U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Risk-Informed Safety Margin Characterization – Industry Application 1

A RELAP5-3D/Core/Fuel/Clad Coupling Application

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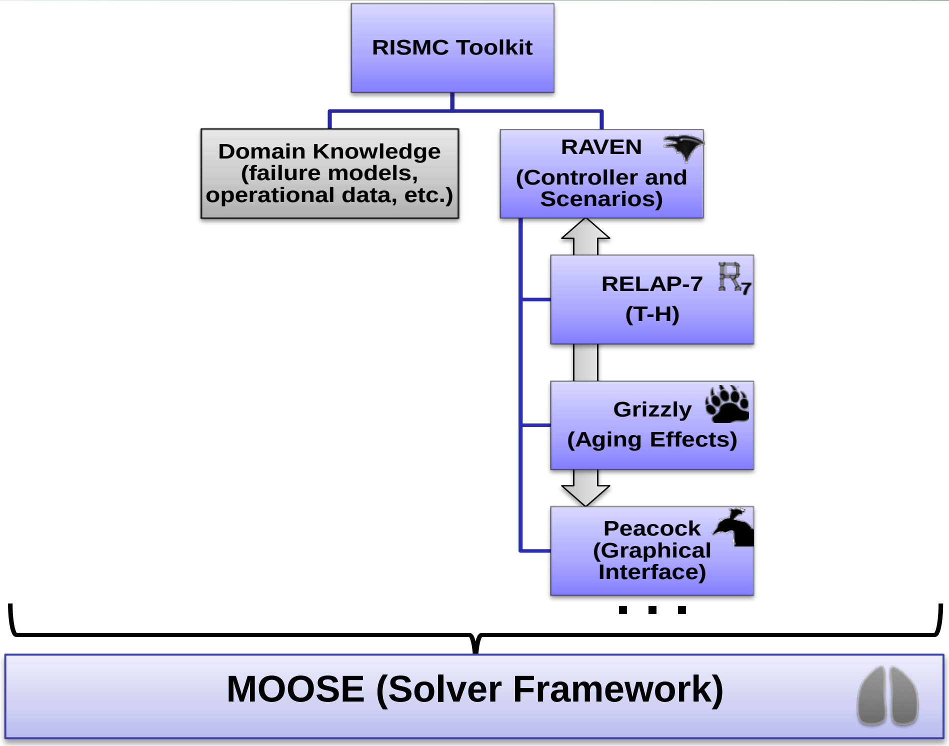
Topics

- **RISMC Overview**
- **Industry Applications**
- **Industry Application #1 (IA #1) Motivation**
- **IA #1 Toolkit for LOCA Analysis (LOTUS)**
  - Core Design Automation
  - Fuels/Clad Performance
  - Systems Analysis
  - Risk Assessment
- **Conclusions**

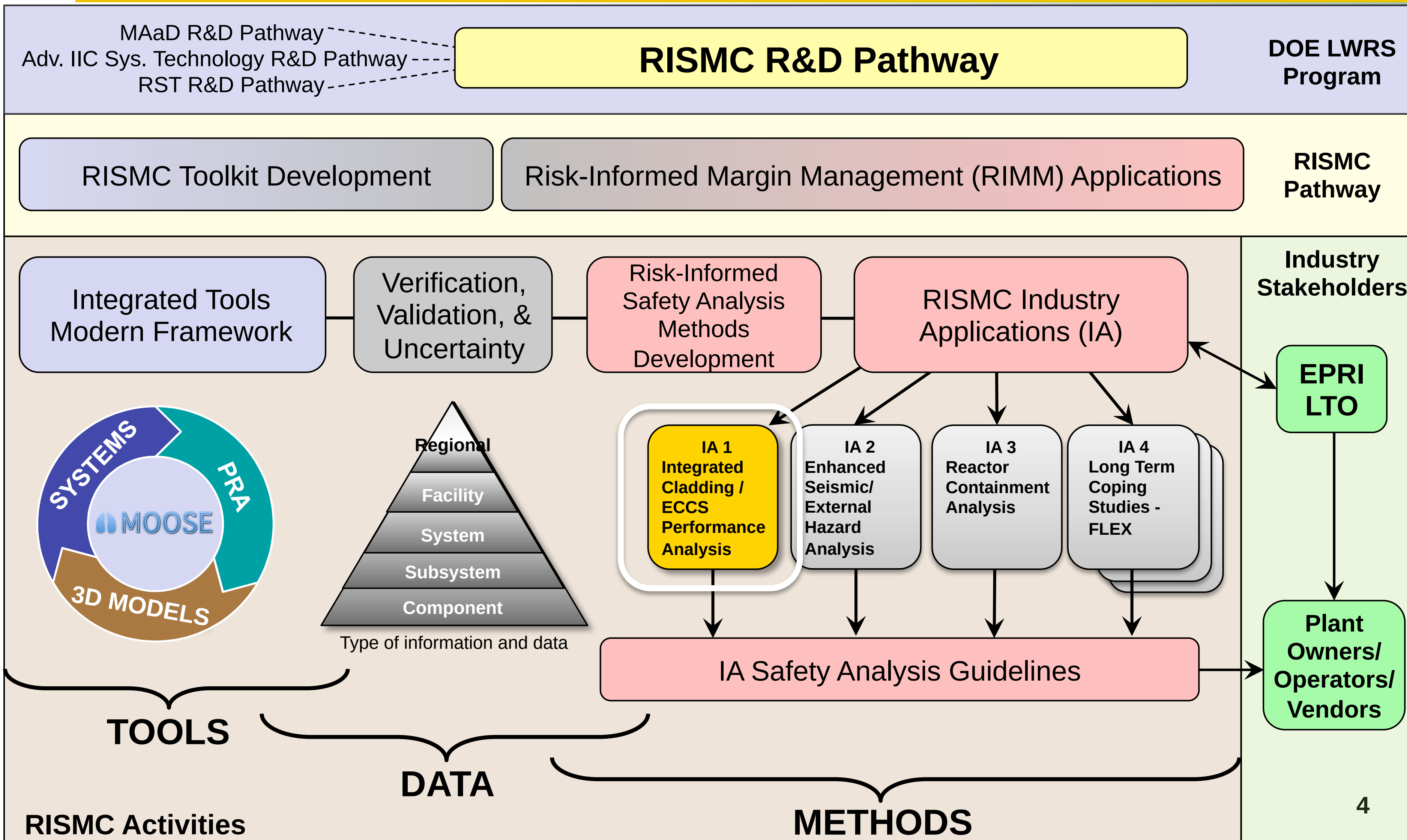
DOE LWRS – Risk Informed Safety Margin Characterization Pathway

- **Support plant decisions for risk-informed margins management**
  - Improved economics, reliability, and sustain safety of current nuclear power plants
- **Goals of the RISMC Pathway**
  - Develop and demonstrate a risk-assessment method coupled to safety margin quantification
    - *Use by NPP decision makers as part of margin recovery strategies*
  - Create an advanced "RISMC toolkit"
    - *Enable more accurate representation of NPP safety margins*



With RISMC, we estimate how close we are (or not) to an event, not just the frequency of an event, providing information on how safety margins can be improved

Industry Applications – Focus on Tools / Data / Methods

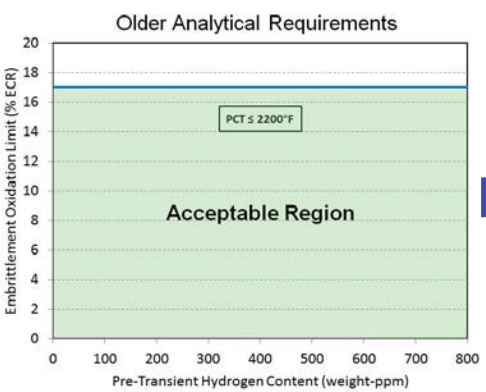


IA 1 – Integrated Cladding/ECCS Performance

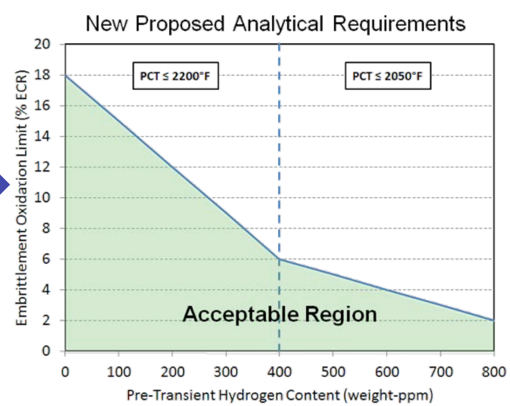
- **Motivation**
  - Based upon recent experiments, NRC proposed new regulations (10 CFR 50.46c)
    - *Peak-clad temp. and embrittlement oxidation more restrictive than current limits*
    - *LWRS program will help industry by using RISMC to demonstrate safety margins for loss-of-coolant-accident (LOCA) analysis including emergency core cooling system (ECCS) performance under* ***realistic plant conditions***
      - Coupled analysis has core physics, cladding behavior, thermal-hydraulics, and scenario-based risk analysis in order to quantify safety margin
- **Potential Impact:**
  - Cost of re-analysis
    - *~65 License Amendment Requests, > $100M (U.S. plants)*
    - *7-year implementation plan*
  - Loss of margin
  - Increased fuel costs
  - Operation flexibility impact
  - Increased complexity

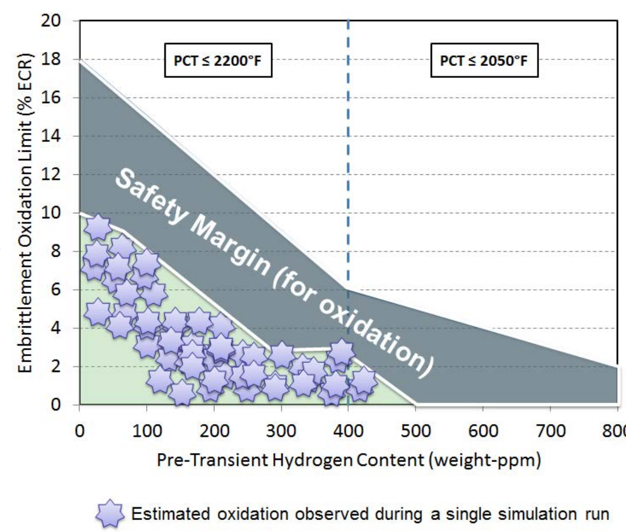
IA 1 – Integrated Cladding/ECCS Performance

- **Proposition:**
  - Re-analysis can be used to better understand/manage margins
  - Efficient assessment of margins (through advanced methods/tools)
  - Opportunity for reload design and operations processes improvements



