EVOLVE Lithium Tray Boiling Analysis

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Overview

- Issues
  - Need void fraction distribution in liquid metal tray to:
    - Determine volumetric energy deposition
    - Structural thermal loading
    - Design for vapor removal
  - Compare drift-flux methodology with other options
    - Will they produce consistent results?
  - Large void fractions are driven by small vapor densities

Void Fraction Determination

- Divide 50 cm tray into “channels” and predict void distribution in each channel
- Channel sizing calculation (Taylor length scale)

$$width = 2\pi\sqrt{\frac{3\sigma}{g\Delta\rho}}$$

width = 8cm, is a maximum bubble size (channel should be at least this wide)
(for simplicity a channel size of 10 cm was chosen)
σ = surface tension (N/m)
g = gravity constant
$\Delta\rho$ = liquid-vapor density difference (kg/m^3)

- Mohamed Sawan (UW) provided nuclear heating (W/cm^3) distribution for OB tray which gives generation rates for W and Li
- Uniform void distribution of 17% used for first calculation

- 25 zone Li pool (5 radial channels, 5 vertical positions)

Void Fraction Determination (continued)

- Nuclear heating (W/cm^3) distribution in OB tray

98.9						
99.4	28.3	22.1	17.6	14.5	12.6	40.4
100.7	28.2	21.9	17.4	14.2	12.2	39.2
101.7	28.2	21.8	17.4	14.2	12.1	38.1
102.5	28.4	21.9	17.4	14.2	12.0	37.1
104.6	28.7	22.2	17.5	14.3	12.2	36.3
103.2	90.3	72.0	58.4	48.2	40.3	34.4
104.0						

FW represented by 0.6 cm thick zone
Trays have 50 cm radial thickness and 15 cm height
Tray bottom and back W plates are 0.5 cm thick
OB neutron wall loading is 10 MW/m^2

- Use energy deposited in Li and W to determine the vaporization rate

Void Fraction Determination (continued)

- The material (Li) vaporized is used to determine the volumetric vapor flux (jg) and the dimensionless superficial gas velocity used in the churn-turbulent flow model

- Empirical study of void fraction in a pool configuration with upward flowing gas (bubbly or churn-turbulent flow regime, Casas & Corradini)

- Drift-flux model used

$$<void>=\frac{<Jg>}{C_o<Jg>+C_1} \qquad Jg=\frac{jg}{\left[\frac{\sigma_f(\rho_f-\rho_g)g}{\rho_f{}^2}\right]^{1/4}} \qquad Z=\frac{\mu_f}{\left[\rho_f\left(\frac{\sigma_f}{(\rho_f-\rho_g)g}\right)^{1/2}\sigma_f\right]^{1/2}} \qquad jg=\frac{m_g}{\rho_g A}$$

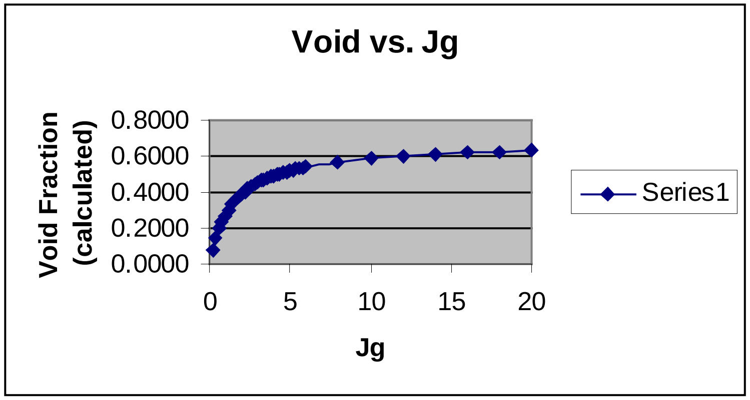
- C_o and C_1 experimentally determined coefficients from tests with mercury, woods metal, water, Freon, dodecane, and silicone oils

Void Fraction Determination (continued)

