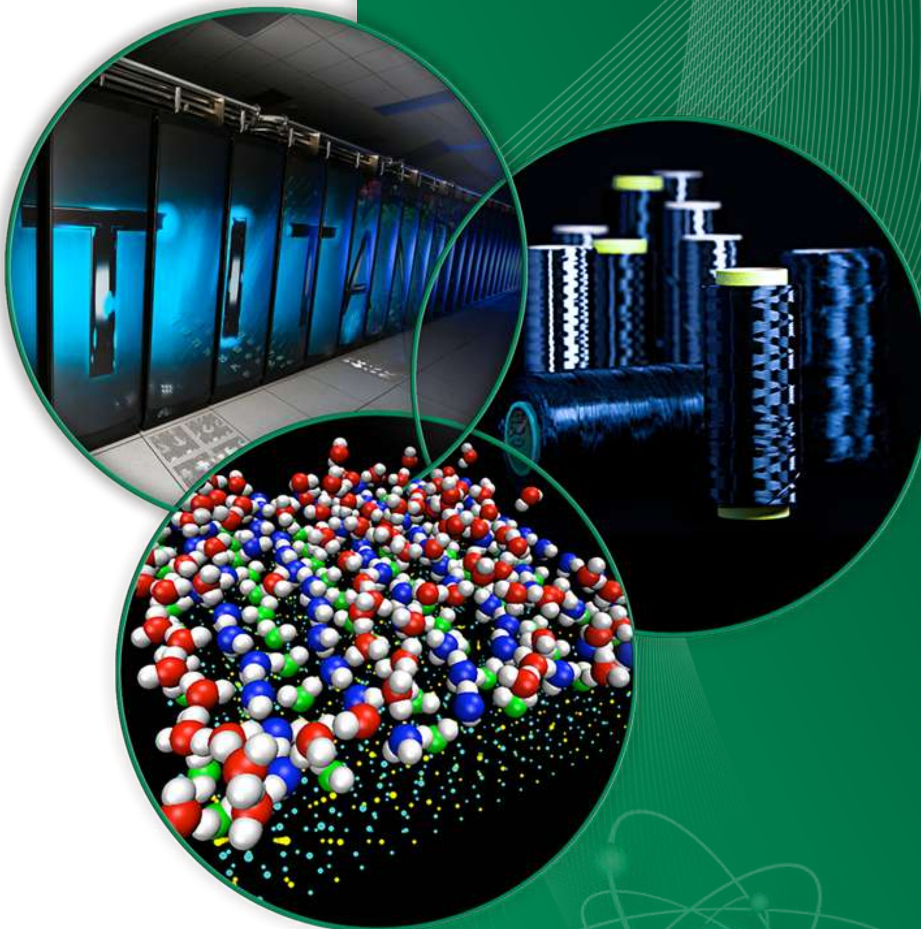
Comparison of Burnup Credit Uncertainty Quantification Methods



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Subcriticality with Burnup Credit

$$k_p(bu) + \Delta k_p(bu) + \beta + \Delta k_\beta + \Delta k_x + \Delta k_m + \beta_i(bu) + \boxed{\Delta k_i(bu)} \leq k_{limit}$$

k_p - calculated multiplication factor
Δk_p - statistical, material/fabrication, and geometric uncertainty
β - bias resulting from the criticality calculation method (including nuclear data bias)
Δk_β - uncertainty in bias β
Δk_x - supplement to β and Δk_β
Δk_m - administrative margin
$\beta_i(bu)$ - depletion/decay code bias
$\Delta k_i(bu)$ - uncertainty in bias $\beta_i(bu)$ (95/95)
k_{limit} - declared upper limit on multiplication factor

Goals

- Test new SCALE/Sampler capability and data
- Compare to ISG-8 and EPRI $\Delta k_i(bu)$

Overview of ISG-8 Recommendations

- Interim Staff Guidance 8 (revision 3), "Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transportation and Storage Casks," US Nuclear Regulatory Commission, September 26, 2012.

- Recommends depletion code validation based on destructive radiochemical assay (RCA)
  – G. Radulescu, I. C. Gauld, G. Ilas, and J.C. Wagner, *An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Isotopic Composition Predictions*, NUREG/CR-7108 (ORNL/TM-2011/509), US Nuclear Regulatory Commission Office of Nuclear Regulatory Research (April 2012).

- Methodology
  – Monte Carlo Uncertainty Sampling Method in NUREG/CR-7108
    - mean isotopic bias ($\bar{X}_n$) and isotopic bias uncertainty (σ_n)
    - $\bar{X}_n$, σ_n → $\beta_i(bu), \Delta k_i(bu)$

Burnup (GWd/MTU)	5-10	18-25	25-30	30-40	45-50	50-60
β_i	0*	0	0	0	0	0
Δk_i	1480	1540	1610	1630	2190	3000

*positive bias not credited

Overview of EPRI Methodology

K. S. Smith, S. Tarves, T. Bahadir, R. Ferrer, *Benchmarks for Qualifying Fuel Reactivity Depletion Uncertainty*, EPRI report 1022909, August 2011.

