Evaluating High Burnup Fuel Behavior under LOCA conditions

Fuel Safety Research Meeting
October 18 – 19, 2016

Michelle Bales and Ian Porter
Division of Systems Analysis
Nuclear Regulatory Research
US Nuclear Regulatory Commission

Contents

- Past work
  - NRC Study: Predictions of Fuel Dispersal During a LOCA
  - NRC Study: Dispersed Fuel Mobility
  - Regulatory Disposition of Fuel Fragmentation, Relocation and Dispersal
- Current work
  - Consistent Fuel Rod Modeling
  - Integrated Code Framework for Modeling LOCA
- Future work
  - Code Development Plans: FRAPTRAN

NRC Study: Predictions of Fuel Dispersal During a LOCA

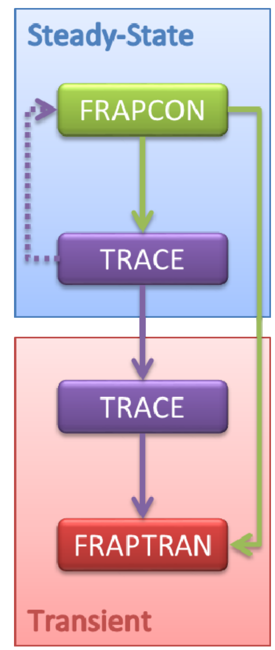
- Study completed by Patrick Raynaud and Ian Porter and published at the WRFPM in 2014, Sendai, Japan
- Objective: to generate best-estimate predictions of the number of rod ruptures and postulate the possible resulting amount of fuel dispersal.
- Three plant designs, five LOCA scenarios at 3 times in cycle life investigated.

Experimental Research

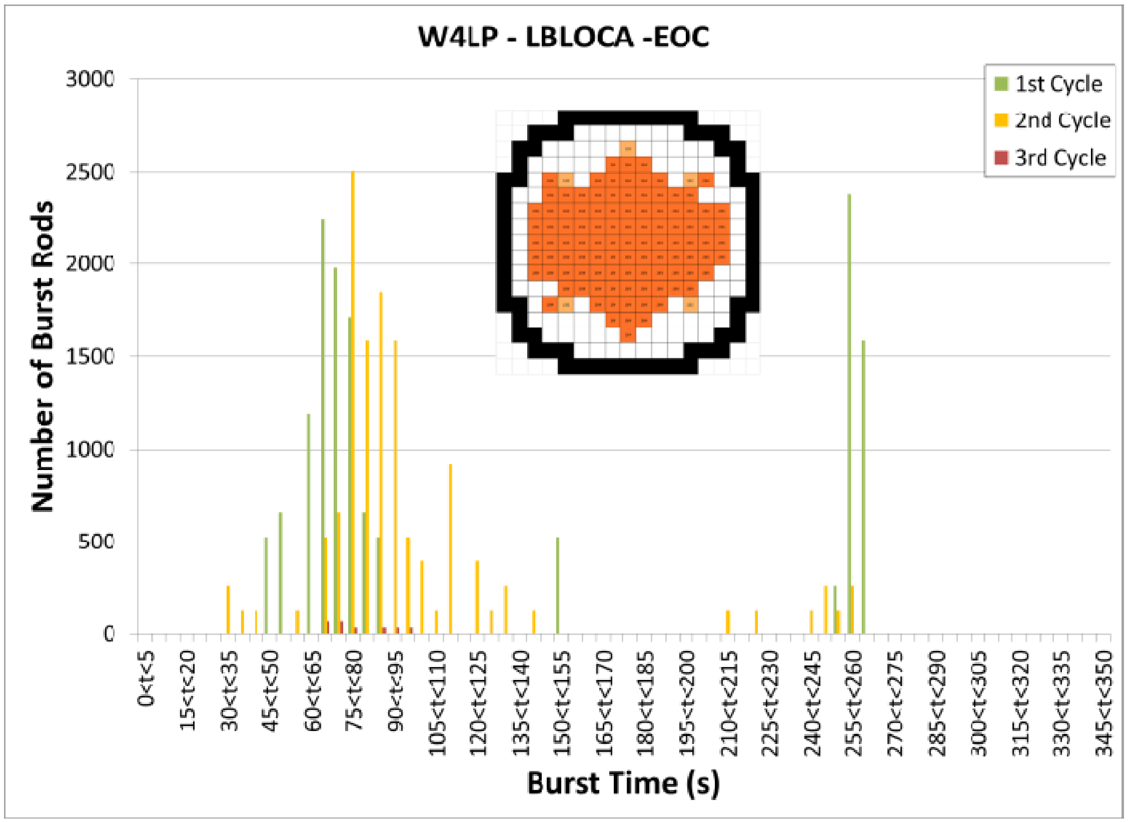
- Fuel rod rupture conditions
- Fuel relocation conditions
- Burnup dependent particle size distribution
- ANL, Halden and Studsvik LOCA research, documented elsewhere

