OPERATIONAL SAFETY BRIEFING

Boiling Crisis & Subchannel Analysis

Engineering & Safety

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Executive Summary

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Briefing Objectives

- **Define the Threat:** Physics of boiling crisis (PWR DNB vs BWR Dryout).
- **Quantify Margins:** Deconstruct DNBR/CPR and statistical limits.
- **Methodology:** 3-Field discretization in modern subchannel codes.

Key Deliverables

- Technical alignment for engineering & operations.
- Validated transient response workflow.

Operational State

STATUS: GREEN
Normal Operation

STATUS: YELLOW
Margin Erosion

STATUS: RED
Limit Exceeded

Phenomenology: The Boiling Transition

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The Definition: A sudden transition from efficient nucleate boiling to an inefficient film boiling regime, causing a rapid, potentially destructive cladding temperature excursion.

Primary Drivers:

- **Heat Flux ↑:** Power maneuvers, peaking factors, crud.
- **Cooling ↓:** Flow coastdown, depressurization, loss of subcooling.
- **Geometry:** Spacer grid deformation, flow blockage.

Critical Terminology

Nucleate Boiling → Film Dryout → Wall Superheat. *The transition is non-linear and cliff-like.*

Safety Targets:

- Cladding Integrity (PCT Limits).
- Fuel Rod Geometry (No ballooning).
- Regulatory Compliance (GDC).

CHF vs. Boiling Crisis

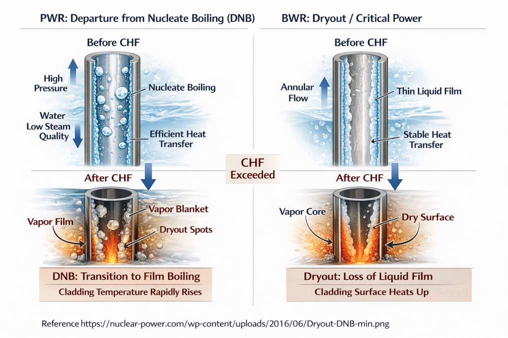
Terminology

- **CHF (Critical Heat Flux):** The maximum heat flux where the wall maintains continuous liquid contact.
- **Boiling Crisis:** The post-CHF regime characterized by vapor blanketing.

Regime Classification:

PWR: **DNB** (Departure from Nucleate Boiling). Subcooled/Low quality.

BWR: **Dryout**. High quality annular flow (liquid film depletion).



Comparison of bubble dynamics (Source: nuclear-power.com)

Regime Map: Operational Parameters

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Governing Physics

1. **Pressure:** Influences saturation temp, fluid properties, and bubble dynamics.
2. **Mass Flux (G):** Drives convective cooling, entrainment, and rewetting.
3. **Quality (x) / Subcooling:** Defines the thermodynamic state along the boiling curve.

Heuristics:

- **PWR DNB:** Driven by local heat flux vs. bubble crowding.
- **BWR Dryout:** Driven by integral power vs. film inventory.

Control Room Monitors

- Pressurizer Pressure
- Loop/Core Flow
- Axial Flux Difference (AFD)
- $F_{\Delta H}$ / F_Q

RULE: Margin $\downarrow$ if Power $\uparrow$ or Flow $\downarrow$

PWR Deep Dive: DNB (Low-Quality)

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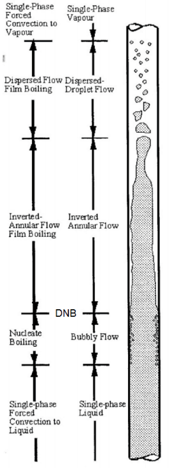
Mechanism:

- Intense nucleate boiling creates bubble crowding at the wall.
- Liquid supply to the surface is choked off.
- Vapor blanket insulates the rod, causing temperature excursion.

Location:

- Hot channel (highest radial peaking).
- Usually slightly downstream of peak power (enthalpy effect).



(a) Low-Quality Flow

BWR Deep Dive: Dryout (High-Quality)

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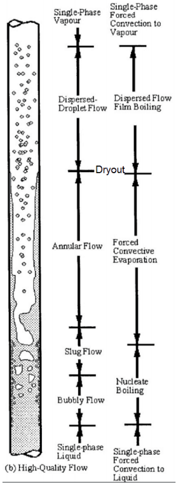
Mechanism:

- Annular flow regime: Vapor core, liquid film on wall.
- Film is depleted by evaporation and entrainment (droplet stripping).
- When film thickness $\rightarrow 0$, dryout occurs.

