Development of Best Estimate Plus Uncertainty (BEPU) Application for RELAP5-3D

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Uncertainties in Nuclear Engineering

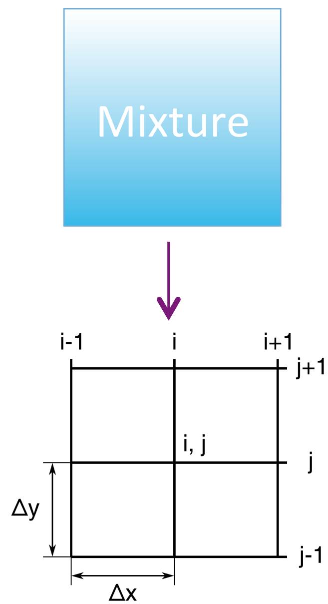
- Unavoidable error from thermal-hydraulics computational tools
  - Epistemic (systematic) uncertainty
- Uncertainty analysis/quantification/estimate/evaluation
  - Prediction of the error expected in engineering calculation results
  - Express with absolute, fractional, or percentage

Navier

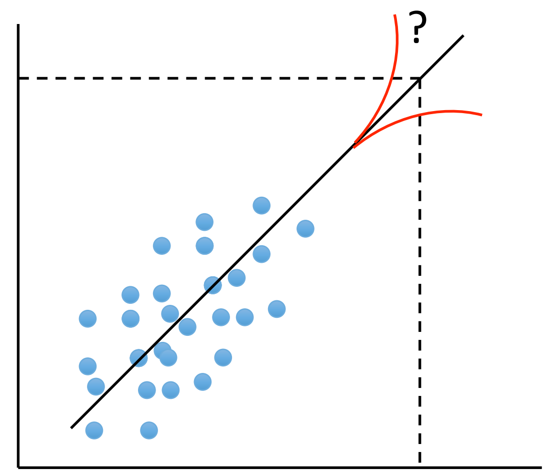
Stokes

Continuum hypothesis
No slip condition
Inviscid fluid
Newtonian fluid
Zero bulk viscosity
Isotropic perfect gas
Boussinesq approximation
Turbulence
Inverse matrix
...

Uncertainty in modeling



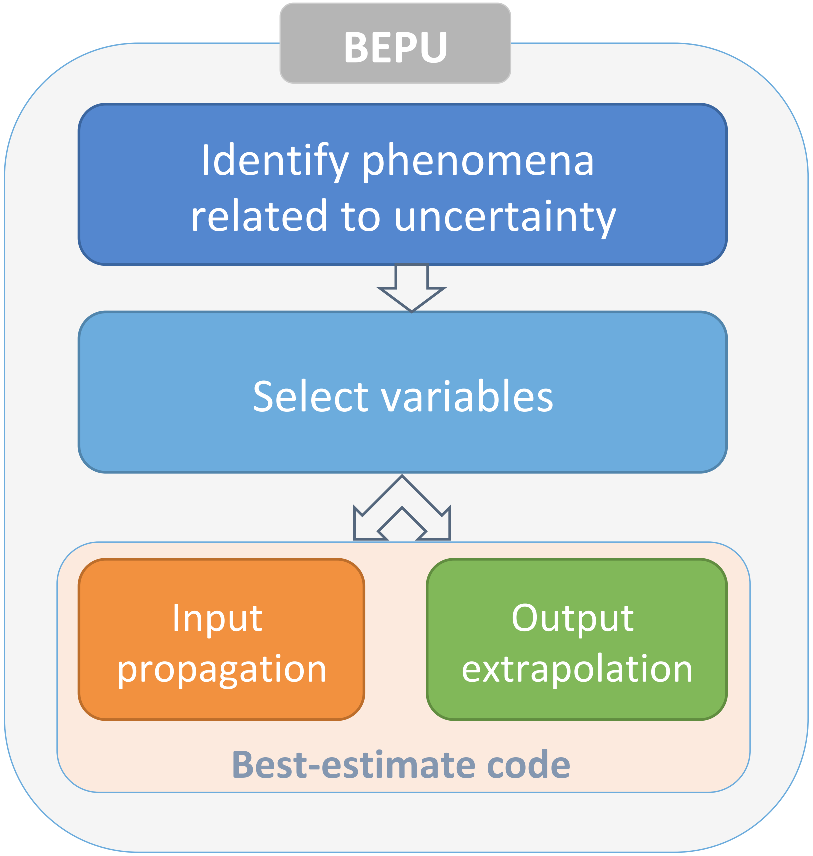
Uncertainty in representation



Uncertainty in scaling

Best-Estimate Plus Uncertainty (BEPU)

