A US Perspective on Validation Methods for Criticality Safety

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Outline

- Simplified Application/Process Example
- Analysis Methodology
- Benchmark Selection
- Validation Approach
  - Solution critical bias and uncertainty
  - Reflector bias
- Summary

Simplified Application/Process Example

- Actual process or potential process upsets involves
  - HEU
  - Water moderation
  - Actual material and geometric details
  - Several potential thick reflectors
- In Criticality Safety Evaluations process details often simplified as reflected, optimally moderated spherical slurry of HEU and water
  - Spherical geometry to minimize leakage (generally conservative)
  - Optimal moderation to minimize critical mass (generally conservative)
  - Neglect diluents and poisons to minimize critical mass (generally conservative)
  - Reflection to minimize critical mass
- Probably no ICSBEP benchmark that closely represents simplified model

Analysis Methodology to Validate Includes

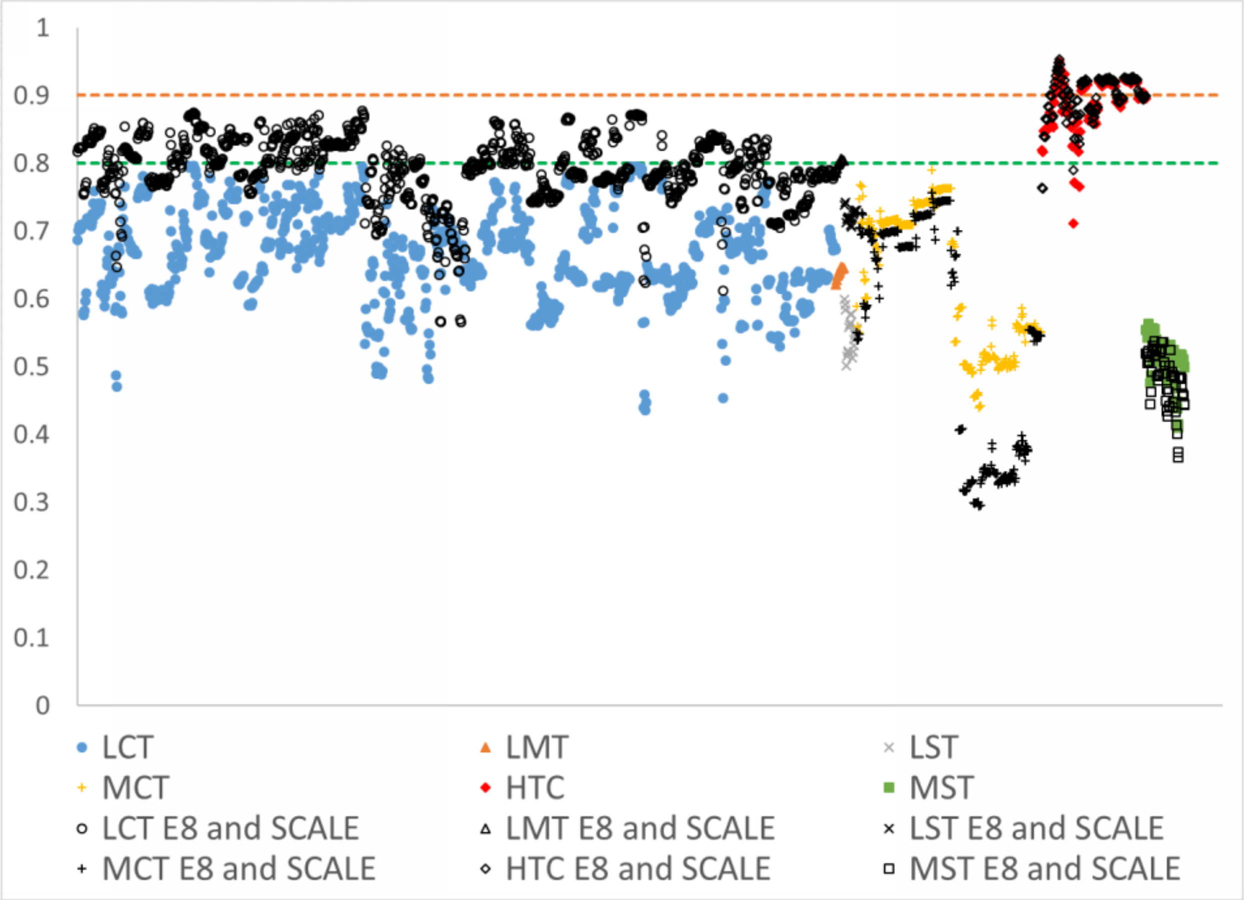
- Analytical Methods
  - Monte Carlo neutron transport code (CE preferred)
  - Nuclear data processing code
    - If not using vendor supplied processed library
- Nuclear Data Library (ENDF/B-VII.0 for example)
  - Often includes hidden modeling approximations
    - RRR reconstruction resolution
    - URR probability table treatment
    - $S(\alpha,\beta)$ - number of discrete angles
    - $S(\alpha,\beta)$ - thermal cut point extended above evaluation (SCT approximation)
- Modeling Standards
  - MC running strategy (statistical uncertainty, mitigation of biases)
  - Material definition standards
  - Isotopic abundances used to prepare material compositions
  - Treatment of material temperature
  - Treatment of thermal neutron scattering for materials where TSL is not available
- Goal is to determine how well the analysis methodology represents reality