- Total bias uncertainty combines HFP reactivity decrement error with additional fuel temperature and data terms

$$\Delta k_i(bu) = 2\sqrt{\left(s_{k_\infty}^{HFP,base}\right)^2 + \left(s_{k_\infty}^{T_{fuel}}\right)^2 + \left(s_{k_\infty}^{*data}(bu)\right)^2}$$

Burnup Credit Terms (pcm)

Burnup (GWd/MTU)	**10**	**20**	**30**	**40**	**50**	**60**
β_i(CASMO-4)	81	140	178	196	192	167
β_i(CASMO-5)	19	46	81	125	177	238
β_i(CASMO-4)	594	**643**	639	627	614	605
β_i(CASMO-5)	250	250	250	250	250	250
$2\,s_{k_\infty}^{T_{fuel}}$	383	383	383	383	383	383
$2\,s_{k_\infty}^{*data}(bu)$	380	452	446	430	410	398

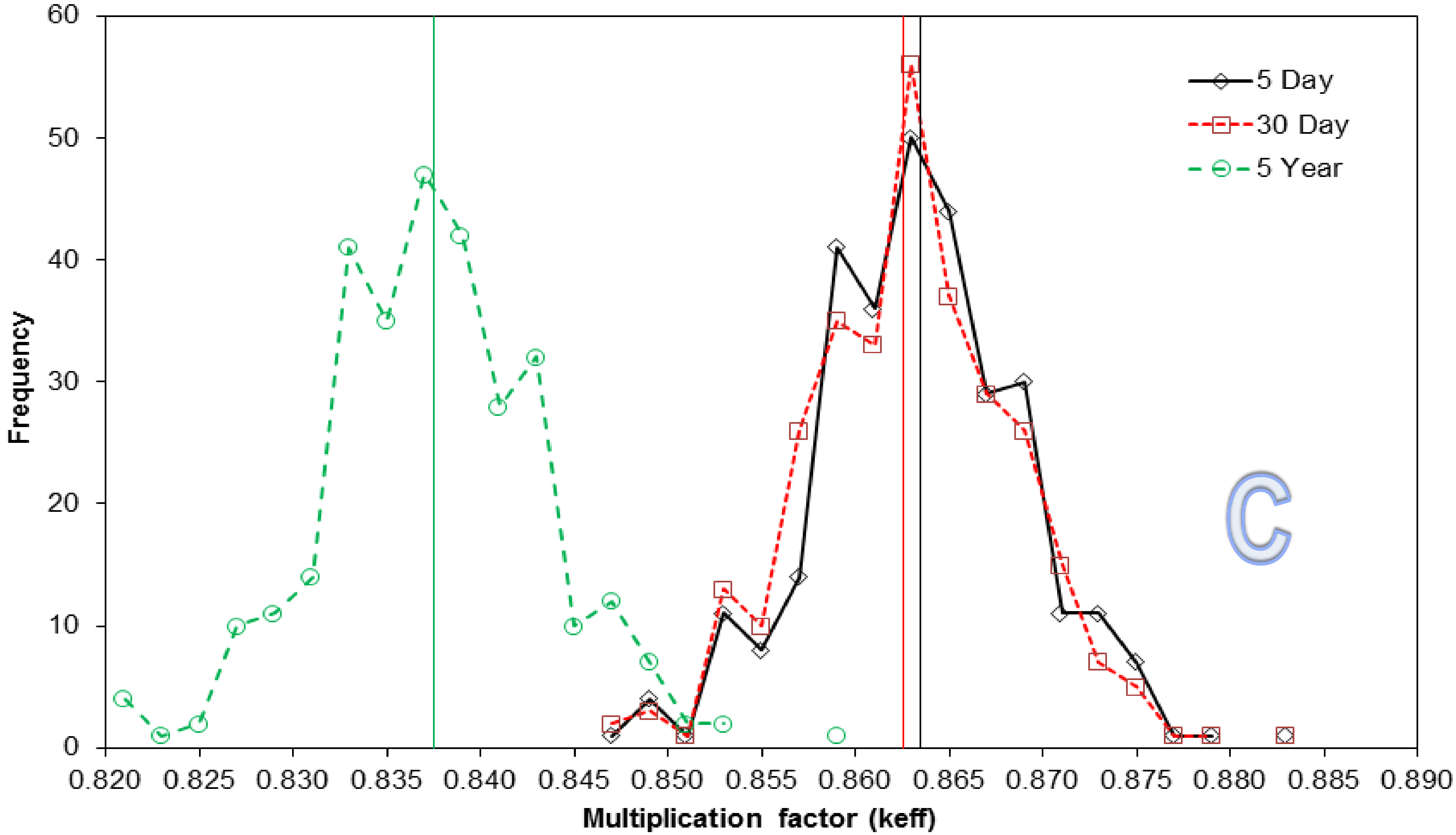
Models
Spent Fuel Pool (SFP)

