

5/22

Expansion Cooling Modeling Overview

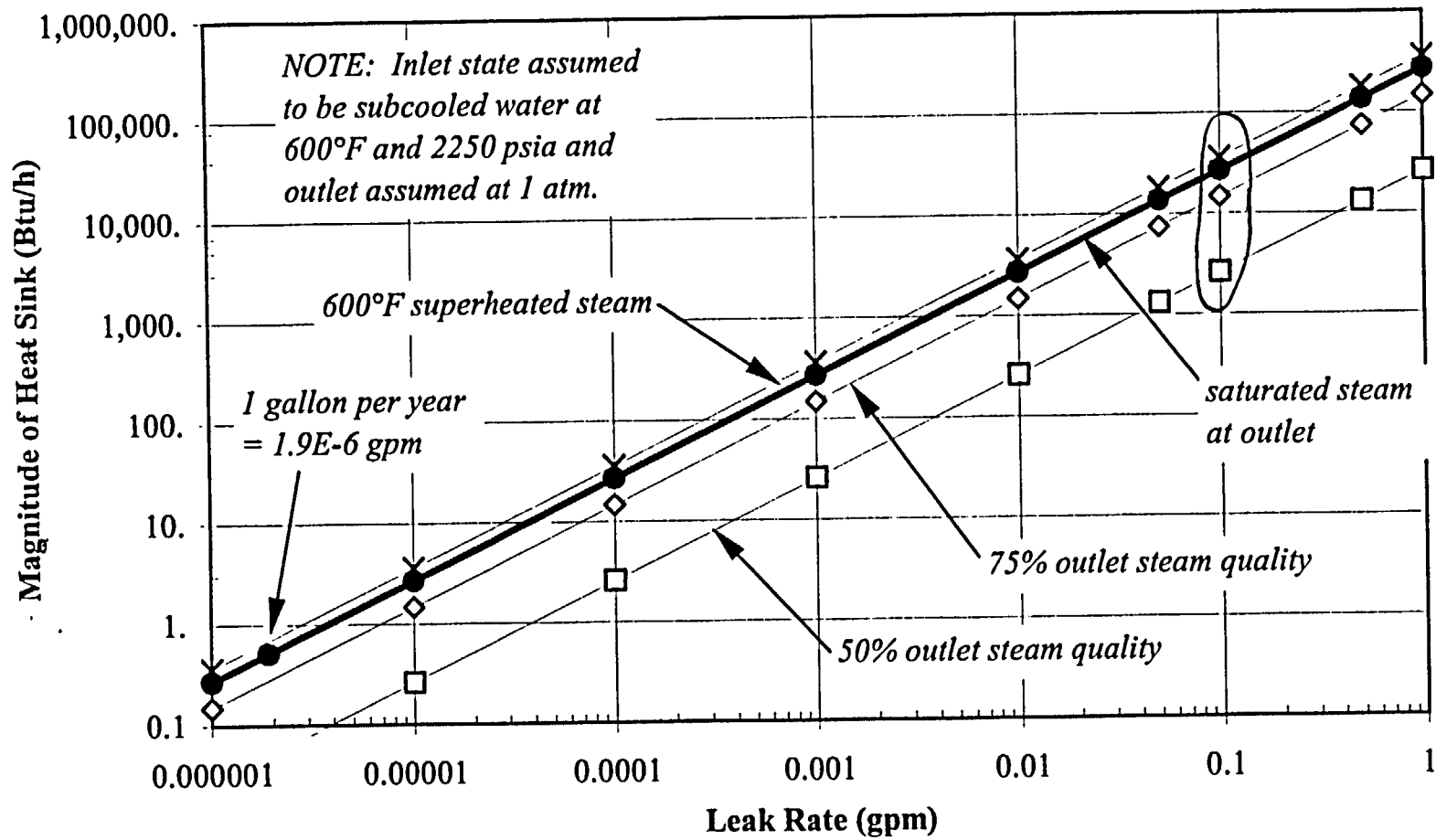
6/4/02

- Approach is to determine extent of cooling along the leak path as a function of leak rate using
 - Heat required to vaporize all leaking liquid is the leak rate times the enthalpy increase (from primary water at 613 Btu/lb to saturated steam at atmospheric pressure at 1150 Btu/lb)
 - FEA heat transfer model of conduction within head materials with convection boundary conditions from primary coolant and to space above
 - Correlations for two-phase and single-phase heat transfer coefficients along the leak path

- Extent of cooling affects important parameters including
 - Location of concentrated liquid
 - pH
 - FAC susceptibility

