Use of ORIGAMI/ORIGEN for International Spent Fuel Safeguards

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Outline

- Background on international spent fuel safeguards
- High-fidelity burnup modeling needed for spent fuel analysis
  - Complex nuclide composition and radiation source terms in spent fuel
- A new interface for 3D fuel assembly burnup calculations
  - ORIGAMI
- Verification of ORIGAMI calculation results
  - Decay heat and total Pu
- The ORIGEN Module for Fork detector
- Summary

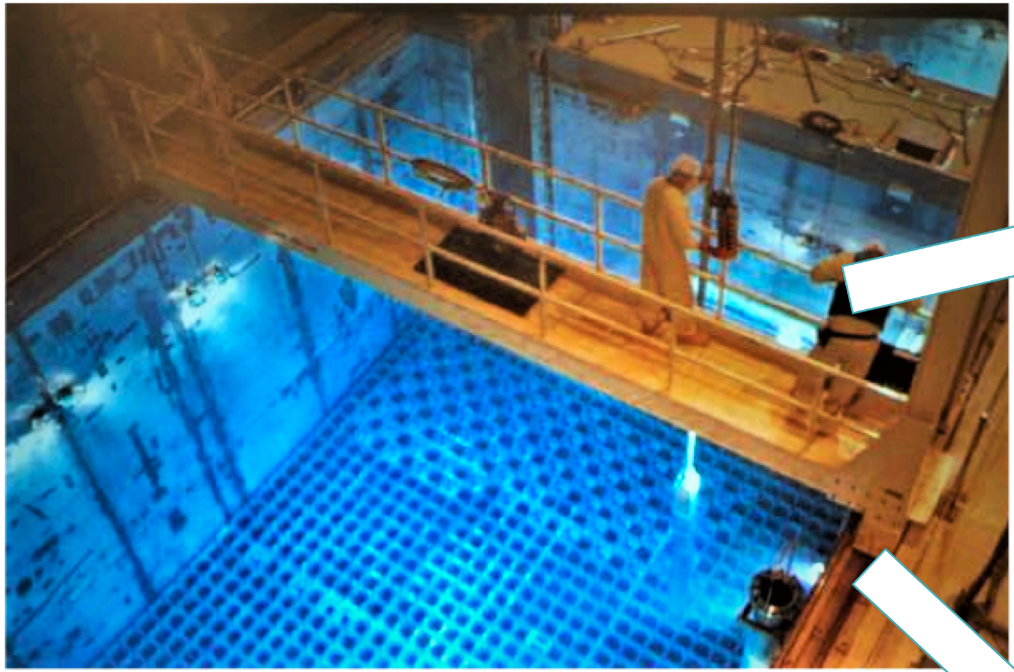
Why Do We Need to Safeguard Spent Fuel?

- World inventory of spent nuclear fuel is > 700,000 assemblies, or 290,000 MT heavy metal
  - A typical PWR assembly contains 450 kg Heavy Metal
  - Heavy metal at discharge is ~1% Pu (~5 kg/assembly)
  - World inventory is ~2,300 MT Pu
  - 1 Significant Quantity (SQ) of Pu is 8 kg
  - Spent fuel inventory represents 287,000 SQ of Pu

