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FRACTIONAL CRYSTALLIZATION REACTIONS IN THE SYSTEM $LiF-BeF_2-ThF_4$

R. E. Thoma and J. E. Ricci[1]

ABSTRACT

Equilibrium and non-equilibrium crystallization reactions in the system $LiF-BeF_2-ThF_4$ are analyzed in relation to their potential application to molten salt reactor fuel reprocessing. Heterogeneous equilibria in the temperature range from the liquidus at 590°C to the solidus at 350°C are described quantitatively and in detail by means of ten typical isothermal sections and by three temperature-composition sections. The implications of metastable fractionation in this temperature interval are discussed as a possible feed control step in reductive extraction reprocessing of molten salt breeder reactor fuels.

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INTRODUCTION

The ORNL Molten Salt Reactor Program is devoted to the development of molten salt breeder reactors which employ mixtures of molten fluorides as core fluids. Until recently, the most promising approach to the development of molten salt breeder reactors appeared to be a two-region reactor with fissile and fertile materials in separate fuel and blanket streams. Thorium would be carried in the blanket salt, in a salt stream which would consist of a ^{7}LiF-BeF_2-ThF_4 mixture. Advances in chemical reprocessing have provided evidence recently that ^{233}Pa and possibly the rare earth fission products can be separated from mixed thorium-uranium salt by reductive extraction methods employing liquid bismuth. This development, along with other design developments, makes possible a single-fluid breeder reactor, one which has greater simplicity and reliability than the two-fluid reactor. The fuel for the single fluid reactor would be composed of ^{7}LiF, BeF_2, ThF_4, and $^{233}UF_4$, and might be expected to contain ~ 12 mole % ThF_4. Optimization of the ^{7}LiF and BeF_2 concentrations is not complete, because the trade-off values of several significant factors have not yet been established. These include selection limitations imposed by the equilibrium phase behavior of the LiF-BeF_2-ThF_4 system ($^{233}UF_4$ concentration will be only 0.2 mole %, and is therefore of little consequence in this connection), physical properties such as viscosity, vapor pressure, thermal conductivity, and the relations of LiF-BeF_2-ThF_4 composition to the development of chemical processes for removal of protactinium and the lanthanides.

Effective separation of the rare earth fission products from fluoride salt streams which contain thorium fluoride is the keystone to development of semi-continuous reprocessing in single-fluid molten salt reactors. Several methods for reprocessing spent LiF-BeF_2-ThF_4-UF_4 fuels are currently under investigation. The method which is regarded as most tractable for engineering development involves the selective chemical reduction of the various components into liquid bismuth solutions at about 600°C, utilizing multistage countercurrent extraction operations. The current status of engineering development of this process has been described by Whatley et al.[2] The initial steps remove uranium and protactinium by reductive extraction.[3] A strong incentive then exists to remove the rare-earth fission products from the remaining salt. The most nearly feasible approach to this separation seems to be their extraction

into bismuth alloy,[3] even though the recycle volumes of extractant are marginally acceptable. The efficiency of this separation step would be greatly enhanced if the concentration of the rare earths in the salt mixture were increased by at least tenfold, and if the residual salt solutions were of a much lower concentration of thorium fluoride. That the $LiF-BeF_2-ThF_4$ phase diagram[4] shows the occurrence of low melting mixtures of low thorium fluoride content which are producible from MSBR single-core fluids by metastable crystallization has suggested the possibility that non-equilibrium fractionation reactions might be exploited as a feed control step in the reductive extraction process.

Because of its relative complexity, the unpublished version of the $LiF-BeF_2-ThF_4$ phase diagram may experience less frequent or less effective application in molten salt reactor technology than is warranted by the developments cited above. We therefore describe in this report further detailed aspects of equilibrium and non-equilibrium behavior in the system.

LIQUID-SOLID PHASE REACTIONS IN THE SYSTEM $LiF-BeF_2-ThF_4$

Methods for interpreting polythermal and isothermal phase diagrams are described extensively in an earlier report[5] where the phase relationships in a number of fluoride systems were analyzed in detail. Interpretation of the equilibrium behavior in the system $LiF-BeF_2-ThF_4$[4] (Figure 1) is somewhat more complex than for the systems analyzed because of the occurrence of an unusual solid solution which is produced as the compound $3LiF \cdot ThF_4$ crystallizes from $LiF-BeF_2-ThF_4$ melts. The crystal phase of nominal composition, $3LiF \cdot ThF_4$, precipitates as a ternary solid solution which, at its maximum in composition variability (near the solidus), is described by a composition triangle with apices at $LiF-ThF_4$ (75-25 mole %), $LiF-BeF_2-ThF_4$ (58-16-26 mole %), and $LiF-BeF_2-ThF_4$ (59-20-21 mole %). Two substitution models may provide an explanation for the single phase solid solution area: (1) a substitution of one Be^{2+} ion for a Li^+ ion with the simultaneous formation of a Th^{4+} vacancy for every four Be^{2+} ions substituted for Li^+ ions to provide electroneutrality and (2) substitution of a single Be^{2+} ion for a Li^+ ion with the simultaneous formation of a Li^+ vacancy. Model (1) would afford a solid solution

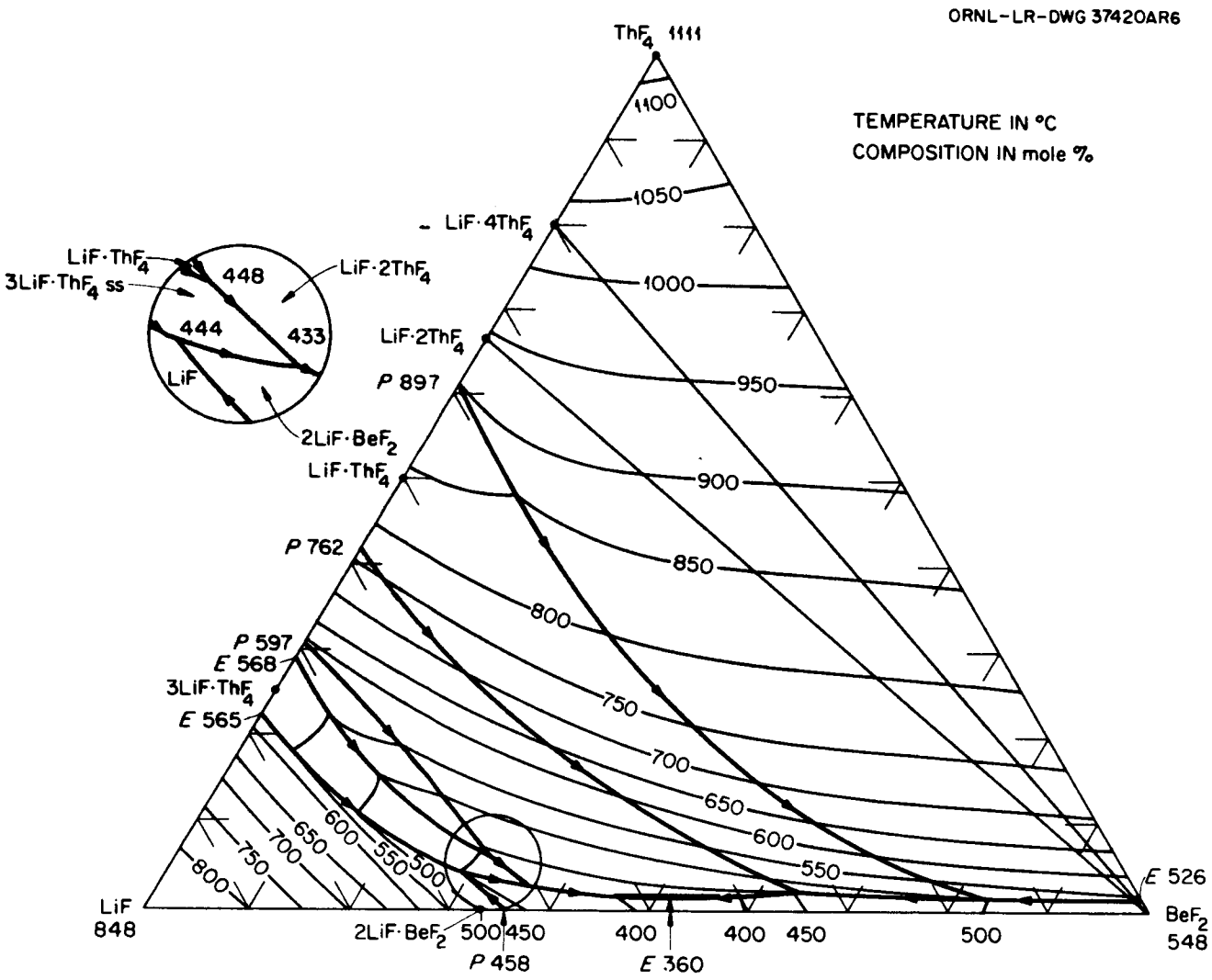

Fig. 1. Polythermal Projection of the LiF-BeF_2-ThF_4 Equilibrium Phase Diagram.

limit in good agreement with the leg of the triangular area with the lesser ThF_4 content whereas model (2) would give a line extending from $3LiF \cdot ThF_4$ toward BeF_2-ThF_4 (60-40 mole %). This is a limiting line which permits considerably higher ThF_4 content than that found experimentally. Accordingly, it appears that both models are simultaneously applicable for the crystallization behavior of $3LiF \cdot ThF_4$ as it crystallizes from LiF-BeF_2-ThF_4 melts. Once the crystal structure of $3LiF \cdot ThF_4$ has been established (a study of the structure is currently in progress[6]) it will be possible to appraise the validity of these models.

Application of ternary phase diagrams to technology often requires a knowledge of the identities and compositions of the various phases in equilibrium at specific temperatures. Such information is represented by equilibrium phase diagrams. Typically, phase diagrams of ternary systems are presented as projections of temperature-composition prisms on their basal planes. When such schematic representation includes liquidus temperatures, equilibrium crystallization and melting reactions can be described in a quantitative manner. Here, the use of isothermal sections is often valuable, particularly if the phase diagram is complex. The chief feature of the isothermal section is that it provides information both about the identity and relative masses of coexisting phases.

