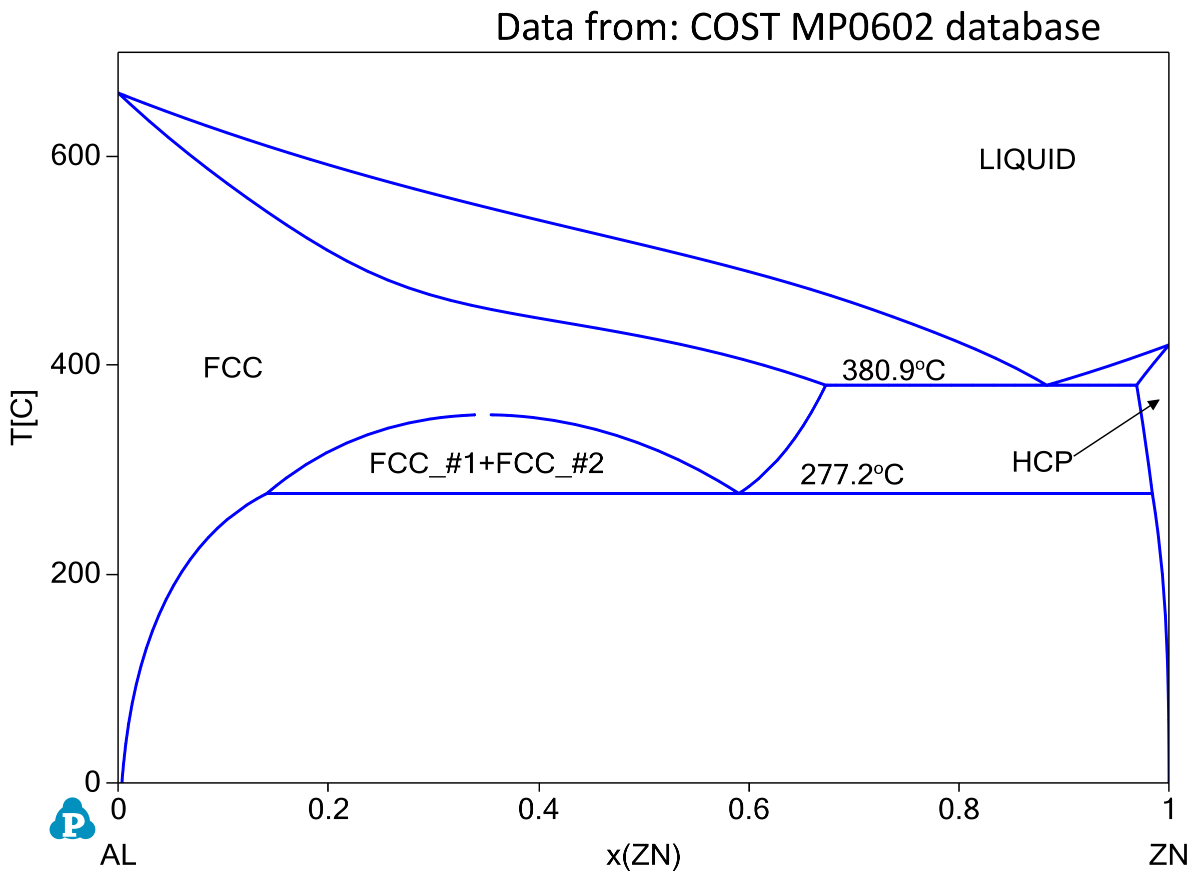
Adapted from www.computherm.com

Examples of monotectic systems: Cu-Pb, Ag-Ni





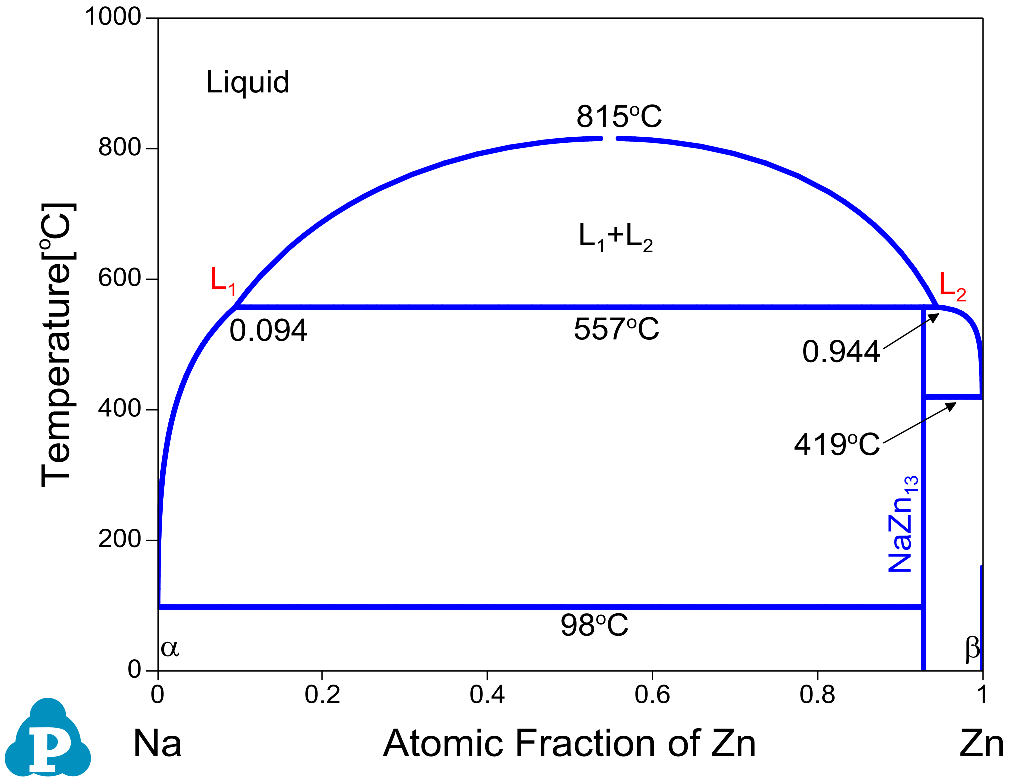
Monotectoid sytems



Information from this diagram:

- Monotectoid reaction occurs at 277.2 °C and 59 at% Zn: **FCC_#2 ↔ FCC_#1 + HCP**
- Solubility limit of Zn in FCC phase varies with temperature, solubility of Zn in FCC phase is 14 at% at 277.2 °C.
- Eutectic reaction occurs at 380.9°C and 88 at% Zn: **L ↔ FCC + HCP**.

Synthetic systems

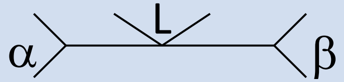
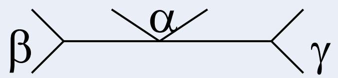
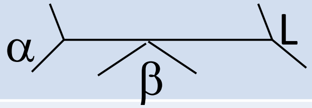
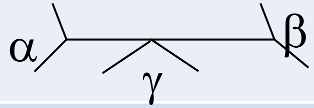
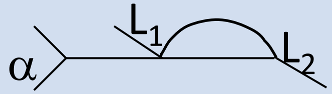
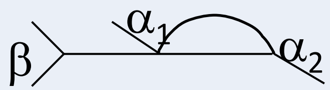
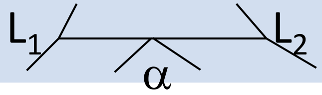


Information from this diagram:

- Syntectic reaction occurs at 557°C: **$L_1 + L_2 \leftrightarrow NaZn_{13}$**.
- Alloys (x_{Zn}<92.3at%) start to melt at eutectic temperature 98°C: $L \leftrightarrow \alpha + NaZn_{13}$.
- Alloys (x_{Zn}>92.3at%) start to melt at eutectic temperature 419°C: $L \leftrightarrow \beta + NaZn_{13}$.
- Alloy (x_{Zn}<9.4at% or x_{Zn}>94.4at%) becomes complete liquid at liquidus.
- Alloy (9.4at%<x_{Zn}<94.4at%) becomes complete liquid mixture (two liquids with different compositions) at 557°C.

Adapted from www.computherm.com

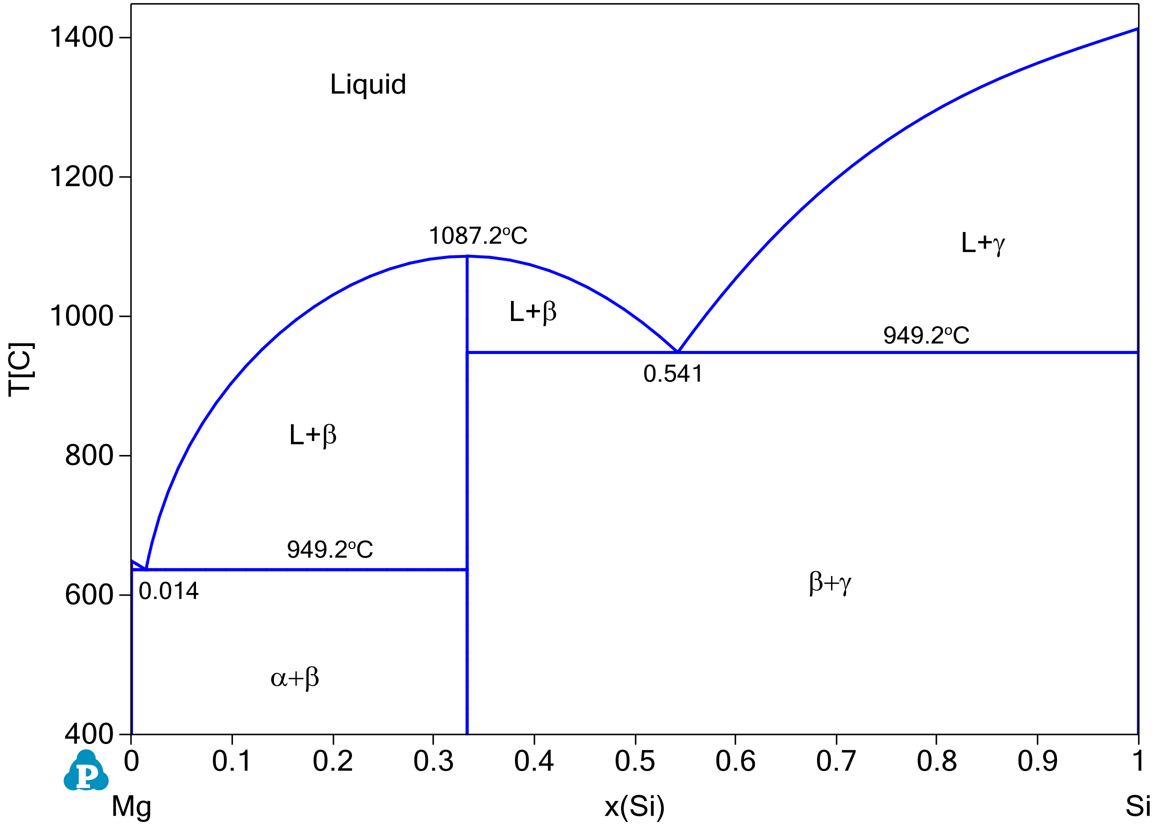
Summary of invariant reactions in binary systems

Reaction	Symbolic equation	Schematic presentation	Example
Eutectic	$L \leftrightarrow \alpha + \beta$		Cu-Ag, Pb-Sn, Al-Si
Eutectoid	$\alpha \leftrightarrow \beta + \gamma$		Fe-C
Peritectic	$L + \alpha \leftrightarrow \beta$		Cu-Fe, Pb-In
Peritectoid	$\alpha + \beta \leftrightarrow \gamma$		Al-Cu
Monotectic	$L_1 \leftrightarrow L_2 + \alpha$		Cu-Pb, Al-In
Monotectoid	$\alpha_1 \leftrightarrow \alpha_2 + \beta$		Al-Zn
Syntectic	$L_1 + L_2 \leftrightarrow \alpha$		Na-Zn

Adapted from www.computherm.com

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Congruent transformations, example: Mg-Si



Data from: COST 507B database

Congruent transformation - when one phase changes directly into another without change in composition.

L ↔ β

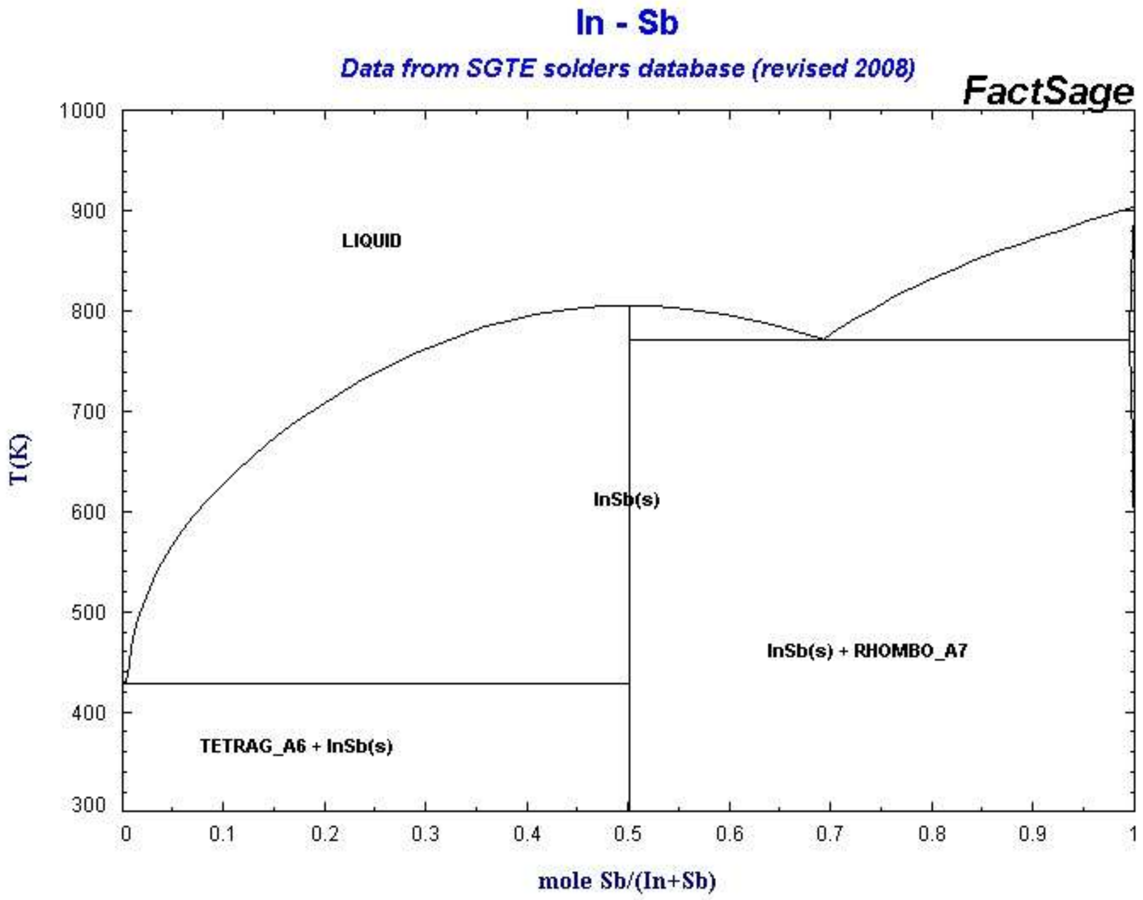
α = (Mg)

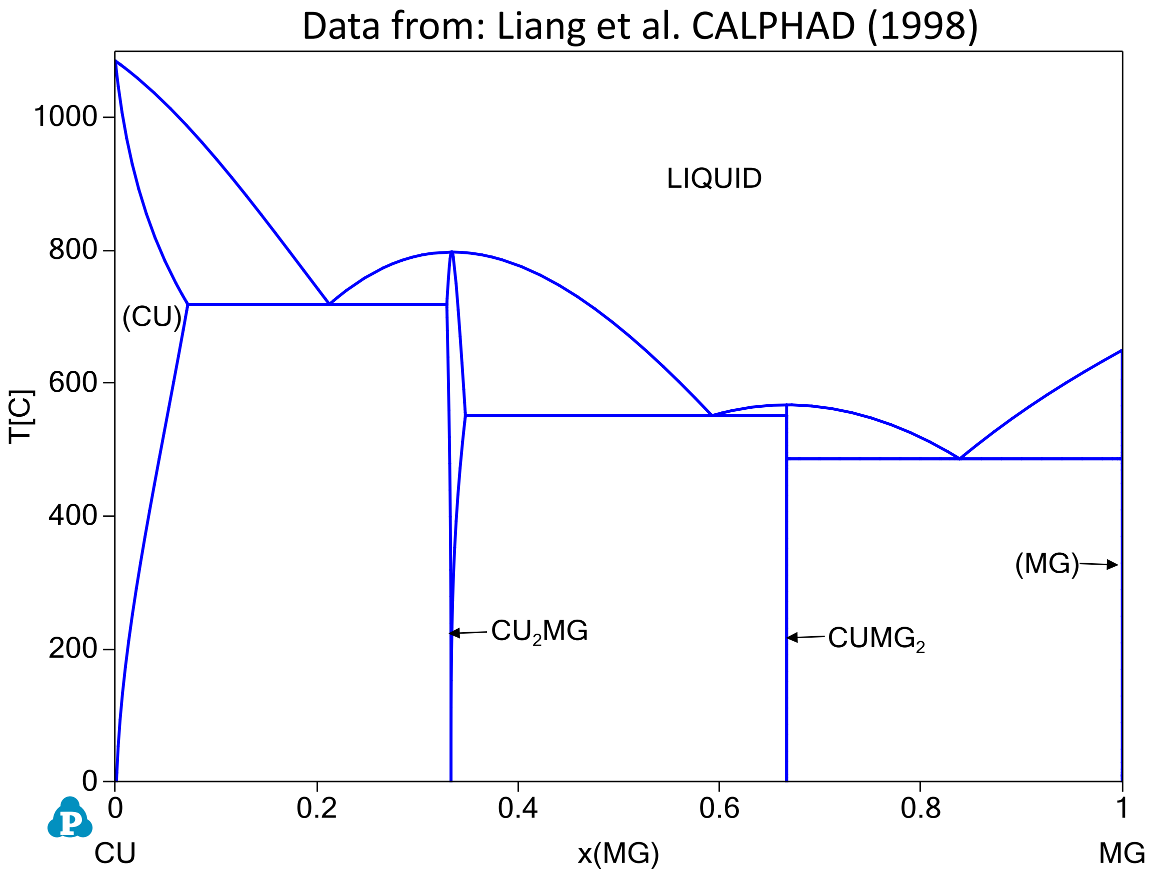
β = Mg_2Si

γ = Si

System can be divided into two independent eutectic systems.

Congruent Transformations, examples: **In-Sb, Cu-Mg**



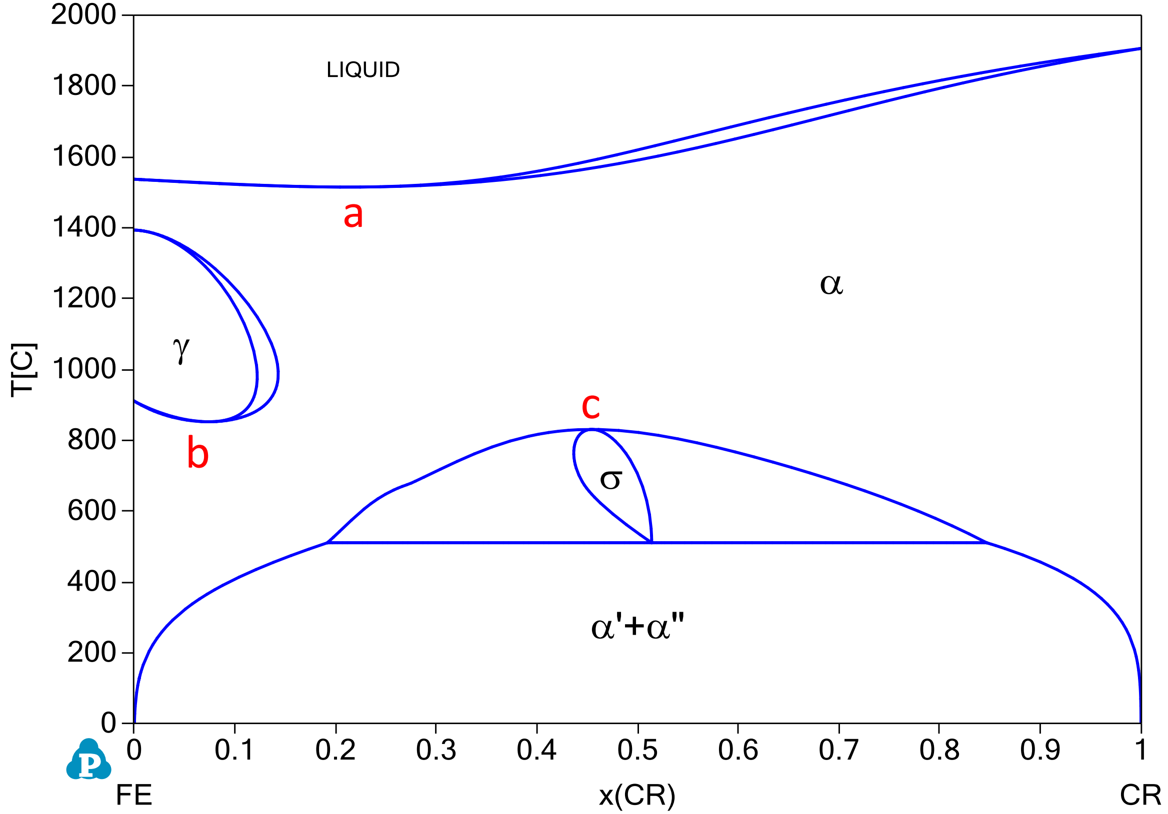


Intermetallic compounds (Phases) - nomenclature

Frequently designated by Greek letters: α, β, γ, δ, …

- Sometimes: → β for bcc phases
  → γ for compounds with g-brass structure (Cu_5Zn_8)
  → σ for compounds with a certain tetragonal structure (as in Fe-Cr system)
- Sometimes designated as compound, like:
  → Mg_2Si, Cu_3Sn, Cu_5Zn_8, …
- Sometimes non-stoichiometry is indicated, for example:
  → $Fe_{1-x}S$, $Ni_{1\pm x}Sb$, …

Congruent Transformations, example: **Fe-Cr**



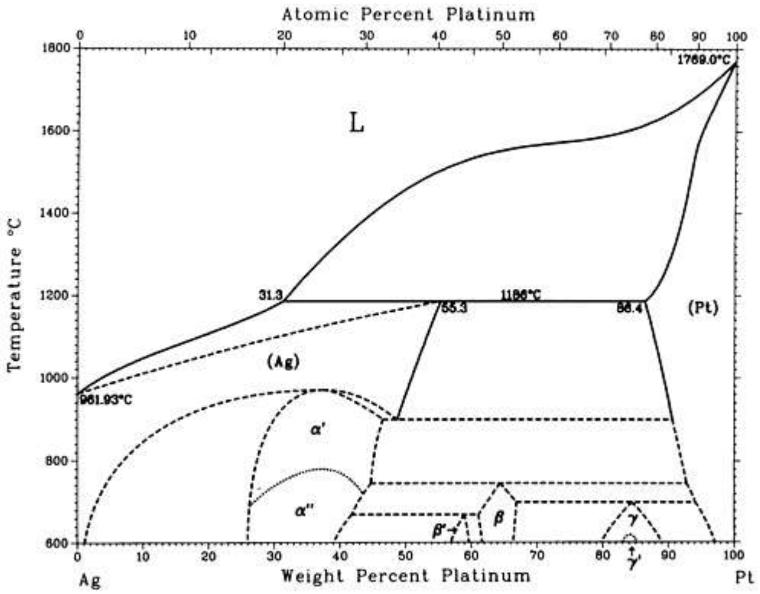
Data from: Lee, CALPHAD (1993)

a: melting point minimum

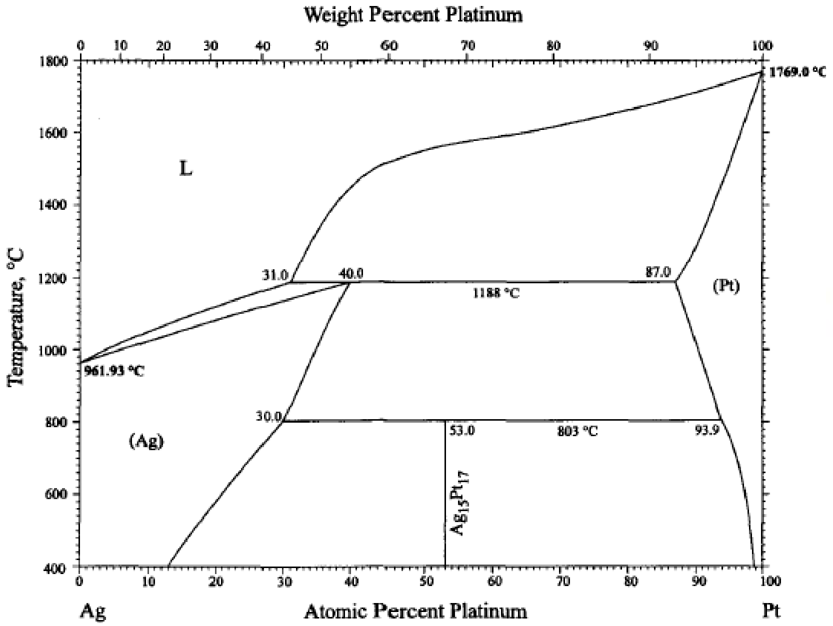
b: congruent transformation γ ↔ α at minimum

c: congruent transformation α ↔ σ at maximum

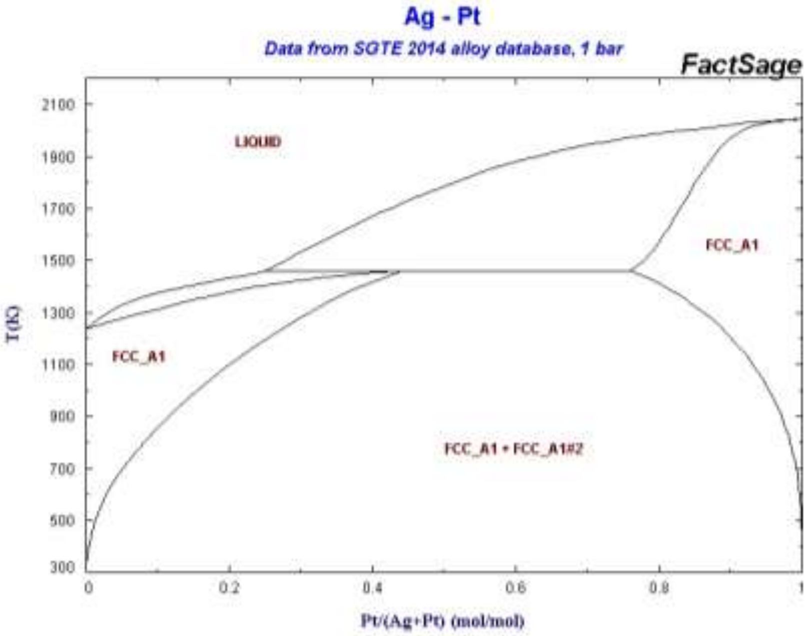
A case of Ag-Pt system



Karakaya & Thomson,
Bull. Alloy Phase Diagr. 1987
(reproduced in ASM Handbooks)