- **17×17 PWR assembly model in a spent fuel storage pool**
  - TRITON fuel assembly calculation
    using NEWT (2-D transport) and ORIGEN (depletion)
  - KENO-V.a spent fuel storage pool criticality simulation
    - assembly-average isotopics in all pins
    - infinite array (no radial leakage)
    - cold, borated conditions
- **Application of SCALE/Sampler stochastic sampling Tool**
  - nuclear data perturbations (~300 isotopes)
    - *cross sections*
    - *decay constants, branching ratios (where available)* ***NEW!***
    - *fission product yields* ***NEW!***
  - 300 samples

Modeling cases

Case	^{235}U enrichment (wt %)	Discharge burnup (GWd/MTU)	Decay time (days)		
A	2.5	10.0	5	30	1825
B	4.0	30.0	5	30	1825
C	5.0	50.0	5	30	1825

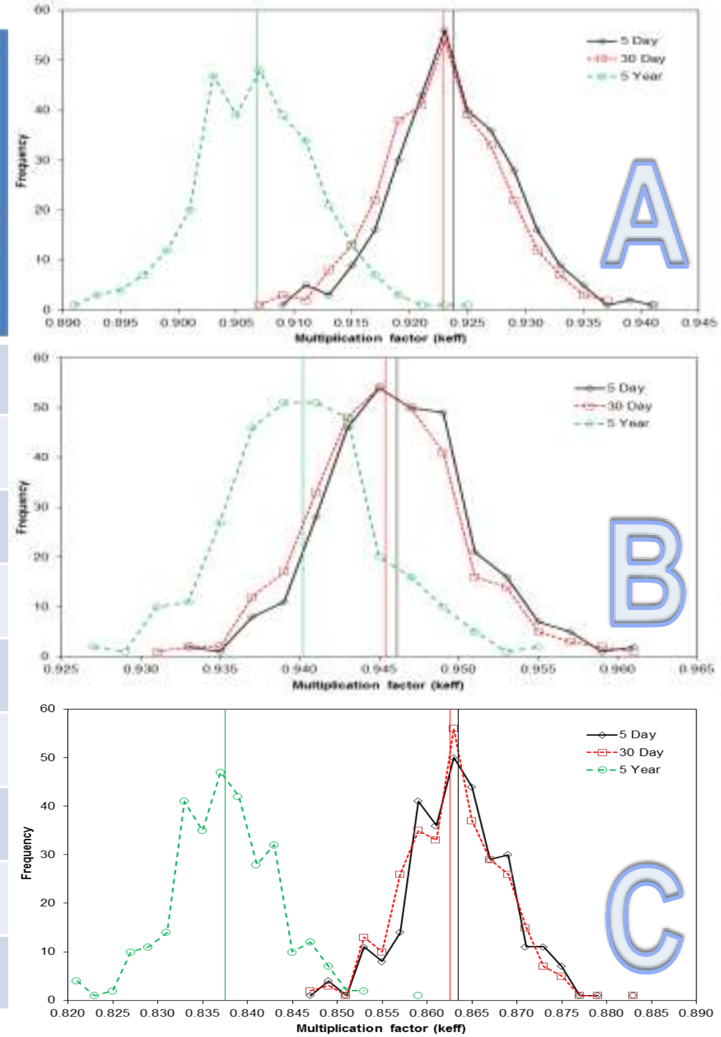
keff for SFP Case C
(50 GWd/MTU / 5.0 wt%)



Keff for All Cases

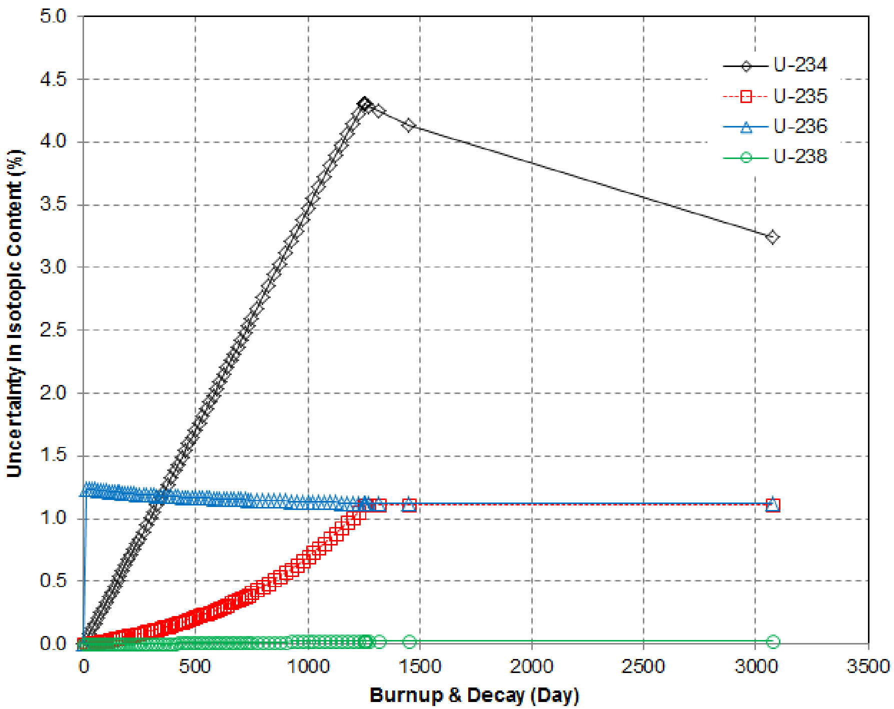
Sample mean & standard deviation due to nuclear data uncertainty