New 10 CFR 50.46c Limits

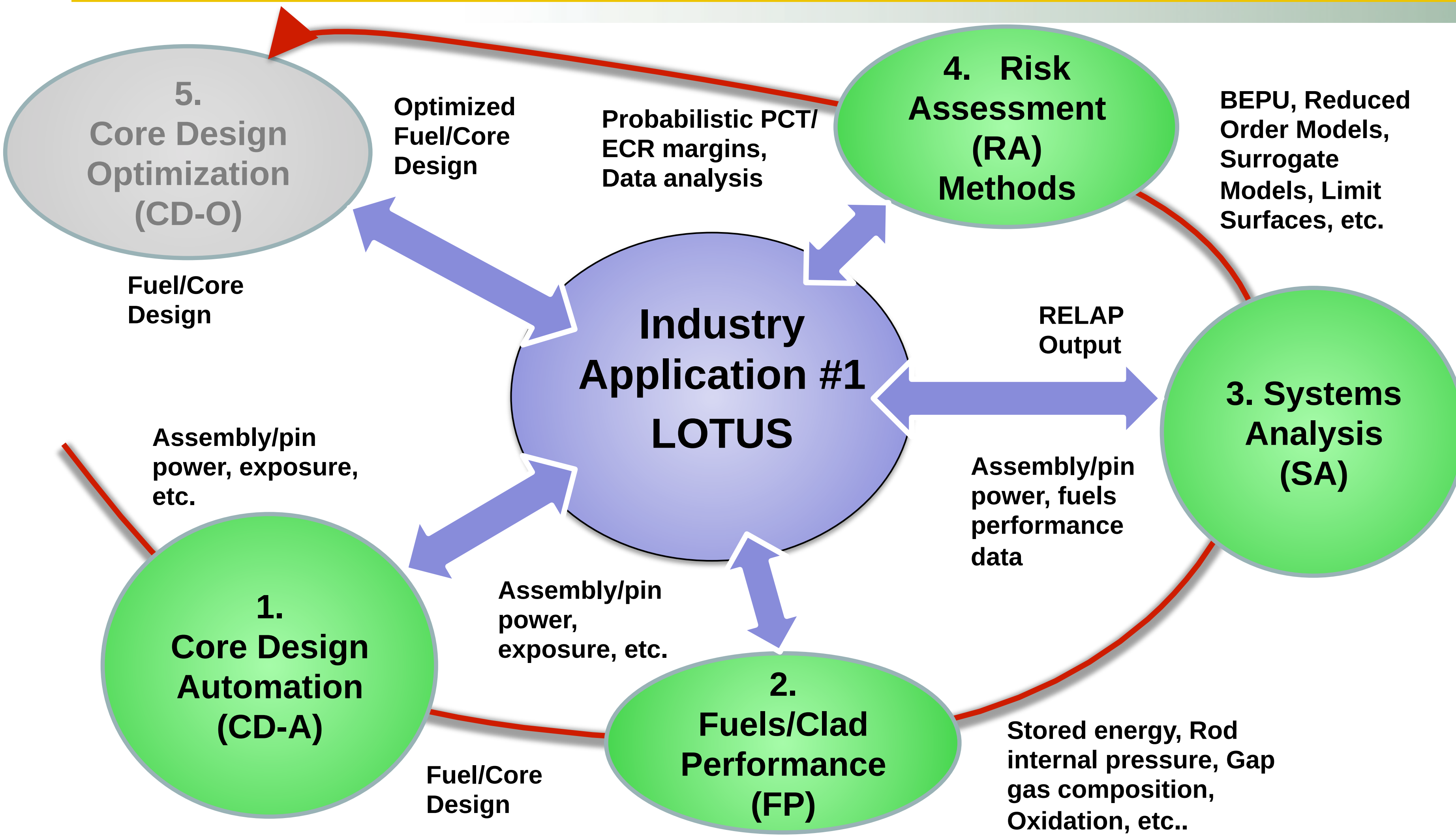




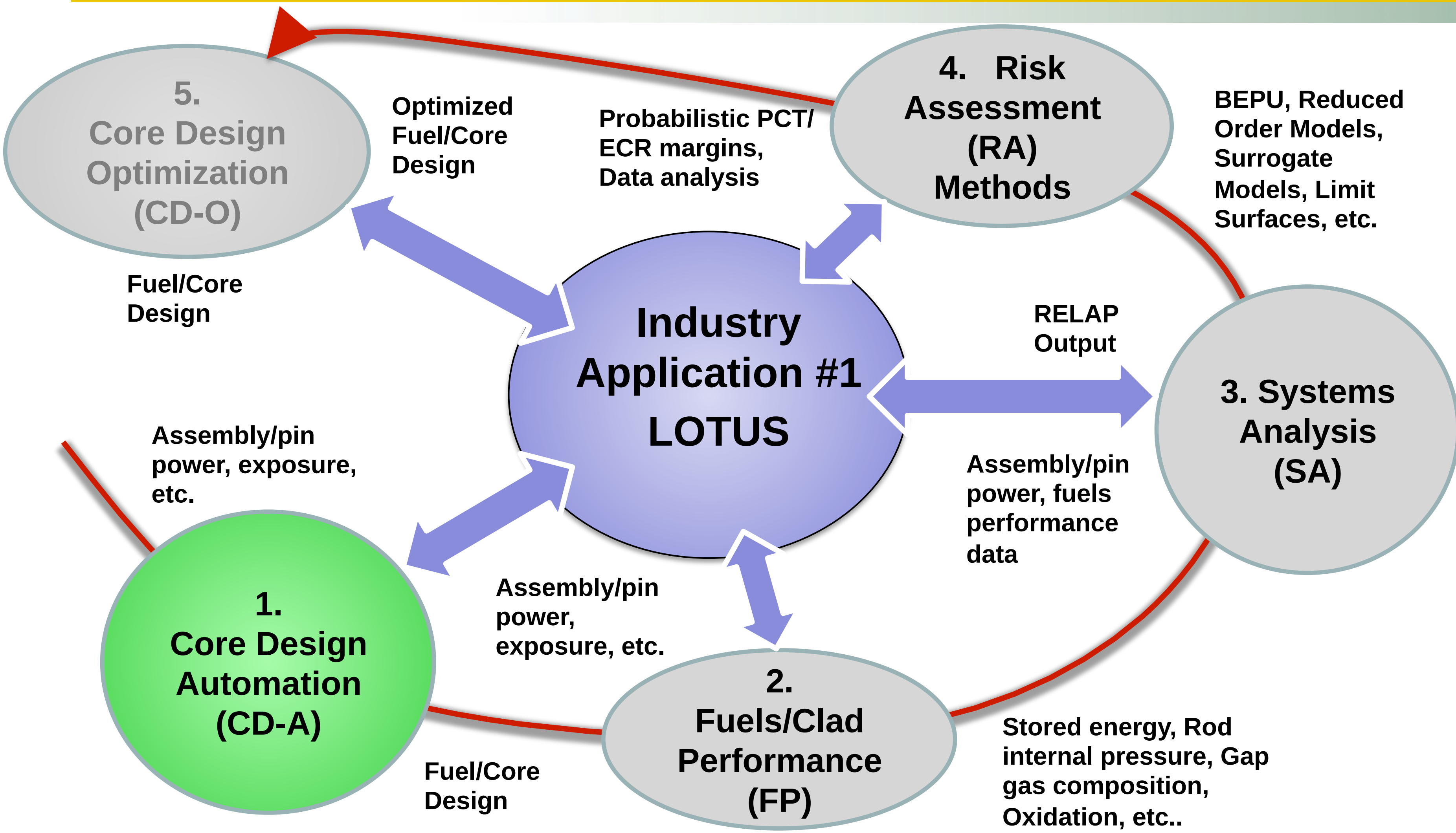
Assessment → ***Optimization***

A targeted value proposition for vendor and/or owner-operator stakeholders
Goal: Industry adoption via pilot/demos/tools

RISMC Application for LOCA Analysis → LOTUS (LOCA Toolkit U.S.)