The crystallization behavior of the $3LiF \cdot ThF_4$ ternary solid solution determines the composition sequence as LiF-BeF_2-ThF_4 melts are cooled. A series of equilibrium isotherms is shown in Figs. 2 to 11, which describe all the equilibrium reactions in the temperature interval from 590°C to 350°C, i.e., the liquidus-solidus interval of chief relevance to the compositions which are likely to have application in molten salt reactor technology, and in which all $3LiF \cdot ThF_4$ solid solution melting-freezing reactions occur. Within this interval all the solid phases of the system are involved. The equilibrium behavior of chief importance to us is described further by the temperature-composition sections, $3LiF \cdot ThF_4$-$2LiF \cdot BeF_2$, $LiF \cdot ThF_4$-$2LiF \cdot BeF_2$, and $LiF \cdot 2ThF_4$-$2LiF \cdot BeF_2$, shown in Figs. 12-14 (schematic, not to scale).

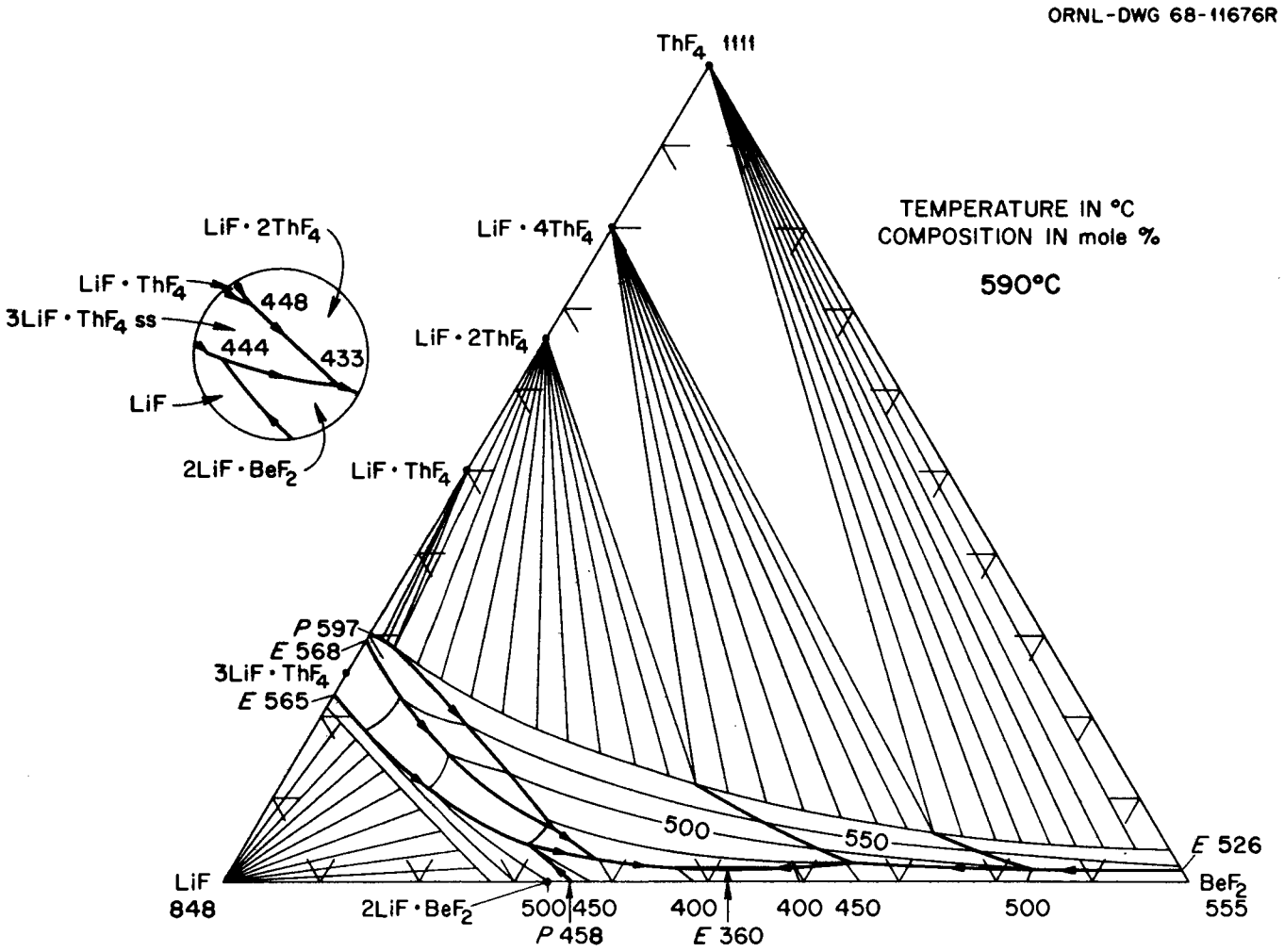

Fig. 2. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $590^{0}C$.

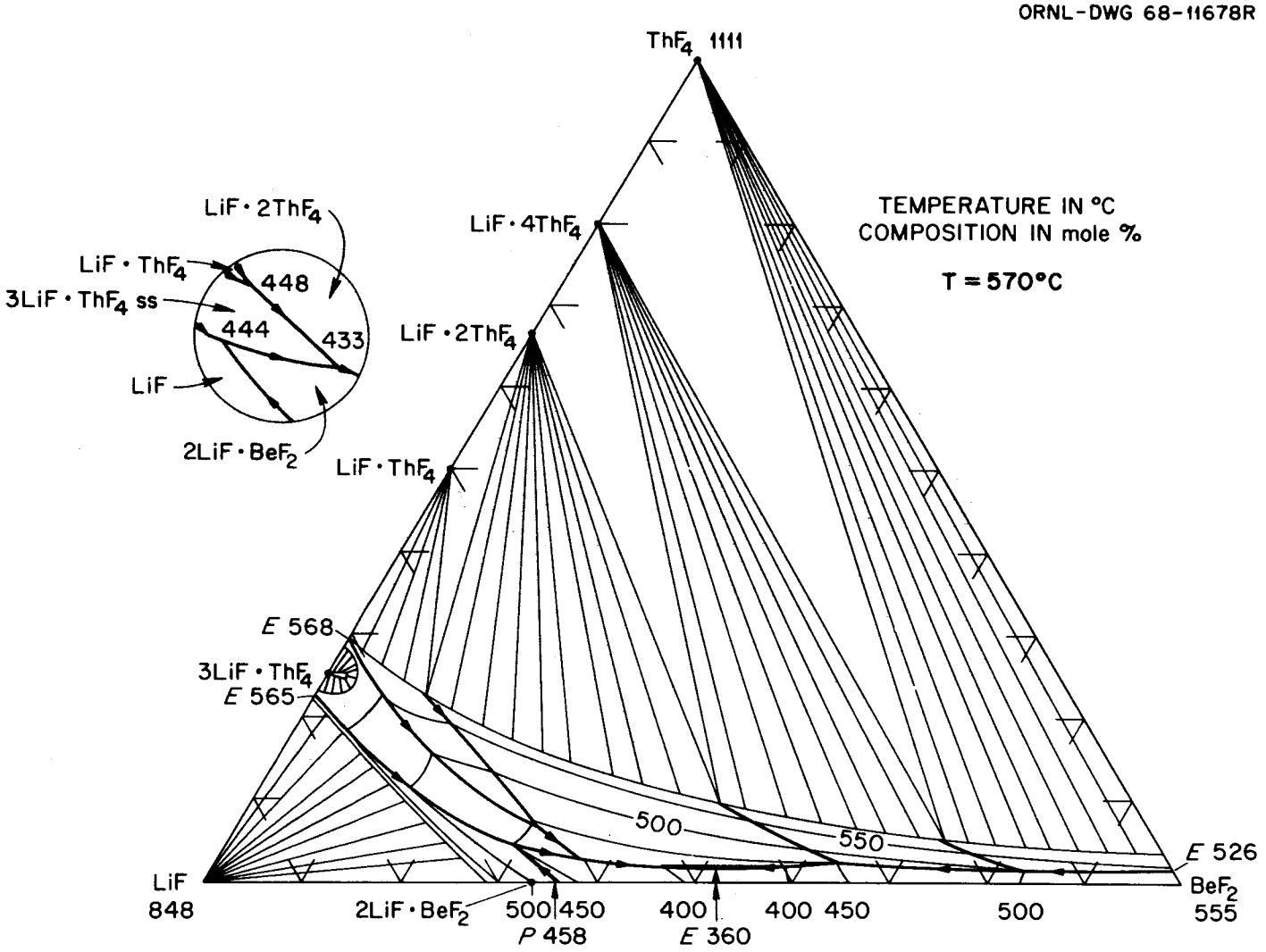

Fig. 3. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $570^{\circ}C$.