Benchmark Selection

- Leverage ICSBEP Handbook
  - Excellent source of evaluated benchmarks
  - Recognize benchmark model uncertainties not perfect
    - Sometimes underestimated when systematic uncertainties not treated correctly
- Personally still recommend traditional benchmark selection approach
  - Expert-based, common sense approach
  - Grounded in an understanding of the physics that is important for the application
- Skeptical about modern S/U methods (TSUNAMI, Whisper)
  - Fundamental issue is low fidelity and immaturity of covariance data
    - BNL-LANL-ORNL (BLO) low-fidelity covariance data intended to exercise method, not accuracy
    - Some uncertainties are grossly underestimated (^{233}U nu-bar for example)
    - Lack of support for important physics
      - Elastic scattering angular distributions
      - Thermal scattering laws
  - Believe methods have promise, may take 1-2 decades to mature covariance data

Example of Covariance Data Immaturity

c_k results – SCALE 6.2 & ENDF/B-VIII



- Same critical experiments and PWR SNF
- SCALE 6.2 (various)
- ENDF/B-VIII plus SCALE data (black)
- This change further reduces MCT systems and increases LCT systems. The result doesn't make sense – LEU can't be representative of SNF.

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Validation Approach

- Analysis methodology example based on
  - MC21 CE Monte Carlo Code
  - NDEX nuclear data processing code
  - ENDF/B-VII.0 cross sections at room temperature (296 K)
  - Isotopic abundances from *Chart of the Nuclides*, 17th Edition
- Bias and uncertainties from suite of HST+LST benchmarks
  - Provides coverage for primary physics effect (water moderation)
  - Provides coverage for bare and water reflected configurations
- Determine reflector bias and uncertainty from suite of bare and reflected benchmarks
  - Provides coverage for secondary physics effect (reflection)
  - Reflection dominated by fast neutron physics
  - Consider HMF, IMF, LCT, HST benchmarks
  - Select benchmarks with strong correlation between bare and reflected configurations
    - Same laboratory, same assembly machine, same fuel, same experimentalists, etc.

HST+LST Benchmark Suite

Benchmark	Shape	Reflector	Cases		Benchmark	Shape	Reflector	Cases
HST001	Cylinder	Bare	10		LST001	Cylinder	Bare	1
HST009	Sphere	Water	4		LST002	Sphere	Bare/Water	3
HST010	Sphere	Water	4		LST003	Sphere	Bare	9
HST011	Sphere	Water	2		LST004	Cylinder	Water	7
HST012	Sphere	Water	1		LST007	Cylinder	Bare	5
HST013	Sphere	Bare	4		LST016	Slab	Water	7
HST032	Sphere	Bare	1		**Total LST**			**32**
HST042	Cylinder	Bare	8					
HST043	Sphere	Bare	3		**HST+LST**			**80**
HST050	Cylinder	Bare	11					
Total HST			**48**					