Case	^{235}U wt%	Burnup (GWd/MTU)	Decay time (days)	$\bar{k}_{eff}$*	s_k^{data} (pcm)
A	2.5	10.0	5	0.94614	459
			30	0.94537	463
			1825	0.94017	464
B	4.0	30.0	5	0.92380	519
			30	0.92289	523
			1825	0.90680	536
C	5.0	50.0	5	0.86345	559
			30	0.86250	563
			1825	0.83748	588

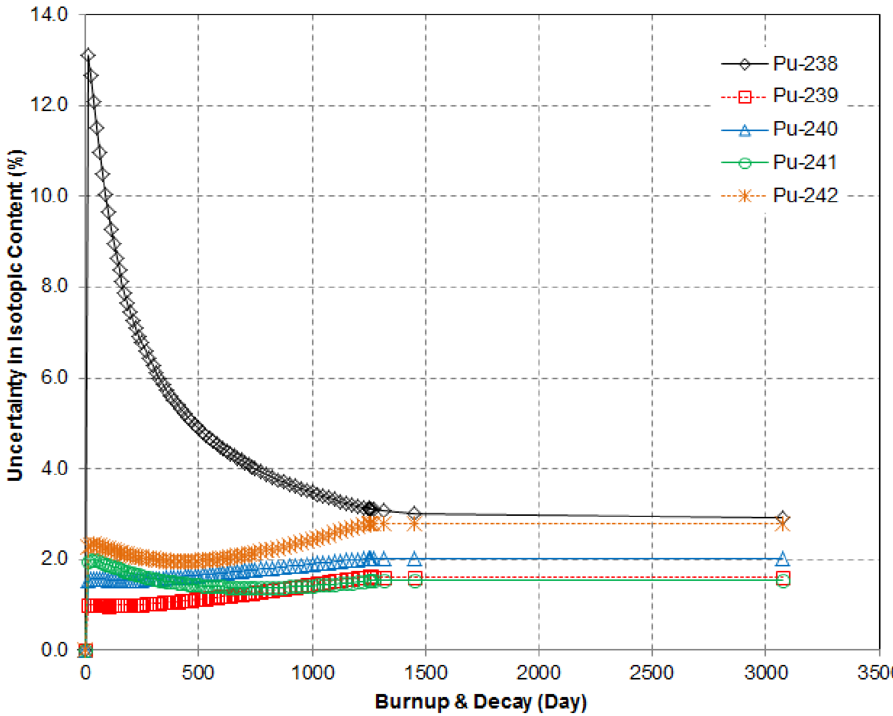


*Maximum standard deviation of KENO-5: 0.00013

Isotopics for SFP Case C
(50 GWd/MTU / 5.0 wt%)