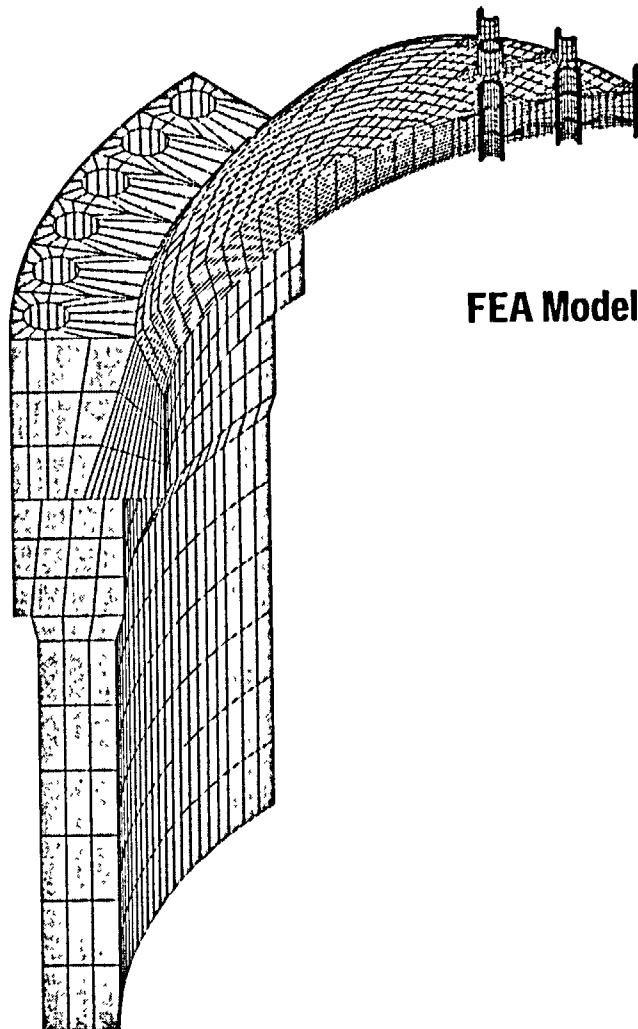
Expansion Cooling Modeling

Magnitude of Heat Sink



Expansion Cooling Modeling

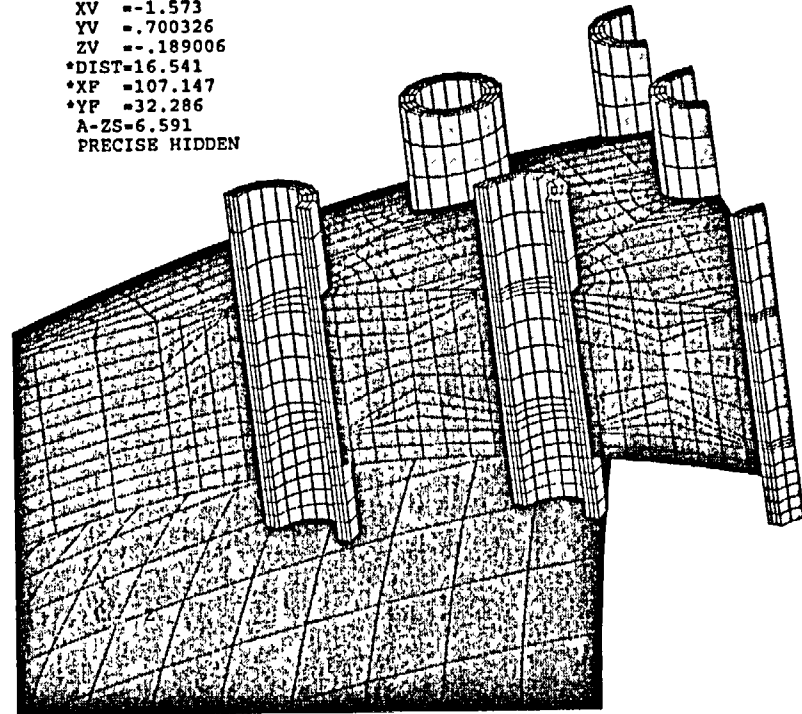
Finite Element Analysis of Head Heat Transfer



FEA Model

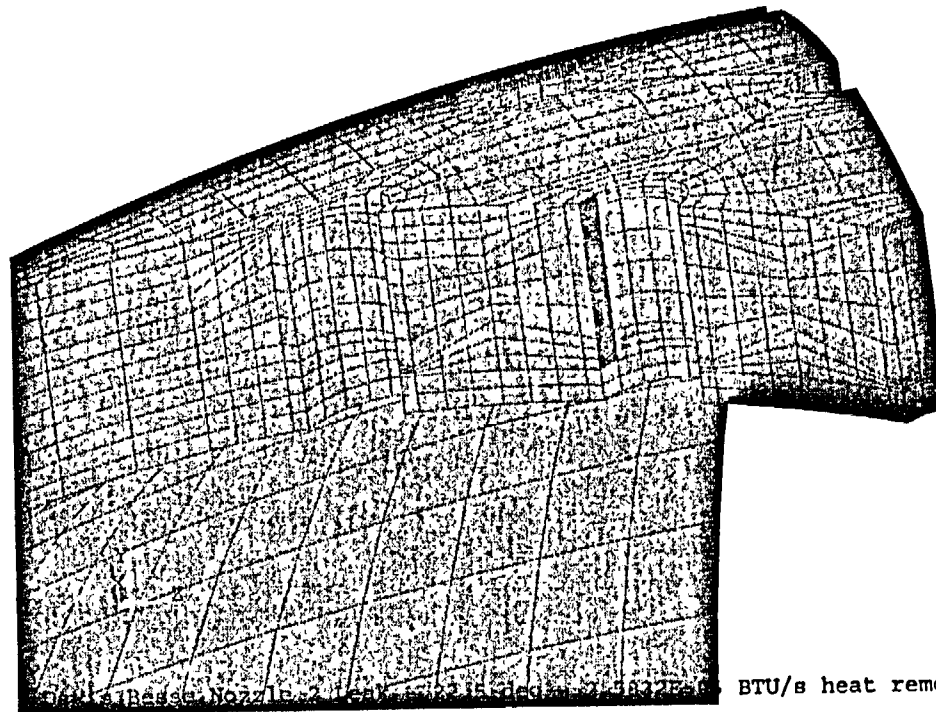
```
ANSYS 5.7  
APR 2 2002  
11:34:11  
PLOT NO. 1  
ELEMENTS  
MAT NUM
```

```
XV = -1.573  
YV = .700326  
ZV = -.189006  
*DIST=16.541  
*XP =107.147  
*YP =32.286  
A-ZS=6.591  
PRECISE HIDDEN
```