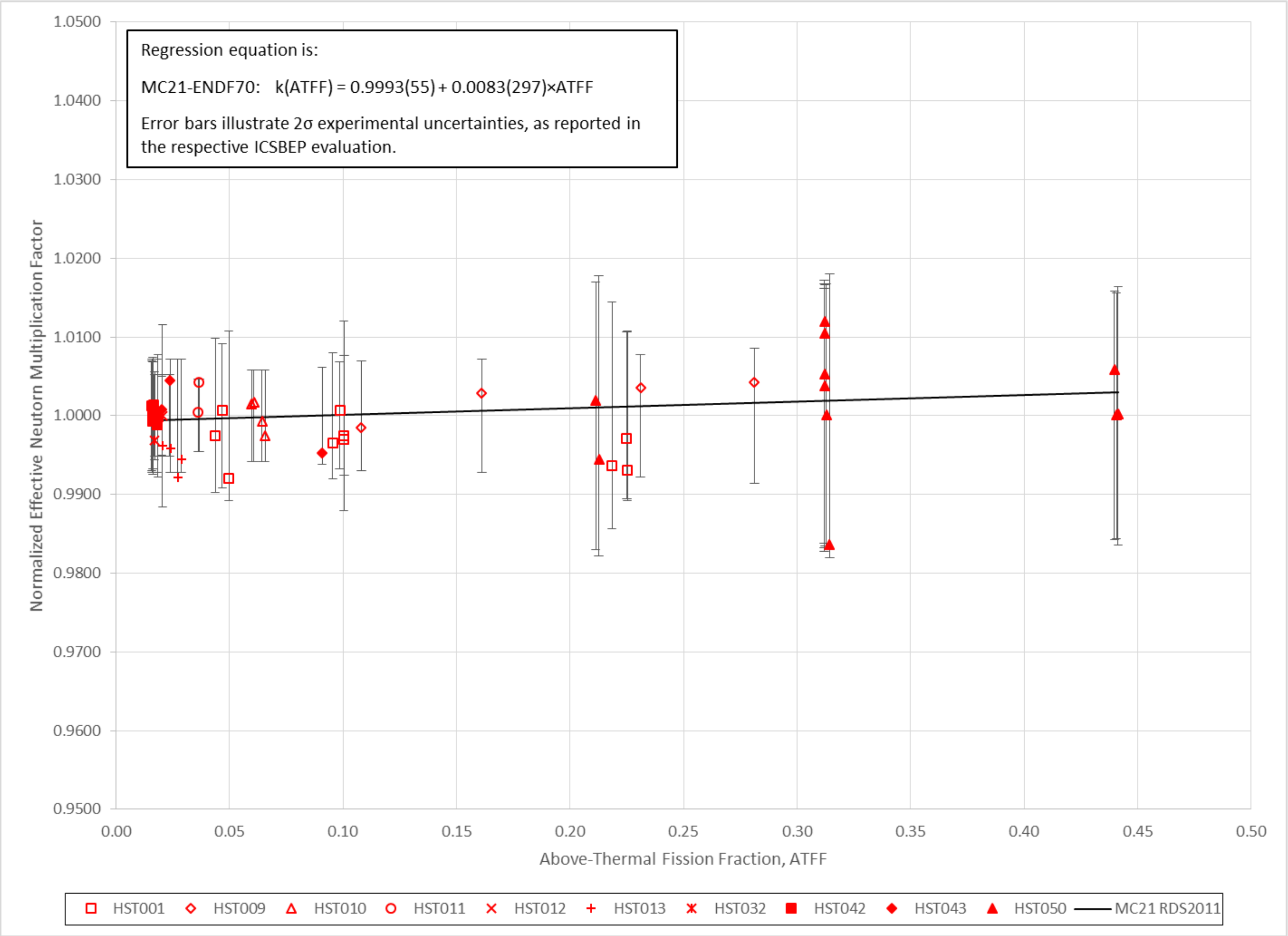
MC21 Running Strategy and k_{crit} Correlation Parameters