Fuel dispersal predictions

- Number, timing, and location of fuel rod ruptures during a LOCA
- Fuel rod characteristics at and near rupture
- Estimation of dispersed fuel based on experimentally determined thresholds



NRC Study: Predictions of Fuel Dispersal During a LOCA

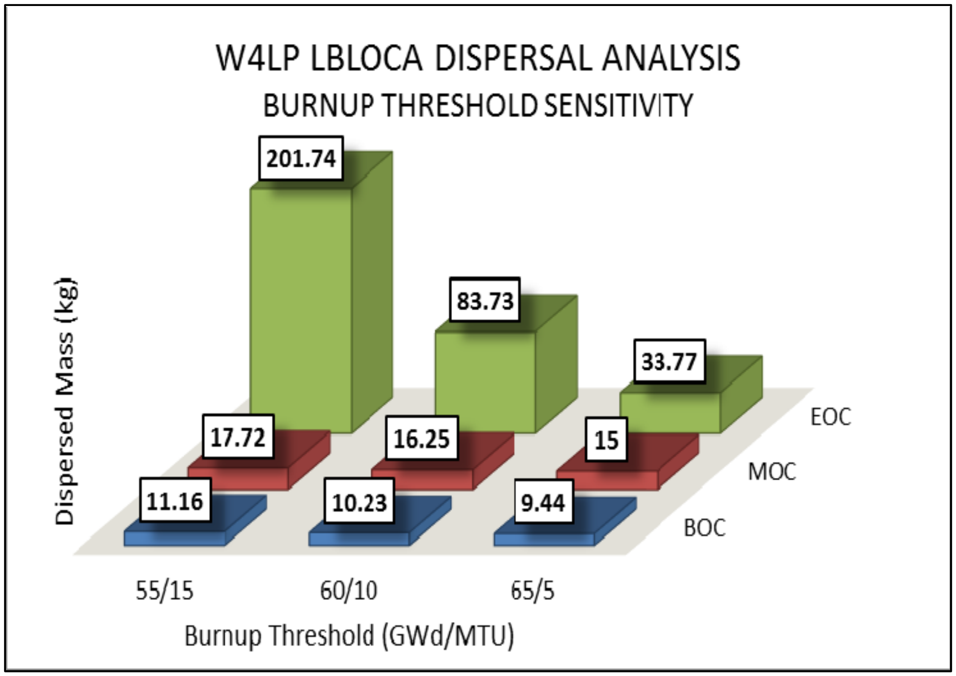


- Largest number of rod bursts predicted at end-of-cycle conditions, because of higher rod internal pressures

- 27,852 fuel rod ruptures (55 % of core)

- Ruptured rods are mostly 1st and 2nd cycle fuel, but one 3rd cycle assembly in center of core