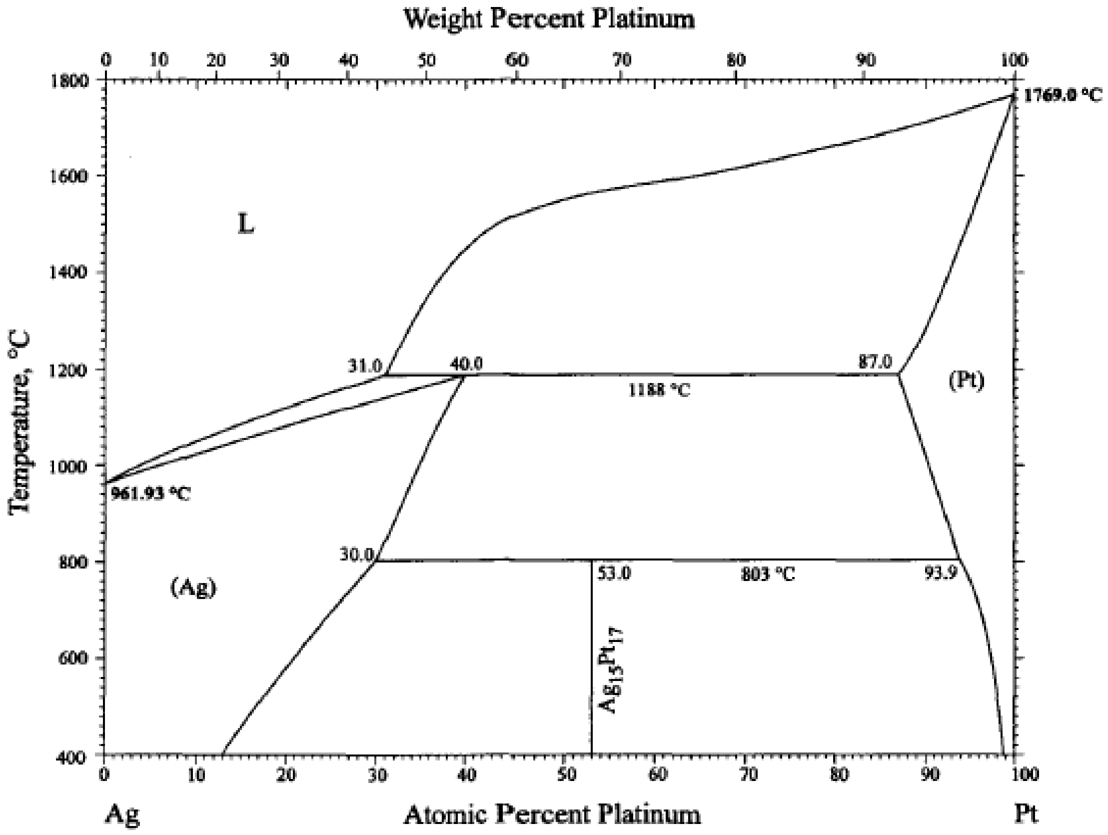
Durussel & Feschotte,
J. Alloy Compd. 1996



(available in commercial database)

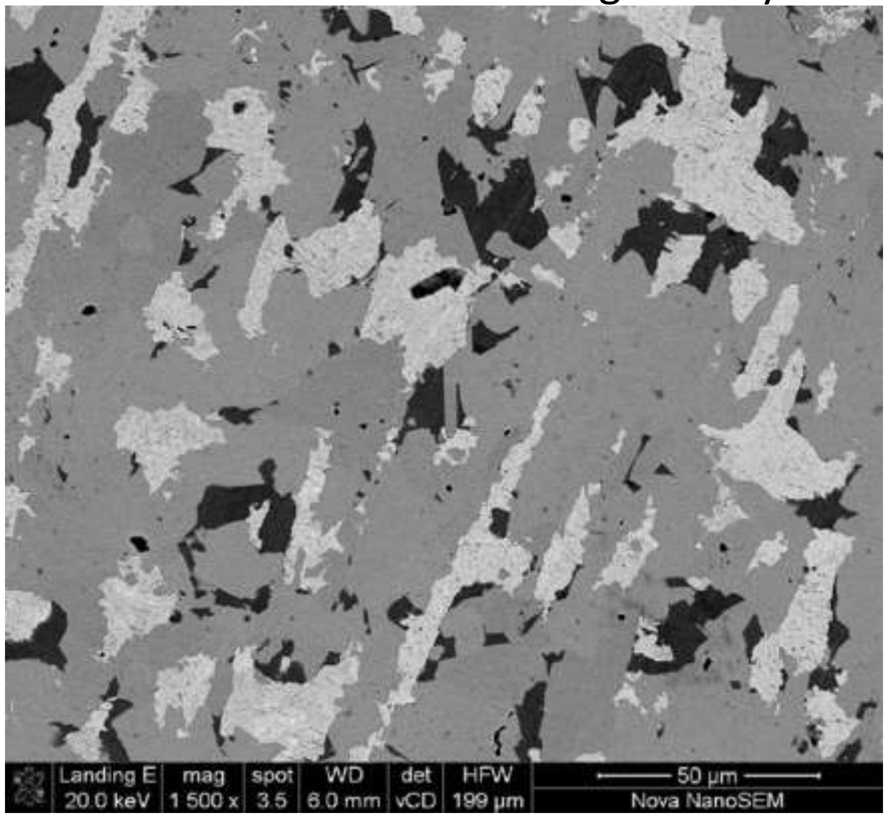
European Funds
Knowledge Education Development
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES
European Union
European Social Fund

A case of Ag-Pt system



Durussel & Feschotte, J. Alloy Compd. 1996

Microstructure of 53 at% Pt Ag-Pt alloy



Hart et al., Acta Mater. 2017

Experimental detemination of phase diagrams

- Isothermal techniques
  - Metallography
  - X-rays
  - Quantitative determination of phase compositions in multi-phase fields
  - Diffusion couples
- Non-isothermal techniques
  - Thermal analysis techniques (TA, DTA, DSC)
  - Chemical potential techniques
  - Magnetic susceptibility techniques
  - Resistivity, dilatometric methods

Main phase diagram software and database sellers

Thermo-Calc Software

FactSage™

CompuTherm FOR MATERIALS DESIGN

PANDAT™ SOFTWARE

Commercial database example: PanMo

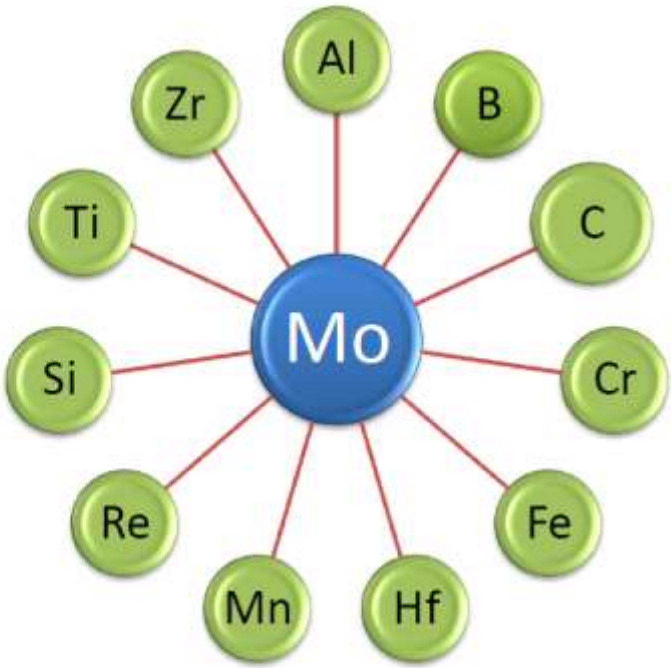


Table 1.3: Modeling status for all the constituent binary systems

	B	C	Cr	Fe	Hf	Mn	Mo	Re	Si	Ti	Zr
Al	■	■	■	■	■	■	■	■	■	■	■
B		■	■	■	■	■	■	■	■	■	■
C			■	■	■	■	■	■	■	■	■
Cr				■	■	■	■	■	■	■	■
Fe					■	■	■	■	■	■	■
Hf						■	■		■	■	■
Mn							■		■		
Mo								■	■	■	■
Re									■	■	
Si										■	■
Ti											■

Table 1.4: Modeling status for all the constituent ternary systems

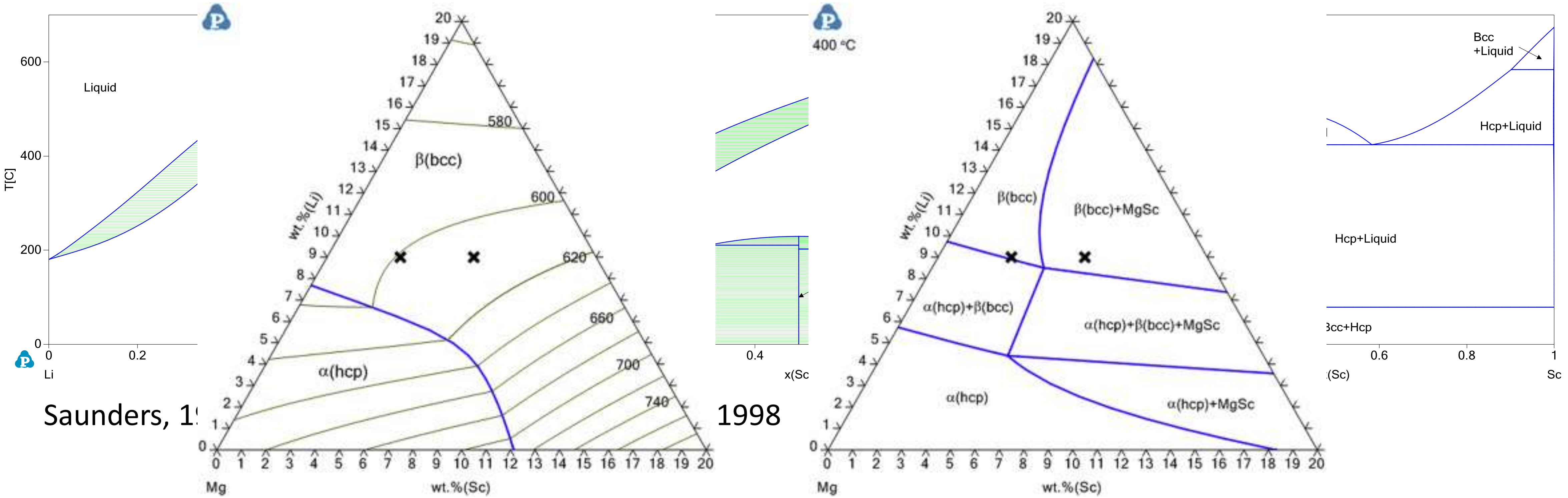
Al-C-Mo	Al-Cr-Mo	Al-Fe-Mn	Al-Fe-Si	Al-Mn-Si	B-C-Mo	B-Hf-Mo	B-Mo-Re
B-Mo-Si	B-Mo-Zr	B-Si-Ti	C-Cr-Mo	C-Fe-Mo	C-Hf-Mo	C-Mn-Mo	C-Mo-Re
C-Mo-Si	C-Mo-Ti	C-Mo-Zr	Cr-Fe-Ti	Cr-Mo-Ti	Cr-Mo-Zr	Fe-Mo-Si	Hf-Mo-Si
Mo-Re-Si	Mo-Si-Ti	Mo-Si-Zr					

■ : Full description

: Full description for major phases

: Extrapolation

Own database example: Li-Mg-Sc system



Saunders, 1 … 1998

J. Dutkiewicz, Ł. Rogal, D. Kalita, **P. Fima**, J. Alloy Compd. 784 (2019) 686-696

Ternary phase diagrams – how to read them

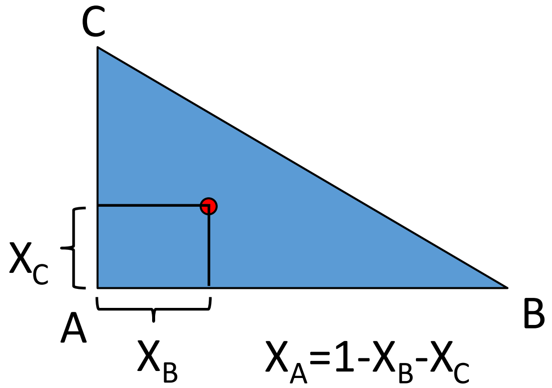
- Isothermal Section
- Isopleth
- Liquidus Projection
- Lever Rule in Ternary Field

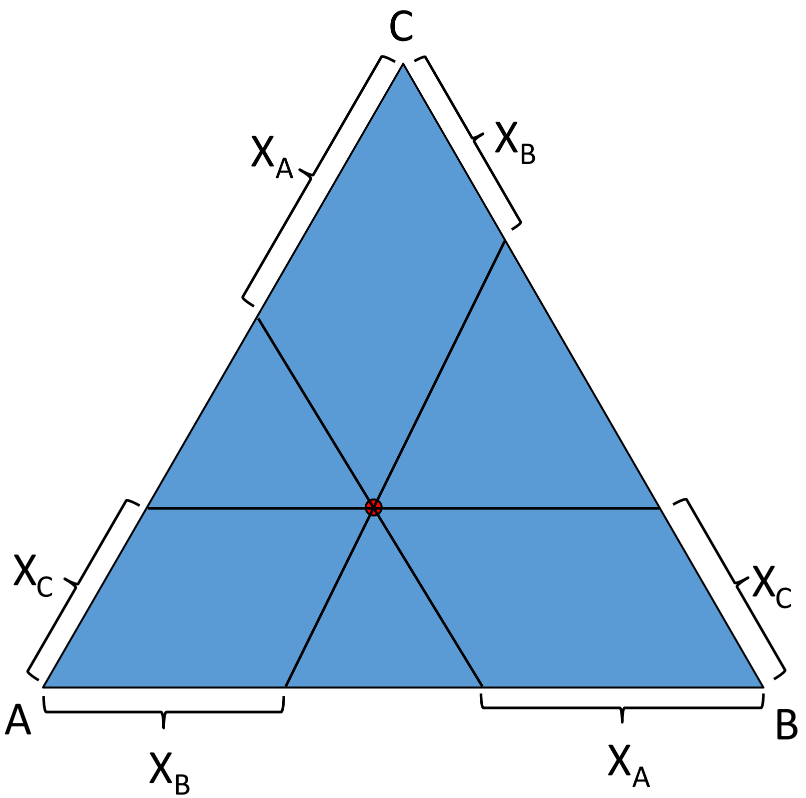
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

European Funds
Knowledge Education Development
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES
European Union
European Social Fund

Reading composition in a ternary phase diagram

- **Isothermal Section:**
- Fixed Temperature
- Composition represented on equilateral Triangle
- For low concentration of one component, use a right-angled triangle (e.g. Fe-Cr-C)



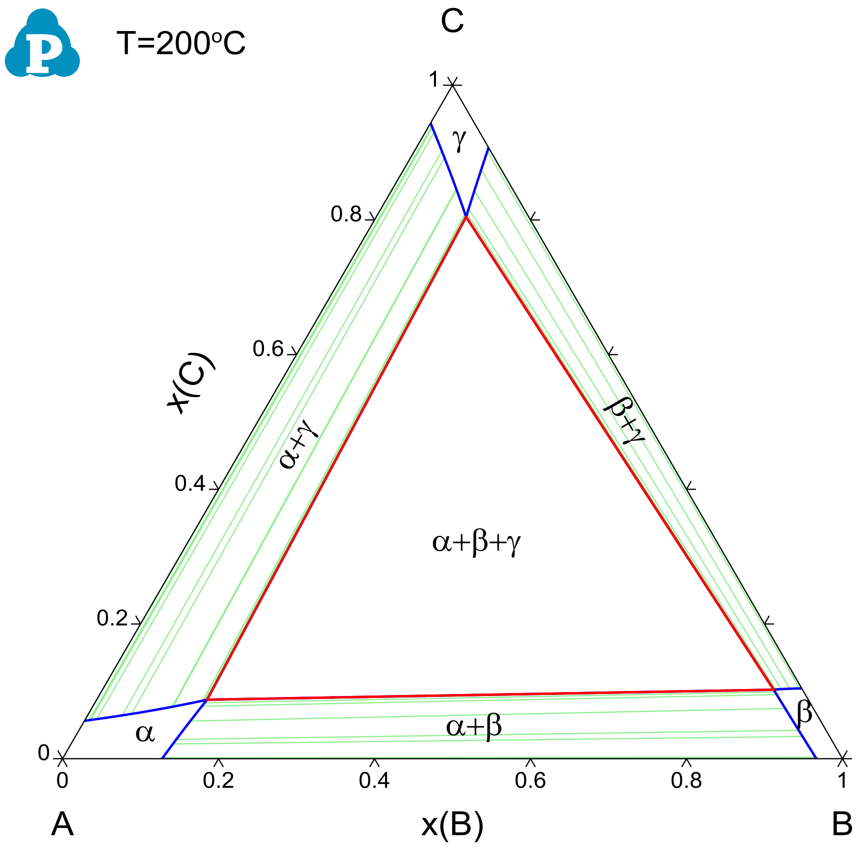


Adapted from www.computherm.com

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Reading a ternary phase diagram

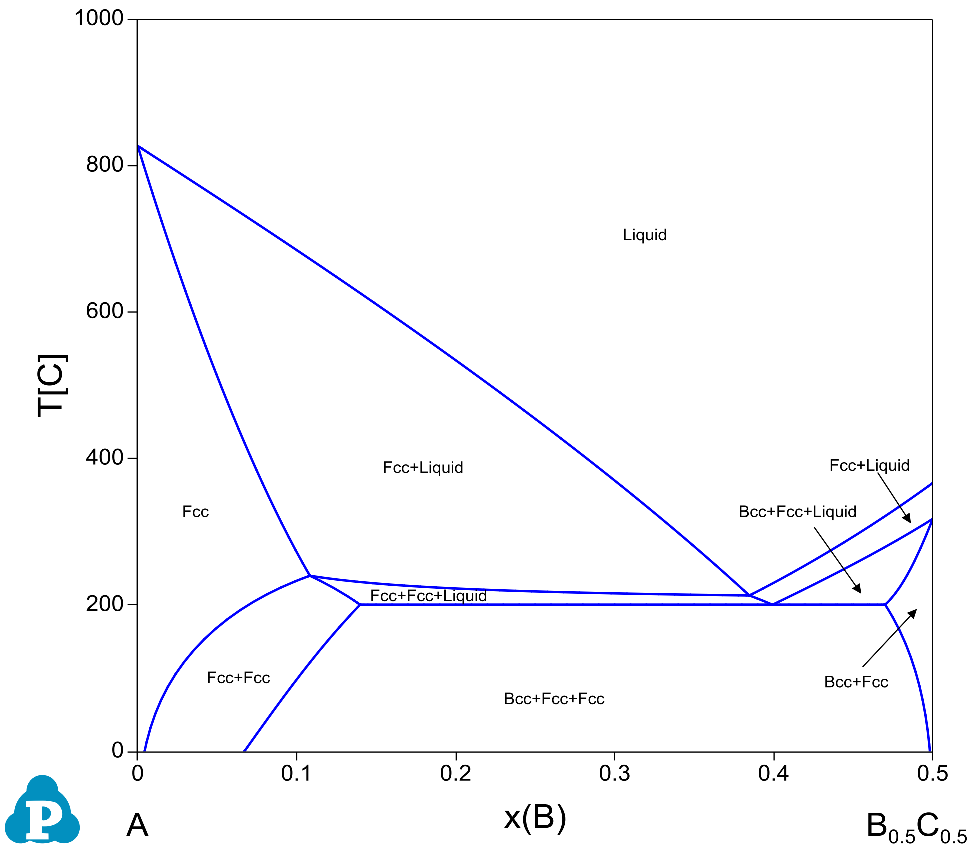
- Isothermal Section:
- Phase boundary (Blue)
- Tie-line (Green)
- Tie-triangle (Red)



Adapted from www.computherm.com

Reading a ternary phase diagram

- Isopleth:
- Y-axis: temperature
- X-axis: composition
- Tie-line may not lie on the section

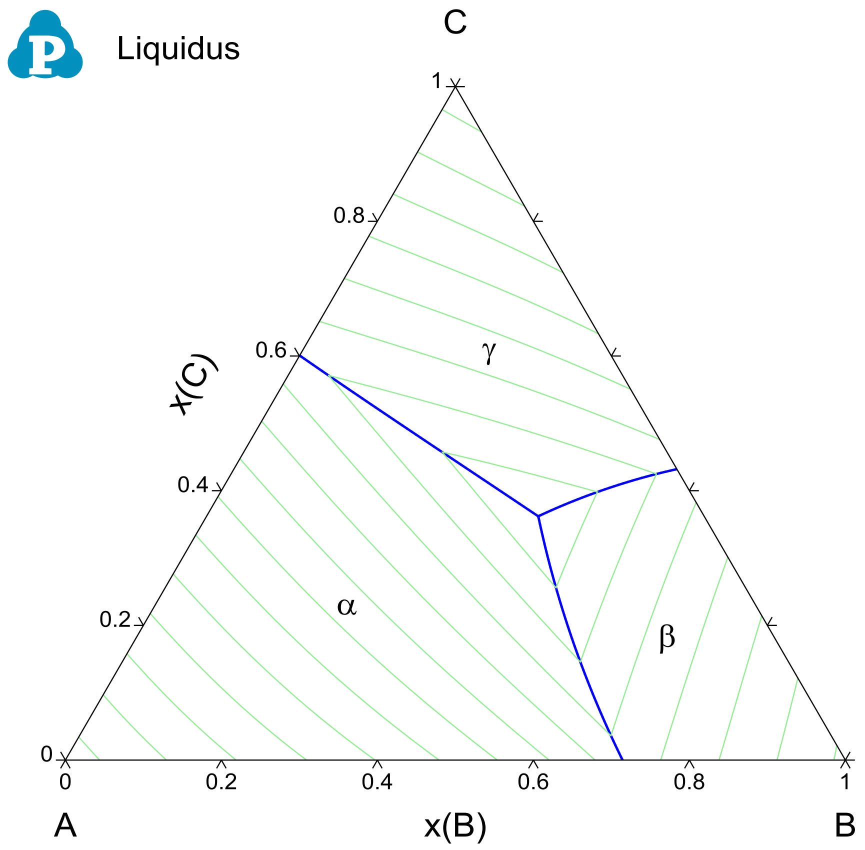


Adapted from www.computherm.com

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Reading a ternary phase diagram

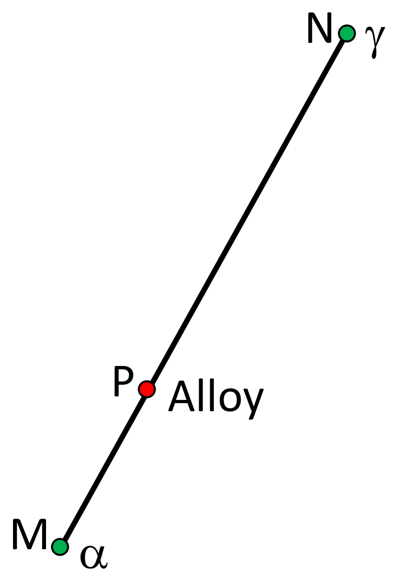
- **Liquidus Projection:**
- Univariant line (Blue)
- Isothermal line (Green)
- Primary phase region