Option	Value
Histories per batch	10^5
Discard batches	100
Active batches	1200
Active Histories	120×10^6

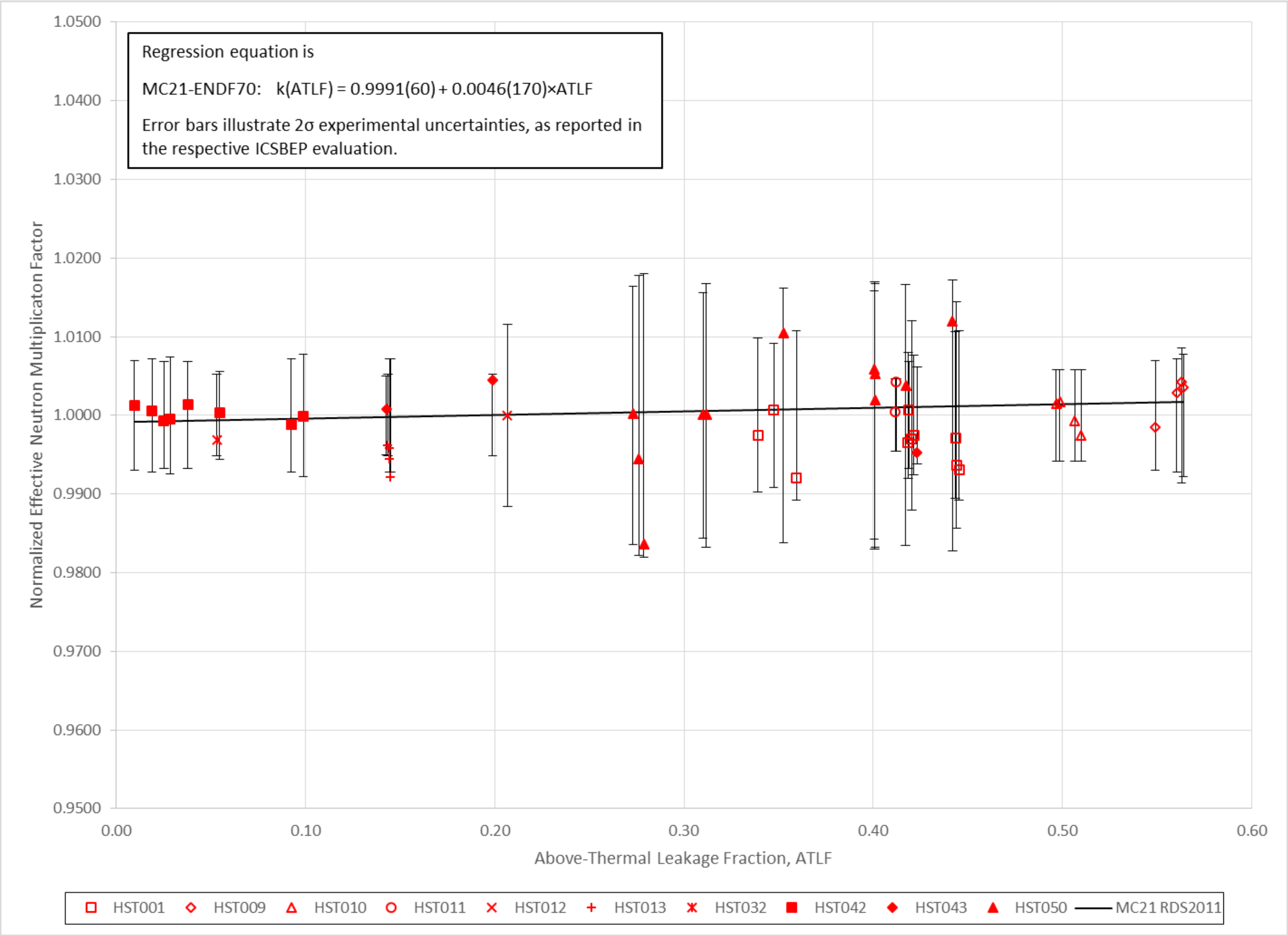
Shannon Entropy used to confirm sufficient number of discard batches used to mitigate start bias.

