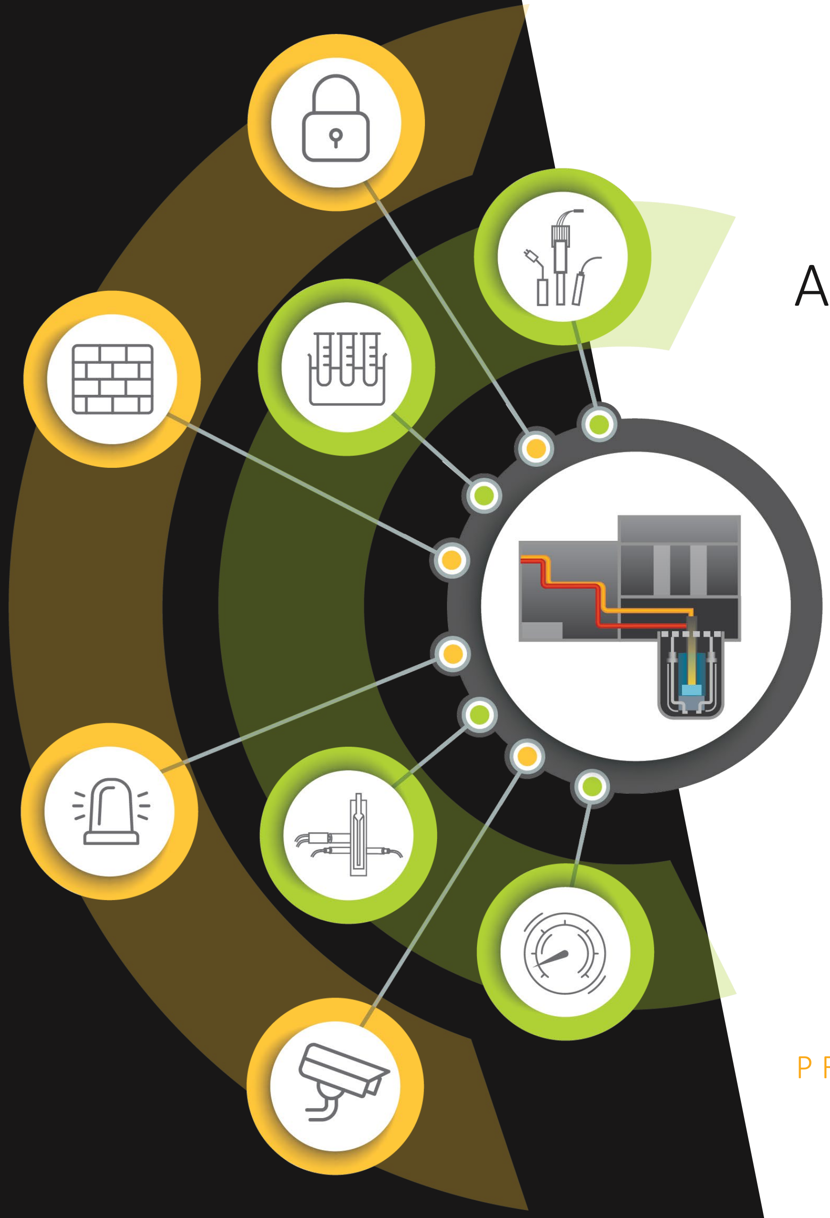

ADVANCED REACTOR SAFEGUARDS

MC&A for Pebble Bed Reactors

October 2023 Program Review (Virtual)

PRESENTED BY

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November 2, 2023 PUB ID 205627

Oak Ridge National Laboratory | Sandia National Laboratories | U.S. Department of Energy

Fiscal Year 2023 Summary Report

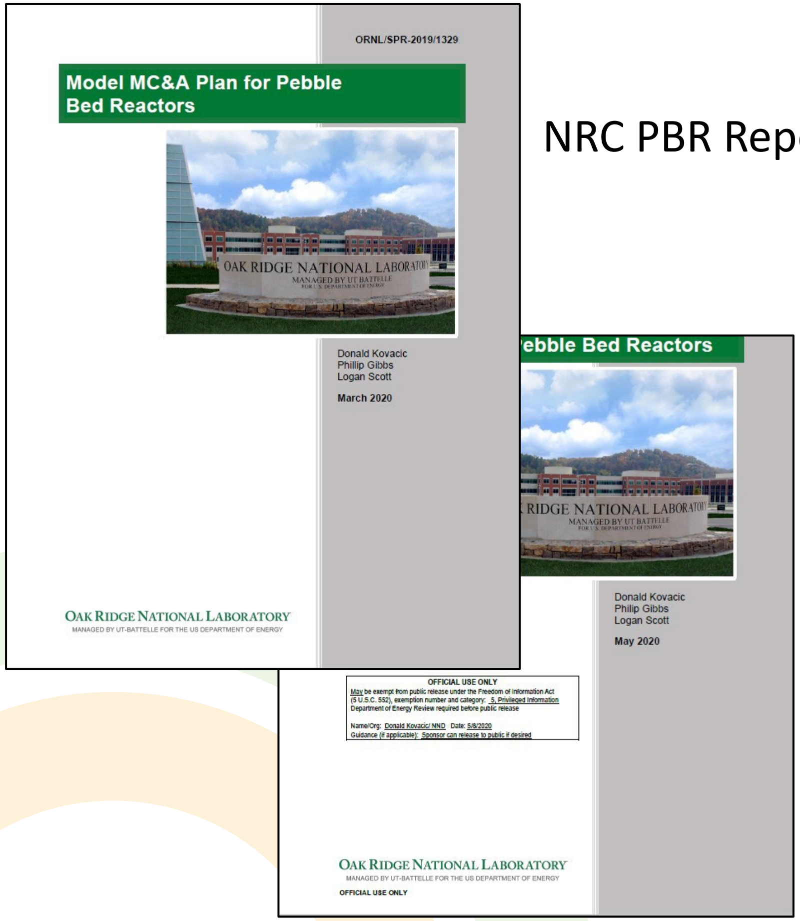
Compile main work done to date on recommended approaches for Pebble Bed Reactor (PBR) Safeguards (M2 Milestone).

