Glass Melting Models Examined Across Length Scales

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The melting of a glass-forming batch is a convolution of thermodynamics, chemical kinetics and transport phenomena.

- **Thermodynamics** determines the energy demand of the melting process & the final equilibrium state, unconstrained by time or kinetics.

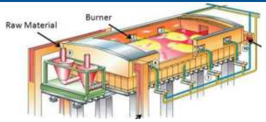
- **Chemical kinetics** is the rate at which bonds are rearranged to transform raw materials into products.
  - There are **multiple types of reaction**: (Dehydration, Crystalline Inversions, Decomposition, Melt Formation, Dissolution), over a wide temperature range (100^o - 1600^{o}C), across three-phases of matter (Solid-Gas-Liquid).

- **Transport phenomena** (Fluid-flow, Heat & Mass Transfer) is entangled with the kinetics of glass melting.

- **All length scales are important**
  - From “equipment scale” down to the “molecular scale”

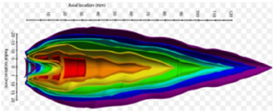
Consider these length scales of the melting process

- **Equipment or Macro Level**



  - Overall material & energy flows, Process Controls

- **Continuum Level**

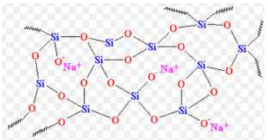


  - Fluid-Flow, Heat-transfer, Species Advection Modeling

- **Particle Level**

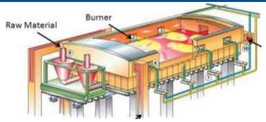
  - Granular Raw materials, Stones, Knots, Bubbles, Cord

- **Molecular Level**



  - Chemistry, Thermodynamics, Glass Structure

Where do various modeling tools fit?

- **<u>Equipment or Macro Level</u>** 

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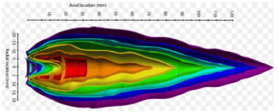
- **<u>Continuum Level</u>** 
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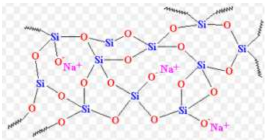
- **<u>Molecular Level</u>** 
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Process Controls

Furnace Math Models

Laboratory Models (Crucible Melts)