- Critical eigenvalue (k_{crit}) correlated to
  - Above Thermal Fission Fraction (ATFF)
  - Above Thermal Leakage Fraction (ATLF)
- Derived parameters traditionally used for thermal critical assemblies

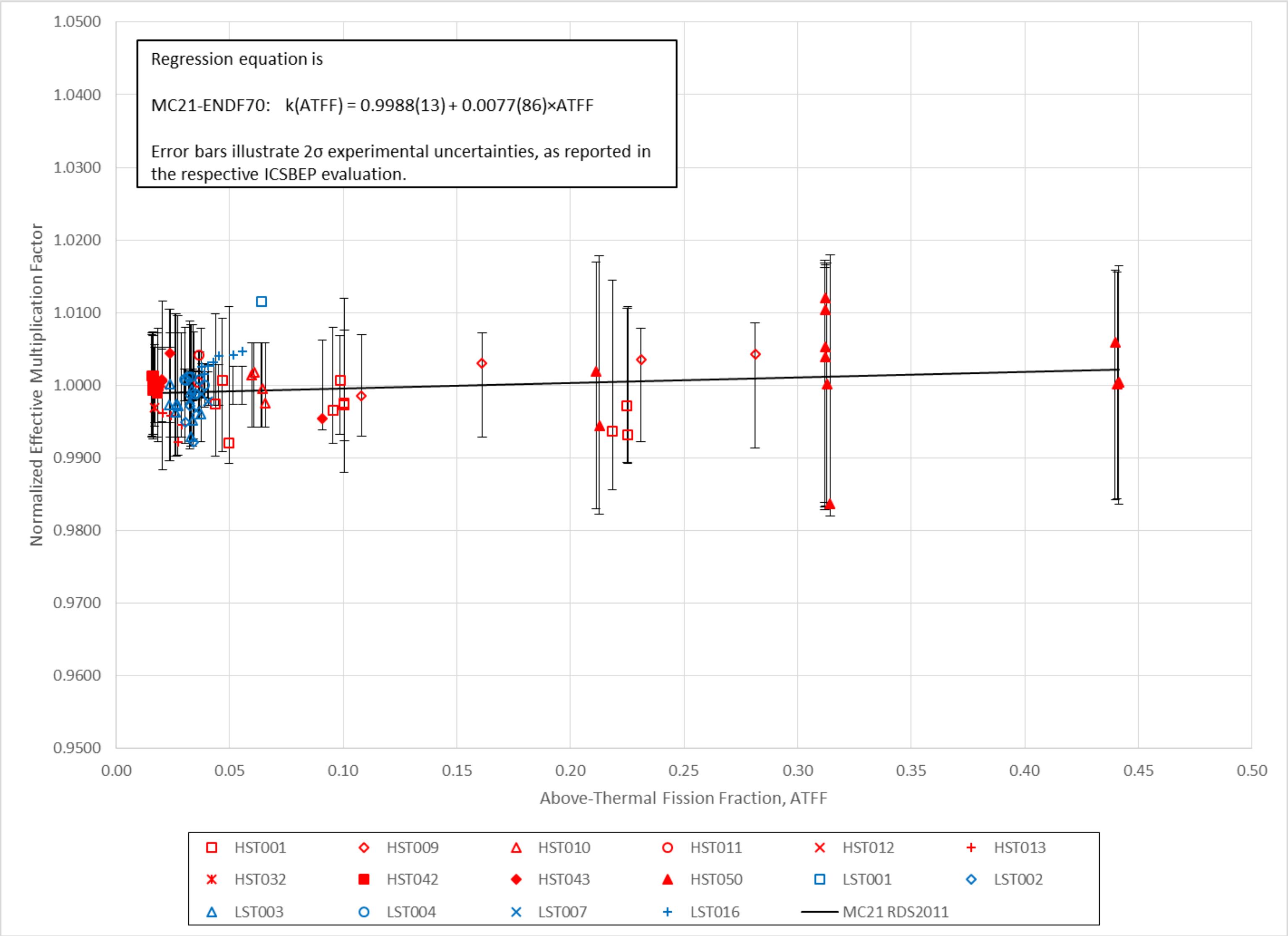
Critical Eigenvalue vs ATFF for HST Suite