(a) U

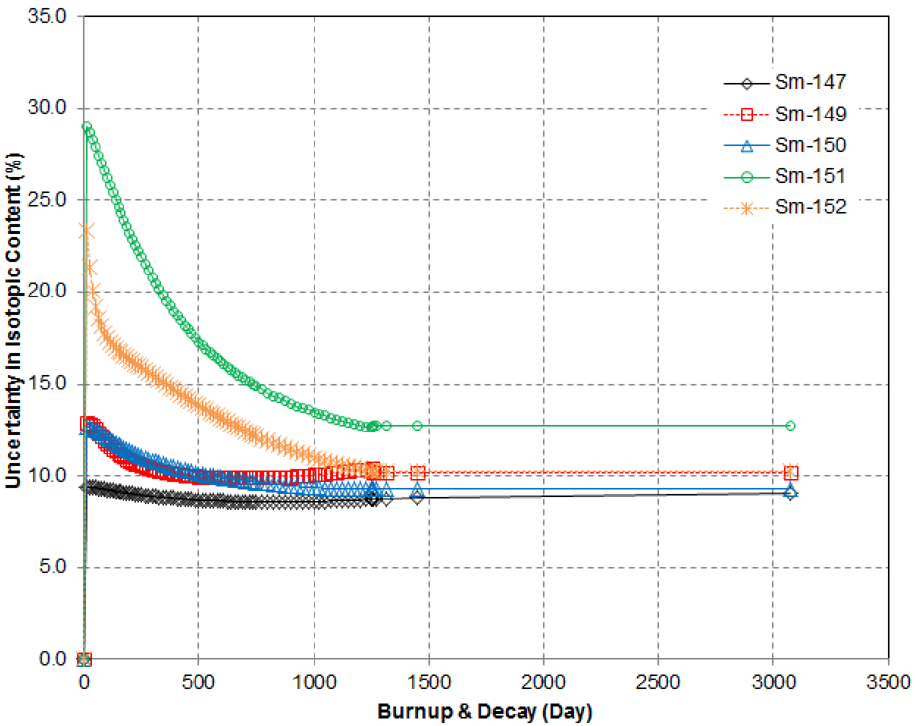


(b) Pu

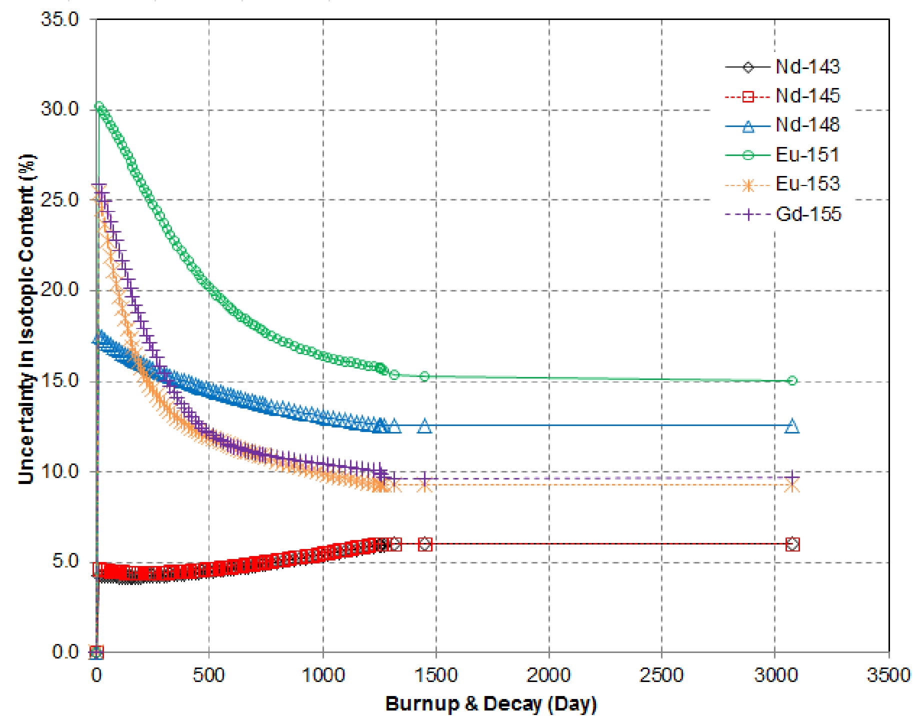
Actinide uncertainties consistent with previous studies with xs perturbations and comparison with UAM participants…

Isotopics for SFP Case C

(50 GWd/MTU / 5.0 wt%)



(e) Sm



(f) Nd, Eu and Gd

Fission Product Uncertainties Appear Too Large!

M. T. Pigni, I. C. Gauld, M. L. Williams, F. Havluj, D. Wiarda, and G. Ilas, “Applications of Decay Data and FPY Covariance Matrices in Uncertainty Quantification on Decay Heat,” presentation at the Working Party on International Nuclear Data Evaluation Co-operation (WPEC), Meeting of Subgroup 37: Improved fission product yield evaluation methodologies at NEA Headquarters, May 22, 2013.

Isolating Yields and Decay Effects

Case B (30 GWd/MTU / 4 wt%) with 5 day decay time

Perturbed Data Sets	s_k^{data} (pcm)
Cross section	476
Cross section + Decay	479
Cross section + F.P. yield	518
Cross section + Decay + F.P. yield	519

k_{eff} Uncertainty Comparisons
ISG-8, EPRI, SCALE/Sampler

- Sampler results ($2\,s_k^{data}$) included nuclear perturbations in criticality calculation
  - actually covered in another term
- hold nuclear data at nominal in criticality calculation ($2\,s_k^{iso}$)