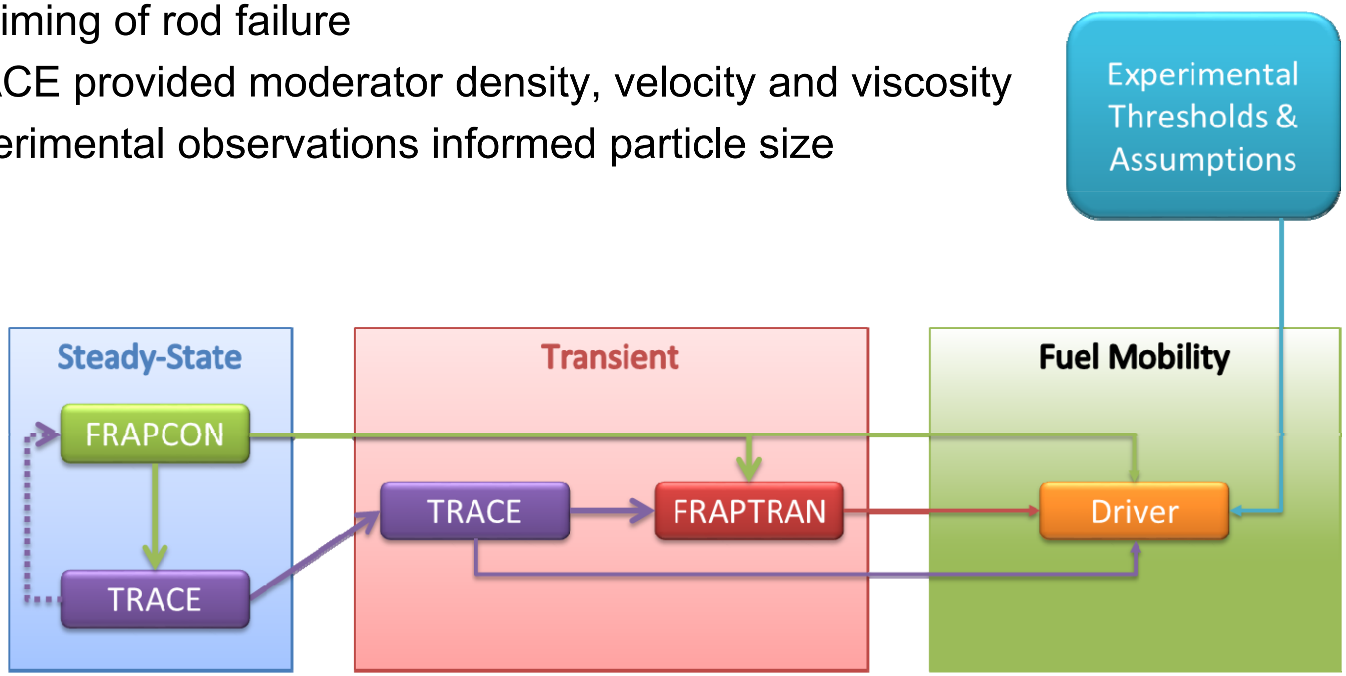
NRC Study: Predictions of Fuel Dispersal During a LOCA



- Three burnup thresholds for fine fragmentation linear transition threshold
  - 55 GWd/MTU to 70 GWd/MTU (55/15)
  - 60 GWd/MTU to 70 GWd/MTU (60/10)
  - 65 GWd/MTU to 70 GWd/MTU (65/5)
- At BOC and MOC, dispersed fuel quantities are relatively insensitive to burnup threshold
  - No fuel rods in core above the threshold
- At EOC, choice of burnup threshold has huge impact on dispersed fuel mass
  - At EOC, many rods have peak local burnups above transition threshold
  - Rupture usually occurs at peak power location
  - Predicted dispersed fuel mass between ~34 kg and ~202 kg at EOC
    - (202kg is less than 0.25% of the UO_2 in the core)
- Although larger balloons were noticed at BOC (which is typically assumed as the most limiting rod time in LOCA analysis), the burnup threshold dependency outweighs the fact that small strains are seen at EOC.

NRC Study: Dispersed Fuel Mobility

- Study completed by Jesse Philiips, Patrick Raynaud and Ian Porter and published at TopFuel in 2015, Zurich, Switzerland
- Objective: analyze the ability for fuel to be swept by the coolant after dispersing from the rod.
- FRAPCON provided axial burnup, a first order factor in fragment size
- FRAPTRAN provided axial cladding strain, a first order factor in relocation, and the timing of rod failure
- TRACE provided moderator density, velocity and viscosity
- Experimental observations informed particle size



NRC Study: Dispersed Fuel Mobility

- A force balance is performed to relate fluid conditions to fragment size in order to approximate fraction of fuel exiting core due to entrainment, or sweeping
- Solving the force balance results in a critical radius, whereby the particle velocity is zero.
  - (Critical radius occurs when buoyancy = -gravitational forces)
  - Particle radius < critical radius, sufficient drag to sweep particle
  - Particle radius > critical radius, particle will settle