- Best-Estimate (BE) aims minimizing error with actual knowledge
  - Conservatism masks lack of knowledge
- Use of fully validated computer code (Best-Estimate code) for uncertainty
  - Validated to model physical phenomena realistically
  - Needs experiment or operation data to promote confidence
- BEPU method provides more realistic information of physics in NPP
  - Identify most relevant safety issue



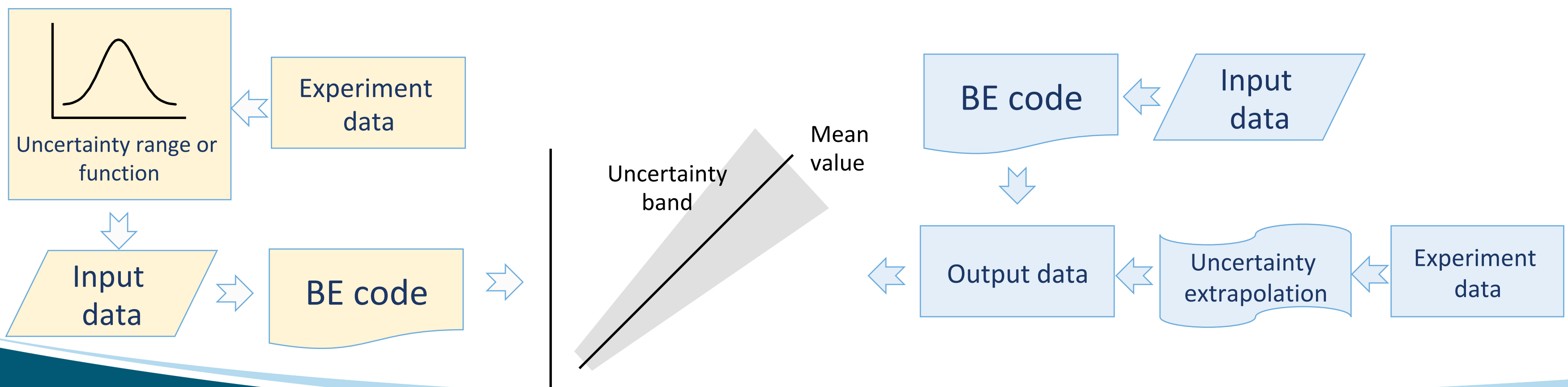
Two Methods for BEPU

Input uncertainty propagation

- Identify uncertain parameter
- Set range or function based on experiment
- Calculate with BE code for uncertainty band
- Can couple with PSA
- More popular for NPP (use in U.S. NRC)
- Used in this research

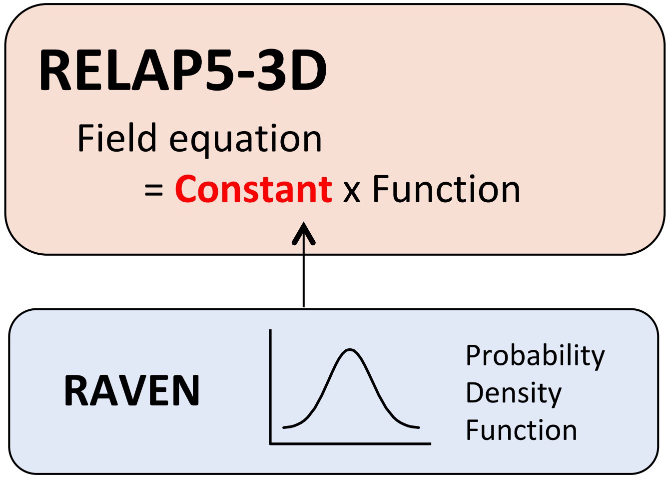
Output uncertainty extrapolation

- Calculation with BE code with normal input data
- Extrapolation of output based on experiment data
- Accuracy evaluation of integral test facility data



