Multi-Physics Best Estimate Plus Uncertainty (MP-BEPU) Analysis Framework LOTUS and RELAP5-3D

LIGHT WATER REACTOR SUSTAINABILITY

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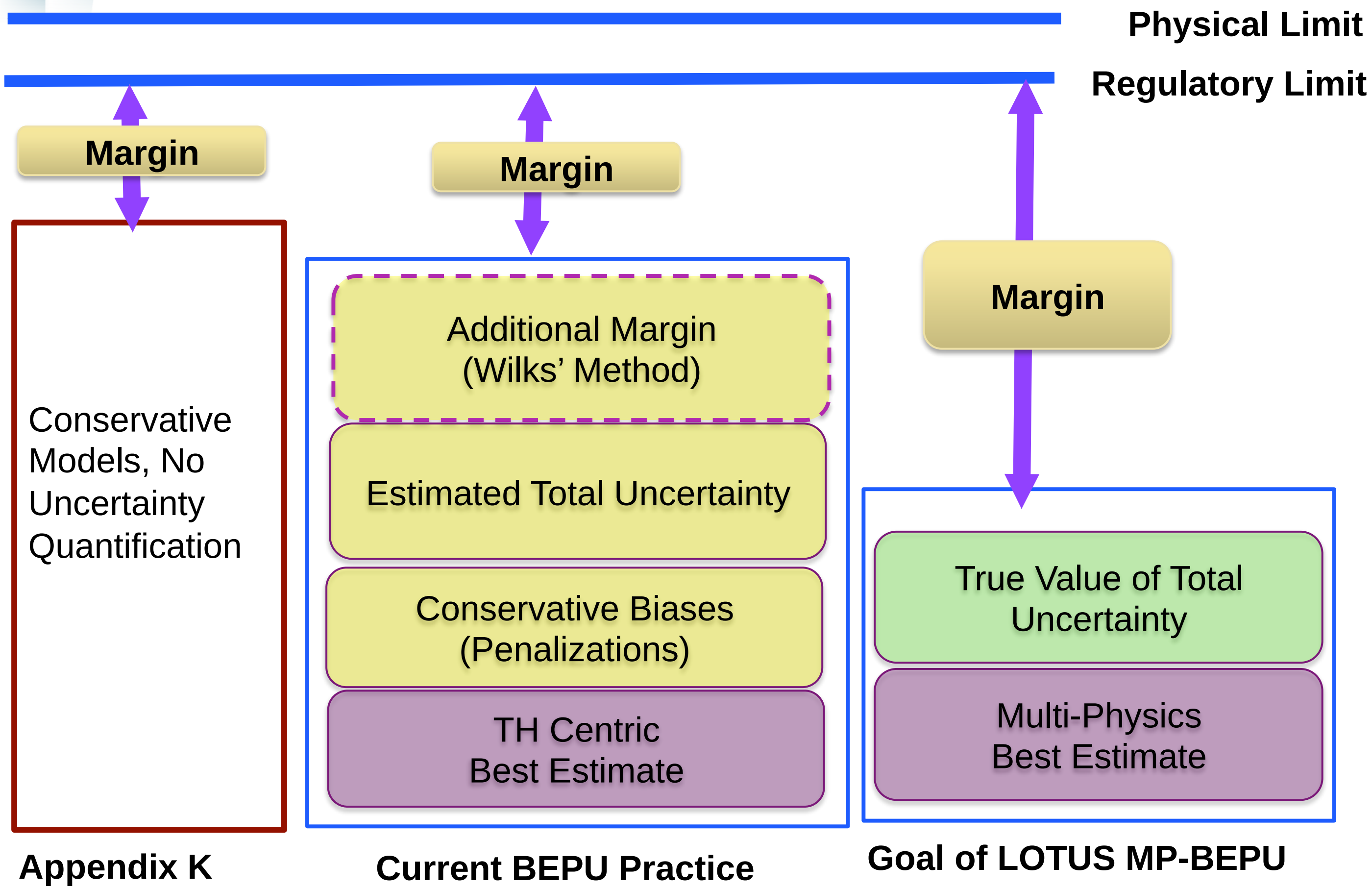
Background

- **The existing NPP fleet is facing economic challenges due to:**
  - Low natural gas price
  - Rapid deployment of renewable energy sources
- **Additionally, the existing NPP fleet is facing regulatory challenges:**
  - 10 CFR 50.46c
- **Reducing fuel cost is one area that contributes to the improved economic viability and enhanced safety of the existing fleet**
  - Accident tolerant fuel
  - Higher burnup of the fuel
  - Optimized fuel and loading pattern design
  - Load following and flexible operating strategies

Multi-physics, multi-scale analysis of core/fuel/systems in the context of best-estimate plus uncertainty (BEPU) methodology is desired.

