CHAPTER 10

Ternary Phase Diagrams

TERNARY SYSTEMS are those having three components. It is not possible to describe the composition of a ternary alloy with a single number or fraction, as was done with binary alloys, but the statement of two independent values is sufficient. For example, the composition of an Fe-Cr-Ni alloy may be described fully by stating that it contains 18% Cr and 8% Ni. There is no need to say that the iron content is 74%. But the requirement that two parameters must be stated to describe ternary composition means that two dimensions must be used to represent composition on a complete phase diagram. The external variables that must be considered in ternary constitution are temperature, pressure, composition *X*, and composition *Y*. To construct a complete diagram representing all these variables would require the use of a four-dimensional space. This being out of the question, it is customary to assume pressure constant (atmospheric pressure) and to construct a three-dimensional (3-D) diagram representing, as variables, the temperature and two concentration parameters. Therefore, in any application of the phase rule, it should be recalled that one degree of freedom has been exercised in the initial construction of the 3-D diagram by electing to draw it at one atmosphere of pressure.

10.1 Space Model of Ternary Systems

To represent completely the phase equilibria at constant pressure in a ternary system, a 3-D model, commonly termed a space model, is required; the representation of composition requires two dimensions, and that of temperature, a third dimension. The model used is a triangular prism (Fig. 10.1), in which the temperature is plotted on the vertical axis, and the composition is represented on the base of the prism, which may be conveniently taken as an equilateral triangle. Thus, in Fig. 10.1, the vertical sides of the prism represent the three binary systems, *AB*, *BC*, and *AC*, that make up the ternary system, *ABC*.

A hypothetical ternary phase space diagram made up of metals *A*, *B*, and *C* is shown in Fig. 10.2. This diagram contains two binary eutectics on the two visible faces of the diagram, and a third binary eutectic between elements *B* and *C* hidden on the back of the plot. Because it is difficult to use

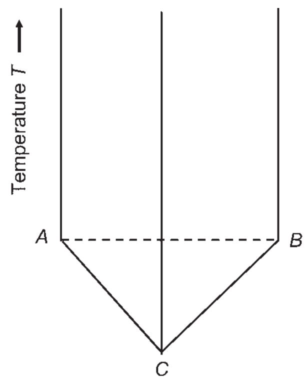

Fig. 10.1 Space model for ternary phase diagrams

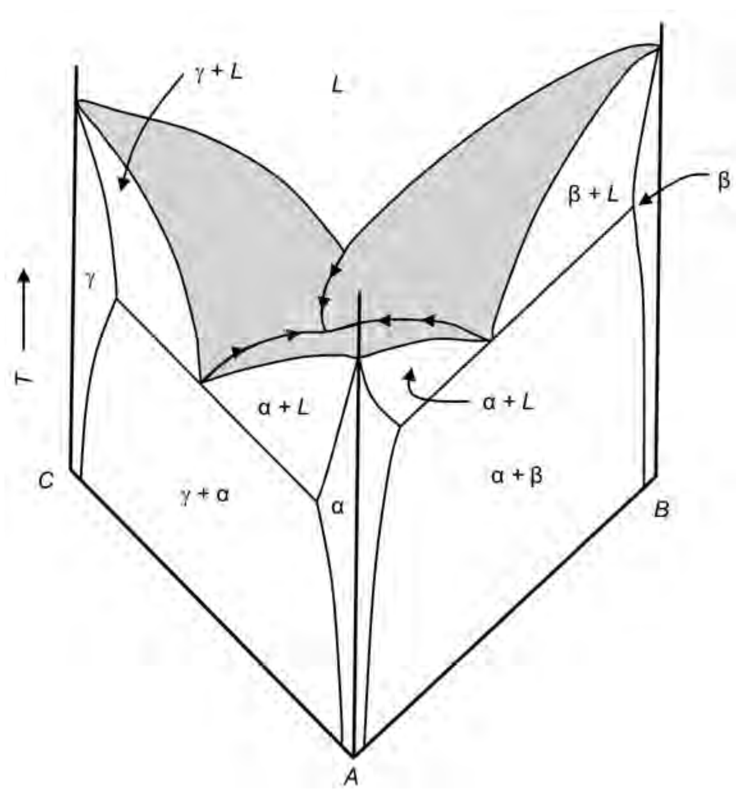

Fig. 10.2 Hypothetical ternary phase diagram. Binary phase diagrams are present along the three faces. Adapted from Ref 10.1

the 3-D ternary plot, the information from the diagrams can be plotted in two dimensions by any of several methods, including the liquidus plot, the isothermal plot, and a vertical section called an isopleth.

