INL/CON-24-80317-Revision-0

Thermal-hydraulics capabilities in predicting the post-CHF conditions

September 2024

Changing the World's Energy Future

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September 2024

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Thermal-hydraulics capabilities in predicting the post-CHF conditions

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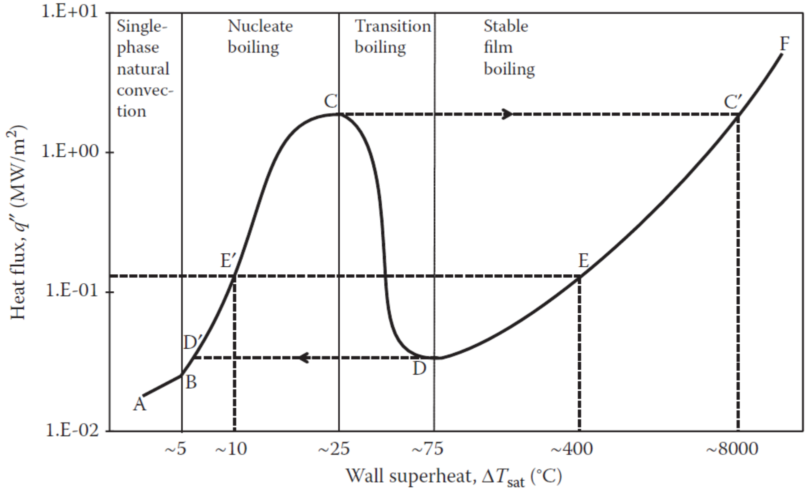
September 12, 2024

Categorizing phenomena

- Need to understand time at temperature (TAT)
  - Material phenomena
  - Thermal hydraulics (TH) phenomena
    - Critical heat flux (CHF)
      - Departure from nucleate boiling (DNB)
      - Dryout
    - Transition (unstable) boiling
    - Film (stable) boiling
    - Re-wetting
- Better characterization, more economic margins



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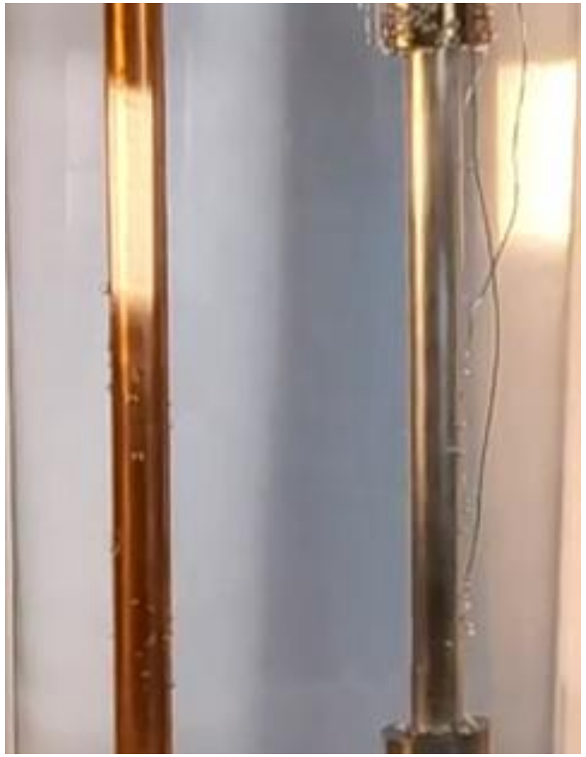