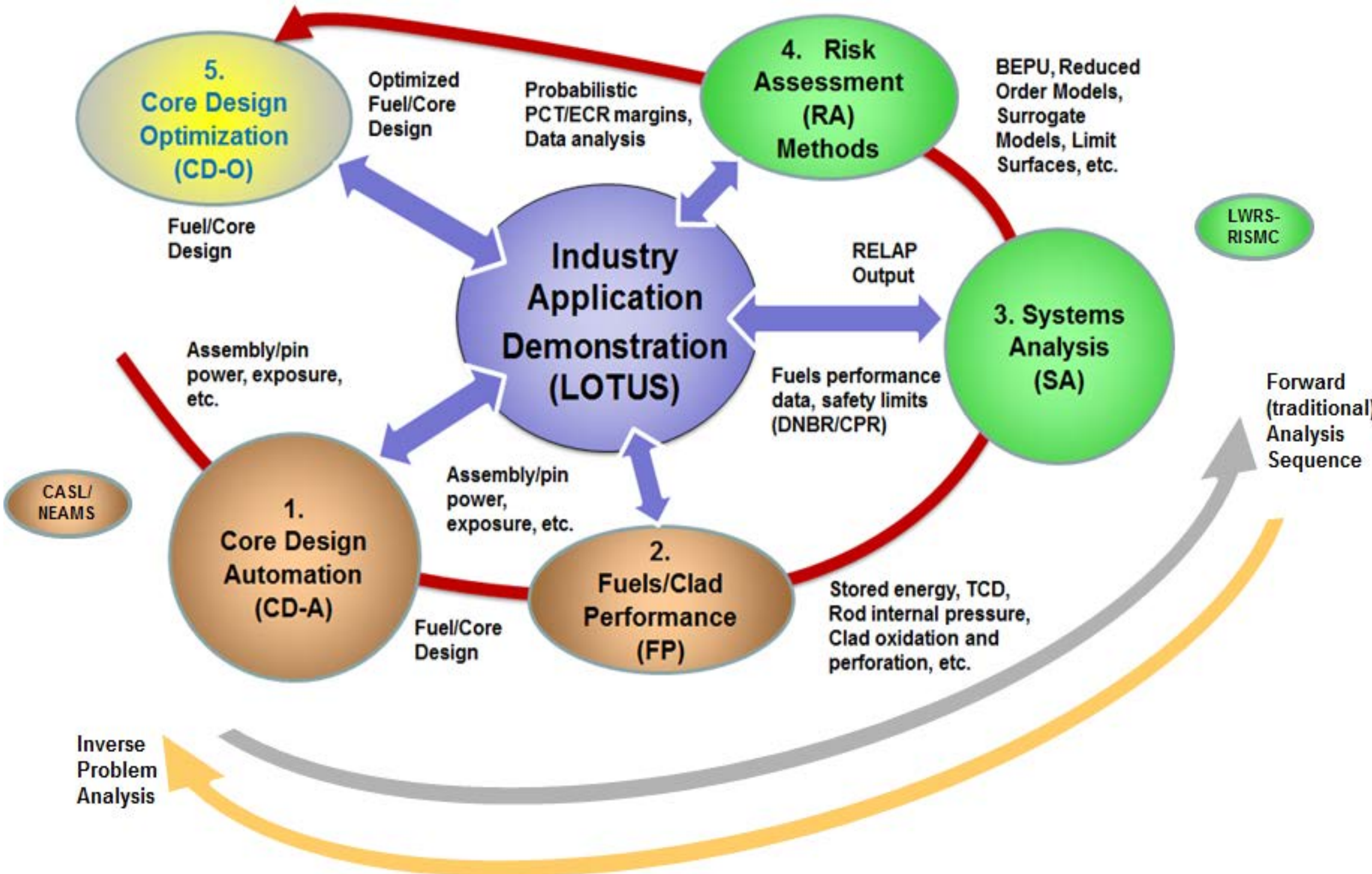
MP-BEPU Framework is NOT designed is compete with multi-physics framework MOOSE or VERA

Margin Recovery Strategy

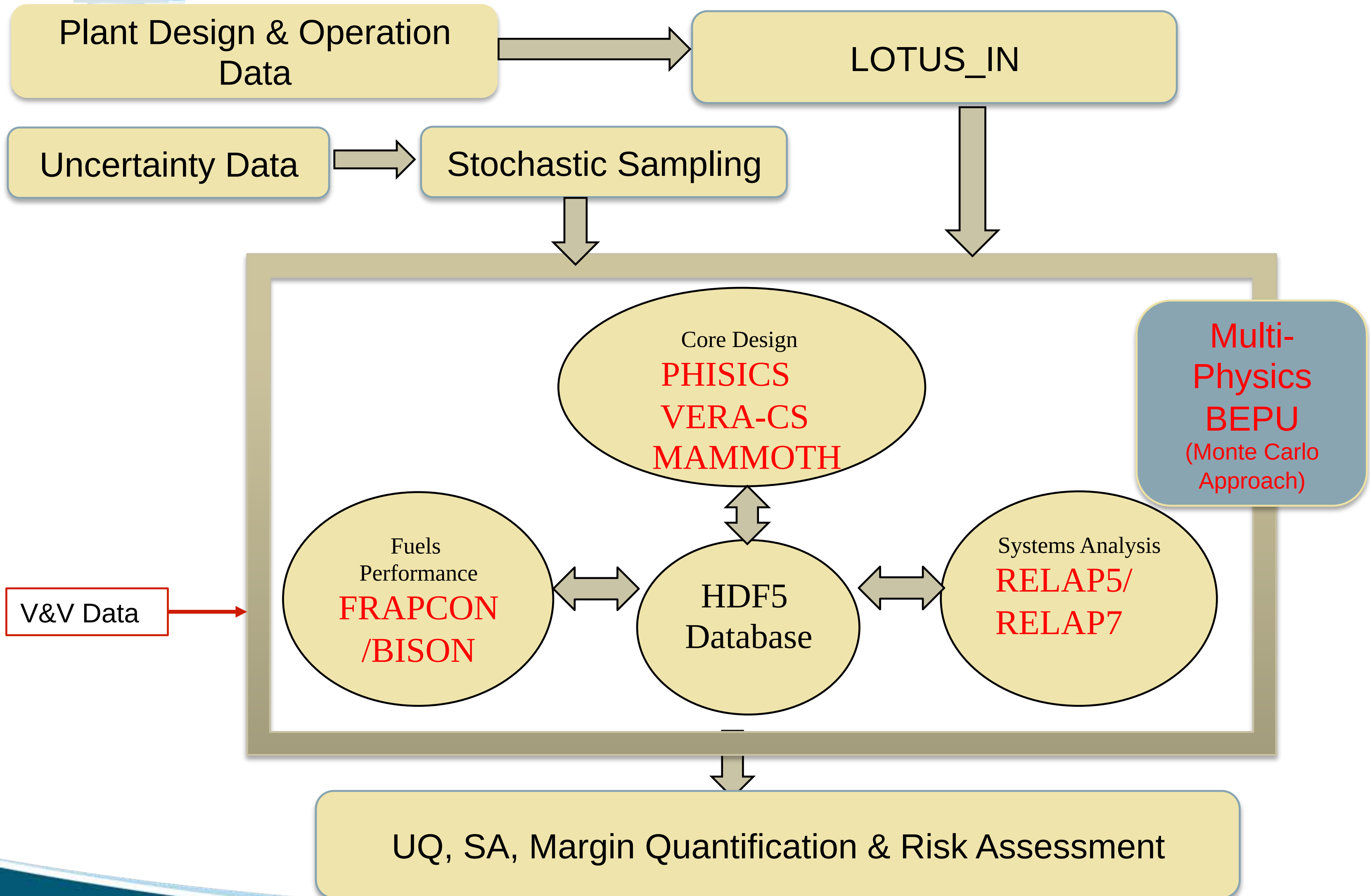


- Higher burnup of the fuel
- Accident tolerant fuel
- flexible operating strategies