Location:

- Typically near the top of the bundle (highest quality).
- Strongly dependent on spacer grid "rewetting" effects.

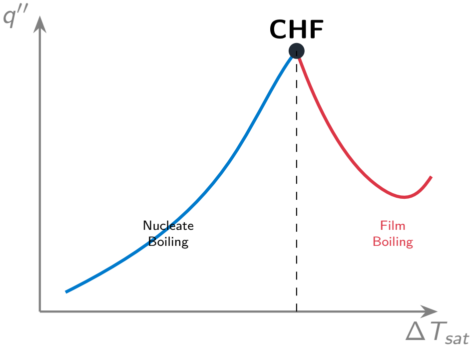


The Heat Transfer Cliff

Why CHF Matters:

- **Pre-CHF:** Nucleate boiling provides high Heat Transfer Coefficient (HTC).
- **At CHF:** Critical limit is reached.
- **Post-CHF:** Film boiling (vapor insulation) drops HTC by orders of magnitude.

CRITICAL
Small hydraulic change = Large ΔT



Safety Limits: DNBR vs. CPR

PWR: DNBR (Ratio)

$$\text{DNBR} = \frac{\text{Predicted CHF}}{\text{Actual Heat Flux}}$$

- **Goal:** Maintain $>$ Limit (e.g., 1.30).
- *Physical Meaning:* Margin against rewet failure.

BWR: CPR (Ratio)

$$\text{CPR} = \frac{\text{Critical Power}}{\text{Bundle Power}}$$

- **Goal:** Maintain $>$ OLMCPR.
- *Physical Meaning:* Margin against film dryout.

Action: Investigate any downward trend.

Scaling Considerations: From Core to Pin

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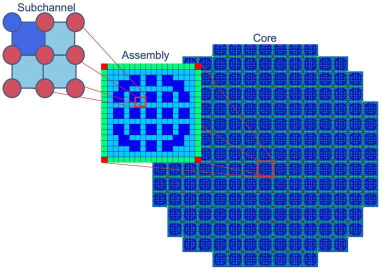
The Resolution Requirement: Core and assembly-level thermal-hydraulics "smear" properties, masking the local extremes where DNB actually occurs. To accurately model safety limits, the resolution must be refined.



Integrated Scaling Hierarchy

Nodalization Hierarchy:

1. **Core Level:** Coarse nodes (1 node/assembly). Sets global Pressure & Flow boundary conditions.
2. **Assembly Level:** Identifies the "Hot Assembly" but misses intra-assembly flow redistribution.
3. **Subchannel Level:** The required scale to capture **complex local effects**:
   - Local mixing from mixing vanes.
   - Radial crossflows within and between assemblies.

Subchannel Analysis: The Method

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Overview: A thermal-hydraulic modeling approach that discretizes fuel assemblies into parallel, coupled flow channels ("subchannels") to solve conservation equations.

Advantages over CFD:

- Computational efficiency allows full-core analysis.
- Validated correlations for mixing and CHF.
- Industry standard (VIPRE, COBRA, CTF).

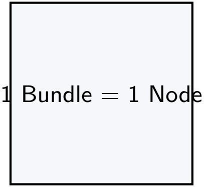
Key Outputs

- Minimum DNBR/MCPR
- Local Quality/Void
- Mass Velocity (G_{local})

"Bundle Weather Forecast"

Discretization: Subchannel vs. System Level

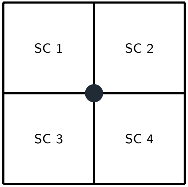
System Level (RELAP/TRACE)



Values are smeared
average of 200+ rods

- **Resolution:** Coarse (1-D flow).
- **Use Case:** LOCA, plant transients.
- **Blind Spot:** No local peaking visibility.

Subchannel (VIPRE/CTF)



Explicit rod-to-coolant
heat transfer

- **Resolution:** Fine (pin-level).
- **Use Case:** DNB/Dryout margin.
- **Key Physics:** Turbulent mixing.