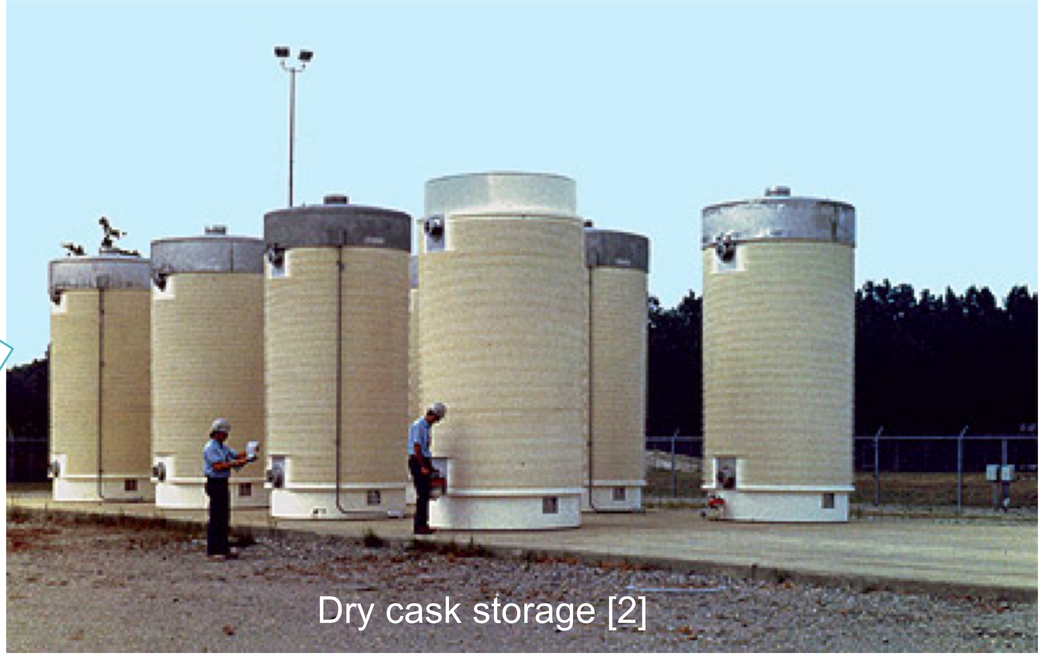
IAEA Safeguards

- IAEA requires measurements to verify declared material quantities – in spent nuclear fuel, this includes uranium and plutonium.
- IAEA requires partial defect measurements to verify the declared information and show that the spent fuel assembly is complete.
- Safeguards rely on Containment and Surveillance (e.g., seals and cameras) and Item Counting
- In general, the verification measurements are performed prior to assemblies becoming difficult-to-access by item counting, item identification and nondestructive assay (NDA).
- Presently, IAEA uses the Fork detector and Cerenkov Viewing Device – however, neither technique is capable of highly reliable partial defect measurements.

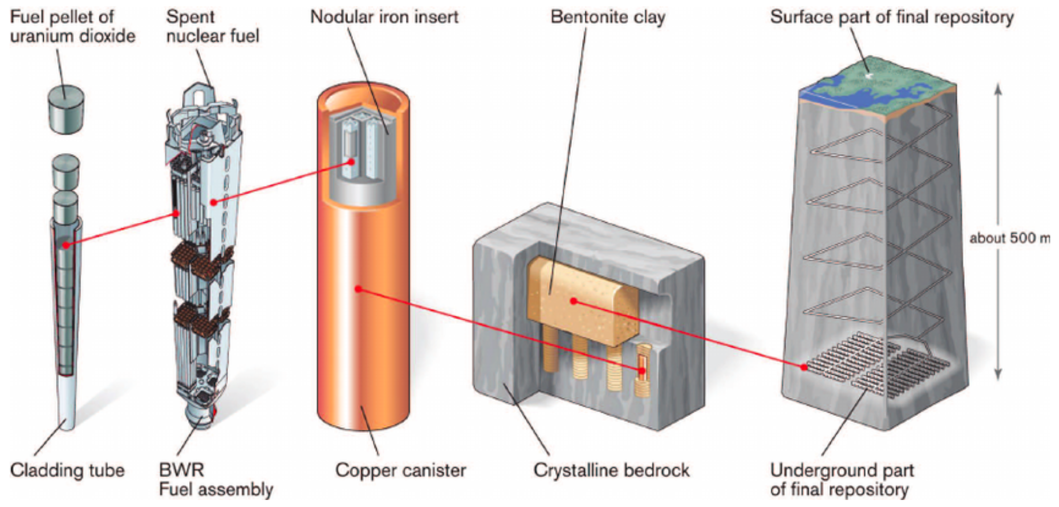
Spent Fuel Safeguards



Spent fuel storage pool [1]



Dry cask storage [2]



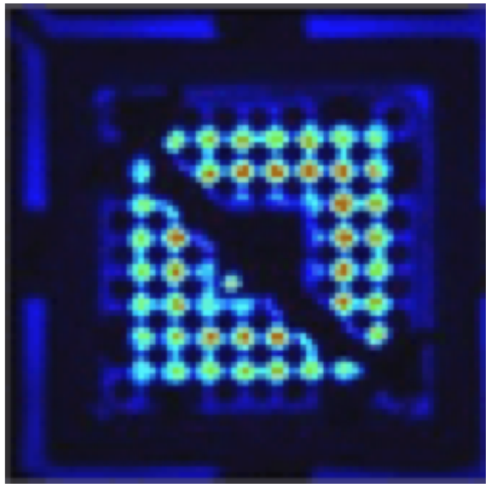
Encapsulation and final disposal [3]

Partial defect tests are required before spent fuel assemblies being transferred to “difficult-to-access” storage.