Expansion Cooling Modeling

Finite Element Analysis of Head Heat Transfer



ANSYS 5.7
APR 2 2002
12:00:37
PLOT NO. 3
ELEMENTS
HGEN RATES
QMIN=-.568E-05
QMAX=0

XV --1.573
YV -.700326
ZV --.189006
*DIST=16.541
*XF =107.147
*YF =32.286
A-ZS=6.591

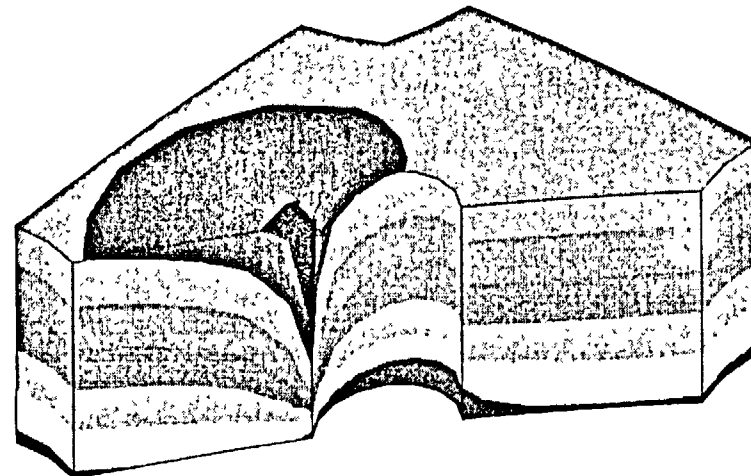
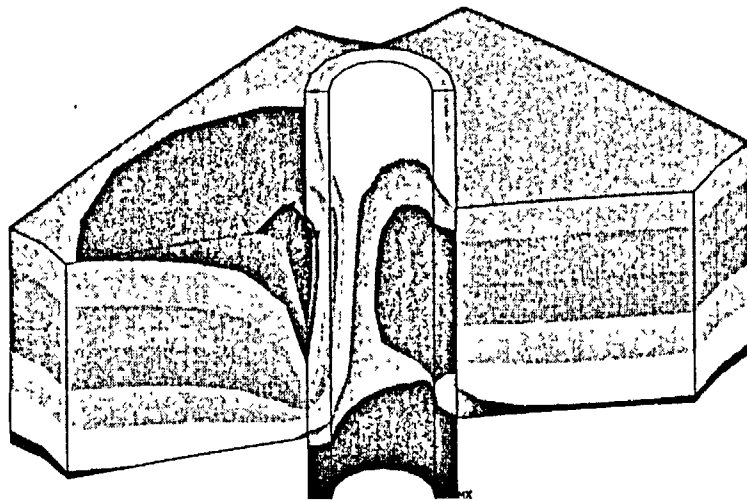
PRECISE HIDDEN
-.568E-05
-.504E-05
-.441E-05
-.378E-05
-.315E-05
-.252E-05
-.189E-05
-.126E-05
-.631E-06
0

BTU/s heat removal

Uniform Surface Heat Sink Along the Leak Path Assumed

Expansion Cooling Modeling

Finite Element Analysis of Head Heat Transfer

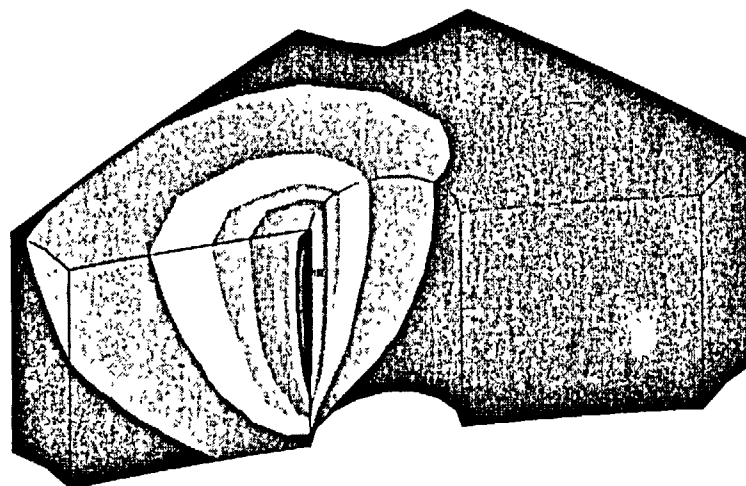
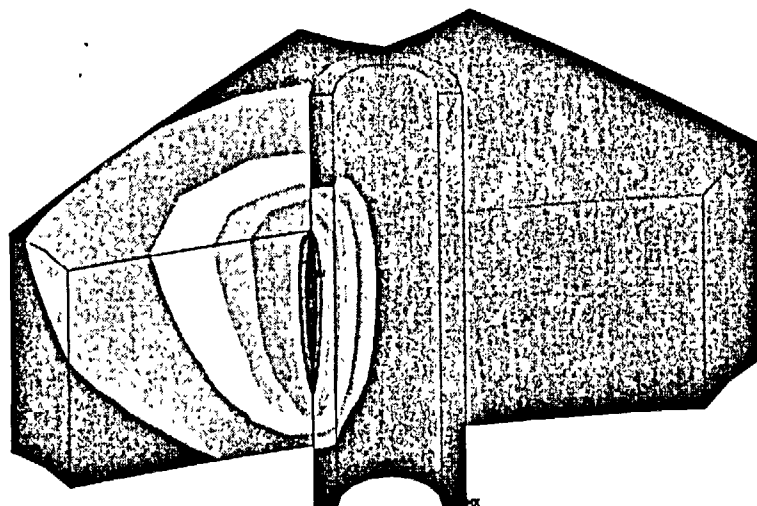