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How the phenomena interact

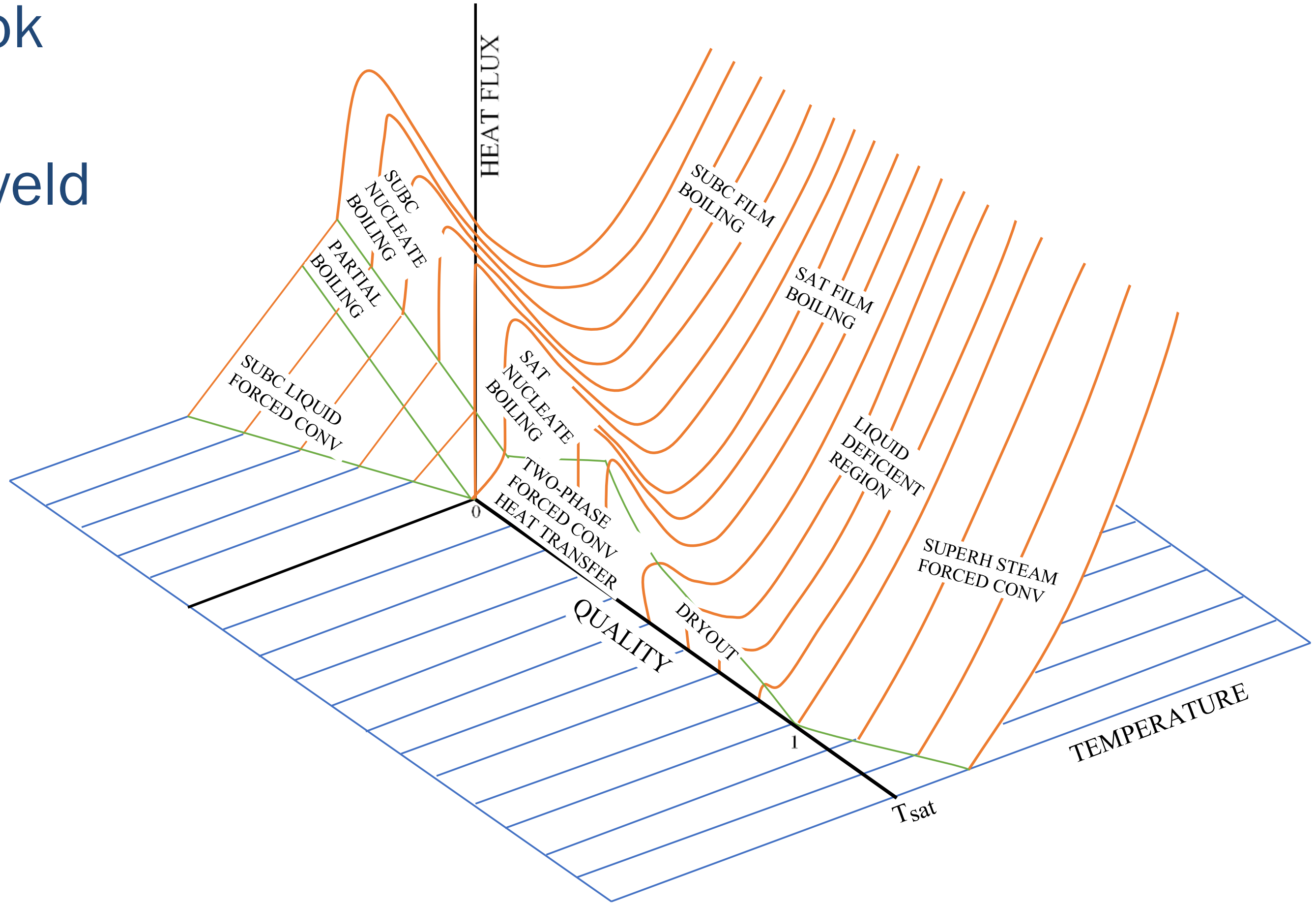
- TH → Material
  - Annealing
    - Cladding temperature (temperature driven properties)
    - Heating rate
    - Duration
  - Collapse, ballooning, buckling
  - Creep
  - Steam oxidation
  - Hydride formation
- Material → TH
  - Thermal properties (capacity, conductivity, wettability, coating type, etc.)
  - Deformation (channel flow area reduction and/or blockage)
  - Exothermic oxidation

Research considerations

- What influence does TH have on a material under TAT?
- TH driven transformation time constants
  - Shorter constants, failure more TH dependent
  - E.g., transient CHF
- Temperature dependency
  - More correlated, failure more TH dependent
  - E.g., eutectic mixture

Predicting CHF

- Threshold/margin figure of merit
- $q''_{CHF} = fcn(\boldsymbol{x_e}, \boldsymbol{G}, \boldsymbol{p}, L, \varepsilon, \mu, t, ?)$
- Diverse flow regimes necessitate look up tables
- Uncertainty estimated (e.g., Groeneveld 2006, RMS 7.1%)
- Prediction methods complications
  - Limiting quality phenomenon
  - Low flow as $x_e \to 1$
  - Intermittent dryout