LOTUS (LOCA Toolkit for U.S. LWRs)



Codes Used in the LOTUS Framework



Demonstration

LOTUS-B (LOTUS with Baseline Tools) Application on a Generic PWR Model Based on STP (South Texas Project) plant

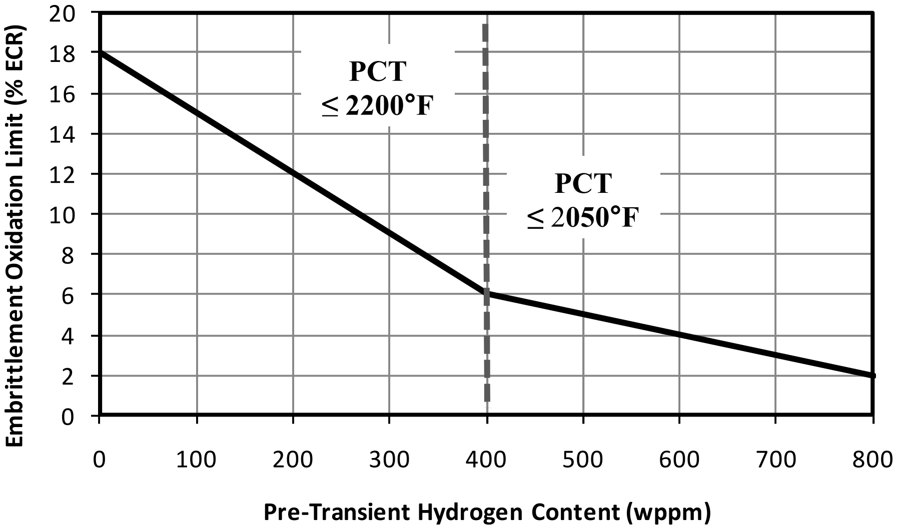
Plant Characteristics: 4-Loop PWR
3853 MWth
14 Feet Fuel

Tools: PHISICS for Core Design Automation
FRAPCON for fuels performance
RELAP5-3D for Systems Analysis
LOTUS for Uncertainty Quantification

Scenario: Double ended guillotine break

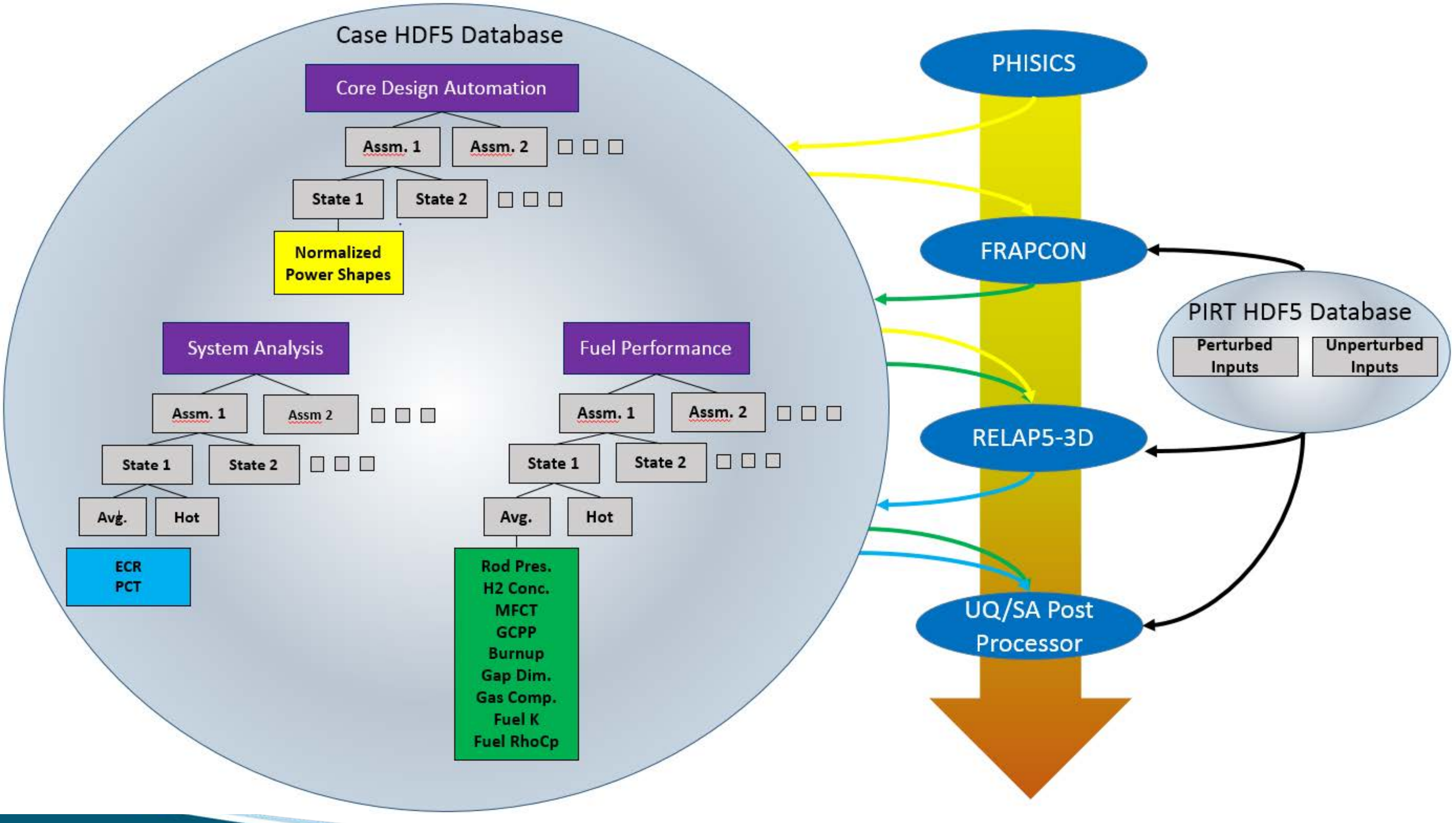
Proposed new rulemaking in 10 CFR 50.46c