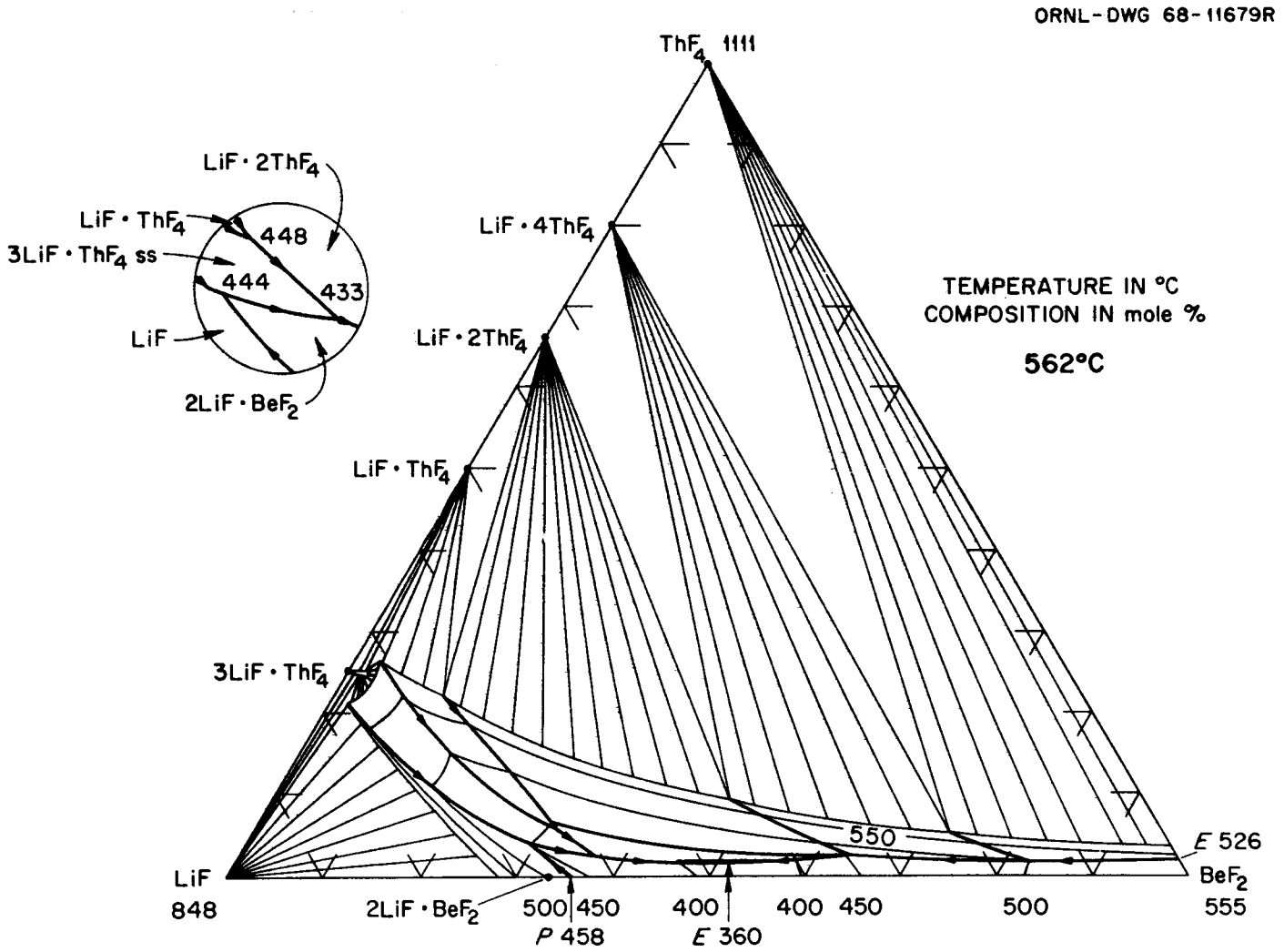

Fig. 4. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $562^{\circ}C$.

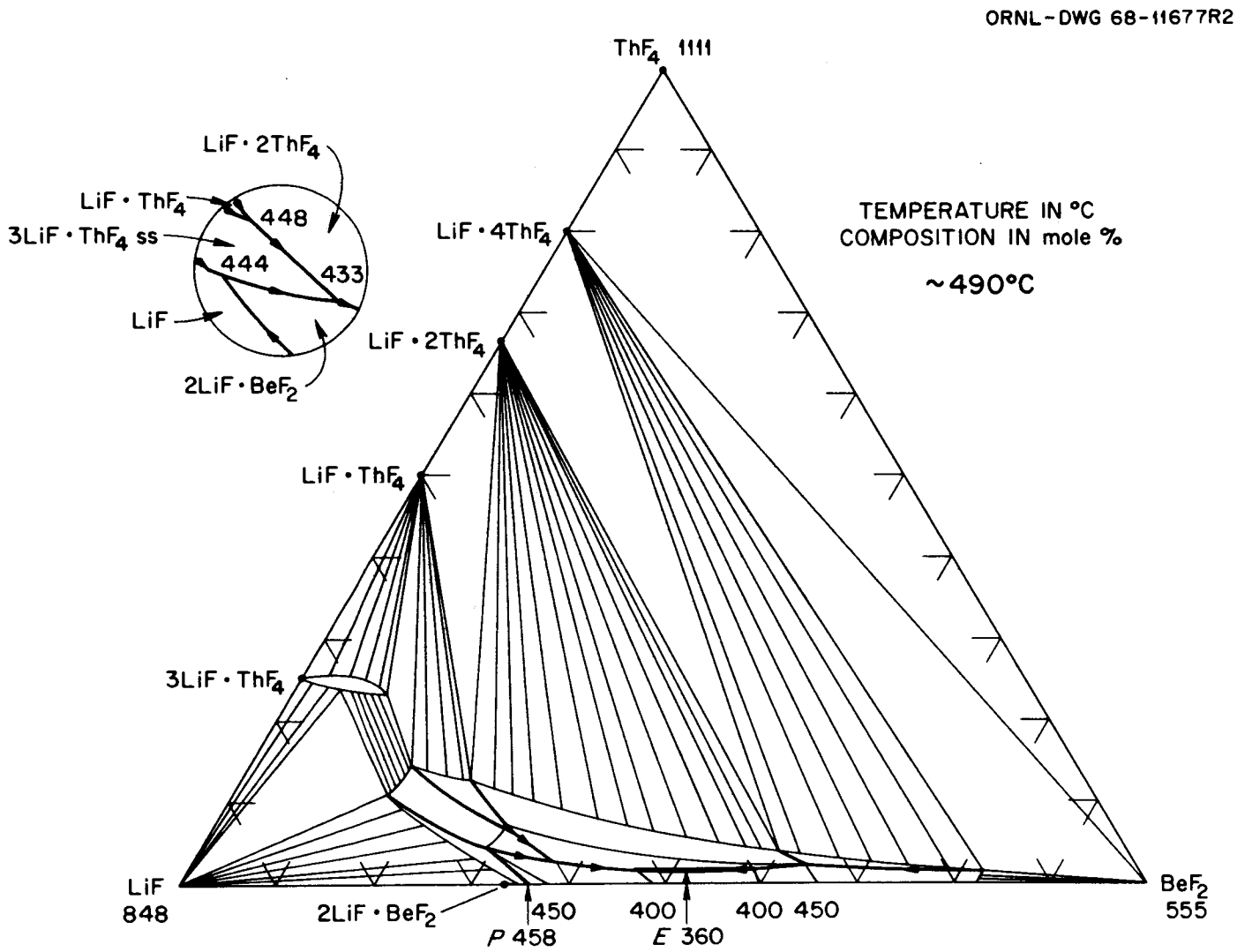

Fig. 5. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at 490^0C.

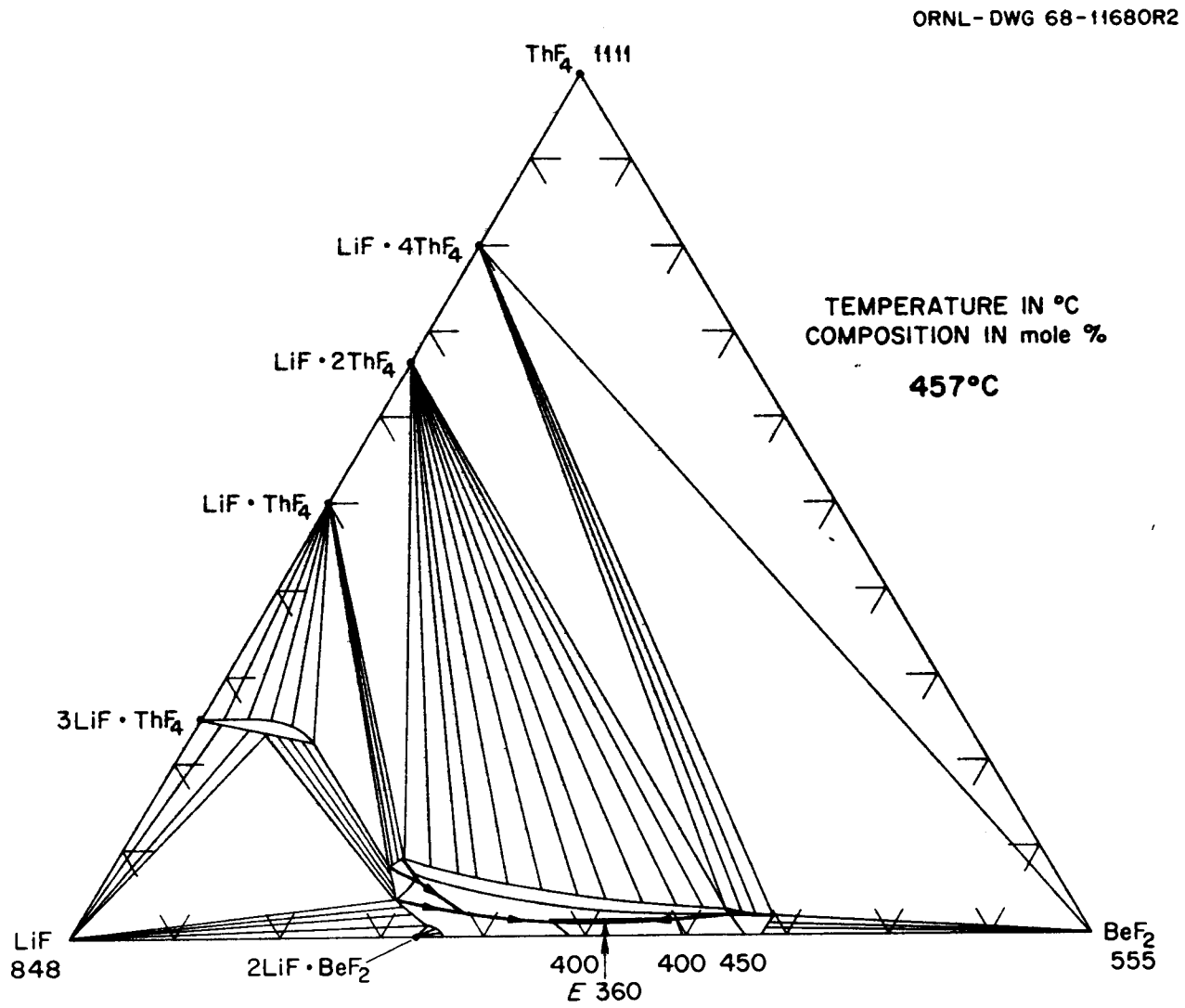

Fig. 6. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $457^{0}C$.