Jg = dimensionless superficial gas velocity
C_o = 0.248 ln(Z) + 3.52
C_1 = $0.502\ h^*_o + 7.27\ 10^{-3}\ \ln(Z) - 0.124\ h^*_o\ \ln(Z) - 0.0295$
Z = Ohnesorge Number
h^*_o = dimensionless pool depth (height/diameter, 15 cm/10 cm)
m_g = vapor mass flow rate

jg = volumetric vapor flux
σ_f = fluid surface tension
μ_f = fluid viscosity
ρ_f = fluid density
ρ_g = vapor density
A = channel area

- Void fractions are driven by Li vapor density (ideal gas calculation) and by nuclear heat loads applied to the Li and W
- Provided below is a plot of void fraction versus superficial gas velocity (Jg) at 1200 C and 0.037 MPa (most superficial gas velocities are above 5)



Void Fraction Determination (continued)

- The superficial gas velocity scales directly to nuclear heating, but you can see that at sufficiently high (~ 5) values changes in nuclear heating minimally affect void fraction
- Assumed void fraction 17% for original nuclear heating values
- As void changes the deposition heating rates will change, ultimately the initial void fraction will be iterated on to converge to some value
- To accurately assess, void fraction must be matched with heating
- Iteration necessary

Iteration Process for Determining Void Fraction Distribution

- Volumetric heating is lower for higher void fractions

- As first order approximation nuclear heating in the Li is scaled linearly with density
  - Neutron attenuation in Li changes with void fraction affecting nuclear heating in Li at back of tray, W back plate, and W bottom plate

- Calculations repeated till convergence

- This approach speeds up the iteration process with 2D neutronics

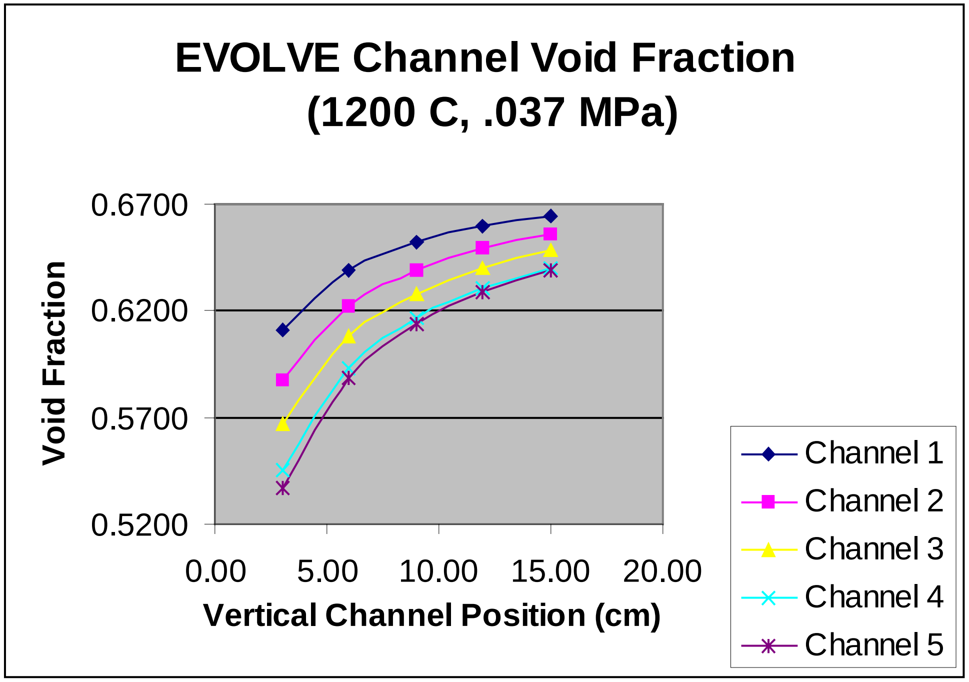
- The higher void fraction (compared to the assumed 17% average value) will reduce TBR and increase structure damage

- Once the void fraction distribution is finalized, nuclear performance parameters will be updated, and the iteration continued

- Iterated void fraction values, starting with 17% void, are shown on the next page

Iterated Channel Void Fractions

- First iteration
- Based on initial uniform 17% void fraction throughout tray



Iterated Channel Void Fraction (continued)