- NRC proposed 50.46c rule introduces new (more restrictive) performance-based requirements.
- Potential Impact:
  - Every fuel rod in the core needs to be analyzed in LOCA analyses.
  - This may require re-analysis of all existing US fleet LOCA bases.



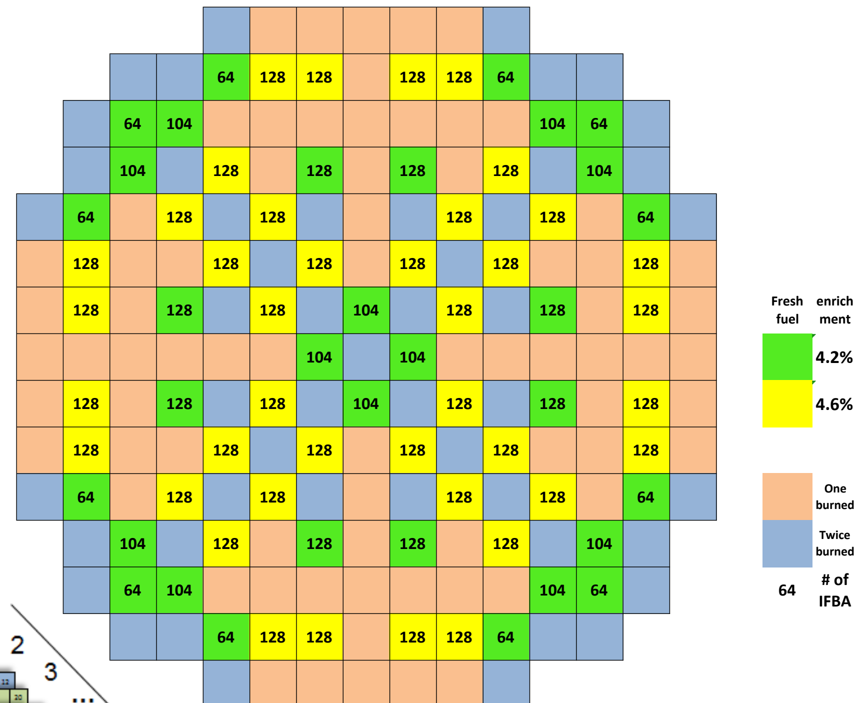
An acceptable analytical limit on peak cladding temperature and integral time at temperature (credit of U.S. NRC)

