Oak Ridge National Laboratory

Identifying Technical Challenges in Safeguards Measurements of Advanced Small Modular Reactor Fuel Elements

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Objective

- **Overall Objective:** to identify potential technical challenges in safeguards measurements (e.g., neutron measurements) of various fresh and spent nuclear fuel elements used in advanced reactors (ARs).
- The AR fuel elements can be significantly different than conventional light water reactor (LWR) fuels, (e.g., sizes, enrichments, and chemical forms).
- Most of the existing safeguards instruments (e.g., UNCL, FNCL*, and Fork detector) are designed for LWR fuels.

AR designs supported by ARDP

DOE program	Reactor name	Company name	Fuel type
Advanced Reactor Demonstration Projects (ARDP)	Xe-100	X-energy	Pebble (TRISO based)
	Natrium	TerraPower	Metal fuel
Risk Reduction for Future Demonstration Projects	Hermes Reduced-Scale Test Reactor	Kairos Power	Pebble (TRISO based)
	eVinci Microreactor	Westinghouse	Compact (TRISO based)
	BWXT Advanced Nuclear Reactor (BANR)	BWXT	Compact (TRISO based)
	Holtec SMR-160 Reactor	Hotec	UO_2 (17 x 17)
	Molten Chloride Reactor Experiment	Southern Company	Molten salt
Advanced Reactor Concepts-20 Projects (ARC-20)	Inherently Safe Advanced SMR for American Nuclear Leadership	Advanced Reactor Concepts, LLC	Metal fuel
	Fast Modular Reactor Conceptual Design	General Atomics	UO_2 in SiC cladding
	Horizontal Compact High Temperature Gas Reactor	MIT	Compact (TRISO based)

*Uranium Neutron Collar (UNCL), Fast Neutron Collar (FNCL).

Comparison of main characteristics among AR fuel elements

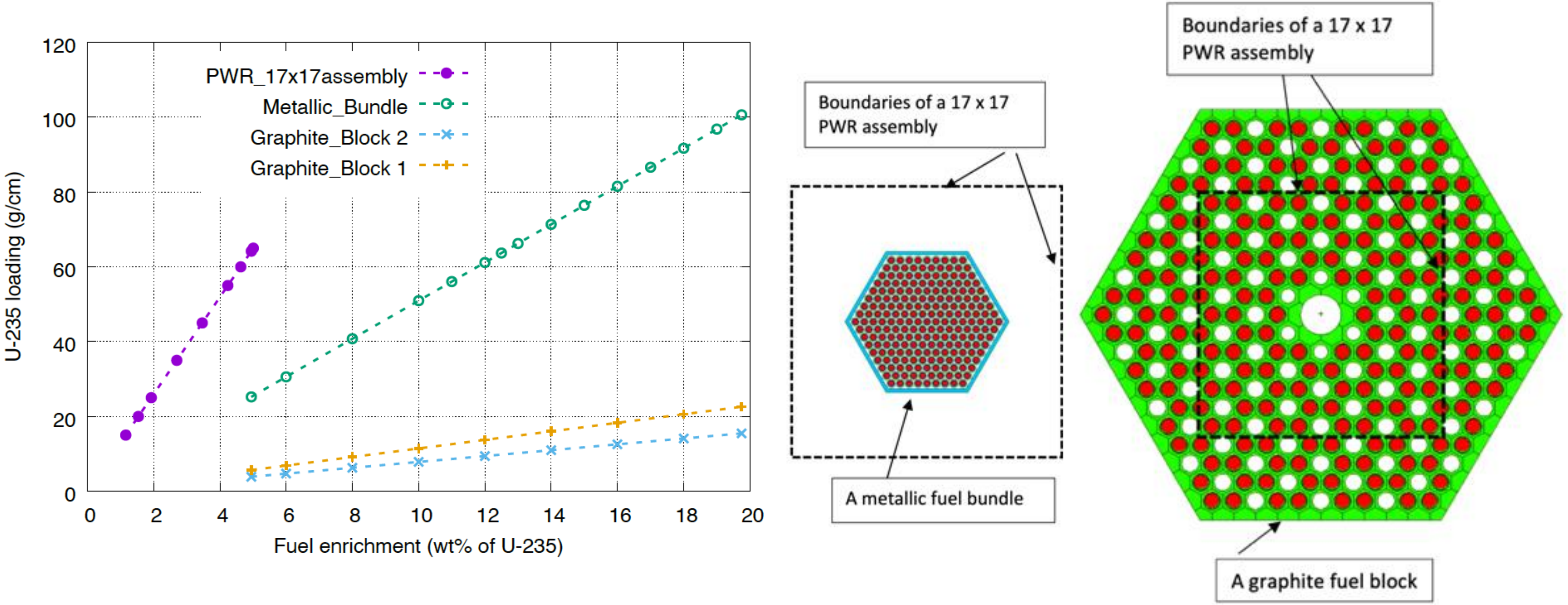
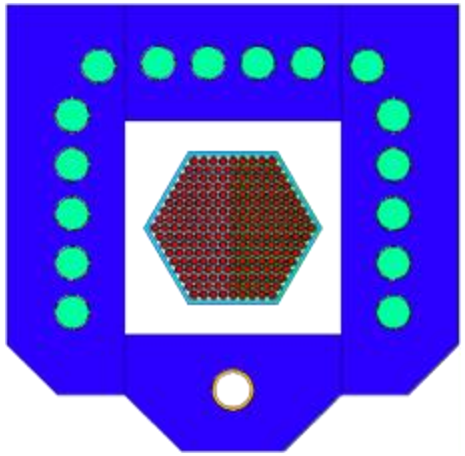
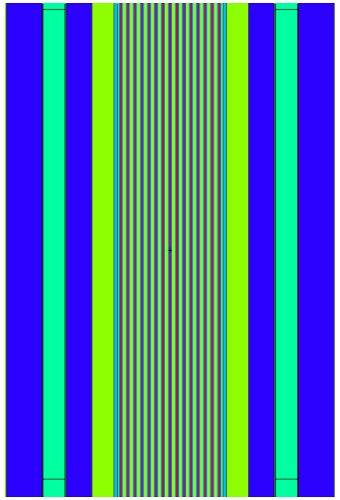


Figure 1. (Left) the ^{235}U loading per unit length in the AR fuel elements compared to that of a PWR assembly; Comparison of the overall dimensions: (middle) between a metallic fuel bundle and a PWR assembly, (right) between a graphite fuel block and a PWR assembly.

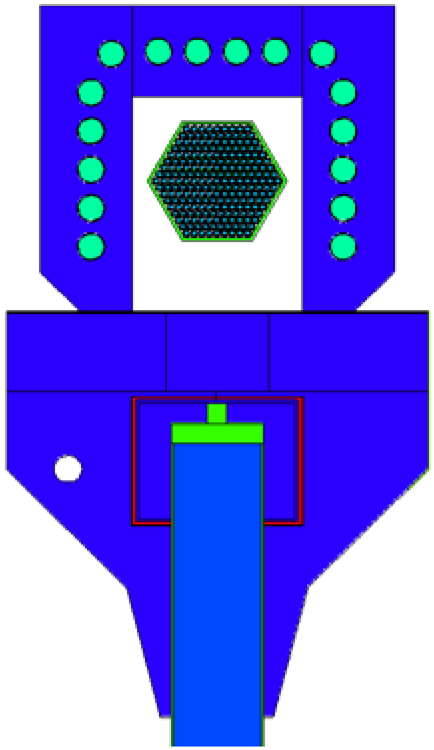
MCNP modeling: Metallic fuel bundle with UNCL-II and FNCL



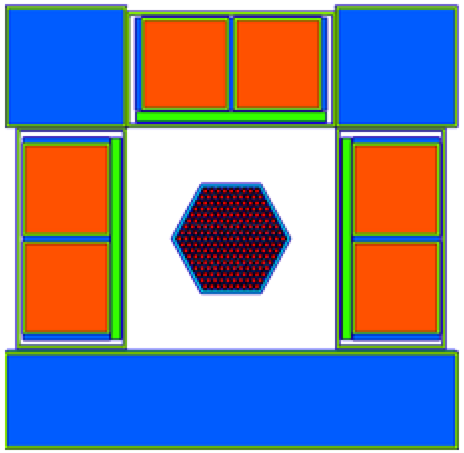
UNCL-II (BWR version) with AmLi source



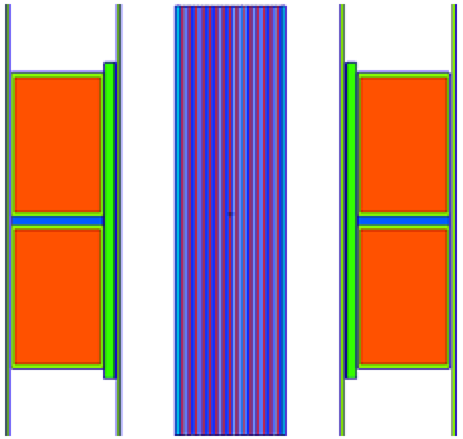
UNCL-II (side view)