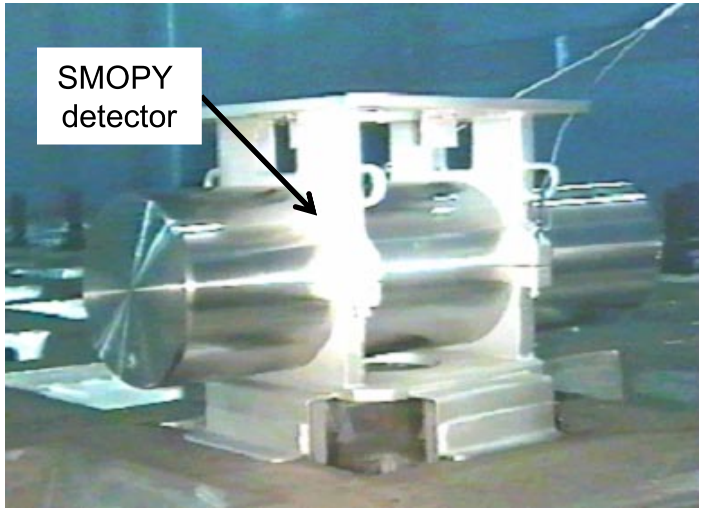
[1]: https://www.linkedin.com/pulse/performance-improvement-case-study-1-outage-duration-todd-mccann
[2]: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dry-cask-storage.html
[3]https://www.researchgate.net/publication/260877239_The_Use_of_Clay_as_an_Engineered_Barrier_in_Radioactive-Waste_Management_-_A_Review/figures?lo=1

What is the State-of-the-Practice in Spent Fuel NDA?

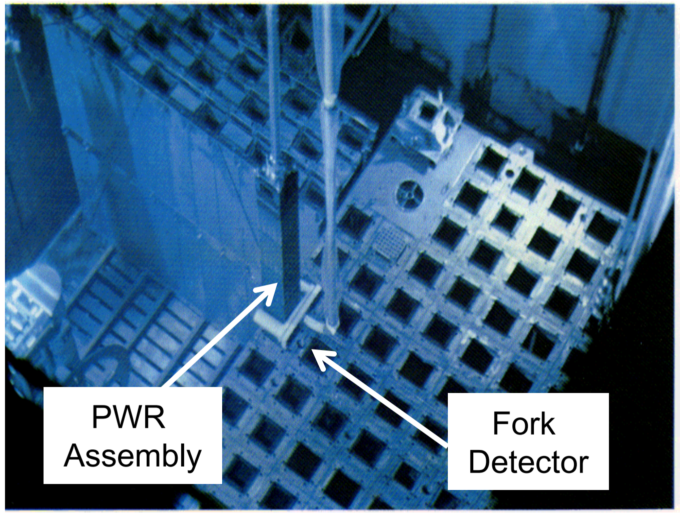
- Cerenkov Viewing Device (ICVD, DCVD)
  - Detects Cerenkov glow from water around assembly
- Spent Fuel Attribute Tester (SFAT)
  - ^{137}Cs is present
- Fork and SMOPY
  - Fission chambers → total neutron (driven by ^{244}Cm)
  - Ion chambers and CdTe → fission fragment gammas
  - Burnup code with SMOPY and Fork