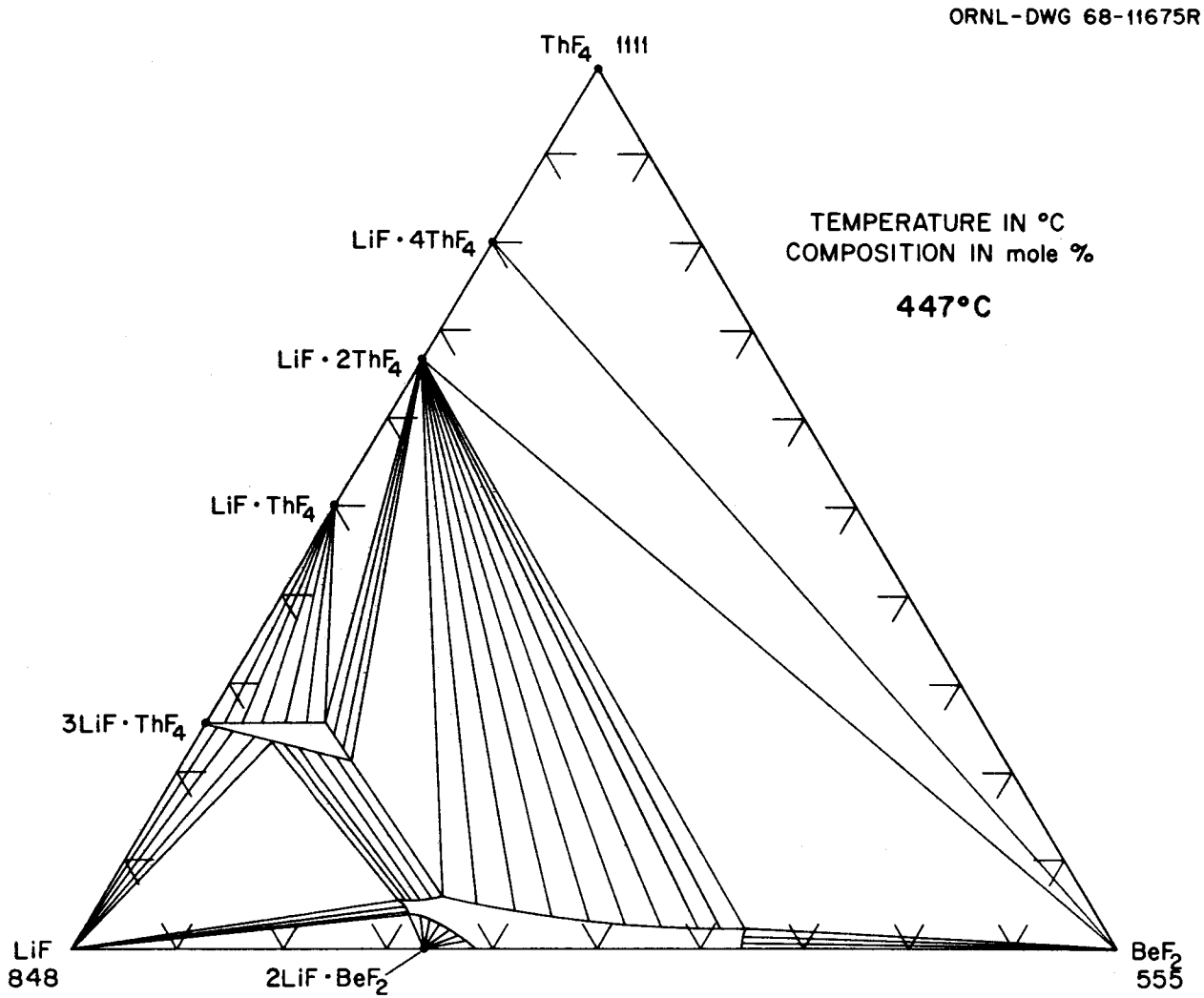

Fig. 7. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $447^{0}C$.

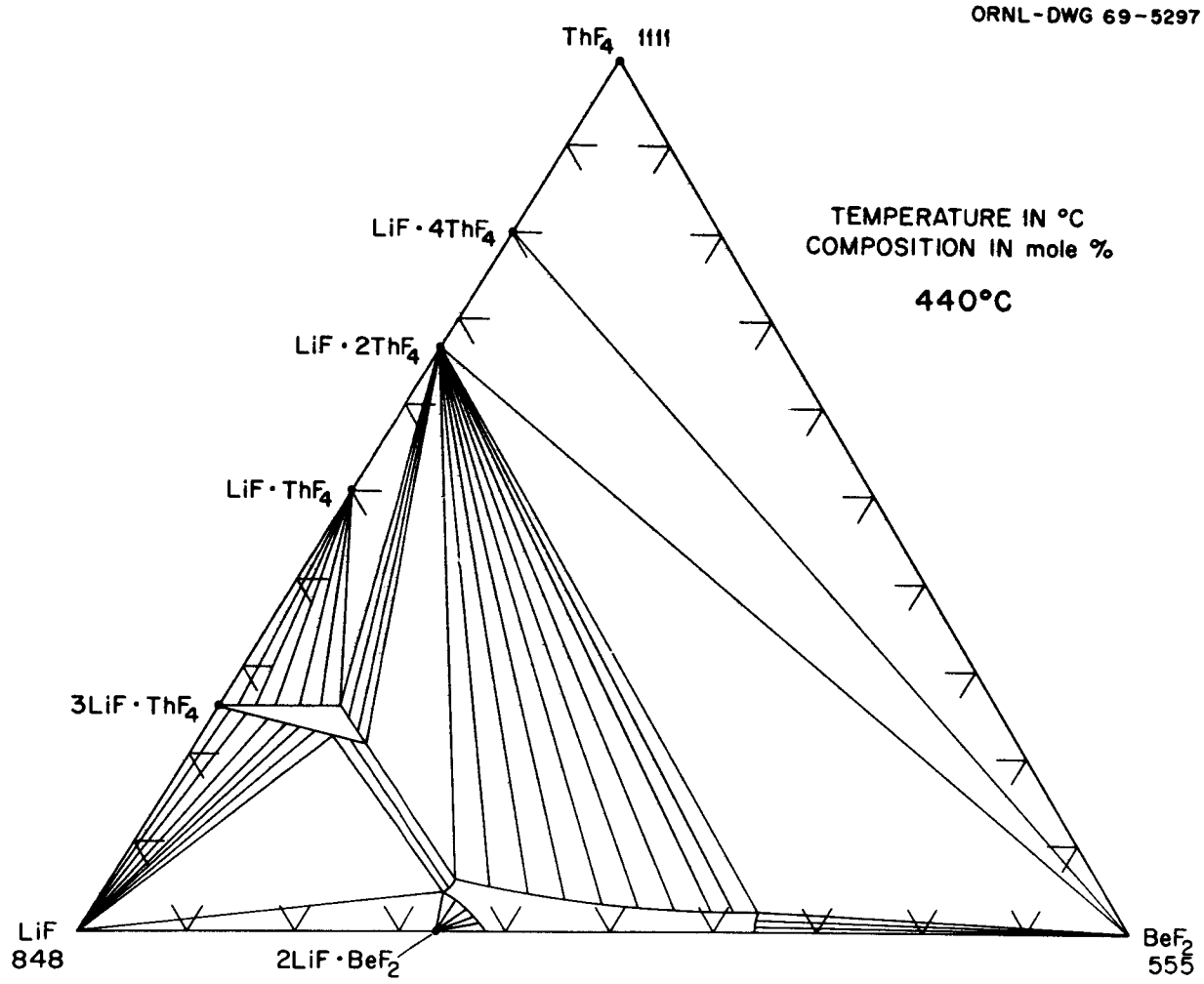

Fig. 8. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $440^{\circ}C$.

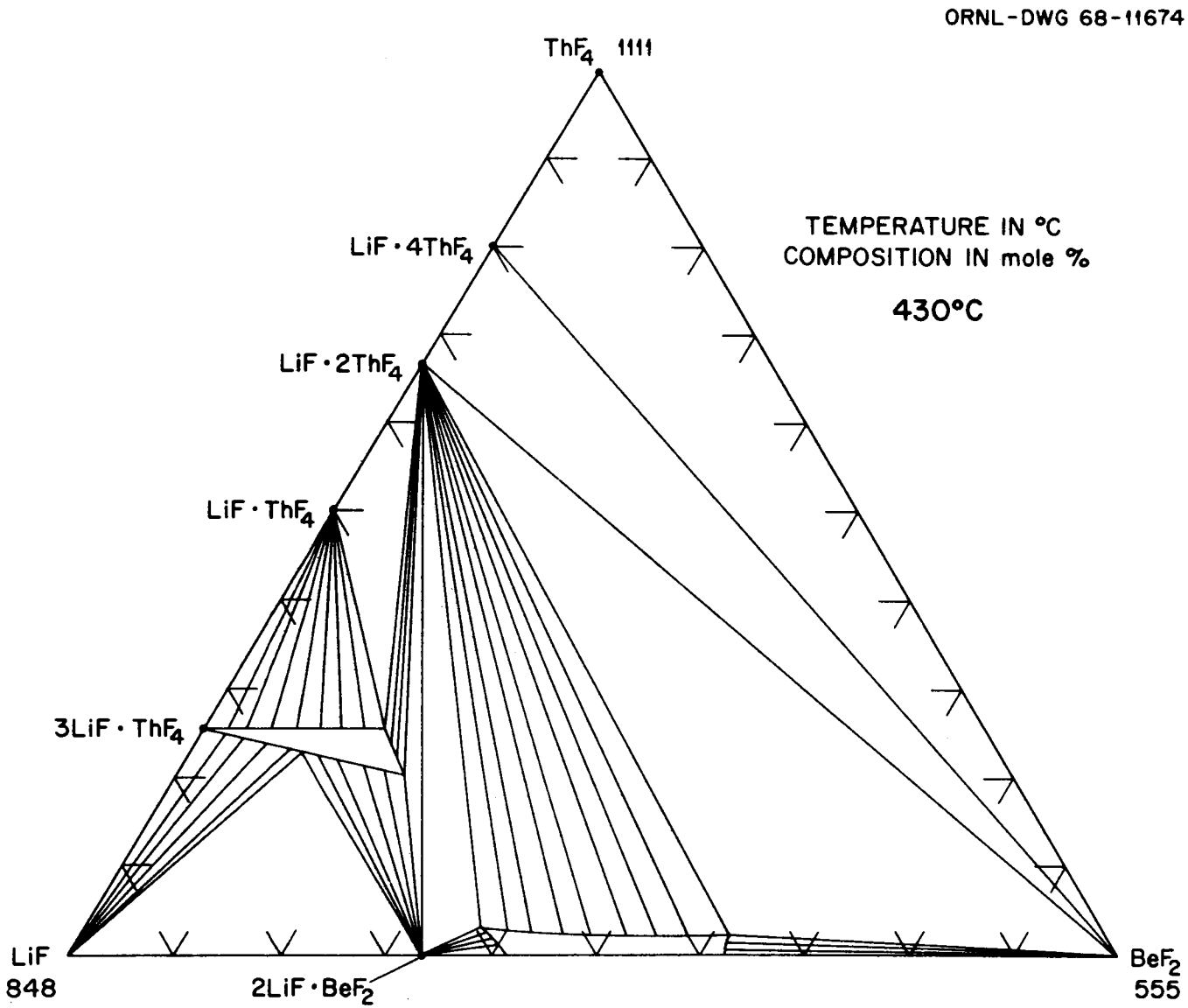

Fig. 9. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $430^{\circ}C$.