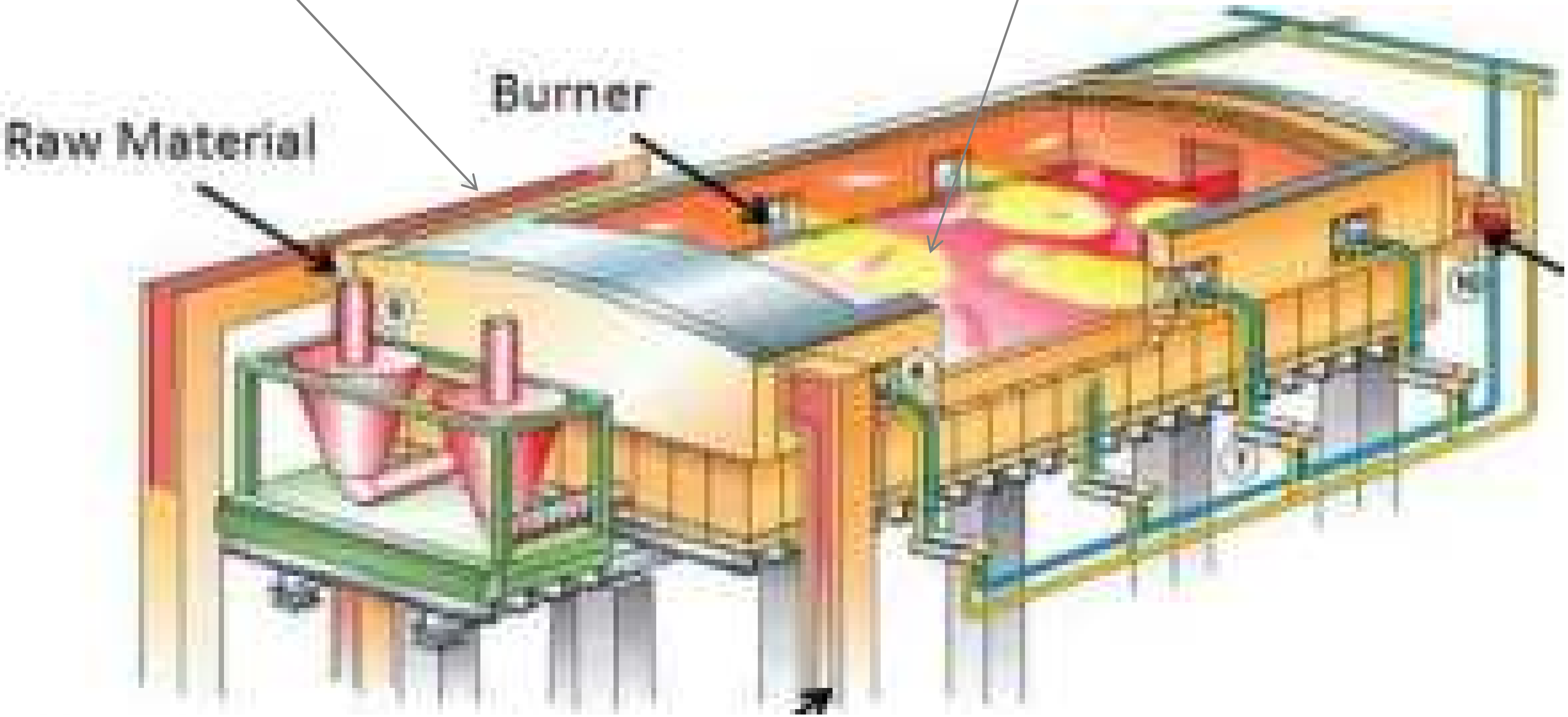
Thermodynamic & Molecular Models

Suitability of Math & Laboratory Models

$\overset{?}{=}$ Math Model (continuum-level)

$$\rho[\frac{\partial V}{\partial t} + (V.\nabla)V] = -\nabla P + \rho g + \mu \nabla^2 V$$

$\overset{?}{=}$ Crucible Melt (particle-level)



Suitability of Math & Laboratory Models

- Today's laboratory & math models can evaluate beforehand, the merits or difficulties of a proposed melting plan. However, these forecasting tools are not perfect, and subject to their limitations.

- Limitations
  - Both Laboratory & Math models are "Partial Models"
  - Laboratory experiments
    - Study of the batch-to-glass conversion (in isolation)
    - Excludes elements of the actual production furnace
    - Reduction in scale (10^{-6} – 10 kg glass) vs. a production unit (10^4-10^6 kg)
  - Furnace Math Models
    - Most suitable for furnace design changes with the same glass.
    - More precarious when changing to a new glass composition or raw material recipe, where glass quality is a concern
    - Is more or less "blind" to details of the batch-to-glass conversion

Scaling Criteria Applied to Furnace Models & Laboratory Experiments

- Geometric Similarity
  - Furnace and its prototype should have the same shape

- Kinematic / Dynamic / Thermal Similarity
  - Ra, Pe, Nu numbers should be equal between Furnace & its prototype
    - $Ra = Gr\ Pr = c_p\ \rho^2\ g\ \beta\ \Delta T\ L^3 / k\ \mu$
    - $Pe = Re\ Pr = c_p\ \rho\ v\ L / k$
    - $Nu = h\ L / k$

- Chemical Similarity
  - Melting kinetics (Requires various Damköhler numbers) :
    - Reaction-to-Diffusion: $k_{rxn}\ L^2_{particle} / \mathcal{D}_{Chem}$
    - Reaction-to-Thermal : $k_{rxn}\ L^2_{Batch\ Pile} / \alpha_{Thermal}$

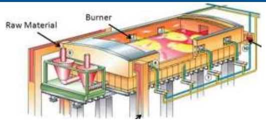
Scaling Criteria Applied to Furnace Models & Laboratory Experiments

- Furnace Math Models
  - Correctly satisfies geometric, kinematic, dynamic & thermal similarity.
  - Model of batch piles size, shape & motion, have compromises.
  - Detailed particle & chemistry level of melting is usually not considered.