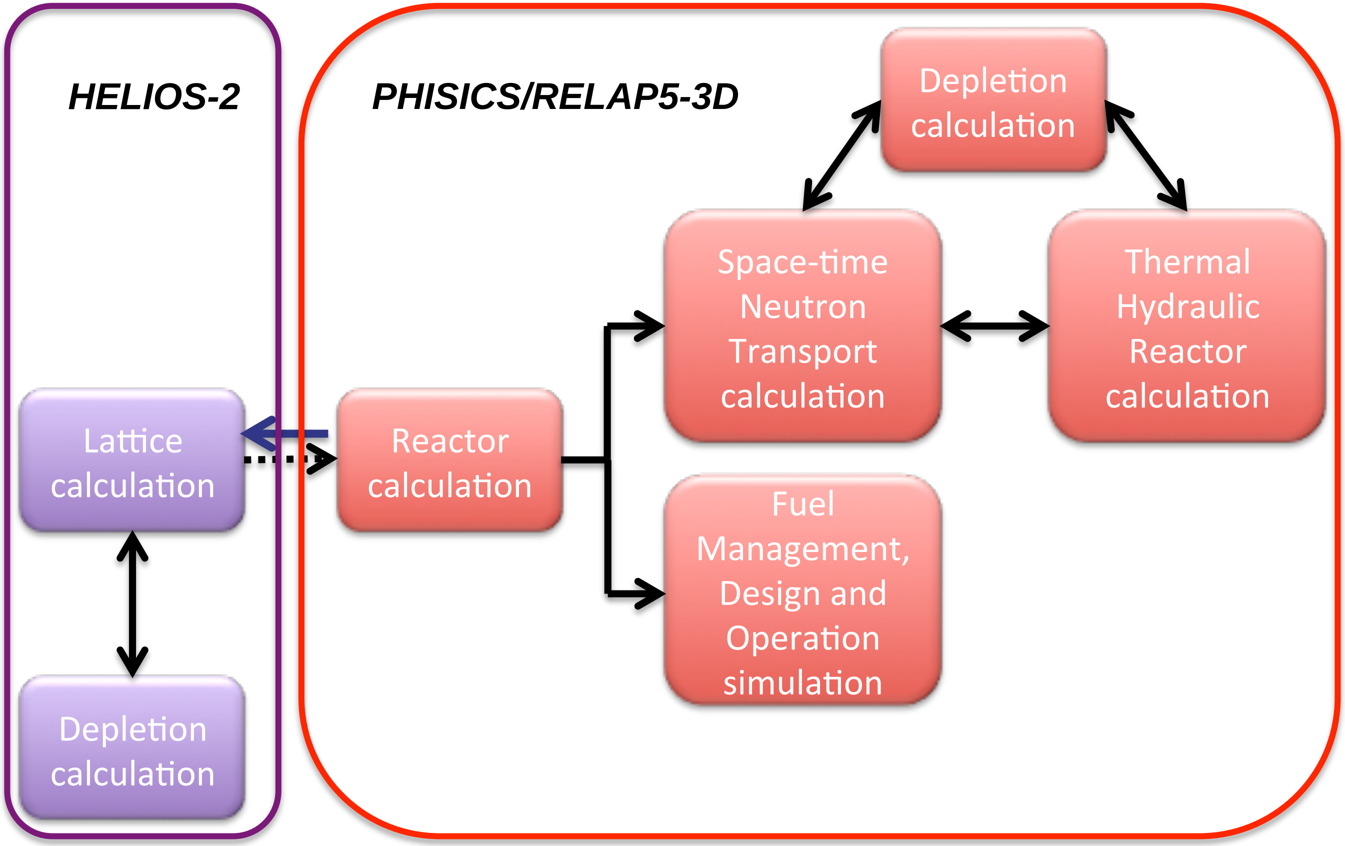


1. Core Design Automation



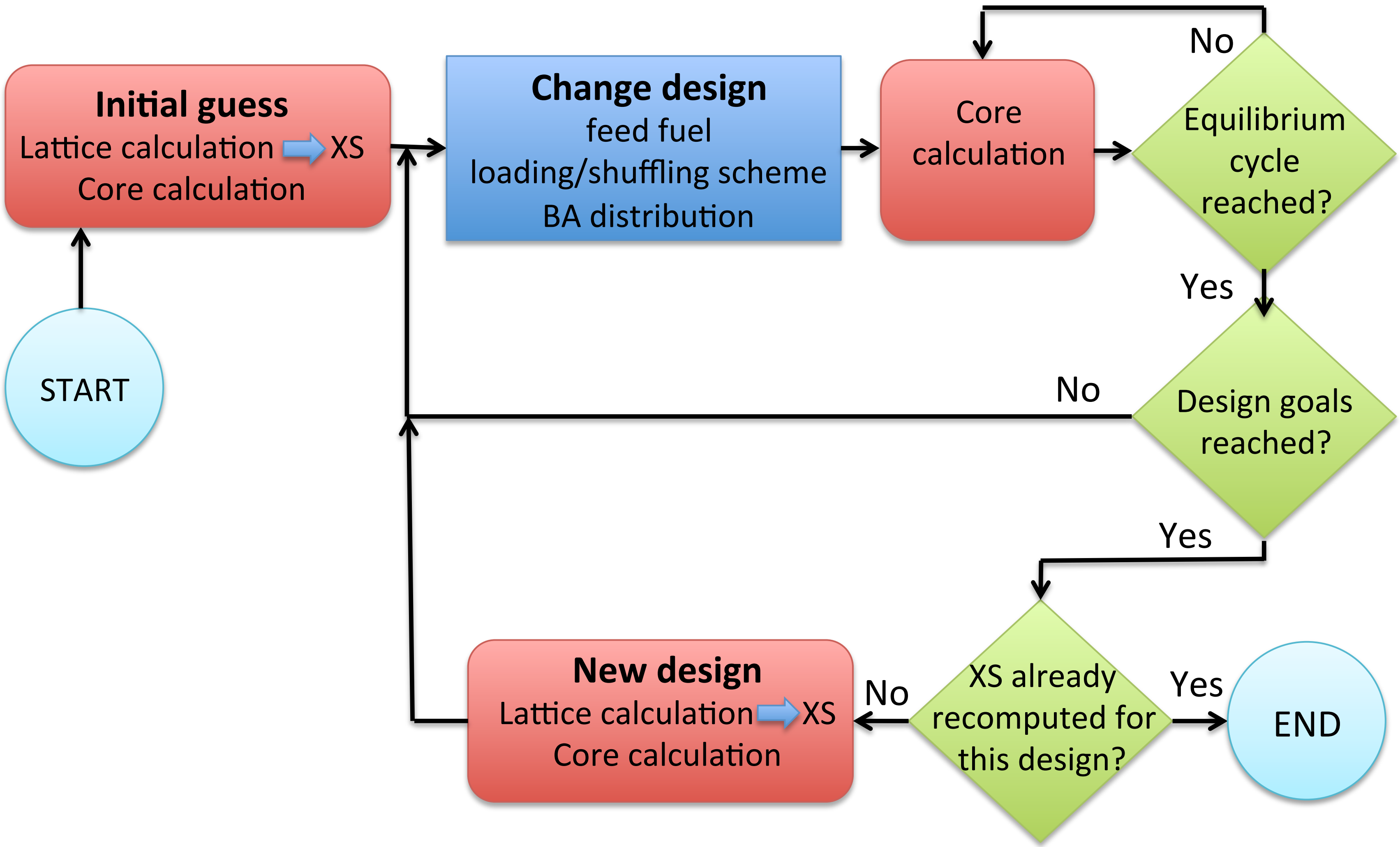
Core design automation (LOTUS base tools)

- **HELIOS-2** → Cross section generation
- **PHISICS** → Reactor neutronics calculation
- **RELAP5-3D** → Reactor thermal-hydraulics calculation



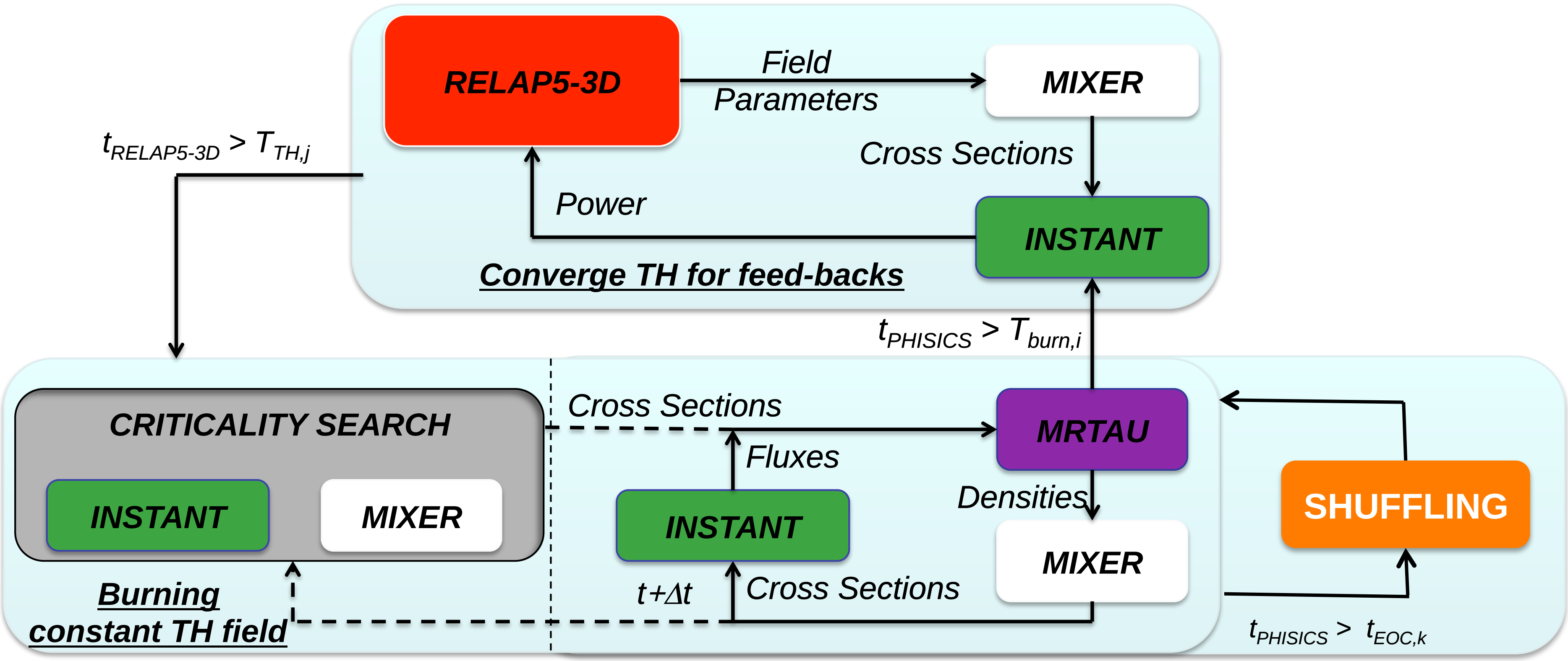
Light Water Reactor Sustainability

Core design methodology



Core design methodology II

- **PHISICS "Depletion Time Evolution & shuffling" coupled with RELAP5/3D**



IA1 PWR demonstration: Geometry

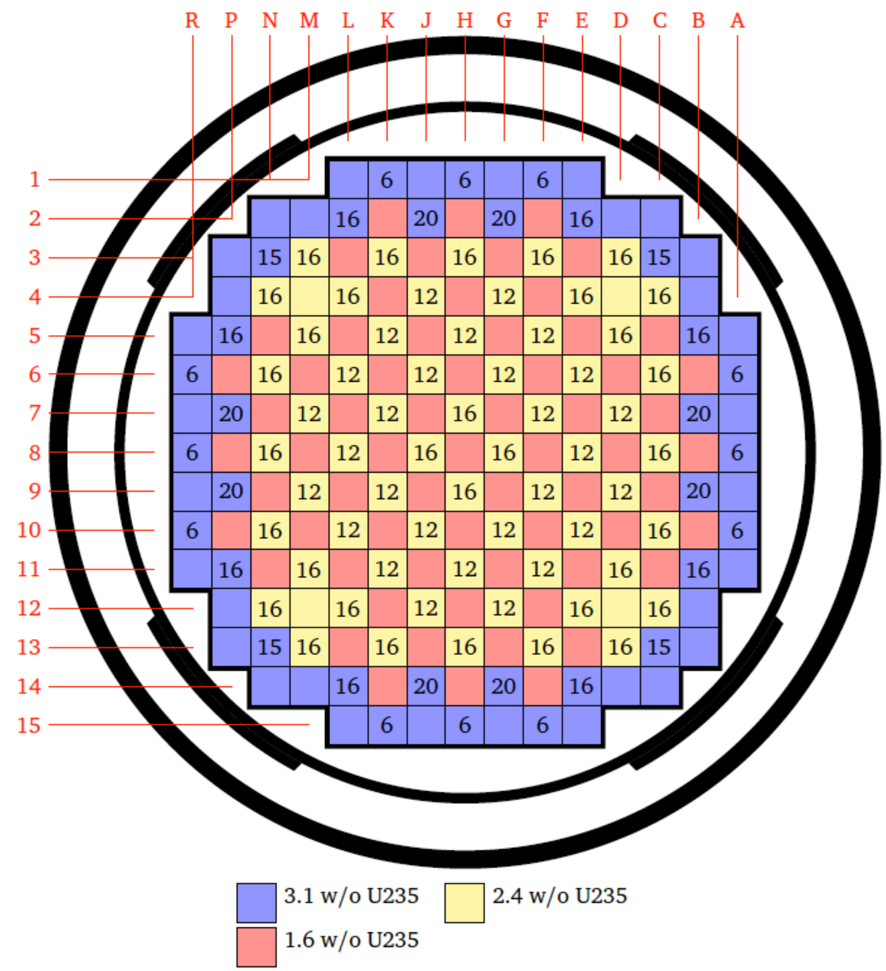
- ***Geometry from BEAVRS***

Assemblies

- *17x17 pin lattice*
- *3.658 m active fuel length*
  - ***18 axial levels modeled***
- *264 fuel rods*
- *8 grid spacers*