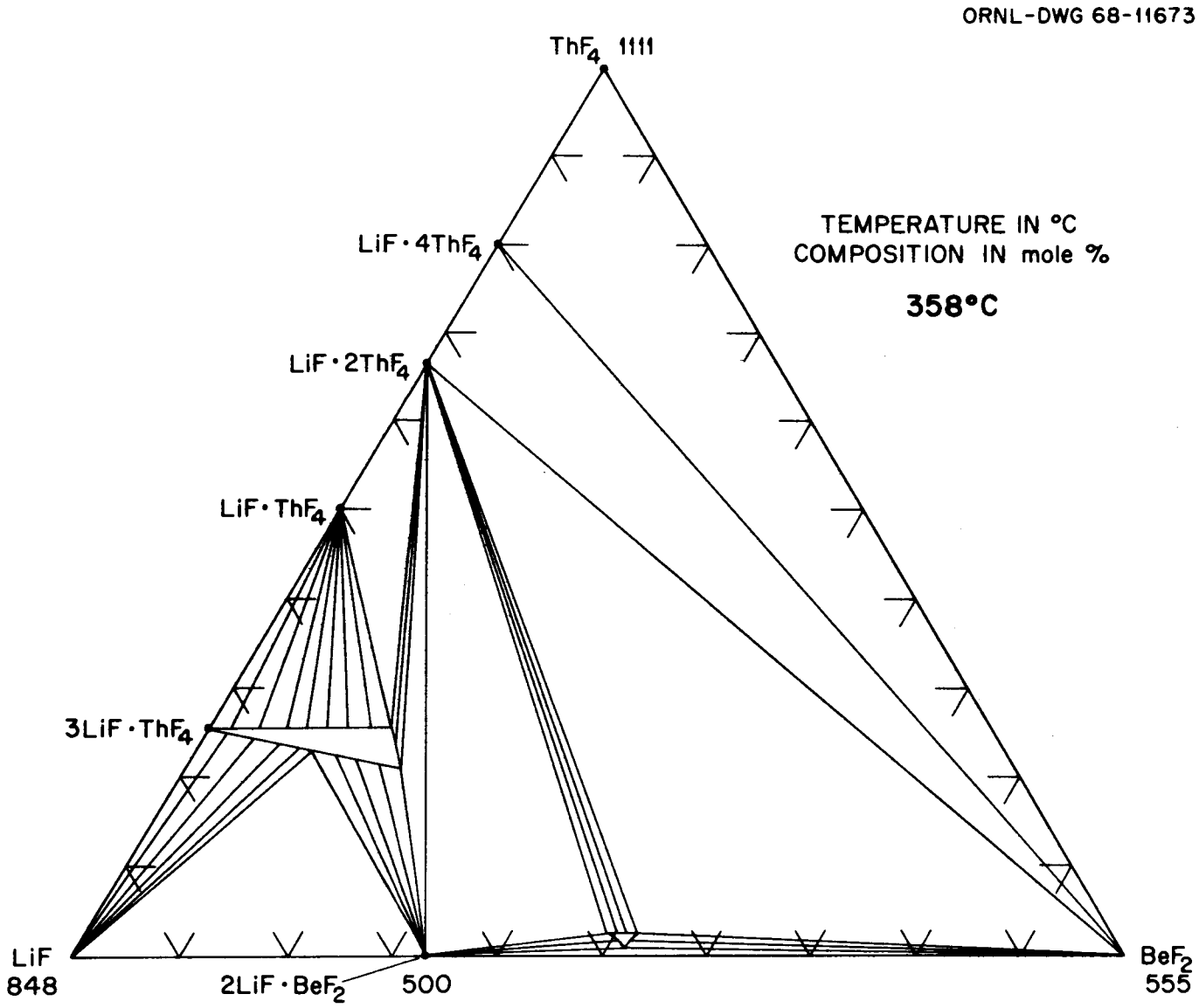

Fig. 10. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at $430^{0}C$.

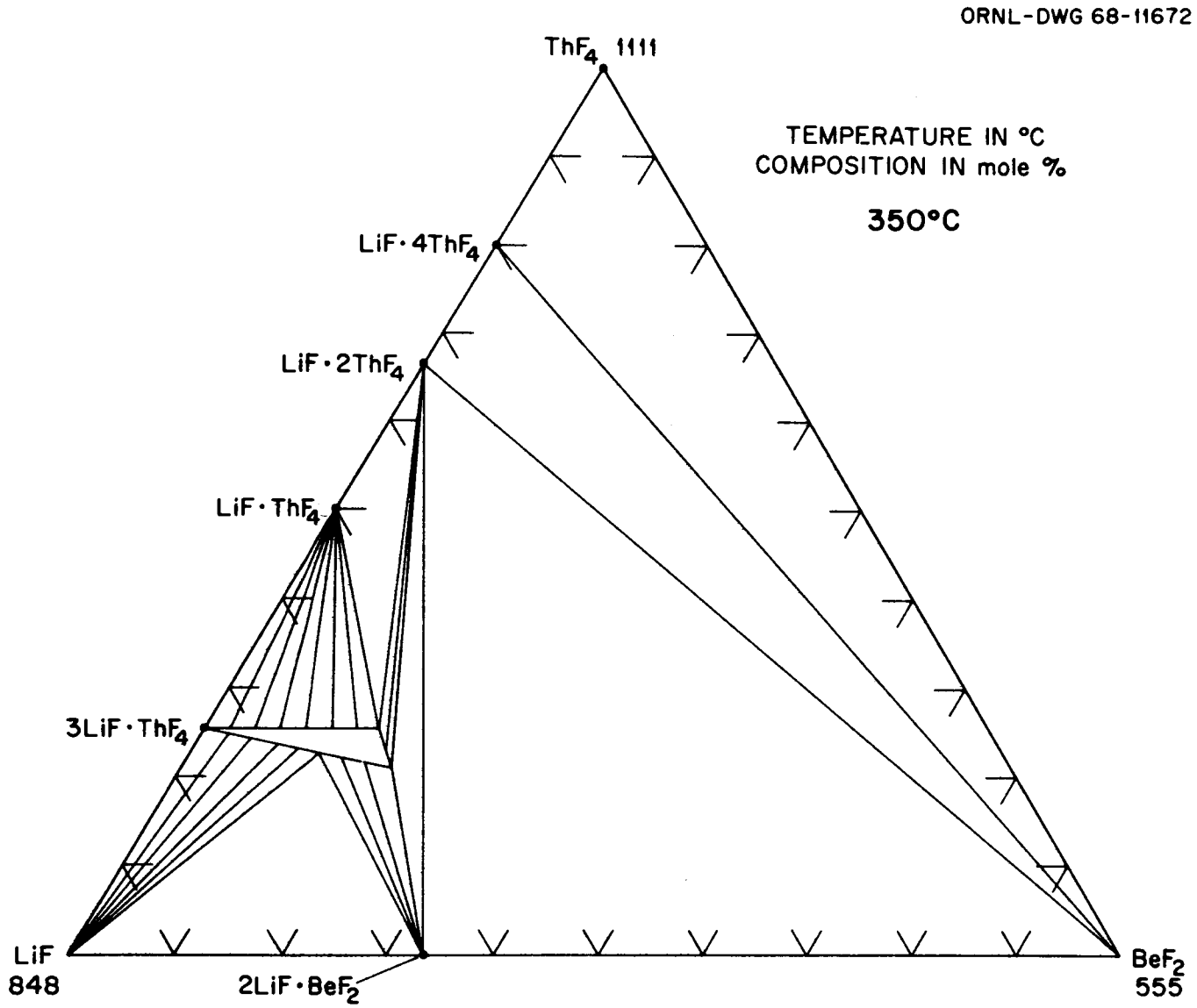

Fig. 11. Isothermal Section of the System $LiF-BeF_2-ThF_4$ at 350^0C.

The isothermal sections included in Figs. 2 to 11 are drawn to scale and represent the experimental results which were the basis of the previously published phase diagram.[4] Composition-temperature relations in the $LiF-BeF_2-ThF_4$ system for LiF concentrations greater than 50 mole % are shown in detail in Fig. 15.

The straight lines appearing in Figs. 2 to 11 are tie-lines (or "conodes") connecting two phases which are in equilibrium. In Fig. 16, point P, as a point on such a tie-line joining points b and z, represents a mixture of the phases (or compositions) b and z with the mole fraction of b equal to the ratio of line lengths zP/zb.

In the case of a mixture of three phases, such as the points a, b, c making up the total composition at point P (Fig. 16), the relative amounts of the phases a, b, c making up P may be determined as follows, with the three fractions defined as x of a, y of b, 1-x-y of c. Then:

(1) Graphically: extend the line bP to fix the point z on the line ac. Then y = zP/zb, and x = (zc/ac) (1-y).