Bundle Nodalization: Subchannels & Gaps

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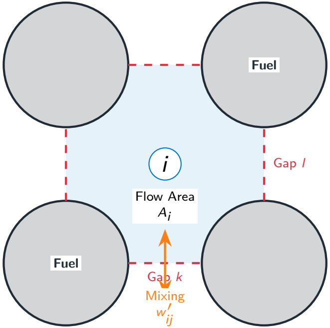
Definitions:

- **Subchannel (i):** The flow area between rods (Control Volume).
- **Gap (k):** Lateral connection between subchannels where crossflow (w_{ij}) occurs.
- **Rod:** Heat source (q'').

Subchannel codes discretize the entire core into thousands of these parallel channels to find local limits.



Subchannel Governing Equations (Mixture Model)

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Conservation Laws (Control Volume i):

Mass Conservation

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial (\rho_i u_i)}{\partial z} + \sum_j w_{ij} = 0$$

Momentum Conservation (Axial)

$$\frac{\partial P}{\partial z} = -\frac{\partial (\rho u^2)}{\partial z} - \left[\frac{f}{D_h} + K\right]\frac{\rho u^2}{2} - \rho g - \sum_j w_{ij} u^*$$

Energy Conservation

$$\frac{\partial (\rho_i h_i)}{\partial t} + \frac{\partial (\rho_i u_i h_i)}{\partial z} = q'_{rod} - \sum_j (w_{ij} h^* + w'_{ij} \Delta h)$$

Key Terms

- w_{ij}: Diversion crossflow (driven by ΔP).
- w'_{ij}: Turbulent mixing (driven by Δh).
- f, K: Friction & Form loss.

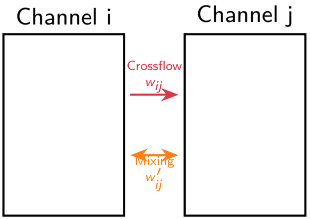
Mixing & Crossflow: The Secret Sauce

Turbulent Mixing (w')

Net zero mass exchange ($\dot{m}_{net} = 0$). Swaps energy and momentum. *Effect:* Cools the hot pin by sharing heat with cooler neighbors.

Diversion Crossflow (w)

Net mass movement ($\dot{m}_{net} \neq 0$) driven by pressure gradients (e.g., blockage, boiling expansion).



Schematic Key: The top arrow (w) shows mass physically leaving one channel for another (Crossflow). The bottom arrows (w') show turbulence swapping equal pockets of fluid (Mixing).

Advanced Modeling: The 3-Field Approach

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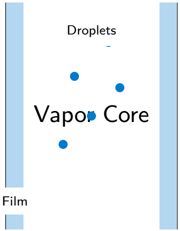
Beyond Homogeneous Equilibrium: Standard models assume liquid and vapor move together. For BWR dryout, we need more physics.

The 3 Fields:

1. **Continuous Liquid:** The film on the wall.
2. **Entrained Liquid:** Droplets in the core.
3. **Vapor:** The gaseous core.



3-Field Equations: Mass Conservation

Three separate mass balances per node:

1. Vapor Mass

$$\frac{\partial(\alpha_v \rho_v)}{\partial t} + \nabla \cdot (\alpha_v \rho_v \vec{v}_v) = \Gamma_{vap}$$

Vapor generation from evaporation.

2. Liquid Film Mass

$$\frac{\partial(\alpha_f \rho_f)}{\partial t} + \nabla \cdot (\alpha_f \rho_f \vec{v}_f) = D - E - \Gamma_{film}$$

D: Deposition of drops to film. **E**: Entrainment of film to drops.

3. Entrained Droplet Mass

$$\frac{\partial(\alpha_d \rho_d)}{\partial t} + \nabla \cdot (\alpha_d \rho_d \vec{v}_d) = E - D - \Gamma_{drops}$$

Dryout happens when Film Mass $\rightarrow$ 0.

3-Field Equations: Momentum Balance

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Momentum Complexity: We solve momentum for each field, allowing different velocities ($v_v \neq v_d \neq v_f$).

Interfacial Drag

The fields interact through drag forces:

$$F_i = C_D \frac{1}{2} \rho (v_{rel}) |v_{rel}| A_{int}$$

- Vapor drags droplets up.
- Vapor shears the film surface.

Operational Impact

If vapor velocity is very high, it shears the film surface, increasing **Entrainment (E)**.

High Entrainment $\rightarrow$ Thinner Film $\rightarrow$ Earlier Dryout.

3-Field Equations: Energy Balance

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Where does the heat go?