TEMP	
SMN	=603.37
SMX	=604.996
	603.37
	603.551
	603.731
	603.912
	604.093
	604.273
	604.454
	604.635
	604.815
	604.996

**Example Calculation for Low Leak Rate
(18.6 Btu/h Heat Sink:
complete vaporization of 7×10^{-5} gpm leak)**

Expansion Cooling Modeling

Finite Element Analysis of Head Heat Transfer



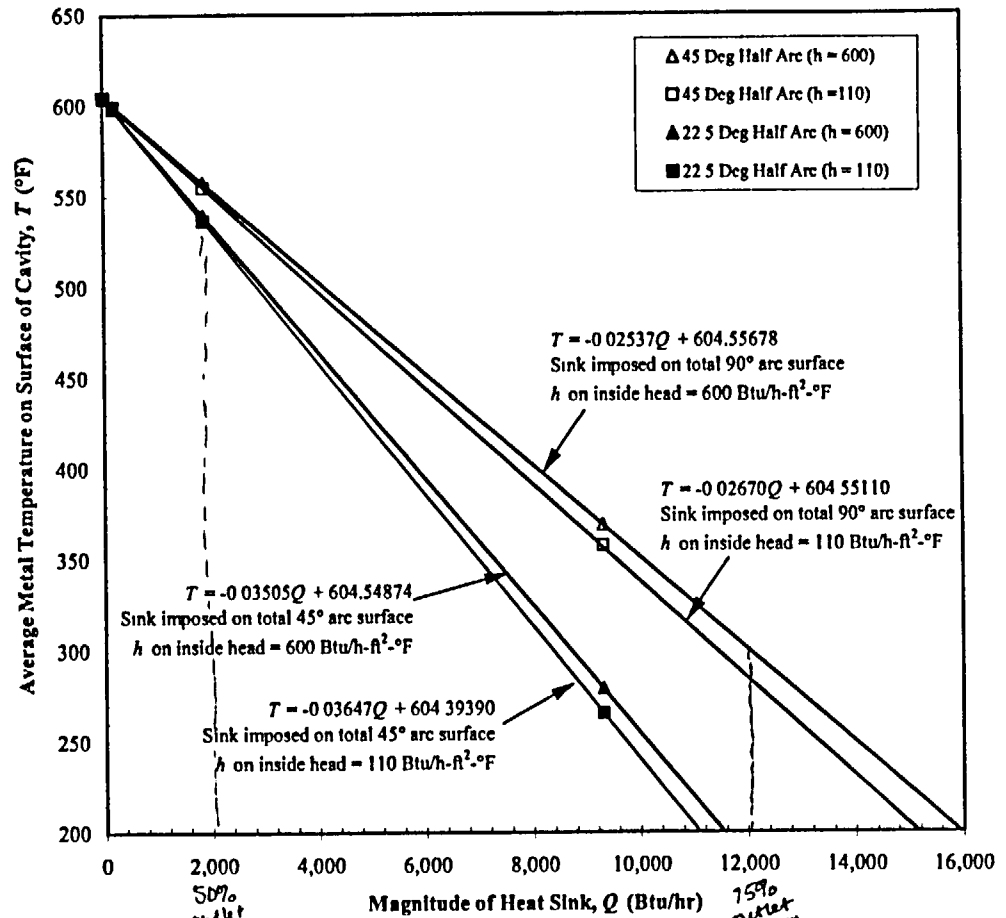
TEMP	
SMN	=514.122
SMX	=604.939
	514.122
	524.212
	534.303
	544.394
	554.485
	564.576
	574.667
	584.758
	594.849
	604.939

**Example Calculation for Moderate Leak Rate
(1860 Btu/h Heat Sink:
complete vaporization of 0.007 gpm leak)**

Expansion Cooling Modeling

Finite Element Analysis of Head Heat Transfer

Average Metal Surface Temperature Along the Leak Path



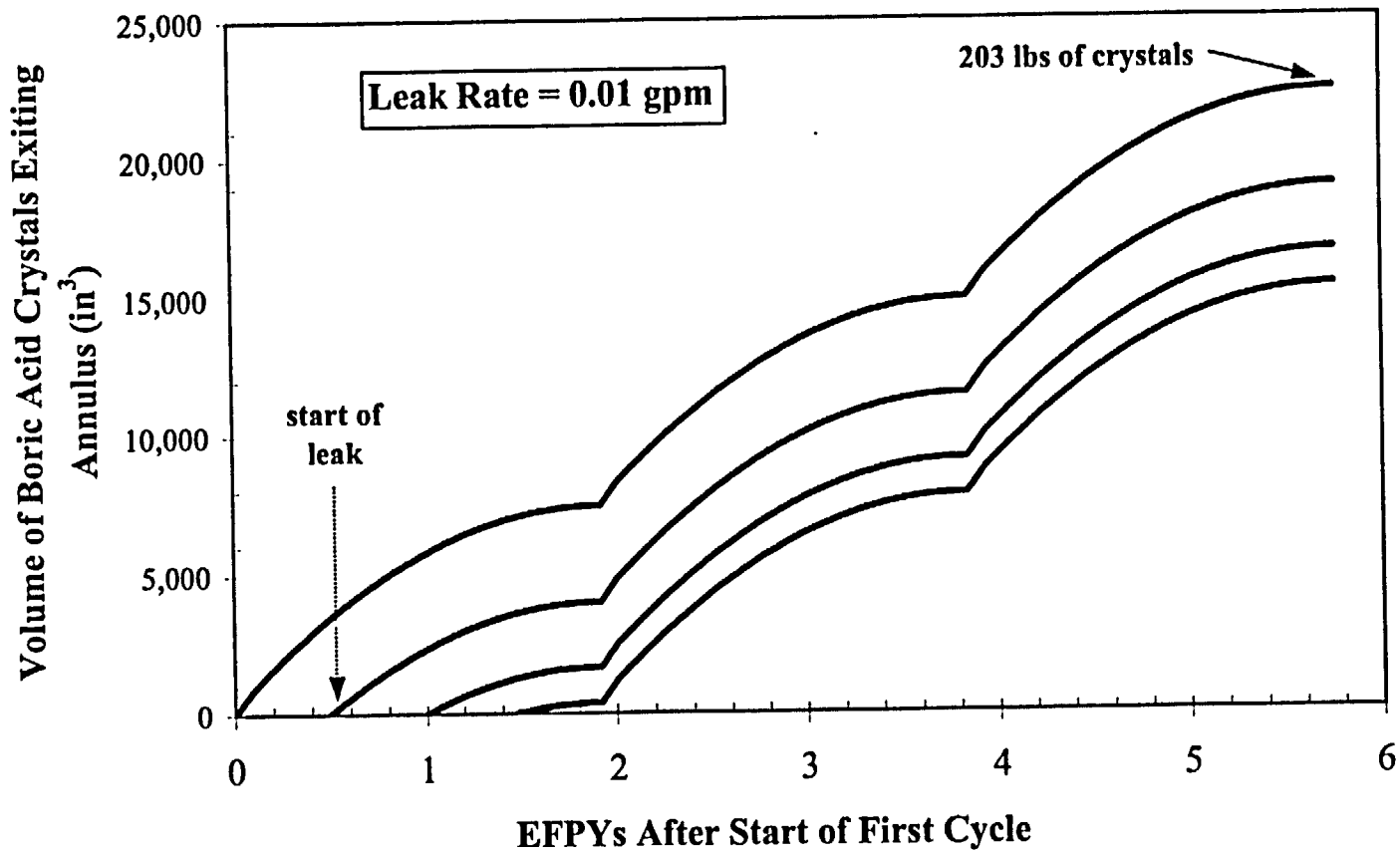
Volume of Boric Acid Deposits on the Vessel Head