UNCL-II (BWR version) with D-D neutron generator



FNCL with AmLi source

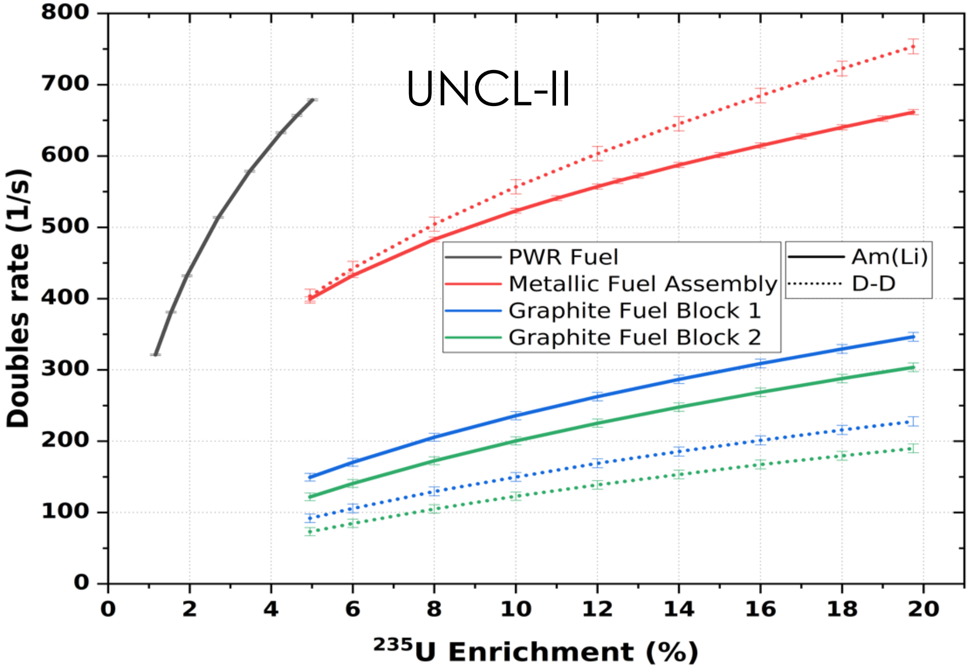


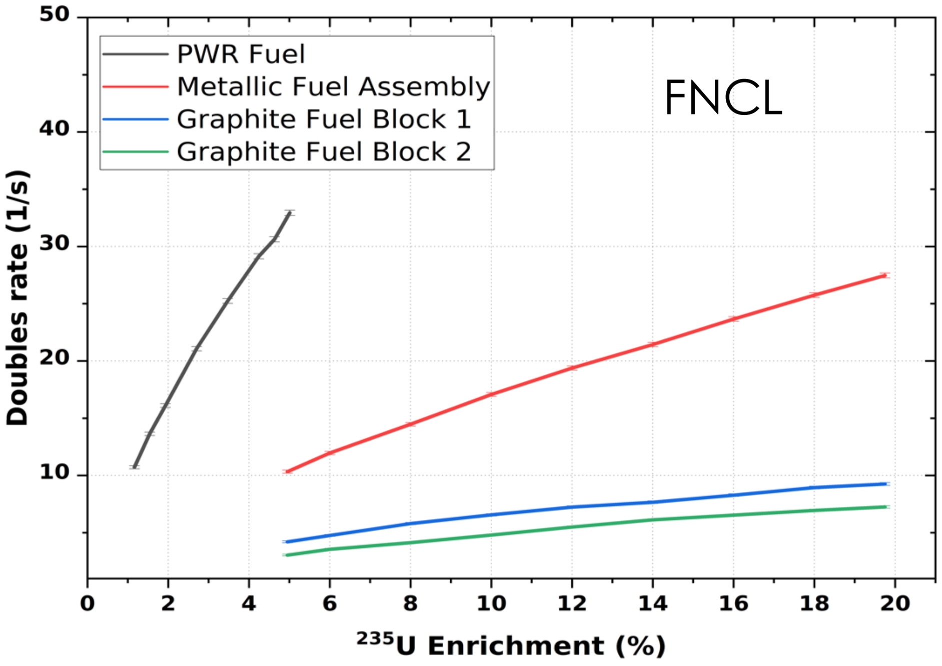
FNCL (side view)

- Detailed 3D modeling used to simulate detector responses.
- A metallic bundle fits loosely in existing detectors.

UNCL-II and FNCL Results

- Compared with PWR results, doubles rates for AR fuel elements have smaller magnitudes and significantly lower sensitivity to enrichment, due to the much lower uranium loading in some AR fuels.
- Use of D-D neutron generator increases the UNCL doubles rate for metallic fuel but not for the graphite fuel blocks.
- For metallic fuel, doubles rate from FNCL has much higher sensitivity to enrichment than UNCL.

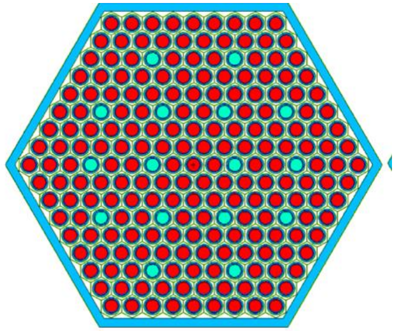




Ability to detect partial defects in fresh AR fuel elements

UNCL-II (10 mins)

Mass diverted (%)	PWR Fuel Assembly		Metallic Fuel		Graphite Fuel Block1		Graphite Fuel Block2	
	95% confidence	99.7% confidence	95% confidence	99.7% confidence	95% confidence	99.7% confidence	95% confidence	99.7% confidence
~ -2	NO	NO	NO	NO	NO	NO	NO	NO
~ -4	YES	NO	NO	NO	NO	NO	NO	NO
~ -5	YES	YES	NO	NO	NO	NO	NO	NO
~ -7	YES	YES	YES	NO	NO	NO	NO	NO
~ -10	YES	YES	YES	NO	YES	NO	YES	NO
~ -13	YES	YES	YES	YES	YES	NO	YES	YES



16 DU pins

FNCL (10 mins)

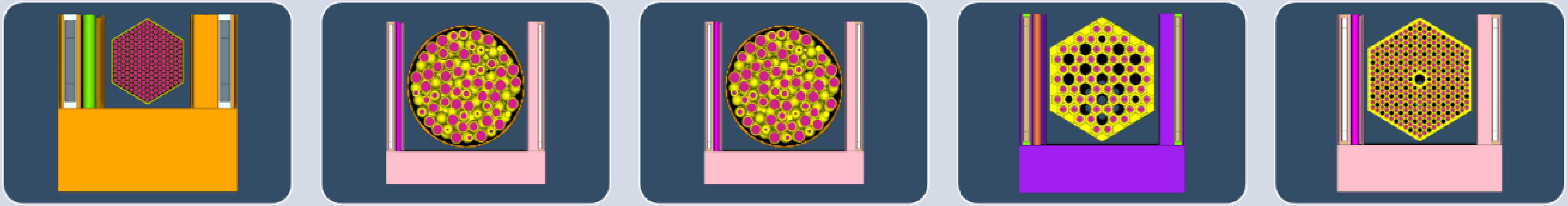
Mass diverted (%)	PWR Fuel Assembly		Metallic Fuel		Graphite Fuel Block1		Graphite Fuel Block2	
	95% confidence	99.7% confidence	95% confidence	99.7% confidence	95% confidence	99.7% confidence	95% confidence	99.7% confidence
~ -2	YES	NO	NO	NO	NO	NO	NO	NO
~ -4	YES	YES	NO	NO	NO	NO	NO	NO
~ -5	YES	YES	YES	YES	NO	NO	NO	NO
~ -7	YES	YES	YES	YES	NO	NO	NO	NO
~ -10	YES	YES	YES	YES	NO	NO	NO	NO
~ -13	YES	YES	YES	YES	NO	NO	NO	NO

Spent AR Fuel items

Five spent AR fuel items were studied.

Compared to a spent PWR assembly, the spent AR fuel items can have significantly higher Pu, ^{239}Pu, fissile nuclide concentrations.

Spent AR fuel items emit significantly less photons, and thus less self-protecting.