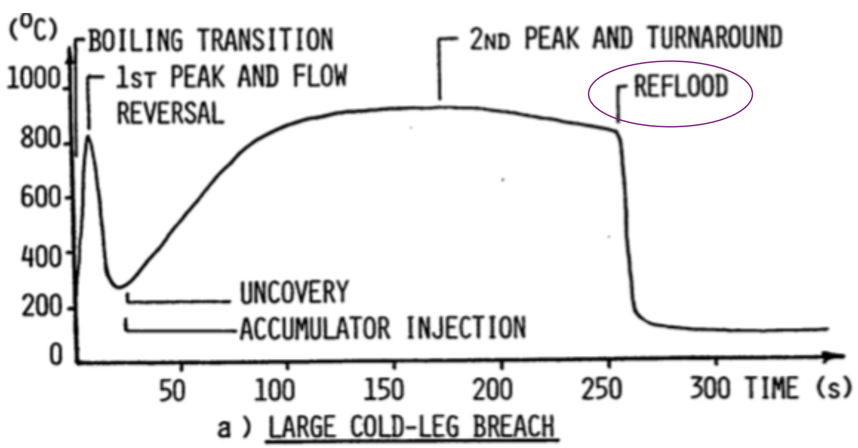
Source Code Upgrade for Input Uncertainty Propagation

- The ideal way is to add uncertainties to field equation
  - Allow generating uncertainty in wide range of physical phenomena
- Previous approaches were limited to add uncertainty input deck
  - Very limited access to propagate field equations
  - Cannot calculate multi-physics
    - Two-phase flow, phase change
- Upgrade of RELAP5-3D source code for uncertainty propagation
  - Field equations related to phenomena to directly receive uncertainty range



Application of RELAP5-3D BEPU Method to LB-LOCA

- BEPU demonstration for LB-LOCA
  - Identification of main T/H scenario parameters
    - LB-LOCA reflood, blowdown and refill phase
    - Interphase friction/heat transfer model, dry/wet wall dispersed flow heat transfer, transition/film boiling
  - RELAP5-3D source code modification
    - User perturbation coefficient to closure laws
    - Dedicated input card added
    - Details are not publicly available
  - Apply in reflood scenario in RELAP5-3D
    - Separate effect test case of RELAP5-3D V&V

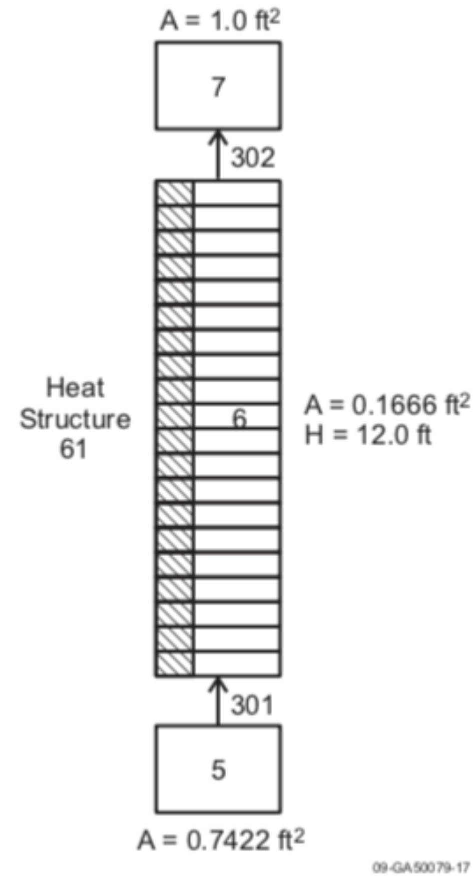


Phenomena	Occurrence
Break flow	Yes
Phase separation (condition or transition)	Yes
Mixing and condensation during injection	Yes
Core wide void + flow distribution	Yes
ECC bypass and penetration	Partially
CCFL (Upper core support plate)	Yes
Steam binding (liquid carry over, etc.)	Yes
Pool formation in upper plenum (UP)	Yes
Core heat transfer including DNB, dry out, return to nucleate boiling	Yes
Quench front propagation	Yes
Entrainment (Core, UP)	Yes
De-entrainment (Core, UP)	Yes
One- and two-phase pump behavior	Partially
Non-condensable gas effects	Partially