Methodology

- Integrate the leaking boron mass over the fuel cycle
- Calculate the volume of leaked boron based on the density of boric acid (H_3BO_3) or boric oxide (B_2O_3) crystals, conservatively assuming no porosity
- The fraction of precipitated boron compounds that deposits on the head adjacent to the leaking nozzle may be affected by
 - Droplet entrainment into the steam flow
 - Boric acid volatility (10% or less)

Volume of Boric Acid Deposits on the Vessel Head

Example Integration of Boron Mass



Boric Acid Morphology and Properties

Boron Phases

➤ Boric acid solutions and dry crystals ✓

- During evaporative concentration, boric acid solutions precipitate boric acid crystals
- The end results depend upon the rate of concentration and drying
 - If drying is fast, boric acid powder will result
 - If drying is slow, a single irregularly shaped mass is likely

➤ Molten boric acid ✓

- When heated above 340-365°F, solid boric acid melts to form a highly viscous liquid that will fuse into a single mass and flow under the influence of gravity
- Molten boric acid can contain 8-14% water by weight and is known to be corrosive

➤ Solid boric oxide ✓

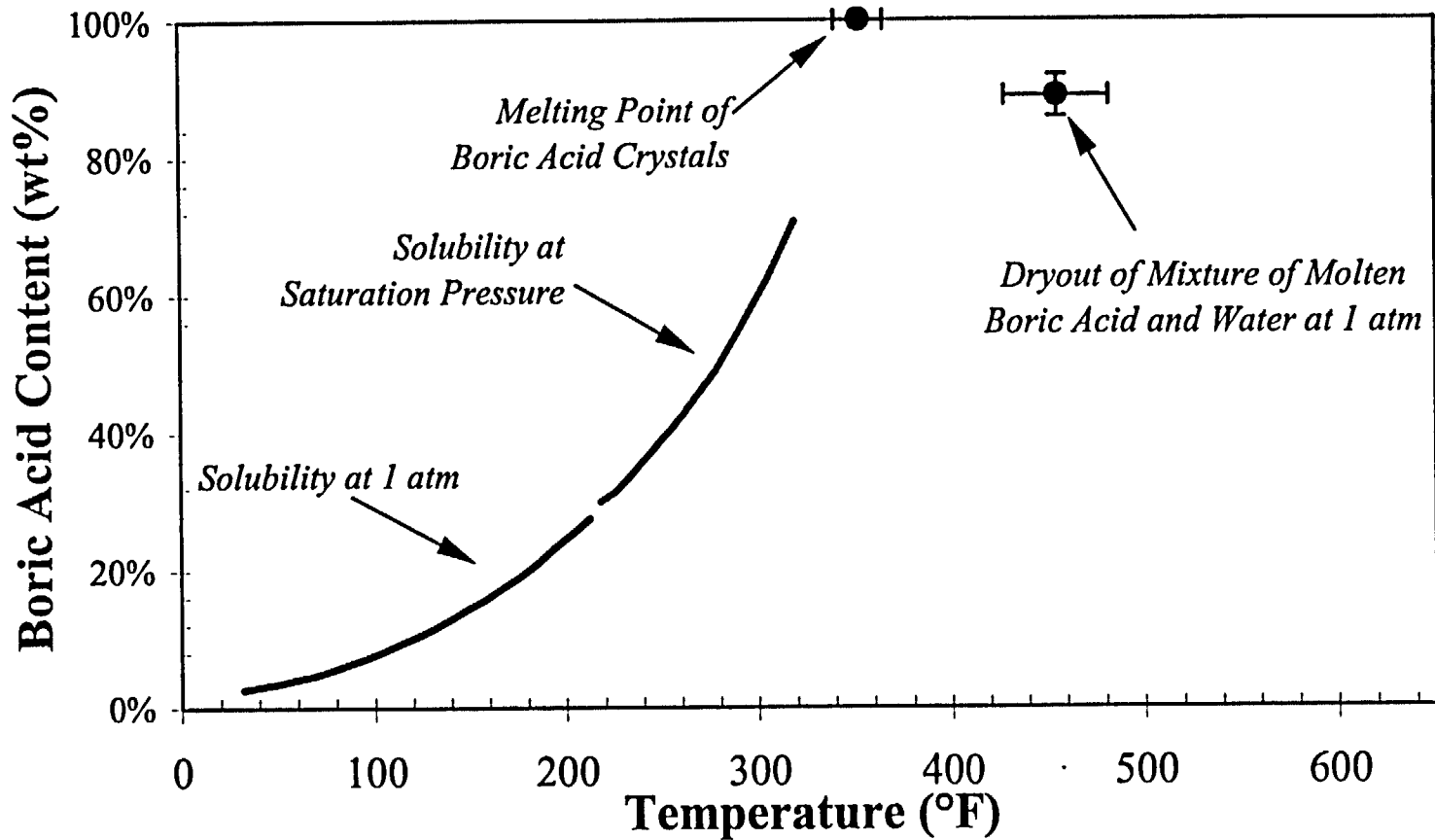
- Above 302°F boric acid is subject to a dehydration reaction to form boric oxide
- The resultant crystalline mass is an anhydrous, white, opaque, non-glasslike, stony solid

➤ Molten boric oxide ✗

- Above 617°F boric oxide begins to soften and at about 842°F becomes a highly viscous liquid