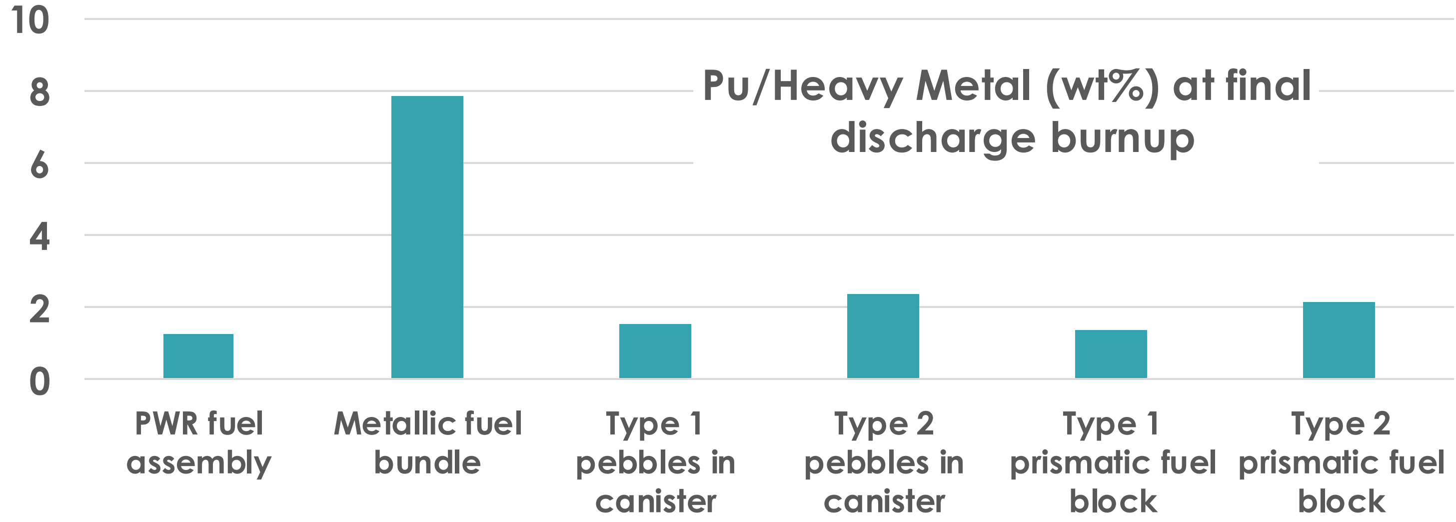
Metallic fuel
- U-10Zr
- **BU:** 25, 50, 75, 100, 125 & 150 GWd/tHM
- **Cooling time:** 1y & 5y

Pebbles type 1 in container
- 2000 UO_2 pebbles
- **BU:** 20, 38, 54, 68, 80 & 90 GWd/tHM
- **Cooling time:** 1y & 5y

Pebbles type 2 in container
- 2000 UCO pebbles
- **BU:** 45, 81, 109, 130, 148, 163, & 171 GWd/tHM
- **Cooling time:** 1y & 5y

Prismatic fuel block type 1
- UCO kernel
- Compact packing fraction 60%
- **BU:** 100,130 & 170 GWd/tHM
- **Cooling time:** 1y & 5y

Prismatic fuel block type 2
- UCO kernel
- Compact packing fraction 40%
- **BU:** 100,130 & 170 GWd/tHM
- **Cooling time:** 1y & 5y

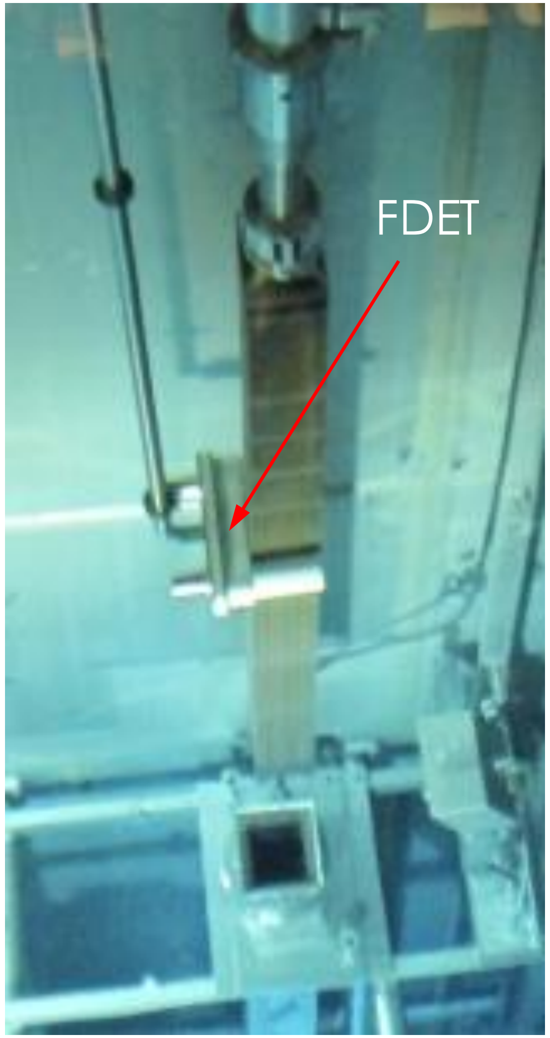


Spent fuel measurements

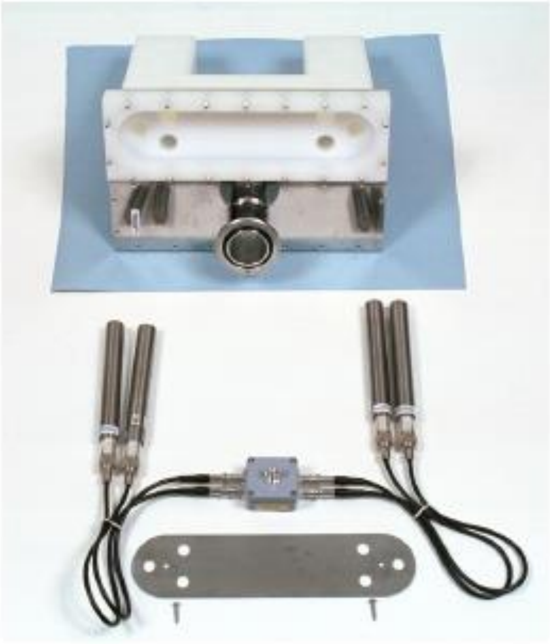
Fork detector (FDET) and various versions of Cerenkov viewing devices (CVD) have been used by the IAEA for decades to verify spent LWR fuel.

Most spent fuel measurements have been done in water.

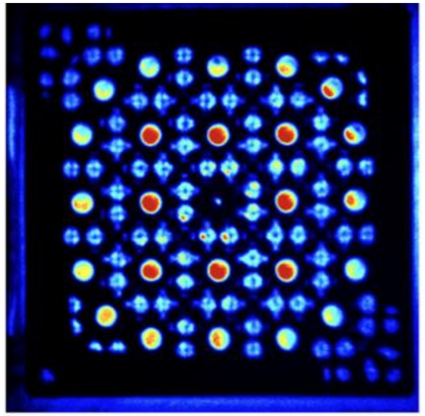
The TRISO-based spent AR fuel items most likely stored in air,
- which might make CVD measurements either impossible or less effective.