Film Energy Equation

Heat from the rod enters the liquid film.

- If $T_{film} < T_{sat}$: Sensible heating.
- If $T_{film} = T_{sat}$: Evaporation (Γ_{film}).

Vapor/Droplet Energy

Typically, droplets are assumed to be at T_{sat}. Vapor can become **superheated** even if droplets exist (non-equilibrium), but in standard dryout analysis, we focus on the film depletion limit.

Critical Logic: Dryout = Integrated Film Depletion

Closure Models: The Entrainment/Deposition War

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The accuracy of a 3-field code (like COBRA-TF) depends entirely on these empirical models:

Entrainment (E)

- **Driver:** Vapor shear vs. Surface tension.
- **Effect:** Rips liquid off the wall.
- **Bad for margins.**

Deposition (D)

- **Driver:** Turbulent diffusion of drops.
- **Effect:** Returns liquid to the wall.
- **Good for margins.**

Spacer Grids: Modern spacers are designed to maximize **D** (Deposition) to replenish the film.

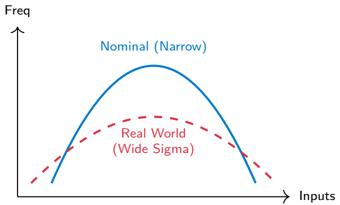
The Uncertainty Challenge

The Problem: Calculating CHF with "nominal" values assumes a perfect world.

Sources of Uncertainty:

- **Plant Data:** Power, Flow, Temp ($\pm 2\%$).
- **Manufacturing:** Rod pitch, Diameter.
- **Code/Model:** Correlation scatter.

Plot: The solid blue line is the "Perfect" distribution. The dashed red line is the "Real World" distribution. Variances widen the bell curve, pushing the "tail" closer to the failure point (Limit), eating up margin.



Impact: Margin $\downarrow$ significantly

Statistical Methodology: RTDP vs. Monte Carlo

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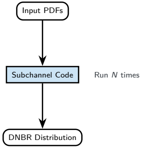
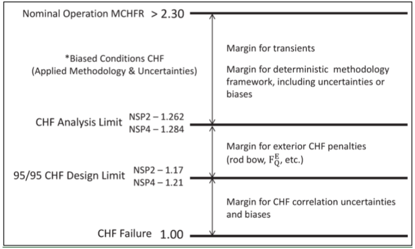
RTDP (Revised Thermal Design Procedure)

- Used in PWRs.
- Combines uncertainties using Root Sum Square (RSS) statistics.
- Result: A single "Design Limit DNBR" (e.g., 1.25).

Monte Carlo Sampling

- Run subchannel code a number of times based on the desired confidence interval.
- Randomly sample inputs from PDFs.
- Determine true failure probability.





Target: 95/95 Confidence/Probability

Operational Response Workflow

1. Confirm State → **2. Update Margin** → **3. Mitigate**

1. Confirm State
   - P, Flow, Power
   - Axial Shape
2. Update Margin
   - Run Subchannel Code
   - Check Min DNBR
3. Mitigate
   - Margin < Limit?
   - Adjust Power, Rods, Borate

Principle: Proactive Margin Management

Mitigation Strategies

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Immediate Actions (Control Room)

- **Reduce Power:** Direct heat flux reduction.
- **Increase Flow:** Improves rewetting and entrainment margin.
- **Shape Control:** Use rods to flatten axial peaks.

Long-Term Engineering

- **Spacer Design:** Enhance deposition (mixing vanes).
- **Fuel Cycle:** Load patterns to minimize peaking.
- **Chemistry:** Prevent crud buildup.

Final Takeaways

- **Physics:** It's about liquid contact. DNB (bubbles blocking) vs Dryout (film exhaustion).
- **Modeling:** 3-Field models are essential for high-quality BWR analysis to track the film.
- **Safety:** Margins are statistical. We operate far from the cliff to account for uncertainty.

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References & Further Reading

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Key Technical Resources

- **Textbooks:**
  - Todreas, N.E. & Kazimi, M.S. *Nuclear Systems Vol I.*
  - Lahey, R.T. & Moody, F.J. *Thermal-Hydraulics of a BWR.*
- **Methodology:**
  - "COBRA-TF: A Three-Field Two-Fluid Model."
  - EPRI Reports on CHF correlations.

Industry Codes

VIPRE-01

COBRA-TF (CTF)

RELAP5-3D