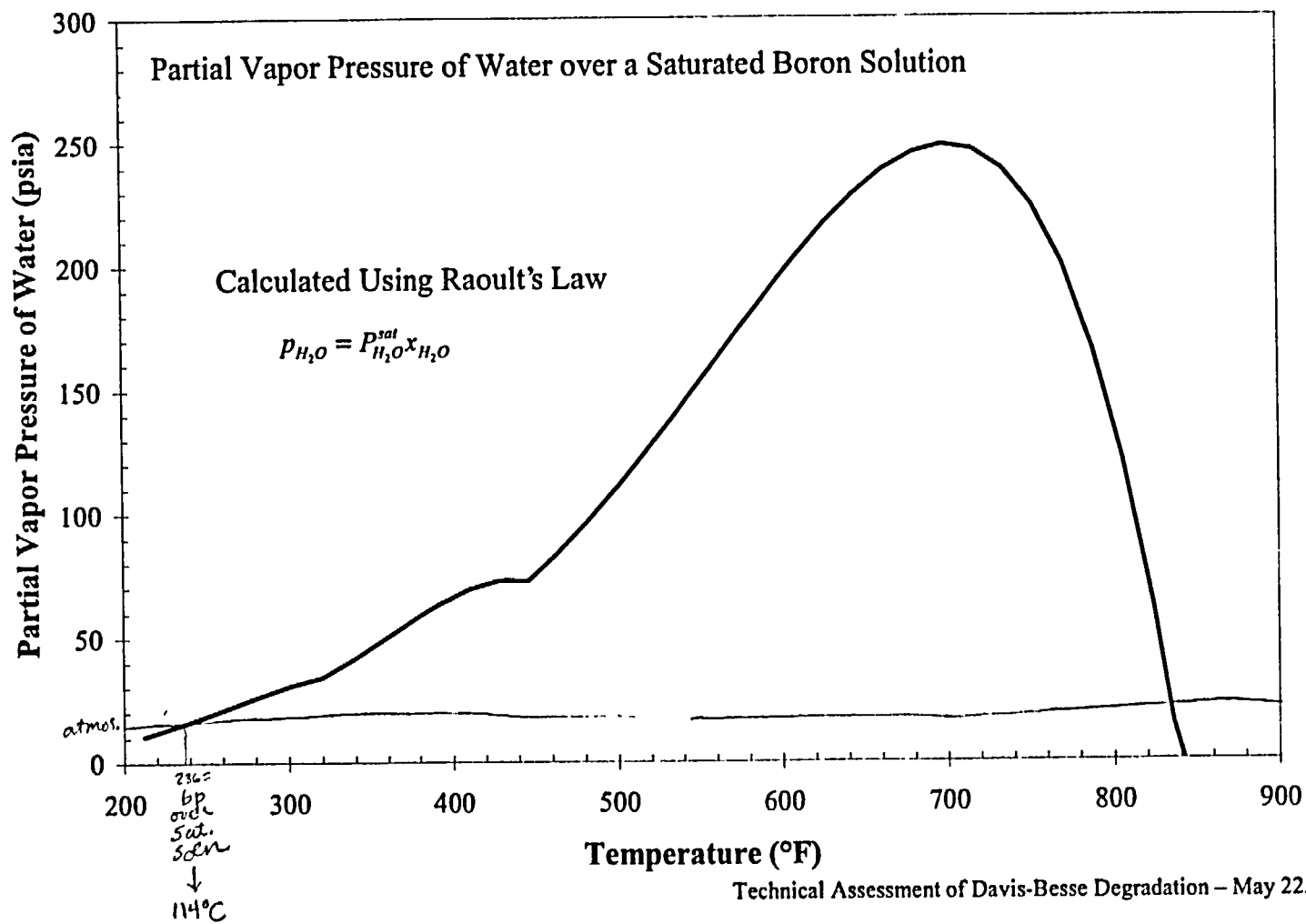
Boric Acid Morphology and Properties

Key Temperature Behavior



Boric Acid Morphology and Properties

Partial Vapor Pressure



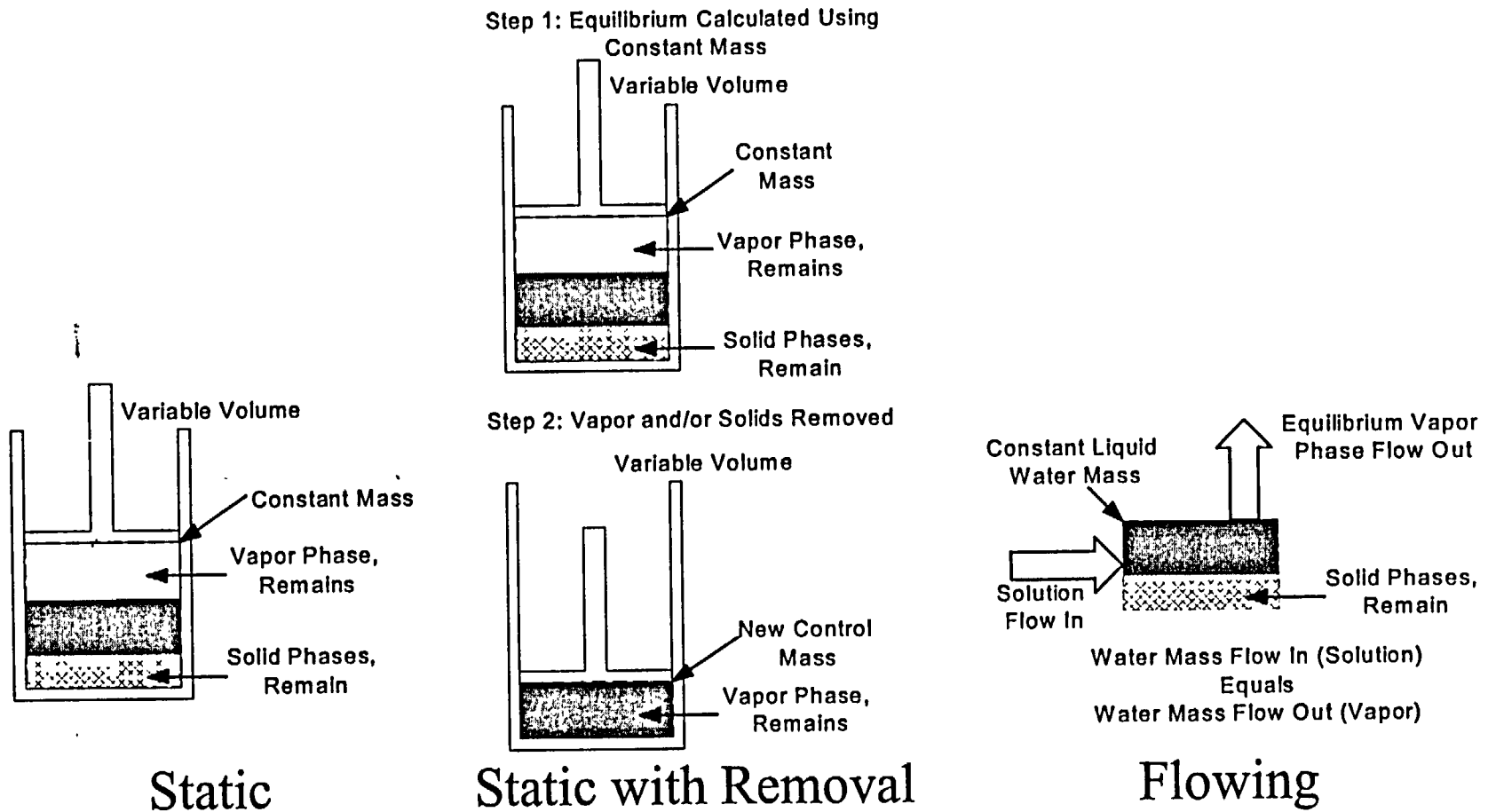
Boric Acid Morphology and Properties

General pH Effects without Large Local Cooling

- For low concentration factors, the solution becomes slightly alkaline, having a small effect on crack growth rates
- For high concentration factors, the solution becomes acidic with a high-temperature pH of 4.5 according to MULTEQ calculations
- The initial high ratio of crevice surface area to volume may allow some buffering by the iron in the head material
- Precipitation of complex lithium and boron compounds occurs and tends to limit pH swings