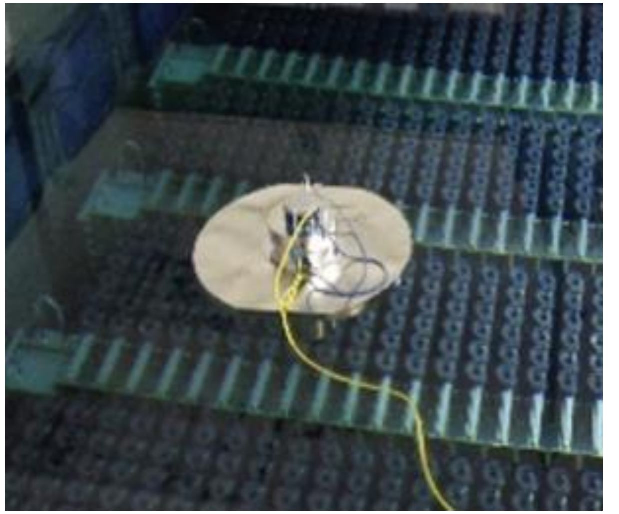
FDET measurement of a PWR assembly



AN unmounted FDET head



A DCVD image of a PWR assembly



A robotized CVD performing tests in a pool

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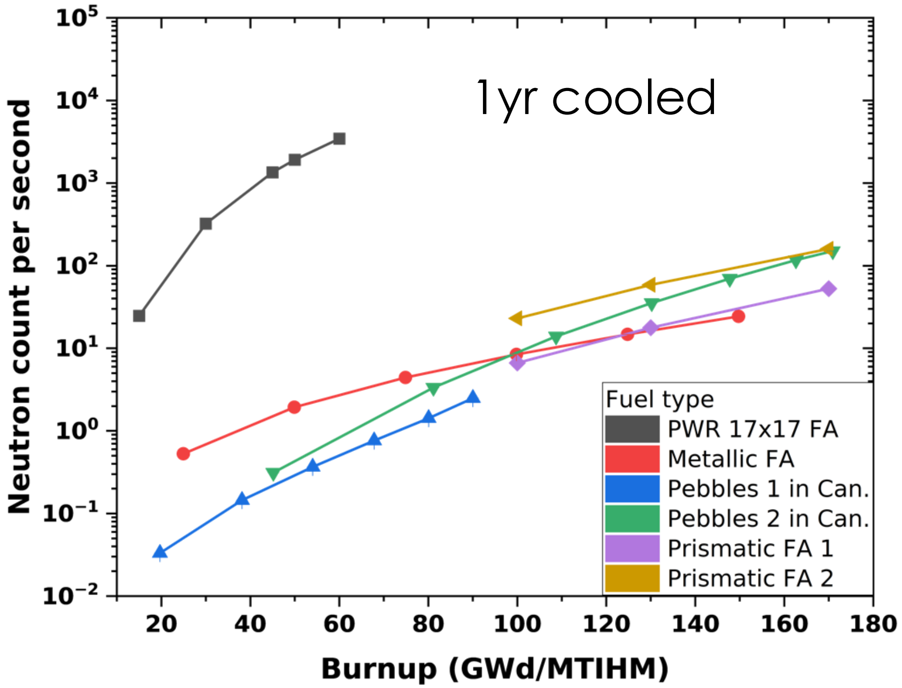
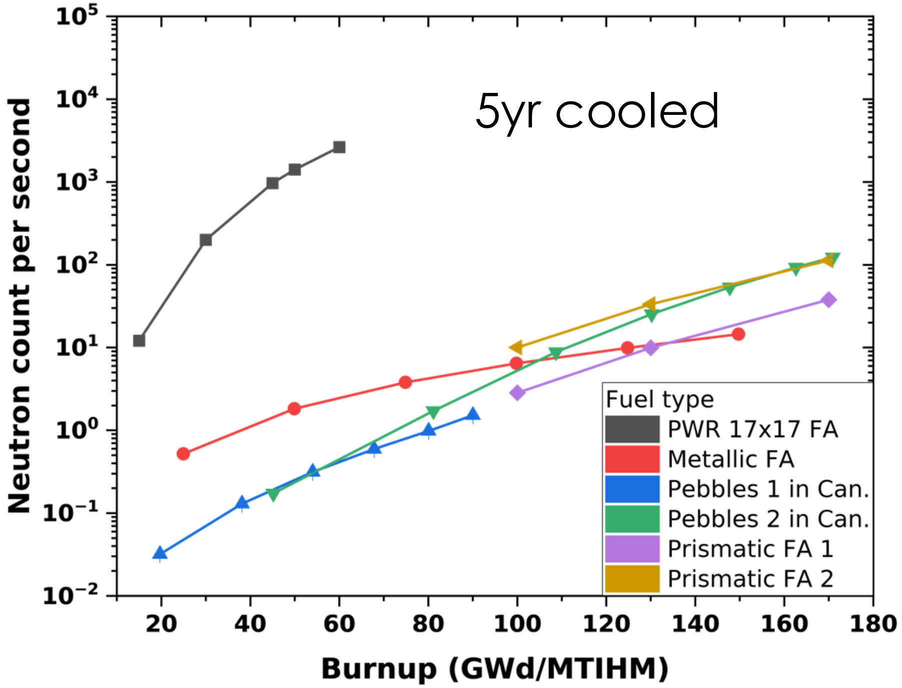
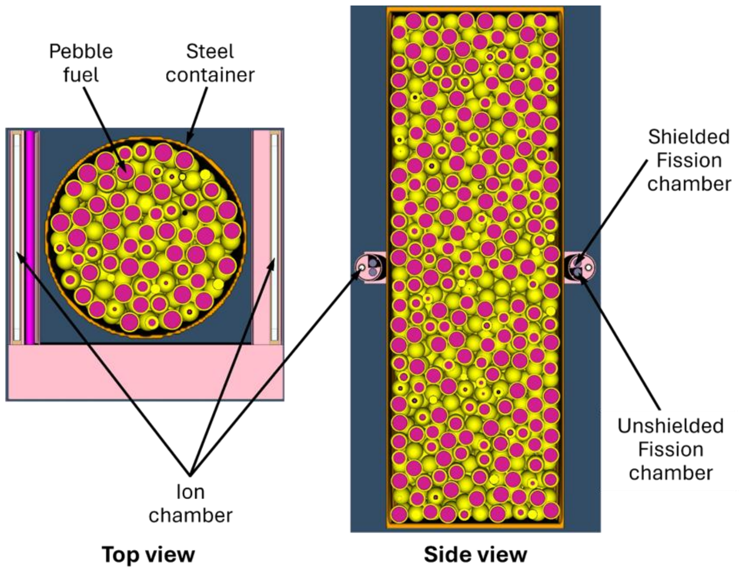
FDET Results

Much lower FDET neutron count rates in all spent AR fuel items than a PWR assembly, due to the much lower uranium loading in the AR fuels.

- Longer measurement times required for spent AR fuel.



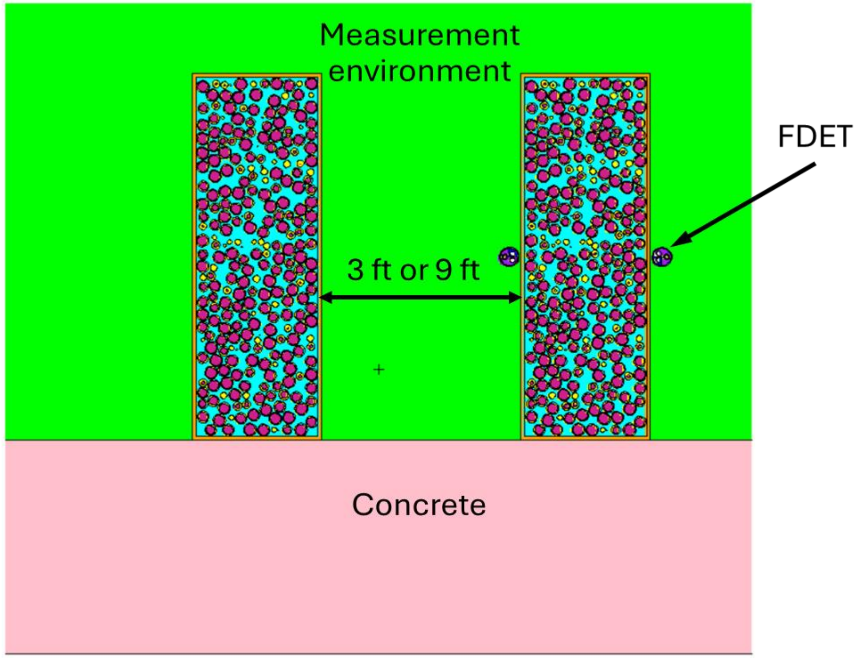




Model of FDET measurement of a spent pebble canister.