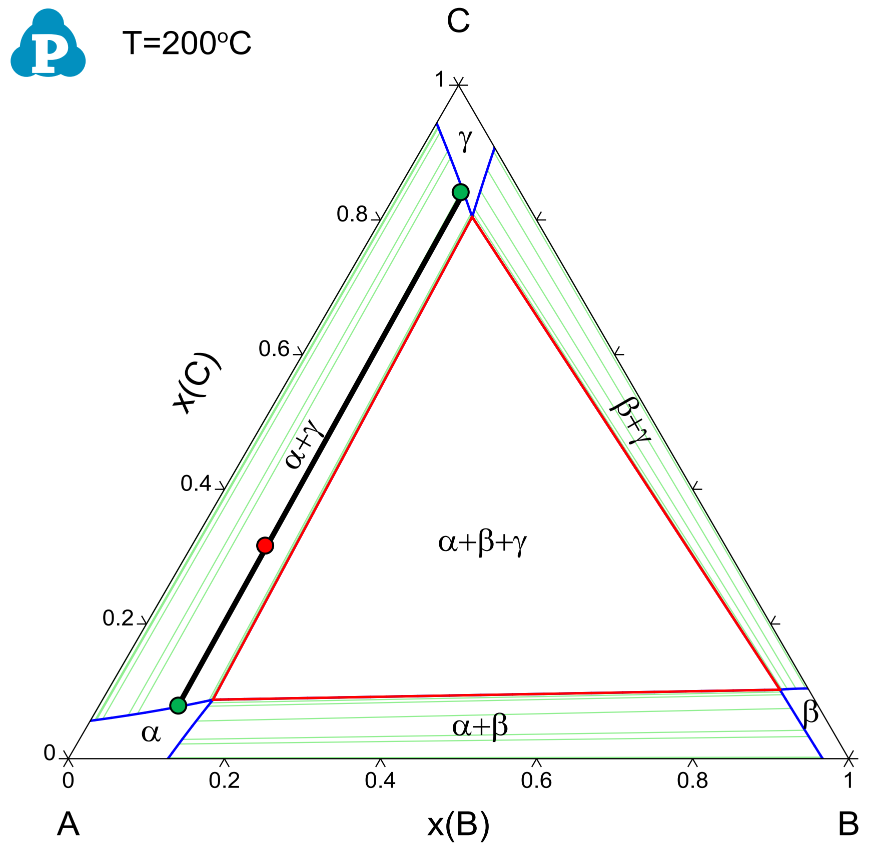


Adapted from www.computherm.com

Reading a ternary phase diagram

- **Isothermal Section:**
- Lever rule on tie-line



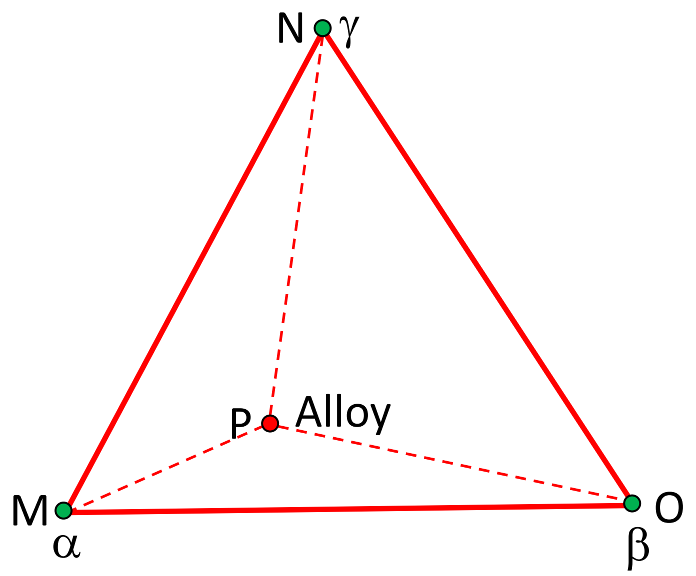


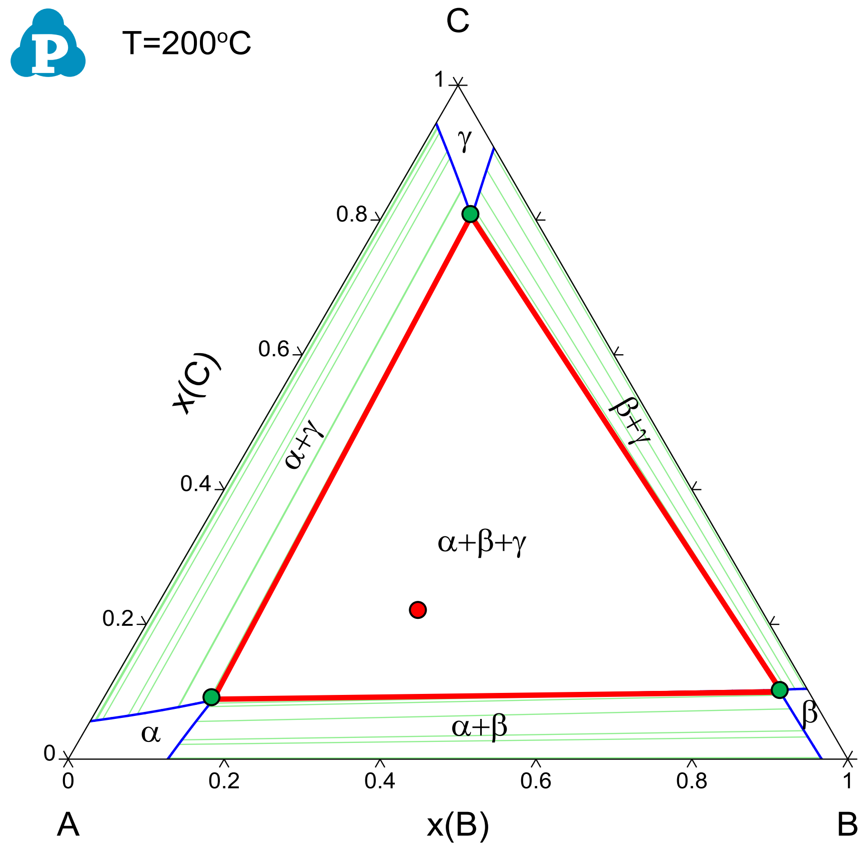
In Alloy P, two phases are in equilibrium:
Fraction of α = Length(PN) / Length(MN)
Fraction of γ = Length(MP) / Length(MN)

Adapted from www.computherm.com

Reading a ternary phase diagram

- Isothermal Section:
- Lever rule on tie-triangle





In Alloy P, three phases are in equilibrium:
Fraction of α = Area(PON) / Area(MNO)
Fraction of β = Area(PMN) / Area(MNO)
Fraction of γ = Area(POM) / Area(MNO)

Adapted from www.computherm.com

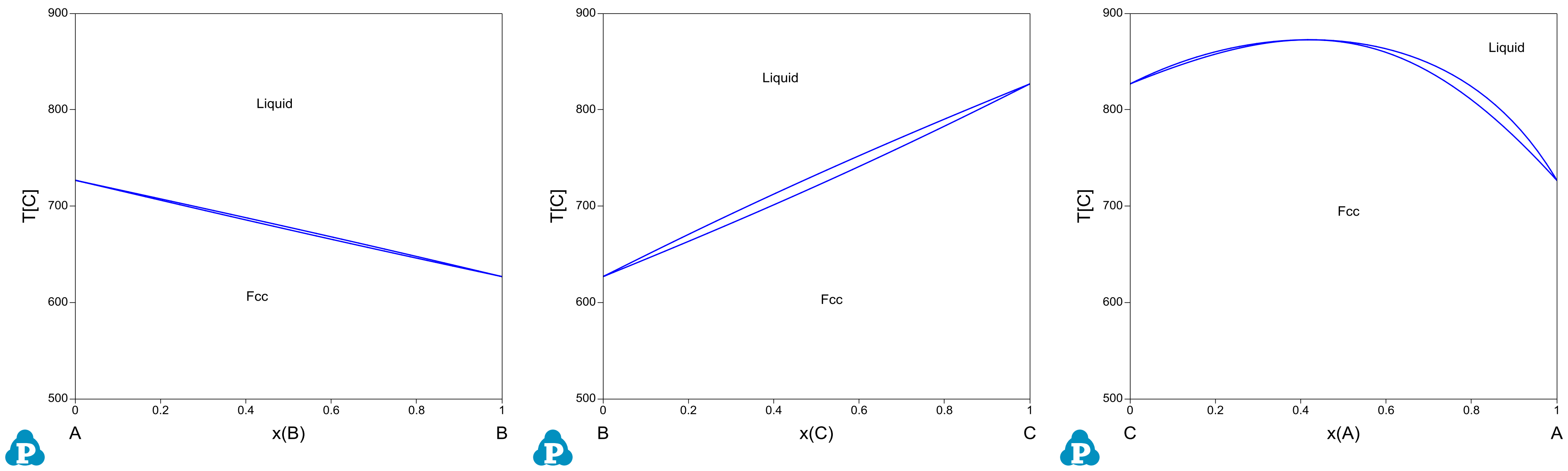
Types of Ternary Phase Diagrams

- Isomorphous System
- Ternary Three-phase Equilibrium
- Ternary Four-phase Equilibrium
  - Class I Reaction
  - Class II Reaction
  - Class III Reaction
- Congruent Transformation
- A Complex System

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Isomorphous system

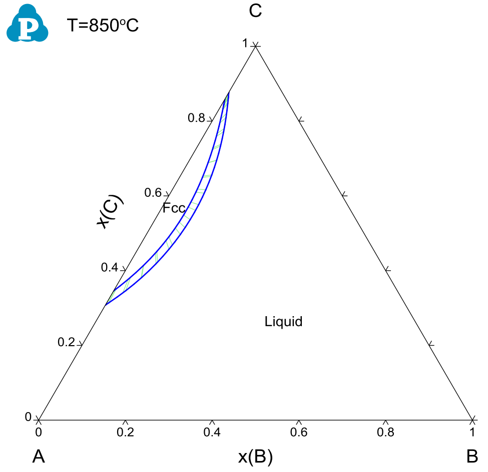
Case: Three binaries are all isomorphous with 2 cigar shape phase boundaries and 1 maximum.

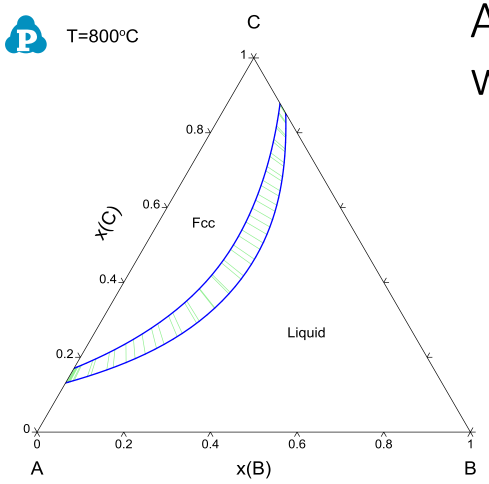


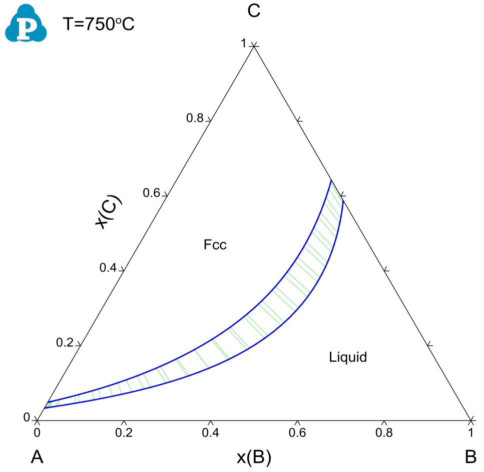
Adapted from www.computherm.com

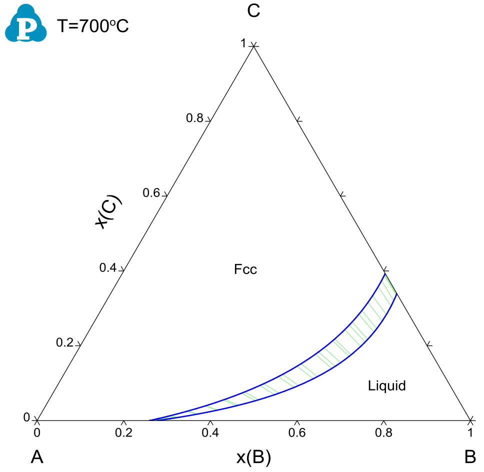
Case: Isothermal sections in decreasing T order.

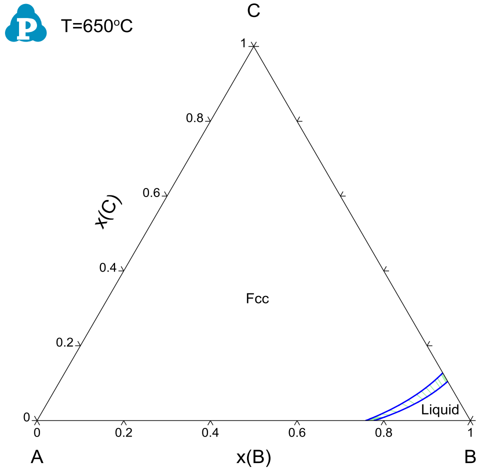
Adapted from www.computherm.com





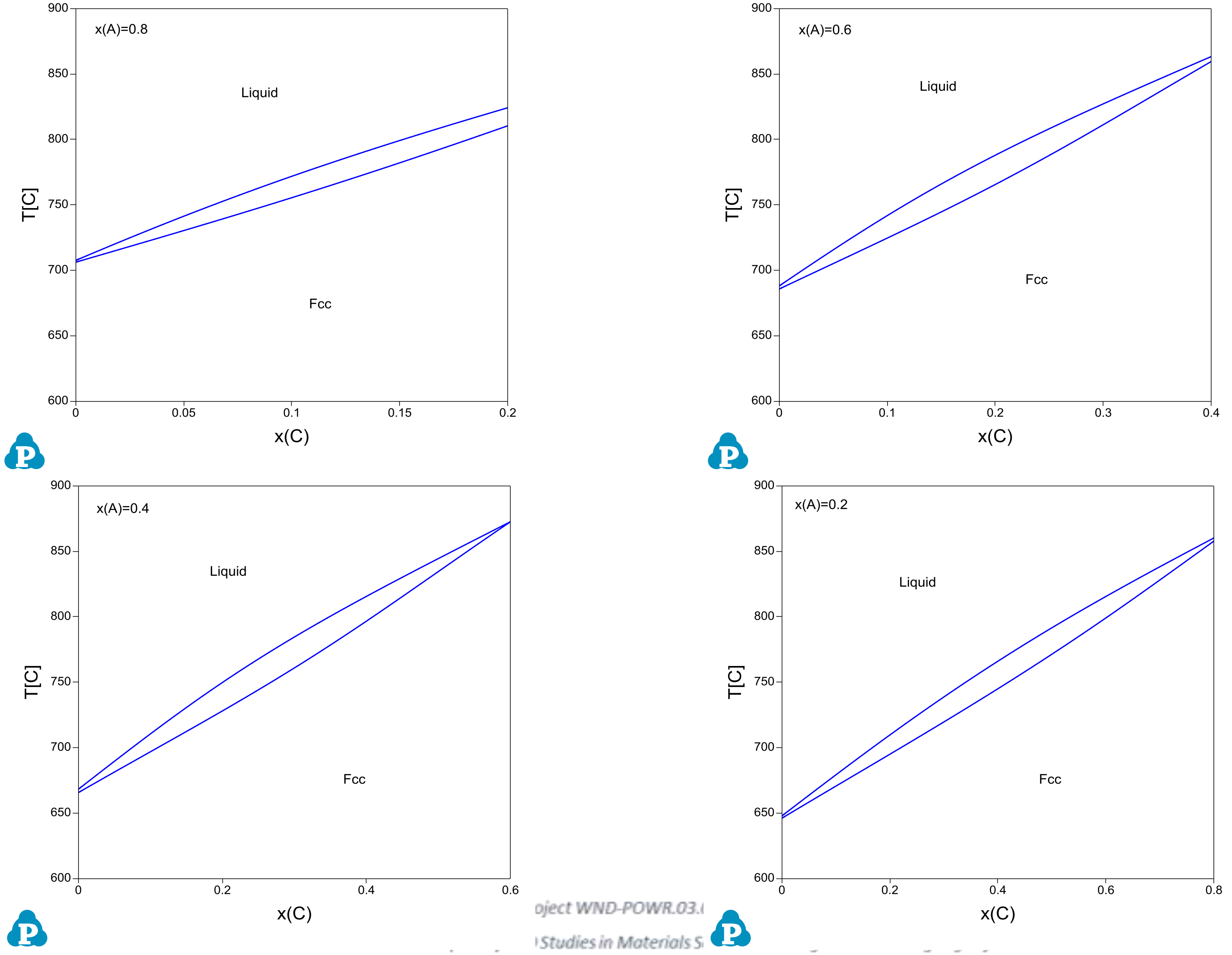






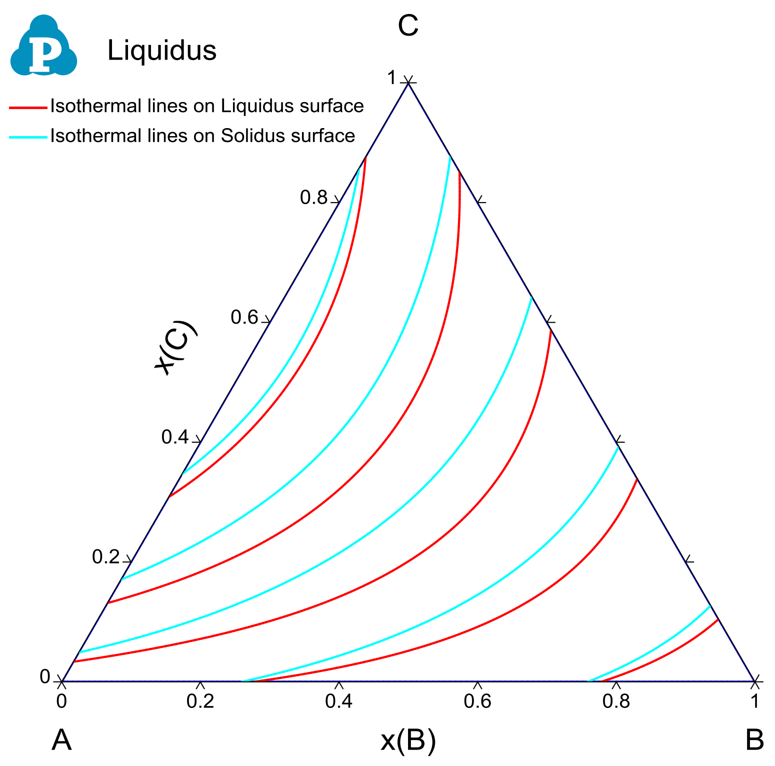
Case: Isopleths parallel to the B-C binary

Adapted from www.computherm.com

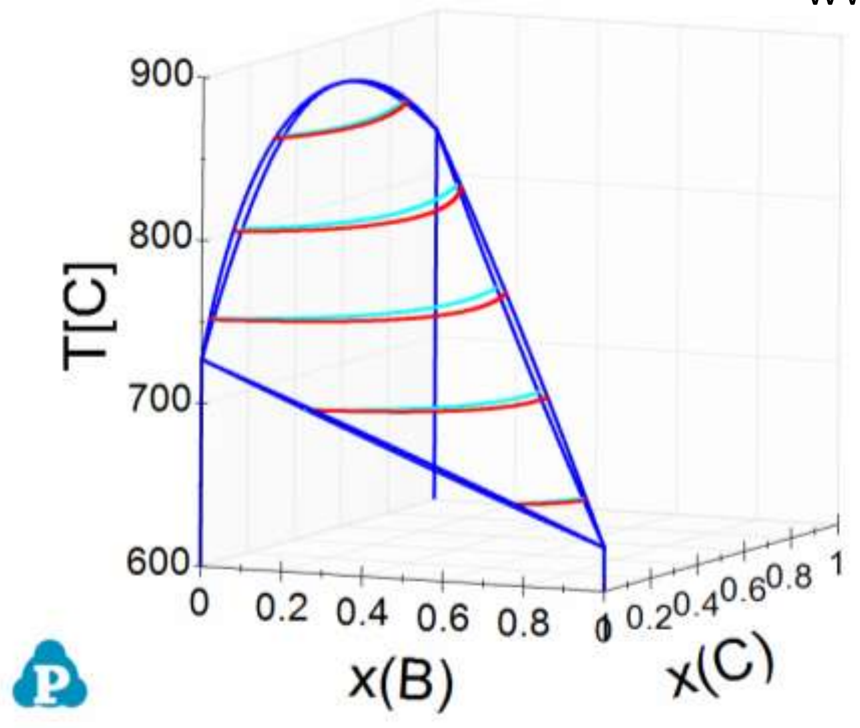


Case: Liquidus projection has no univariant line.

Adapted from www.computherm.com



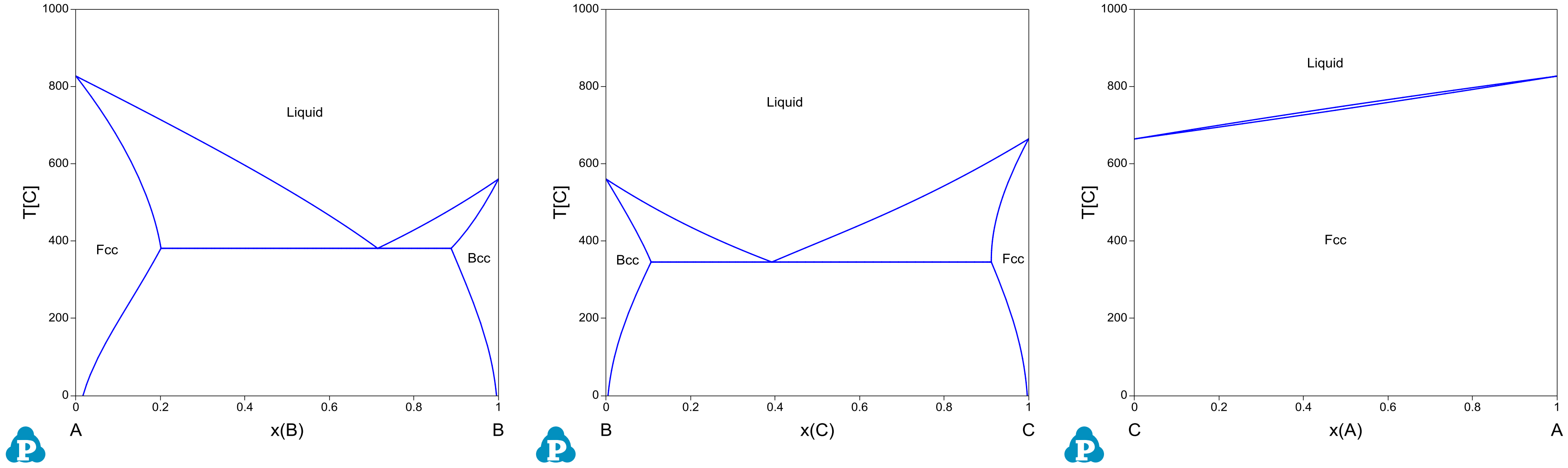
Liquidus Projection in 2-D view



Liquidus Projection in 3-D view

Ternary Three-Phase Equilibrium

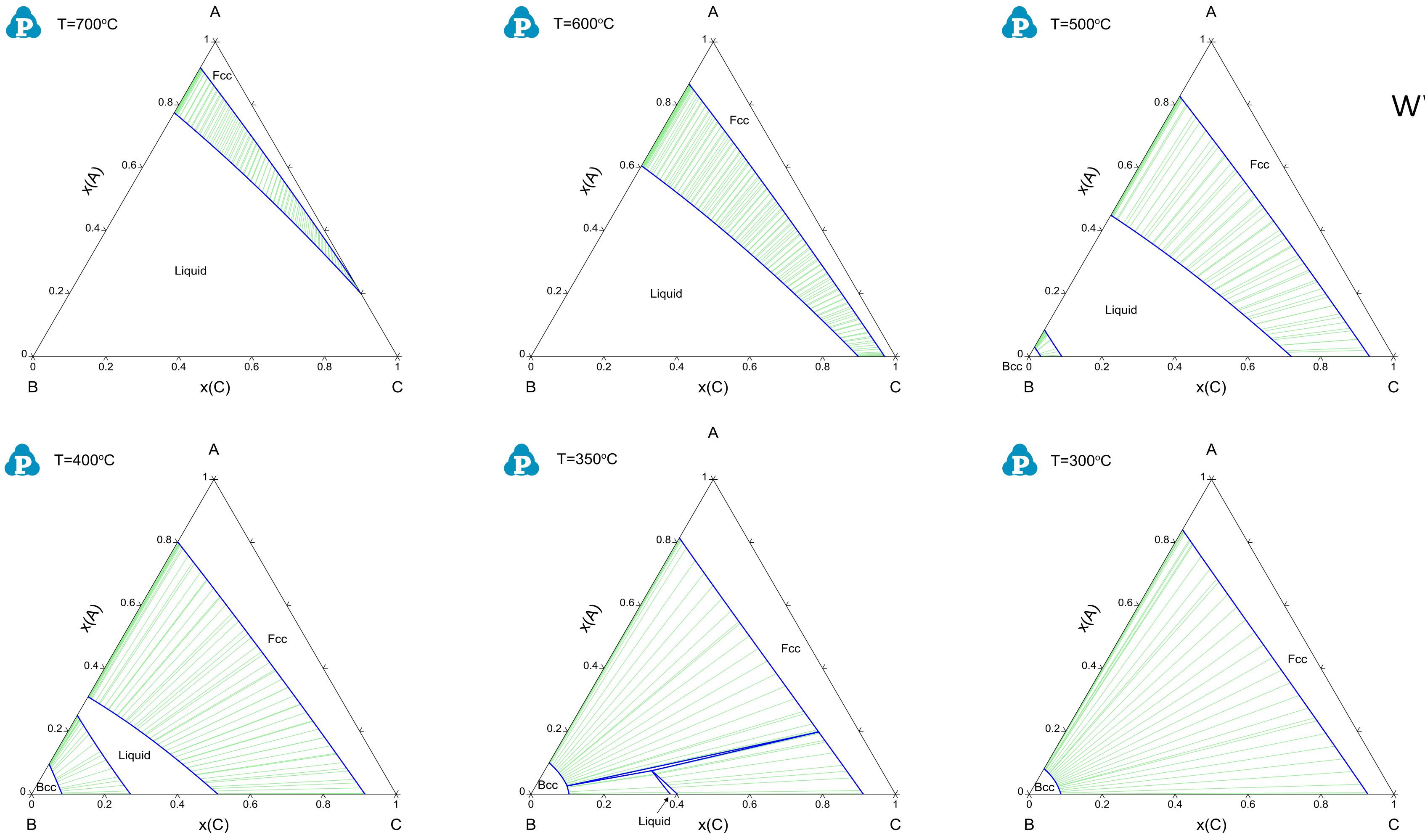
Case I: Two eutectic binary systems and one isomorphous with Cigar shape phase boundary.