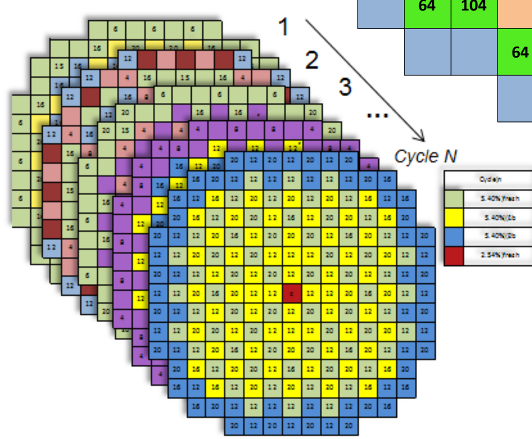
LOTUS Data Flow with Baseline Tools



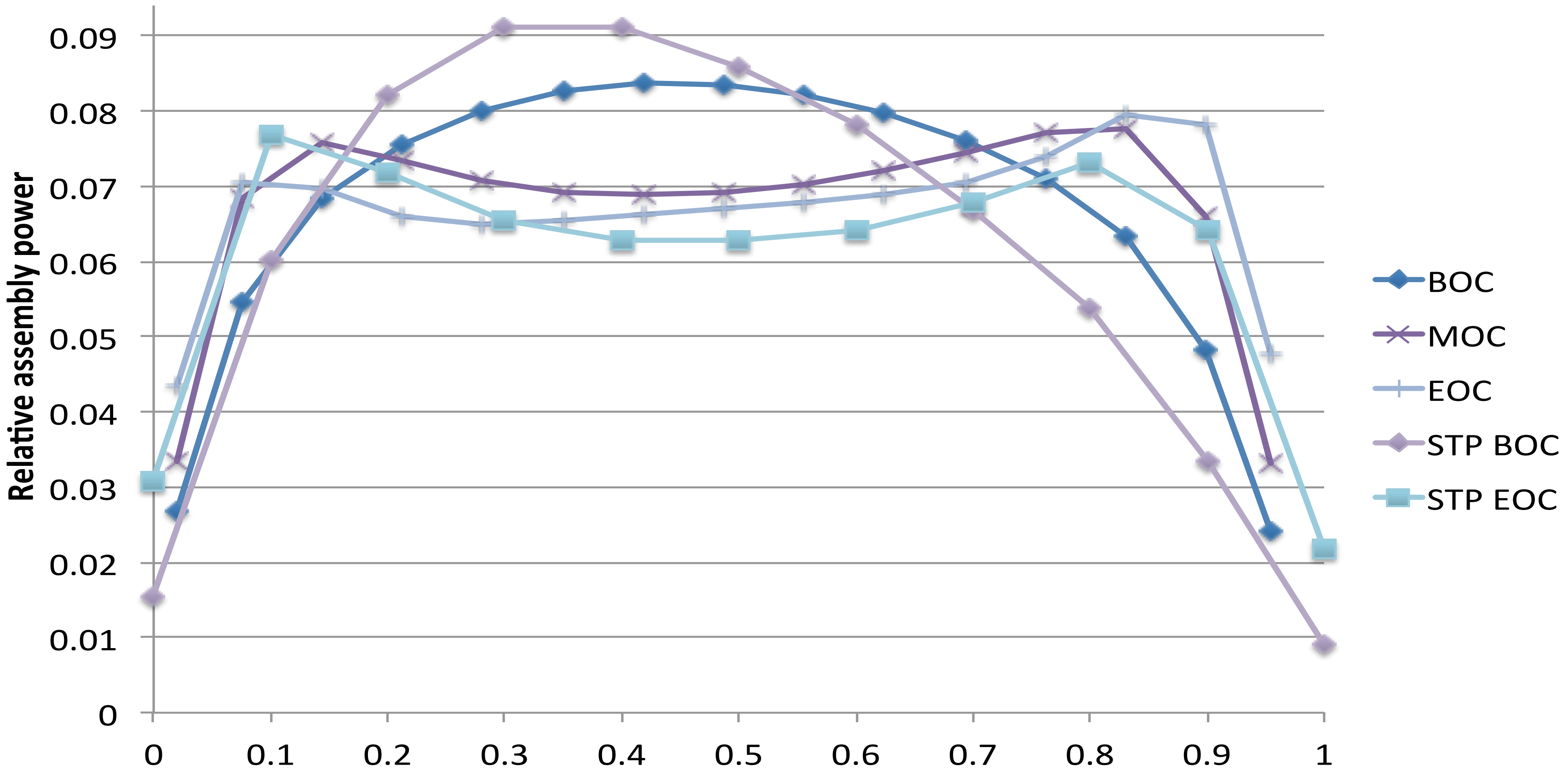
PWR Core Design – Generic Design Based on STP (Credit to Aaron Epiney)

- **Coupled RELAP5/PHISICS**
  - 1 TH channel per assembly
  - Boundary conditions at
    lower and upper plena
- **Developed PWR core similar to STP core**
  - 3.8 GWth
  - 14 feet Westinghouse core
- **Design Criteria**
  - 18 month cycle
  - High energy/low leakage
  - Equilibrium assumed
    after 8 cycles
  - Enrichment 4.2%-4.6 %
  - Fresh/1/2/burned map from a similar PWR
  - IFBA distribution obtained by optimization process





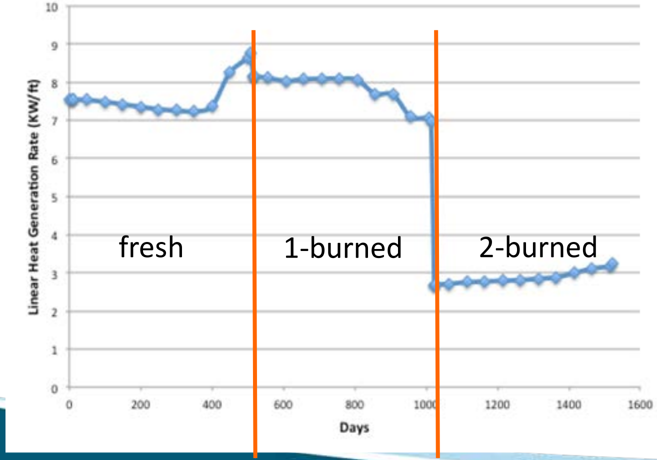
Calculated Power vs. Plant Data



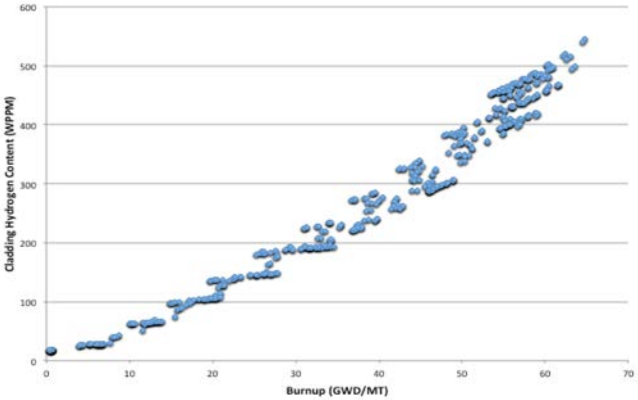
Fuels/Clad Performance (Baseline)

- **Fuel mechanics**
  - RELAP5-3D includes *rupture model* and *ballooning model*
  - But we need detailed analysis of fuel rods' behaviors such as the fission gas released, rod internal pressure, and fuel-cladding mechanical interaction, cladding H content etc., → **FRAPCON**
- **The power history data is automatically retrieved by LOTUS from the core design results going into a FRAPCON input**

Power history for the hot rod (one assembly)



Cladding hydrogen content vs. rod average burn-up (all assemblies)



RELAP5 nodalisation for a generic four-loop PWR based on STP

- A RELAP5 model is built for a generic PWR based on the STP NPP:
  - Reactor Vessel
    - Downcomer
    - Bypass
    - Lower/Upper plena
    - Core
    - Upper head
  - Reactor coolant system
    - 4 primary loops
  - ECCS
    - Low pressure injection (LPI)
    - High pressure injection (HPI)