- Industry Collaboration
- US NRC MC&A Plan Development
- Reactor Core Modeling
- Material control, transfers, shipments/receipts, and Inventory
- Fresh/Spent fuel measurements
- Statistical approaches
- Reporting / Material Control and Accounting System

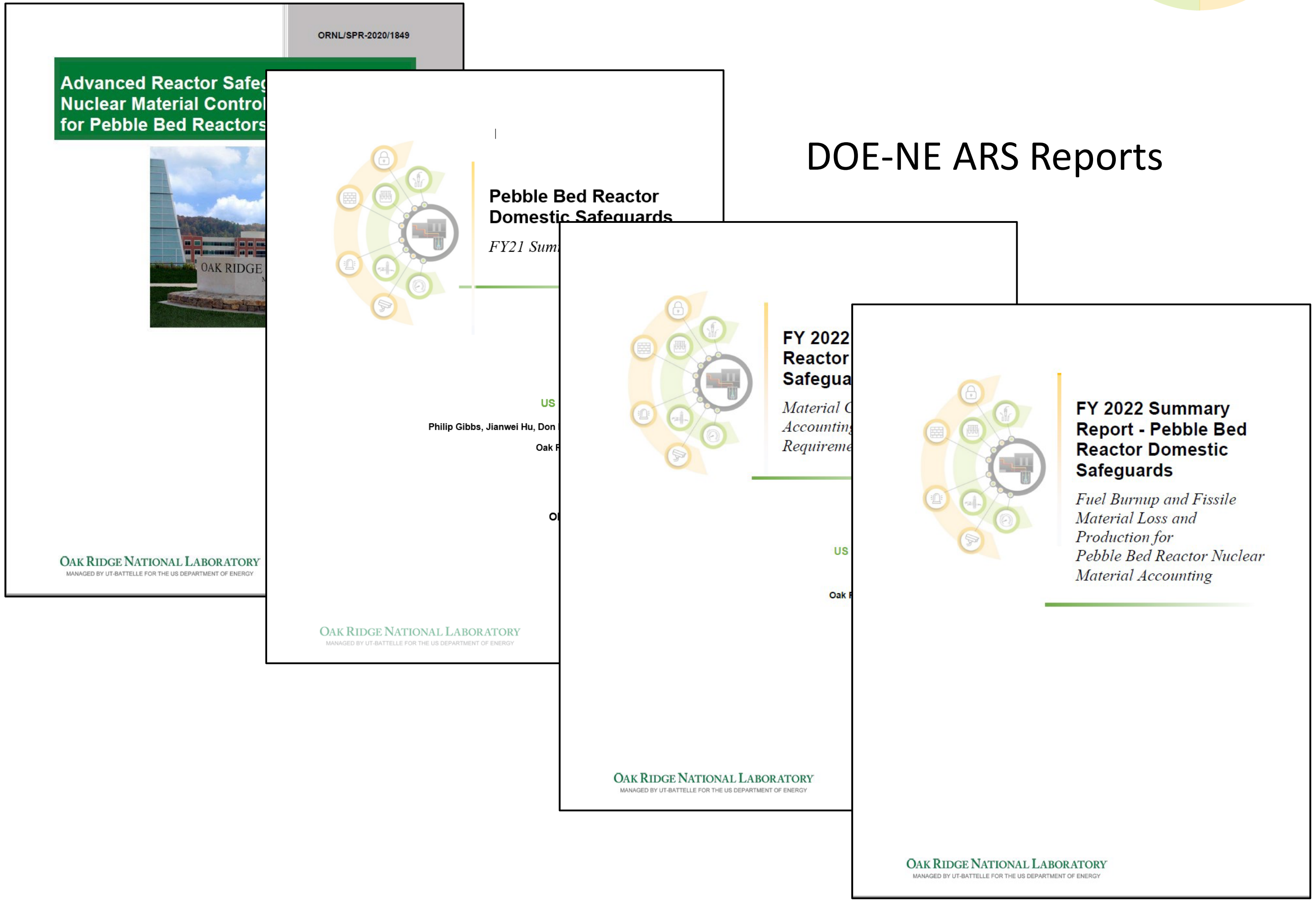
Key theme – MC&A in PBRs is about counting pebbles

ORNL PBR Related Work – 2019-2022

NRC PBR Reports



DOE-NE ARS Reports



Direct Industry Collaboration

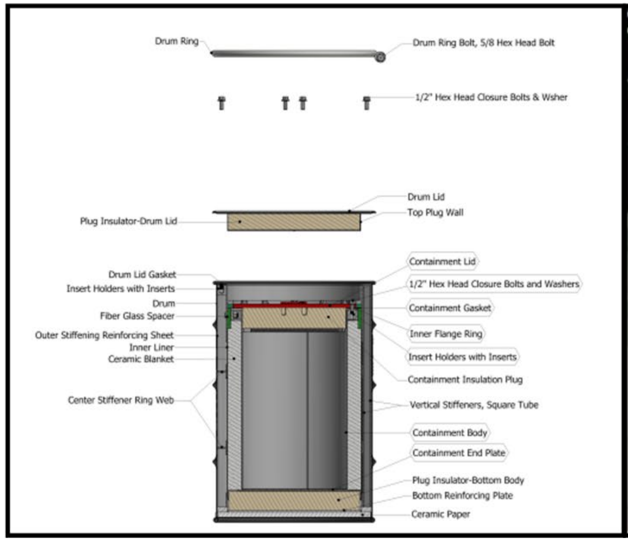
- X-Energy/ Xe-100 Reactor NDA in place and collaboration since 2020 and now continuing work under ADRP Award.
  - Support Burnup modeling and BUMS
  - Support development of MC&A Plan as part of licensing approach
  - Support consultations with IAEA on safeguards approach (NNSA ARISE program)
- Kairos Power – NDA in place and initial collaboration in 2021 and planning to continue under ARDP award
- Coordination with DOE-NE Material Protection Accounting and Control Technologies (MPACT) for MC&A for Ultra Safe Nuclear Corporation's (USNC) pilot TRISO fuel fabrication facility currently operating in Oak Ridge.
  - Support development of MC&A FNMCP for TRISO lines being installed in in Richland WA under a Joint venture with Framatome Fuel Services

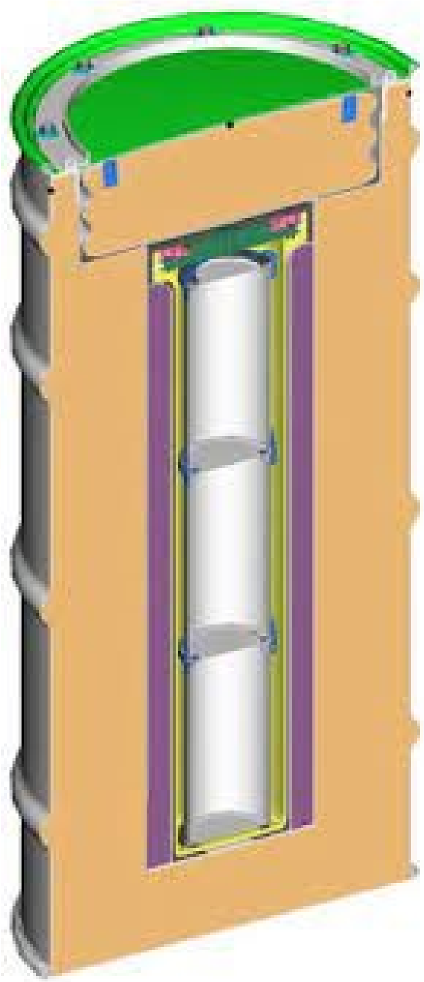
MC&A Plan Development for PBRs

- 10CFR Part 50 provides automatic exception for power reactors for submitting FNMC Plan as part of license
- 10CFR Part 52 does not provide an automatic exception, licensee must request an exception and provide justification.
- 10CFR Part 53 Risk Informed Technology Inclusive Regulatory Framework is not ready for use by applicants.
- Description of MC&A Plan <u>is required</u> as part of license submittal
- Unclear if MC&A templates for current NRC LWR licensees will be acceptable and if NRC will approve exemption requests, especially for Category II material (HALEU)
  - Current: Regulatory Guide 5.29 Special Nuclear Material Control and Accounting Systems for Nuclear Power Plants and ANSI N15.8-2009 NMC&A Systems for NPPs
  - Possible NUREG-2159, Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Special Nuclear Material of Moderate Strategic Significance