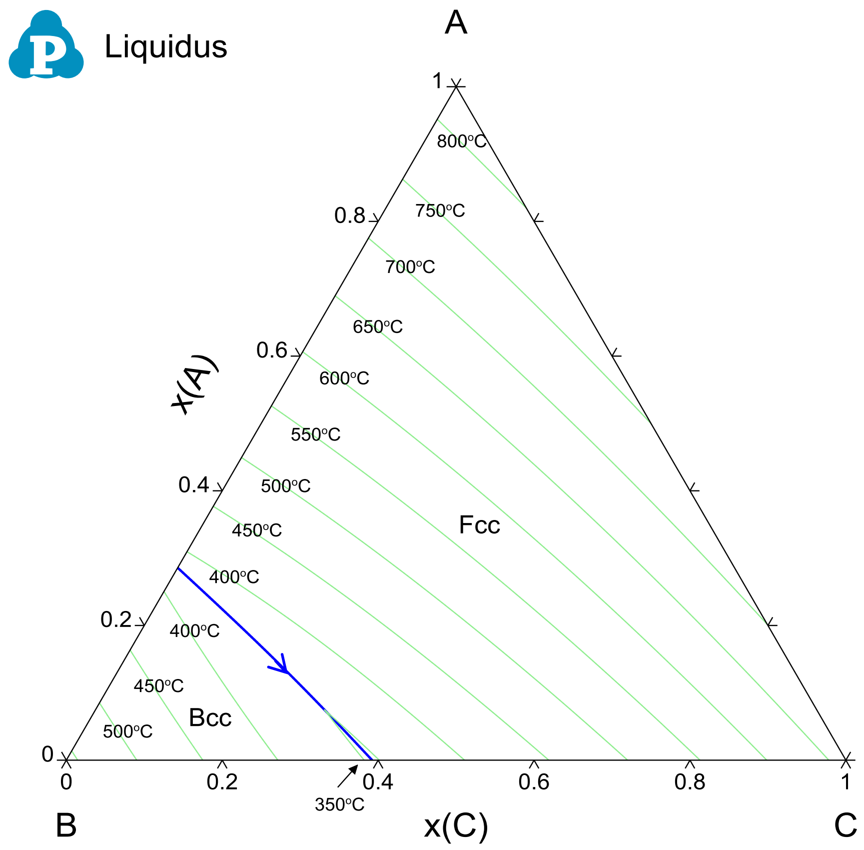
Adapted from www.computherm.com

Case I: Isothermal sections in decreasing T order.

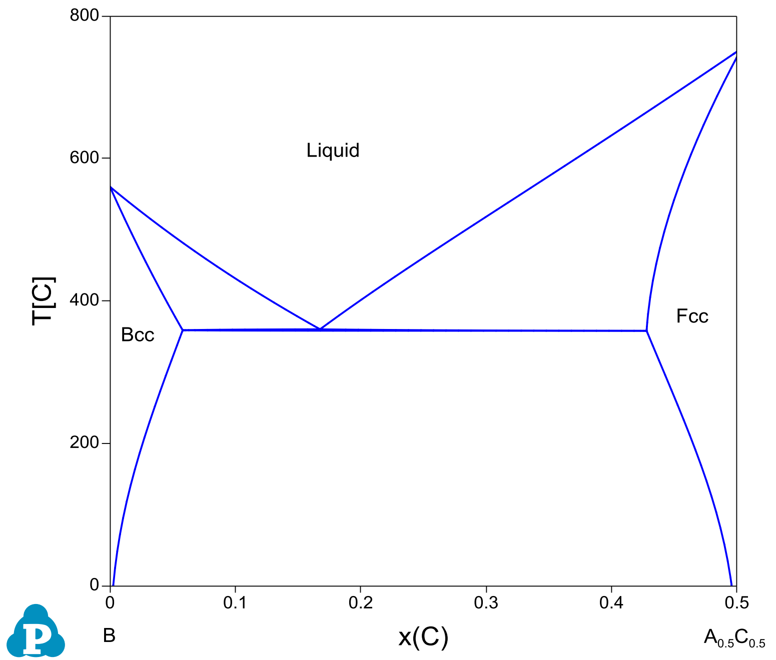
Adapted from www.computherm.com



Liquidus has one univariant line starting from A-B binary and ending at B-C binary, which separates 2 primary phase fields, Fcc and Bcc.



Isopleth through B-$A_{0.5}C_{0.5}$

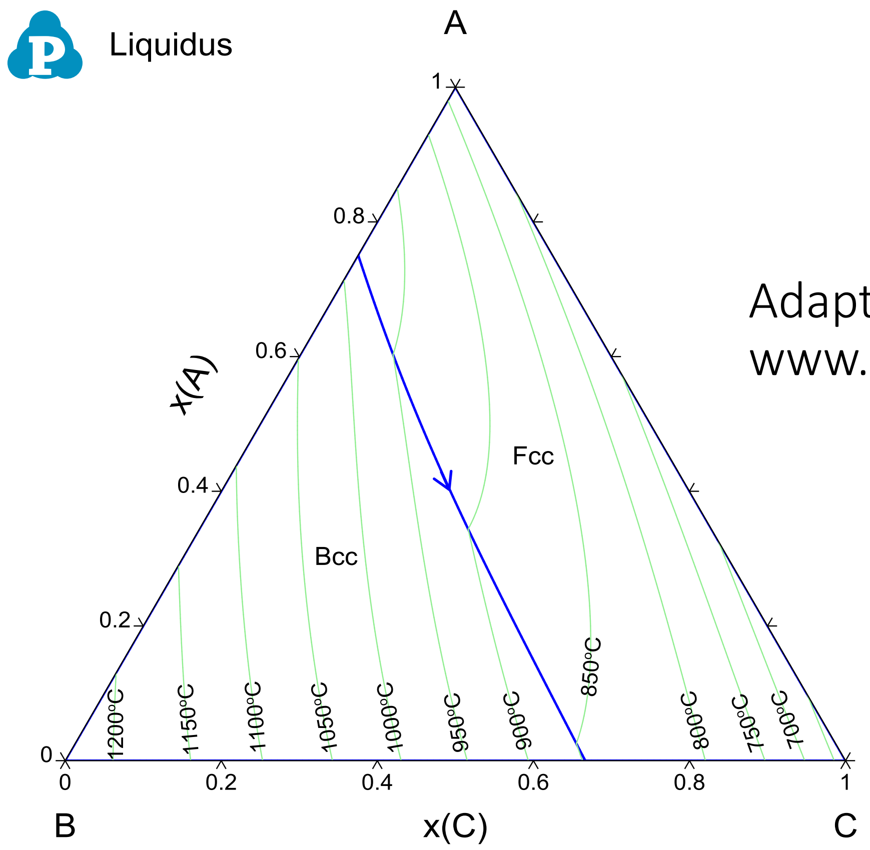


Adapted from www.computherm.com

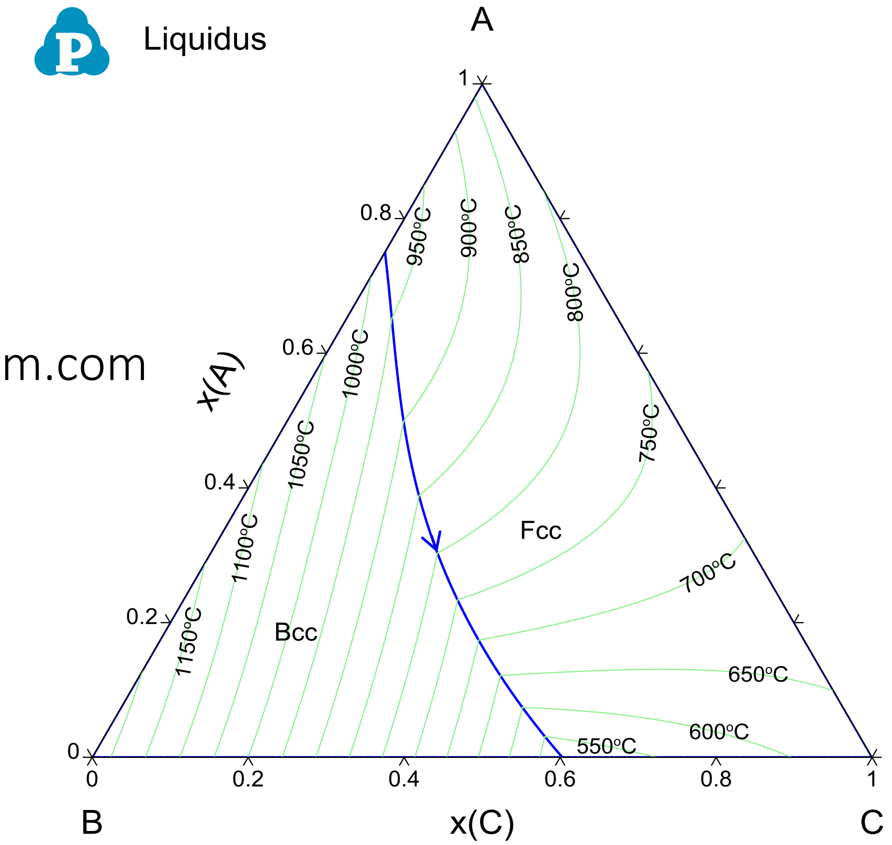
Liquidus looks similar for:

Case II: Two peritectic binary systems and one isomorphous with cigar shape phase boundary.

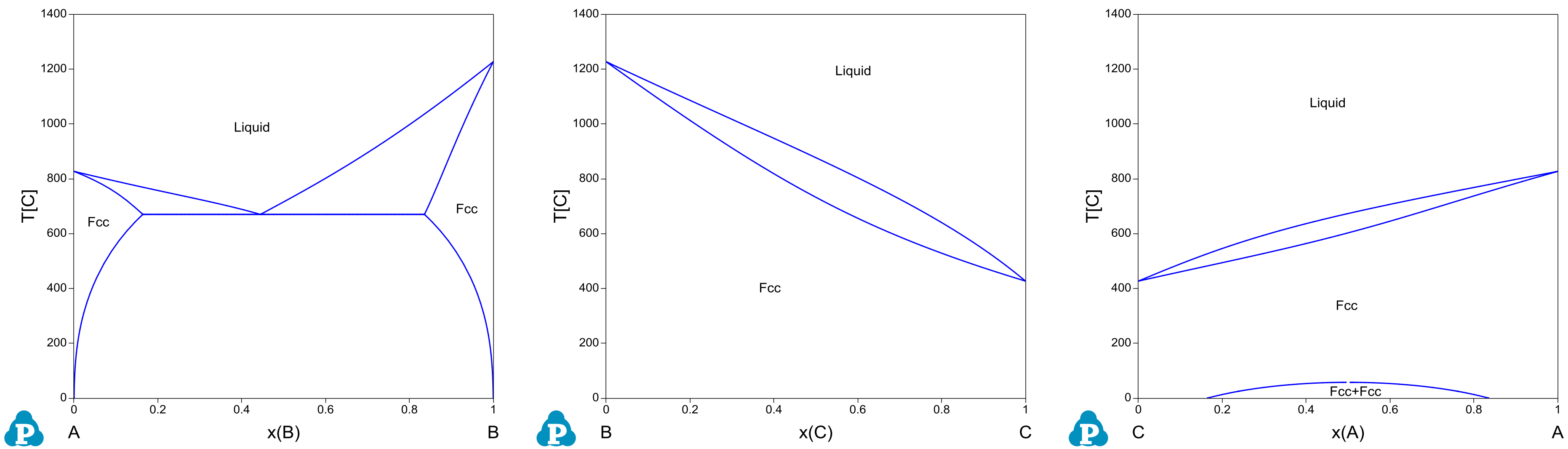
Case III: One peritectic binary, one eutectic binary and one isomorphous with cigar shape phase boundary.



Adapted from www.computherm.com

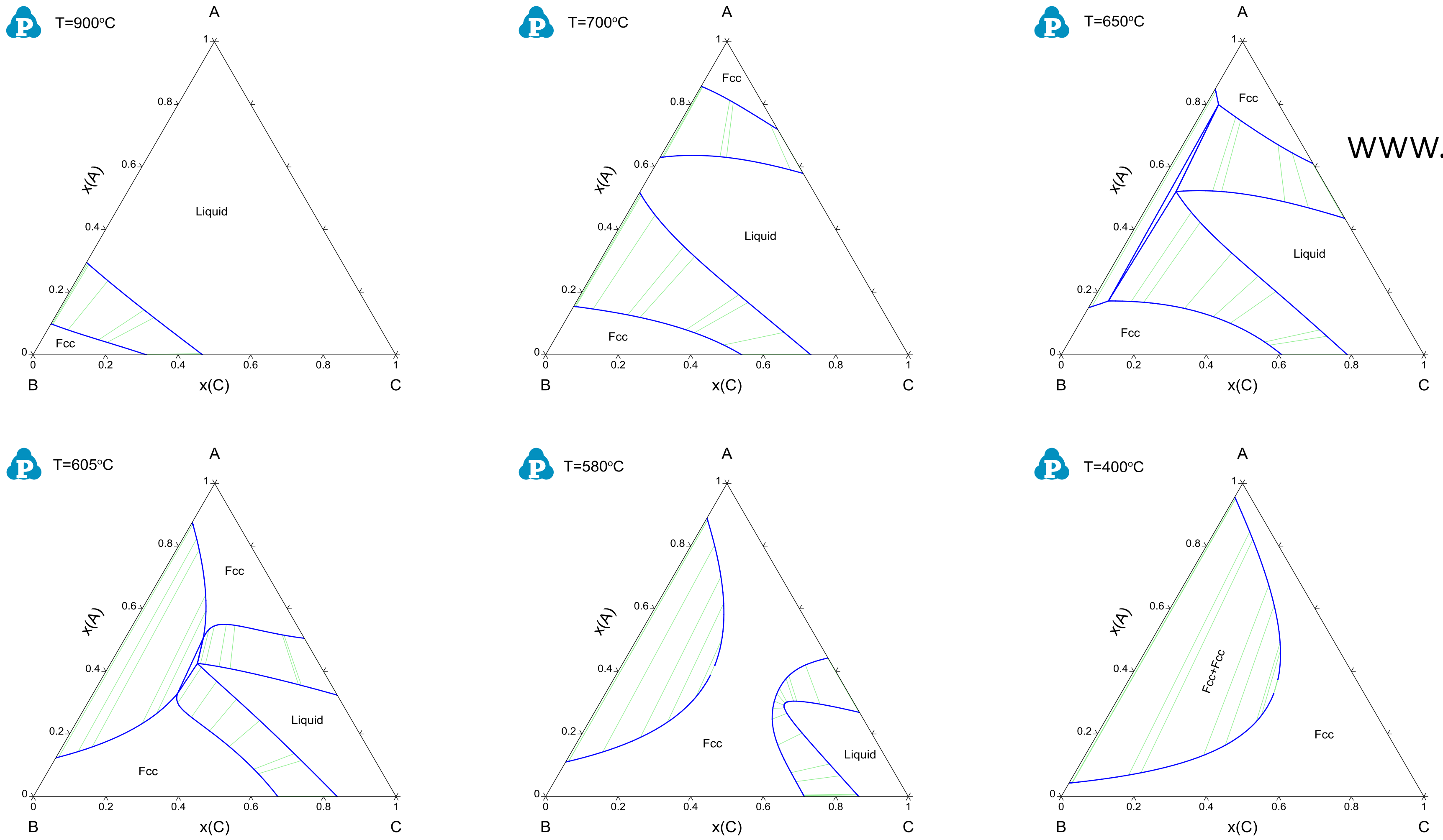


Case IV: One eutectic binary and Two isomorphous with Cigar shape phase boundary.



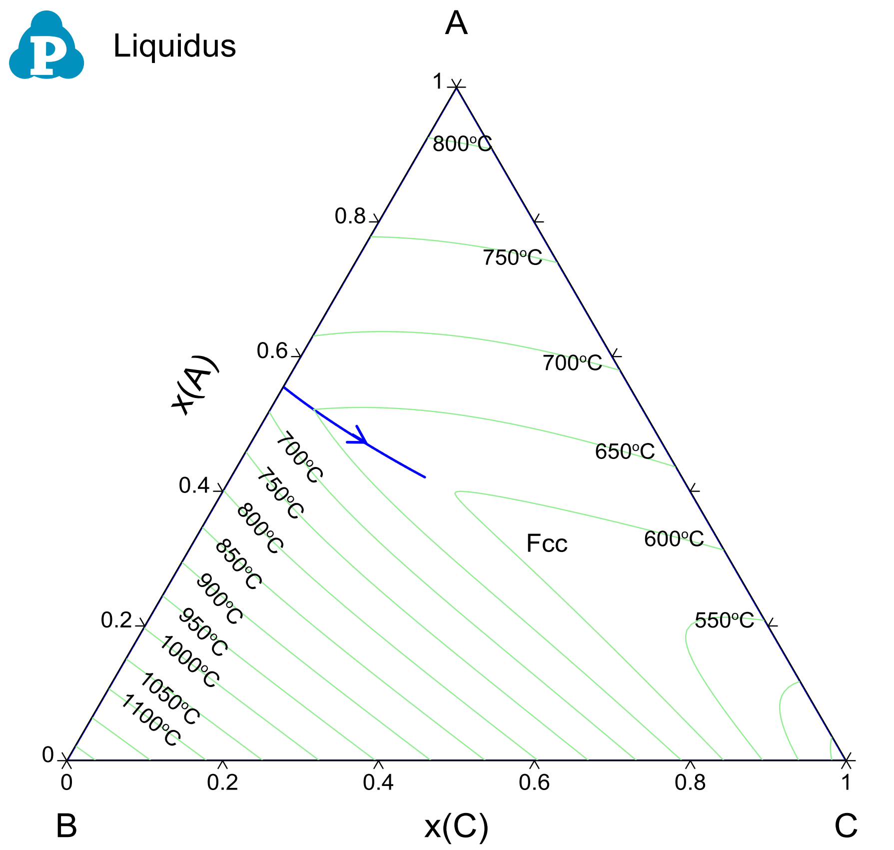
Adapted from www.computherm.com

Case IV: Isothermal sections in decreasing T order.



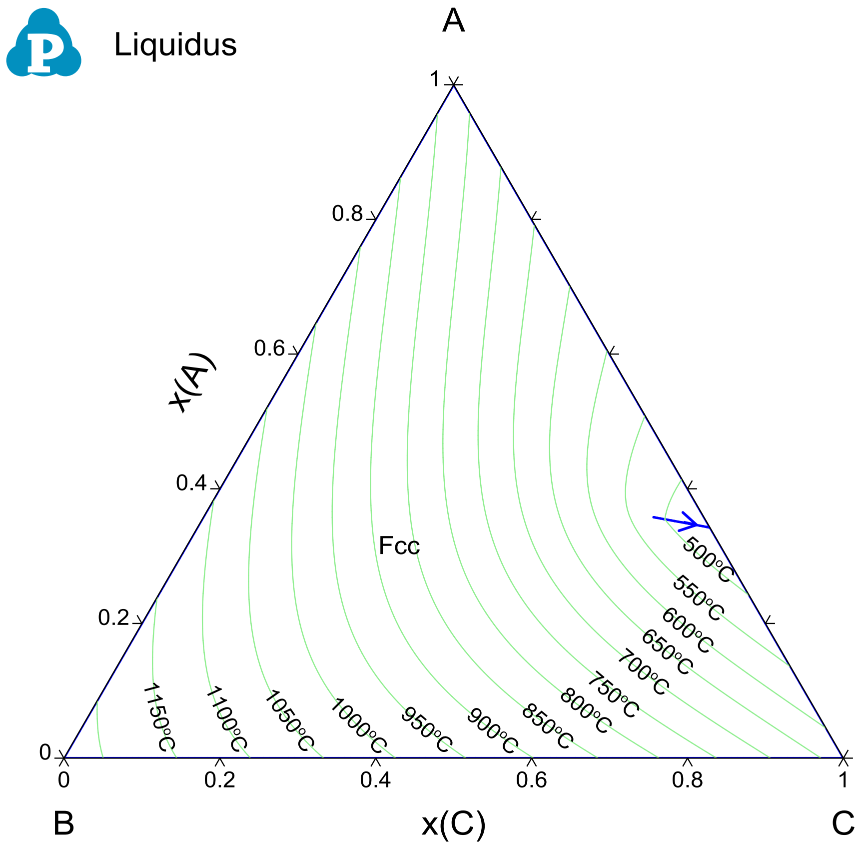
Adapted from www.computherm.com

Liquidus has one univariant line starting from A-B binary and ending at a minimum in the ternary field, and only one primary phase field, Fcc.



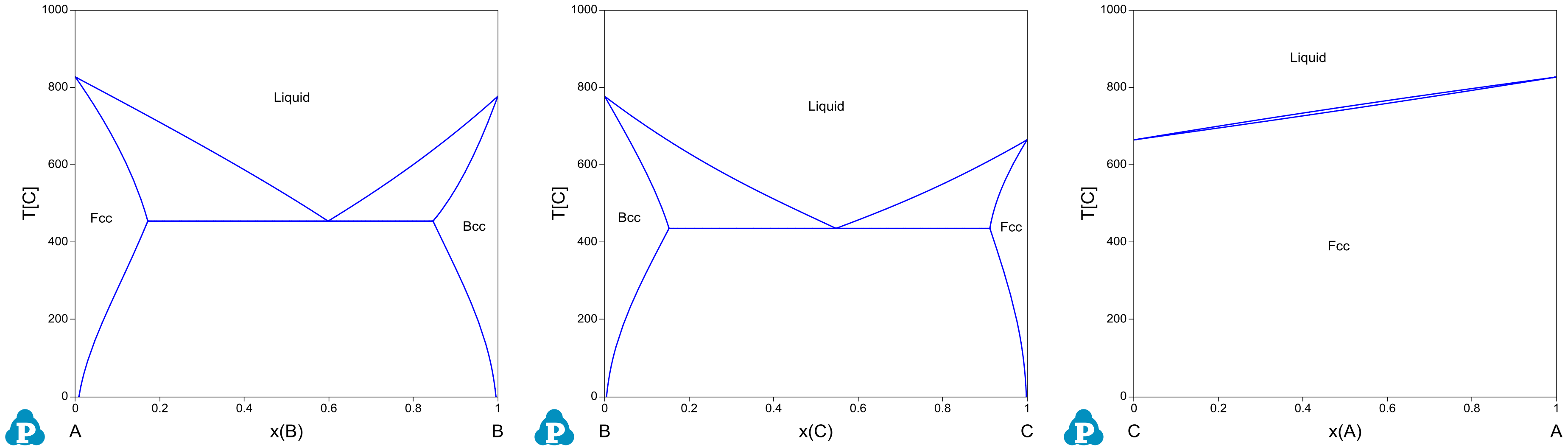
Adapted from www.computherm.com

Liquidus has one univariant line starting from a maximum in the ternary field and ending at A-C binary, and only one primary phase field, Fcc.



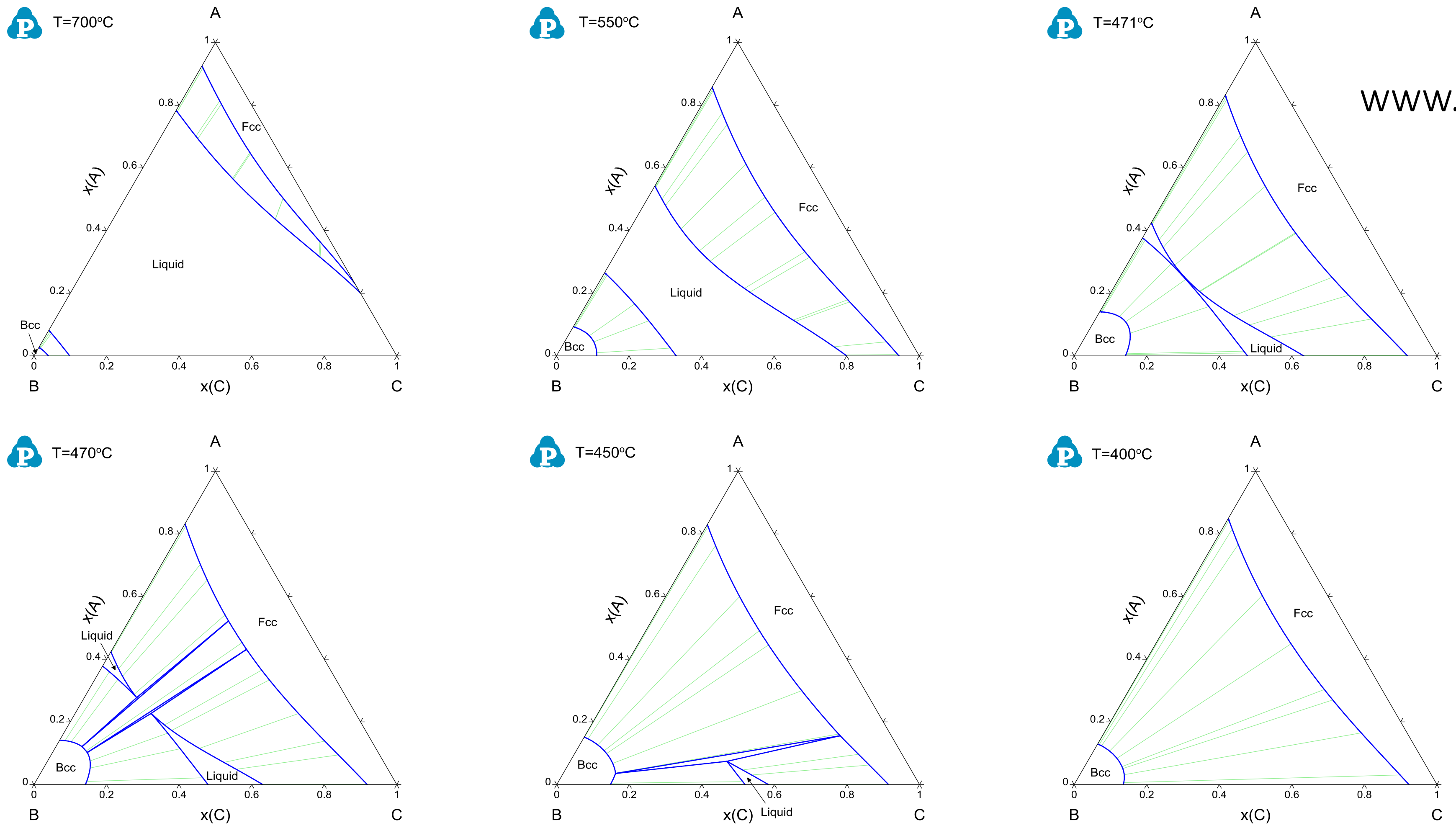
Adapted from www.computherm.com

Case VI: Two eutectic binary systems and one isomorphous with Cigar shape phase boundary.