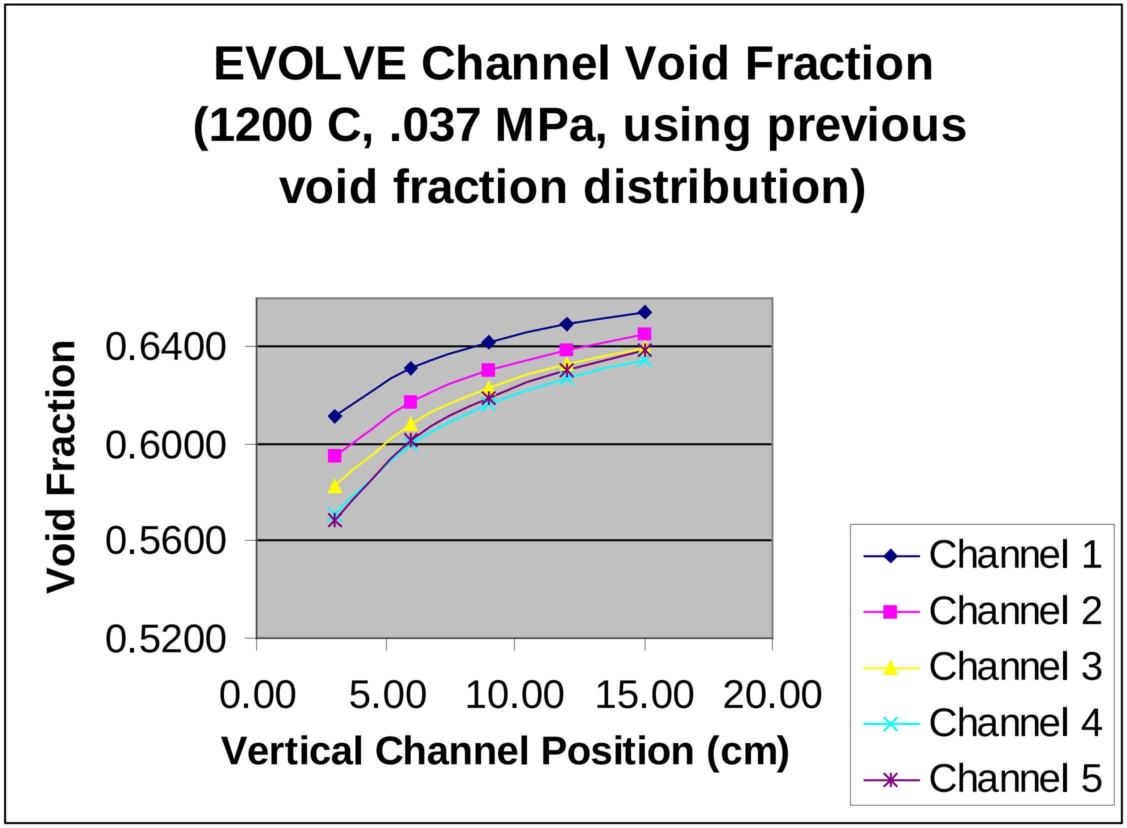
- New nuclear heating values are calculated based on the previous void fractions

Nuclear Heating (W/cm^3) Distribution in OB Tray Using First Iteration Vapor Fraction Distribution

103.8						
103.9	13.7	12.2	10.8	9.8	8.8	55.1
104.9	14.0	12.5	11.1	10.1	9.0	54.2
105.9	14.5	13.1	11.7	10.6	9.5	53.2
106.7	15.5	14.0	12.6	11.4	10.3	52.1
108.9	27.3	23.5	20.3	18.0	16.1	51.0
108.2	97.3	83.2	71.6	62.6	55.1	48.8
109.4						

Iterated Channel Void Fraction (continued)