Liquidus Plots. The temperature at which freezing begins is shaded in Fig. 10.2. In Fig. 10.3, these temperatures for each composition are transferred onto a triangular diagram; the liquidus temperatures are plotted as isothermal contours. This presentation is helpful in predicting the freezing temperature of an alloy. Note that the liquidus lines have arrows indicating the freezing direction toward the ternary eutectic point. The liquidus plot also gives the identity of the primary phase that will form during solidification for any given alloy composition. Similar plots, known as solidus plots, showing solidus freezing are sometime presented.

Isothermal Plots. An isothermal plot shows the phases present in any alloy at a particular temperature and is useful in predicting the phases and their amounts and compositions at that temperature. An isothermal section from Fig. 10.2 at room temperature is shown in Fig. 10.4. Isothermal plots are by far the most useful because they allow compositional analysis, while liquidus and isopleth plots do not allow compositional analysis.

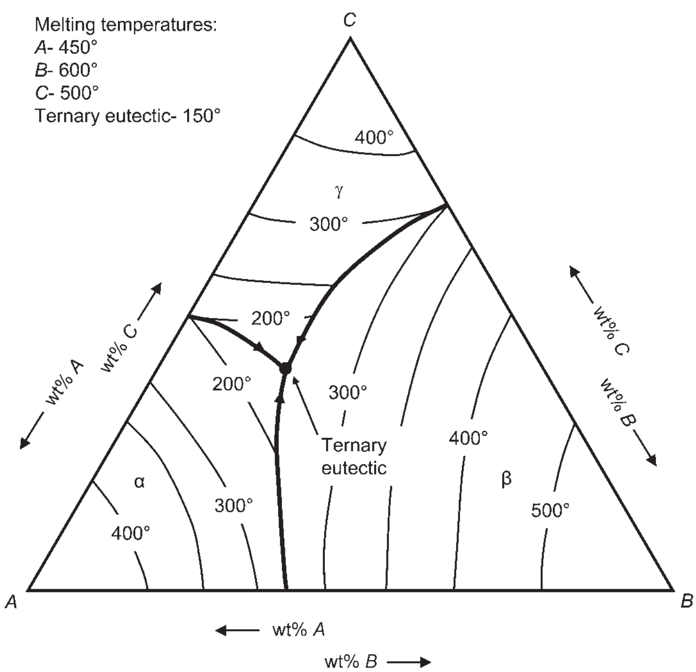

Fig. 10.3 Liquidus plot for hypothetical ternary phase diagram. Adapted from Ref 10.1