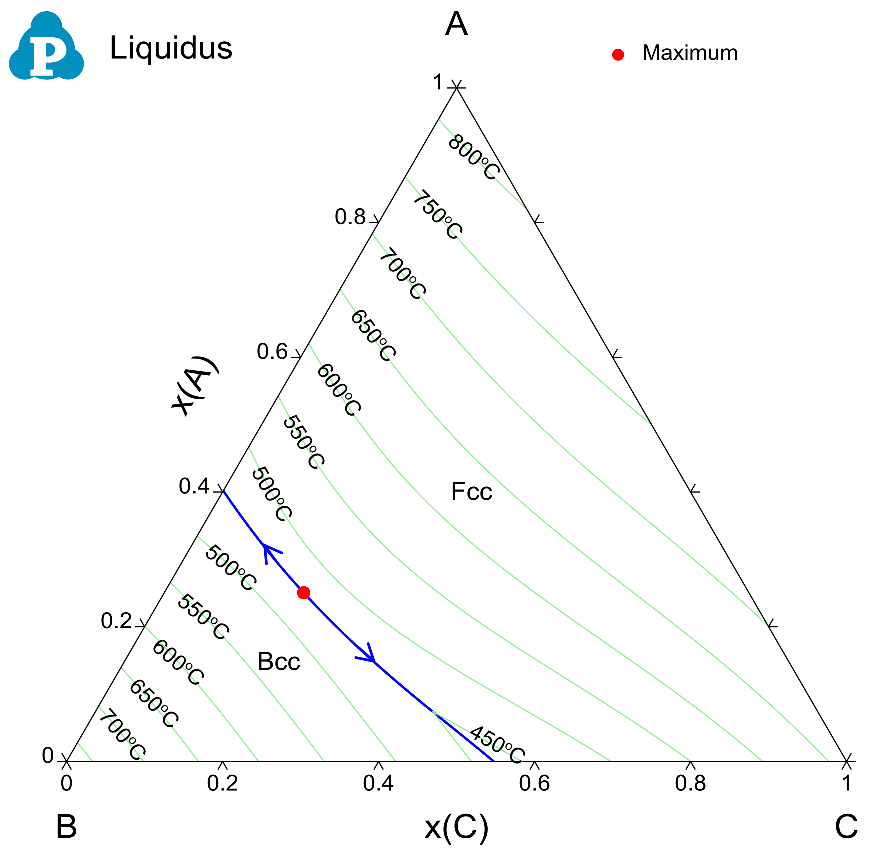
Adapted from www.computherm.com

Case VI: Isothermal sections in decreasing T order.



Adapted from
www.computherm.com

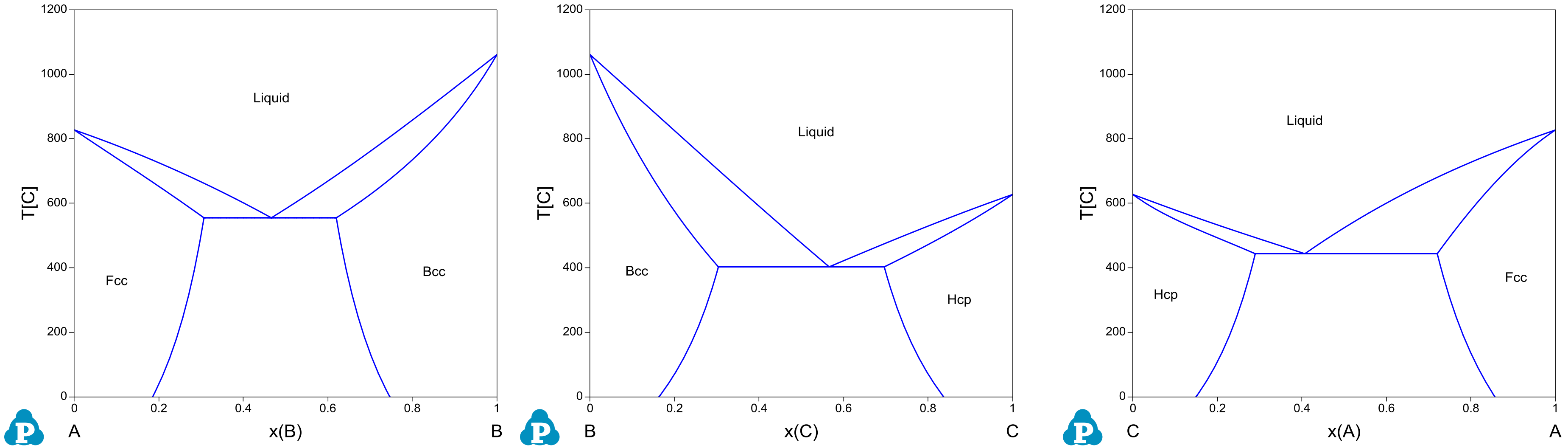
Liquidus lines start from a maximum in the ternary field, go separately in opposite directions and end at the two eutectic reactions in the binaries. Two primary phase fields, Fcc and Bcc.



Adapted from www.computherm.com

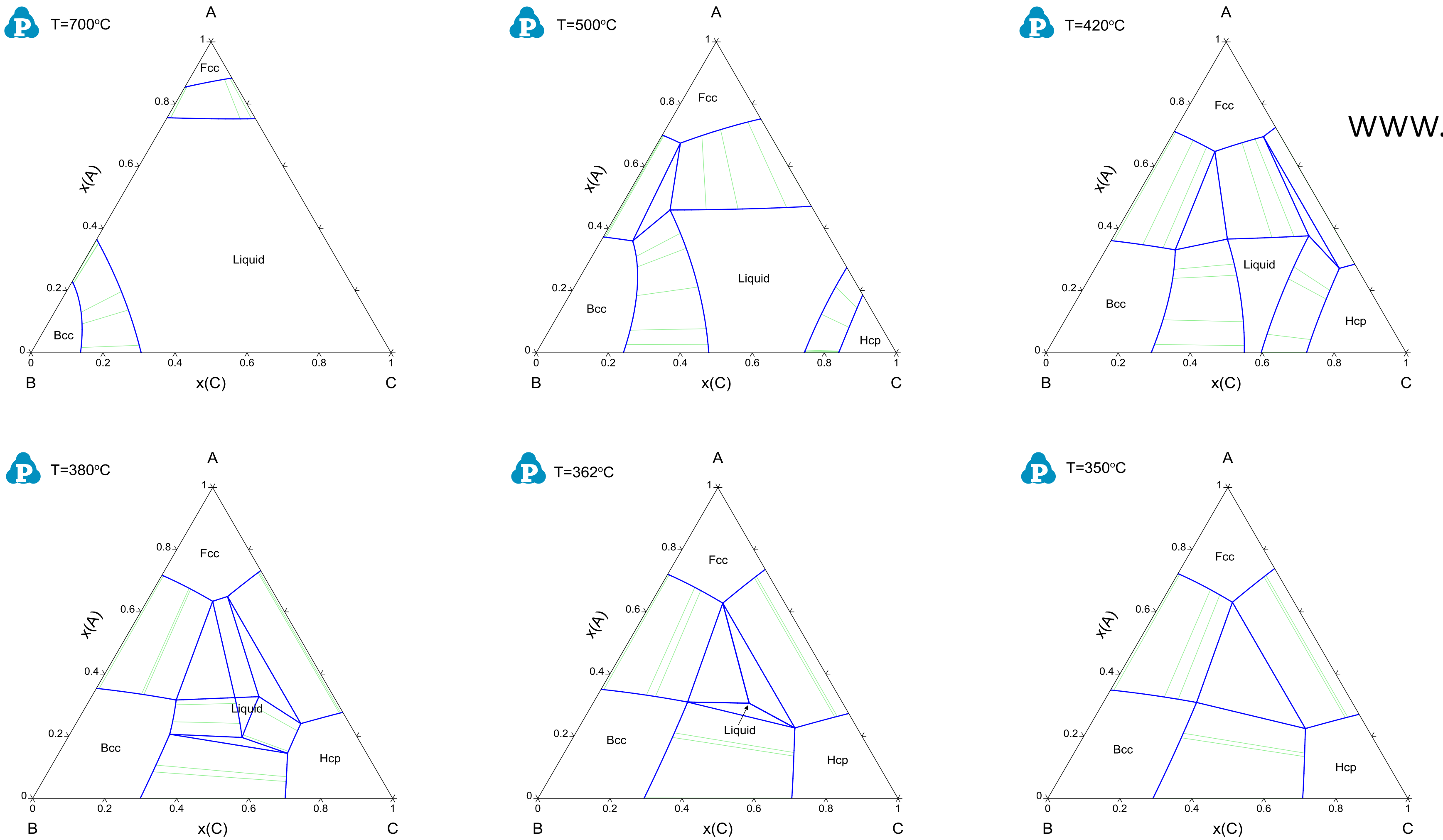
Ternary four-phase equilibria – class I

Class I: Three eutectic binary systems.



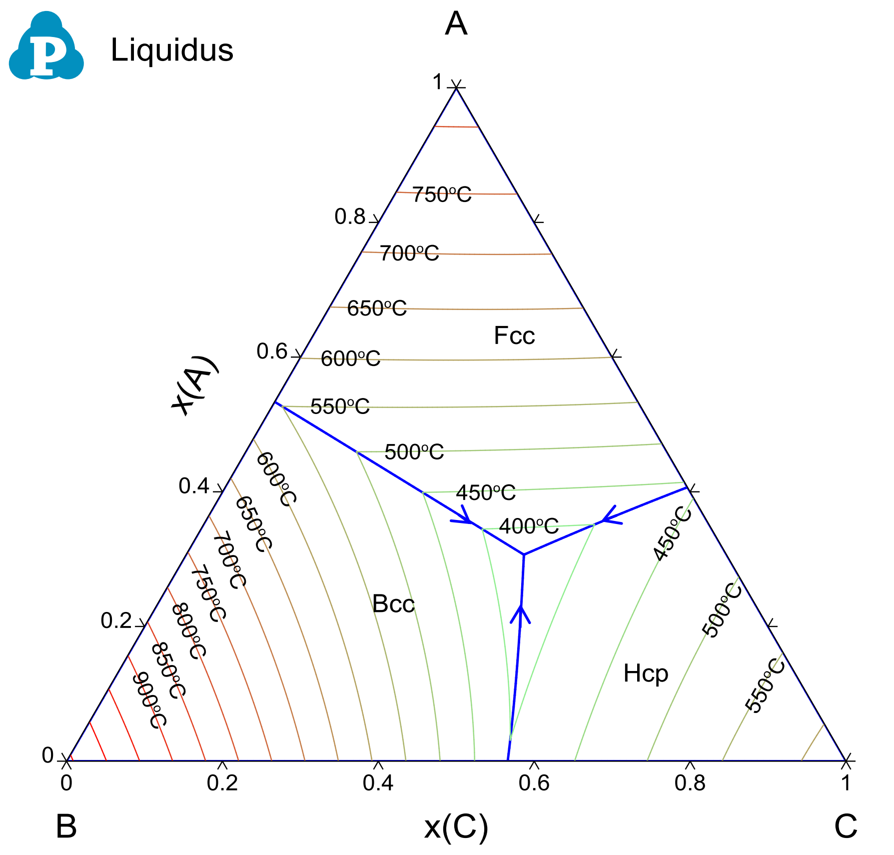
Adapted from www.computherm.com

Class I: Isothermal sections in decreasing T order.



Adapted from www.computherm.com

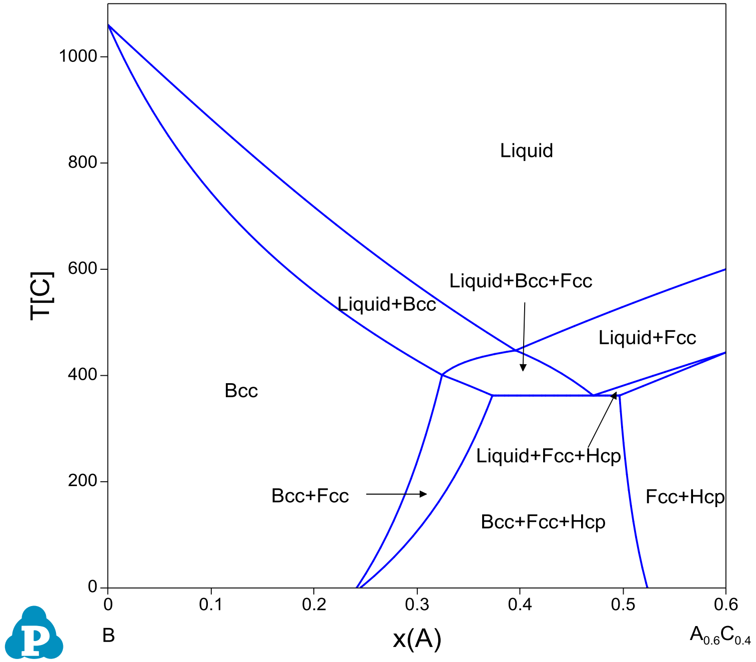
Liquidus lines start from the three eutectic reactions in the binaries, join together at one point in the ternary field. Three primary phase fields, Fcc, Bcc and Hcp.

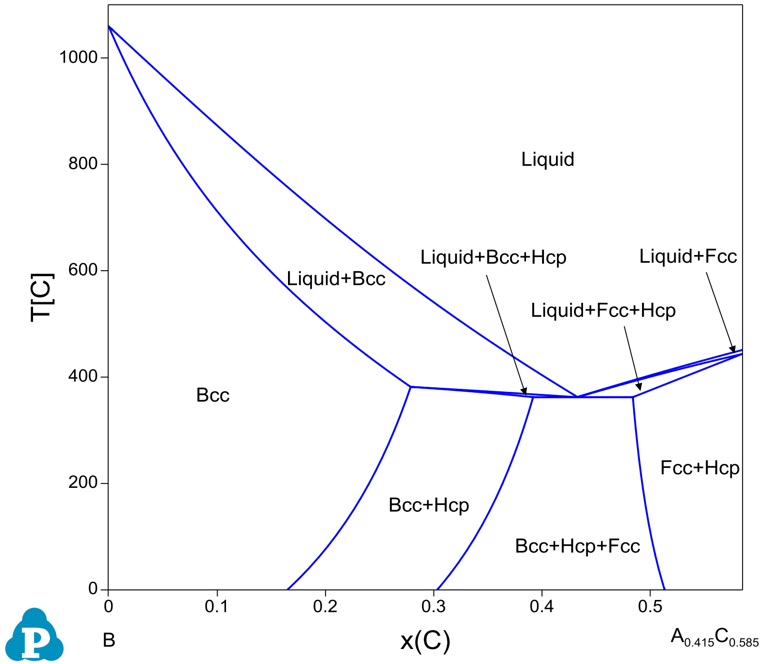


Adapted from www.computherm.com

International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Isopleths through B-$A_{0.6}C_{0.4}$ and B-$A_{0.415}C_{0.585}$





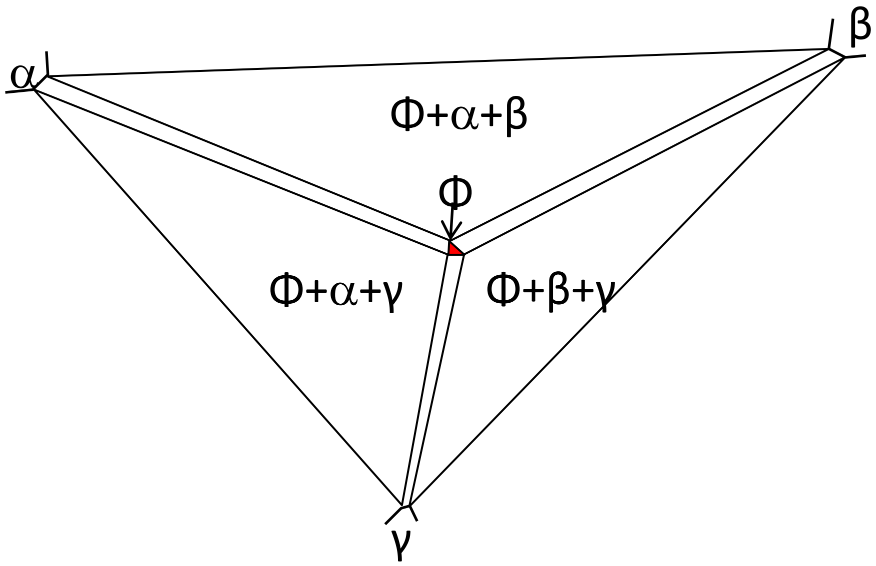
Adapted from www.computherm.com

European Funds Knowledge Education Development
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES
European Union European Social Fund

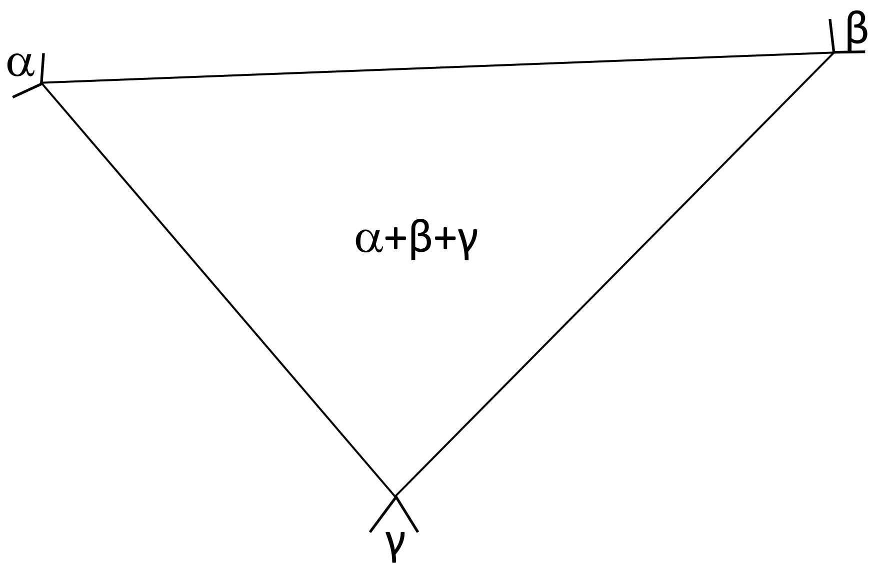
Characteristics to determine whether it is a Class I four-phase equilibrium:

Before Reaction: 3 three-phase triangles

After Reaction: 1 three-phase triangle



Before Reaction



After Reaction

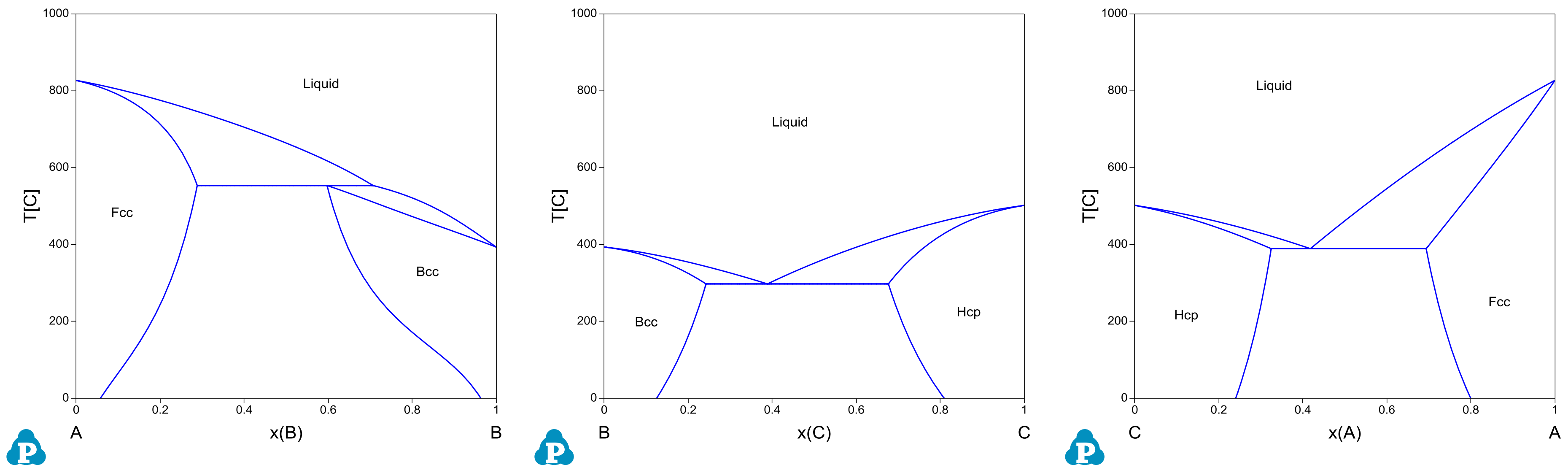
Class I reaction: $\Phi \Rightarrow \alpha + \beta + \gamma$

Adapted from www.computherm.com

European Funds
Knowledge Education Development
INSTITUTE OF METALLURGY
AND MATERIALS SCIENCE
POLISH ACADAMY OF SCIENCES
European Union
European Social Fund

Ternary Four-Phase Equilibrium – Class II

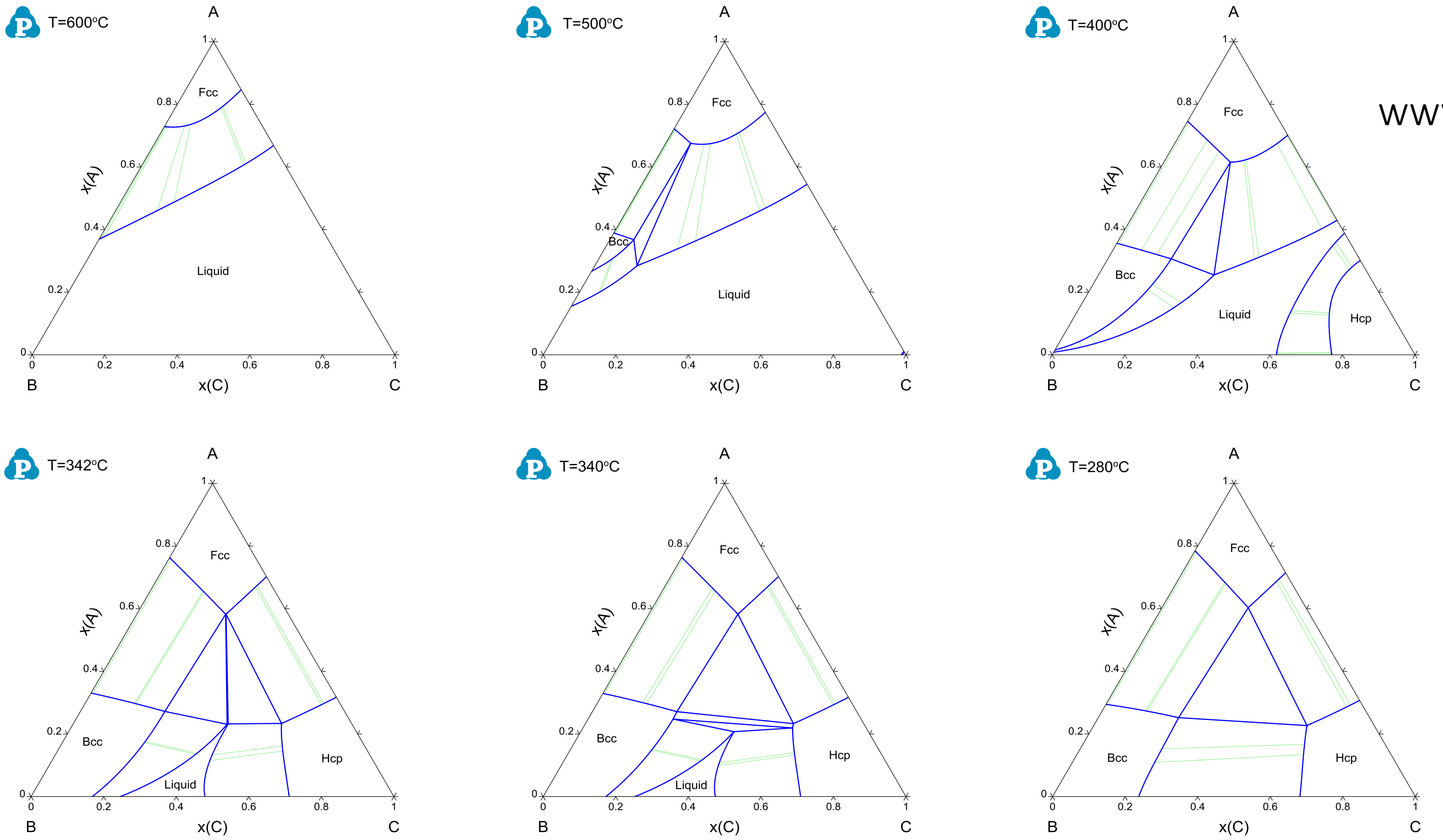
Class II: Two eutectic binary and one peritectic binary systems.



Adapted from www.computherm.com

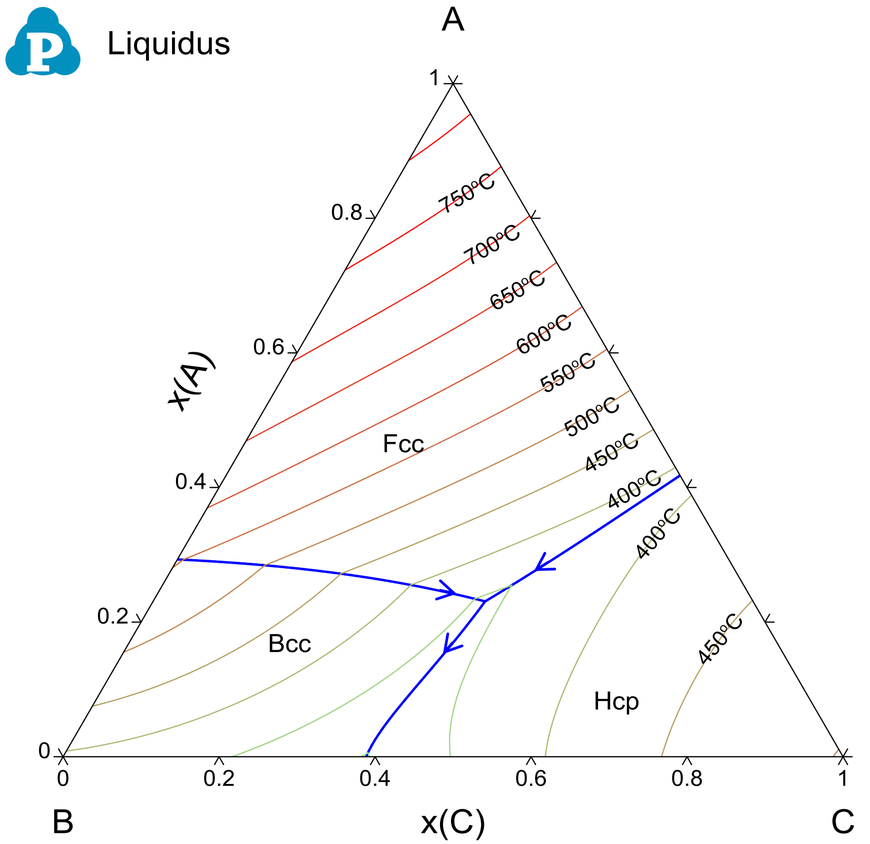
Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

Class II: Isothermal sections in decreasing T order.