- Laboratory Experiments
  - A down-scaled lab experiment using glass can not maintain Ra/Pe/Nu similarity criteria
  - Reaction/Diffusion ratios can be maintained if the experiment uses the same raw materials as production
  - Reaction/Thermal ratios can not be maintained on small-scale melting experiments (crucible melts, HTO, TGA/DSC), but the natural heating of a batch pile can be approximately satisfied on the large end of lab experiments.

Next, consider thermodynamic phase diagrams applied to melting

- **Equipment or Macro Level**



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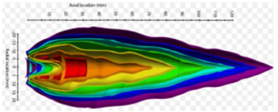

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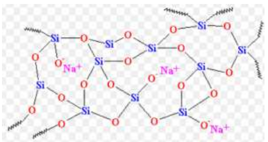
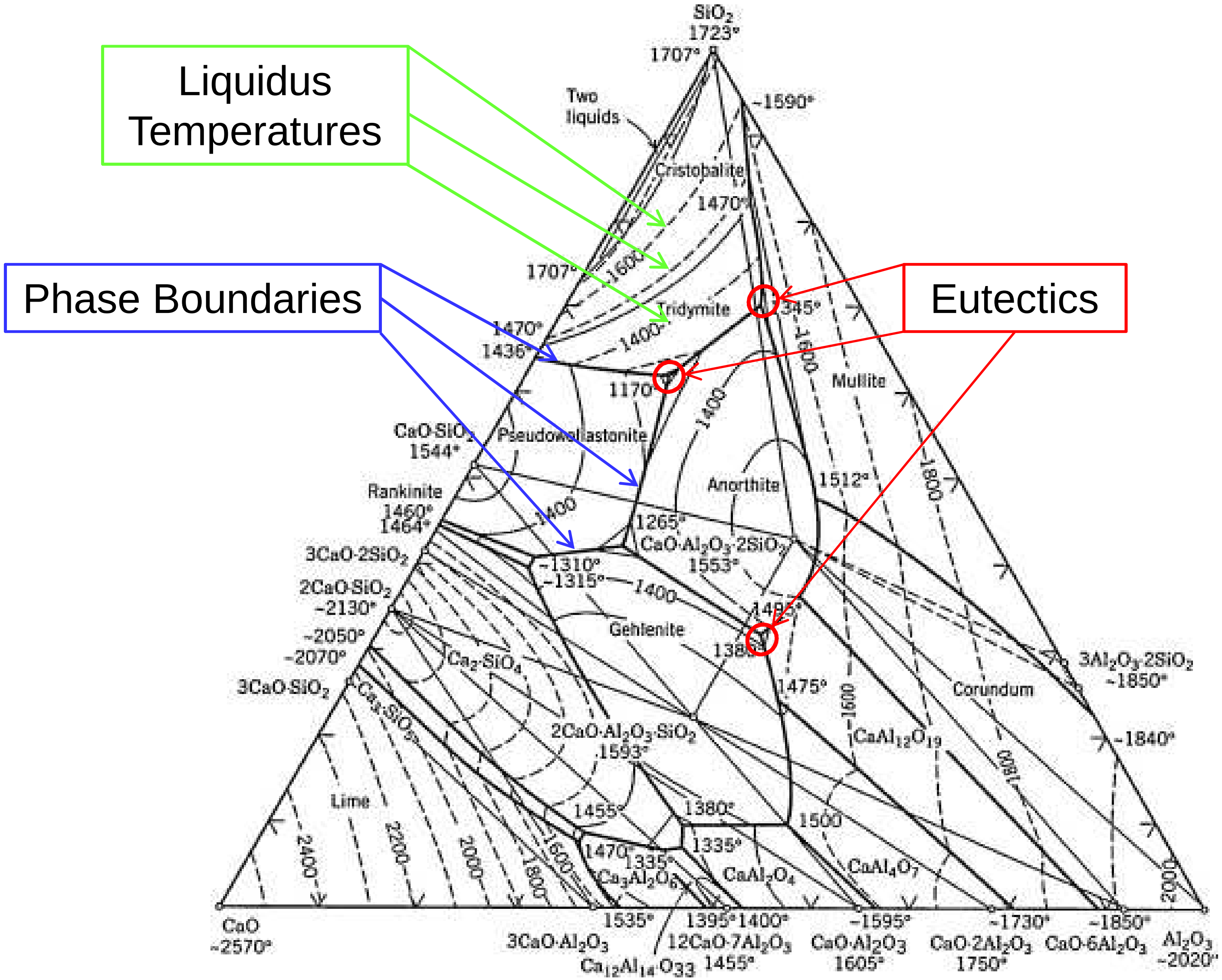