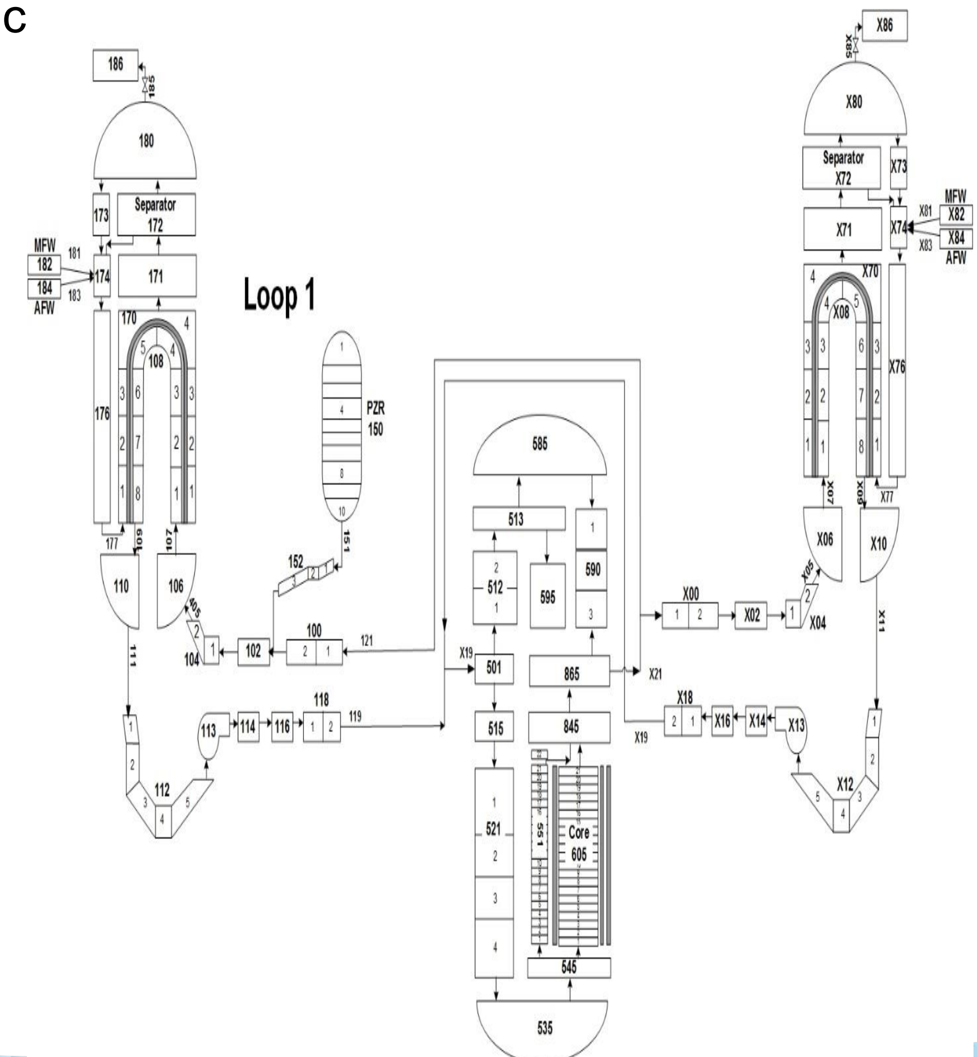


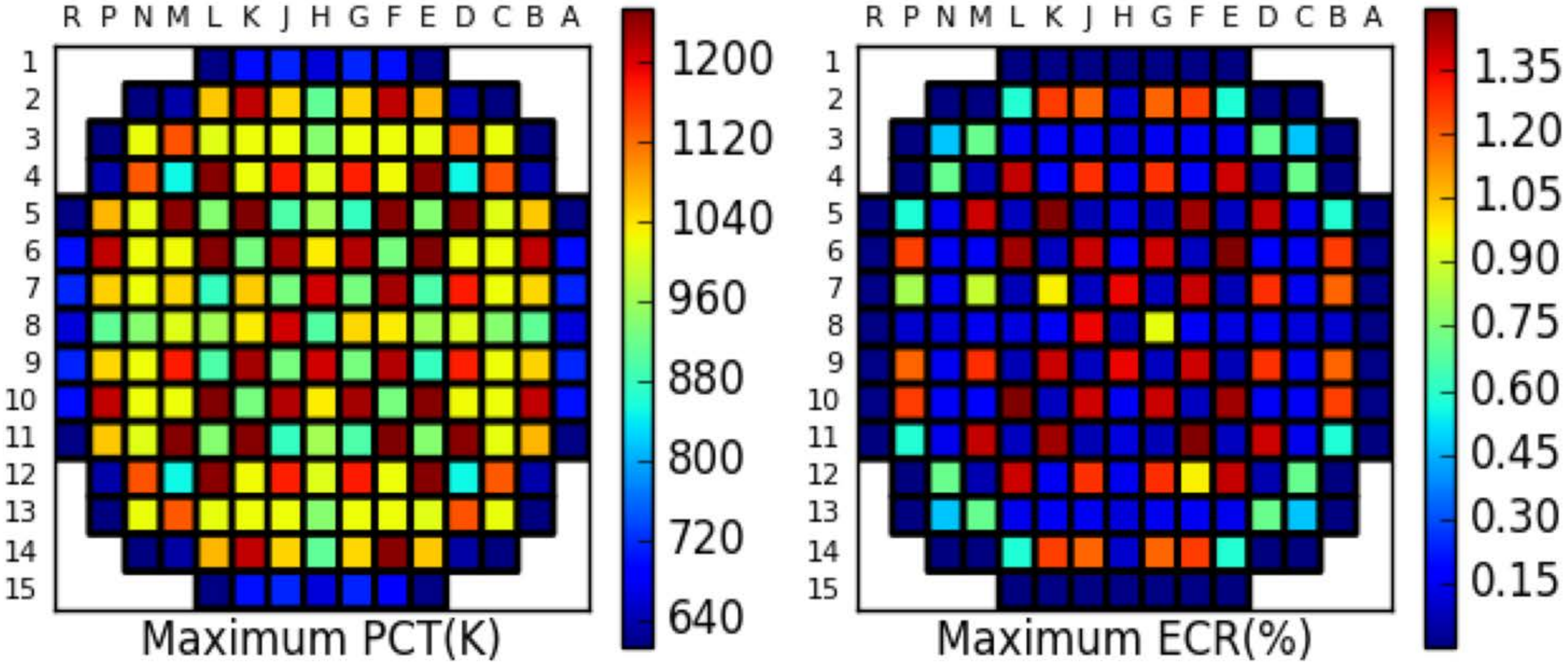
Table of Uncertain Parameters

Parameter	Nominal	Range (+/-)	Distribution	FRAPCON	RELAP5-3D
Fuel Radius	0.40956 cm	0.001 cm	Truncated Normal	X	X
Clad Outer Radius	0.47498 cm	0.002 cm	Truncated Normal	X	X
Clad Thickness	0.05715 cm	0.002 cm	Truncated Normal	X	X
Plenum Fill Gas Pressure	3.0 MPa	0.08 MPa	Truncated Normal	X	*
Percent Theoretical Density	94.5%	1.6%	Truncated Normal	X	X
Fuel Thermal Conductivity	-	10%	Truncated Normal	X	X
Core Power	3.85 GW	2%	Truncated Normal	X	X
Direct Moderator Heating	0.02	10%	Truncated Normal	X	*
Decay Heat Multiplier	1	0.06	Uniform		X
Accumulator Pressure	606 psi	10%	Truncated Normal		X
Accumulator Liquid Temperature	126 °F	25	Uniform		X
Accumulator Liquid Volume	1250 ft^3	8	Uniform		X
Sub-Cooled Counter Flow Multiplier (Pump Side)	1	0.2	Uniform		X