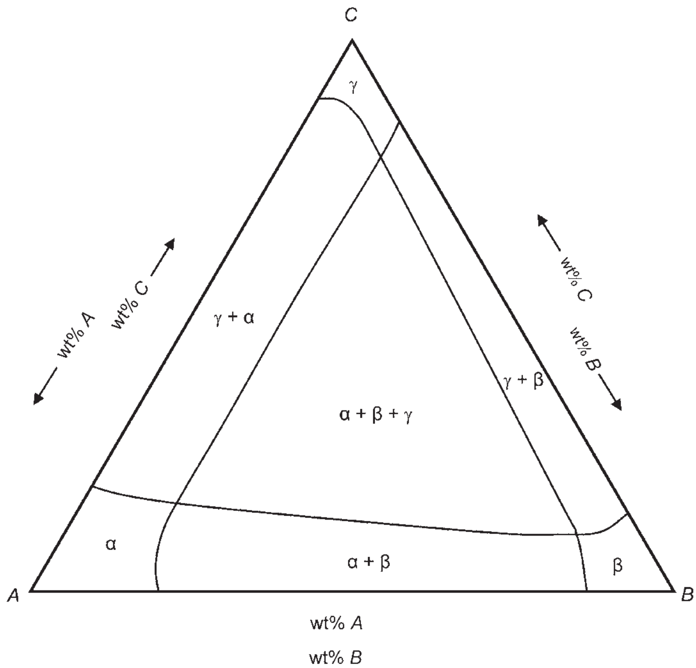

Fig. 10.4 Isothermal plot at room temperature for hypothetical ternary phase diagram. Adapted from Ref 10.1

Isopleth Plots. Certain groups of alloys can be plotted as vertical sections, also called isopleths. These sections often represent a fixed composition of one of the elements, while the amounts of the other two elements are allowed to vary. These plots show how the phases and structures change when the temperature varies and when two of the elements present change their respective amounts. Tie lines usually do not lie in the plane of a vertical section and cannot be used to obtain amounts and compositions. An isopleth through the hypothetical diagram (Fig. 10.2) at a constant 40% *C* is shown in Fig. 10.5. An alloy containing 30% *A* and 30% *B* will begin to freeze near 350 °C (660 °F), with primary β forming first. Near 275 °C (530 °F), γ will also begin to form. Finally, at approximately 160 °C (320 °F), α forms and the last liquid freezes. The final microstructure contains α, β, and γ. Isopleths are quite valuable in showing the phases that are present during equilibrium cooling and heating. They also show the temperatures at which the various phase changes occur.

Single-Phase Boundary and Zero-Phase Fraction Lines. Two-dimensional (2-D) sections of any multicomponent phase diagram, whether it is an isotherm or an isopleth, can be read by focusing on two lines that refer to one particular phase. These lines are shown in the Fig. 10.6 isopleth for Fe-17%Cr-%C alloys.

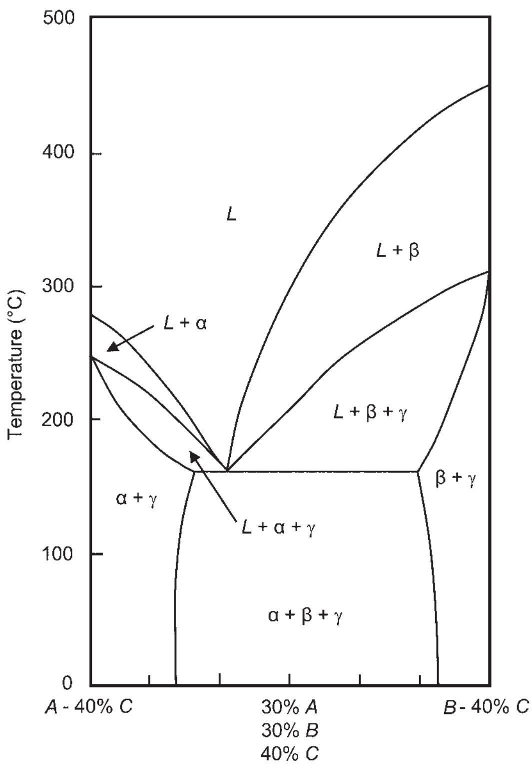

Fig. 10.5 Isopleth through hypothetical ternary phase diagram at a constant 40% *C*. Adapted from Ref 10.1

SPB Line. The single-phase boundary line is found on any section that contains a single-phase region. The line is what its name implies. It is the boundary line around that single-phase region. It can be used, for example, to determine compositions and temperatures where an alloy can be thoroughly solutionized.

ZPF Line. The zero phase fraction line is a line that surrounds all regions on the diagram where the phase occurs. On one side of the line there are regions with the phase, and on the other side of the line there are regions without the phase. Because the line surrounds a region of compositions and temperatures where the phase forms, it can be used to avoid a phase, for example an embrittling phase, or promote a phase, for example a precipitation-hardening phase.