  - Chemistry, Thermodynamics, Glass Structure

Phase diagrams are useful for glass composition development, diagnosis of solid inclusions & study of reacting batch



Eutectics on the Silica-Alumina-Calcia ternary were starting points for the development of many important glass compositions

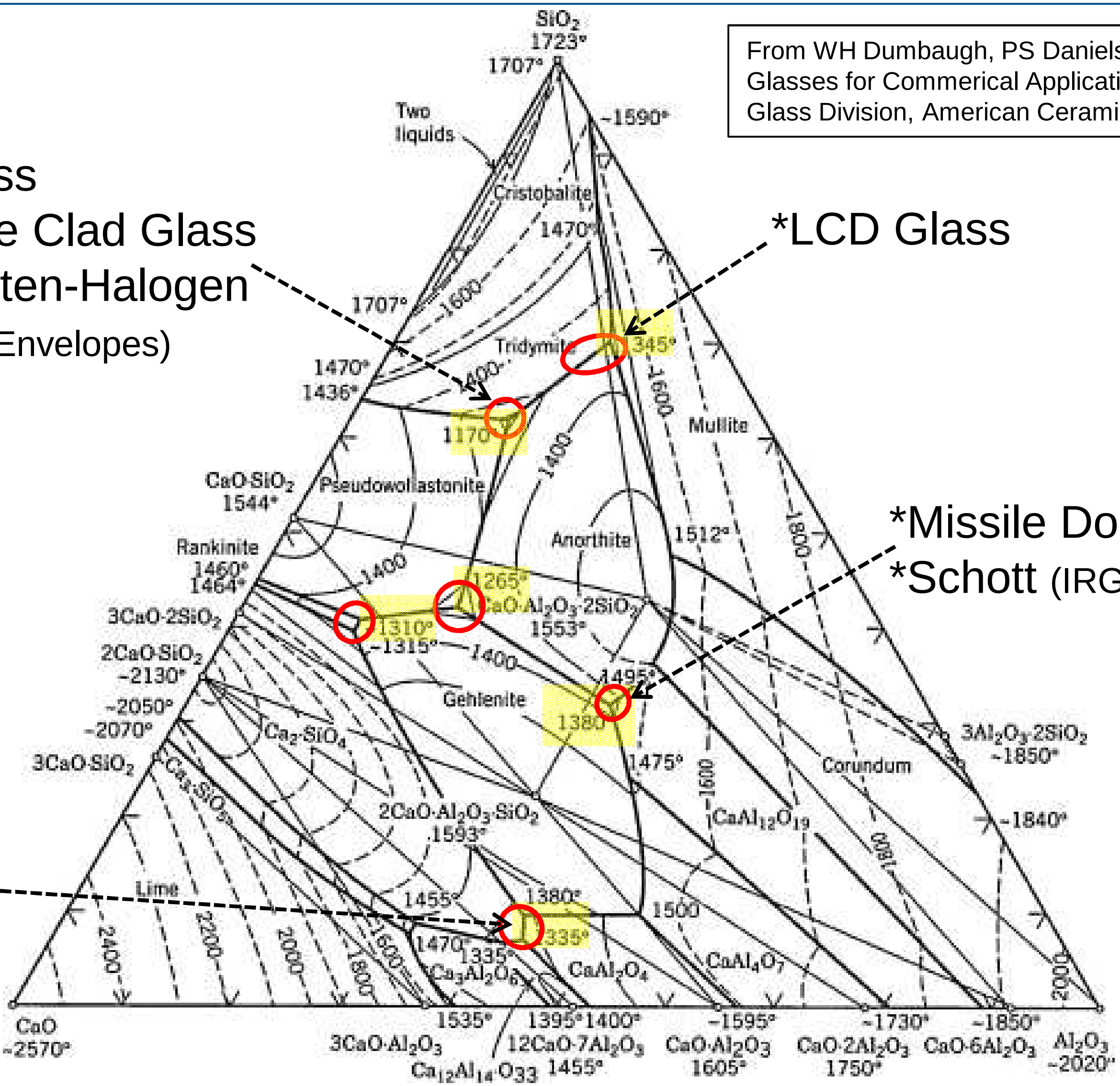
From WH Dumbaugh, PS Danielson, “Aluminosilicate Glasses for Commerical Applications”, 1984 Fall Meeting, Glass Division, American Ceramic Society