Two-Phase Counter Flow Multiplier (Pump Side)	1	0.2	Uniform		X
Super-Heated Counter Flow Multiplier (Pump Side)	1	0.2	Uniform		X
Sub-Cooled Counter Flow Multiplier (Vessel Side)	1	0.2	Uniform		X
Two-Phase Counter Flow Multiplier (Vessel Side)	1	0.2	Uniform		X
Two-Phase Counter Flow Multiplier (Vessel Side)	1	0.2	Uniform		X
Turbulence Heat Transfer Multiplier	1	0.3	Uniform		X
Nucleate Boiling Heat Transfer Multiplier	1	0.3	Uniform		X
Critical Heat Flux Multiplier	1	0.3	Uniform		X
Transition Boiling Heat Transfer Multiplier	1	0.3	Uniform		X
Film Boiling Heat Transfer Multiplier	1	0.3	Uniform		X
Condensation Heat Transfer Multiplier	1	0.3	Uniform		X
Natural Convection Heat Transfer Multiplier	1	0.3	Uniform		X
Laminar Heat Transfer Multiplier	1	0.3	Uniform		X

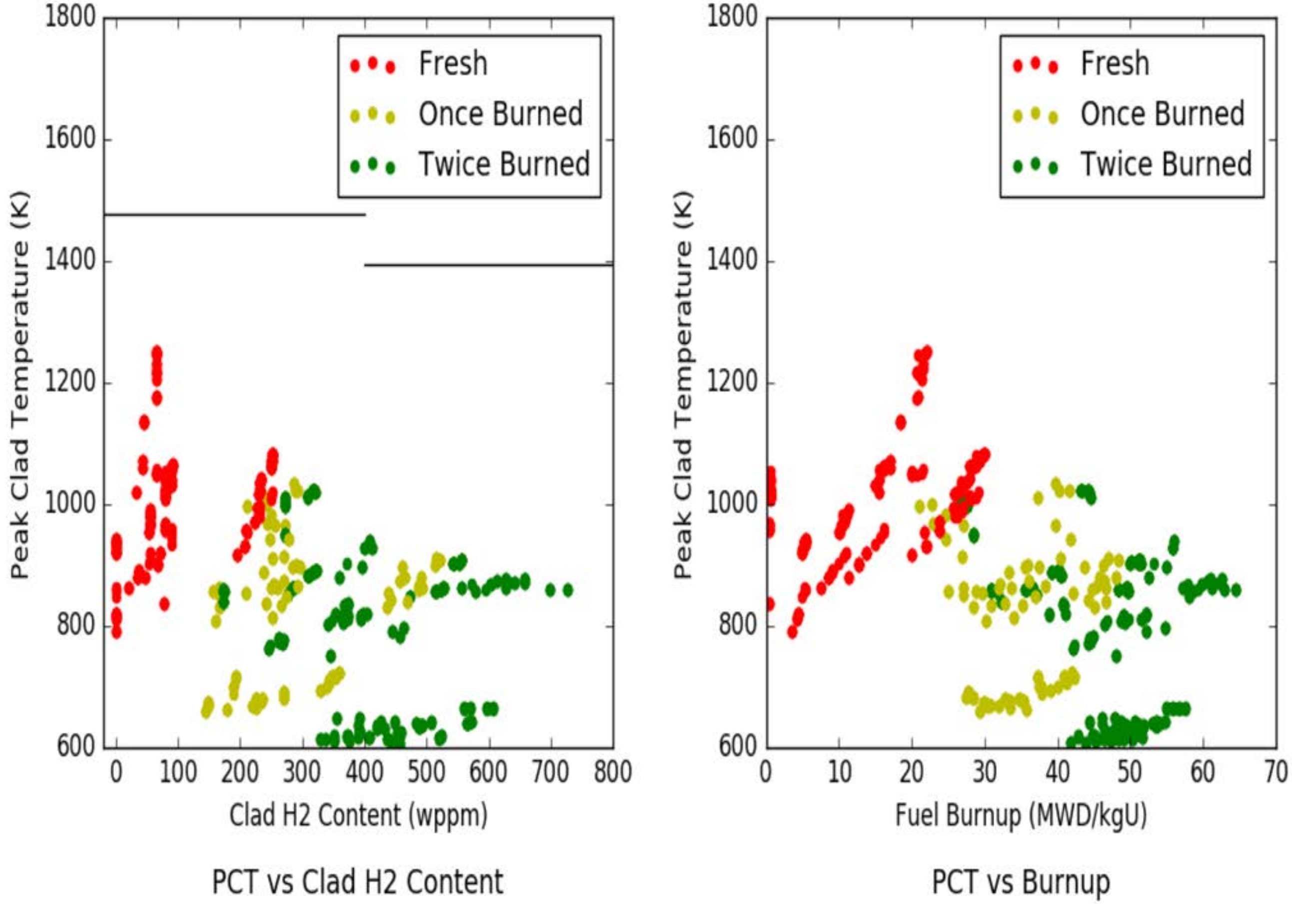
Table of Uncertain Parameters (Continues)