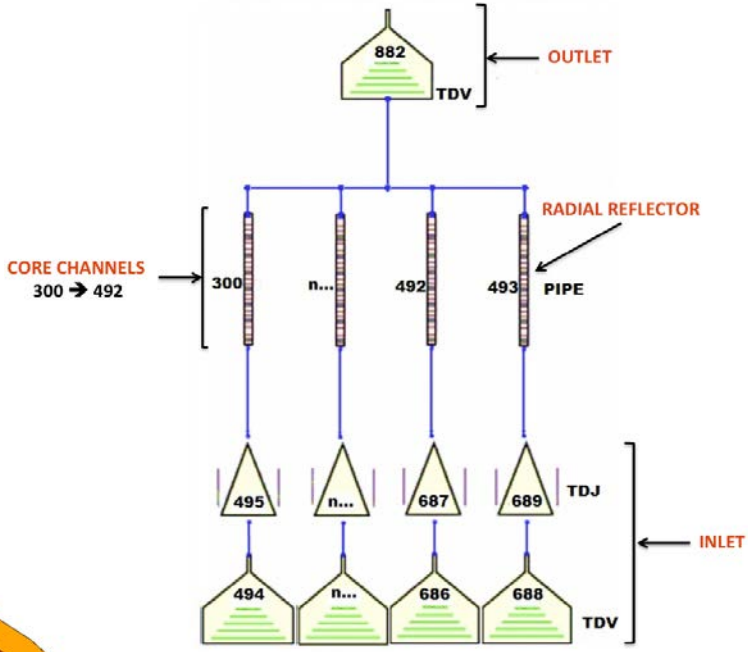
Core

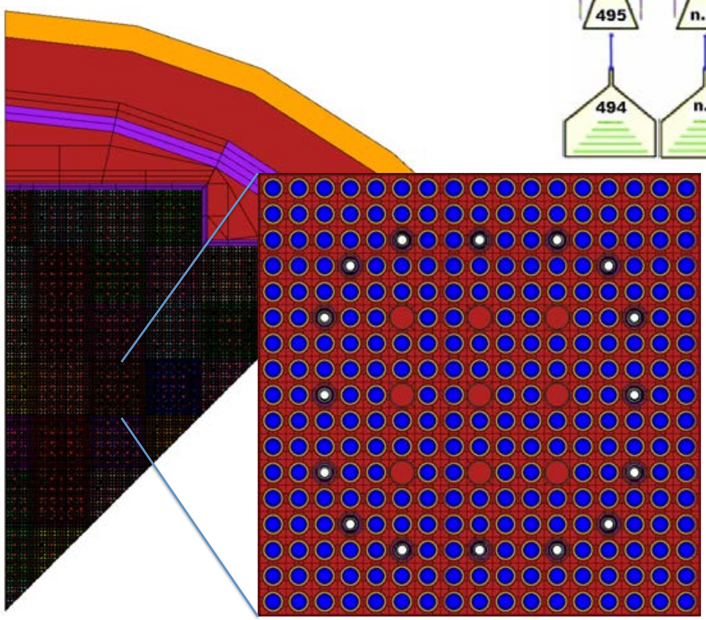
- *193 fuel assemblies*
- *3411 MWth core power*
- *155 bar operating pressure*
- *17 t/sec core flow rate*



IA1 PWR demonstration: Core design nodalisations

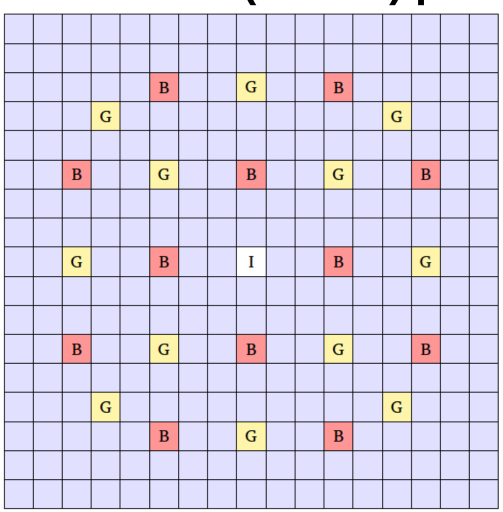
- **Coupled RELAP5/PHISICS**
  - 1 TH channel per assembly
  - Boundary conditions at lower and upper plena
  - 6% core bypass
- **Cross section generation**
  - 1/8 Core in HELIOS
  - 62 libraries generated
    - *29 fuel assemblies (with and w/o spacers)*
    - *1 radial reflector (with and w/o spacers)*
    - *1 top and 1 bottom reflector*
  - ***8 energy groups***
  - 4 tabulation dimensions
    - *Fuel temperature (3)*
    - *Moderator density (4)*
    - *Boron concentration (3)*
    - *Burn-up (4)*



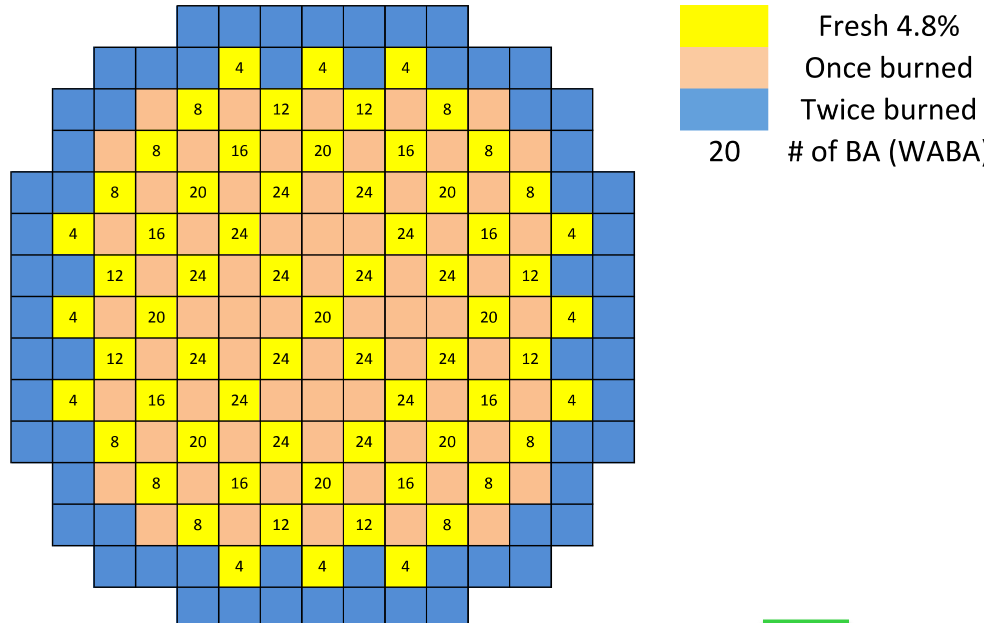


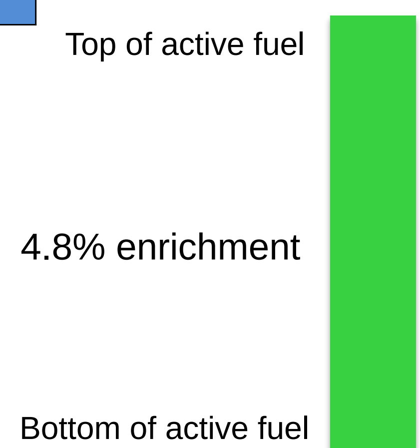
IA1 PWR core design HE-LL

- **Design criteria**
  - 18 month cycle
  - "HE-LL" design
    - *High energy/low leakage*
    - *Twice burned fuel at the periphery*
  - Equilibrium assumed after 8 cycles
- **25 GT and BA (WABA) positions**



Assembly example with 12 WABA





IA1 PWR HE-LL Equilibrium cycle

BOC

1.61 1.65 1.93 0.00	1.45 1.50 1.72 25.45	1.47 1.51 1.73 20.85	1.22 1.26 1.42 29.51	1.62 1.67 1.94 0.00	1.17 1.21 1.38 29.47	1.11 1.15 1.33 0.00	0.27 0.28 0.33 52.57
1.45 1.50 1.72 25.45	1.69 1.74 2.06 0.00	1.55 1.60 1.86 19.63	1.66 1.71 1.99 0.00	1.35 1.39 1.59 27.64	1.53 1.58 1.83 0.00	0.67 0.69 0.79 47.04	0.24 0.25 0.30 52.54
1.47 1.51 1.73 20.85	1.57 1.61 1.88 19.19	1.70 1.76 2.08 0.00	1.45 1.50 1.73 24.48	1.56 1.60 1.86 0.00	1.10 1.13 1.29 31.89	1.02 1.06 1.23 0.00	0.24 0.25 0.29 52.50
1.22 1.26 1.42 29.51	1.67 1.72 2.00 0.00	1.46 1.50 1.74 24.15	1.60 1.64 1.91 0.00	1.18 1.22 1.39 31.49	1.33 1.37 1.59 0.00	0.47 0.49 0.57 51.84	0.15 0.15 0.19 52.52
1.62 1.67 1.94 0.00	1.35 1.39 1.59 27.56	1.55 1.60 1.85 0.00	1.17 1.21 1.39 31.53	1.35 1.39 1.62 0.00	0.68 0.70 0.81 30.49	0.24 0.25 0.30 51.01	
1.17 1.21 1.38 29.47	1.52 1.57 1.82 0.00	1.08 1.11 1.26 32.28	1.31 1.35 1.56 0.00	0.67 0.69 0.80 30.32	0.28 0.29 0.34 51.15	0.11 0.11 0.14 44.23	
1.11 1.15 1.33 0.00	0.67 0.69 0.79 47.27	1.00 1.03 1.20 0.00	0.44 0.46 0.53 51.84	0.22 0.23 0.28 53.59	0.11 0.11 0.14 43.91		
0.27 0.28 0.33 52.57	0.23 0.24 0.29 53.58	0.23 0.23 0.28 52.50	0.14 0.14 0.18 52.65				