Fresh Fuel Packaging and Receipt

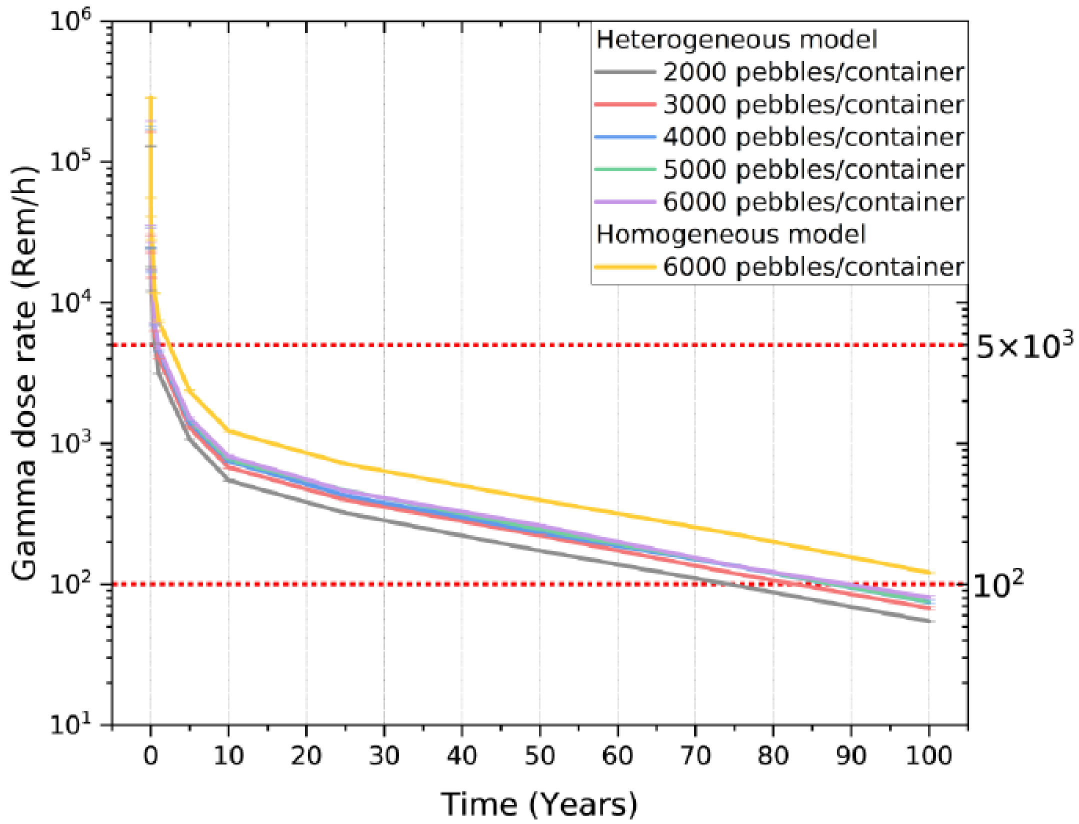
- Work done in FY22 was based on existing packaging concepts.
- Packaging is evolving
- Transportation of fresh HALEU packages are currently being designed and licensed
- Receipt, shipment, transfer, storage, handling, and item monitoring will be straight forward.

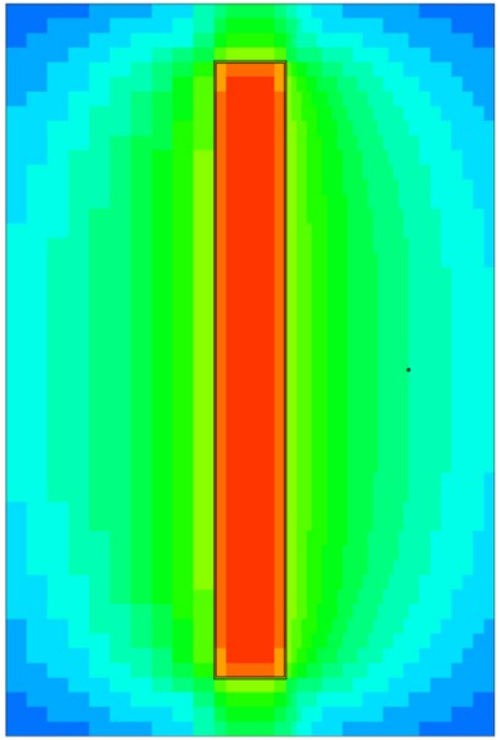


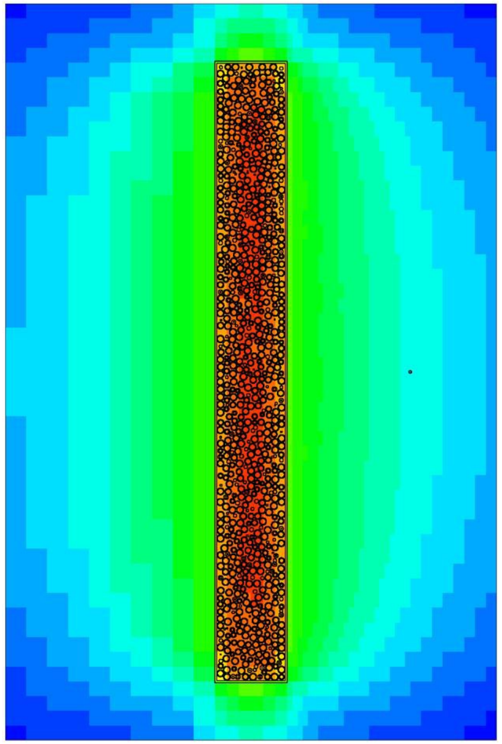


Spent Fuel Cannisters

- Design of spent fuel cannisters is ongoing
- Questions regarding wall thickness, height, and diameter will affect measurements
- Dose rate calculations will determine time for self-protection