(2) Analytically: let the fractions of the components A and B at each of the four points (a, b, c, P) be

$$A_a \; A_b \; A_c \; A_p,$$

$$B_a \; B_b \; B_c \; B_p.$$

Then by similar triangles, we have

$$\frac{B_a - B_z}{A_a - A_z} = \frac{B_a - B_c}{A_a - A_c} = \alpha$$

$$\frac{B_b - B_z}{A_b - A_z} = \frac{B_b - B_p}{A_b - A_p} = \beta$$

Then $B_z = B_b - \beta A_b + \beta A_z = B_a - \alpha A_a + \alpha A_z$

Hence $$A_z = \frac{(B_a - B_b) + \beta A_b - \alpha A_a}{\beta - \alpha}$$

$$B_z = B_b - \beta A_b + \beta (A_z).$$

Then $$y = \frac{B_p - B_z}{B_b - B_z}$$

and $$x = \frac{A_z - A_c}{A_a - A_c} \; (1 - y).$$

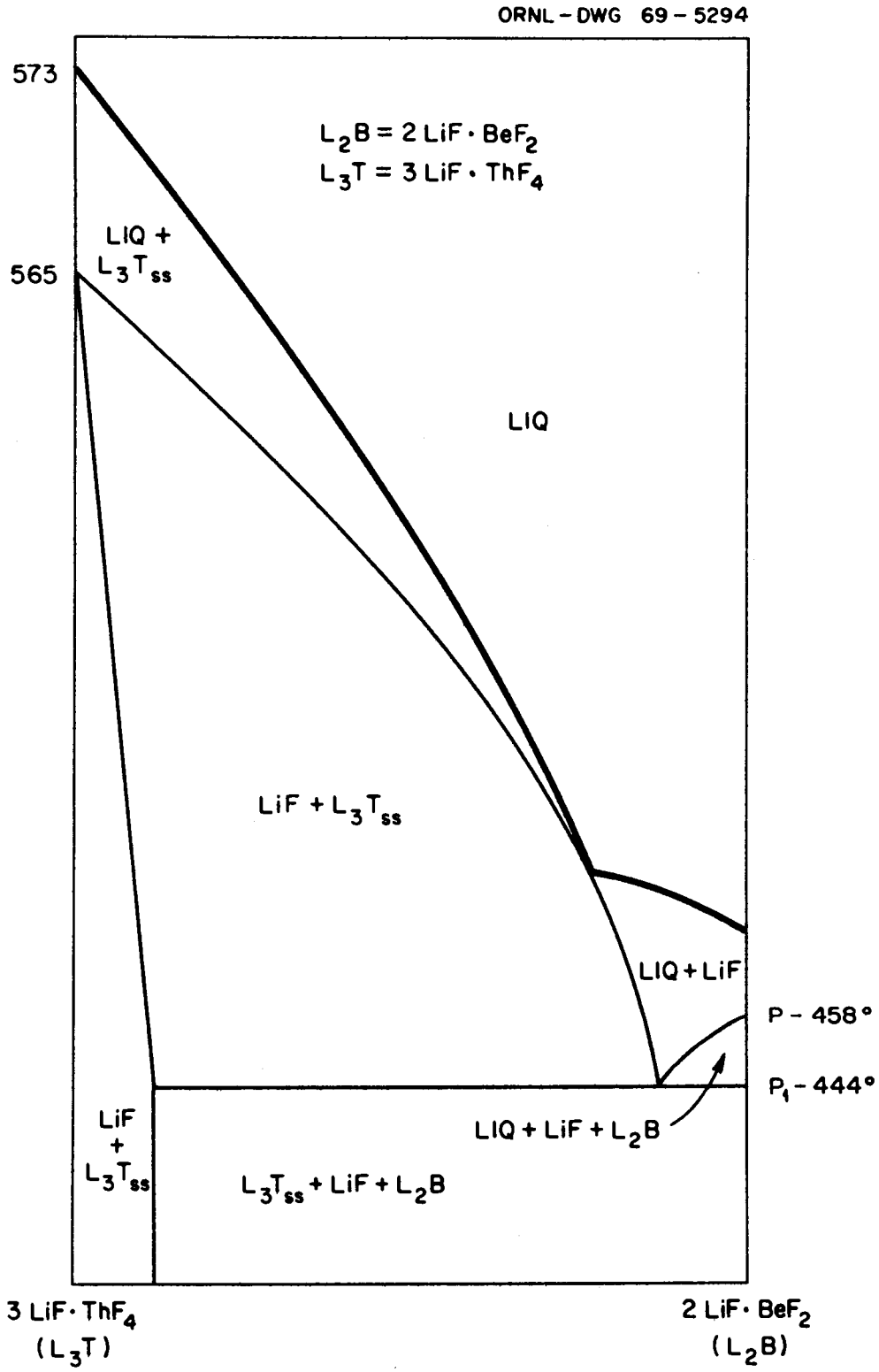