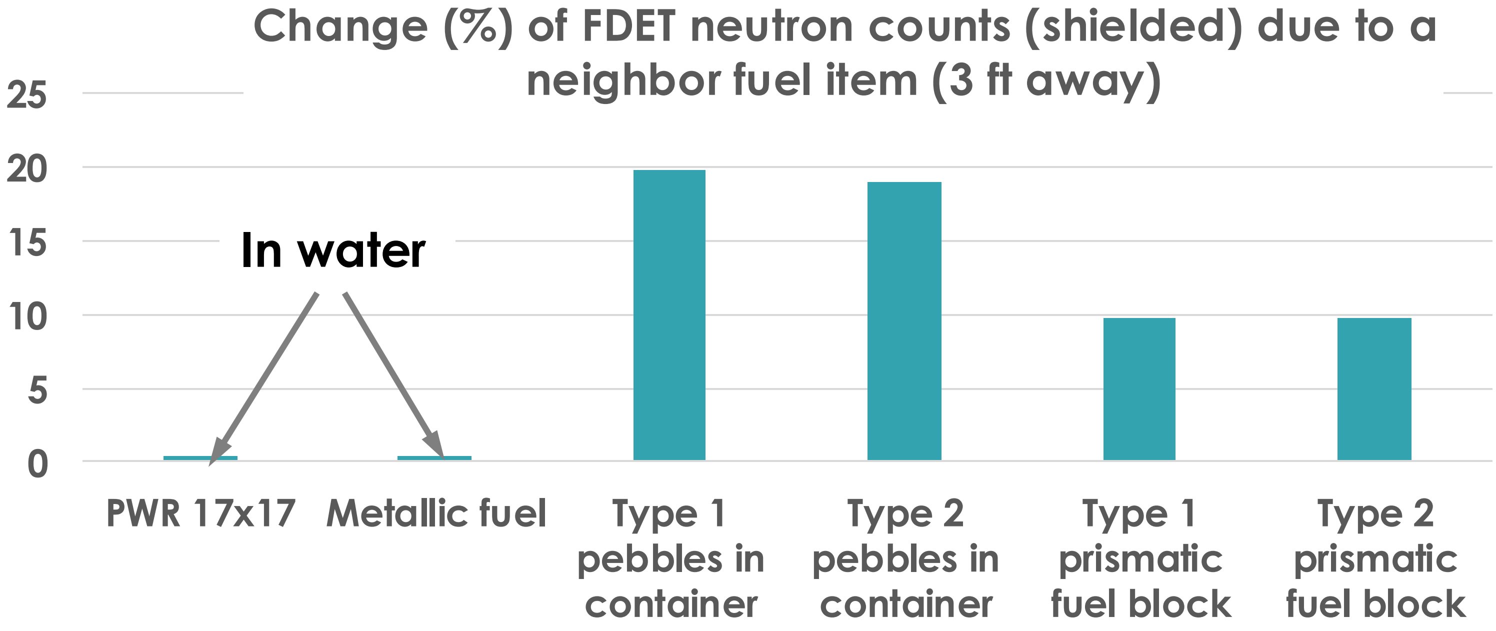
Interference of neighbor fuel on FDET

All the TRISO-based spent fuel (pebbles, graphite blocks) likely stored in air-filled hot cells instead of water-filled pools.



A neighboring fuel item has significantly larger impacts on FDET neutron and gamma signals in air (AR) than in water, especially when the distance is smaller.

Difficult to avoid neighbor interference because measurement space is likely limited in hot cell.



Summary and Conclusions

- Significant challenges found in safeguards measurements of **fresh** AR fuels
  - Incompatibilities between the dimensions of fuel elements and the detectors.
  - Doubles rates of both UNCL-II and FNCL for AR fuel elements have smaller magnitudes and lower sensitivity to enrichment than those of a PWR assembly.
  - Both UNCL-II and FNCL were found to have relatively poorer performance in detecting partial defects in AR fuel elements than in a PWR assembly.

- Significant challenges found in safeguards measurements of **spent** AR fuels
  - The TRISO-based spent AR fuel items most likely stored in air, which may make CVD measurements either impossible or less effective.
  - For in-air FDET measurements, the neighboring fuel has significantly greater impacts on the FDET measurement signals.
  - All spent AR fuel items were found to have significantly lower FDET neutron count rates.

- **Timely technology development needed for safeguards measurements of fresh and spent AR fuels.**

Acknowledgements

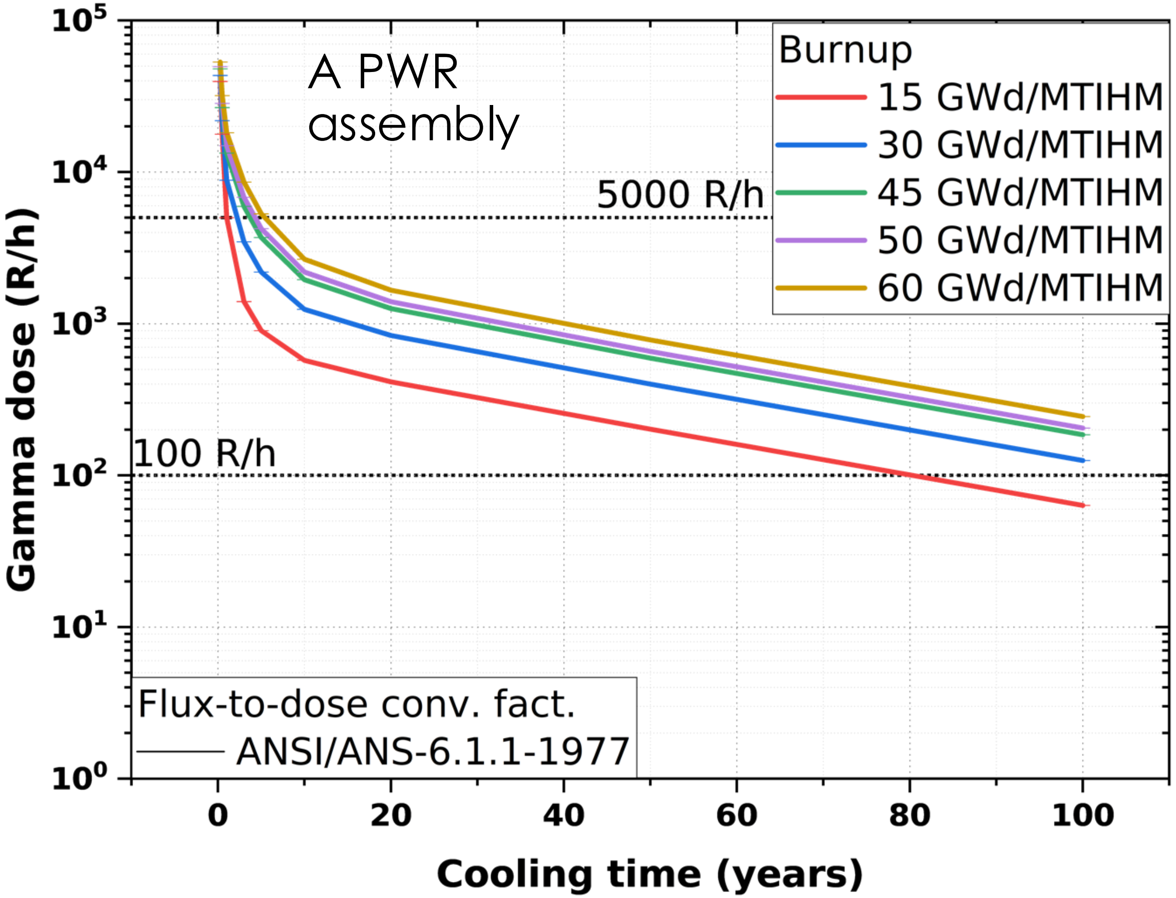
- This work is funded by the National Nuclear Security Administration of the U.S. Department of Energy, Office of International Nuclear Safeguards, Advanced Reactor International Safeguards Engagement (ARISE) program.