*E-Glass
*Corelle Clad Glass
*Tungsten-Halogen
(Lamp Envelopes)

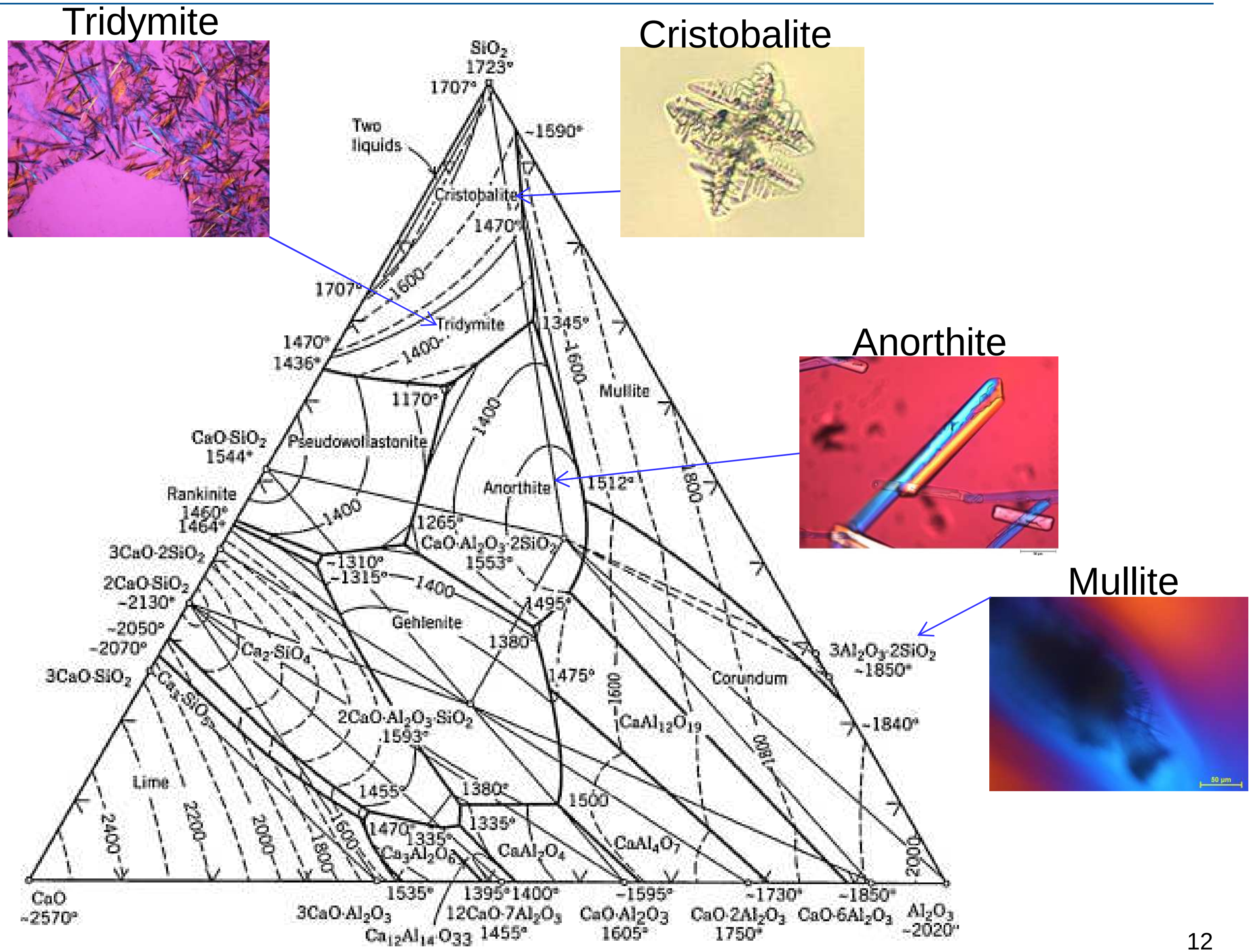
*LCD Glass

*Missile Domes (CGW9753)
*Schott (IRGN6LCD Glass)