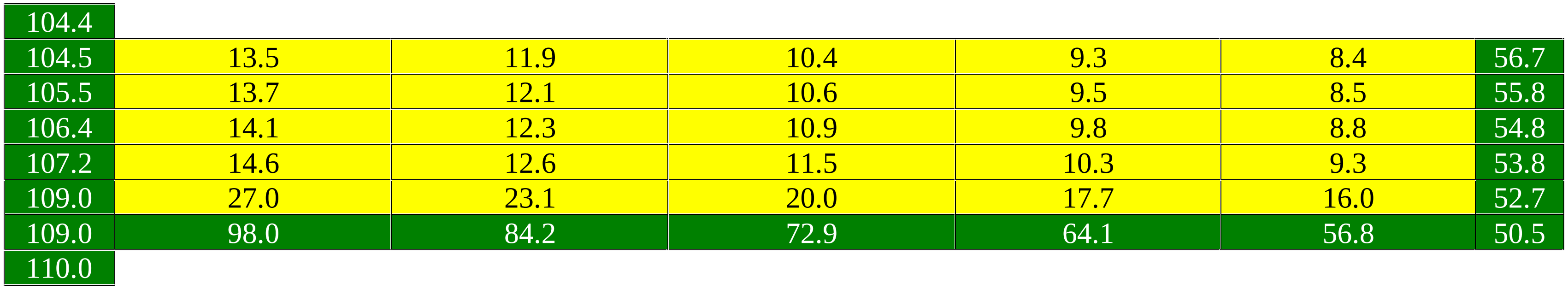
- 2^{nd} Iteration void fraction distribution calculated from previous nuclear heating values



Iterated Channel Void Fraction (continued)

- New nuclear heating values are calculated based on the previous void fractions

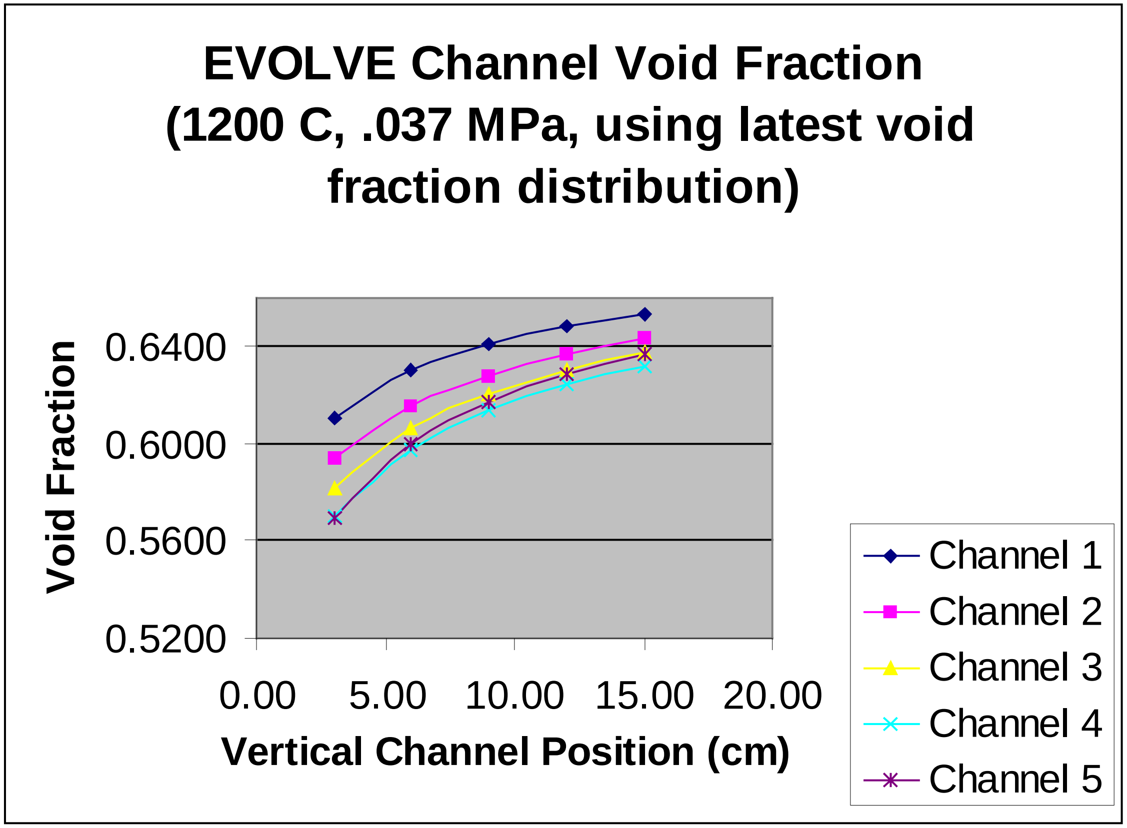
Nuclear Heating (W/cm^3) Distribution in OB Tray Using Second Iteration Vapor Fraction Distribution



