CASL SCIENCE & TECHNOLOGY
Consortium for Advanced Simulation of Light Water Reactors

Departure from Nucleate Boiling (DNB) Multi-Physics Approach & Applications using VERA

Departure from nucleate boiling (DNB) serves as a critical parameter in nuclear power plant operational and safety analysis. It occurs when a fuel rod clad surface is overheated due to the formation of a local vapor layer on the waterside surface, causing a dramatic reduction in heat transfer capability. DNB is a complex phenomenon that has been experimentally and analytically investigated over the past several decades. Its complexity is inherent in the multi-scale and multi-physics processes (fluid flow, heat transfer, material and surface effects) that govern its occurrence. Simulation is further complicated by the geometric complexity of the fuel assembly design, variability of operating power profiles, and scarcity of open and microscopic experimental test data.

Although DNB is generally associated with local and microscopic vapor formation during overpower conditions (subcooled boiling), liquid film dryout can also occur during some high coolant temperature and low flow accident scenarios. Because of the diverse nature of the physics involved and the importance of the phenomenon, CASL's work on DNB is by nature extremely collaborative, bringing together experts in DNB phenomenology, modeling and simulation, experimental methods & data, and validation and uncertainty quantification (VUQ) methods.

Industry predictions of DNB are currently based on empirical correlations derived from small scale rod bundle tests that simulate each unique fuel assembly design. With the data in hand, a subchannel thermal-hydraulic code is applied to calculate the local fluid conditions in the rod bundle for each test point and these local fluid conditions are then used to develop an empirical DNB correlation. Commercial PWRs must apply regulatory-approved DNB correlations as part of the plant safety analysis.

CASL's coupled multi-physics approach currently utilizes two primary tools: Computational Fluid Dynamics (CFD) is used to provide design-specific turbulent mixing data and subchannel analysis is used for practical application (full reactor core) simulations using CFD-generated results for refinement of the local fluid turbulence. An example of the approach is provided within CASL-I-2014-0119-000 to analyze a postulated PWR main steamline break (MSLB) event initiated at the hot zero power (HZP) with all coolant pumps continuing in operation (i.e., the high flow case).

During a postulated PWR main steamline break (SLB) event initiated from the hot zero power (HZP) condition, the increased steam flow rate from the broken steam pipe on one of the steam generators would result in a significant reduction in the primary coolant temperature and an increase in the reactor core average power and the peak fuel rod power, thus imposing a challenge to the Departure from Nucleate Boiling (DNB) criterion. As required in a PWR safety analysis, the most reactive shutdown control rod assembly is assumed to be stuck in its withdrawn position. A return to power following a steam line rupture is problematic mainly because of the high power peaking factors that exist as a result of the postulated stuck control rod. The core is ultimately shut down by the boric acid injection delivered by the safety injection system.

Westinghouse researcher Yixing Sung is leading CASL's effort to model DNB performance with coupled mulitphysics. For this initial demonstration, the team used a five step approach to model the WBN-1 core:

1) Deplete the core to the end of cycle 1 and create a restart point for HZP conditions using VERA;
2) Generate a reactor system state point with Westinghouse's version of RETRAN from the HZP MSLB transient calculation for use as core boundary conditions;
3) Generate the core inlet temperature distribution using CFD (in this case, CD-adapco's STAR-CCM+ was used);
4) With VERA's coupled neutronics/T-H capability, predict the quasi-steady state core response (e.g., pin-by-pin power and local fluid conditions in each subchannel); and
5) Using the results from 4), calculate the DNB Ratio (DNBR) with VERA's CTF subchannel code.

For this analysis, the RETRAN-generated boundary conditions included:

- 20% of rated power
- 421°F inlet average; -37/+10°F variation across the distribution
- 460 psi system pressure
- Full core geometry (all 193 assemblies)
- 0 ppm soluble boron concentration
- All control rods inserted with one rod stuck in the withdrawn position.