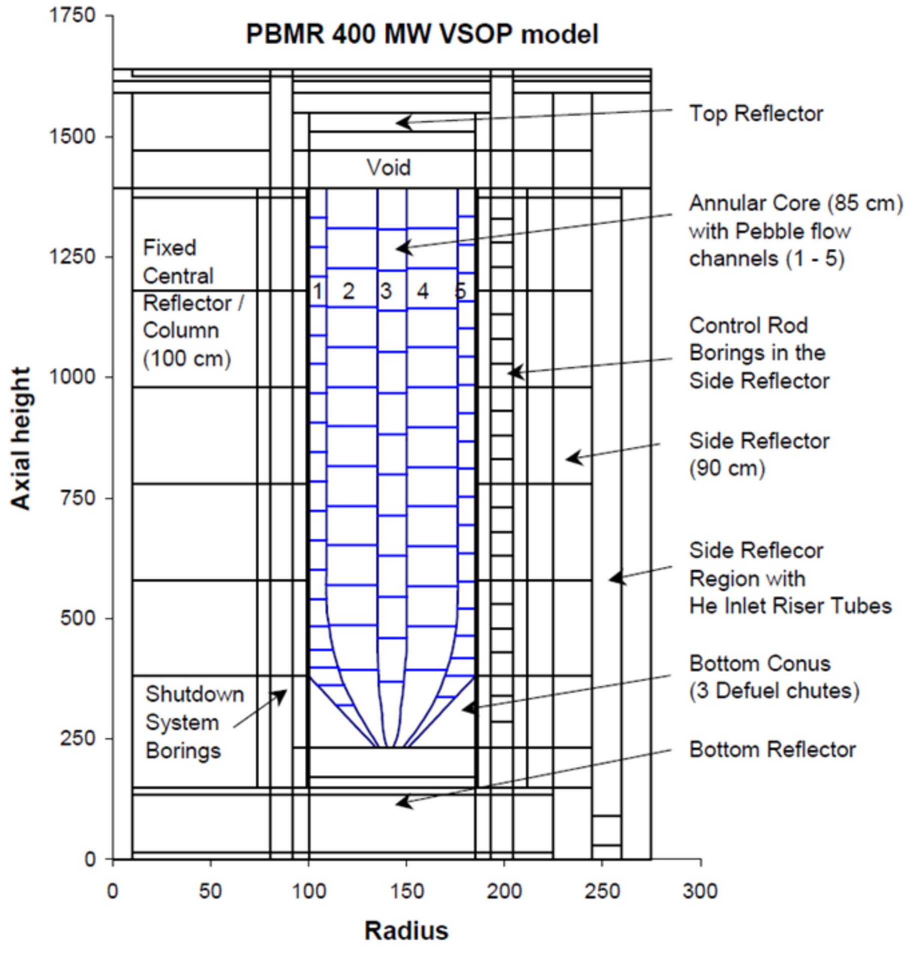






Burnup Modeling

- Using PBMR-400 as generic reactor design based on publicly available data using SCALE/ ORIGAMI codes.
- This work is being extrapolated to specific vendor designs as part of NDA and is controlled for IP.
- Reactor core is divided into axial and radial zones to model possible pebble pathways
- Pebbles typically achieve full burnup by the 6th pass.
- Results are then used to
  - Provide actinide isotopics for U/Pu loss and production
  - Develop statistical models for max burnup, target burnup, and decision for when to discharge a pebble
  - Develop synthetic spectra using GADRAS to determine potential gamma signatures for use in BUMS.



SNM Content of a Spent Pebble

Table 1. Comparison of average isotopic mass (mg) per pebble with previous work.

Nuclide	Initial	Retired pebbles	All pebbles after pass 6 (this work)	All pebbles after pass 6 (previous work [21])
^{234}U	7.690	4.8 ± 0.1	4.8 ± 0.1	N/A
^{235}U	864.00	141.8 ± 19.6	145.5 ± 21.9	185 ± 11
^{236}U	3.974	116.1 ± 2.2	115.6 ± 2.5	N/A
^{238}U	8,124.34	7,755.8 ± 21.1	7,753.1 ± 13.6	7,690 ± 50
Total U	9,000	8,018.4 ± 28.9	8,019.1 ± 25.9	7,875 ± 51.2
^{238}Pu	0	2.3 ± 0.3	2.3 ± 0.3	2.8 ± 0.2
^{239}Pu	0	52.2 ± 6.0	53.6 ± 5.3	57 ± 9
^{240}Pu	0	35.5 ± 1.3	35.7 ± 0.9	30 ± 3
^{241}Pu	0	19.3 ± 1.5	19.7 ± 1.1	28 ± 4
^{242}Pu	0	14.6 ± 1.6	19.4 ± 1.5	20 ± 2
Total Pu	0	123.9 ± 6.5	125.9 ± 4.6	137.8 ± 10.5

Estimate U and Pu inventories in an APR-1400 spent fuel assembly

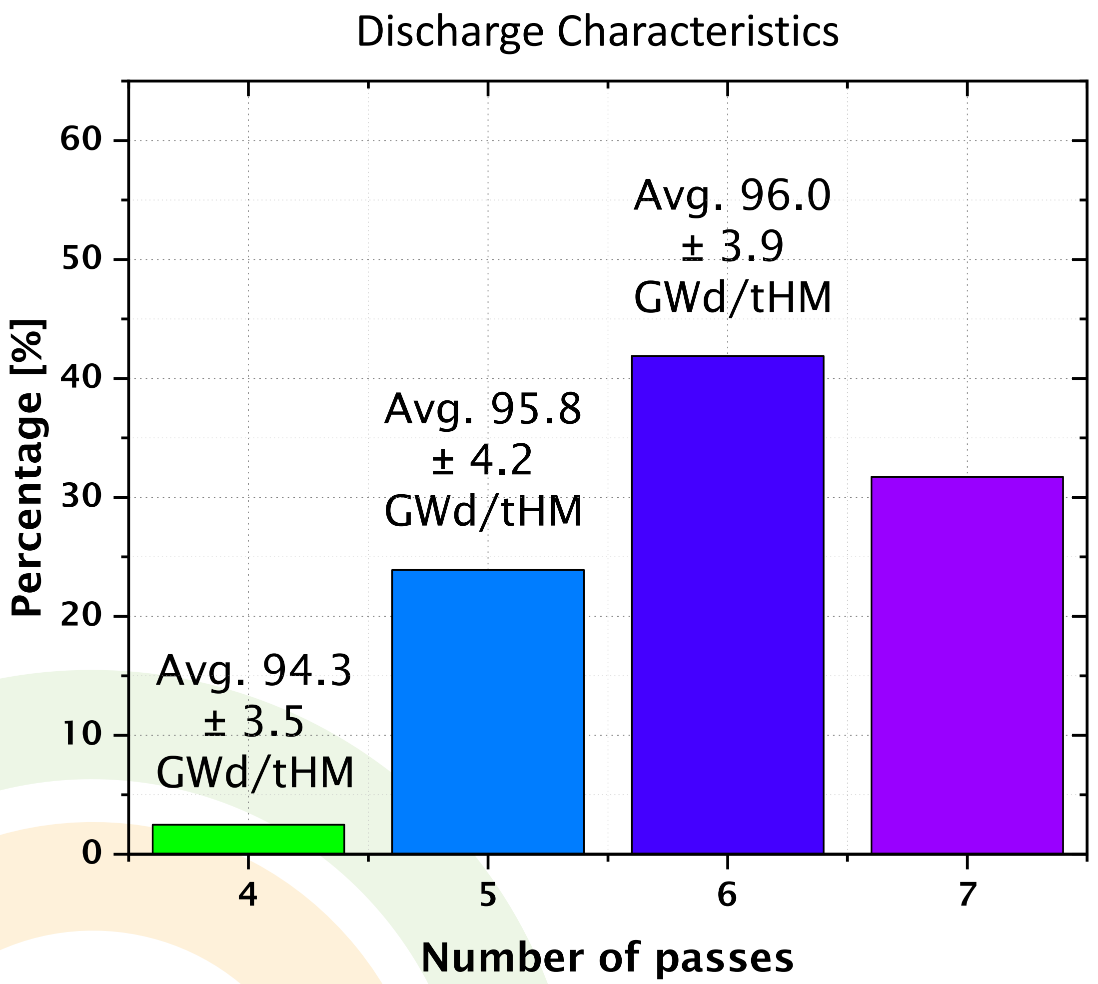
Isotope	Inventory (kg)
U total	397.2
^{234}U	0.071
^{235}U	2.61
^{236}U	2.44
^{238}U	392.0
Pu total	4.45
^{238}Pu	0.16
^{239}Pu	2.60
^{240}Pu	1.30
^{241}Pu	0.73
^{242}Pu	0.43