Cerenkov Image

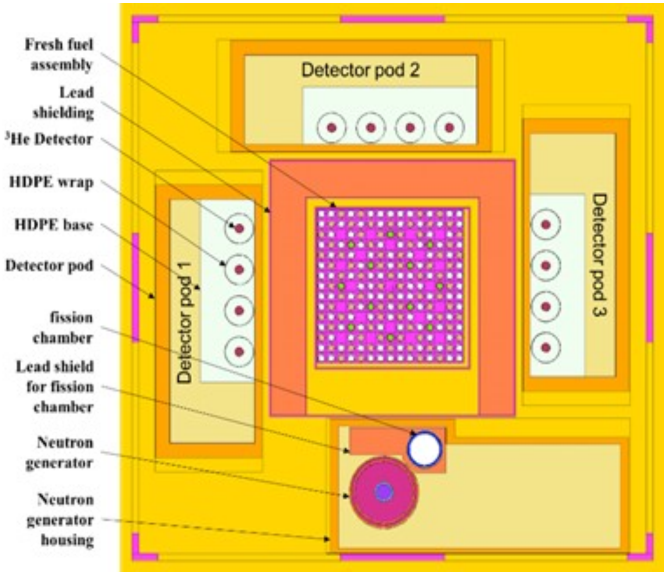


Canberra LLC

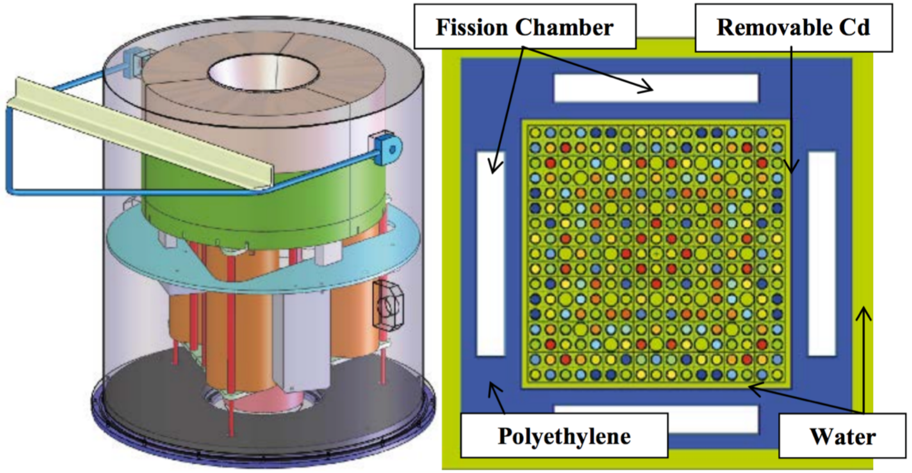


Ref: S.J. Tobin, et. al., Prototype Development and Field Trials under the Next Generation Safeguards Initiative Spent Fuel Non-Destructive Assay Project, the ESARDA annual meeting, 2013.

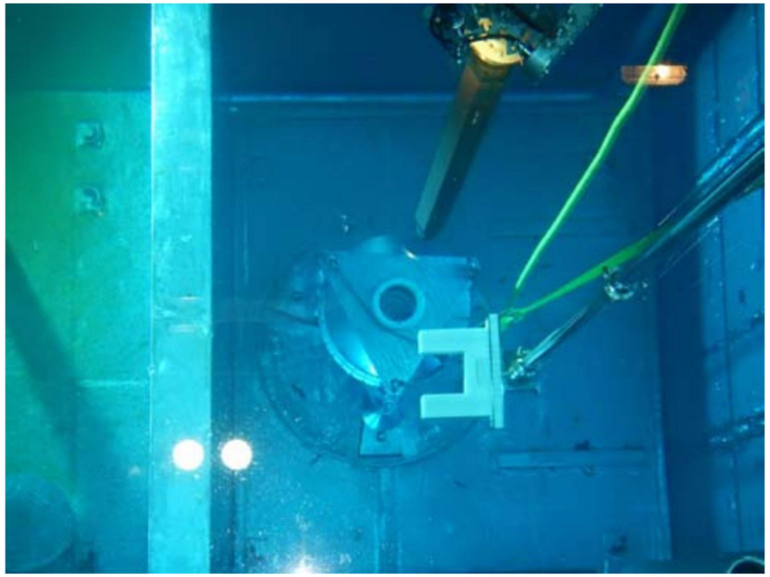
Advanced detectors for spent fuel safeguards



DDA [1]



PNAR [2]



PGET together with Fork detector in Loviisa NPP, Finland, 2017 [3]

[1] H. Trellue, et al., Spent fuel nondestructive assay project experiences and successes, INMM, 2018

[2] S.J. Tobin, P. Jansson, Nondestructive assay options for spent fuel encapsulation, LA-UR-13-22050, 2014