BEPU with Reflood Separate Effect Test

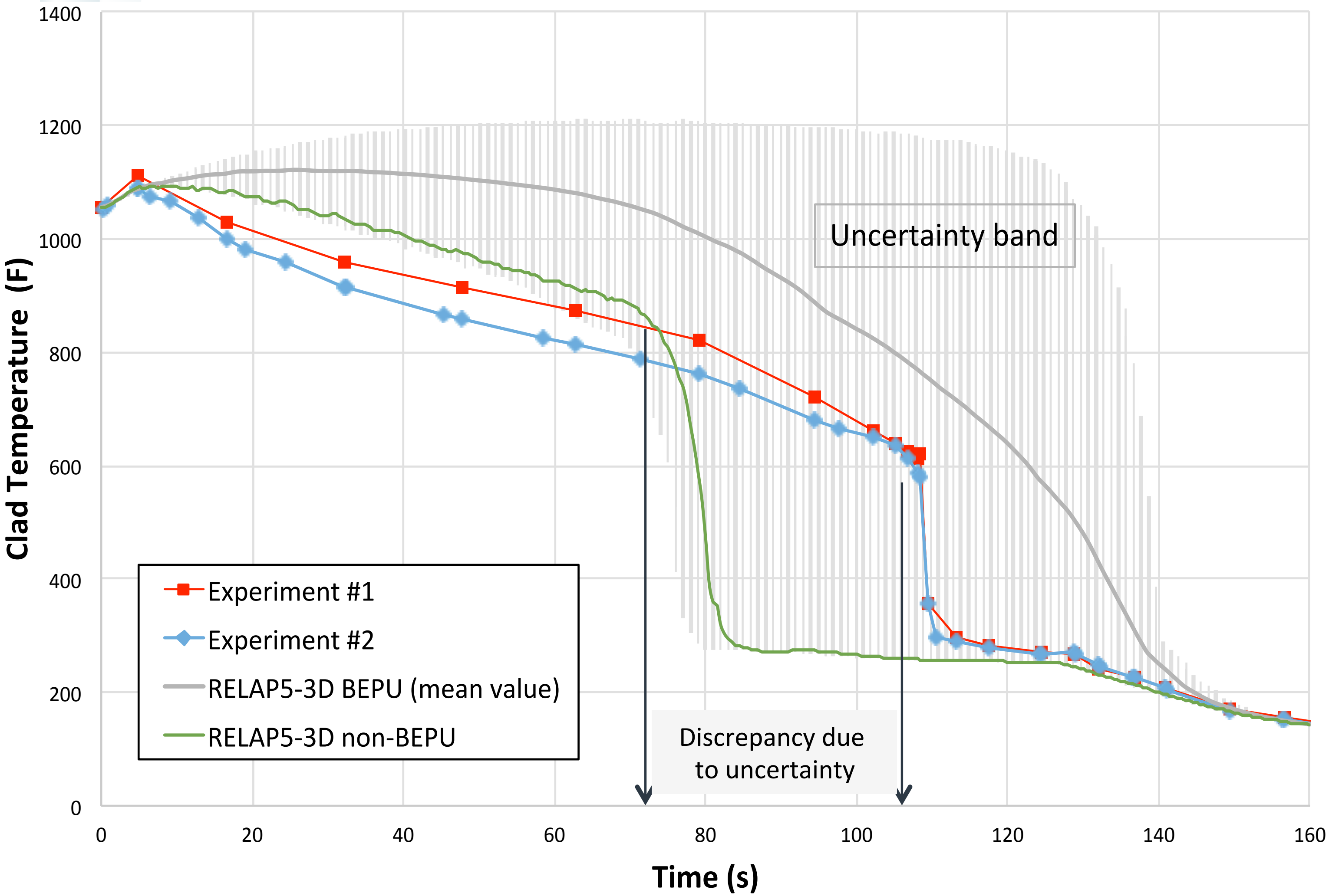
- FLECHT-SEASET forced and gravity reflood test
  - Early 80s from EPRI/NRC/WH unblocked core (17x17 PWR)
  - RELAP5-3D code standard V&V suite
  - Use RAVEN code for logic control and sampling of uncertainties
- Upgrade following RELAP5-3D source code