<u>Assumptions:</u>

- Homogenous fluid conditions
- Force balance solved assuming steady-state
- Fuel particles are spheres (non-conservative)
- No obstructions to mobility (no grid spacers)

NRC Study: Dispersed Fuel Mobility

- By assuming that all particles < 1mm are able to escape the fuel rod rupture opening, four size bins were established to characterize the dispersed particle size for mobility analysis

- The critical radius at the axial rupture node was then compared to the dispersed particle size (assuming uniform distribution within each bin) to determine fuel mobility

- Assuming the 55/15 burnup threshold, the total swept fuel mass was calculated as 107kg, or 52.7% of the total dispersed fuel.

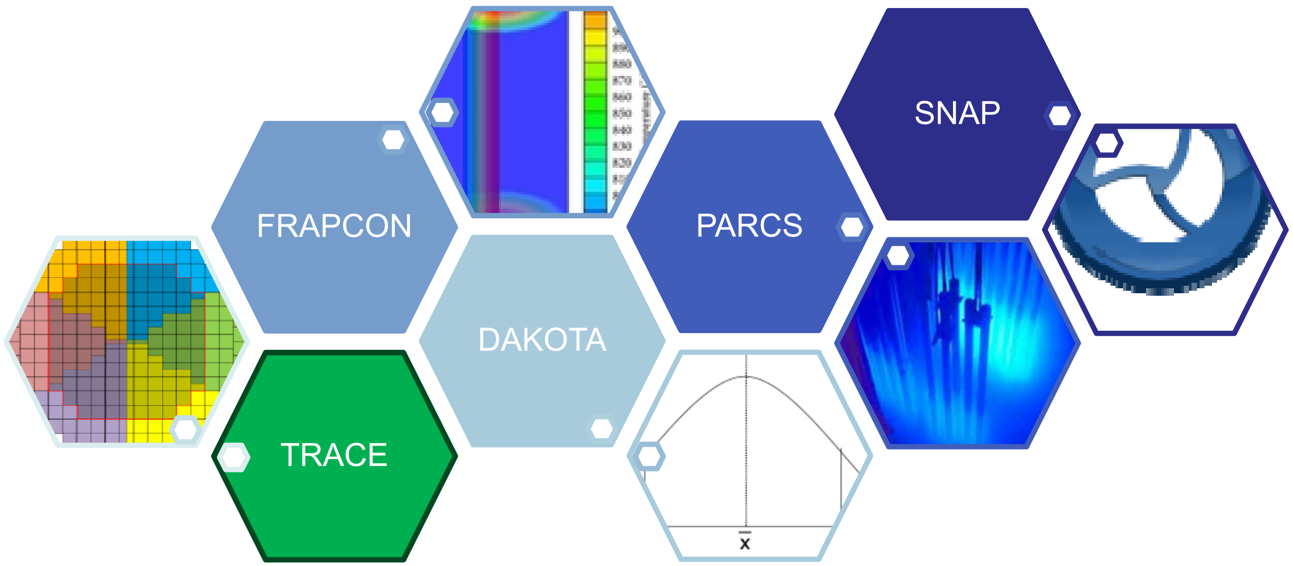
Staff Evaluation: FFRD and LOCA Rulemaking

- Calculation scheme described above was employed in, “Evaluation of Fuel Fragmentation, Relocation and Dispersal Under Loss-of-Coolant Accident (LOCA) Conditions Relative to the Draft Final Rule on Emergency Core Cooling System Performance During a LOCA (50.46c)”
  - When fuel rod ruptures were predicted, they were predominantly in the high-power, low-burnup first and second cycle fuel rods. This information, combined with the empirical thresholds on fragmentation size as a function of burnup and fuel relocation propensity, allowed the staff to estimate dispersed fuel mass for several postulated LOCA scenarios and for three different plant types.
  - Estimates of dispersed fuel mass were relatively small for the scenarios investigated.
  - Near-term regulatory action is not needed to address FFRD phenomena at this time.
  - Study presented to the Advisory Committee on Reactor Safeguards (ACRS), on December 4, 2013 (ADAMS Accession No. ML13356A004).