104.4						
104.5	13.5	11.9	10.4	9.3	8.4	56.7
105.5	13.7	12.1	10.6	9.5	8.5	55.8
106.4	14.1	12.3	10.9	9.8	8.8	54.8
107.2	14.6	12.6	11.5	10.3	9.3	53.8
109.0	27.0	23.1	20.0	17.7	16.0	52.7
109.0	98.0	84.2	72.9	64.1	56.8	50.5
110.0						

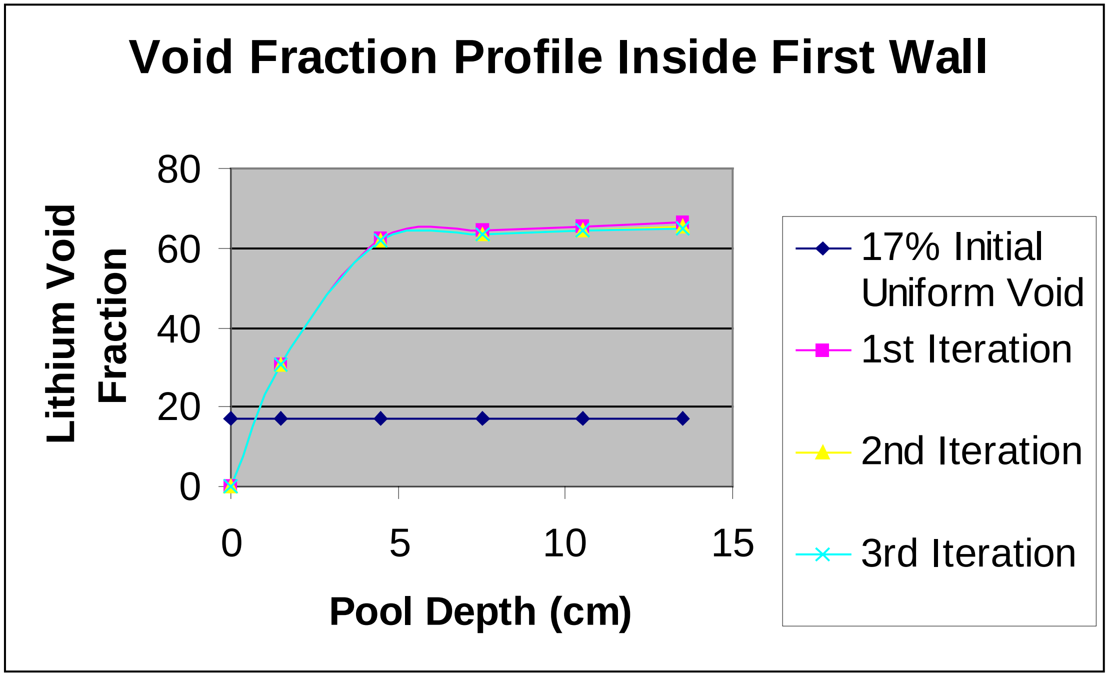
Final Iterated Void Fraction Distribution

- Essentially no change from previous void distribution (convergence)