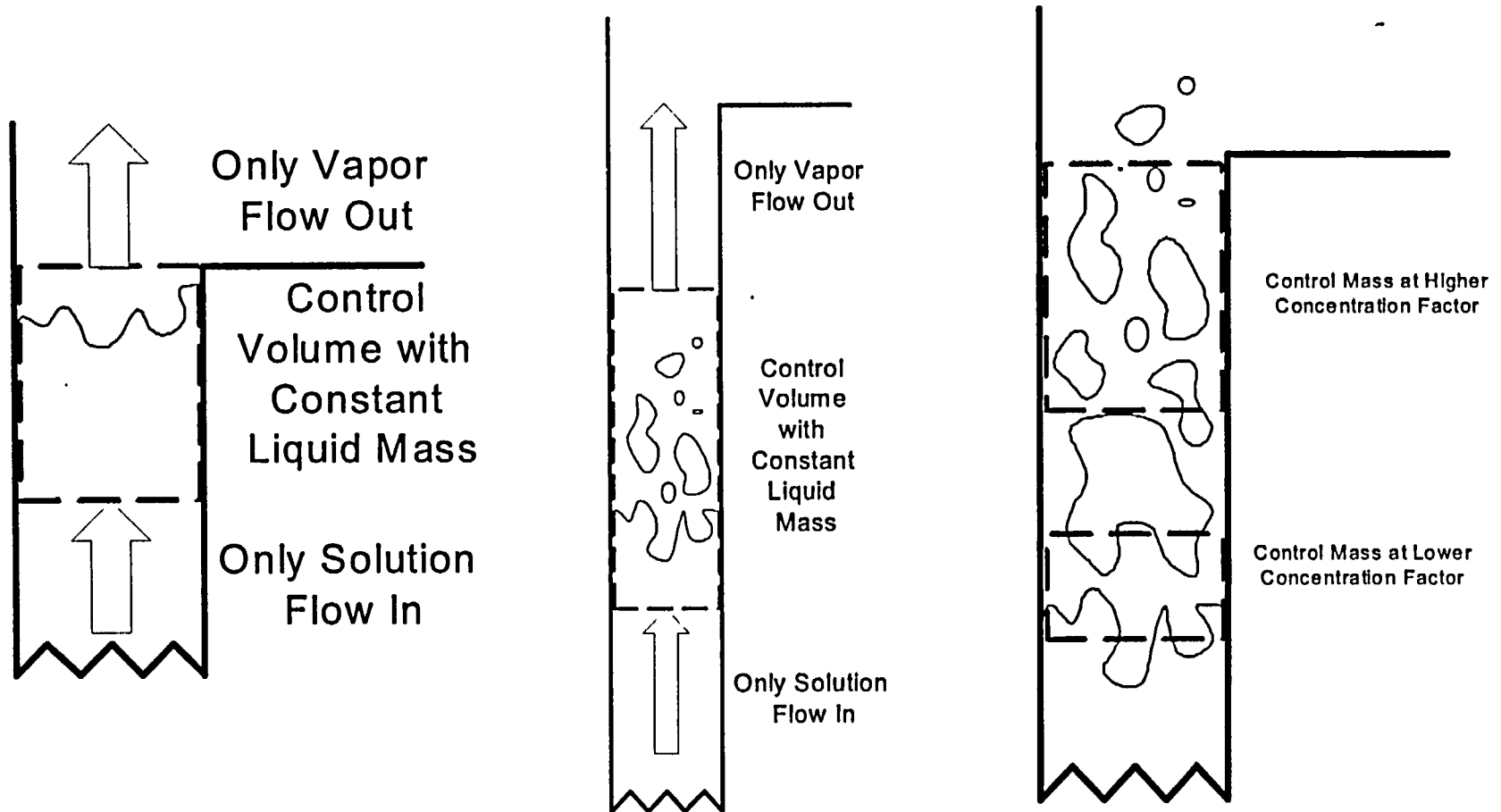
MULTEQ Modeling

Three Main Flow Models Available



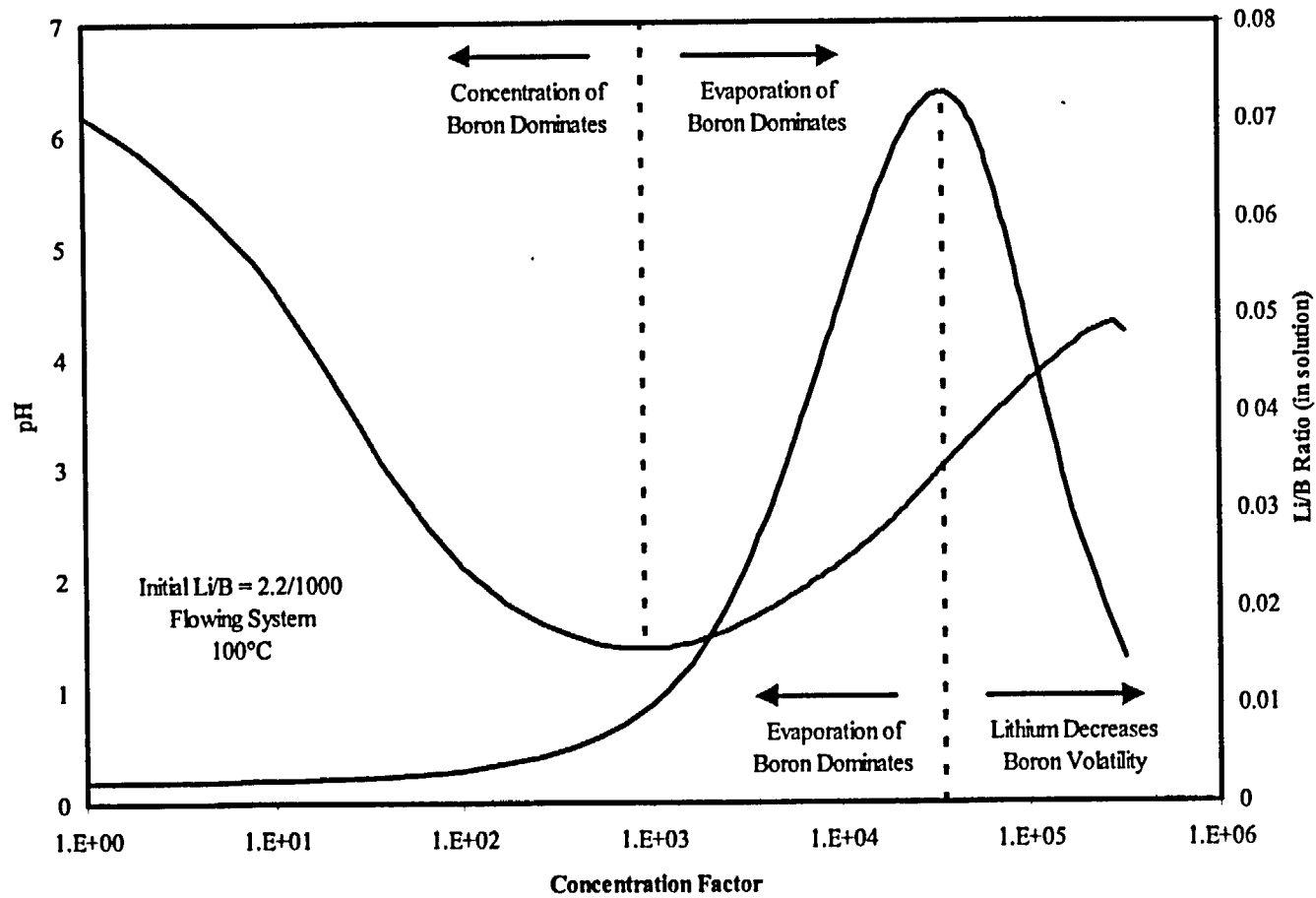
MULTEQ Modeling

Available Control Volumes



Example MULTEQ Calculation

pH in a Flowing System at 100°C



Molten Boric Acid

Orthoboric Acid- H_3BO_3 Metaboric Acid- HBO_2 Boric Oxide B_2O_3

- Corrosion in molten boric acid largely unstudied
- Degradation:
 - Melting point above the degradation point
 - Orthoboric acid: melts at 170.9°C (340°F); degrades to metaboric acid at 169.6°C (337°F)
 - Metaboric acid: melts at 236°C (457°F); degrades to boric oxide at 235°C (455°F)
 - Degradation reaction is slow
 - Effect of degradation products on corrosion largely unknown
 - (degradation probably lower in boric oxide, B_2O_3 , than in either acid)
 - Degradation products highly hygroscopic
 - Analysis of deposits not likely to indicate their at-temperature composition
- Solubility issues largely unstudied
 - Miscibility limits unknown
 - For pH calculations, molten boric acid could be an additional precipitate
 - Degradation products not included in MULTEQ

Molten Boric Acid

Molten Salt Corrosion

- Molten salt corrosion is electrochemically very similar to aqueous corrosion, depending on a reaction couple:
 - $\text{Fe} \rightarrow \text{Fe}^{2+}$ anodic reaction
 - $\text{O}_2 \rightarrow \text{OH}^-$ or $\text{H}^+ \rightarrow \text{H}_2$ cathodic reaction
 - Additional cathodic reactions unlikely in molten boric acid
 - Typical molten salt corrosion occurs through de-passivation
 - Not relevant since LAS and CS are not passive in acidic media

- Acceleration possible due to high conductivity of molten salts
 - Unlikely to lead to a qualitative difference relative to highly concentrated solutions

Molten Boric Acid Issues

Molten Salt Corrosion (continued)

- Solubility of corrosion products likely to be less in molten boric acid than in water
 - Leads to lower corrosion rates

- Molten boric acid corrosion likely to be significantly slower than corrosion in aqueous solution
 - Lower O_2 and H^+ concentrations (slower cathodic reactions)
 - Possibly lower conductivity
 - Likely lower corrosion product solubility (slower anodic reactions)

- Corrosion in molten boric acid is a particular case of corrosion in boric acid solutions, not a separate phenomenon