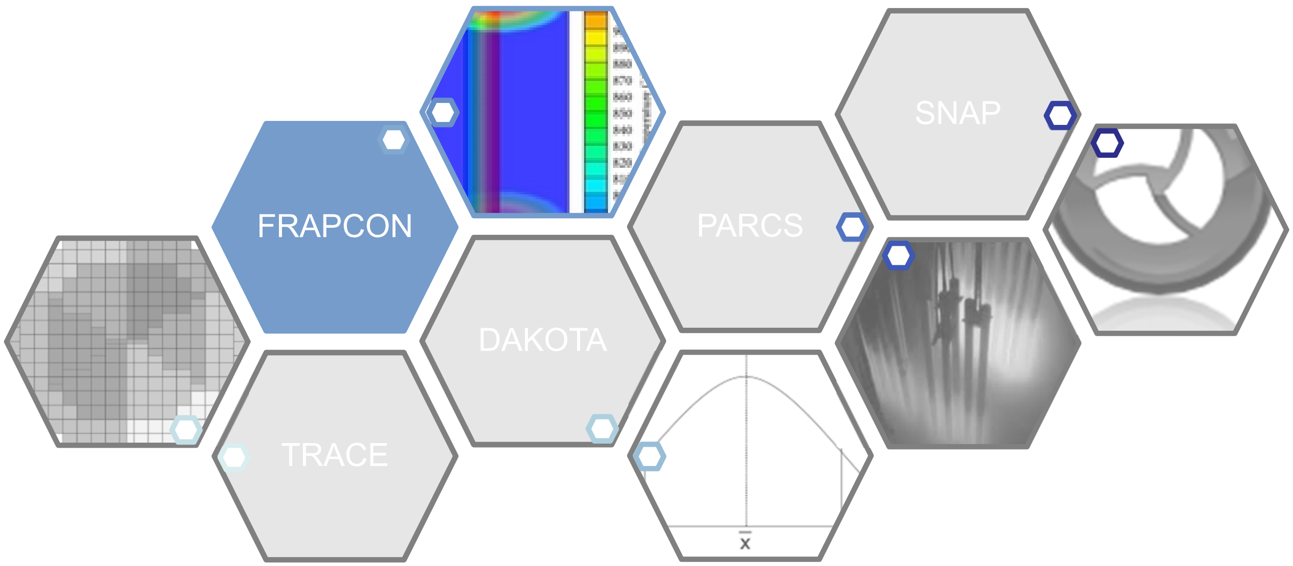
- Study also revealed that fuel dispersal is linked to current fuel design limits and how high-burnup fuel is operated.