Phenomena	Modified Routine/Module
Interfacial heat transfer	Interphase heat transfer
Wall heat transfer	Heat transfer coefficients for the non-reflood side boundary of the reflood model
	Reflood heat transfer coefficient using the pattern obtained in above subroutine
	Post-DNB forced convection heat transfer coefficient
Interfacial friction	Interphase drag
	Junction interphase drag term for bubbles and droplets
	Interphase friction coefficients in bubbly/slug flow



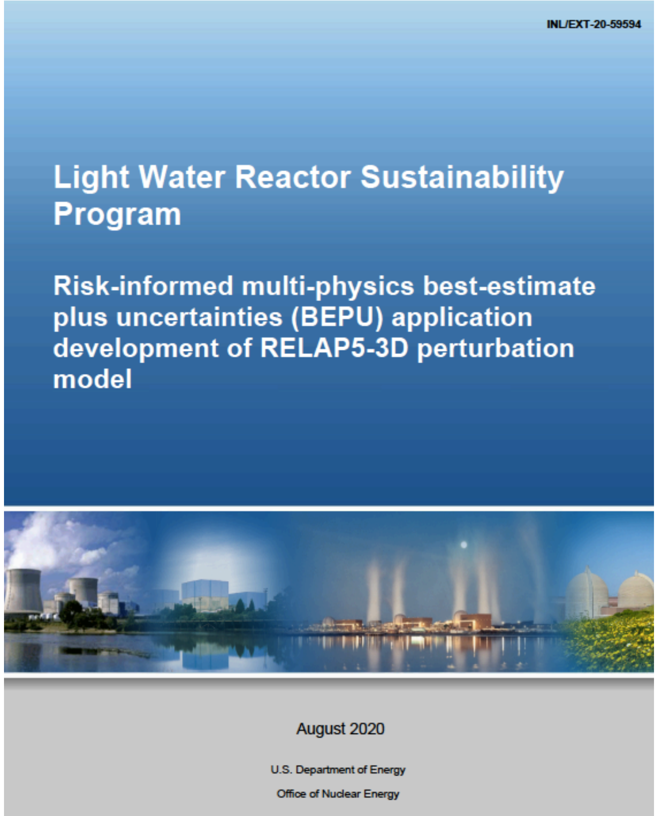
FLECHT-SEASET RELAP5-3D model

Sample Result at 2.834m Elevation



Remark and Future Works

- RELAP5-3D now has “official” BEPU capability
  - This feature will be included in newly released version
  - Sampling PDF, logic control and output data processing tool is needed (i.e., RAVEN)
- Ongoing and future works
  - Apply to blowdown and refill LOCA phase and other transients
  - Integration with simulation based dynamic PRA and HRA (human reliability)
  - BEPU in other LWRS projects
    - Risk-informed on enhanced resilient plant (ERP)
    - Digital I&C risk assessment
    - Plant fuel reload optimization
- Prospective
  - Multiphysics approach
  - Application to advanced nuclear systems



Report in LWRS webpage (Link)