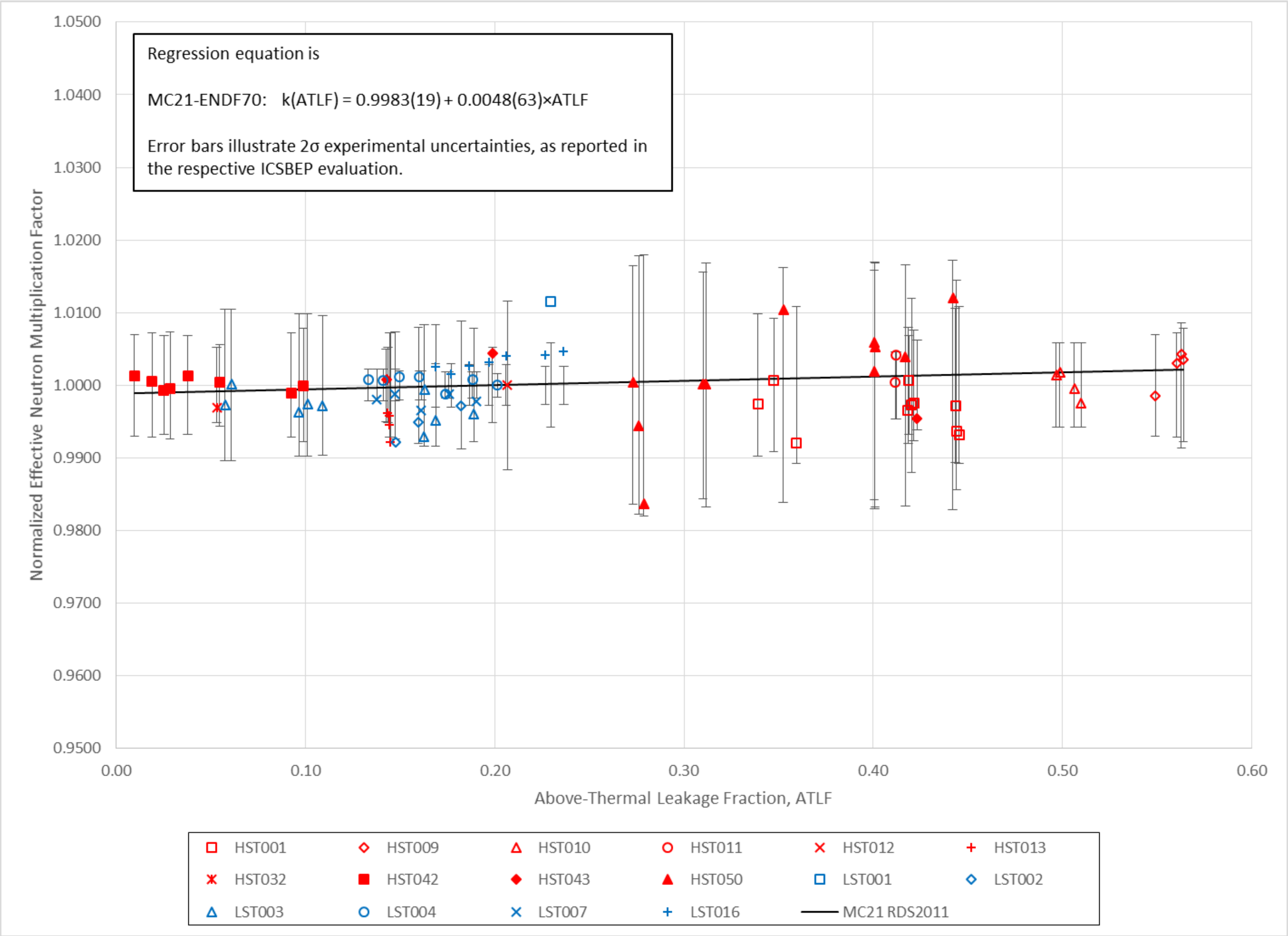
Critical Eigenvalue vs ATLF for HST Suite