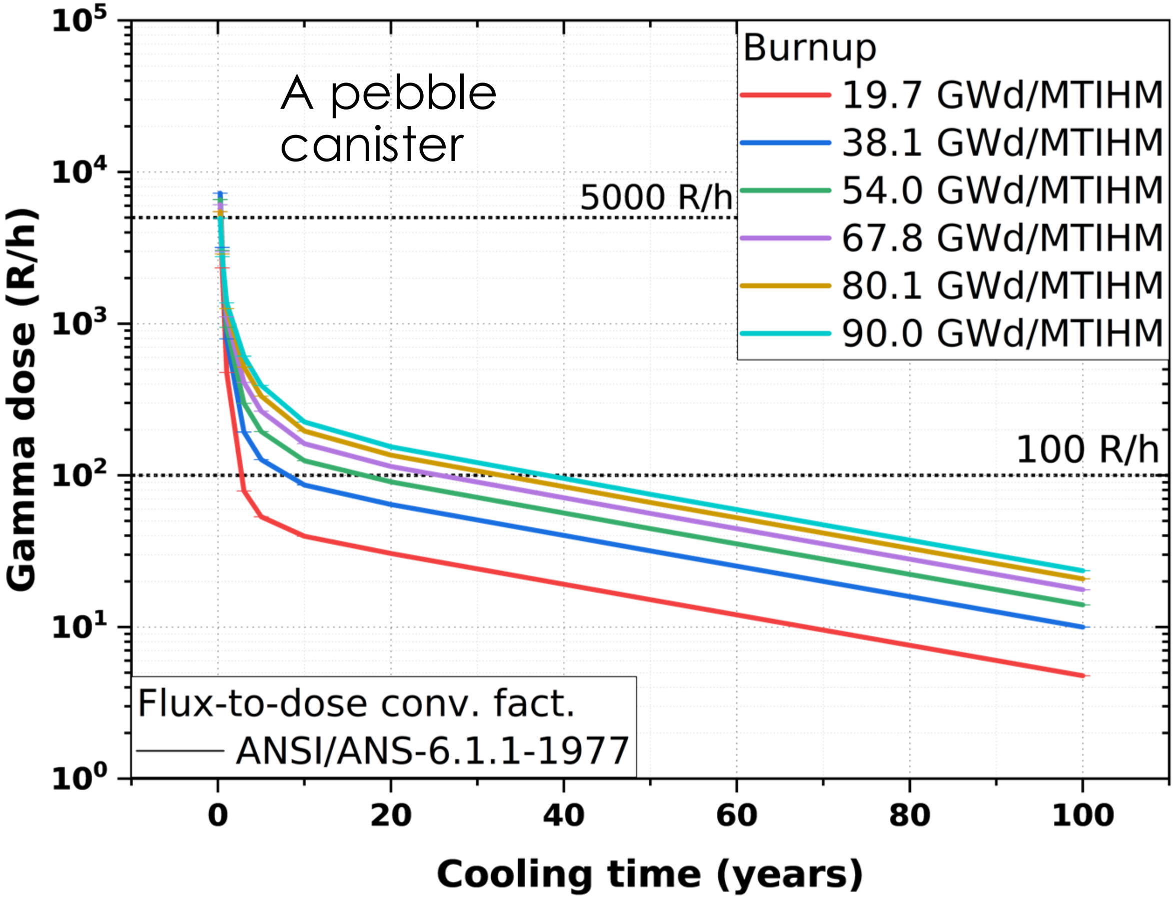
Backup slides

Comparison of main characteristics among AR fuel elements (1)

	Metallic Fuel Bundle	Graphite Fuel Block 1	Graphite Fuel Block 2	PWR 17x17 Assembly
Fuel form	U-10Zr alloy	TRISO particles (with UCO kernel) embedded in **graphite matrix** and then in graphite holes.	TRISO particles (with UCO kernel) embedded in **SiC matrix** and then in graphite holes.	UO_2 ceramic
Fuel density (g/cc)	15.8	10.4	10.4	10.4
Overall width (cm)	11.2 (flat-to-flat)	36 (flat-to-flat)	36 (flat-to-flat)	21.4
No. of rods	217	216	54	264
Pellet radius (cm)	0.23	0.615	0.92	0.41
Rod pitch (cm)	0.74	1.88	3.84	1.26
U loading (g/cm)	510	114.3 (40% packing fraction)	78.4 (60% packing fraction)	1295
Nominal enrichment (wt% ^{235}U)	19.75	19.75	19.75	3 to 4.95
^{235}U (g/cm)	101	23	15	39 to 64

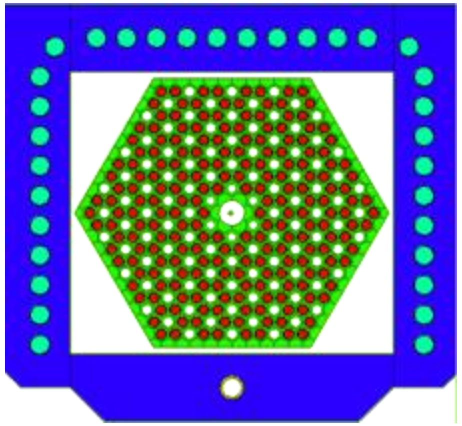
Spent AR fuel items are less self-protecting



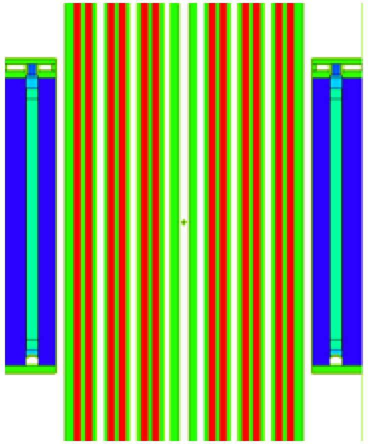


The gamma dose rate at 1 m away from the pebble transportation canister surface is > 10x lower than that of a PWR assembly, mainly due to the much lower heavy metal loading in the canister.

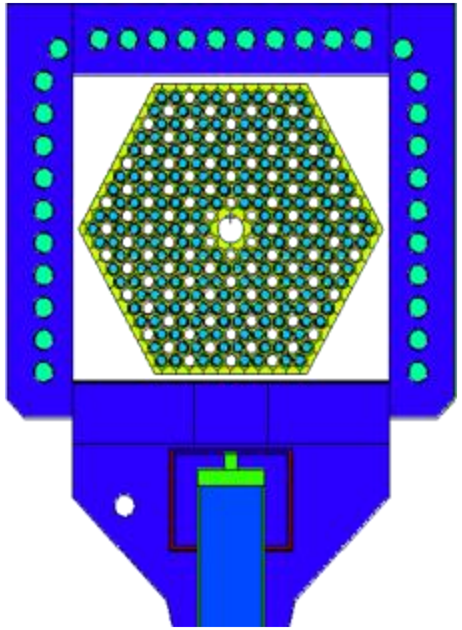
Graphite fuel block (type 1) with UNCL-II and FNCL



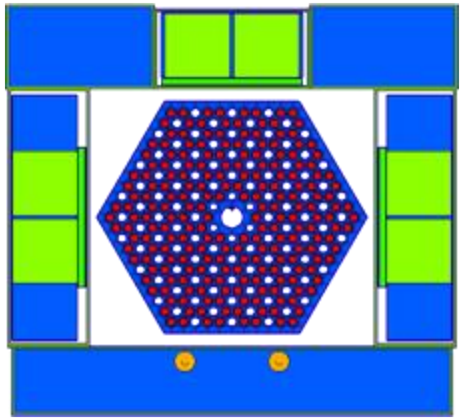
UNCL-II (expanded) with AmLi source



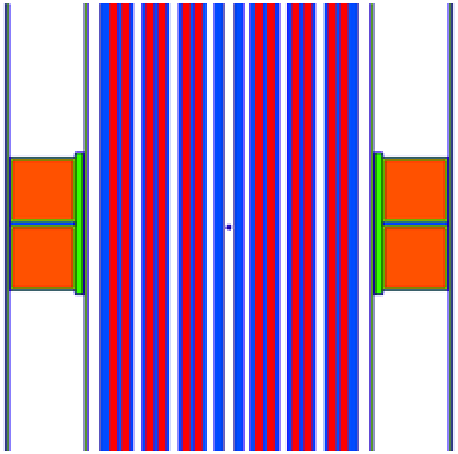
UNCL-II (side view)



UNCL-II with D-D neutron generator



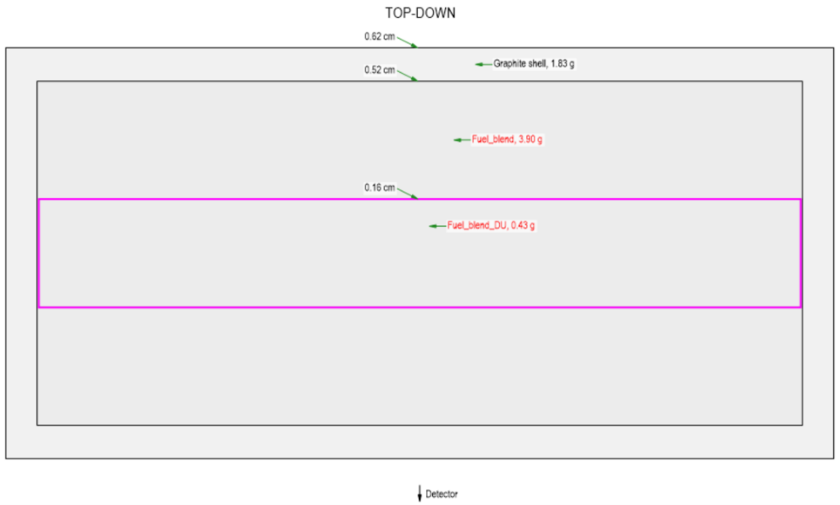
FNCL with AmLi source

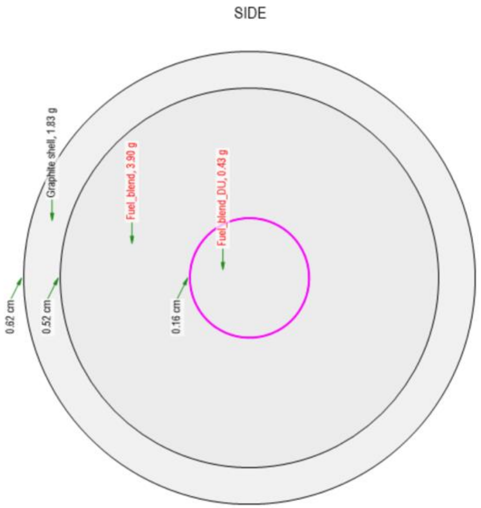


FNCL (side view)