	max
Pbar	1.70
FDH	1.76
Fq	2.08
Burnup	53.59

- Fresh
- Once burned
- Twice burned

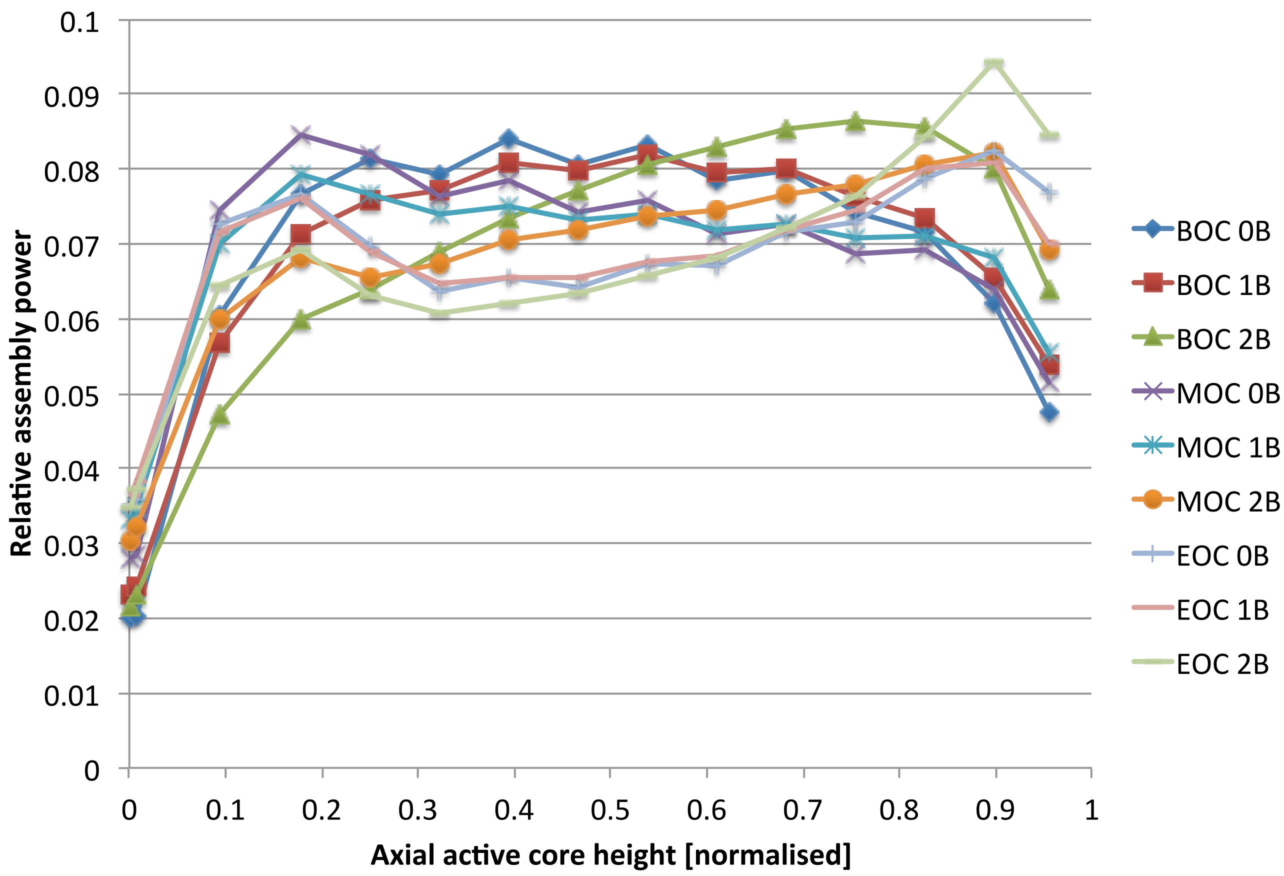
EOC

1.49 1.54 1.87 31.30	1.25 1.29 1.70 51.91	1.22 1.25 1.56 47.08	1.21 1.25 1.48 52.57	1.43 1.47 1.65 30.50	1.15 1.19 1.35 50.99	1.26 1.30 1.43 20.83	0.36 0.37 0.45 58.22
1.25 1.29 1.70 51.91	1.49 1.54 1.89 31.95	1.29 1.33 1.65 47.56	1.52 1.57 1.79 31.52	1.25 1.29 1.47 52.61	1.46 1.51 1.67 27.62	0.73 0.75 0.85 59.86	0.34 0.35 0.42 57.73
1.22 1.25 1.56 47.08	1.29 1.33 1.65 47.32	1.53 1.57 1.80 32.32	1.31 1.35 1.56 51.41	1.44 1.49 1.65 29.52	1.15 1.18 1.36 52.40	1.21 1.25 1.37 19.58	0.34 0.35 0.44 56.50
1.21 1.25 1.48 52.57	1.53 1.57 1.79 31.57	1.31 1.35 1.56 51.20	1.45 1.50 1.67 30.33	1.18 1.21 1.38 53.55	1.40 1.44 1.57 24.42	0.56 0.58 0.67 56.90	0.23 0.24 0.30 55.91
1.43 1.47 1.65 30.50	1.25 1.29 1.47 52.54	1.44 1.49 1.64 29.47	1.18 1.21 1.38 53.53	1.57 1.62 1.78 25.49	0.87 0.89 1.03 44.19	0.34 0.35 0.42 56.23	
1.15 1.19 1.35 50.99	1.46 1.51 1.67 27.54	1.14 1.18 1.35 52.56	1.39 1.43 1.56 24.13	0.86 0.89 1.02 43.88	0.40 0.41 0.54 57.31	0.20 0.21 0.26 46.92	
1.26 1.30 1.43 20.83	0.73 0.75 0.85 60.00	1.20 1.23 1.36 19.21	0.54 0.55 0.64 60.76	0.33 0.34 0.41 58.53	0.20 0.20 0.25 46.56		
0.36 0.37 0.45 58.22	0.34 0.35 0.41 58.66	0.33 0.34 0.41 57.44	0.22 0.23 0.28 55.80				

	max
Pbar	1.57
FDH	1.62
Fq	1.89
Burnup	60.76

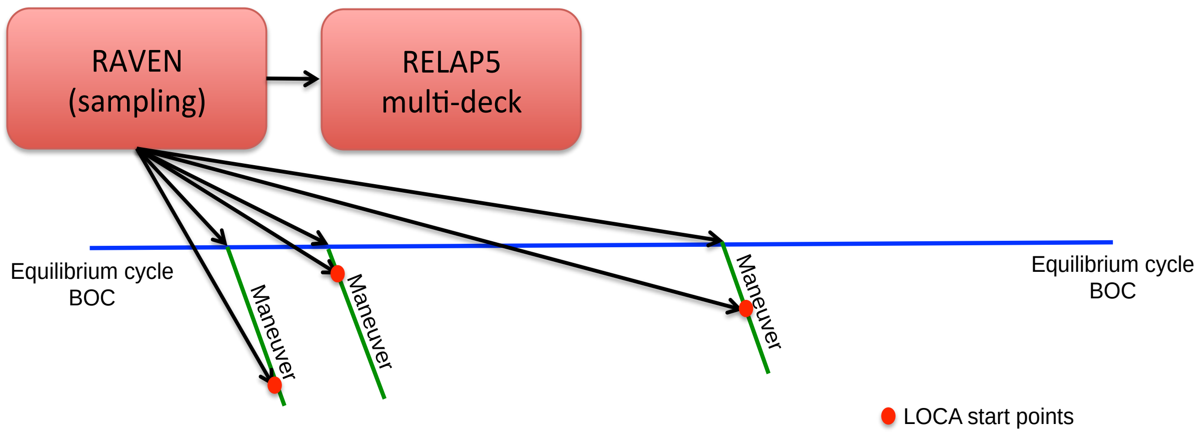
- Fresh
- Once burned
- Twice burned

IA1 PWR HE-LL Equilibrium cycle



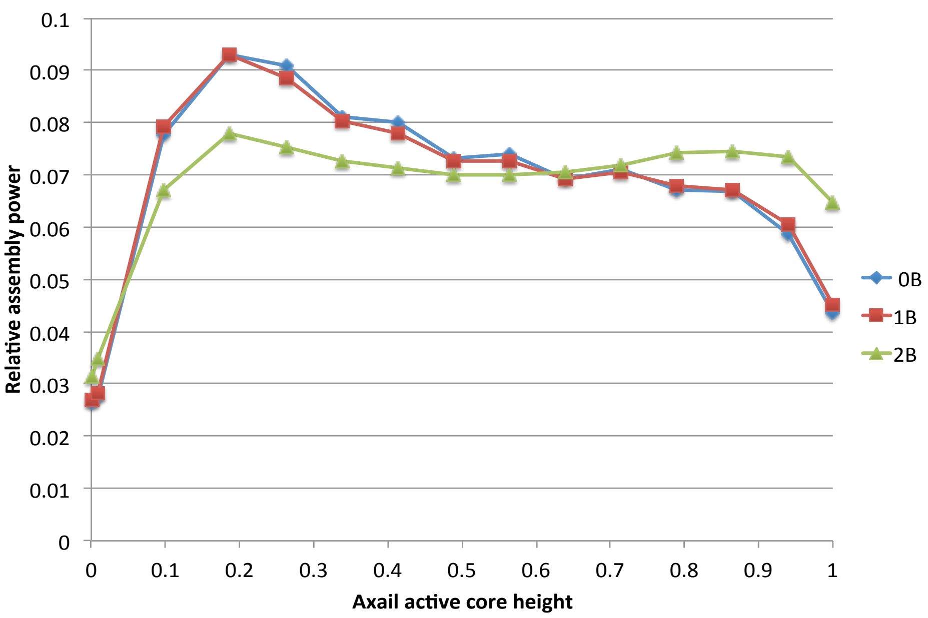
Core design data for LOTUS

- The core status at BOC, MOC and EOC does not determine challenging conditions for the LOCA analysis
- LOCA scenarios for the assessment of the safety margins are generally performed considering the reactor right after a maneuver that can initiate, for example, a Xenon transient.
- Maneuver: load-following operation of the reactor (using the PHISICS CS module)