Consistent Fuel Rod Modeling

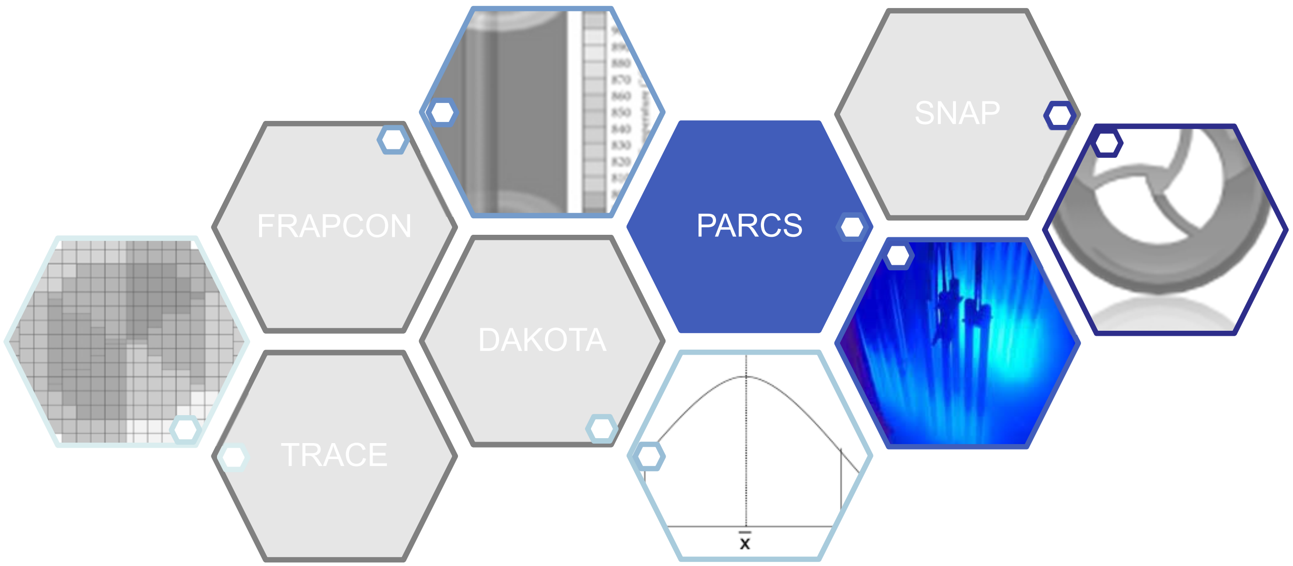
- NRC’s fuel performance codes (FRAPCON and FRAPTRAN, single rod codes used for fuel thermal-mechanical parameter predictions) and NRC’s thermal hydraulic code (TRACE, a systems code used to evaluate LOCA acceptance criteria) did not produce the same prediction of fuel temperature and rod internal pressure in LOCA simulations. To improve fuel rod temperature predictions in TRACE, several fuel models have been incorporated:
  - 2-D array (axial, radial) for fuel burnup – affects fuel thermal conductivity
  - Axial array for fuel swelling/densification – affects gap thickness
  - Axial array for cladding creepdown – affects gap thickness
  - Axial array for oxide thickness – affects thermal solution by adding another barrier to heat removal
  - Axial array for crud thickness – affects thermal solution by adding another barrier to heat removal
  - TRACE directly incorporated FRAPCON’s model for calculating RIP and plenum temperature.



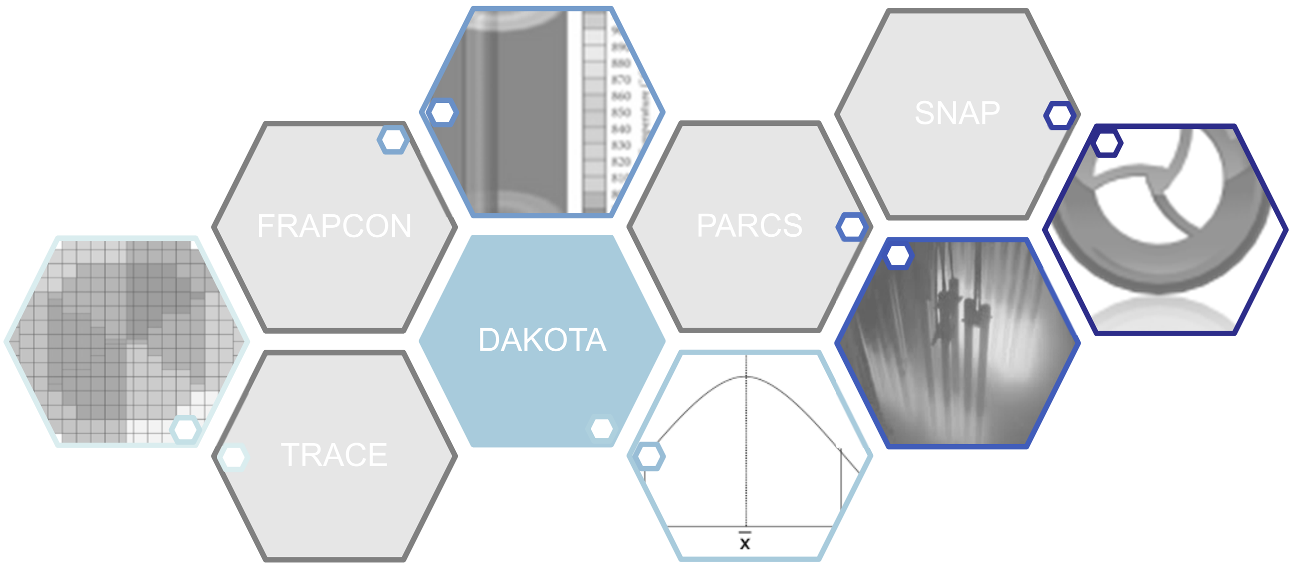
New LOCA requirements require more detailed fuel rod modeling in LOCA calculations. A number of computational tools are being employed to perform increasingly complex and detailed calculations.