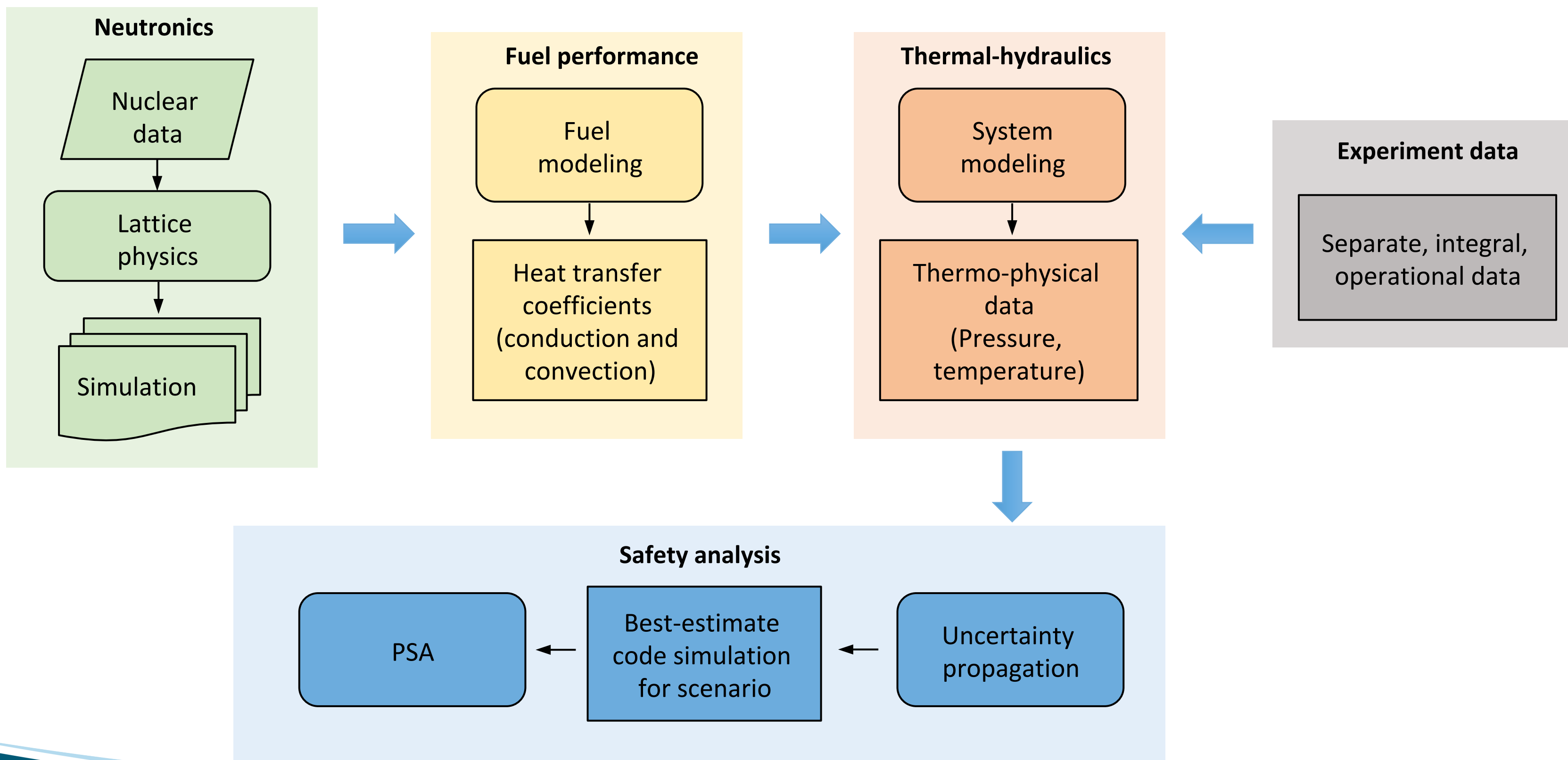
BEPU and Risk-Informed Approach

Option	Code	System assumptions	Input data	Remark
Conservative	Conservative	Conservative	Conservative	10CFR50.46, App K
Combined	Best estimate	Conservative	Conservative	Not in U.S.
Best estimate	Best estimate	Conservative	Realistic plus uncertainty	State-of-art
Risk informed	**Best estimate**	**Derive from PSA**	**Realistic plus uncertainty**	**Future perspective**

Multiphysics Risk-Informed Best-Estimate Plus Uncertainties (MP-RI-BEPU)

Example of Multi-Physics Approach

- Analyze combined multiphysics to consider their feedback
  - Neutronics, fuel, core, material, thermal-hydraulics, natural hazard, human factor, etc.
- OECD Nuclear Energy Agency initiatives under Nuclear Science Committee



Application to Advanced Nuclear Systems*

- Safety goal of advanced nuclear systems include
  - Secure highest safety in all circumstances
  - Sustain system integrity and resiliency through the lifetime
  - Minimize risk and maximize economics
- System reliability is major factor to risk assessment
  - Uses many passive features of autonomous and maintenance free
  - Reliability and risk assessment of passive features became main issue
    - Huge uncertainties in natural circulation heat transfer (liquid metal cooled pool/ heat pipe)
- New regulatory guidelines are necessary based on system characteristics
  - Need new safety analysis approach then LWR: deterministic and probabilistic
  - Secure experiment data, prototypes, test facility and operation history
  - Describe correct uncertainties from innovative design and features
  - Standardize end of life determination process

Risk-informed multiphysics BEPU method will be useful for risk assessment and licensing support of advanced nuclear systems

* Gen-IV, SMR, Micro-reactor

LWRS

LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

http://lwrs.inl.gov