Fig. 12. The Section $3LiF \cdot ThF_4$-$2LiF \cdot BeF_2$

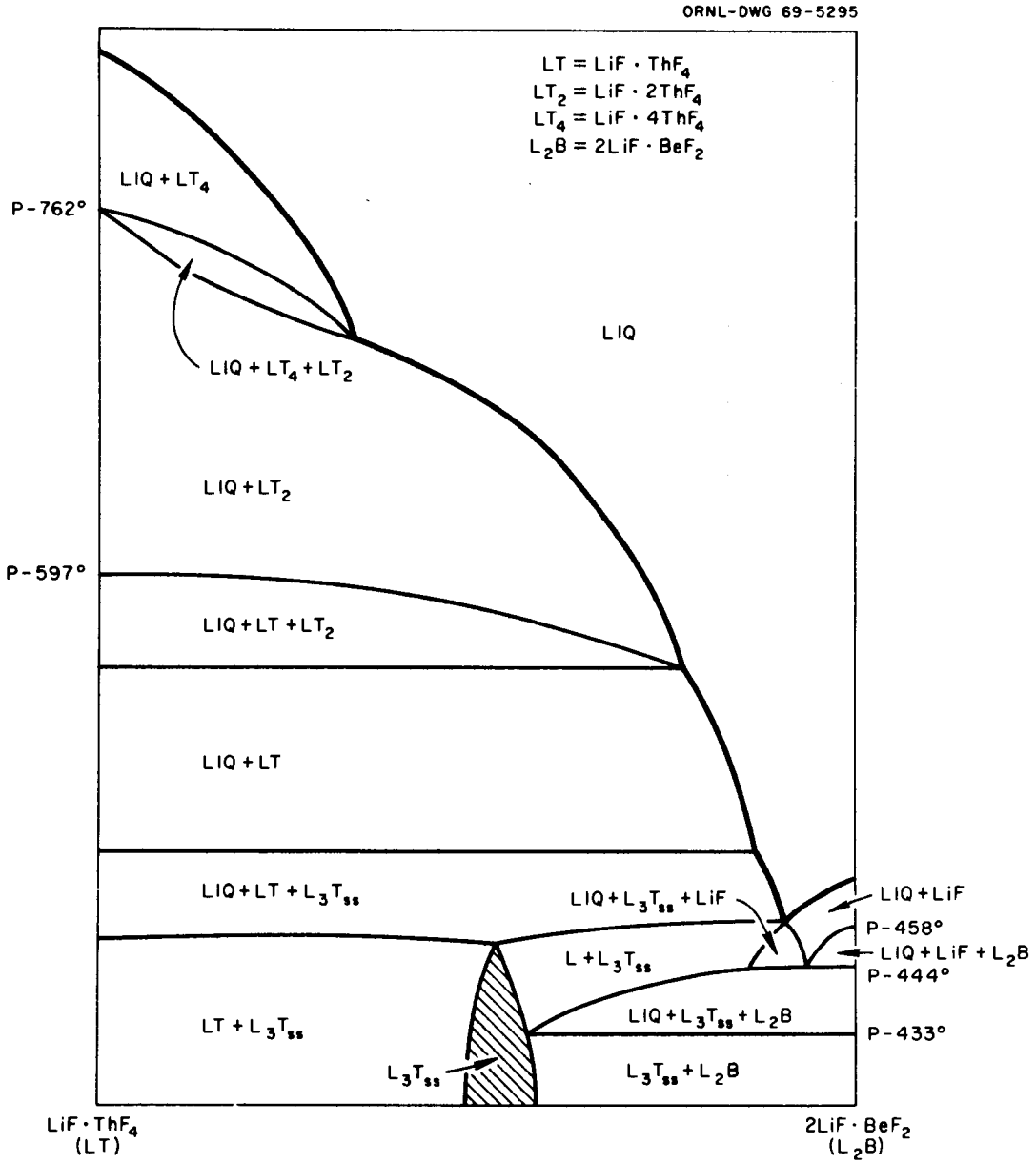

Fig. 13. The Section $LiF \cdot ThF_4$-$2LiF \cdot BeF_2$

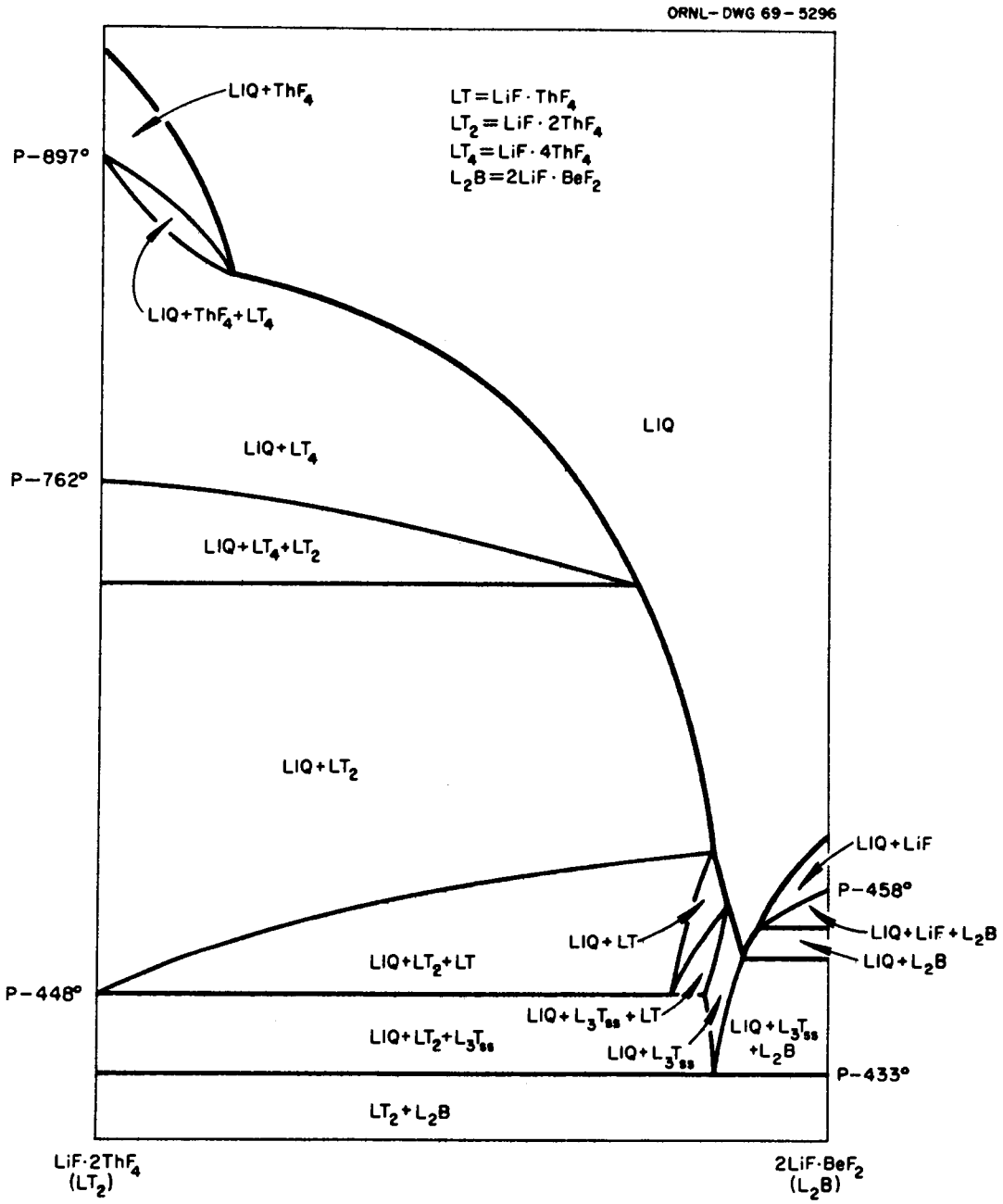

Fig. 14. The Section $LiF \cdot 2ThF_4$-$2LiF \cdot BeF_2$

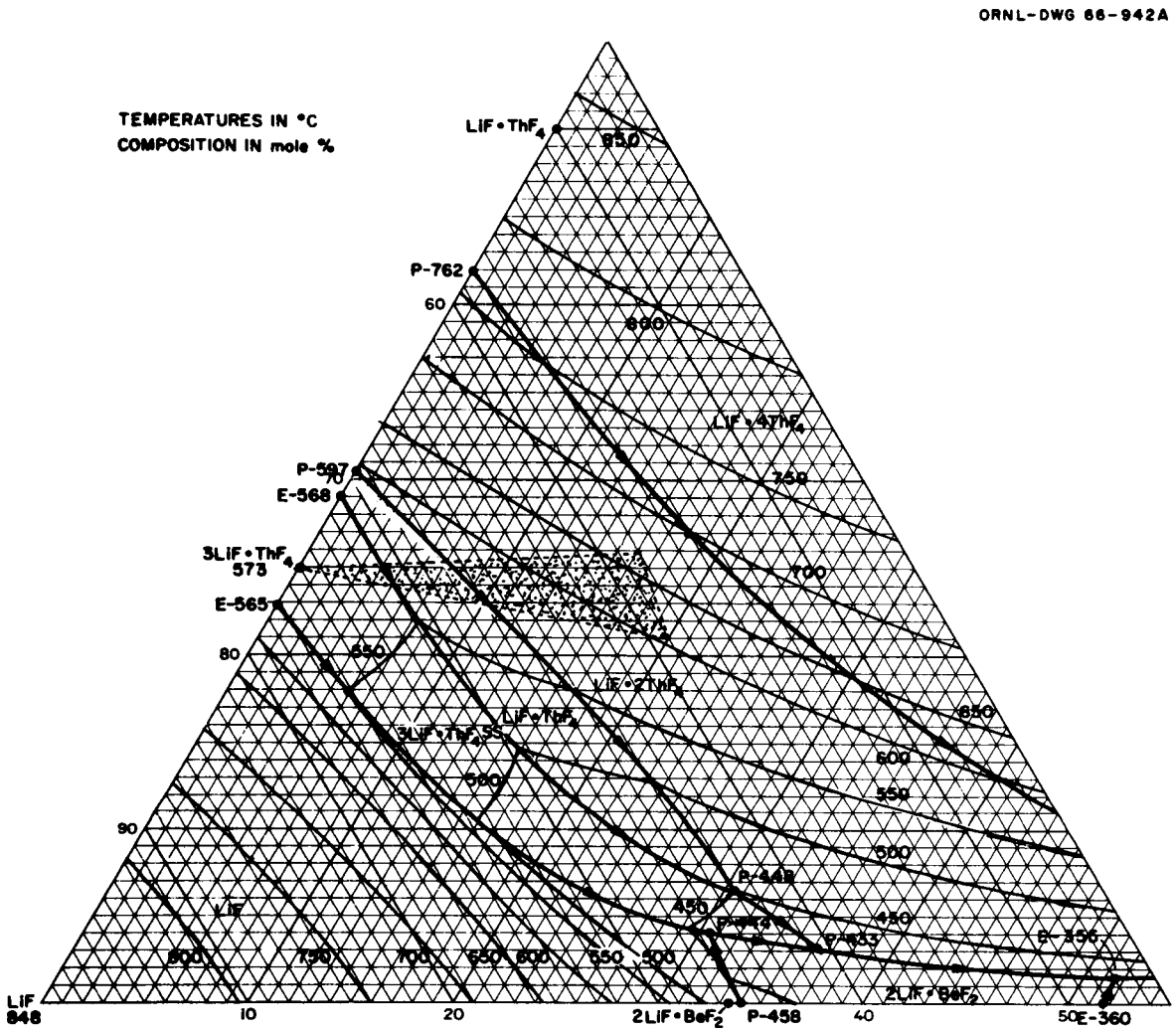

Fig. 15. Phase Diagram of the $LiF-BeF_2-ThF_4$ System for Compositions 50 - 100 mole % LiF.

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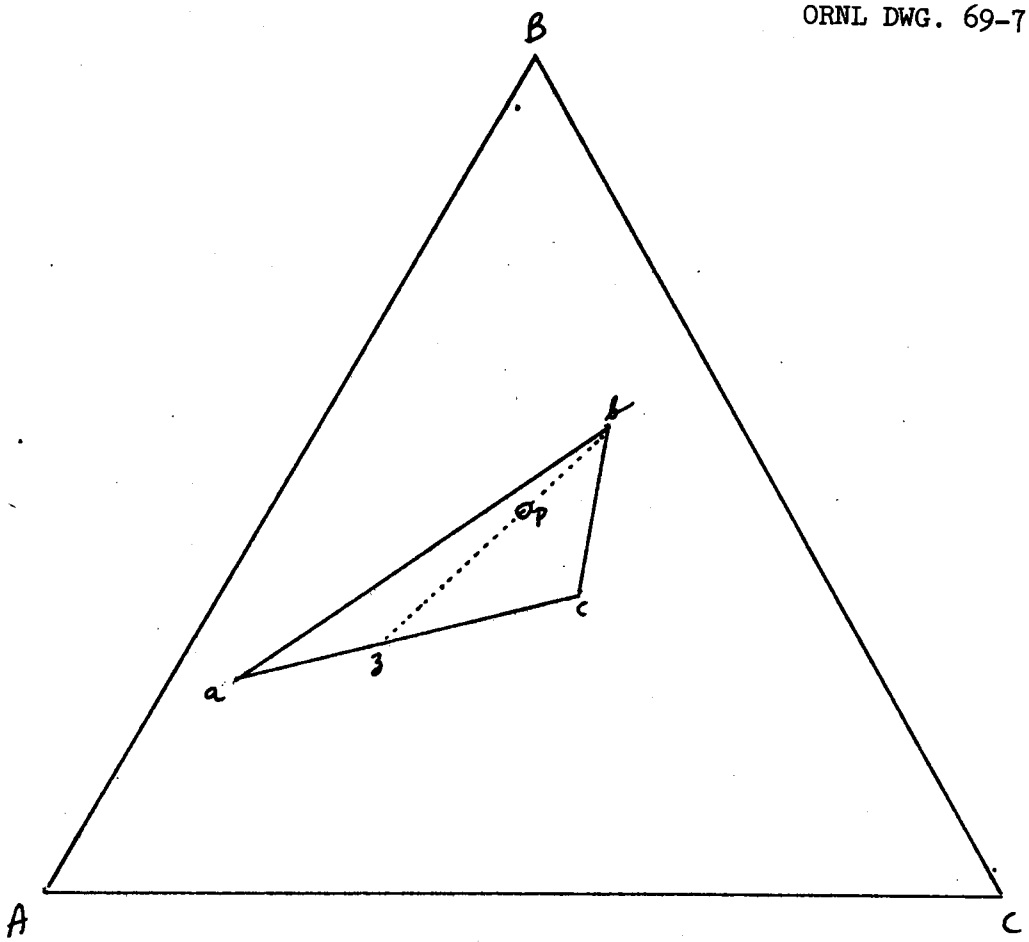


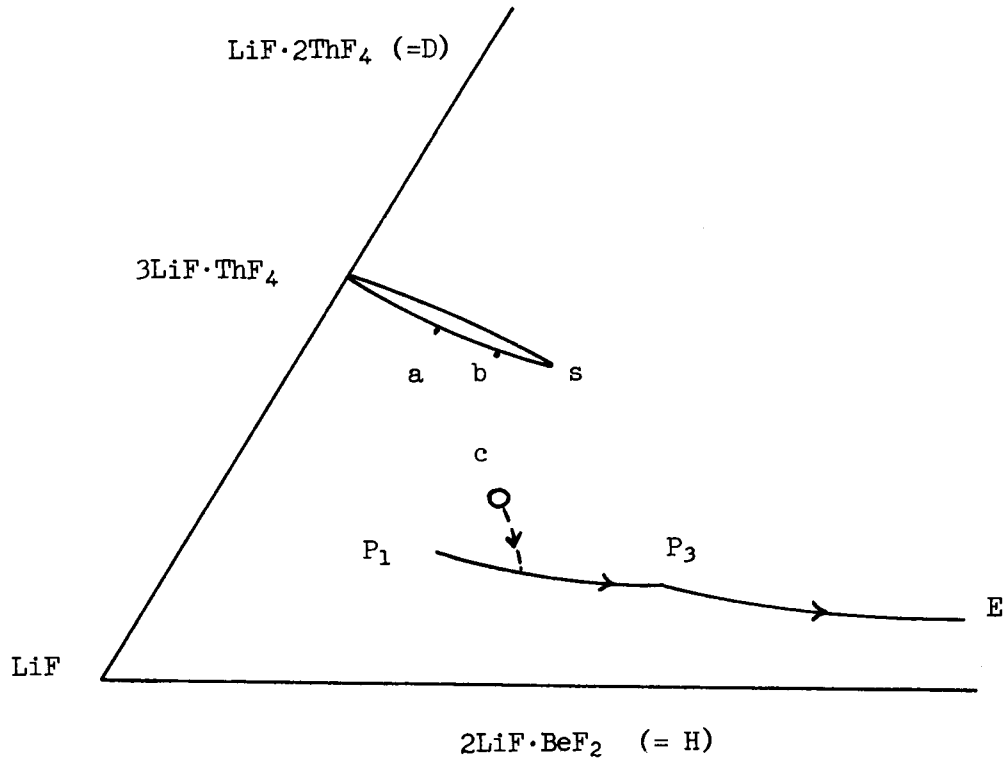
Fig. 16. Schematic Drawing for Use in Calculating Relative Fractions of Coexisting Phases at Point P.