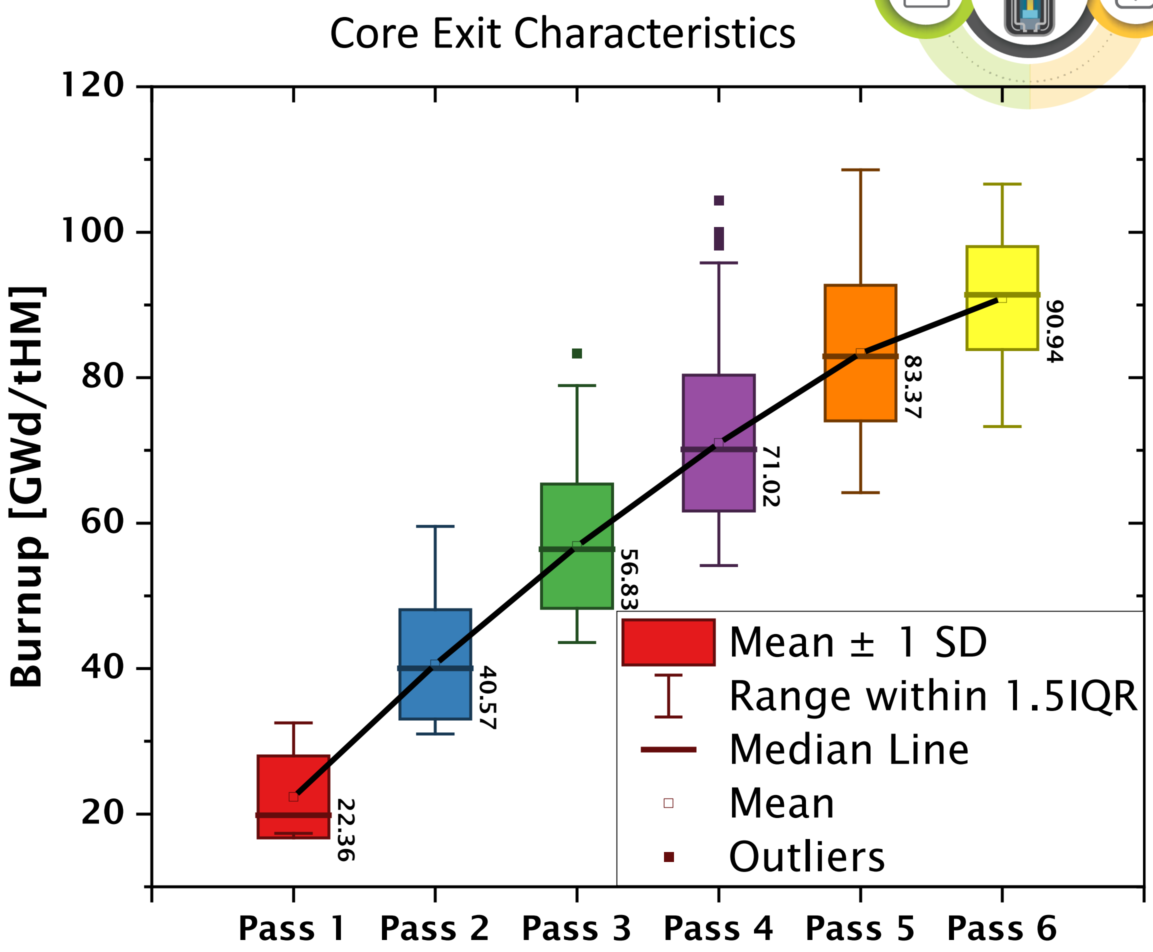
Assuming 2000 pebbles in spent fuel container = 0.276 kg

Statistical Approaches for PBRs

1. Burnup measurement discharge decision
2. Burnup measurement versus reactor code comparison
3. Analysis of Variance (ANOVA) between reactors

1 - Burnup Measurement Discharge Decision



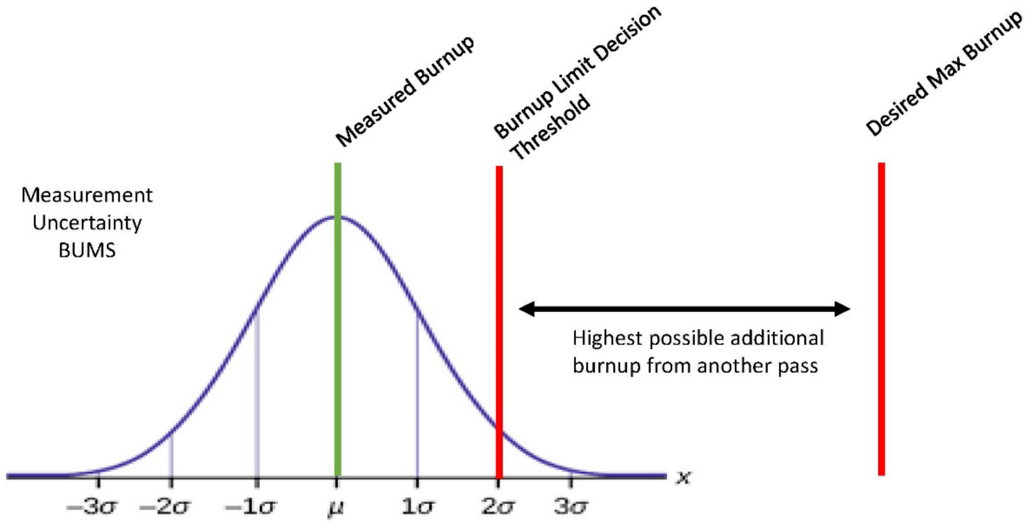


Target discharge burnup is 90 GWd/MTU achieved for about 65% of pebbles in 6 passes.

Outliers are those pebbles outside of the 1.5 Inter-Quartile Range (IQR). For a normal distribution, this would be outside approx. +/- 3σ.

Statistical Approach

- Decision to "retire" (discharge) a pebble based on measured burnup values by BUMS
- Pebble should be discharged at optimal time before exceeding maximum allowable burnup based on the highest energy path that might be taken
- Burnup measurement and model uncertainties must be considered.