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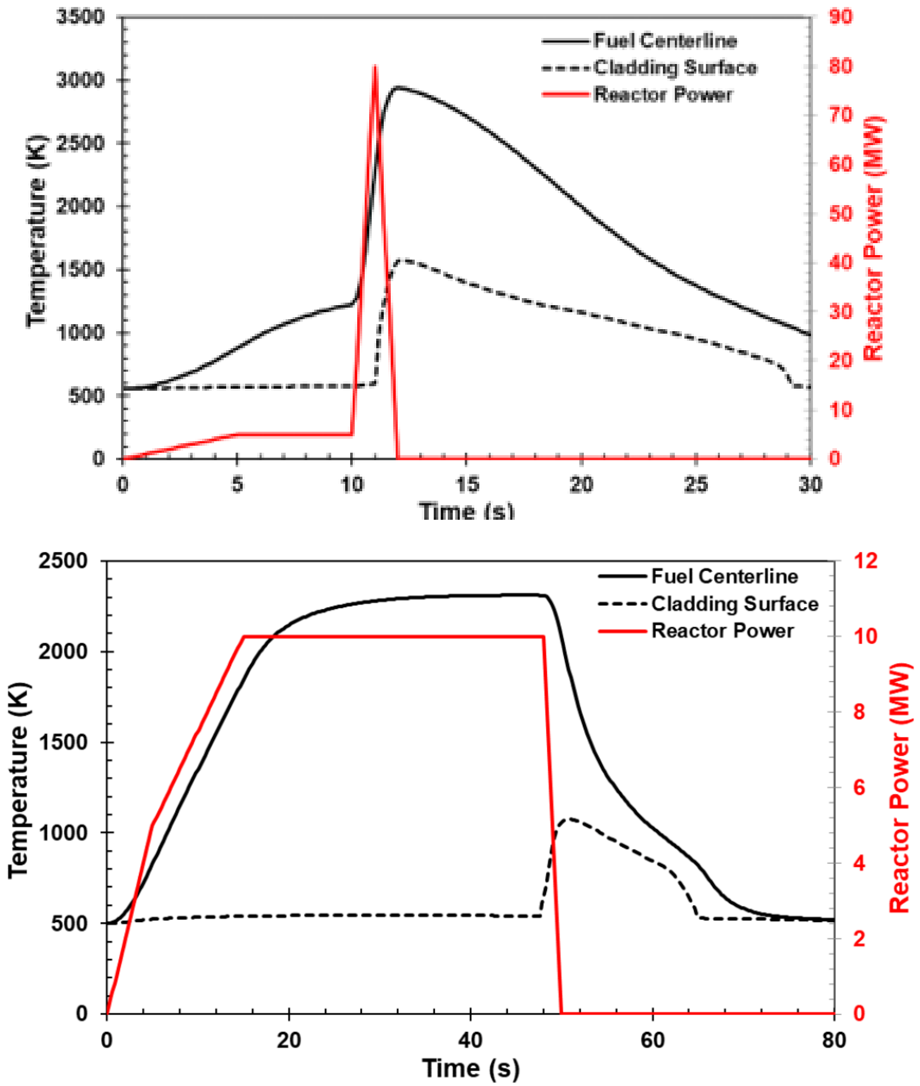
Uncertainty in predicting CHF

- Design basis accidents (DBAs) vs anticipated operational occurrences (AOOs)
  - Reactivity initiated accident (RIA), e.g. Control Rod Ejection → DNB
  - Pump trip → intermittent dryout
- Consider the type of AOO and the flow regime it encompasses