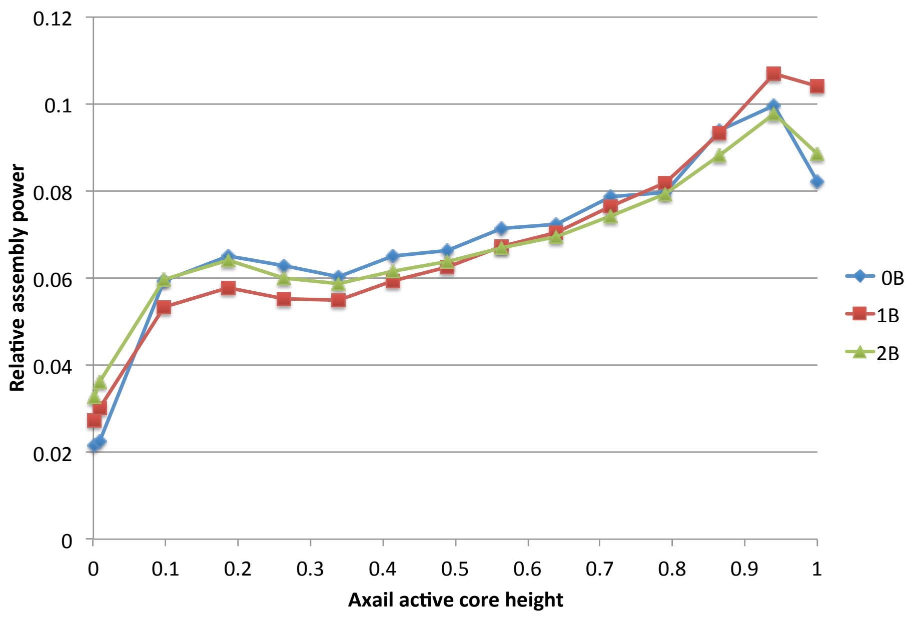


Core design data for LOTUS II

- **Core Average Axial Power Distributions for Fresh (0B), Once Burned (1B) and Twice Burned (2B) Fuel Assemblies**

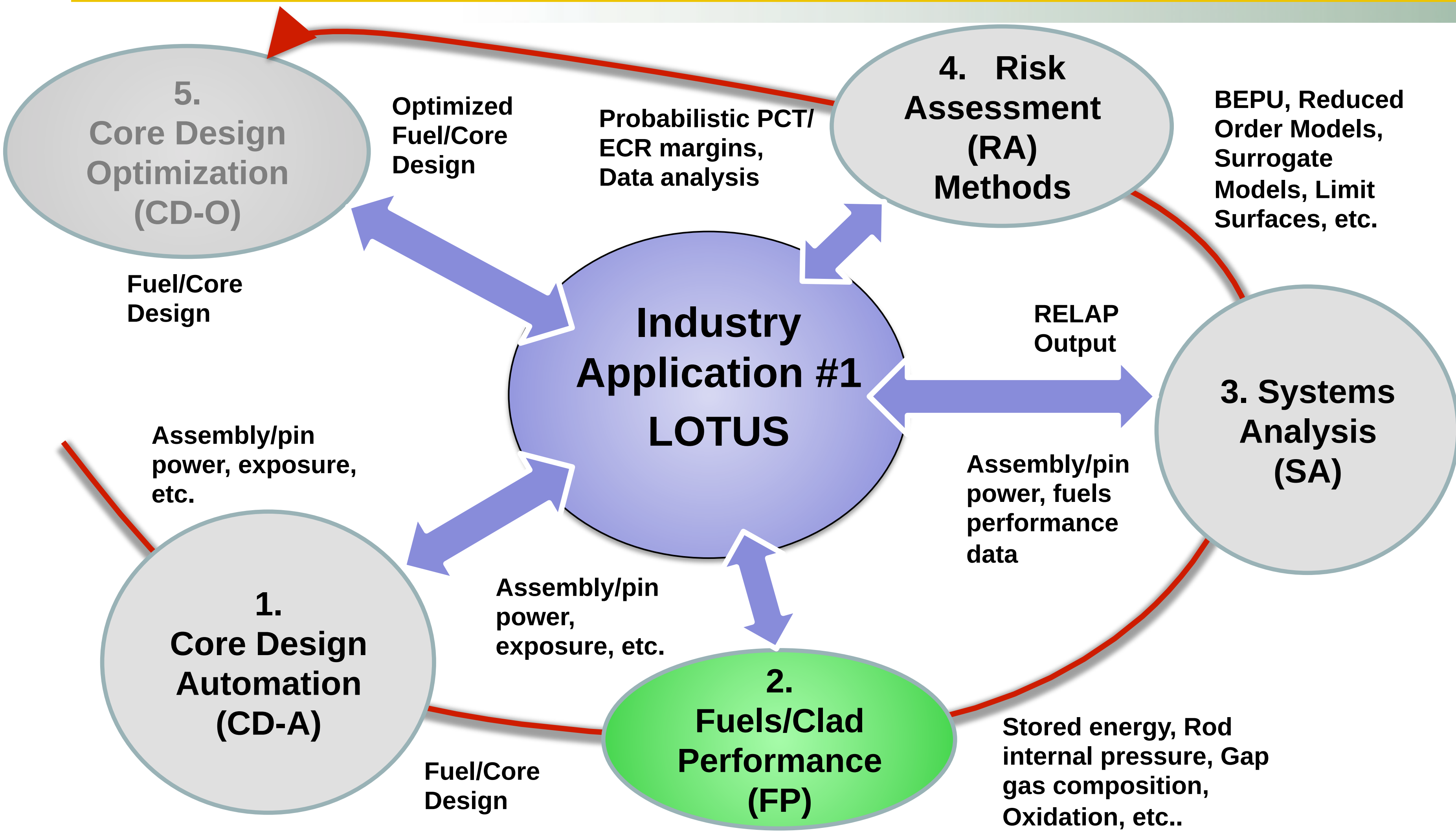


BOC



EOC

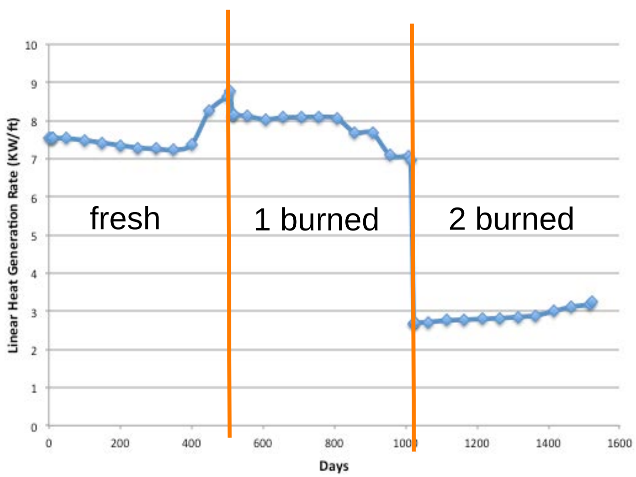
2. Fuel/Clad Performance



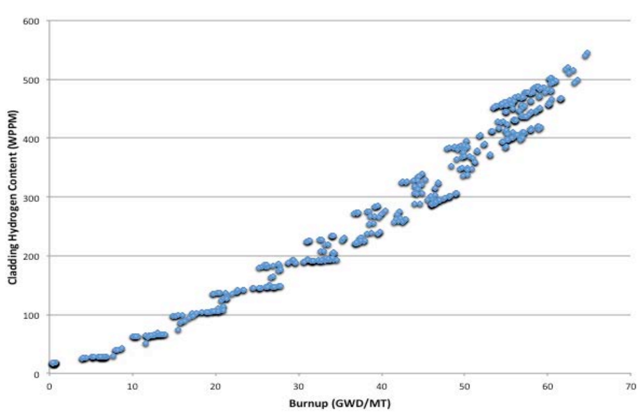
2. Fuels/Clad Performance (baseline)

- **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, etc., ➡ **FRAPCON**
- **The power history data is automatically retrieved by LOTUS from the core design results and included in the FRAPCON input**

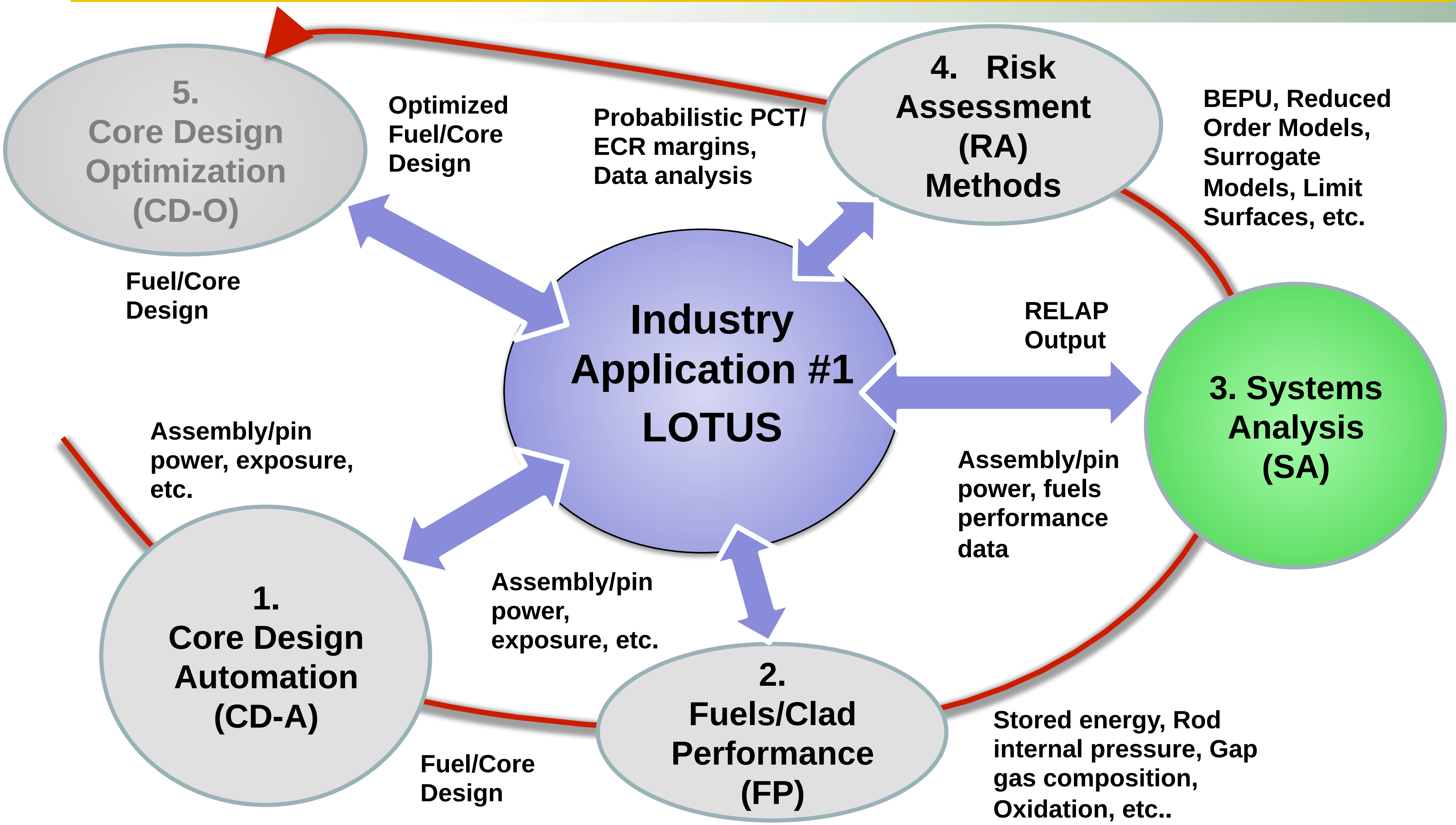
Power history for the hot rod (one assembly)