POTENTIAL APPLICATION OF FRACTIONAL CRYSTALLIZATION IN CHEMICAL REPROCESSING

Under equilibrium conditions, the crystallization end-point in three component systems such as in the $LiF-BeF_2-ThF_4$ system, depends on the "compatibility" or three solid phase triangles of the equilibrium diagram. As an example, compositions in the triangle $LiF - 3LiF \cdot ThF_4 - 2LiF \cdot BeF_2$ have their crystallization end-point at the 444^0C peritectic reaction point. As noted previously,[7] dynamic crystallization of $LiF-BeF_2-ThF_4$ mixtures does not follow the equilibrium crystallization diagram exactly; instead, non-equilibrium crystallization proceeds characteristically by sub-cooling (i.e., delayed crystallization under dynamic cooling), and by incomplete recombination of liquid and solid phases at the peritectic reaction points. Thus, liquids are produced from mixtures which are of interest to us, primarily those containing high concentrations of LiF, which are richer in BeF_2 than their equilibrium counterparts, and which crystallize as described by the lower melting areas of the phase diagram. The consequence of non-equilibrium fractionation is thus to produce liquid residues which are lower in ThF_4 content than at equilibrium.

Let us examine the difference between equilibrium and non-equilibrium crystallization behavior of a liquid composition that would partially typify the reactions of MSBR salts. Suppose the composition c, $LiF-BeF_2-ThF_4$ (63-32-5 mole %), undergoes equilibrium crystallization. On complete solidification, the frozen salt will consist of the three crystalline phases, $3LiF \cdot ThF_4$ ss, $2LiF \cdot BeF_2$ and $LiF \cdot 2ThF_4$ in proportions given by the position of point c in the corresponding triangle of Figs. 9, 10, and 11.

For non-equilibrium crystallization this triangle has no significance. The non-equilibrium process consists of four consecutive steps, seen on the basis of the following diagram:



Step (1): freezing starts at ~ 446^{0}C for composition c, and the liquid travels on the solid solution liquidus surface to reach curve P_1 - P_3 at some point ℓ (at ~ 440^{0}C), while precipitating some solid solution of composition between a and b, say a' as average.

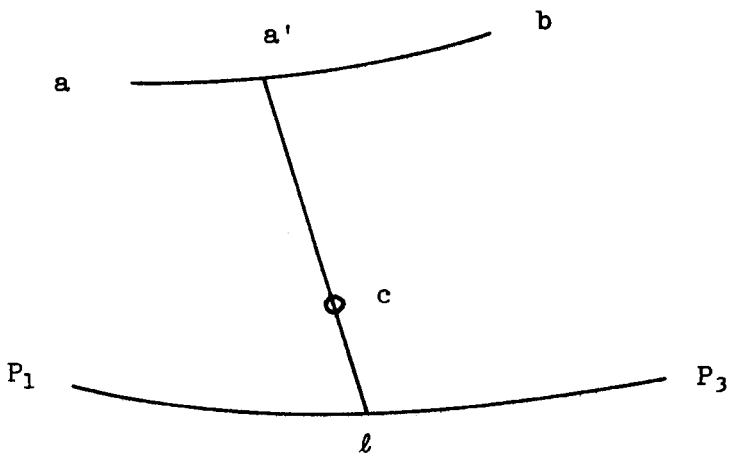
Step (2): liquid travels on curve P_1-P_3, to reach P_3 (433^{0}C), while precipitating a mixture of solid solution (of composition between b and s, say b' as average) and $2LiF \cdot BeF_2$.

Step (3): liquid travels on curve P_3-E, to reach E(356^0) while precipitating mixture of $LiF \cdot 2ThF_4$ + $2LiF \cdot BeF_2$.

Step (4): liquid at E(356^0) freezes to mixture of $LiF \cdot 2ThF_4$ + $2LiF \cdot BeF_2$ + BeF_2.

Quantities involved for 1 mole of starting composition c:

Step (1): draw straight line a'c and extend it to curve P_1-P_3, to fix point ℓ:



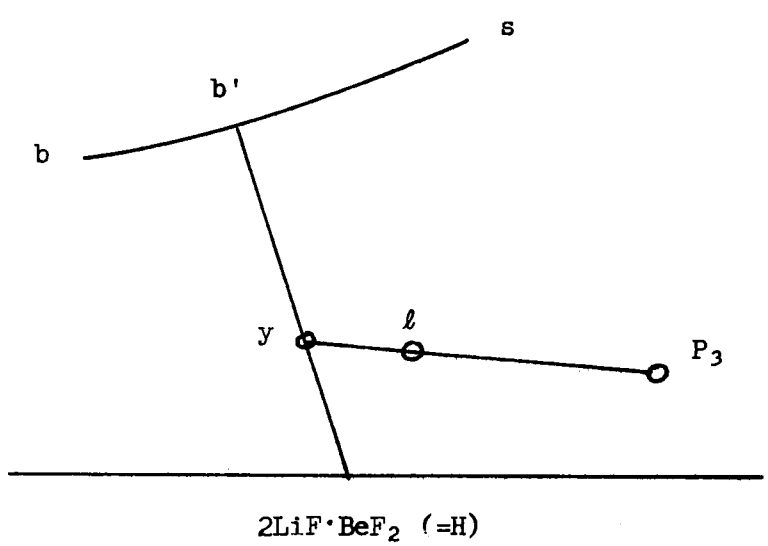
Moles of liquid reaching $\ell = \frac{a'c}{a'\ell} = m_1$;

Moles of ThF_4 precipitated (in step 1, or between 446 and 440^0)

$$= x_{a'} (1-m_1) = p_1,$$

in which $x_{a'}$ = mole fraction of ThF_4 at a', etc.

Step (2): draw straight line b'-H, and extend straight line ℓP_3 back to fix point y on line b'-H:

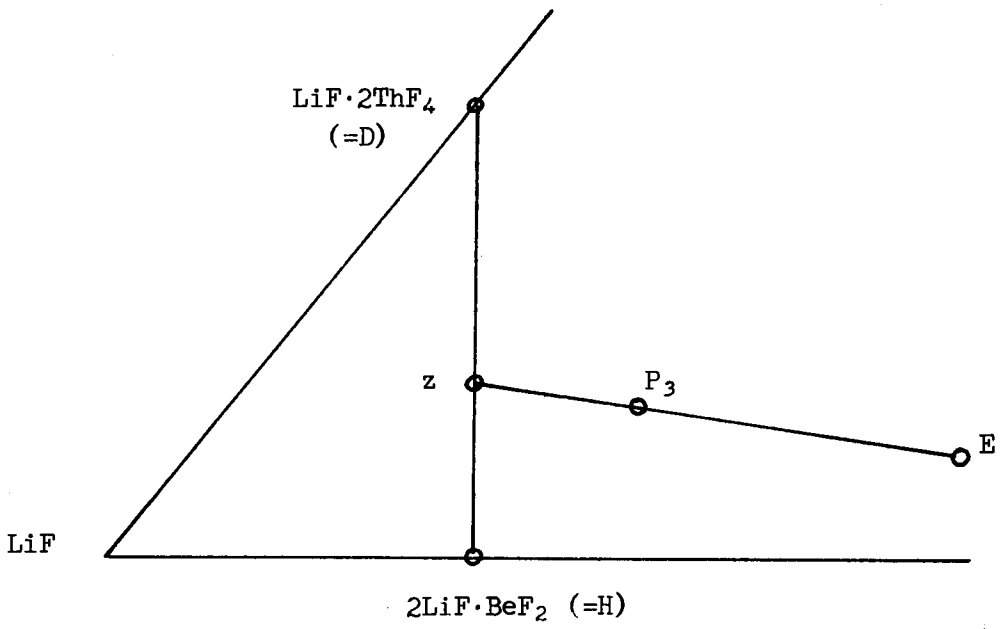


Moles of liquid reaching $P_3 = \frac{y\ell}{yP_3}(m_1) = m_2$;

Moles of ThF_4 precipitated (in step 2, or between 440^0 and 433^0)

$$= x_{b'} \frac{yH}{b'H}(m_1 - m_2) = p_2.$$

Step (3): draw straight line DH and extend straight line P_3E back to fix point z on the line DH:



Moles of liquid reaching $E = \frac{zP_3}{zE}(m_2) = m_3$;

Moles ThF_4 precipitated (in step 3, or between 433^0 and 356^0)

$$= \frac{2}{3}\left(\frac{zH}{DH}\right)(m_2 - m_3) = p_3,$$

since $x_D = 2/3$.

Step (4): moles ThF_4 precipitated in this step (at 356^0)

$$= x_c - (p_1 + p_2 + p_3).$$

Thus, given the original composition c on the phase diagram as we have it, one can make estimates regarding what happens in steps (1) and (2), and these estimates fix what happens in steps (3) and (4), for the

limit of non-equilibrium behavior. This means a process in which there is never any interaction between precipitated solid and solution. Actual behavior will of course be somewhere between this and the equilibrium process.

Since non-equilibrium fractionation of $LiF-BeF_2-ThF_4$ melts produces final liquids which are low in thorium, and since the concentrations of rare earths in the solutions are expected to be about 20 ppm at the time when fuel processing is economically mandatory, one might anticipate that a semi-zone refining step might well produce and transport liquids of low thorium concentration and containing a relatively high concentration of rare earths (the solubility of the lanthanide trifluorides in any of the melts one might encounter is almost certainly to be at least 200 ppm at the low temperatures which would be present in this part of the feeder apparatus). The efficiency of this concentration step could possibly be impaired seriously if the rare earth trifluorides either formed intermediate compounds (such compounds are formed only for the lanthanides of ≥ 63) which interacted with the crystallizing phases or otherwise formed solid solutions with any of the crystallizing phases. The structure of $2LiF \cdot BeF_2$[8] and $LiF \cdot ThF_4$[9] are known and believed to be incapable of serving as solid state hosts for the rare earth fluorides. The $3LiF \cdot ThF_4$ solid solution is an unknown factor in this consideration and could conceivably act as a solvent for lanthanide ions. This possibility as well as the possibility that $LiF \cdot 2ThF_4$ might also serve as a solid state solvent for lanthanide ions could be examined easily through a small scale laboratory program.

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