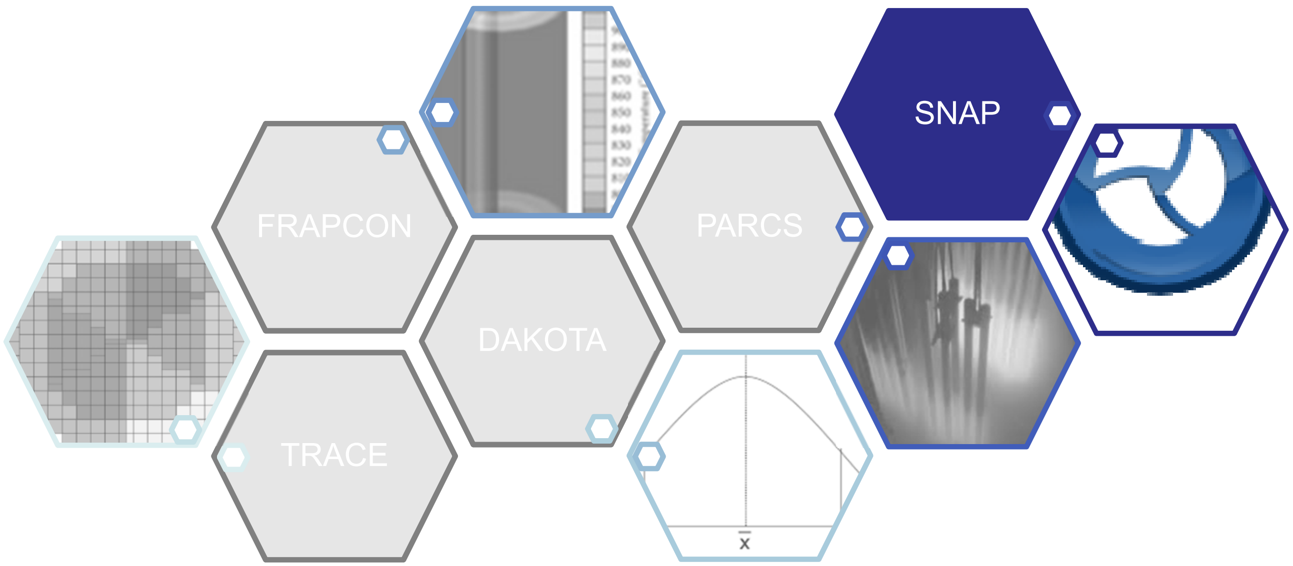
TRACE requires detailed burnup-dependent fuel rod parameters, such as 2-D (axial, radial) power profiles for each rod to capture the power distribution within each pellet, especially for high BU fuel with the radial power peaking. FRAPCON (NRC's steady state fuel performance code) is being used to generate this data with sufficient detail.



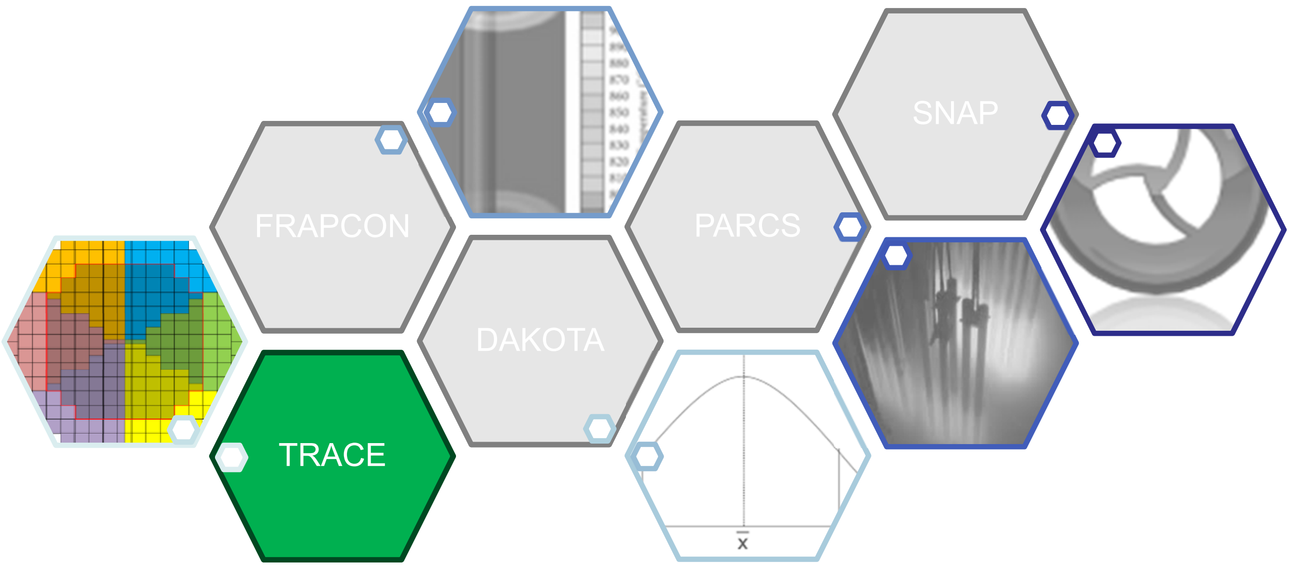
FRAPCON/PARCS are being coupled in order to provide PARCS with a detailed fuel temperature distribution, and PARCS will provide the axial power distribution to FRAPCON, which is currently supplied by the user.