By drawing these lines, the reader is able to focus on one phase at a time and ignore the lines that concern other phases. Although it is true that the lever rule cannot be used here, it can be assumed that moving closer to an SPB line will likely increase the amount of the phase, while moving closer to the ZPF line will decrease the amount of the phase. The liquidus and solidus lines are SPB and ZPF lines for the liquid, respectively. Also, it is

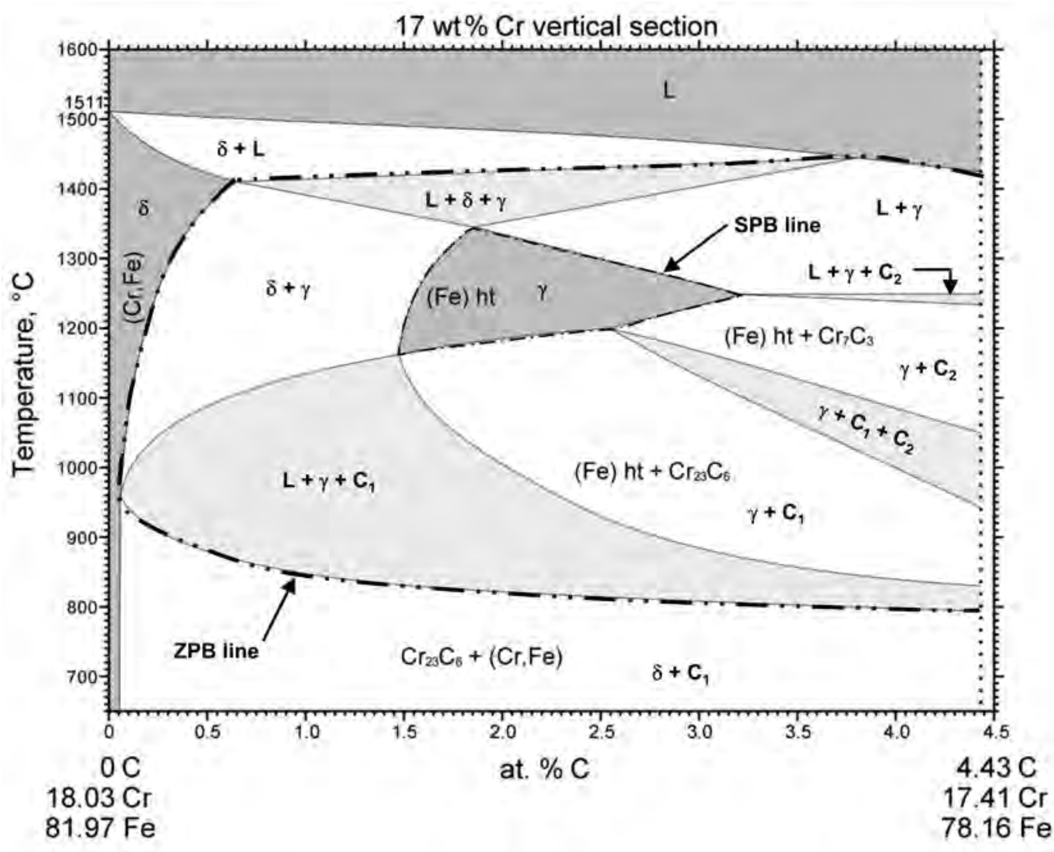

Fig. 10.6 C-Cr-Fe isopleth showing single-phase boundary (SPB) lines and zero-phase boundary (ZPB) lines. Source: Ref 10.2

worth noting that an isopleth is a collection of ZPF lines for the various phases present. Computer programs that predict phase diagrams can give a phase diagram in the form of ZPF lines alone. In this case, the lines are labeled instead of the regions.

10.2 The Gibbs Triangle

Because of its unique geometric characteristics, an equilateral triangle provides the simplest means for plotting ternary composition. On the Gibbs triangle, which is an equilateral triangle, the three pure component metals are represented at the corners, *A*, *B*, and *C*, as shown in Fig. 10.7. Binary composition is represented along the edges, that is, the binary systems *AB*, *AC*, and *BC*. And ternary alloys are represented within the area of the triangle, such as at point *P* in Fig. 10.7.