Simulation of gamma detector measurements of AR fuel elements

	Metallic Fuel Pin	TRISO Compact 1	TRISO Compact 2	Pebble 1	Pebble 2	PWR Fuel Pin
Fuel form	U-10Zr alloy	TRISO particles in graphite matrix with graphite shell.	TRISO particles in SiC matrix with SiC shell.	TRISO particles in graphite matrix with graphite shell.	Similar as type 1 but has an inner graphite ball.	UO_2 ceramic
Fuel matrix density (g/cc)	15.8	2.23 (40%PF)	3.05 (60%PF)	1.86	2.2	10.4
Fuel radius (cm)	0.23	0.52	0.92	2.5	[1.52, 1.9]	0.41
"Cladding" radius (cm)	0.315	0.617	1.15	3	2	0.475
Fuel length	200	2.5	3	3	2	366





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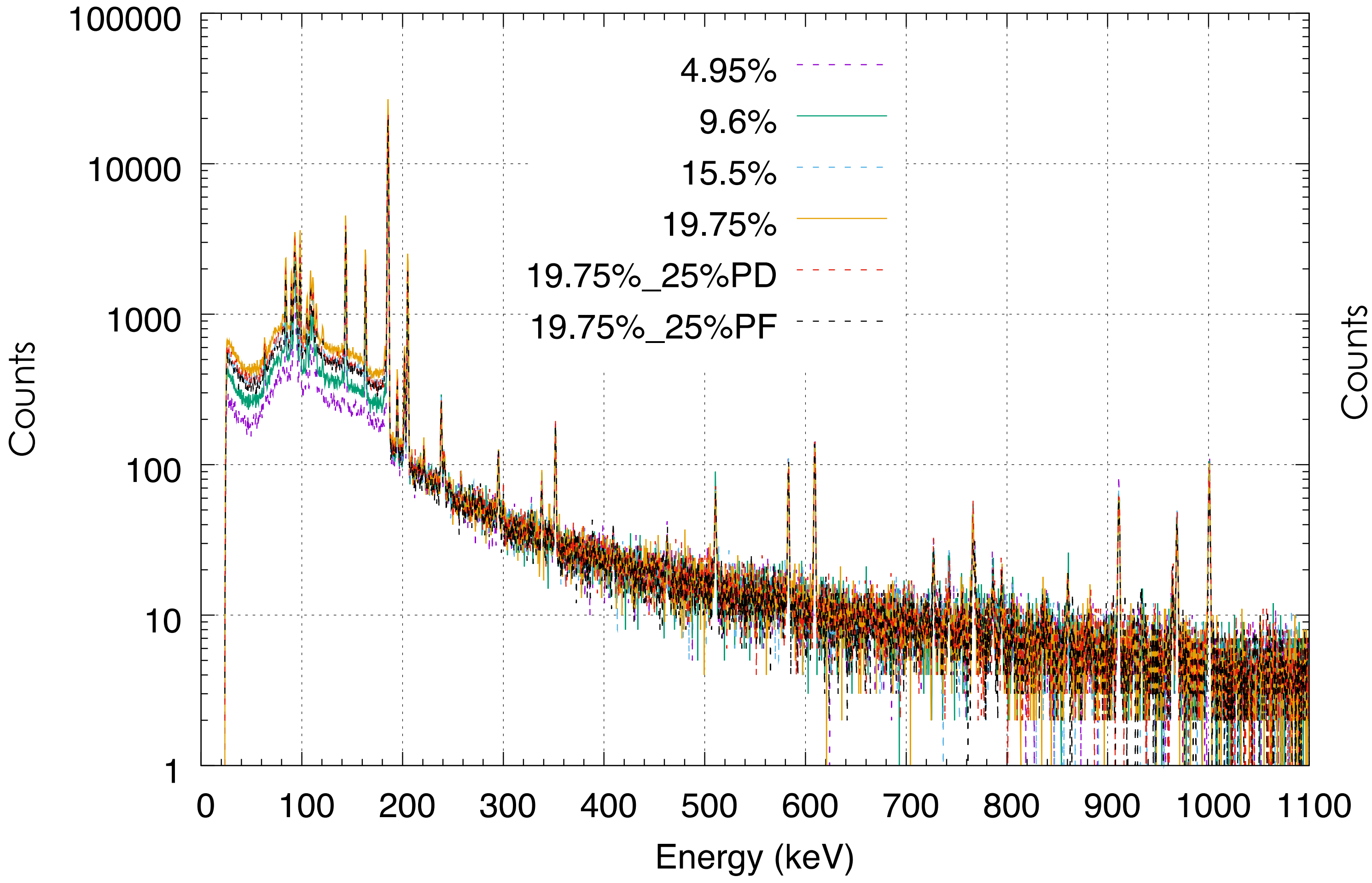
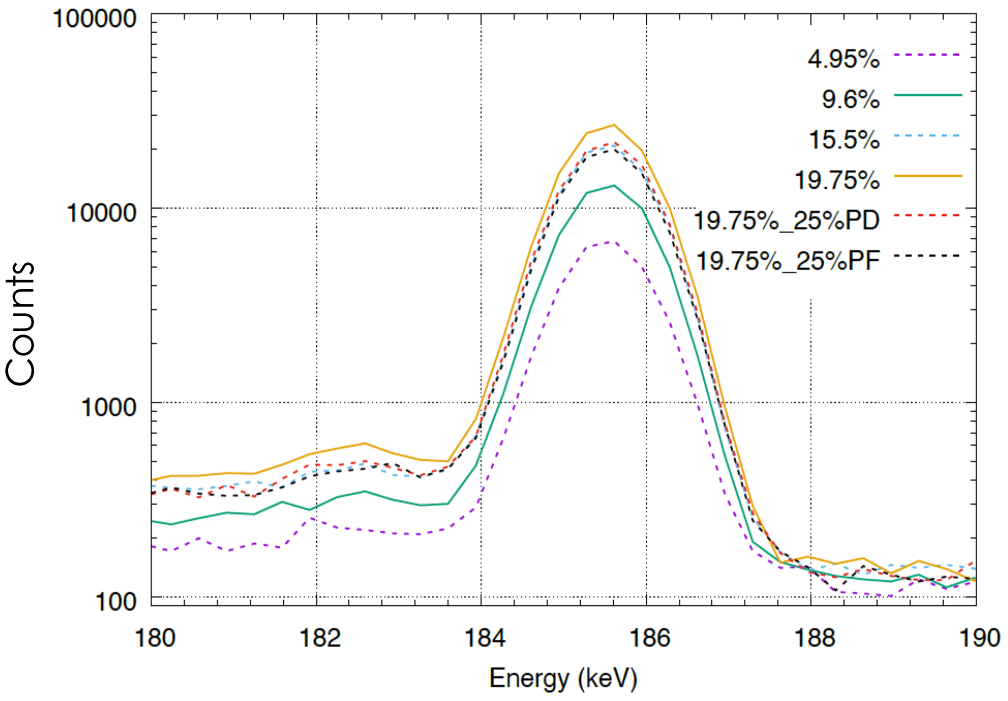
Simulated gamma spectra (TRISO compact 1)





Good gamma signal separations among different fuel enrichments.

Lower signals are seen in the PD cases than the base case, but PD case can be masked by lower enrichment cases.