*Infrared Transmitting Windows
*BS37A

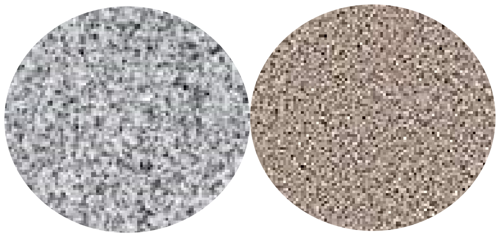


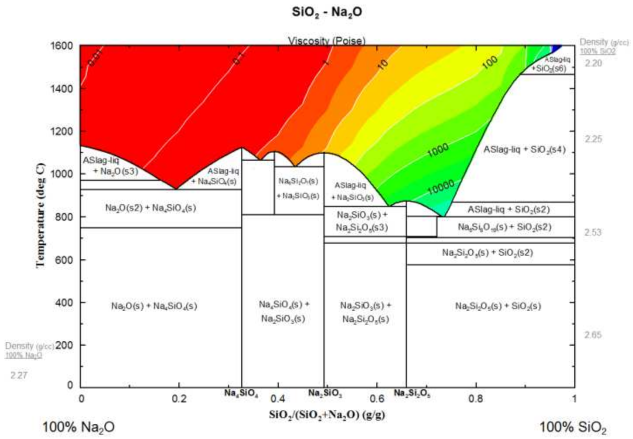
Phase diagrams are useful for diagnosis of solid inclusions in glass (both batch & refractory sourced)



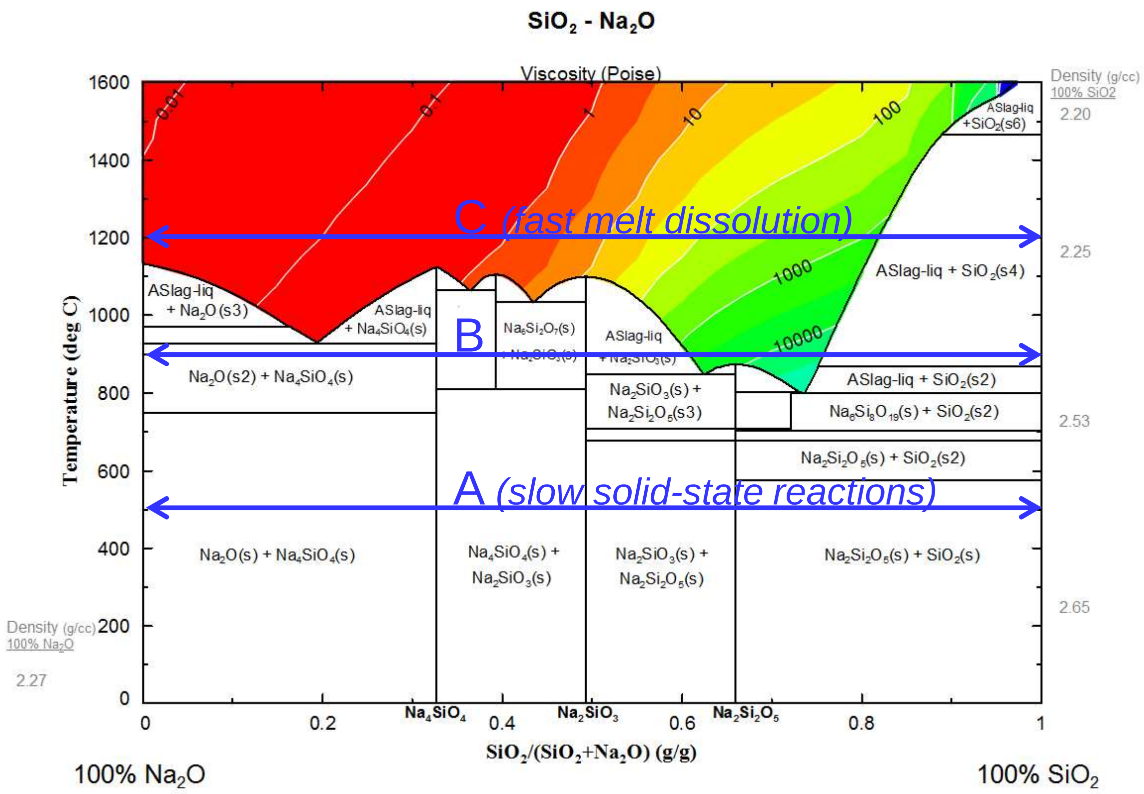
Phase Diagrams are useful for studying the batch-to-glass conversion