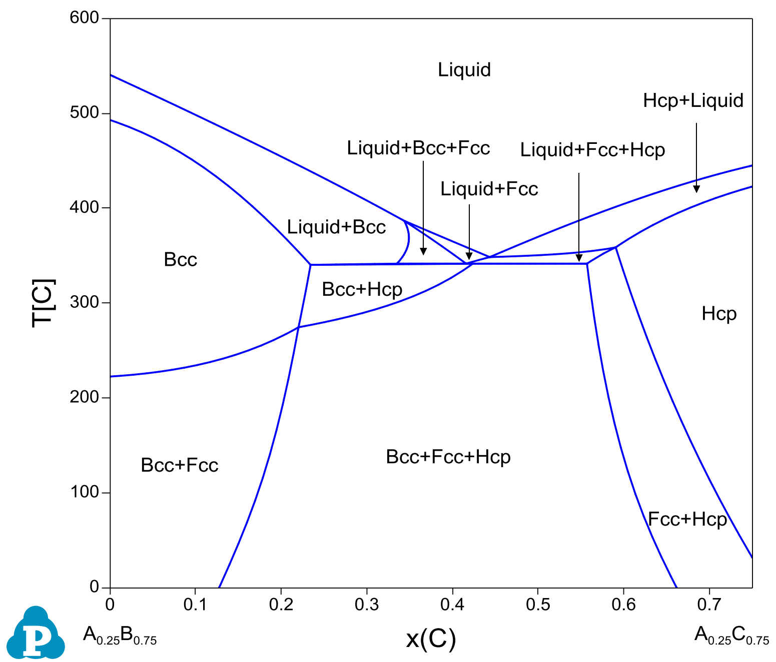
Adapted from www.computherm.com

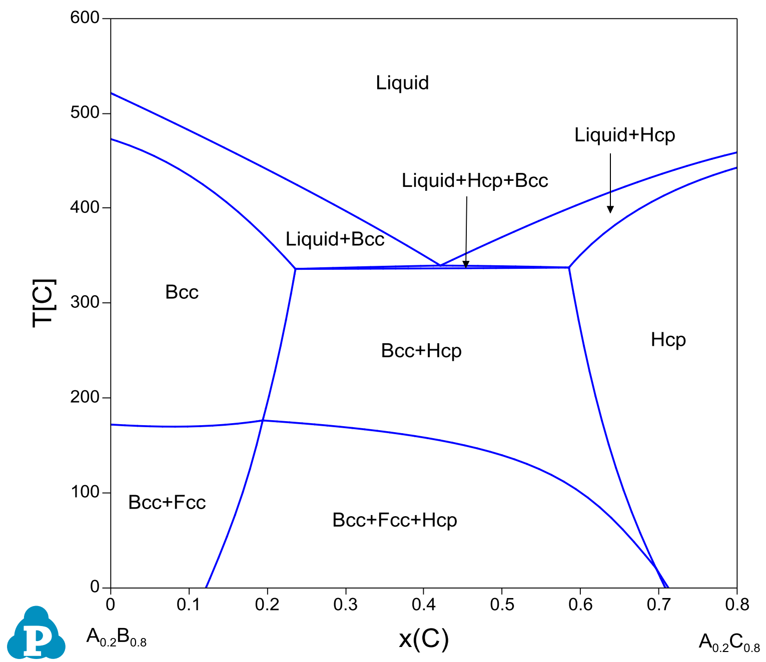
Liquidus lines start from the peritectic reaction in A-B binary and the eutectic reaction in A-C binary, join together at one point in the ternary field and then go to the eutectic reaction in B-C binary. Three primary phase fields, Fcc, Bcc and Hcp.



Adapted from www.computherm.com

Isopleths through 25 at.% A and 20 at.% A



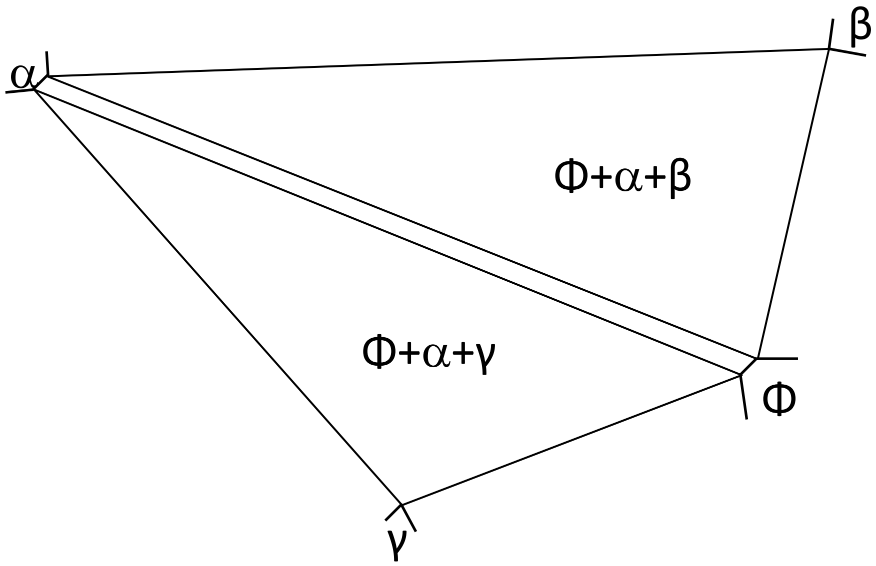


Adapted from www.computherm.com

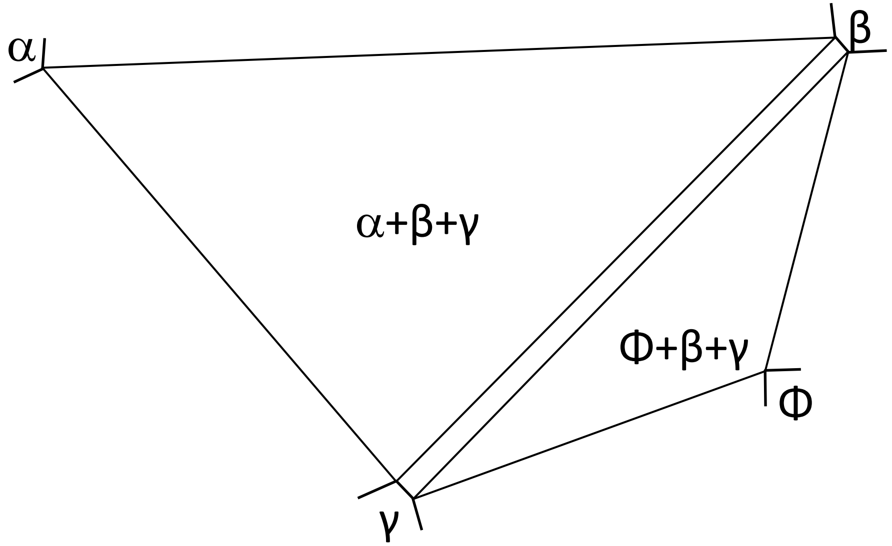
Characteristics to determine whether it is a Class II four-phase equilibrium:

Before Reaction: 2 three-phase triangles

After Reaction: 2 three-phase triangles



Before Reaction



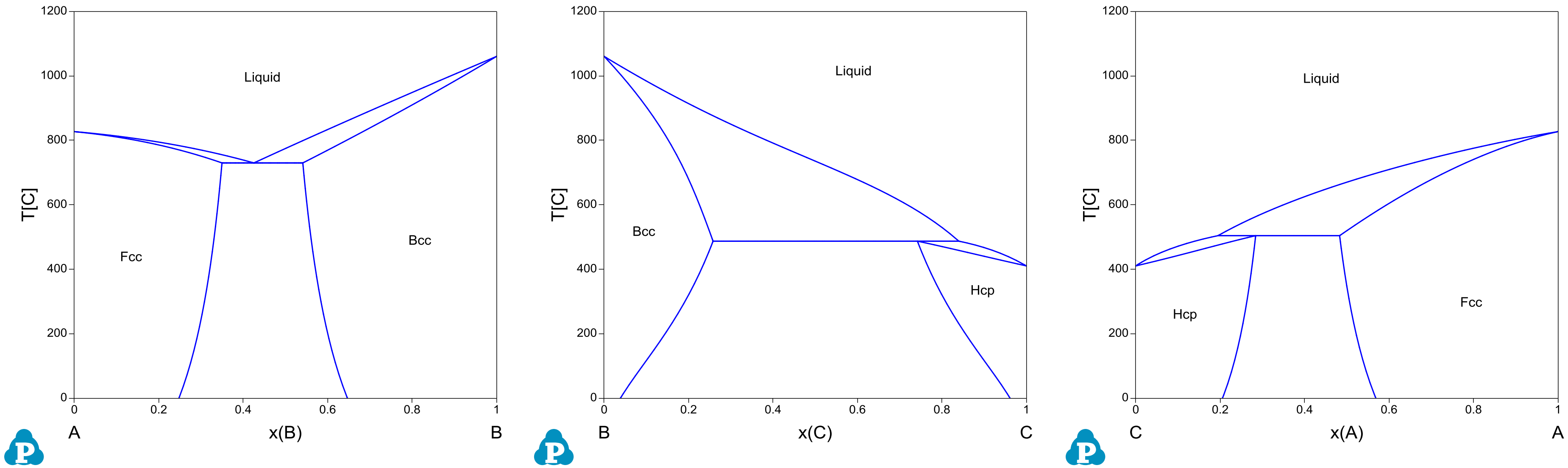
After Reaction

Class II reaction: $\Phi + \alpha \Rightarrow \beta + \gamma$

Adapted from www.computherm.com

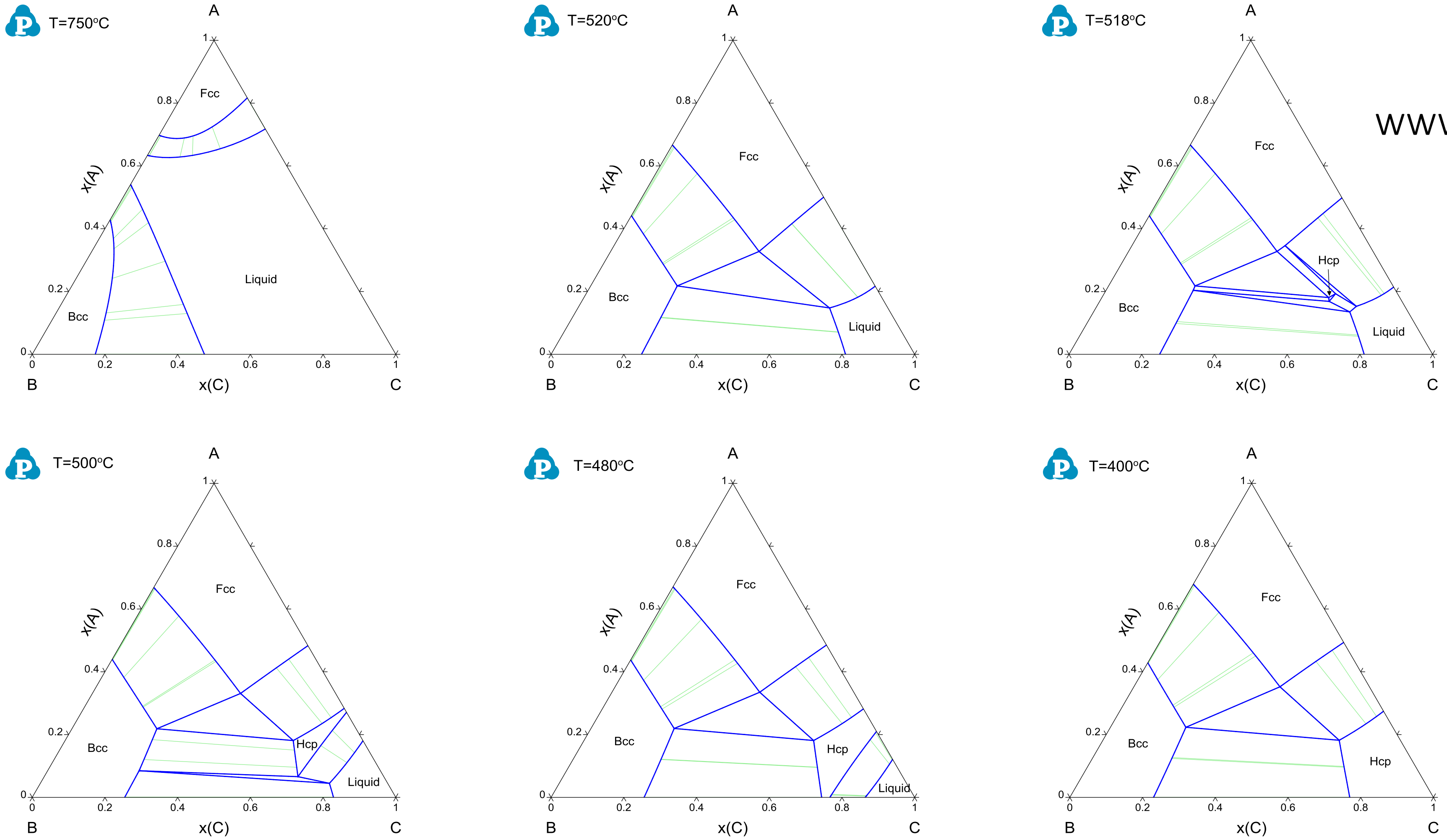
Ternary Four-Phase Equilibrium – Class III

Class III: One eutectic binary and two peritectic binary systems.



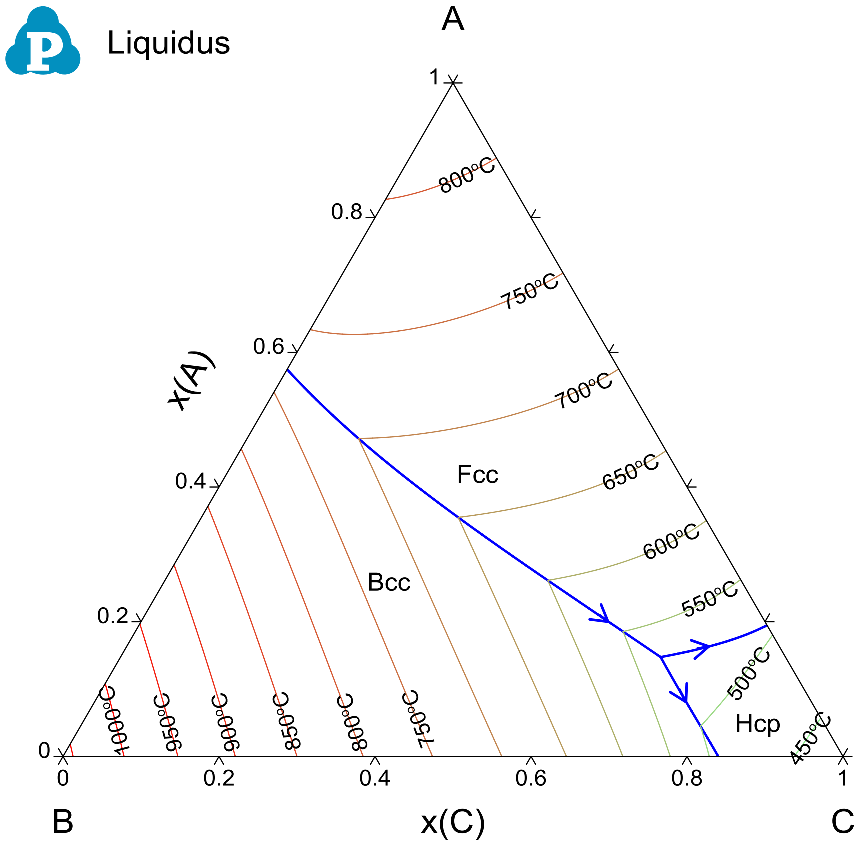
Adapted from www.computherm.com

Class III: Isothermal sections in decreasing T order.



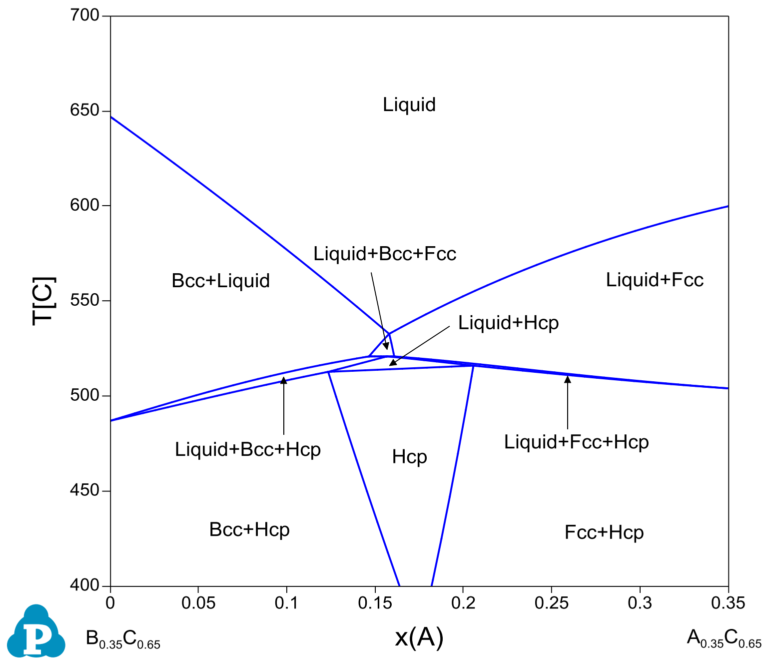
Adapted from
www.computherm.com

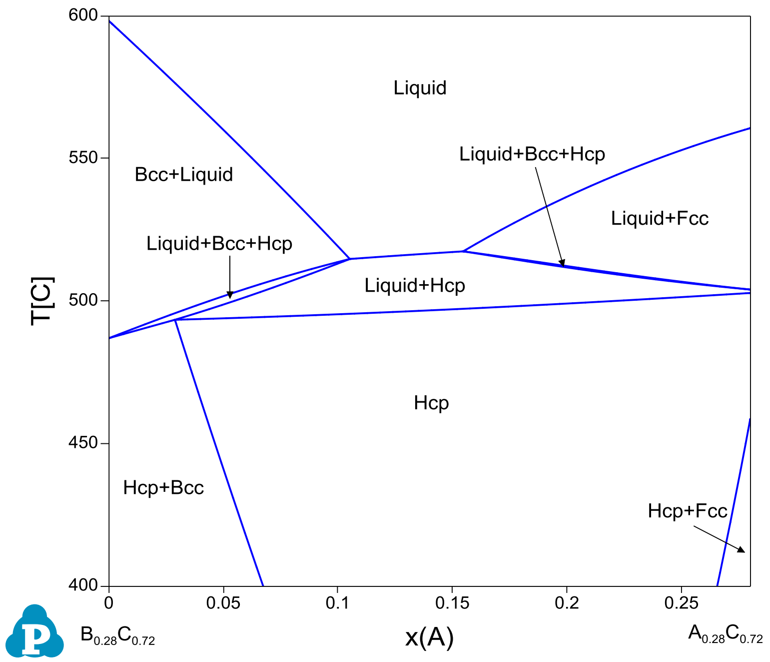
Liquidus lines start from the eutectic reaction in A-B binary, split into two directions in the ternary field and end at the peritectic reactions in A-C and B-C binaries. Three primary phase fields, Fcc, Bcc and Hcp.



Adapted from www.computherm.com

Isopleths through 65 at.% C and 72 at.% C





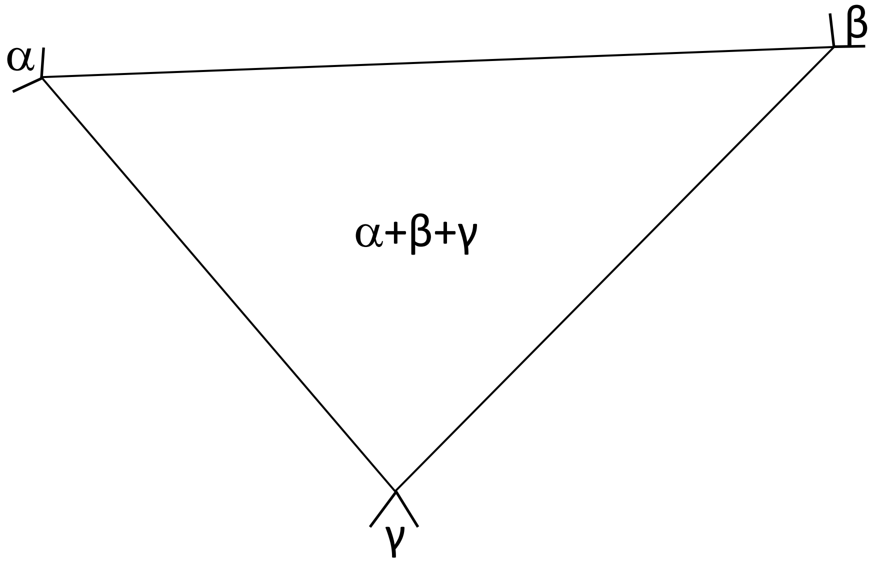
Adapted from www.computherm.com

European Funds Knowledge Education Development
INSTITUTE OF METALLURGY AND MATERIALS SCIENCE POLISH ACADAMY OF SCIENCES
European Union European Social Fund

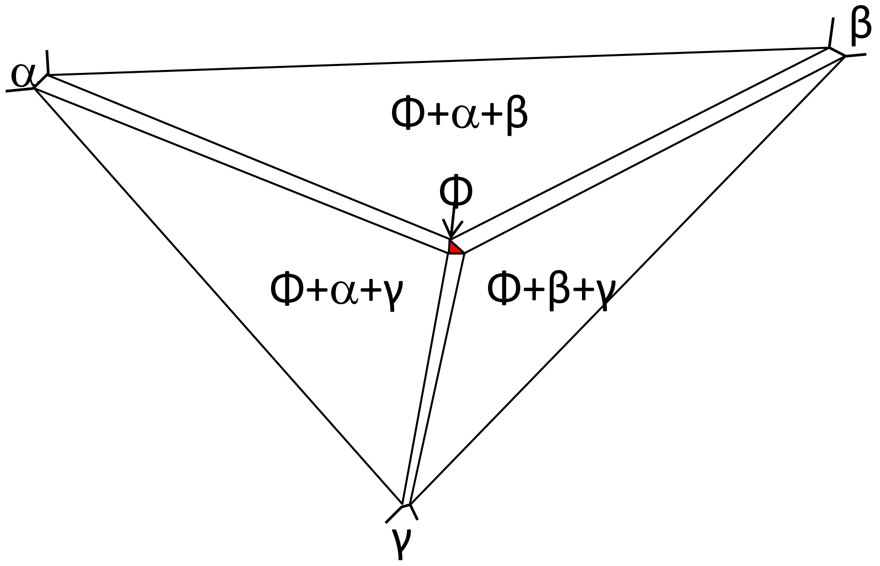
Characteristics to determine whether it is a Class III four-phase equilibrium:

Before Reaction: 1 three-phase triangle

After Reaction: 3 three-phase triangles



Before Reaction



After Reaction

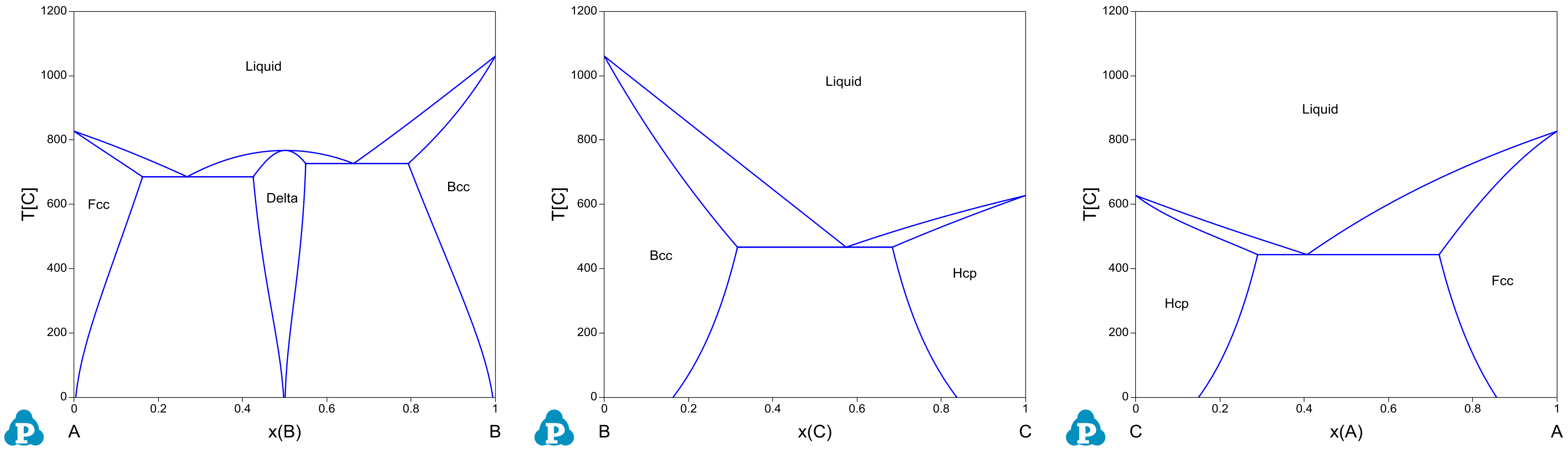
Class III reaction: $\alpha + \beta + \gamma \Rightarrow \Phi$