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

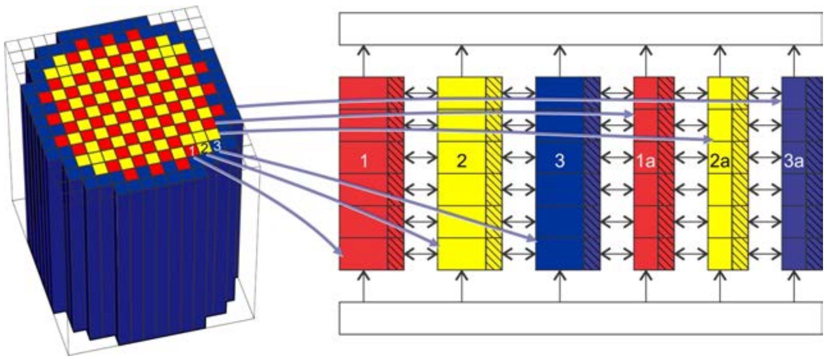


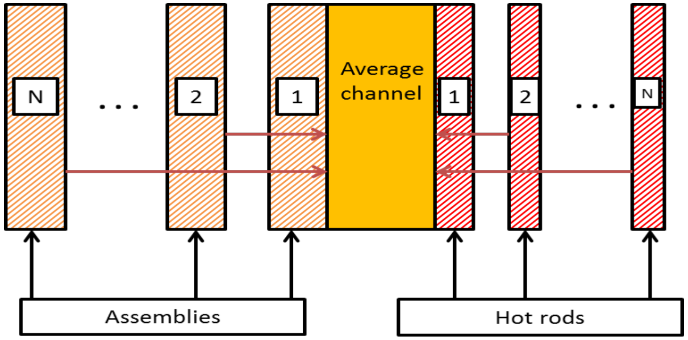
3. System Analysis

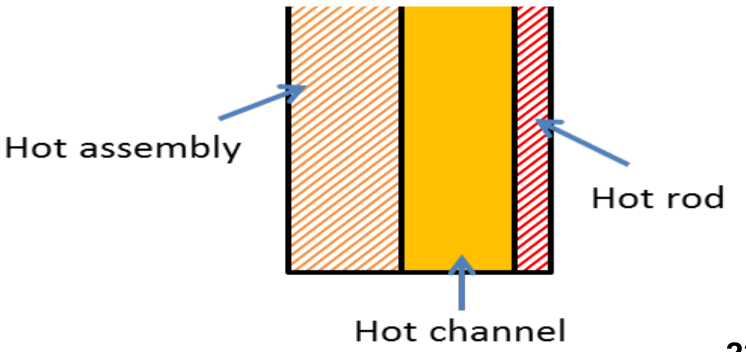


Safety Analysis – Core Hydraulic Homogenization

- **An existing RELAP5 PWR model is modified to analyze the HE-LL core:**
  - A core hydraulic homogenization is performed
  - Heat structures for the hot assembly in each group are connected to the hot channel in that group (2 sets of heat structures for each assembly)

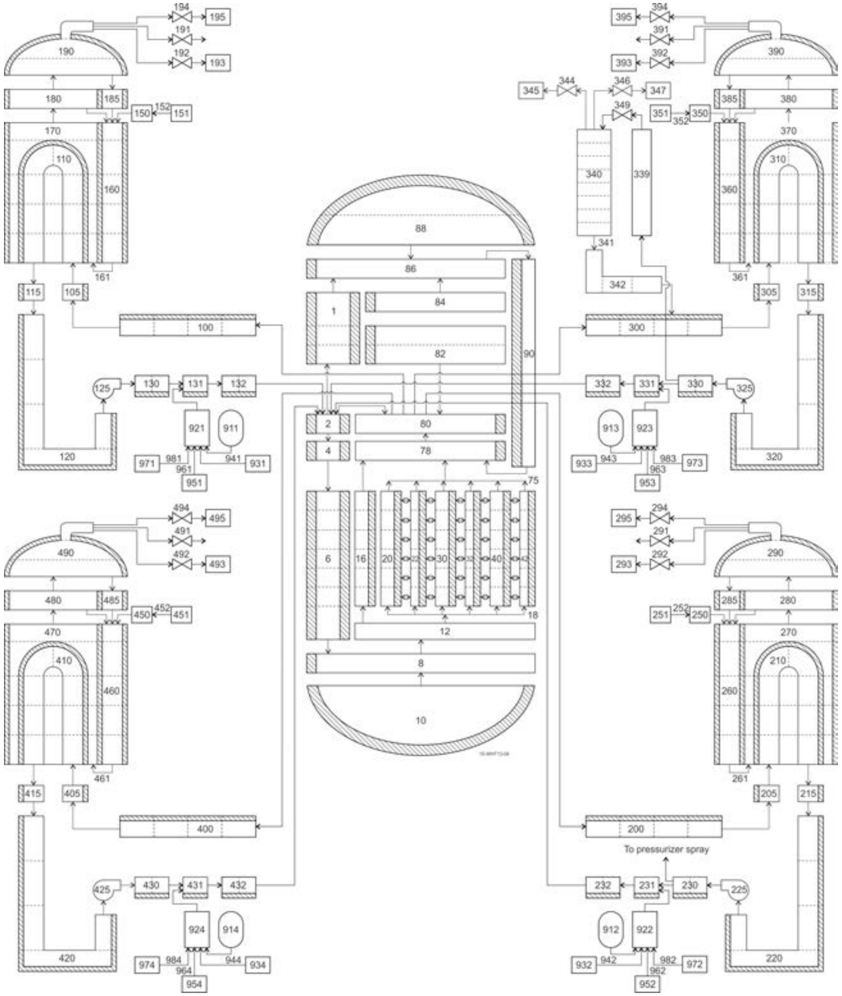




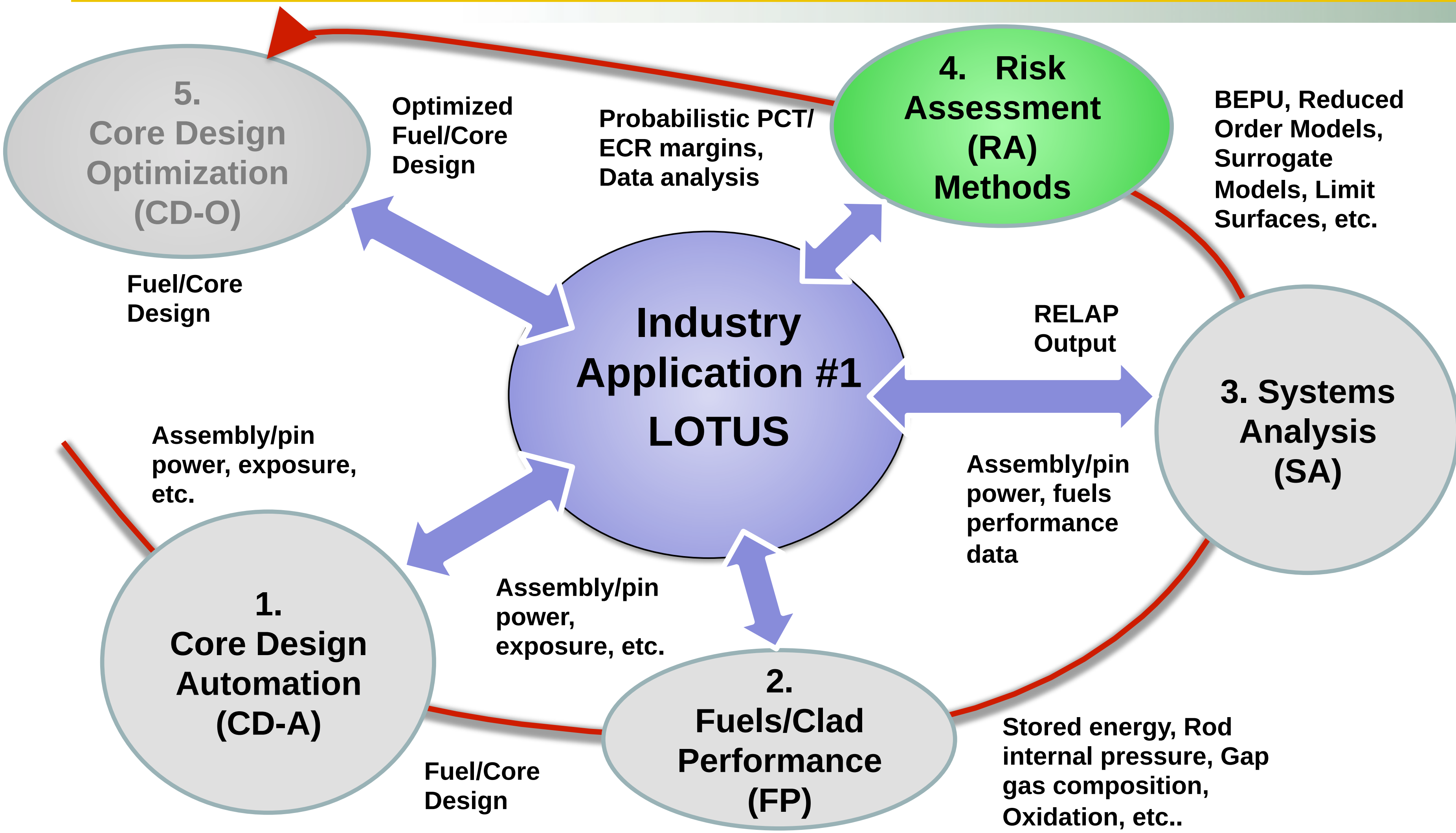


RELAP5 nodalisation

- **An existing RELAP5 PWR model is modified to analyze the HE-LL core:**
  - Reactor Vessel
    - *Downcomer*
    - *Bypass*
    - *Lower/Upper plena*
    - *Core*
    - *Upper head*
  - Reactor coolant system
    - *4 primary loops*
    - *Secondary side up to turbine governor valves*
  - ECCS
    - *Low pressure injection (LPI)*
    - *High pressure injection (HPI)*