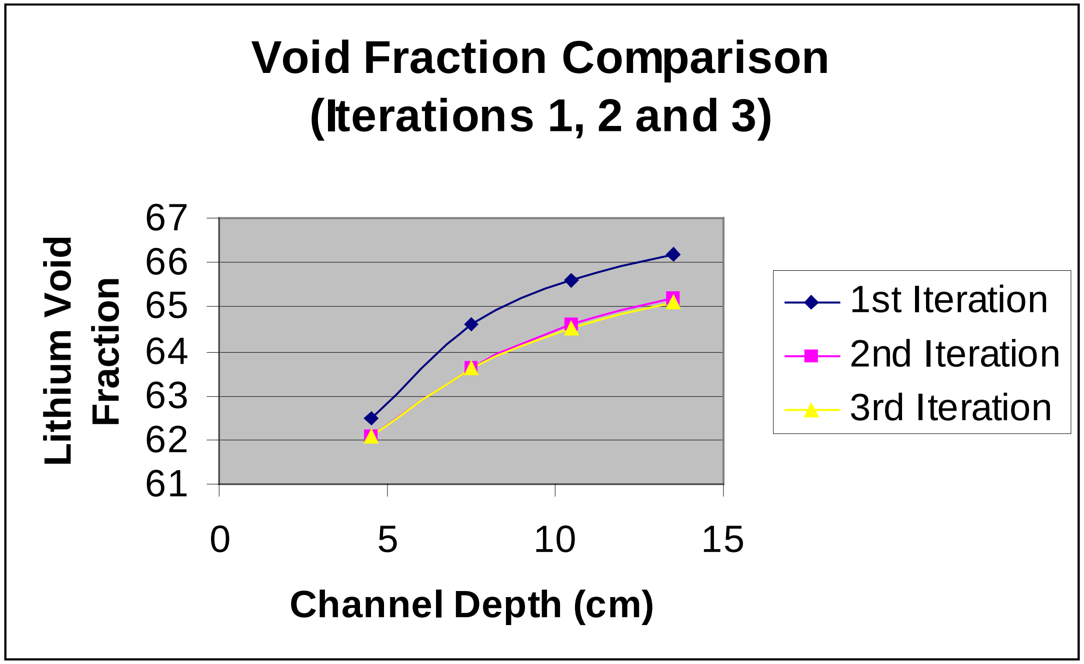
Iteration Comparison

- Iteration comparison for void distribution near 1st wall, 2nd and 3rd iterations converge



Iteration Comparison (continued)

- Channel #1 (nearest 1st wall) iteration comparison
  - ♦ Convergence seen from 2nd to 3rd iteration



Alternative Void Distribution Methodology

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- “Void Distribution in Boiling Pools with Internal Heat Generation”, Kazimi & Chen, (LMFBR core accidents with molten fuel pools forming)
- Paper concerned with analytical and experimental study of void distribution in an internally heated boiling pool (no channels, entire pool)
- Vertical profiles of the void fraction in a heated pool were obtained and favorably compared to an analytical models proposed
- Analytical model proposed

$$\alpha = 1 - \exp\left[\frac{-GY}{\lambda \rho_v B V_{\inf}}\right]$$

α = void fraction
G = heat consumed in vaporization
Per unit liquid volume per time
Y = vertical position in channel (cm)

λ = heat of vaporization
ρ_v = vapor density
B = 1.55 $(V_s/V_{\inf})^{0.65}$
$V_{\inf}$ = terminal rise velocity of a bubble in a stagnant liquid

Alternative Void Fraction Methodology (continued)

- The paper also proposes a classic drift-flux expression to predict macroscopic pool behavior (again no channels, entire pool)