Adapted from www.computherm.com

Project WND-POWR.03.02.00-00-I043/16
International interdisciplinary PhD Studies in Materials Science with English as the language of instruction
Project co-financed by the European Union within the European Social Funds

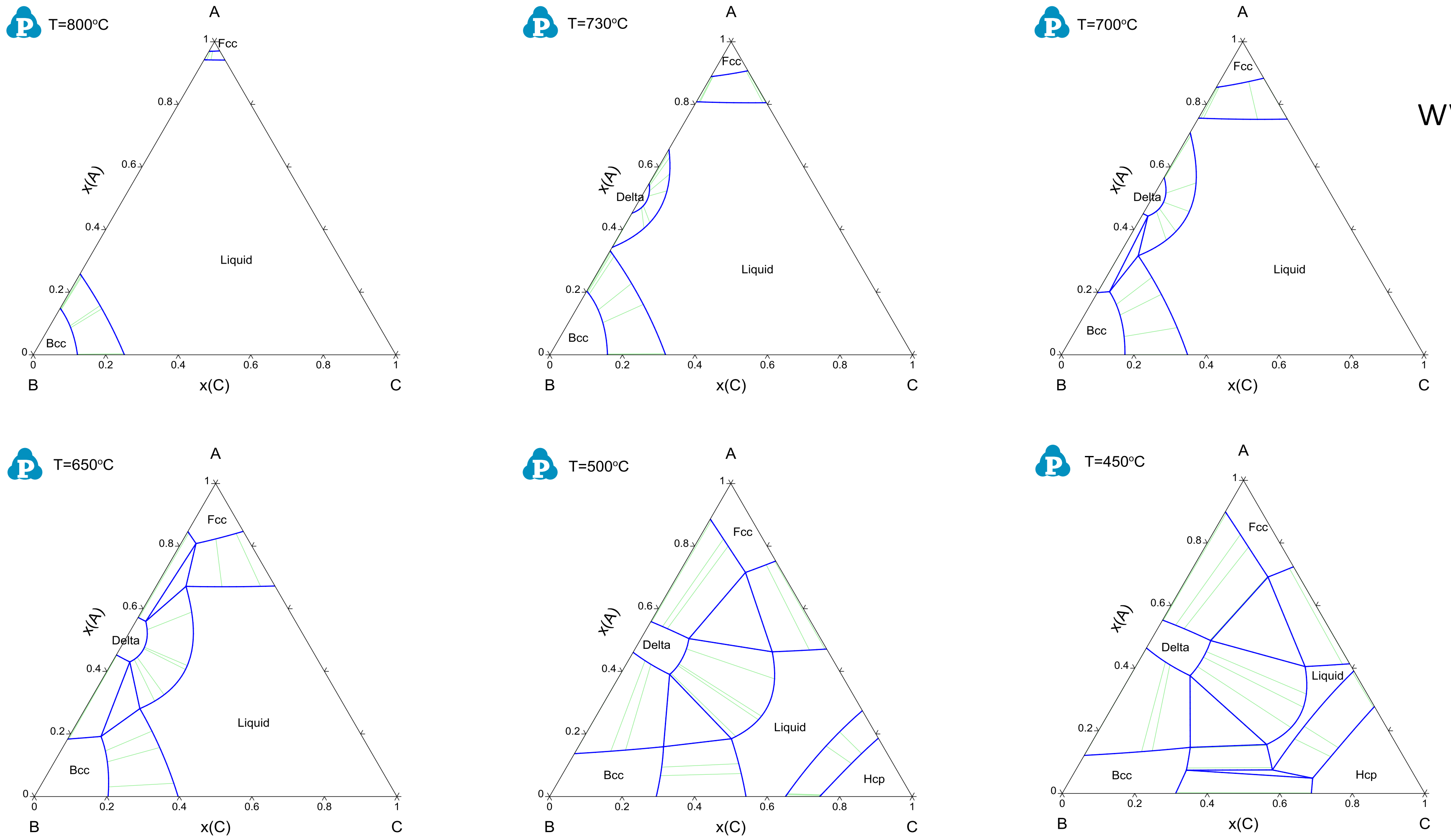
Congruent Transformation

Case I: Congruent melting in one binary and form a pseudo-binary in the ternary field.



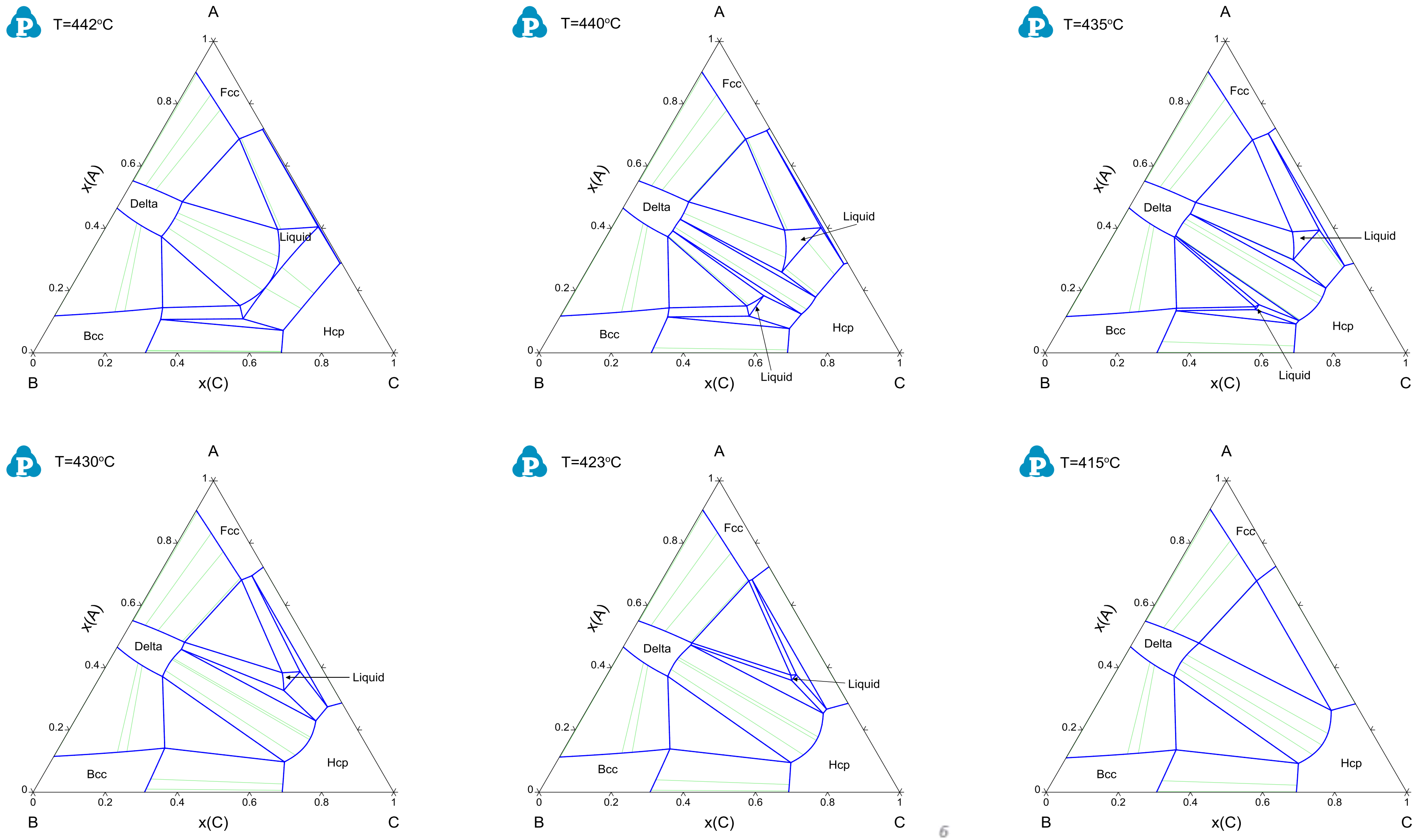
Adapted from www.computherm.com

Case I: Isothermal sections in decreasing T order.



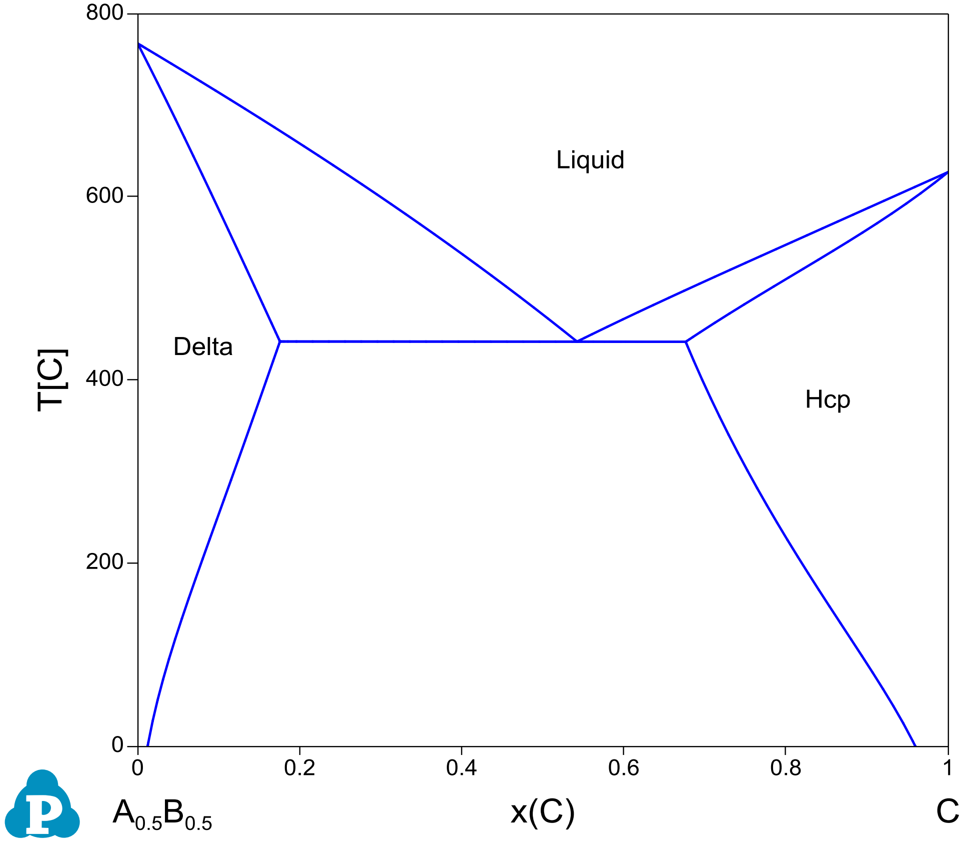
Adapted from www.computherm.com

Case I: Isothermal sections in decreasing T order.



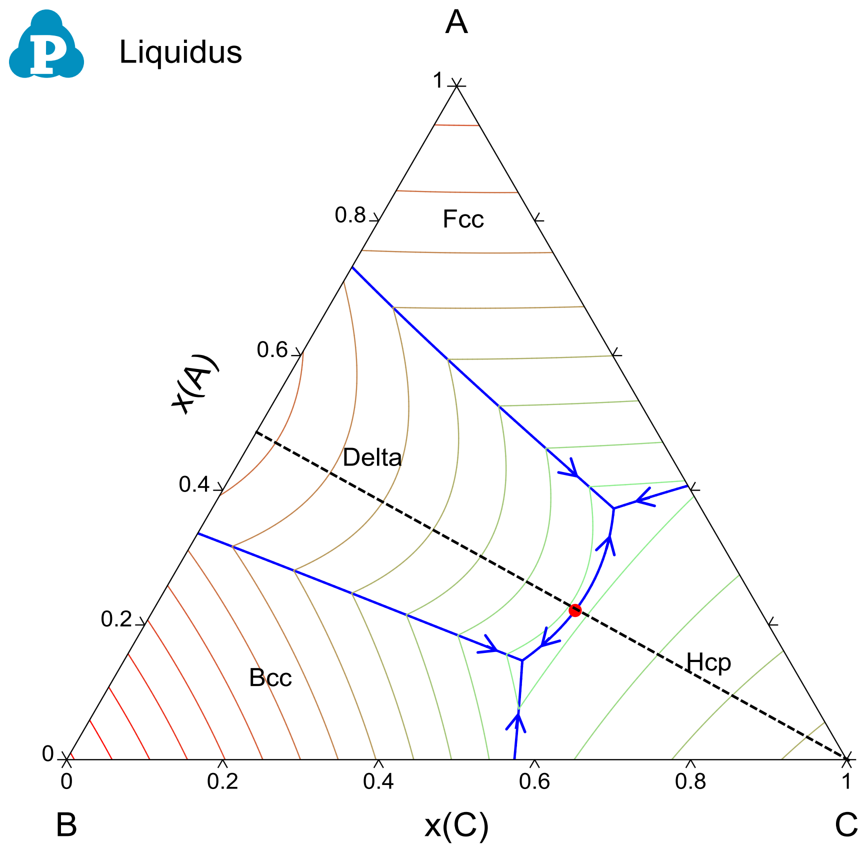
Adapted from
www.computherm.com

The isopleth through $A_{0.5}B_{0.5}$-C is a pseudo-binary system.



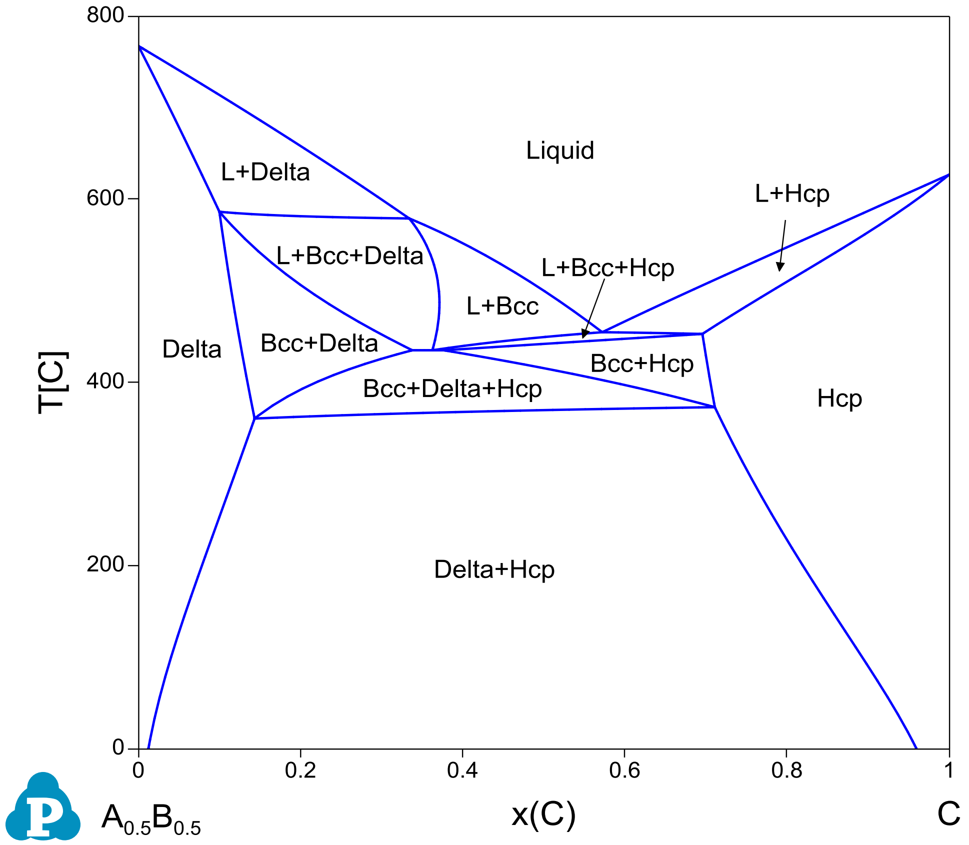
Adapted from www.computherm.com

The isopleth through $A_{0.5}B_{0.5}$-C cuts the liquidus projection into two parts and each one contains a class I four-phase equilibrium. The red point is a maximum in the liquidus surface.



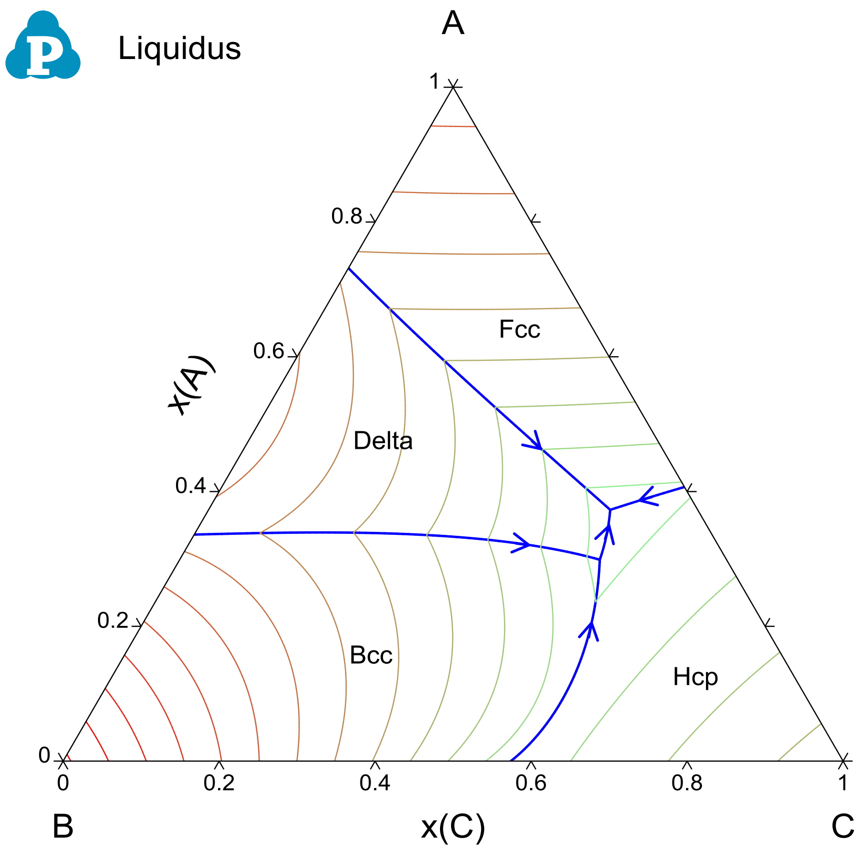
Adapted from www.computherm.com

The isopleth through $A_{0.5}B_{0.5}$-C is not a pseudo-binary system.



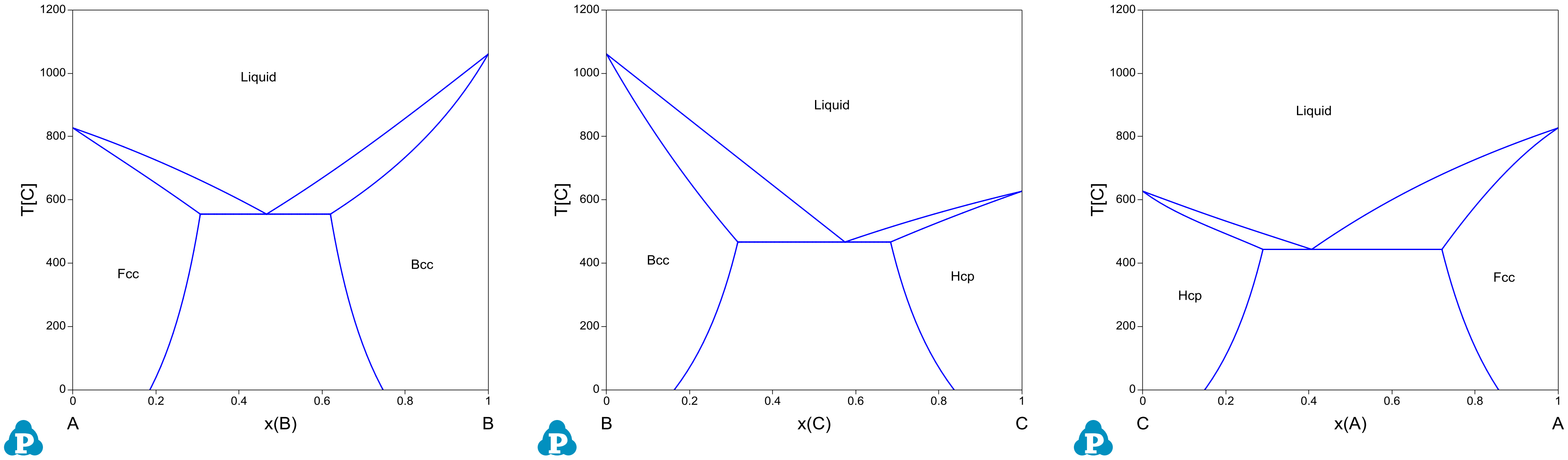
Adapted from www.computherm.com

The liquidus projection contains one class I four-phase equilibrium and one class II four-phase equilibrium.



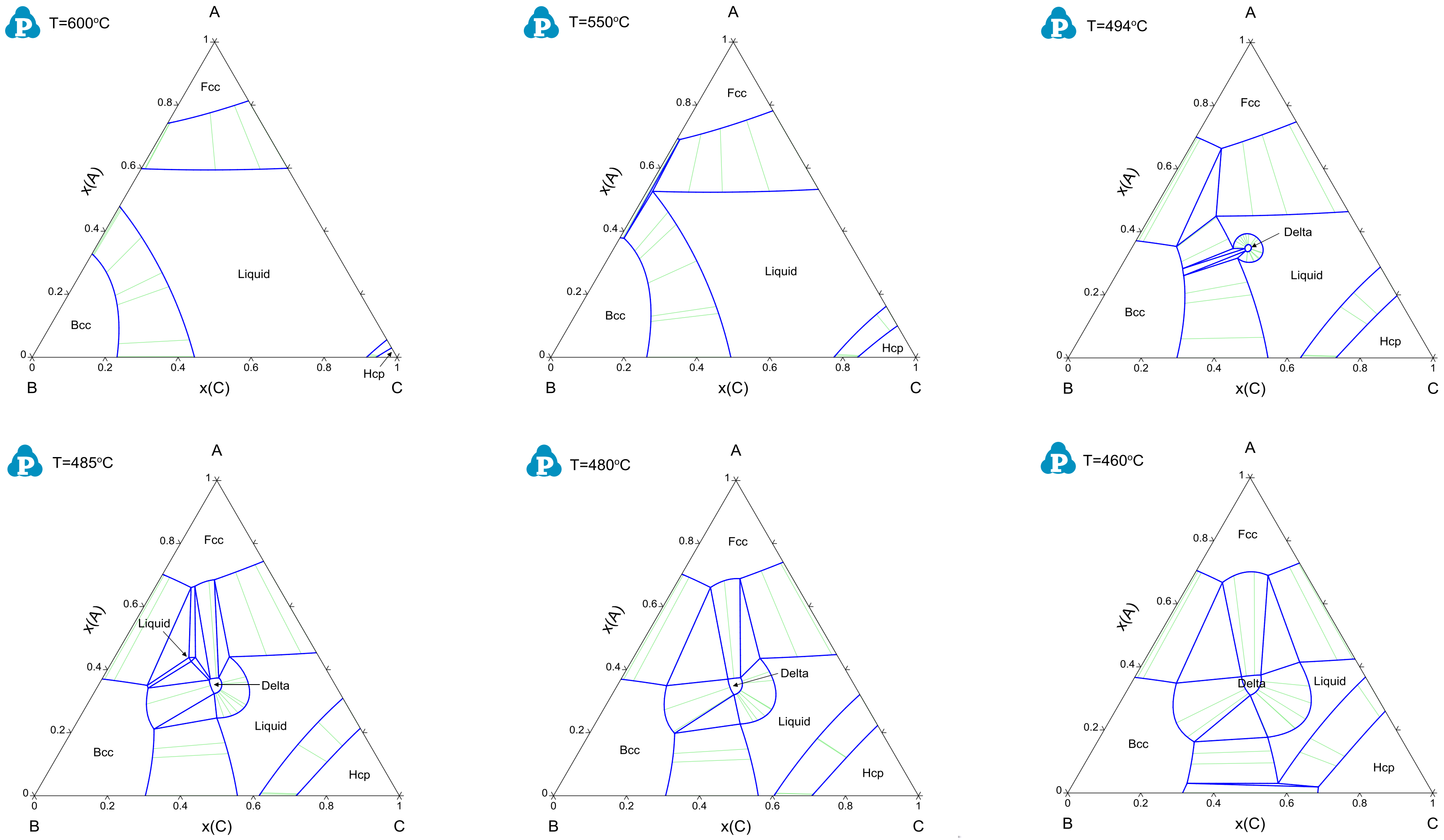
Adapted from www.computherm.com

Case III: Binaries are all eutectic systems, and there is a ternary compound which melts congruently in the ternary field.



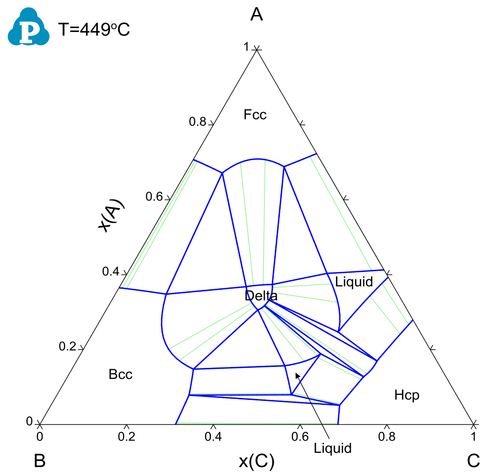
Adapted from www.computherm.com

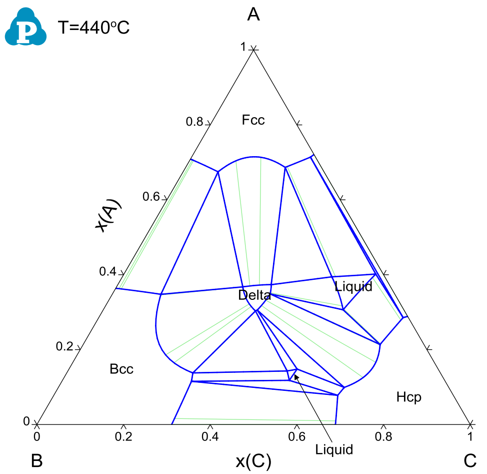
Case III: Isothermal sections in decreasing T order.