4. Risk Assessment



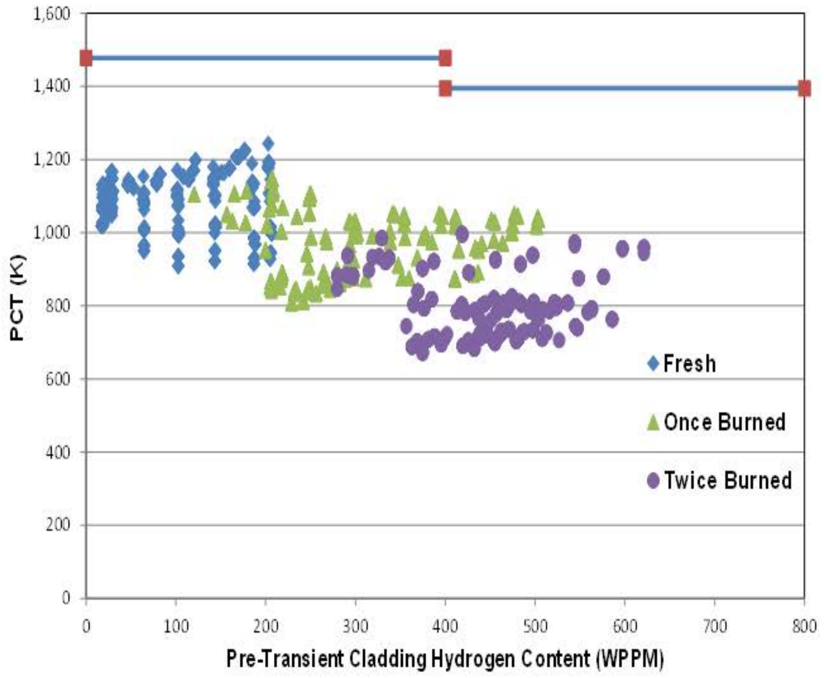
Risk Assessment – Baseline BEPU

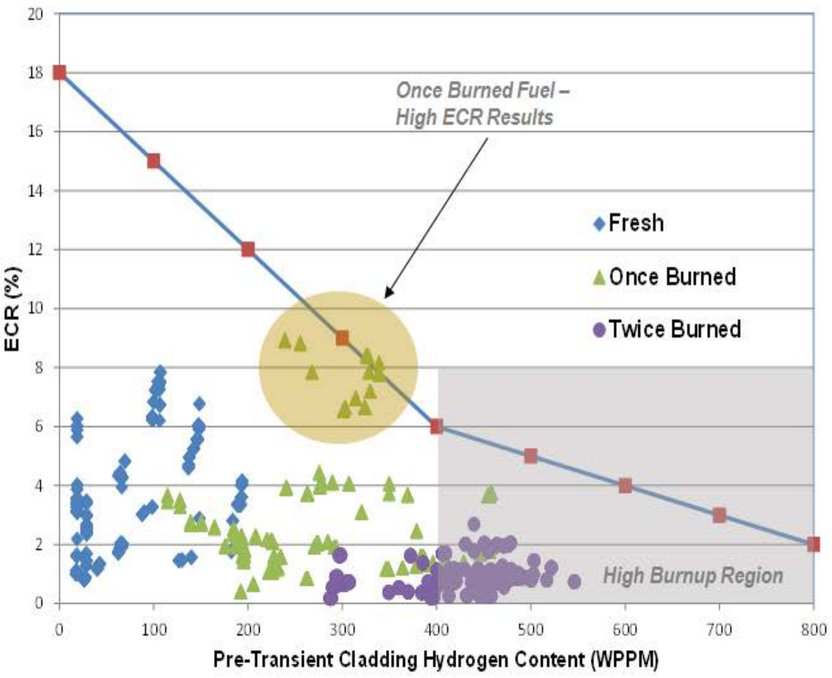
- **LB-LOCA with a double-ended guillotine break in a cold leg**
- **BEPU analysis**
  - PIRT Reduces set of parameters with high importance
- **Automatically mapped parameters from fuel performance and core design**
  - cladding pre-transient hydrogen up-take contents, rod internal pressure, gap gas mole fraction, power distribution, etc.
- **7 LOCA start times in cycle and maneuver**
- **1000 Monte Carlo samples for each start time**

Distribution of Parameter Uncertainties

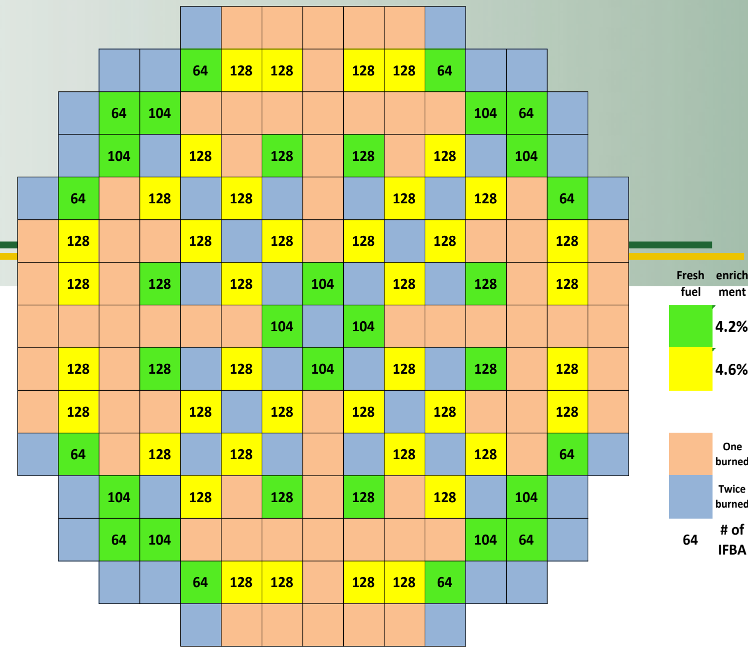
Parameter	PDF type	Min	Max	Comments
Reactor thermal power	Normal	0.98	1.02	Multiplier
Reactor decay heat power multiplier	Normal	0.94	1.06	Multiplier
Accumulator pressure	Normal	-0.9	1.1	Multiplier
Accumulator liquid volume (m^3)	Uniform	-0.23	0.23	Additive
Accumulator temperature (K)	Uniform	-11.1	16.7	Additive
Subcooled multiplier for critical flow	Uniform	0.8	1.2	Multiplier
Two-phase multiplier for critical flow	Uniform	0.8	1.2	Multiplier
Superheated vapor multiplier for critical flow	Uniform	0.8	1.2	Multiplier
Fuel thermal conductivity	Normal	0.93	1.07	Multiplier
Average core coolant temperature (K)	Normal	-3.3	3.3	Additive
Film boiling heat transfer coefficient	Uniform	0.7	1.3	Multiplier

Risk Assessment HE-LL results

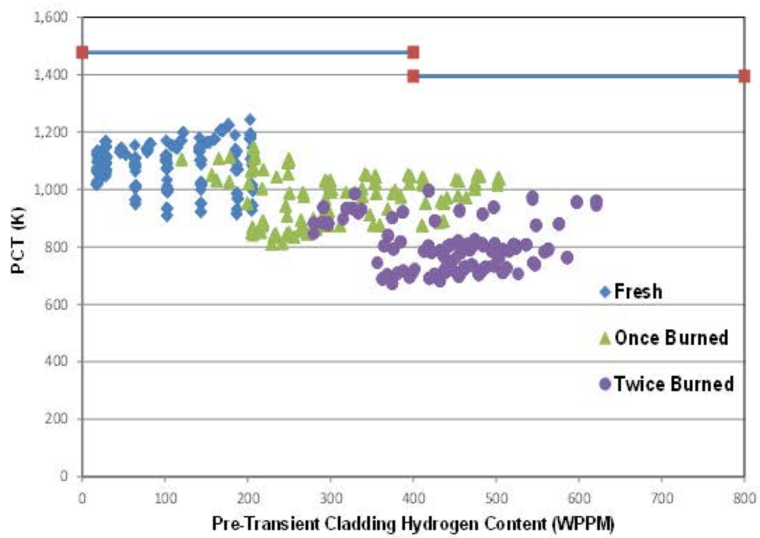


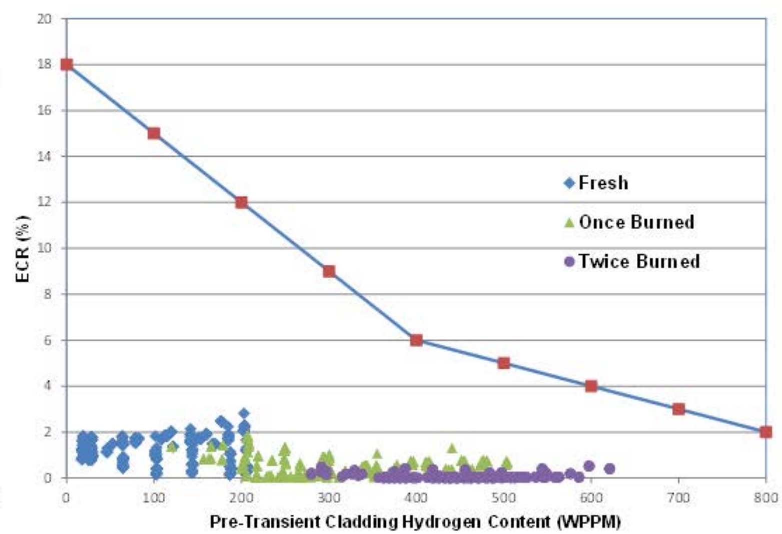


HE-LL-O Case



- **HE-LL optimized case**
  - Modern loading/shuffling scheme
  - Different fresh fuel enrichments
  - IFBA instead of WABA





Still margin to go to higher burn-up

Conclusions

- IA#1 is a challenging problem, demonstrating the multi-physics and multi-model approach we are advocating within RISMC
- RELAP5-3D part of core design, system analysis and risk assessment in baseline LOTUS
- Comparisons between the Wilks approach vs. Monte Carlo approach demonstrate that margins can be gained
- Coupling neutronics/ T/H with fuel/clad performance is necessary to ensure the system analysis captures correct fuel behavior
- HE-LL core design shows that accurate margin characterization is needed, since margin is small for higher burn-up fuel for the new LOCA/ ECCS rule 10 CFR 50.46c
- After the margin characterization, core optimization can be envisaged

Helping to Sustain National Assets

LWRS

Light Water Reactor Sustainability