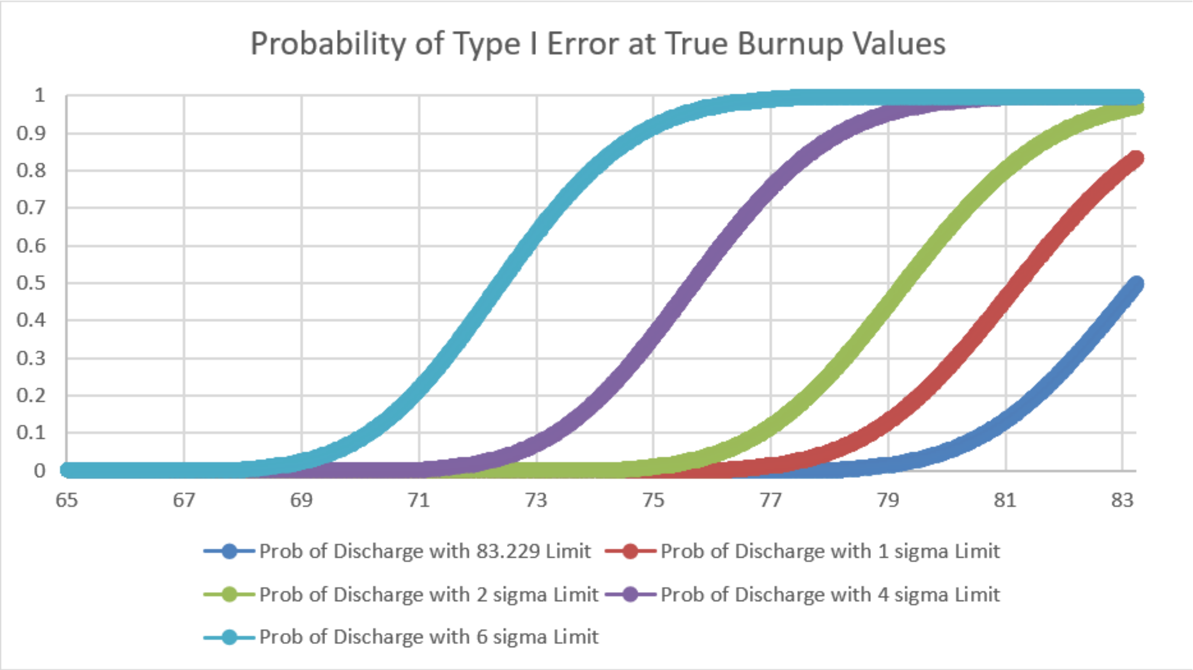
- Type I error—Discharging a pebble when it should have been returned to the reactor, resulting in underutilized fuel **(false positive).**
- Type II error—Returning a pebble to the reactor when it should have been discharged, resulting in a pebble exceeding the maximum desired burnup and creating possible safety concerns and/or less-than-desirable operational performance **(false negative).**

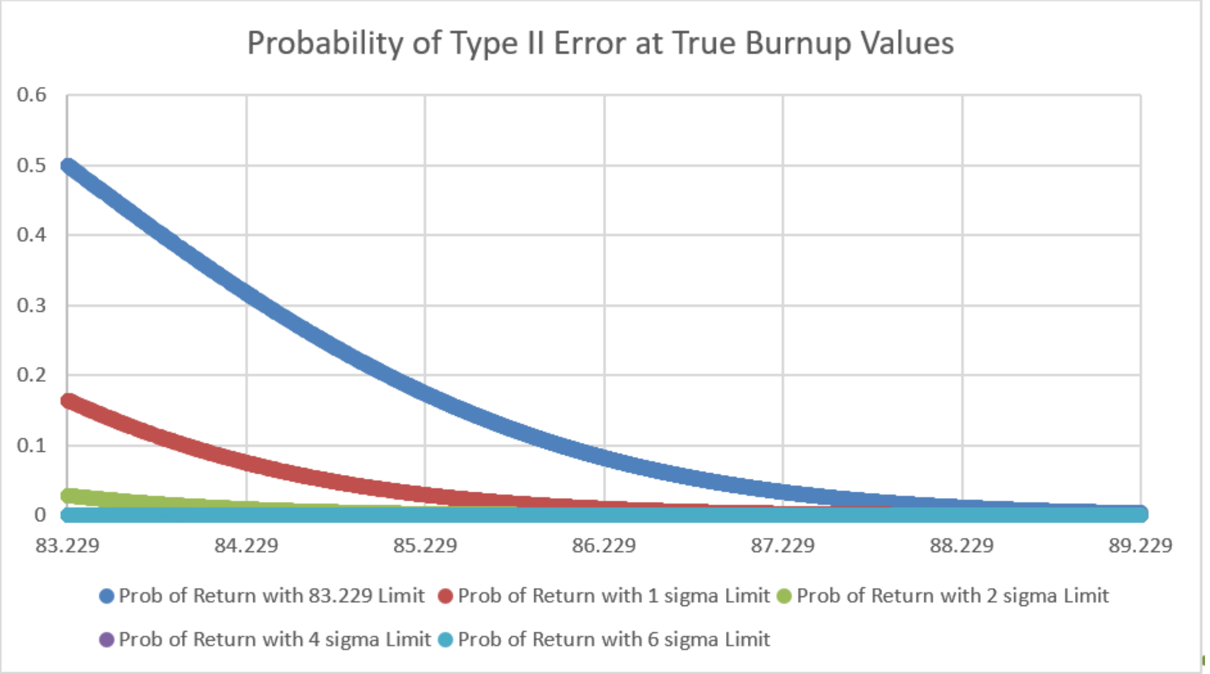
Case Study – Can be Applied by Designers

- Develop generic algorithm/ approach based on assumptions that can be changed for specific designs
- Consider maximum allowable burnup of 100 GWd/tU (PBMR-400 value based on safety reference case) and the target burnup of 90GEd/tU
- Largest additional burnup based on highest pathway is 16.771 GWd/tU, therefore the Threshold value (T) = 83.229 GWd/tU – (in a real system this will be a distribution based on isotopics of specific pebble, probability of maximum energy pathway, and transit time)
- BUMS measurement uncertainty was assumed to follow a normal distribution with mean μ equal to the true value and a standard deviation σ=2.5%.
  - Type I Error: $\alpha = P(m \geq L | x < T)$
  - Type II Error: $\beta = P(m < L | x \geq T)$
- Choosing the decision point for the measured burnup is a balance of Type I/ Type II error.

Type I vs. Type II Errors

- Highly conservative measurement bounds results in Type I errors – **premature retirements**
- However, results in high safety margin – very few "**overburned" pebbles**
- Non-conservative bounds maximize fuel performance but may result in increased overburned pebbles
- **Operators must decide the balance – 1, 2, 4, 6 σ**





Results of Statistical Analysis

Total Number of Measured Pebbles with true burnup less than 83.229 GWD/tU, n=47,752		
Decision Point for Measured Burnup (GWd/tU)	Average Number of Pebbles Discharged Prematurely	Proportion of Pebbles Discharged Prematurely, Type I Error Estimate
83.229	517	0.01082
81.1990	1482	0.03103
79.2657	2945	0.0617
75.6627	6780	0.1420
72.3730	8958	0.1876