If lines are drawn through Alloy *P* parallel to each of the sides of the triangle, it will be found that these have produced three smaller equilateral

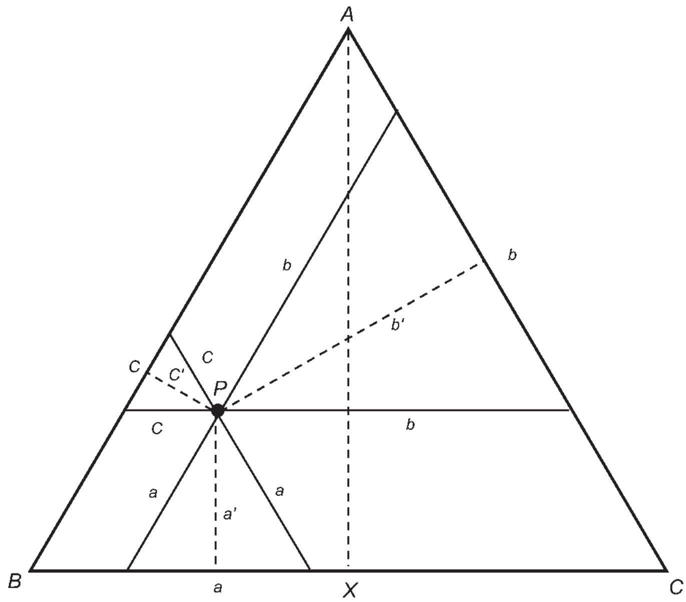

Fig. 10.7 The Gibbs triangle. Adapted from Ref 10.3

triangles: *aaa*, *bbb*, and *ccc*. The sum of the lengths of the nine sides of these three triangles is equal to the sum of the lengths of the three sides of the major triangle, *ABC*, within which they are inscribed; or the sum of the lengths of one side from each of the minor triangles is equal to the length of one side of the major triangle: $a + b + c = AB = AC = BC$. Also, the sum of the altitudes of the minor triangles is equal to the altitude of the major triangle: $a' + b' + c' = AX$.

If one side of the Gibbs triangle is divided into 100 equal parts, representing 100% on the binary composition scale, it is found that the same units can be used to measure the composition at point *P*. Let the length *a* represent the percentage of *A* in *P*, the length *b* the percentage of *B*, and the length *c* the percentage of *C*. Because these lengths total the same as one side of the Gibbs triangle, and together they must equal 100%, it is evident that 1% has the same length, whether measured along an edge of the diagram or along any inscribed line parallel to an edge. A similar result could be obtained by using altitudes, but this is less convenient. It should be noted that in either case, the percentage of *A* is measured on the side of *P* away from the *A* corner and similarly with *B* and *C*.

For convenience in reading composition, an equilateral triangle may be ruled with lines parallel to the sides (Fig. 10.8). Composition may then be read directly, for example, $P = 20\%\ A + 70\%\ B + 10\%\ C$. At point *P*, the percentage of *A* is represented by the line *Pa* (or equivalently *Pa′*), which is 20 units long; the percentage of *B* by the line *Pb* (or *Pb′*), 70 units long; and