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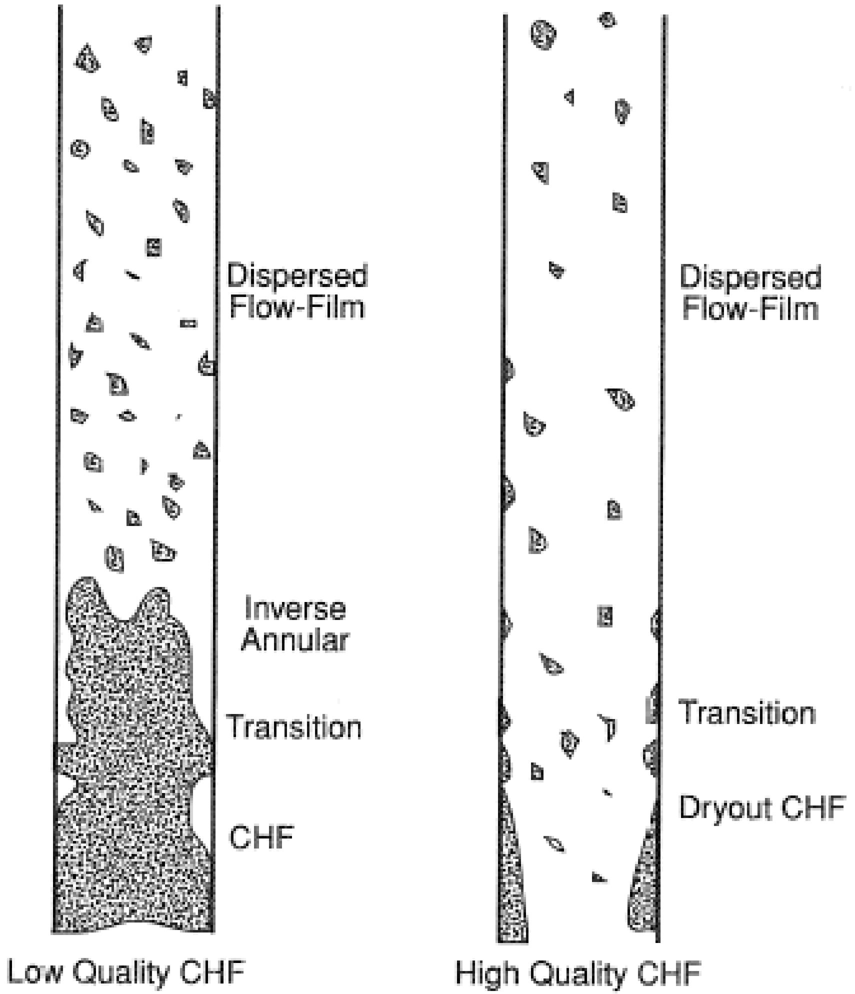
Predicting film boiling

- Flow regimes
  - Inverted annular film boiling
    - Low quality
  - Inverted slug film boiling
  - Dispersed flow film boiling (mist)
    - High quality
- Similar application to the CHF LUT (e.g., 2001 film boiling LUT (RMS 10.5%))
  - $T_{wall}\ or\ HTC_{film} = fcn(\boldsymbol{x_e}, \boldsymbol{G}, \boldsymbol{p}, \dots)$
- Complications
  - Thermodynamic nonequilibrium
  - Entrance effects
  - Grid effects
  - Non constant axial power



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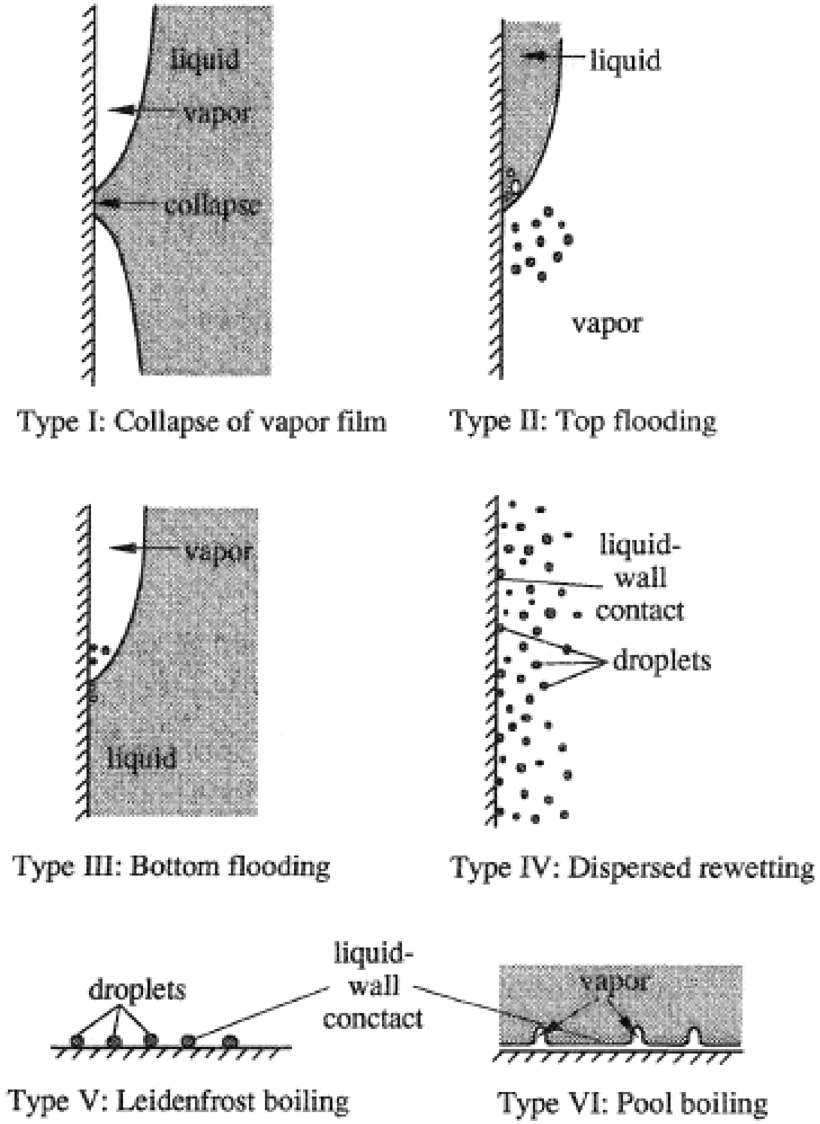
Rewetting of hot surfaces