Parameter	Nominal	Range (+/-)	Distribution	FRAPCON	RELAP5-3D
Fuel Enrichment	2.6/4.2/4.6	0.003%	Truncated Normal	X	
Fuel Roughness	2.0 µm	0.33333 µm	Truncated Normal	X	
Clad Roughness	1.0 µm	0.2 µm	Truncated Normal	X	
Fuel Thermal Expansion	-	15%	Truncated Normal	X	
Fission Gas Release Biasing	-	+200%/-67%	Truncated Normal	X	
Fuel Swelling	-	20%	Truncated Normal	X	
Clad Creep	-	30%	Truncated Normal	X	
Clad Axial Growth	-	50%	Truncated Normal	X	
Clad Oxidation	-	40%	Truncated Normal	X	
CladH2Pickup	-	80 ppm	Truncated Normal	X	
Outlet Pressure	2275 psi	2%	Truncated Normal	X	
Inlet Mass Flux	2605453 lb/hr-ft^2	2%	Truncated Normal	X	
Fuel Enrichment	2.6/4.2/4.6	0.003%	Truncated Normal	X	
Fuel Roughness	2.0 µm	0.33333 µm	Truncated Normal	X	
Clad Roughness	1.0 µm	0.2 µm	Truncated Normal	X	

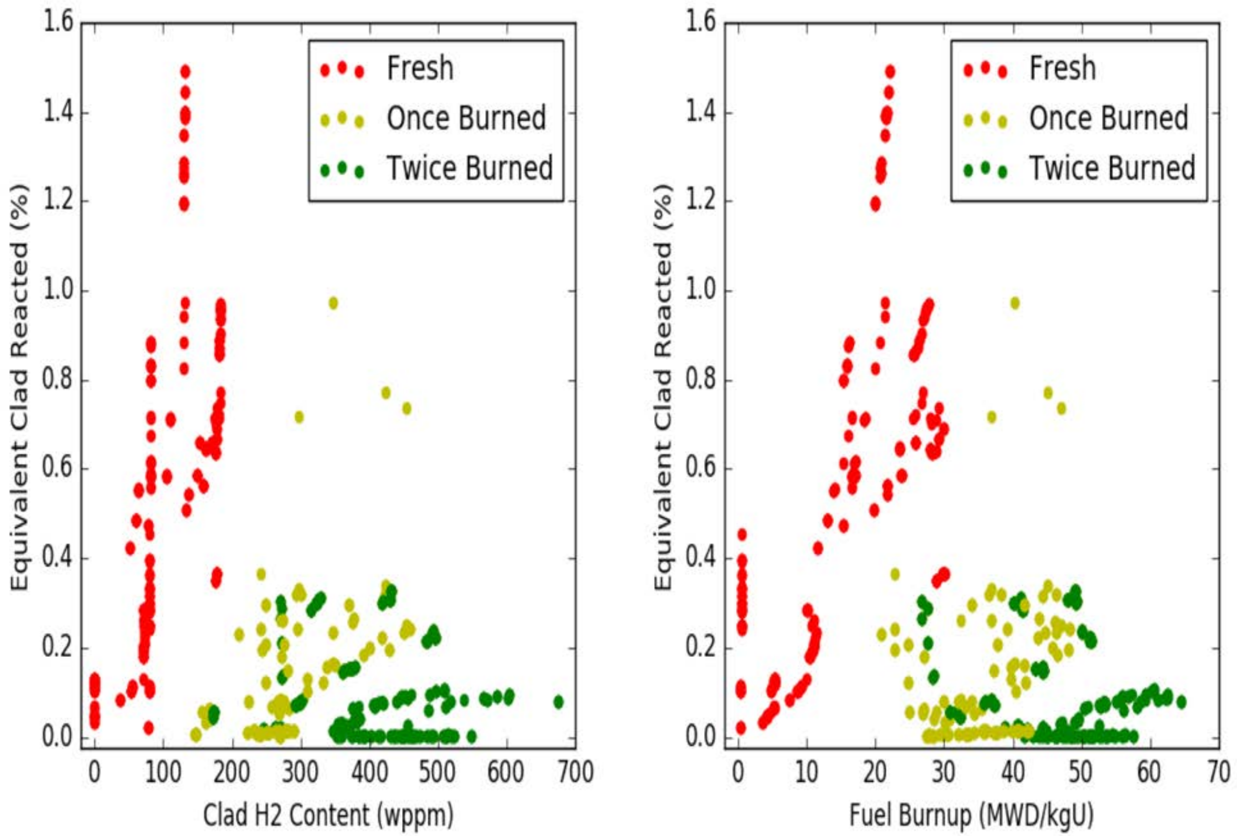
PCT & ECR Distribution for the Limiting Case at 400 Days



PCT vs Cladding Hydrogen Content and Burnup for Limiting Cases



ECR vs Cladding Hydrogen Content and Burnup for Limiting Cases



ECR vs Clad H2 Content

ECR vs Burnup

Conclusions

- UQ studies within a multiphysics allow for appropriate, less conservative estimates of safety metrics
- LOTUS is designed as a "Plug-and-Play" environment aiming at integrating computer codes in core design, fuels performance and systems analysis to enable BEPU analysis
- UQ of PHISICS/FRAPCON/RELAP5-3D has been demonstrated with a generic PWR model based on STP
- Future work includes integration of advanced computer codes being developed such as VERA-CS, MAMMOTH, BISON and RELAP7
- LOTUS also built in both low order and high order sensitivity analysis techniques to provide superior elucidation of relations between input and output uncertainties.

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