A framework is being developed to run LOCA calculations with DAKOTA (a statistical analysis package), to apply uncertainties in parameters to both the FRAPCON and the TRACE runs. The framework will be extended to FRAPTRAN as well.



A framework in SNAP (Symbolic Nuclear Analysis Package, NRC's GUI tool designed to simplify the process of performing engineering analysis) is being developed to automate the data transfer and manipulation needed to run FRAPCON and TRACE in sequence.



TRACE is being used to generate ***pin-by-pin*** predictions of fuel rod parameters of interest for LOCA evaluation.

Code Development Plans: FRAPTRAN

- Data from Halden and SCIP will be used to evaluate possible improvements in the **transient fission gas release model** in FRAPTRAN
- Recent data from Halden and SCIP, along with historic data, will be used to determine if an **axial fuel relocation model** can be developed and validated in FRAPTRAN
- Modifications will be made to FRAPTRAN to **facilitate improved data sharing** with TRACE. The goal is to allow TRACE to drive the FRAPTRAN calculations, providing boundary conditions to FRAPTRAN, and allowing FRAPTRAN to provide TRACE with corresponding temperatures, cladding dimensional changes, fuel rod failure and flow blockage **continuously**.

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION *Protecting People and the Environment*

For more information, see

- P. A. Raynaud, "Core-Wide Estimates of Fuel Dispersal During a LOCA," in *Proc. TOPFUEL 2013*, Charlotte, NC, Sep. 15-19, 2013.
- P. A. Raynaud and I. E. Porter, "Predictions of Fuel Dispersal During a LOCA," in *Proceedings of WRFPM 2014*, Sendai, Japan, Sep. 14-17, 2014.
-
- M. E. Flanagan, B. C. Oberlander and A. Puranen, "Fuel Fragmentation, Relocatoin and Dispersal Under LOCA Conditions: Experimental Observations," in *Top Fuel 2013*, Charlotte, NC, Sep. 15-19, 2013.
- P. A. Raynaud, "NUREG-2121: Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident," U.S. Nuclear Regulatory Commission, Washington, DC, 2012.
- A. Haider and O. Levenspiel, "Drag Coefficient and Terminal Velocity of Spherical and Nonspherical Particles," *Powder Technology,* vol. 58, pp. 63-70, 1989.
- SECY-15-0148: Evaluation of Fuel Fragmentation, Relocation and Dispersal Under Loss-of-Coolant Accident (LOCA) Conditions Relative to the Draft Final Rule on Emergency Core Cooling System Performance During a LOCA (50.46c) (ML15230A200)

Conclusions

- Quantifying the extent of FFRD required more detailed fuel rod modeling and interchange of information between existing separate codes.

- New LOCA requirements require more detailed fuel rod modeling in LOCA calculations. A number of computational tools are being employed to perform increasingly complex and detailed calculations.

- Work continues to improve code modeling capabilities to meet the evolving needs of LOCA evaluation.