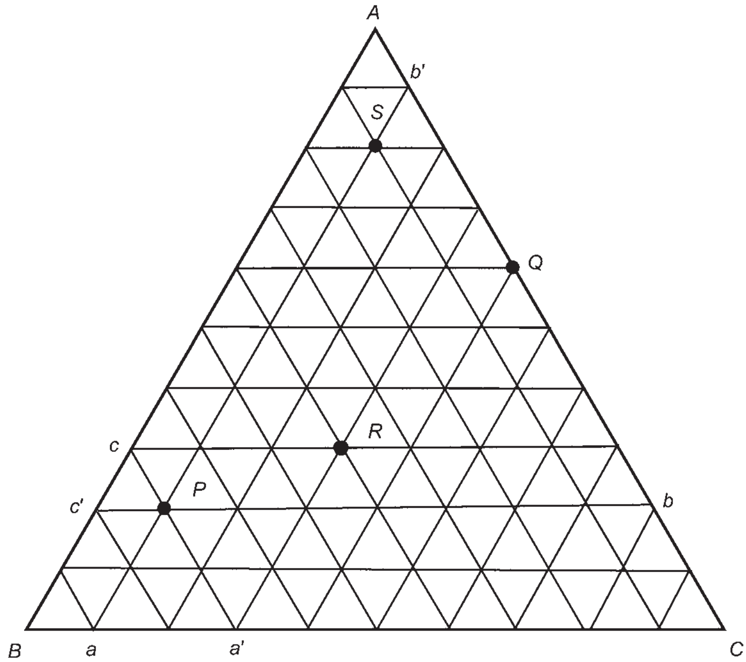

Fig. 10.8 The Gibbs triangle with composition lines. Adapted from Ref 10.3

the percentage of *C* by the line *Pc* (or *Pc′*), 10 units long. Other examples shown in Fig. 10.8 are: Alloy *R* = 30% *A* + 40% *B* + 30% *C*, Alloy *S* = 80% *A* + 10% *B* + 10% *C*, and Alloy *Q* = 60% *A* + 0% *B* + 40% *C*.

10.3 Tie Lines

If any two ternary alloys are mixed together, tie lines can be shown. The composition of the mixture will lie on a straight line joining the original two compositions. This is true regardless of the proportions of the two alloys in the mixture. Conversely, if an alloy decomposes into two fractions of differing composition, the compositions of the two portions will lie on opposite ends of a straight line passing through the original composition point. Consider Fig. 10.9. Points *S* and *L* represent two ternary alloys of respective composition: 20% *A* + 70% *B* + 10% *C* and 40% *A* + 30% *B* + 30 % *C*. Suppose that one part of *S* is mixed with three parts of *L* and the mixture is analyzed. The analytical result will be:

$$0.25 \times 20\%\ A + 0.75 \times 40\%\ A = 35\%\ A$$
$$0.25 \times 70\%\ B + 0.75 \times 30\%\ B = 40\%\ B$$
$$0.25 \times 10\%\ C + 0.75 \times 30\%\ C = 25\%\ C$$

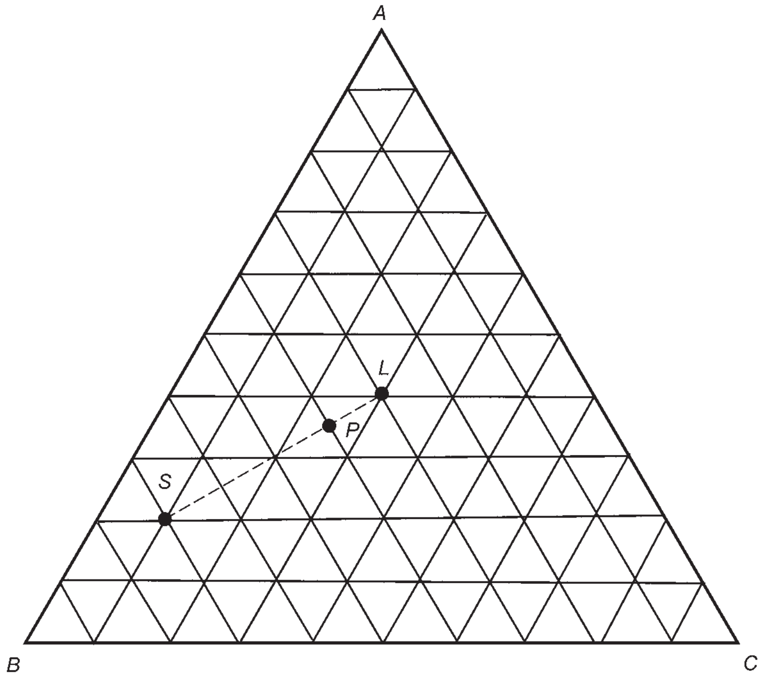

Fig. 10.9 The Gibbs triangle with tie line. Adapted from Ref 10.3

As can be seen by inspection of Fig. 10.9, this composition lies at *P*, which is a point on the straight line connecting *S* and *L*. Regardless of the compositions chosen or in what proportions they had been mixed, the total composition would have occurred on the line joining the two original compositions.