- Estimate of number of pebbles discharged prematurely in a population

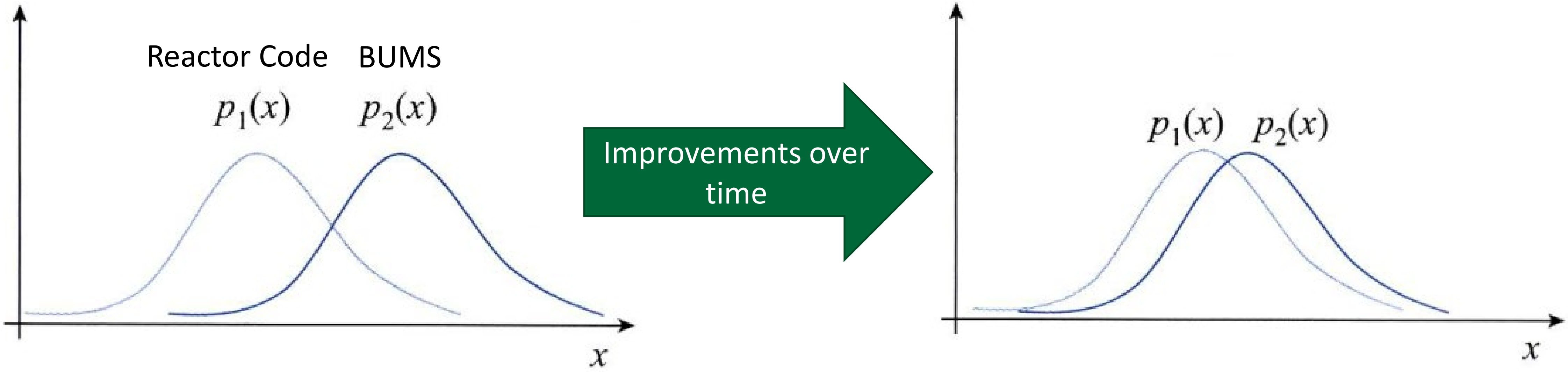
- Analysis based on Monte Carlo simulation on a large population

Decision Point for Measured Burnup (GWd/tU)	Average Burnup of Discharged Pebble (GWd/tU)	Type I Error Estimate Mean	Type I Error Estimate SD	Type II Error Estimate Mean	Type II Error Estimate SD
85.0000	90.1867	0.00280	0.000234688	0.14245	0.002353471
83.2290	88.7127	0.01079	0.000409156	0.05836	0.002017674
81.1990	87.1999	0.03101	0.000559823	0.01286	0.001155108
79.2657	85.5135	0.06165	0.000655822	0.00178	0.000501737
75.6627	81.2152	0.14202	0.000714746	1.01E-05	5.59E-05
72.3730	78.3929	0.18890	0.000363925	0*	0*

*0 indicates below machine precision.

2 - Burnup Measurement (BUMS) versus Reactor Code Comparison

- BUMS and reactor code comparison constitute a powerful tool to accurately measure burnup and improve the accuracy over time (better than current LWRs)
- A statistical sample of pebbles will be selected for more accurate NDA methods or DA. These results will be used to calibrate the BUMS burnup measurements and validate the reactor code predictions for burnup and SNM content.



First deployments – 2030s

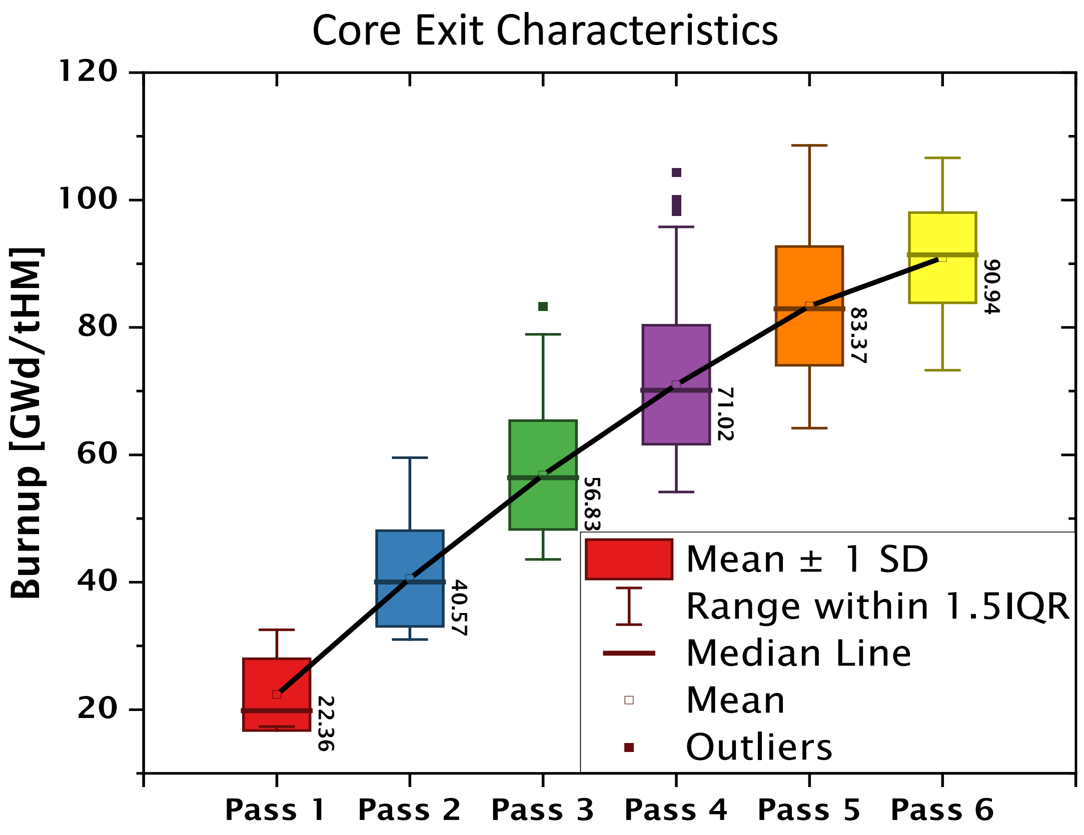
Fully mature technologies

3 - Analysis of Variance – differences between reactors

Analysis of Variance (ANOVA) is a statistical formula used to compare different groups. A range of scenarios use it to determine if there is any difference between the different groups.

For PBRs could be used to:

- Misuse of reactor
- Operational
  - Instrumentation Issues
  - Fuel flow through core
  - Fuel optimization



NDA Measurements - Gamma

- BUMS will rely on gamma signatures
- GADRAS synthetic spectra evaluated potential signatures of pebbles
- 100 hours cooling time
- Cs137 absolute quantity is a good indicator of burnup