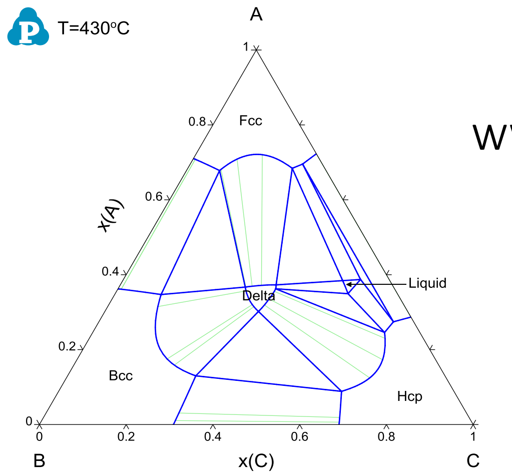


Adapted from www.computherm.com

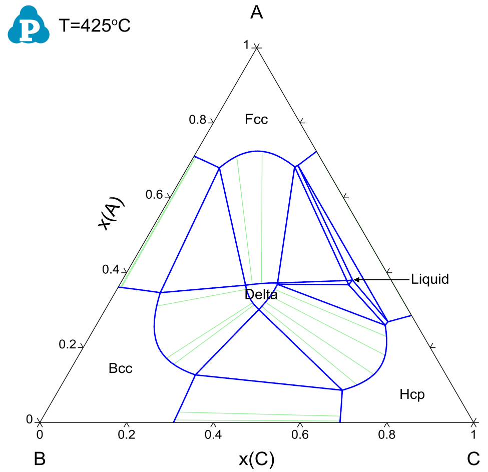
Case III: Isothermal sections in decreasing T order.

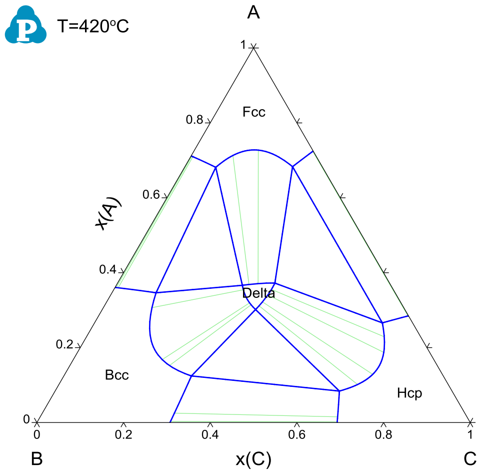


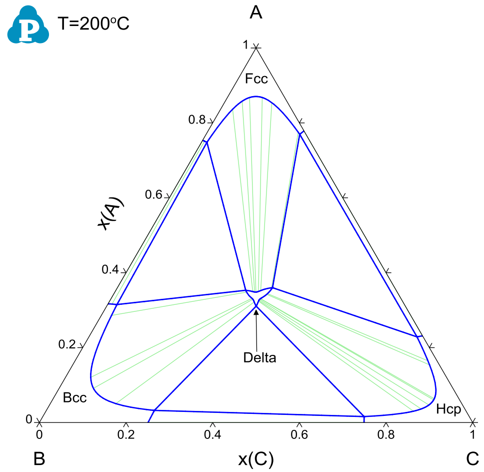




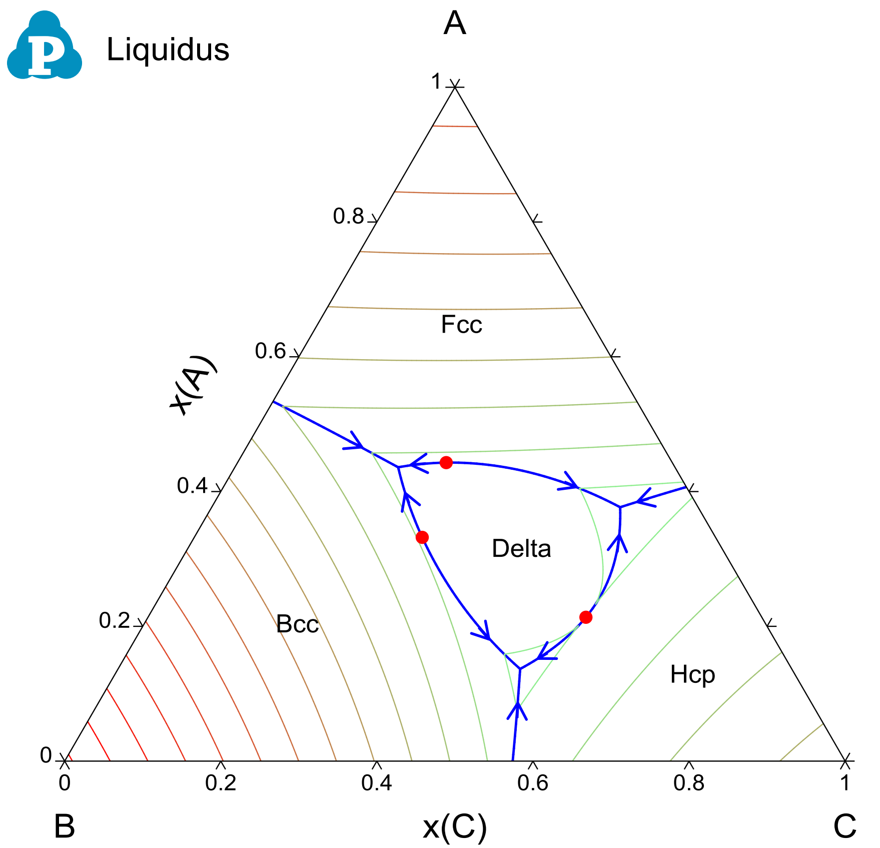
Adapted from
www.computherm.com







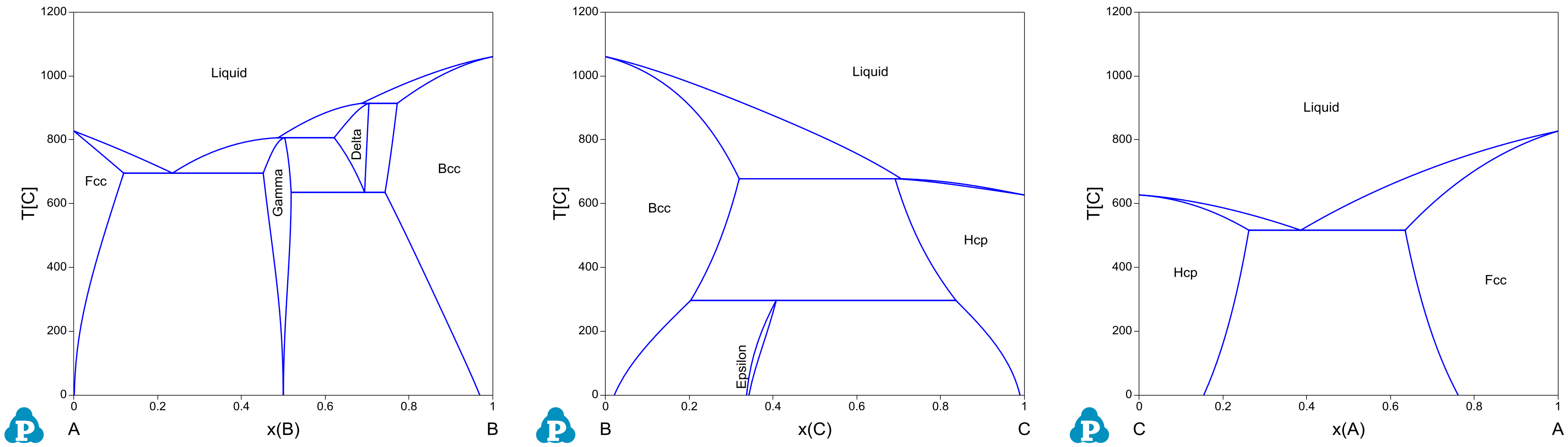
The delta primary phase appears as an island in the ternary field and there are three class I four-phase equilibria. The red points are three maximums in the liquidus surface.



Adapted from www.computherm.com

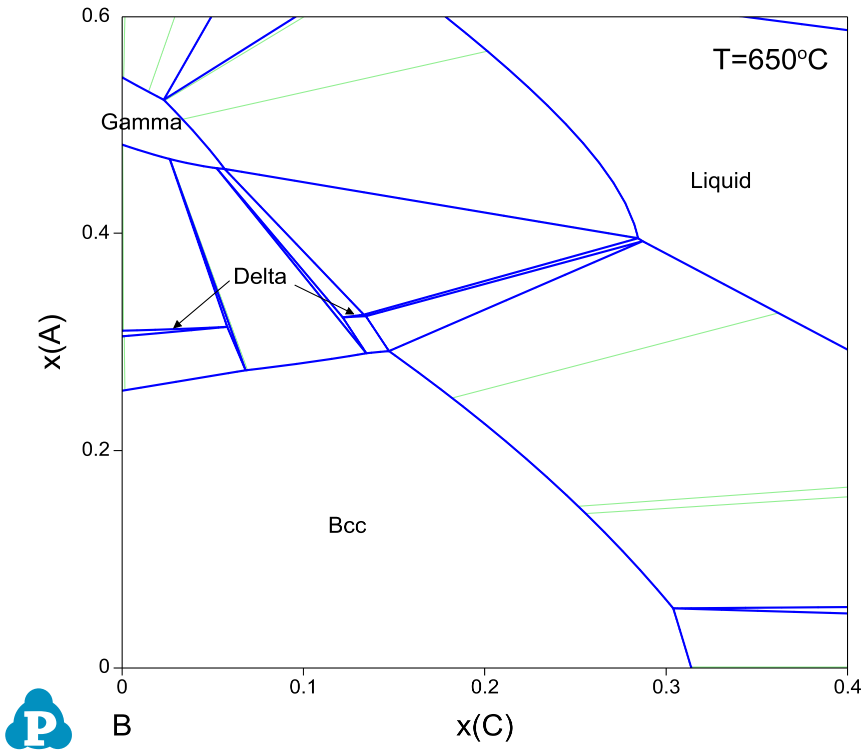
A complex ternary system

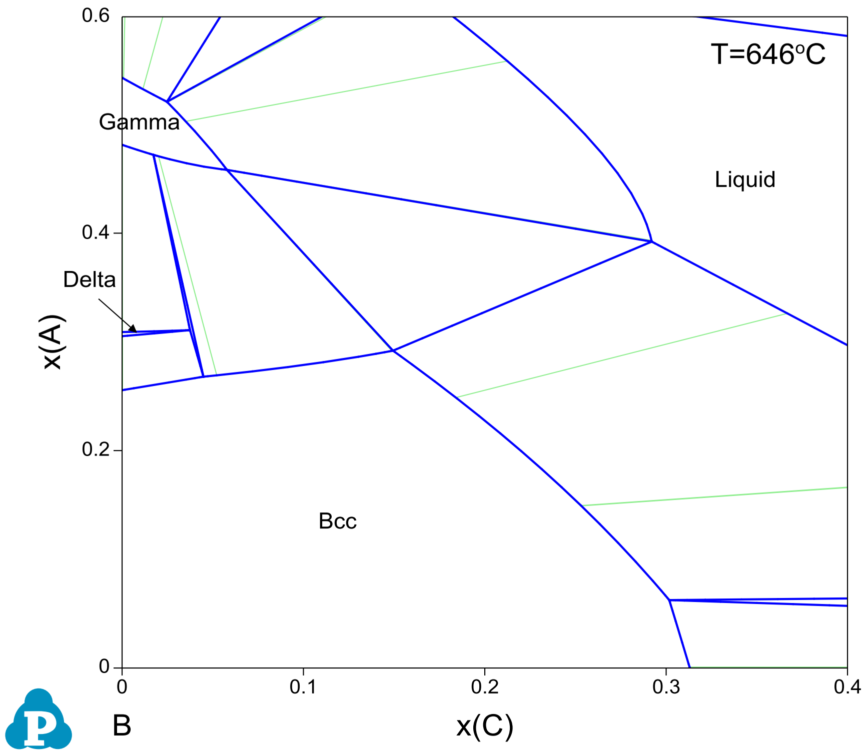
A complex ternary system involving all three classes of four-phase equilibrium.
Binaries contain three solid solution phases: Fcc, Bcc, and Hcp, and three intermetallic compounds: Delta, Gamma and Epsilon.



Adapted from www.computherm.com

Isothermal sections showing the invariant reaction 1 in detail.

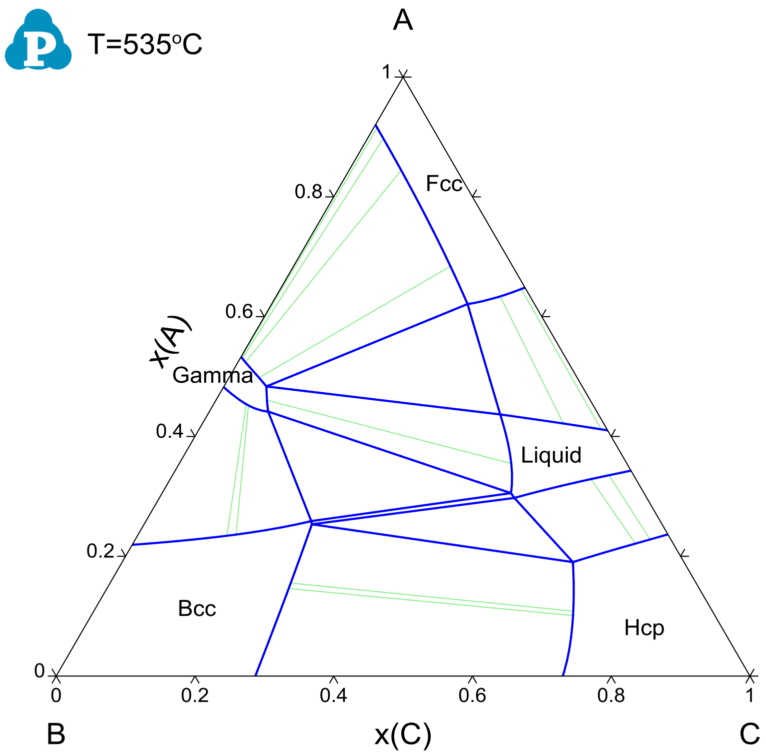


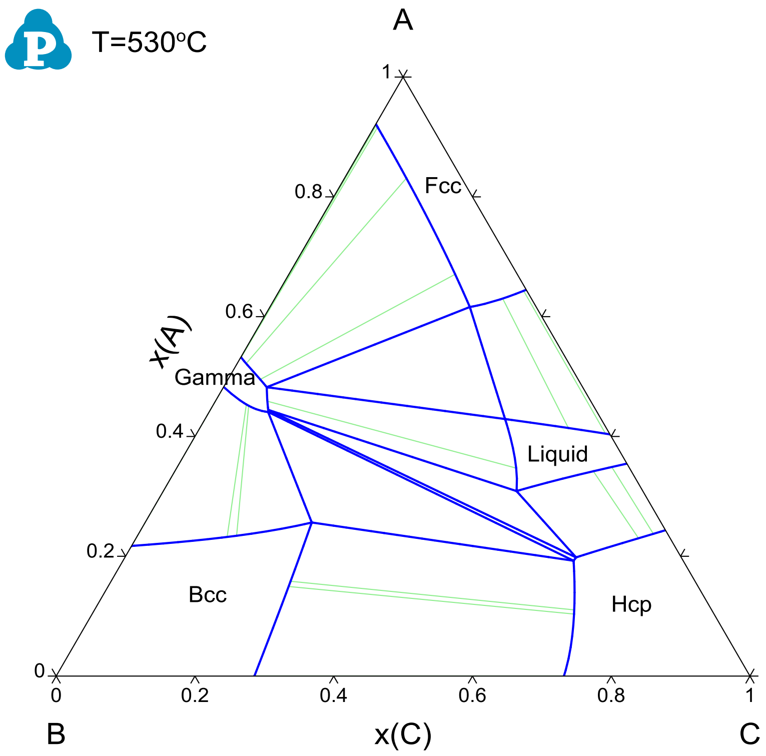


Class I: Delta => Liquid + Gamma + Bcc

Adapted from www.computherm.com

Isothermal sections showing the invariant reaction 2 in detail.

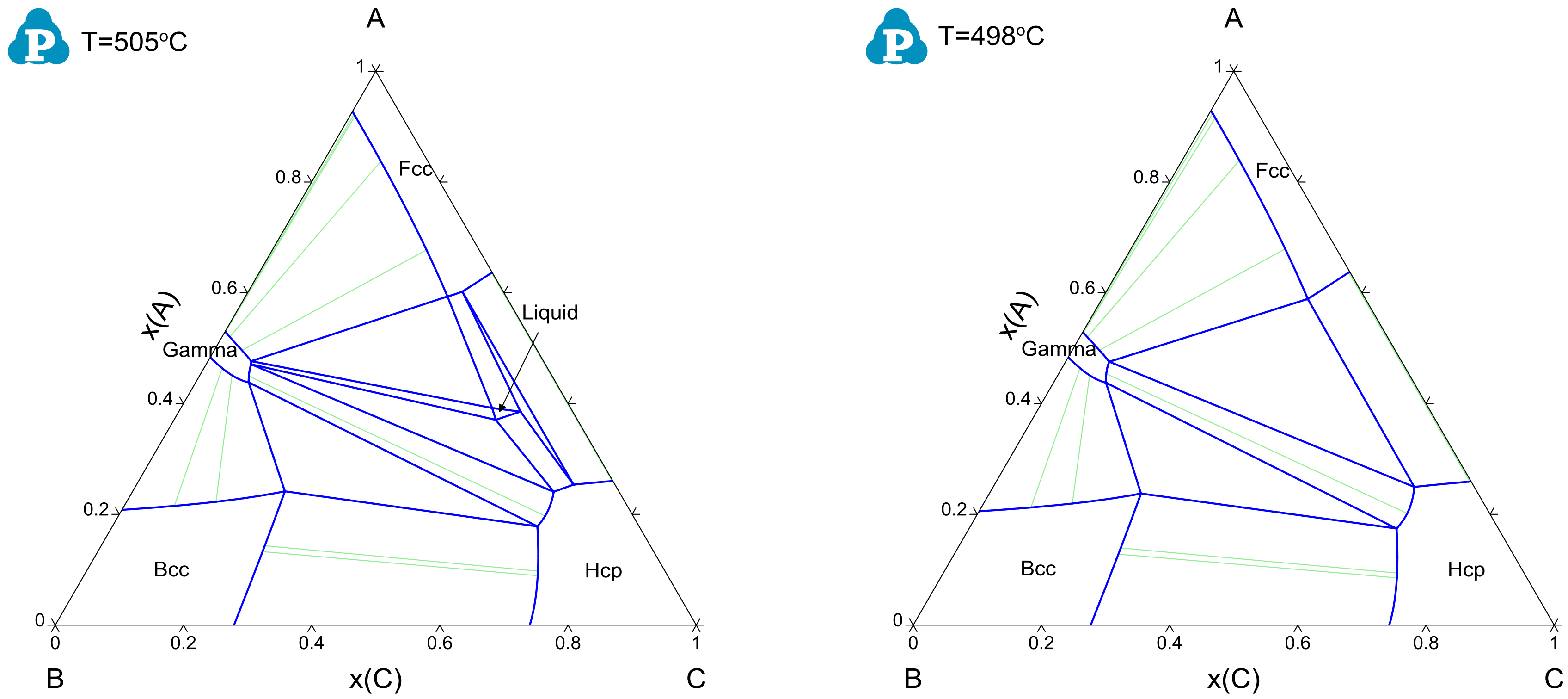




Class II: Liquid + Bcc => Gamma + Hcp

Adapted from www.computherm.com

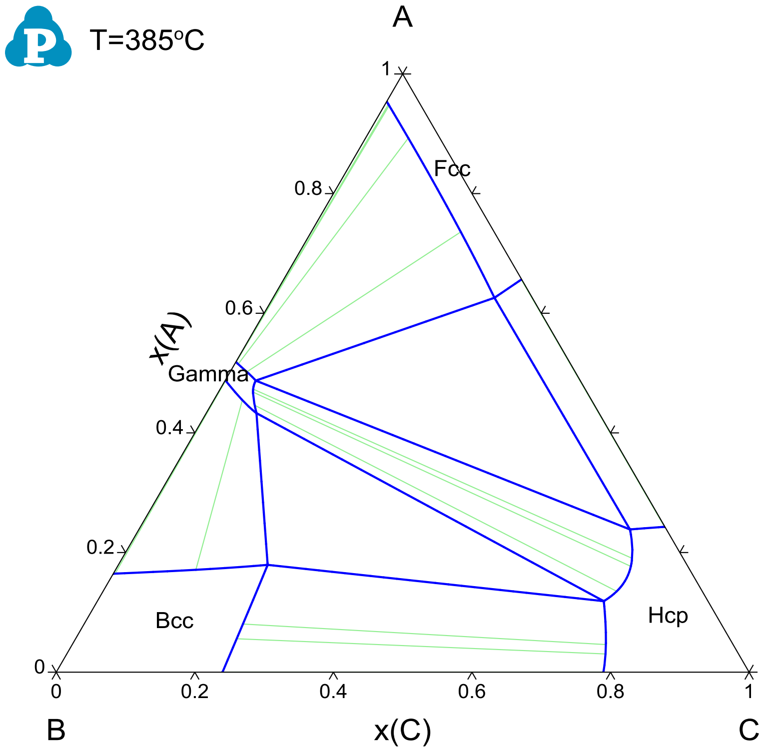
Isothermal sections showing the invariant reaction 3 in detail.

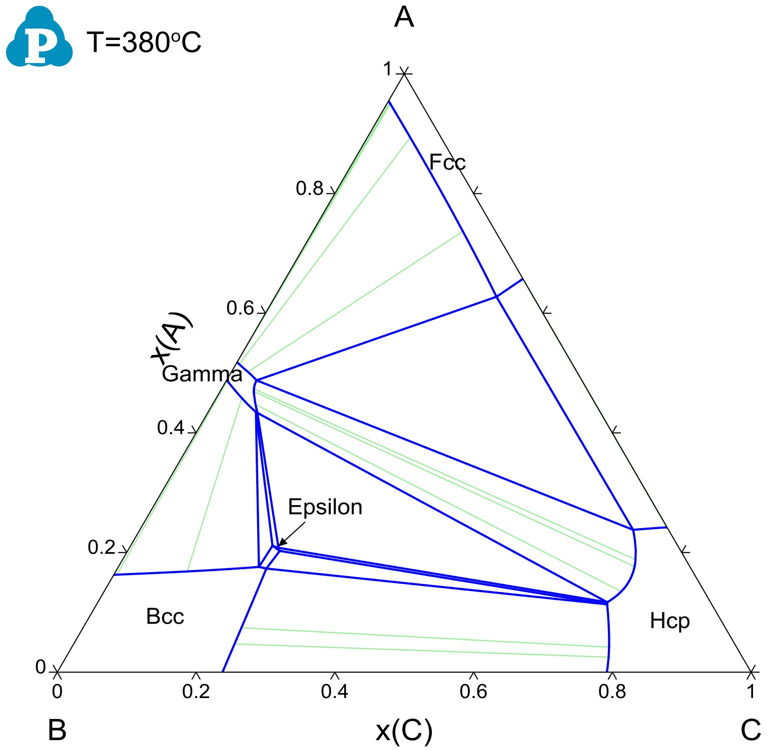


Class I: Liquid => Gamma + Fcc + Hcp

Adapted from www.computherm.com

Isothermal sections showing the invariant reaction 4 in detail. This reaction occurs in the solid state.

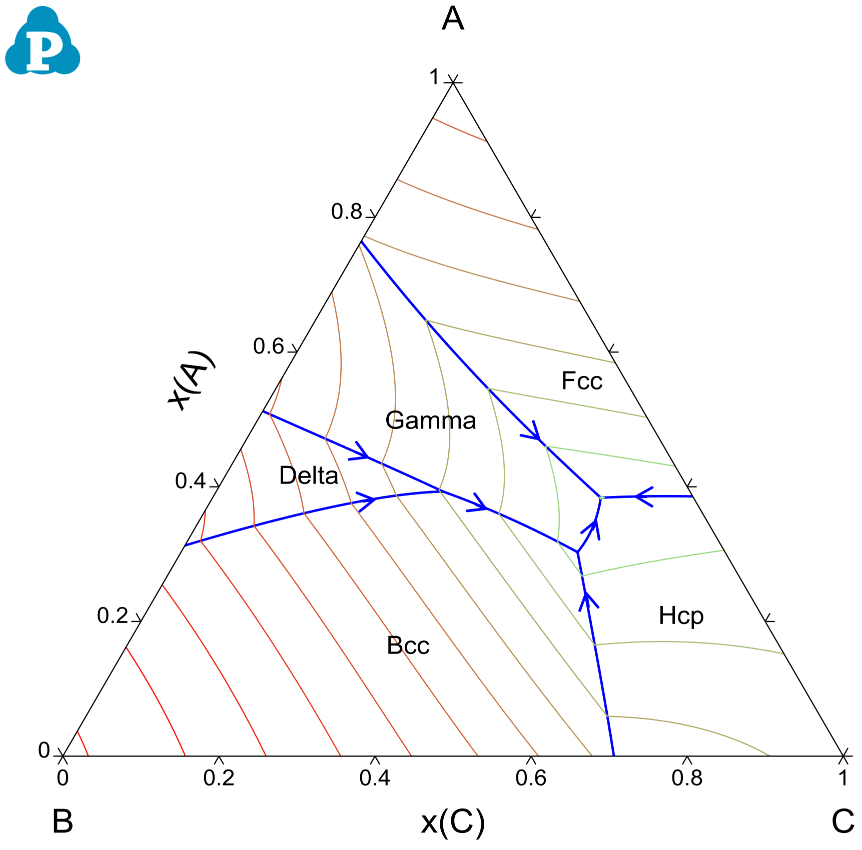




Class III: Gamma + Bcc + Hcp => Epsilon

Adapted from www.computherm.com

There are three four-phase equilibria on the liquidus surface, two Class I reactions and one Class II reaction.



Adapted from www.computherm.com

Acknowledgment

Many slides were adapted from: ”Binary Phase Diagrams and Microstructures” and ”Ternary Phase Diagrams”
www.computherm.com © CompuTherm LLC

Ag-Au-Cu system