First, the CFD-predicted local temperature and flow rates at the lower core inlet were generated for use as boundary conditions for downstream analysis. Although during the event the low temperature coolant is injected from one cold leg, a cold stream is predicted between the injection cold leg and the adjacent cold leg due to swirling of the flow. Also, the CFD solution exhibits an oscillatory behavior that is attributed to both physical and numerical causes; strong vortex flow in the lower plenum induces a non-uniform pressure upstream and the multi-hole geometry

Table 1 Comparison of Hot Channel Parameters for High-Flow SLB Sensitivity Study

Parameter	Uniform Inlet Flow	Non-uniform Inlet Flow	Inlet Temp. Distribution T_MIN	Inlet Temp. Distribution T_MAX
Max. Pin Linear Power (W/cm)	257.0	243.3	232.8	264.9
Max Clad Temp (°C)	274.1	269.9	267.2	276.4
Max Fuel Temp (°C)	1016.6	958.2	906.0	1051.2
MDNBR	10.5	10.5	11.7	10.2
CHF (W/m²)	8474.0	8274.8	8472.3	8474.6
Heat Flux (W/m²)	805.1	787.1	724.3	827.3
Eq. Quality	-0.061	-0.067	-0.078	-0.059
Mass Flux (kg/m²/s)	4462.9	5473.5	4413.4	4410.6

of the lower core plate tends to promote manometer effects numerically. Therefore, a search for bounding cases was conducted. The search was concluded when the flow rate and temperature at the monitored location repeated themselves during iteration and for this simulation the values are considered pseudo-global extremes.

For depletion calculations, a quarter-core model was used in VERA using coupled neutronics/T-H to end of cycle (EOC) 1 at 441 Effective Full Power Days (EFPD), at which point quarter-core model was expanded into a full-core model for the SLB scenario and a restart file was created. The restart state point was set to the limiting DNBR conditions as determined by RETRAN, and the CFD-predicted inlet temperature and mass flow rate distributions were input to VERA.

The rupture of a steam line in one of the four primary coolant loops resulted in a highly asymmetric vessel inlet coolant temperature and an asymmetric core power distribution. Because the most reactive control rod was assumed to be stuck outside the core in the same region of the vessel affected by the loop with the steamline break, high power peaking factors occurred in and around the assembly with the stuck rod. Also, because this analysis assumed that offsite power was available, the core flow rate was relatively large at 20% of the nominal. Figure 1 shows the calculated pin power distribution at 45.8 cm from the bottom of the core, along with the full core power distribution and predicted coolant temperature distribution. As illustrated by the figure, the core power distribution was highly asymmetric; the high power assemblies were clustered in and around the stuck control rod location. The hot channel factor was calculated to be ~7.02 with a bottom peaked axial power profile.

Because the axial power was bottom peaked, cross-flow from the surrounding channels into the hot channel appeared to occur only in the first 50 cm of the channel, after which the axial flow either stayed the same or slowly decreased. The enthalpy rise in the hot channel was not rapid, and as a result, the liquid reached saturation temperatures only after 70 cm from the top of the active fuel. Figure 1 shows the 3D liquid temperature distribution, demonstrating the enthalpy rise in high powered regions (i.e., channels surrounding the assembly with the stuck rod). The locations of the cold regions are consistent with the inlet temperature distribution.

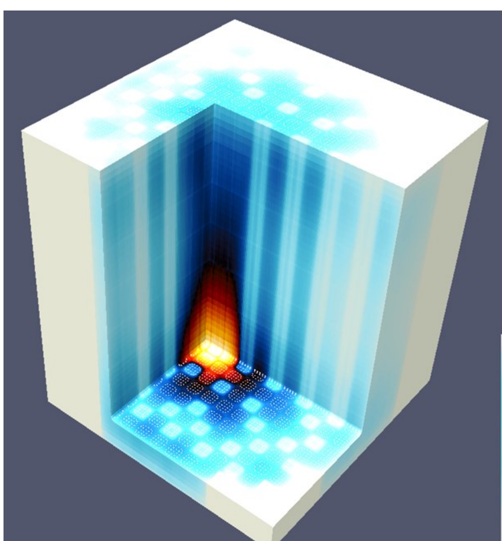
A sensitivity calculation was performed to evaluate the impact of the CFD-predicted inlet flow distribution. For a uniformly distributed inlet flow, the effects of inlet turbulence begin to dissipate within the first 122 cm of core entry due to mixing with high flow rates. Although the hot channels are the same for the uniform and non-uniform cases, the axial profiles and hot rods differ due to the higher flow in the non-uniform case. However, the rod temperatures in the non-uniform case quickly drop below those predicted in the uniform case at higher elevations due to larger cross-flow mixing. The equilibrium quality is small in both cases. Boiling starts later in the non-uniform inlet flow case due to larger mixing. The maximum heat flux, hence the margin to DNB failure in terms of minimum DNBR (MDNBR), occurs at the same axial elevation in both cases.