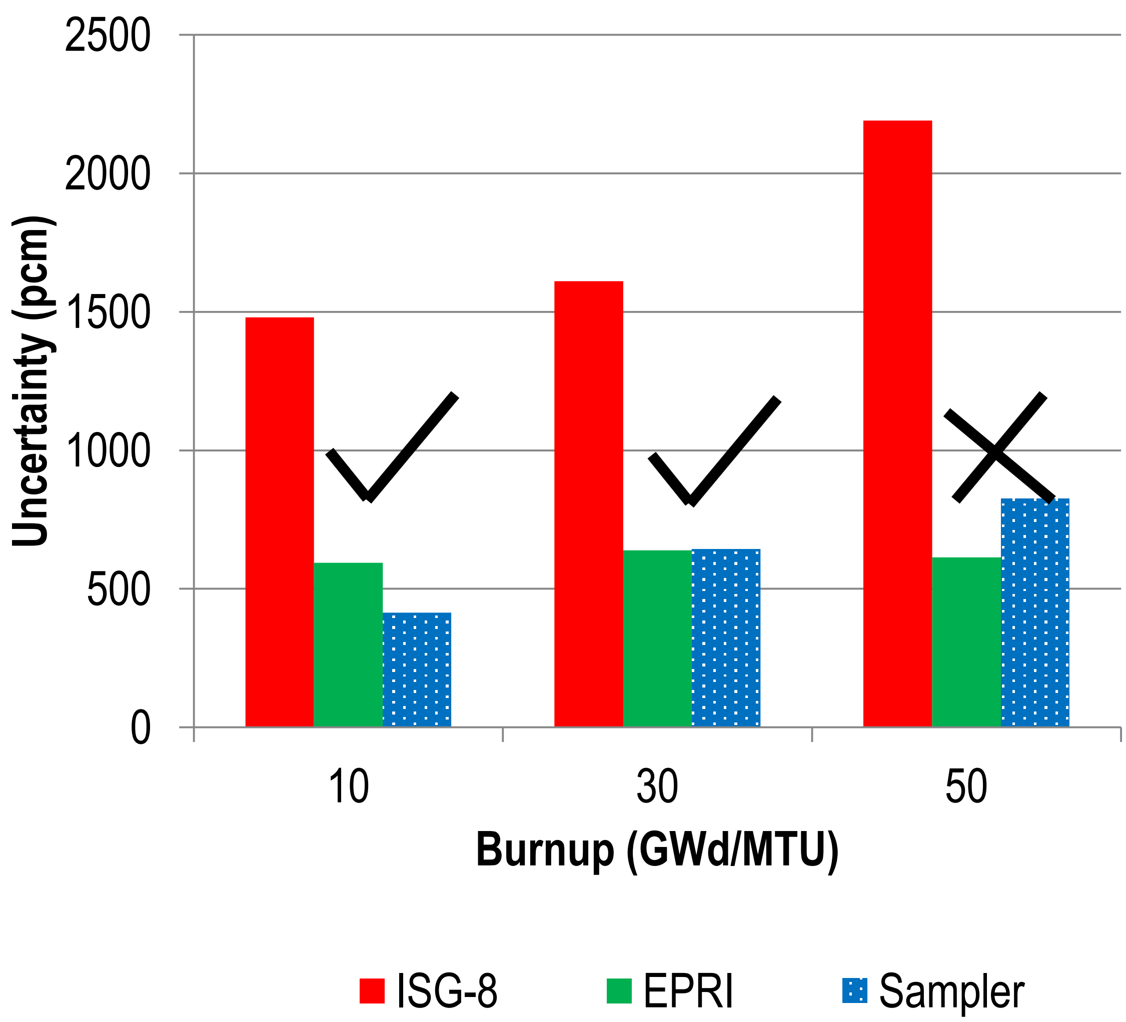
Case: Burnup (GWd/MTU)*	SCALE/Sampler Predicted uncertainty	
	total nuclear data $2\,s_k^{data}$	nuclear dat $2\,s_k^{data}$
A: 10	±928	±414
B: 30	±1072	±644
C: 50	±1176	±826

k_{eff} Uncertainty Comparisons
ISG-8, EPRI, SCALE/Sampler

-
- expect Sampler's uncertainty predictions to satisfy

$$2\, s_k^{iso} \leq \Delta k_i$$

- at 50 GWd/MTU either Sampler is too high or EPRI is too low



Conclusions

- Applied SCALE/Sampler to a simple SFP BUC analysis
  - SCALE/Sampler model forecasts
    - ~400 pcm at 10 GWd/MTU and
    - ~800 pcm at 50 GWd/MTU
  - ISG-8 rev. 3 RCA-based methodology Δk_i ~1400 to ~2200 pcm
  - EPRI reactivity decrement methodology Δk_i ~600 pcm
- SCALE 6.2/Sampler is a powerful, emerging uncertainty analysis tool
  - currently developing new uncertainty data (yields & decay)
  - not just nuclear data, but any input parameter can be varied
  - further testing/validation/benchmarking needed
    - Beta2 release in December→email scalehelp@ornl.gov