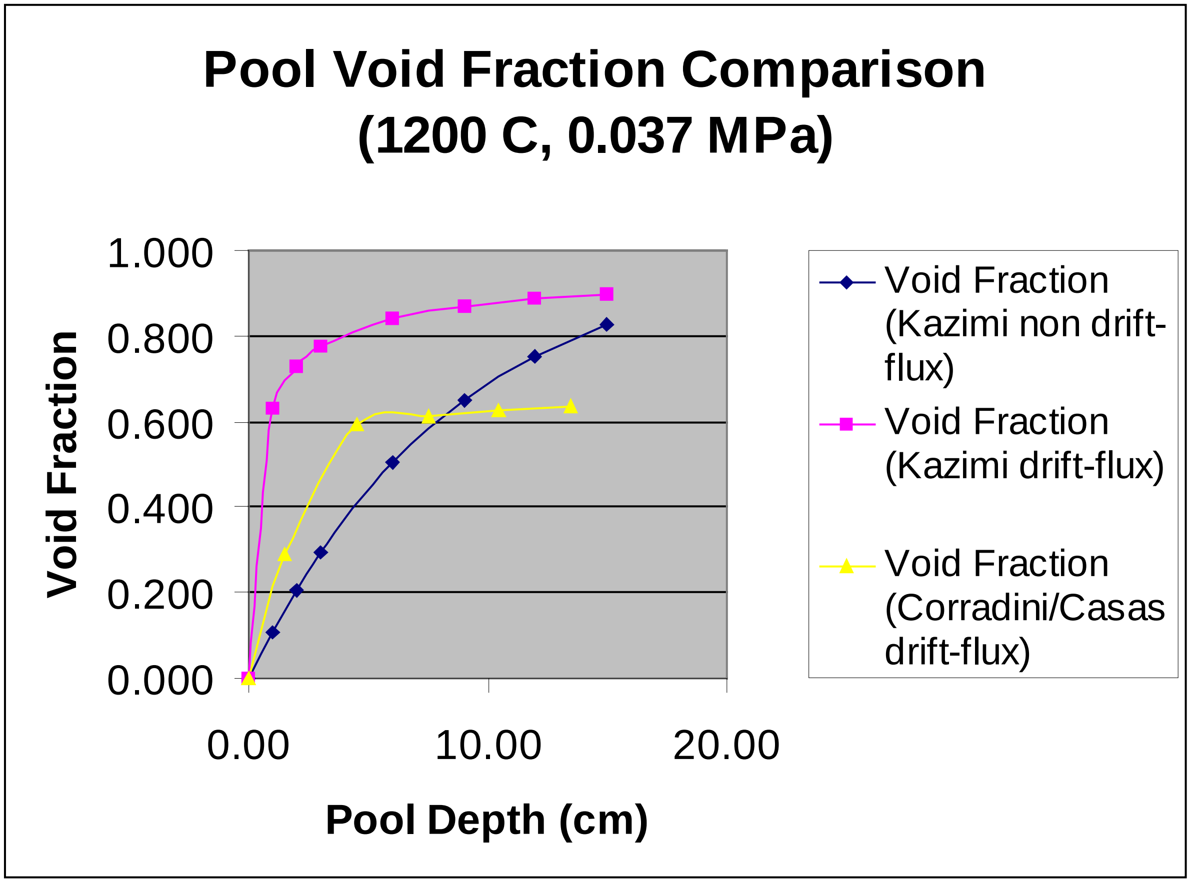
- For churn-turbulent flow

$$\alpha = 1 - \frac{1}{\left[1 + \frac{2GY}{\lambda \rho_v V_{\inf}}\right]^{1/2}}$$

- Plots of total pool void fraction versus vertical channel are provided on the following page

- Kazimi & Chen’s (uses average lithium heat generation rate from final iteration)
  - ♦ Analytical expression
  - ♦ Drift-flux
- Casas & Corradini’s
  - ♦ Drift-flux