The effect of different inlet temperature distributions with a uniform inlet flow distribution was also evaluated by comparing hot channel conditions. Table 1 summarizes the results from the two inlet temperature distribution cases (T_MIN and T_MAX), as well as the original uniform and non-uniform inlet flow cases. Results indicate that a higher inlet temperate in the stuck rod assembly position yields slightly more limiting results in terms of fuel and clad temperatures, heat flux, and DNBR.

The DNBR was calculated using VERA CTF's default correlation (Biasi). At each iteration of the coupled code calculation, CTF performs a series of pseudo-transient calculations until convergence is achieved on mass and energy balances. Calculated moderator temperature, density and fuel temperatures are exchanged with VERA's neutronics subcomponent to calculate a power distribution. Iterations between the two codes continue until convergence is achieved on the coolant temperature and density.

These simulations required approximately 20 neutronics/T-H iterations for global convergence, with a total wall-clock time of ~6.5 hours each on the OLCF Titan computers. The neutronics model used 58 axial mesh regions. Flux calculations used a 47-energy group library. Transport sweeps were performed on 1,243x12=14,906 Titan processors. To accommodate the full core model at restart, 1,243x16= 19,888 processors were allocated for memory. The T-H model included 56,288 subchannels, 112,064 gaps and 55,777 rods that were solved in parallel on 193 cores.

For more information, see CASL-EC-2015-0173-000 .



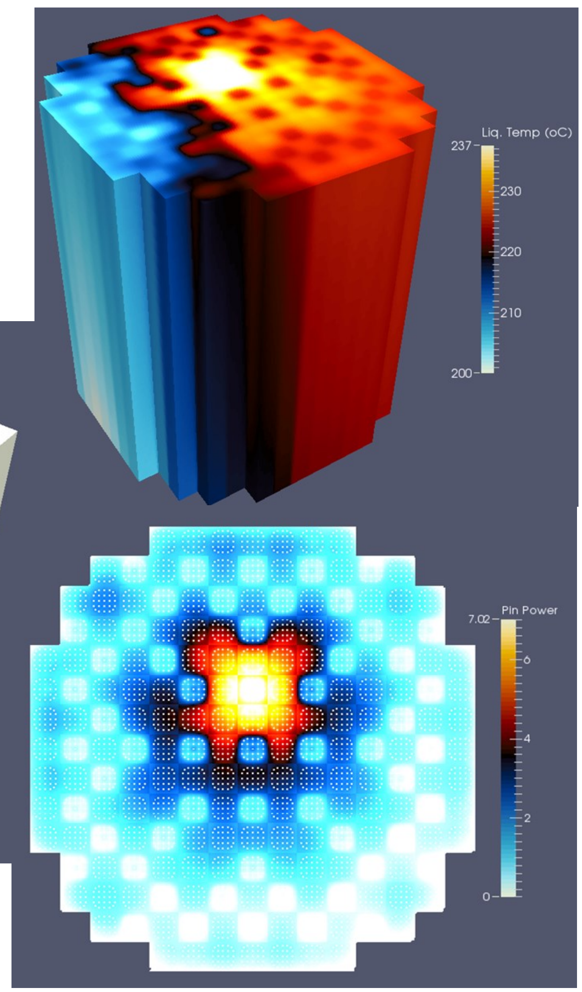


Figure 1 [top] 3-D Coolant Temperature Distribution ; [left] Whole-Core Pin Power Distribution; [bottom]Pin Power Distribution at z=+45.8cm