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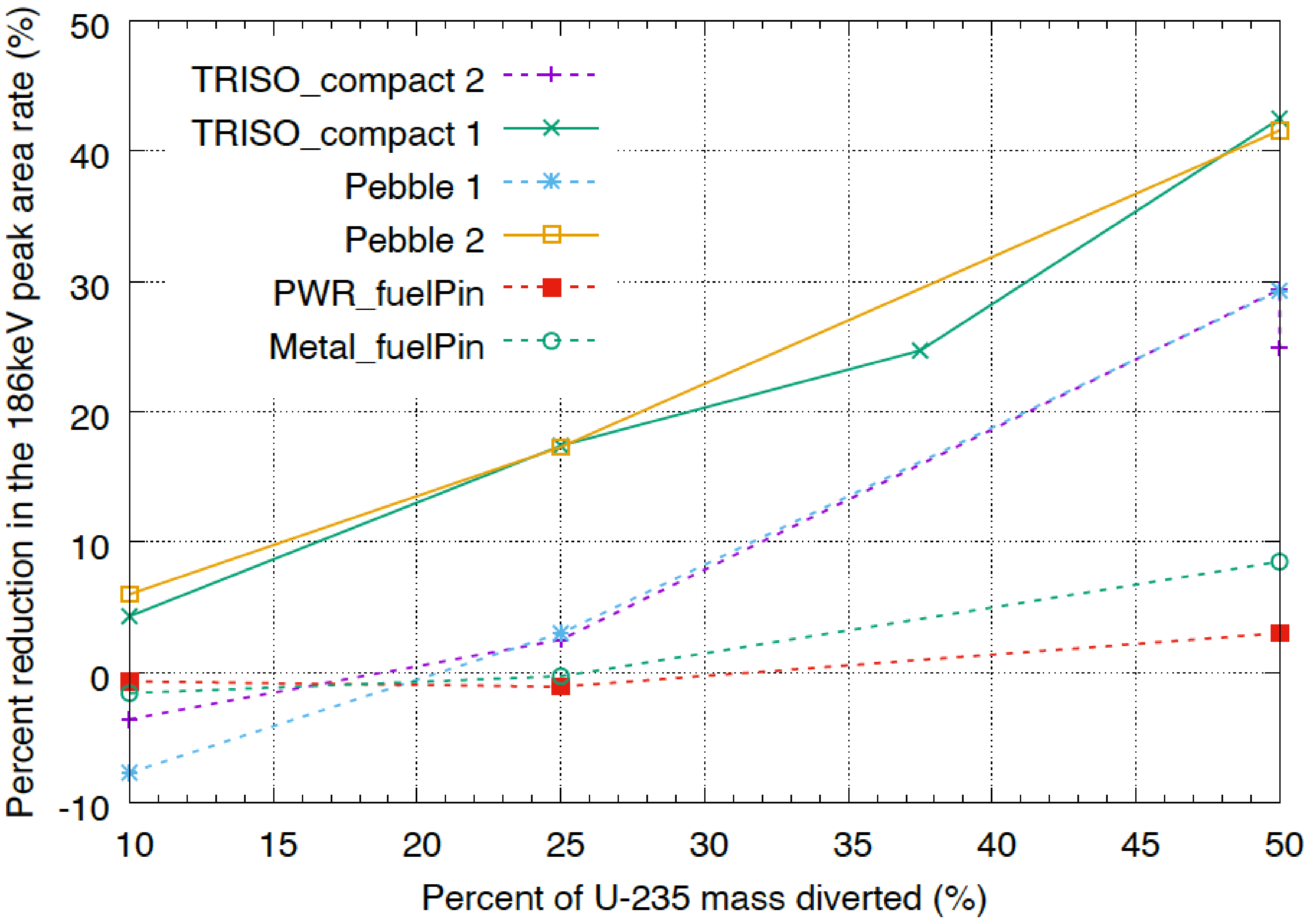
Sensitivity of gamma signals to partial defects

- Gamma signal of Pebble 1 and Compact 1 are sensitive to fuel diversion.
- Gamma signal of the other 4 fuel elements are not sensitive to fuel diversion.



Fork gamma results

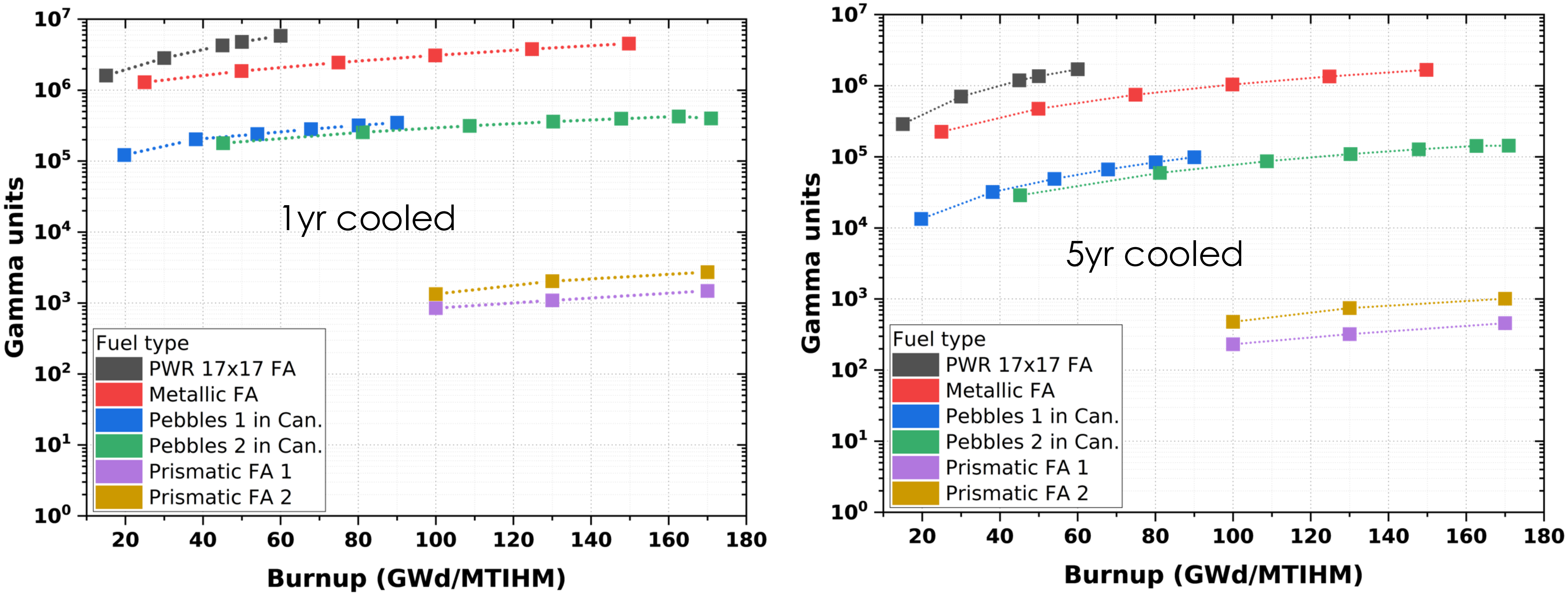


Figure 37. Summary of the gamma units of an FDET.

FDET Partial Defect Test Results

FDET's performance in detecting diversion is worse for a pebble canister than for a PWR assembly.

The unshielded neutron detector in FDET is much less sensitive to fuel diversion in the pebble canister than in a PWR assembly.

The impacts of neighboring assemblies or canisters were accounted for in these tests.

Table 1. FDET diversion results for a PWR assembly based on neutron detector signals.

Number of diverted pins	Diverted pins [%]	Unshielded neutron count rate reduction [%]	Total sigma [%]	Ability to detect diversion within 1 min measurement time		Ability to detect diversion within 10 min measurement time	
				2σ	3σ	2σ	3σ
12	5	-5.2	1.2	YES	YES	YES	YES
28	11	-12.8	1.2	YES	YES	YES	YES
40	15	-18.7	1.2	YES	YES	YES	YES

Number of diverted pins	Diverted pins [%]	Shielded neutron count rate reduction [%]	Total sigma [%]	Ability to detect diversion within 1 min measurement time		Ability to detect diversion within 10 min measurement time	
				2σ	3σ	2σ	3σ
12	5	-5.5	6.6	NO	NO	NO	NO
28	11	-12.8	6.6	NO	NO	NO	NO
40	15	-18.6	6.6	YES	YES	YES	YES

Table 2. FDET diversion results for a pebble canister based on neutron detector signals.

Number of diverted pebbles	Diverted pebbles [%]	Unshielded neutron count rate reduction [%]	*Total sigma [%]	Ability to detect diversion within 1 min measurement time		Ability to detect diversion within 10 min measurement time	
				2σ	3σ	2σ	3σ
100	5	−4.6	8.6 / 2.9	NO	NO	NO	NO
200	10	−8.3	8.8 / 2.9	NO	NO	YES	NO
500	25	−25.4	9.7 / 3.2	YES	NO	YES	YES

Number of diverted pebbles	Diverted pebbles [%]	Shielded neutron count rate reduction [%]	*Total sigma [%]	Ability to detect diversion within 1 min measurement time		Ability to detect diversion within 10 min measurement time	
				2σ	3σ	2σ	3σ
100	5	−5.0	3.6 / 1.5	NO	NO	YES	YES
200	10	−9.3	3.7 / 1.5	YES	NO	YES	YES
500	25	−26.2	4.1 / 1.6	YES	YES	YES	YES

*Measurement time 1 min / 10 mins