Pool Void Fraction Methodology Comparison



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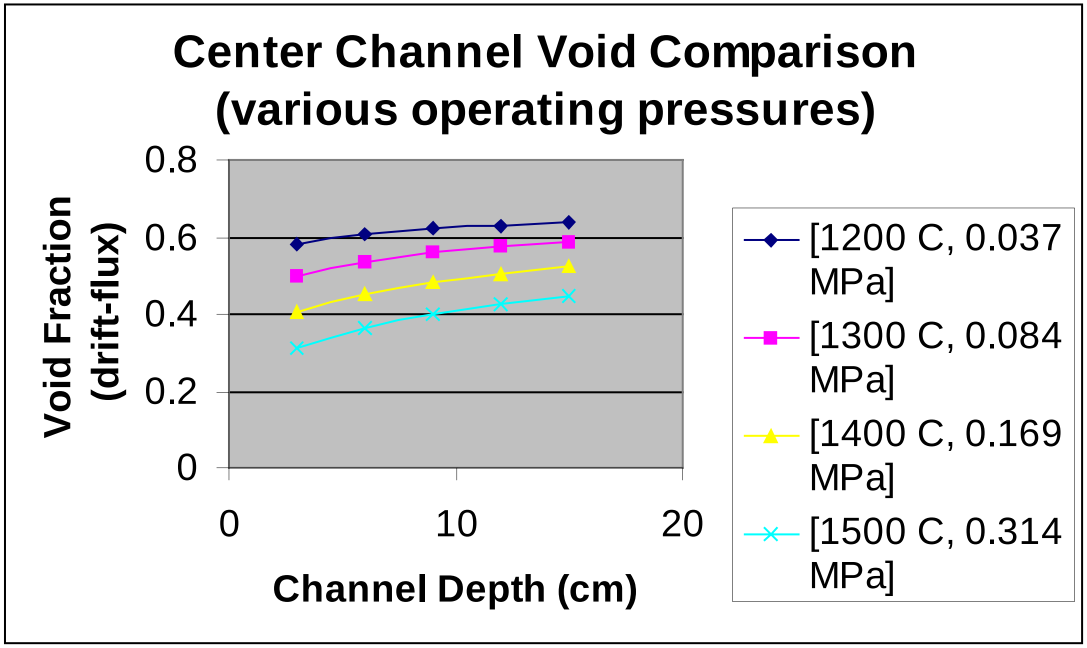
Conclusion

- Voids appear to be significant (mainly because of low operating pressure)
  - ♦ Can be reduced by increasing operating pressure



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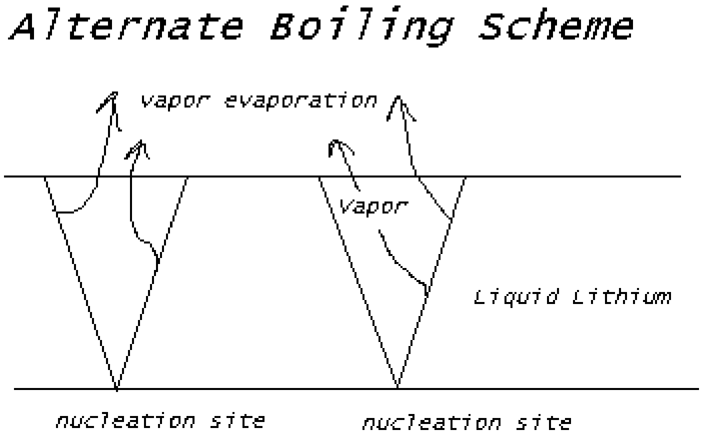
Conclusion (continued)

- Alternative boiling flow regime proposed by S. Malang (FzK)
  - Utilize MHD effects to hold channels open with minimal liquid lithium movement
    - Channels initiated at nucleation sites on bottom of lithium tray
      - Spaced as needed for heat removal with no additional boiling
  - Potential for smaller void fractions with stable liquid channels



- Need to perform first principle balance to estimate void fractions

Conclusion (continued)

- Drift-flux model
  - Magnitude of nuclear heating 2nd order, when Jg large (>5)
  - Low pressure ensures large void fractions
    - Low vapor density drives void fraction
      - At 0.037 MPa, lithium ρ_f/ρ_g= ~17000
      - sodium ρ_f/ρ_g= ~ 7400
      - water ρ_f/ρ_g= ~ 4500

- Agreement between Casas & Corradini drift-flux and Kazimi & Chen's two correlations (drift-flux and analytical) appears good

- Voids in excess of 50% will be seen

Conclusion (continued)

- Future work
  - ♦ Perform mass, momentum and energy balances on proposed alternative boiling flow regime with MHD effects
    - Determine whether the boiling lithium mass will act in such a manner
    - Will bubbly boiling regime transition to an orderly channel type arrangement?
  - ♦ Review MHD effects on drift-flux boiling model
    - With vigorous boiling, MHD appears to be of 2nd order
    - Lykoudis paper
      - ☐ Magnetic effect may cause "channeling", seen at small voids (~10%)
  - ♦ Analyze thermal-hydraulic effects of blanket capillary cooling
  - ♦ Determine dynamic (vibrations) loads to trays during boiling

- Show that a large bubble will not form inside 1st wall