Acknowledgements

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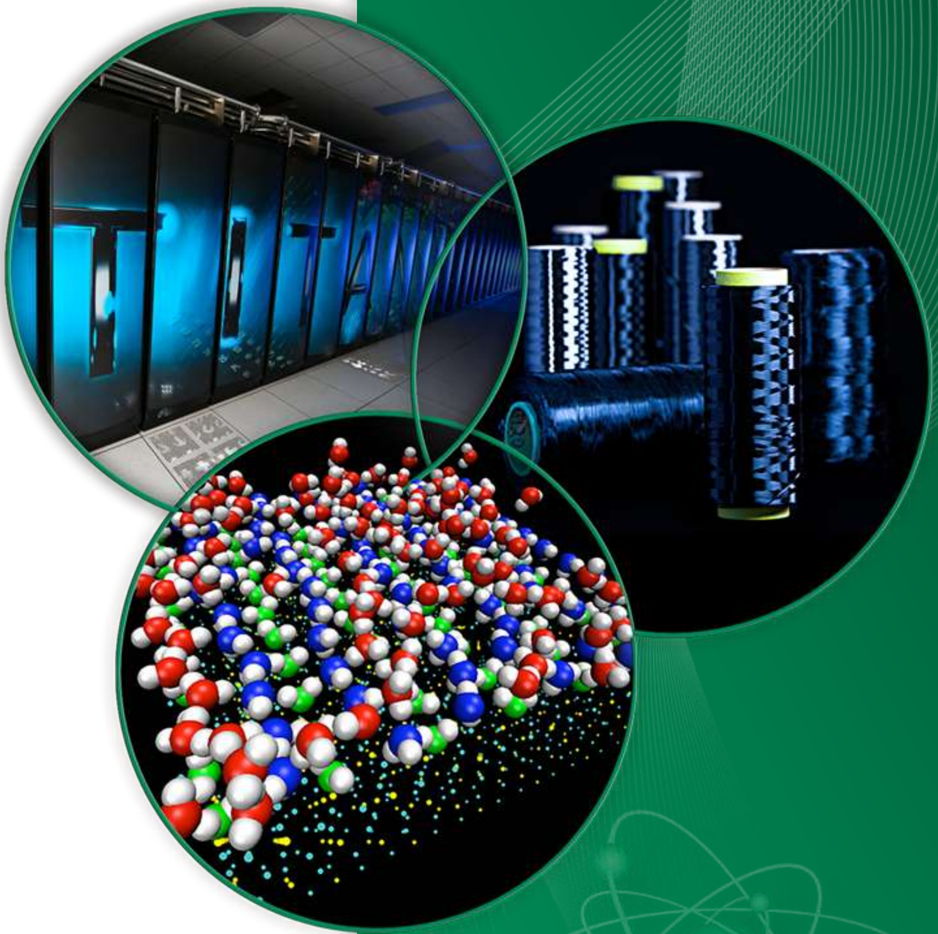


Overview

- Introduction
  - Overview of ISG-8 Recommendations
  - Overview of EPRI Methodology
- SCALE/Sampler Methodology
  - Nuclear Data Uncertainty in SCALE 6.2
  - 17x17 Westinghouse PWR Model
- Results
- Discussion
- Conclusions

Overview of EPRI Methodology

- K. S. Smith, S. Tarves, T. Bahadir, R. Ferrer, *Benchmarks for Qualifying Fuel Reactivity Depletion Uncertainty*, EPRI report 1022909, August 2011.

- Estimates "reactivity decrement" bias & uncertainty using flux trace measurements at plant
  - Search for burnup correction Δx_m for batch *m*
    - minimize error between calculated and measured reaction rate shapes of fission detector response at central IT in subset of assemblies

$$\min_{\Delta x_m} \sum_{n \in m} \left(C_{rr}^{n}(bu_n + \Delta x_m) - M_{rr}^{n}\right)^2,$$

  - Reactivity decrement error given as

$$\Delta k_{\infty}^{HFP,m}(bu_n) = k_{\infty}^{HFP}(bu_n + \Delta x_m) - k_{\infty}^{HFP}(bu_n)$$

  - Mean bias given as

$$\beta_i(bu) = regress(\Delta k_{\infty}^{HFP,m}(bu_n))$$

  - Uncertainty in bias is estimated by removing fission products

$$s_{\Delta k_\infty}^{HFP,base} = \max_{bu} |\beta_i(bu) - \beta_i^{no\ LFP}(bu)|$$

SCALE/Sampler Overview

- Sampler is a "new super sequence" to be released in SCALE 6.2
  - general stochastic sampling-based uncertainty quantification (UQ)
  - nuclear data and/or "input data" perturbations
  - all perturbed nuclear data fully propagated through all sequences
- Essential components of sampling-based UQ
  - develop uncertainties and correlations for data parameters
  - create *N* samples for each data parameter
  - perform a calculation for each sample set
  - statistically analyze the distribution of *N* outputs