It is evident that the line *SL* has the characteristics of a tie line: It is both isobaric and isothermal, because it lies in the composition plane, which is drawn perpendicular to the temperature axis and corresponds to the case of constant atmospheric pressure (i.e., it would be drawn perpendicular to the pressure axis if a fourth dimension were available). The lever principle is applicable to this line. Therefore, the line *SL* might represent the condition of an alloy of composition *P* that is partially frozen, at the temperature under consideration, and consists of 25% solid of composition *S* and 75% liquid of composition *L*:

$$\%\,S = \frac{PL}{SL} \times 100$$

$$\%\,L = \frac{SP}{SL} \times 100$$

10.4 Ternary Isomorphous Systems

A temperature-composition (*T*-*X*-*Y*) diagram of an isomorphous system is shown in Fig. 10.10. The composition plane forms the base of the figure, and temperature is measured vertically. Here, the liquidus and solidus become surfaces bounding the $L + \alpha$ space. Above the liquidus, all alloys are fully molten; below the solidus, all are completely solid. As in binary systems, the two-phase region, $L + \alpha$, is composed of tie lines joining conjugate liquid and solid phases. In the ternary system, however, the tie lines are not confined to a 2-D area but occur as a bundle of lines of varying direction, but all horizontal (isothermal), filling the 3-D two-phase space.

Isothermal Sections. The location of the tie lines can be visualized more easily by reference to isothermal (horizontal) sections cut through the temperature-composition diagram at a series of temperature levels. The three isotherms presented in Fig. 10.11 are taken at the temperatures designated T_1, T_2, and T_3. It is seen that the first tie line on each edge of the $L + \alpha$ region is the bounding line of the figure; that is, it is the binary tie line at the temperature designated. The directions of tie lines lying within

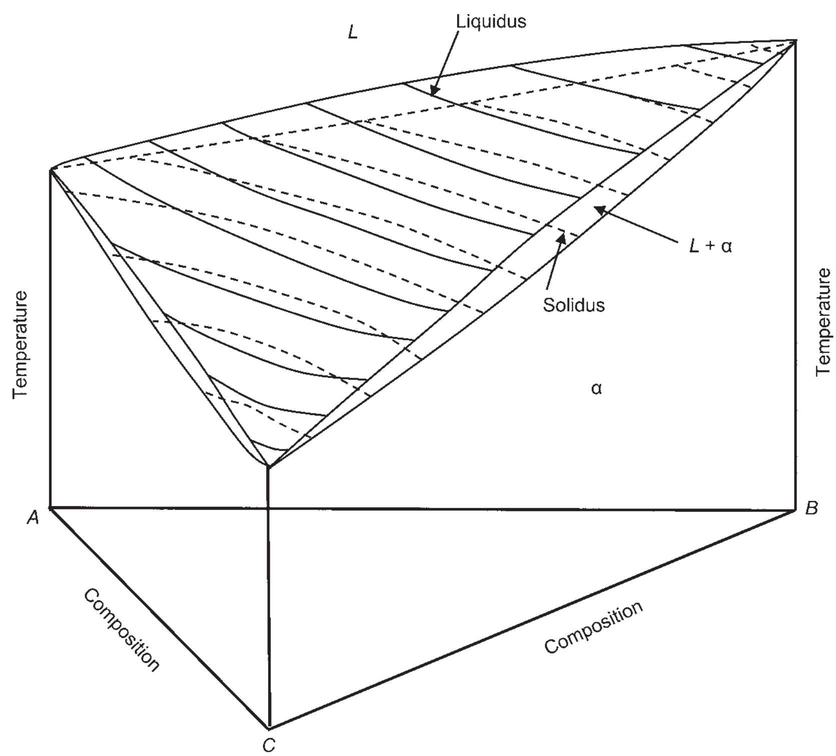

Fig. 10.10 Temperature-composition space diagram of a ternary isomorphous system. Adapted from Ref 10.3