Critical Eigenvalue vs ATFF for HST+LST Suite



Critical Eigenvalue vs ATLF for HST+LST Suite



Small (+0.0005 Δk) Bias
No Statistically Significant Trend with ATFF or ATLF

HST Benchmark Suite

Linear Regression

$$k_{crit}^{HST}(\text{ATLF}) = 0.9995 + 0.0047(81) \times (\text{ATLF} - \overline{\text{ATLF}})$$
$$\overline{\text{ATLF}} = 0.3117$$
$$95\%\ \text{PI} = 0.0096\Delta k$$

$$k_{crit}^{HST}(\text{ATFF}) = 0.9995 + 0.0084(81) \times (\text{ATFF} - \overline{\text{ATFF}})$$
$$\overline{\text{ATFF}} = 0.1321$$
$$95\%\ \text{PI} = 0.0095\Delta k\ .$$

Multivariate Regression

$$k_{crit}^{HST}(\text{ATFF,ATLF}) = 0.9995(96)$$
$$95\%\ \text{PI} = 0.0097\Delta k\ .$$

HST+LST Benchmark Suite

Linear Regression

$$k_{crit}^{HST+LST}(\text{ATLF}) = 0.9995 + 0.0048(63) \times (\text{ATLF} - \overline{\text{ATLF}})$$
$$\overline{\text{ATLF}} = 0.2519$$
$$95\%\ \text{PI} = 0.0087\Delta k$$

$$k_{crit}^{HST+LST}(\text{ATFF}) = 0.9995 + 0.0077(86) \times (\text{ATFF} - \overline{\text{ATFF}})$$
$$\overline{\text{ATFF}} = 0.0937$$
$$95\%\ \text{PI} = 0.0087\Delta k\ .$$

Multivariate Regression

$$k_{crit}^{HST+LST}(\text{ATFF,ATLF}) = 0.9995(87)$$
$$95\%\ \text{PI} = 0.0088\Delta k\ .$$

Reflector Bias Validation

- Determine reflector bias and uncertainty from suite of bare and reflected benchmarks
  - Select benchmarks with strong correlation between bare and reflected configurations
    - Same laboratory, same assembly machine, same fuel, same experimentalists, etc.
  - Reflection dominated by fast neutron physics
- Benchmark Series to Consider
  - VNIIEF Spheres (HMF & IMF)
  - VNIITF Cylinders (HMF)
  - PNNL & Valduc rod arrays (LCT)
  - RF Rothe concrete reflected solutions (HST)
- Include benchmarks from multiple sites to ensure consistency and mitigate bias
- For conservatism, do not credit negative biases

Reflector Bias – HEU VNIIEF Spheres Example

Reflector Material	Reflector Thickness (cm)	Unreflected Case		Reflected Case		Reflector Bias
		Benchmark	k_{norm}	Benchmark	k_{norm}	Δk
DU	4.70	HMF018	1.0003(1)	HMF029	1.0057(1)	-0.0054(2)
Pb	3.25	HMF018	1.0003(1)	HMF027	1.0009(1)	-0.0006(2)
Steel	9.70	HMF018	1.0003(1)	HMF021	0.9974(1)	+0.0029(2)
Aluminum	3.90	HMF018	1.0003(1)	HMF022	0.9976(1)	+0.0027(2)
Graphite	3.45	HMF018	1.0003(1)	HMF019	1.0072(1)	-0.0069(2)
Polyethylene	1.45	HMF018	1.0003(1)	HMF020	1.0006(1)	-0.0003(2)
Polyethylene	17.45	HMF018	1.0003(1)	HMF031	1.0053(2)	-0.0050(2)

Summary

- Personally recommend traditional, expert-based benchmark selection approach
- Informed by physics-based understanding of application
  - Side benefit – skill mix helps detect and understand discrepancies

- Believe new covariance data based S/U methods have promise
  - Currently hampered by low-fidelity of covariance data
  - Likely to take 1-2 decades to mature covariance data