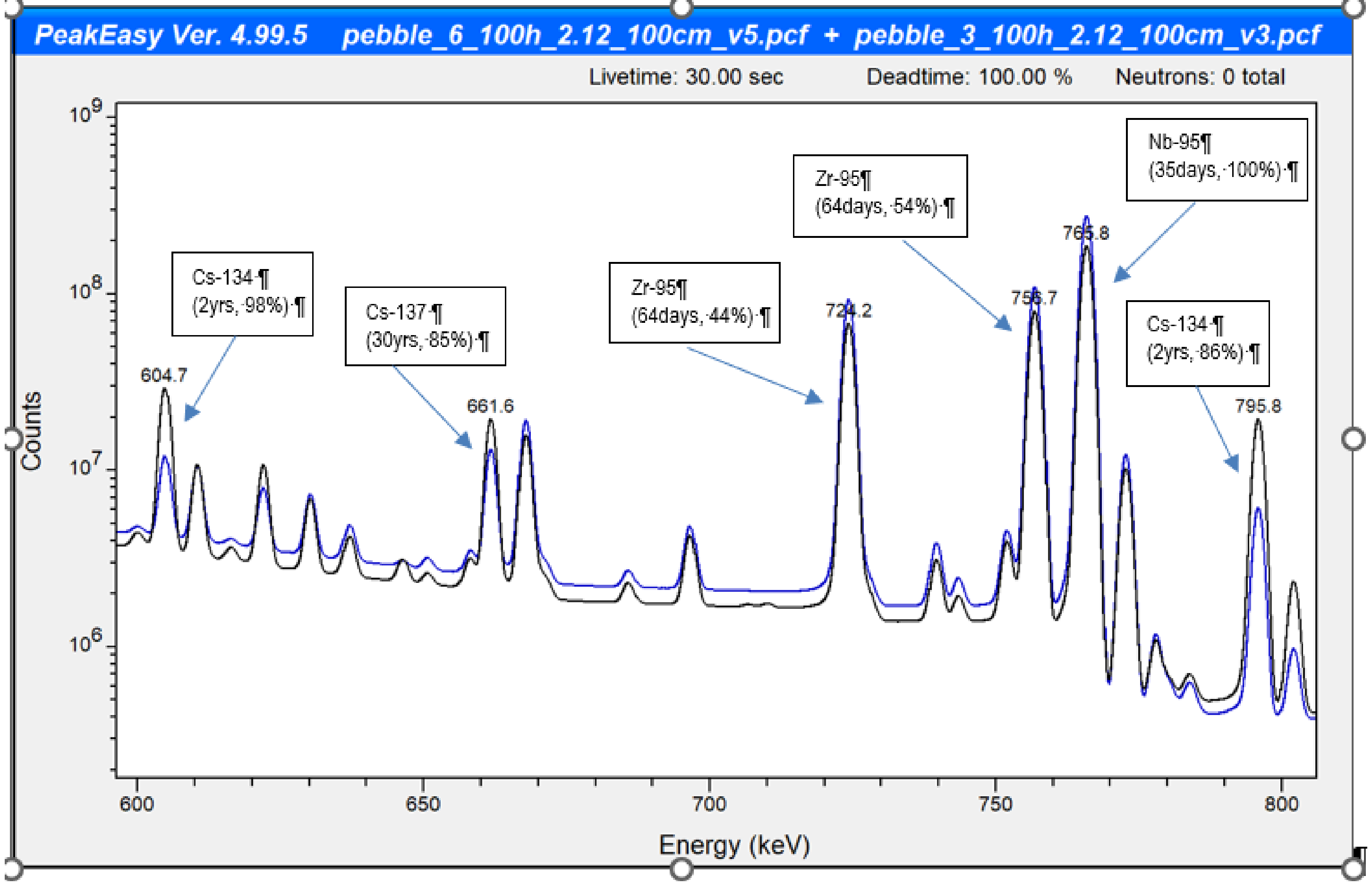
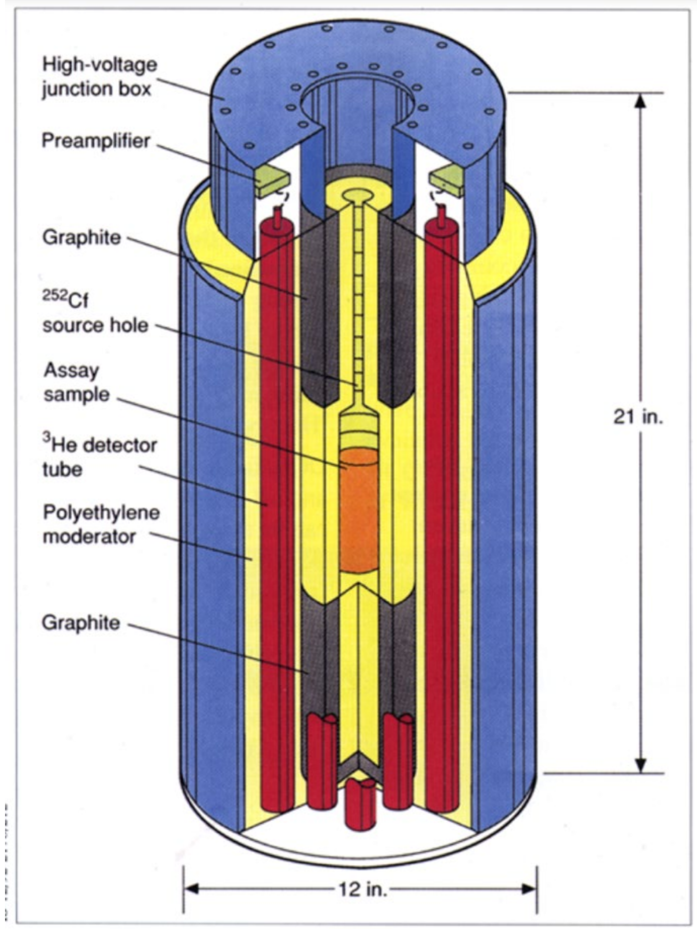


Figure 20. Close-up of the synthetic HPGe gamma spectra generated by GADRAS for Pebble 3 (blue) and Pebble 6 (black) in the energy range of 600–800 keV with the prominent gamma lines labeled. The labels include the primary emitter, its half-life, and the branching ratio (in percentage) of the respective gamma line.

NDA Measurements - Neutron

- Neutron measurements being considered to complement gamma, especially to distinguish between different initial enrichments.
- More sensitive than gamma for burnup
- Challenging radiation and thermal environments
- An alternate neutron-moderating material, - PolyEtherEtherKetone (PEEK), is a semicrystalline thermoplastic with excellent strength and ductility, has good neutron moderating power, and is suitable for continuous-use at temperatures up to 260°C



An example of a PNCC: an inventory sample counter

Pebble Rounding Errors and MC&A Systems

- Rounding Errors
  - Because of limitations of some MC&A systems, small U/ Pu values per pebble will cause rounding errors.
  - Example of rounding errors were provided
  - Not a major technical issue but needs to be addressed
- Inventory Management and Accounting Systems
  - Should allow full life cycle tracking from receipt, to operation, to spent fuel management
  - Ability to electronically import/ export inventory information
  - Ability to handle all regulatory reporting
  - Two commercially available systems were reviewed
  - A full listing of functional specifications was provided including detailed explanation of how it is applied to a facility's MC&A program.

Summary

- This work addressed the major features of PBRs with respect to MC&A
- Pebble counting and statistics will play a major role in MC&A program
- Models must continue to improve, especially for non-equilibrium cases - startup, run-in cores, defueling and refueling of irradiated (used) fuel.
- Statistical sampling and NDA/ DA of irradiate spheres will validate reactor models and improve BUMS calibration and accuracy.
- Operator must balance Type I and Type II errors for economics and safety
- Pebble rounding errors must be taken into consideration in MC&A program
- Operator must select adequate MC&A system based on needs/ requirements
- Now transitioning to direct vendor support through ARDP and ARPA-E

THANK YOU!