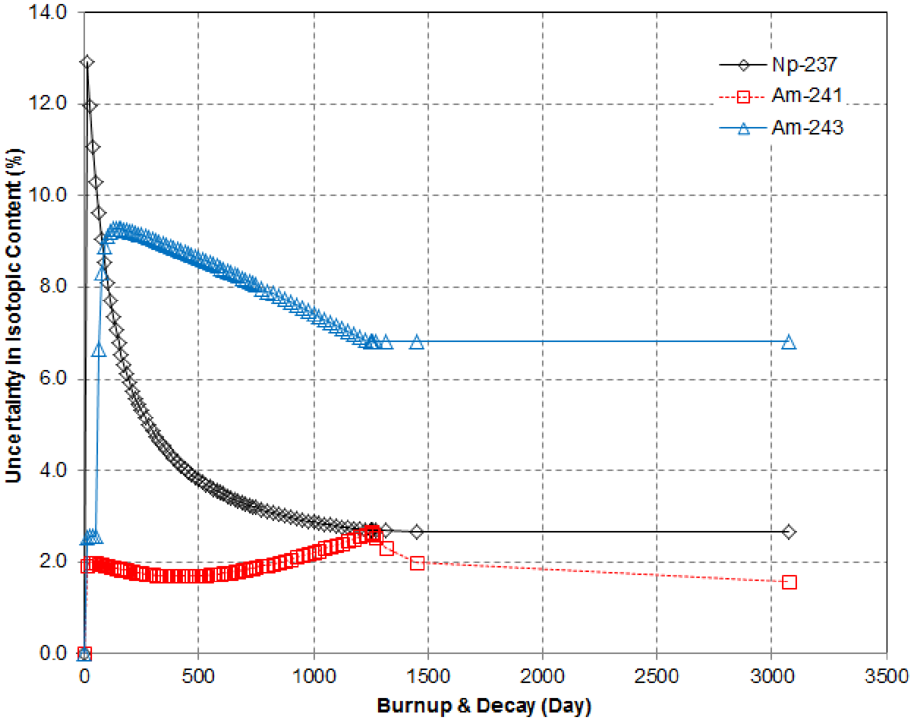
sample mean

$$\bar{k}_{eff} = \frac{1}{N}\sum_{n=1}^{N} k_{eff}^{(n)}$$

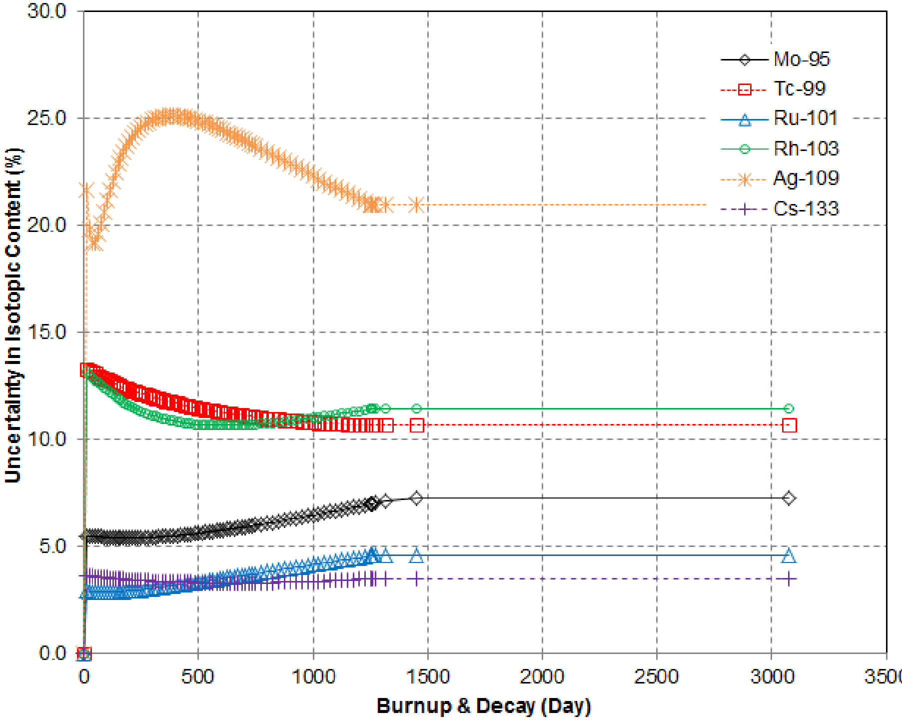
sample variance / standard deviation

$$\left(s_k^{data}\right)^2 = \frac{1}{N-1}\sum_{n=1}^{N}\left(k_{eff}^{(n)} - \bar{k}_{eff}\right)^2$$

Spent Fuel Storage Pool
Isotopic Results for Case C
(50 GWd/MTU / 5.0 wt%)



(c) Np and Am



(d) Mo, Tc, Ru, Rh, Ag and Cs