- Termination of time at temperature
- Categorized by flow regime
- Determining minimum film boiling temperature (Leidenfrost, quenching, etc.), T_{MFB}
- Ex. BWR instabilities due to vapor-power feedback



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Post CHF existing experimental data

- BWR Full-size Fine-mesh Bundle Test Benchmark volume*
  - 8x8 bundle, dryout
- High Pressure Heat Transfer Facility
  - 2x2 bundle, dryout and rewetting
- Oak Ridge National Laboratory Rod Bundle Thermal-Hydraulic Test Facility*
  - 8x8 bundle, CHF and film boiling
- Karlstein Thermal-Hydraulic Experimental Facility (KATHY loop)
  - Up to 12x12 bundles, CHF through rewetting
- Royal Institute of Technology Tube Test 261*
  - Post dryout heat transfer
- Bennett Heated Tube Tests
  - Dryout location
- UW facility
  - Time in DNB for Cr-coated zircaloy cladding

*in RELAP5-3D assessment cases or RELAP5-3D simulated

Challenges

- Codes are not as well validated for post-CHF heat transfer
- **RELAP5-3D** leverages decades of validation and use in two phase thermal-hydraulic
  - 3D system TH code resolution, 2 phase, 2-fields
  - Use Groenveld 2006 LUT as default option
  - Have CHF alternate models
    - Osmachkin CHF model (RBMK reactors)
    - PG-CHF model based on NRI Czech dataset
      - verified on Westinghouse and Combustion Engineering bundles
  - Capabilities to model the pre- and post-CHF flow regimes using other correlations
    - e.g., modified Bromley for film boiling, Chen for nucleated boiling
  - For transition regime an interpolation between the pre- and post-CHF is adopted for calculating important factors (e.g., phasic wall friction, etc.)

RELAP5-3D
Reactor Excursion & Leak Analysis Program
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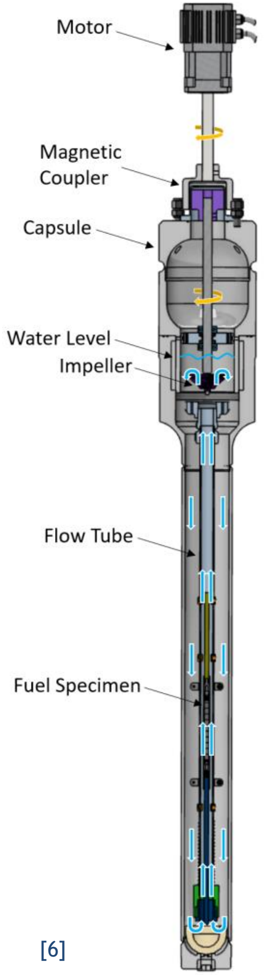

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Challenges

- Define the TAT problem space to assess current models
  - Sensitivity and uncertainty analysis
  - Use current experimental data
- Design and plan additional tests specific to TAT, including ATF materials
  - Endurance cycling of materials
  - Rewetting/quenching of in-pile transient testing
- INL has capabilities to work on
  - Experiment (e.g., TREAT capsule)
  - Data analysis (RELAP5-3D/RAVEN code)
  - Coupling with subchannel codes (RELAP5-3D/COBRA-TF) and 3D thermomechanical code (RELAP5-3D/BISON) via MOOSE
  - Pre-, post- and CHF thermal-hydraulic models improvement (RELAP5-3D)

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6. Folsom, Charles P., Robert J. Armstrong, Nicolas E. Woolstenhulme, Devin D. Imholte, Klint Stephens Anderson, and Colby B. Jensen. Thermal-hydraulic and Fuel Performance Scoping Studies of a Flowing Water Capsule in TREAT. No. INL/CON-22-67496-Rev001. Idaho National Laboratory (INL), Idaho Falls, ID (United States), 2022.
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