- For example, during the initial heating of a batch, contact points between particles are “mini-binary systems”.

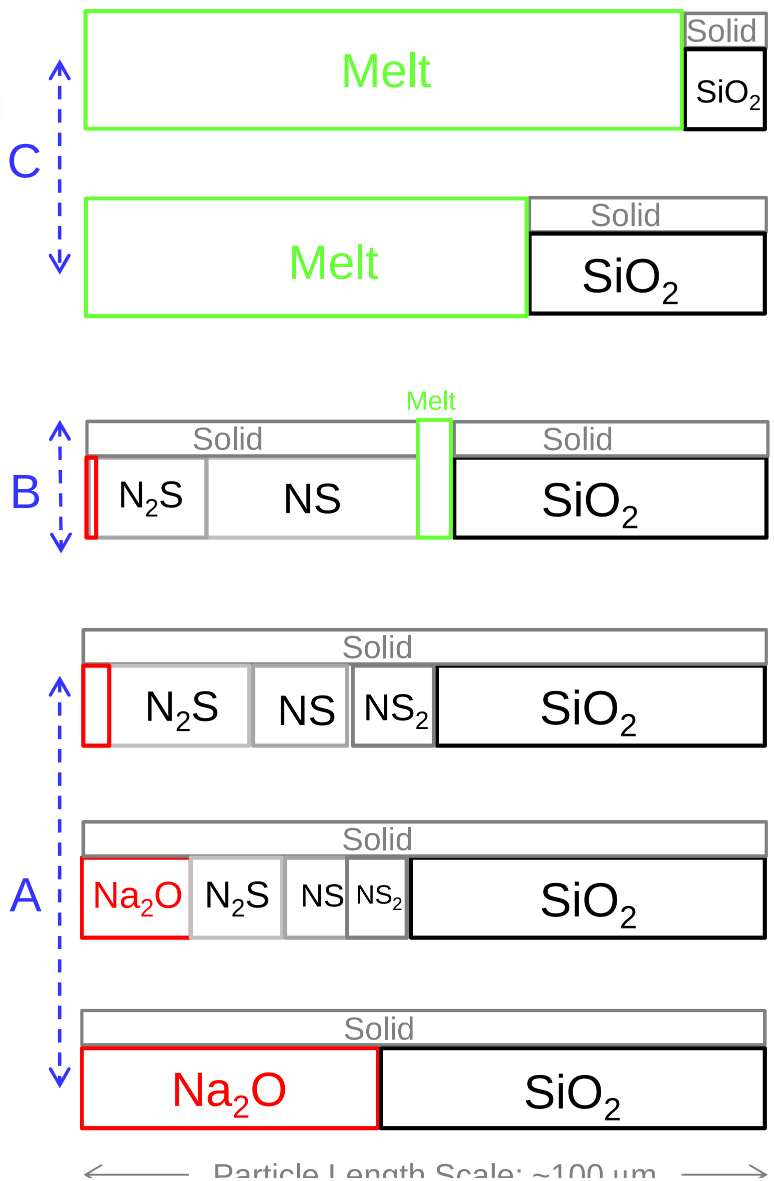




Silica-Soda Binary Phase Diagram



Phases across reaction-diffusion region (qualitative)



Summary

- Technical aspects of melting span all length-scales from the "equipment scale" to "molecular scale". This is one reason for the complexity we face simulating glass melting

- All our math modeling and lab experimental tools are "partial models" of the full chemistry & physics of a melting process.
  - The relative merits & drawbacks of each were discussed.

- True advancements in Furnace Modeling will likely be from integrating knowledge of the batch-to-glass conversion from the particle & chemical levels.

CORNING