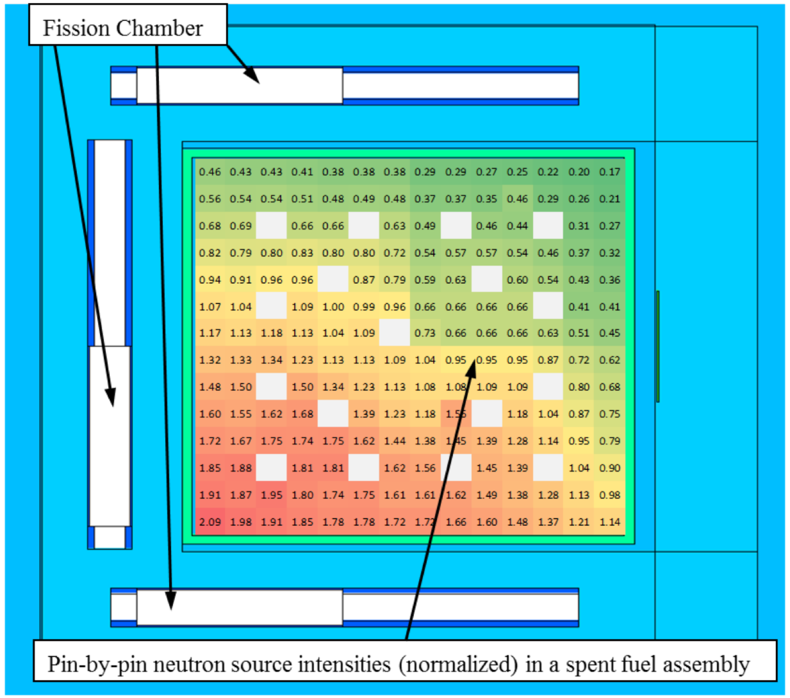
[3] Implementing nuclear non-proliferation in Finland, Annual report of 2017, STUK-B 222, 2018

Why is high-fidelity spent fuel modeling and simulation needed?

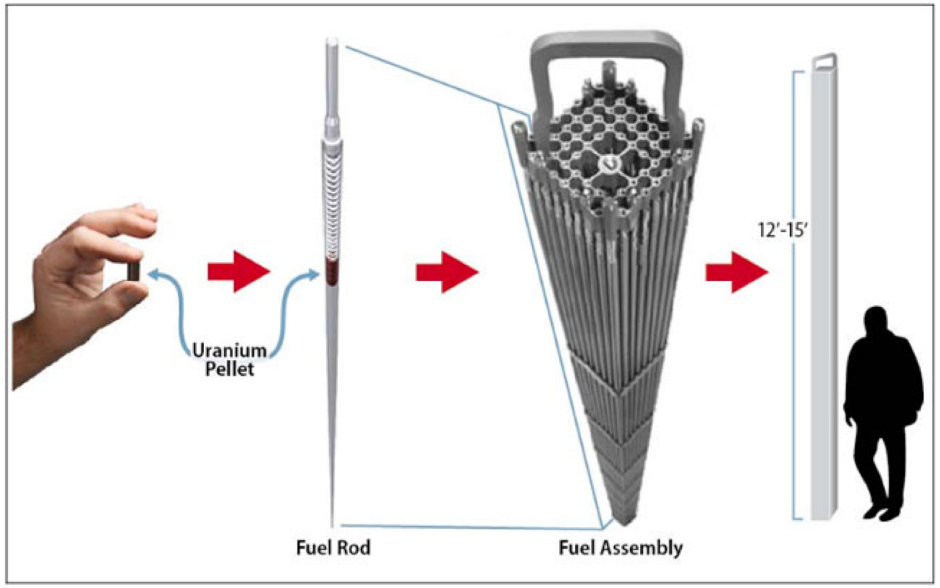
- Detailed nuclide compositions and spatial distribution are needed for 3D NDA modeling and simulation, in order to quantify instrument performance.
- Calculations provide a) correlations between measured data and the quantities of interest not directly measured and b) verification of measurements since the actual assembly inventories cannot be measured.

28.2	27.8	27.5	27.3	27.1	27.0	26.9	25.4	25.3	25.0	24.6	24.0	23.2	22.3
29.6	29.5	29.7	29.1	28.8	29.2	28.7	27.1	27.4	26.8	28.3	26.0	24.8	23.6
31.0	31.4		31.3	31.1		30.7	29.0		28.8	28.3		26.5	24.8
32.1	32.2	32.8	32.5	32.8	32.5	31.5	29.6	30.3	30.2	29.3	28.7	27.2	25.8
33.2	33.4	34.0	34.2		33.4	32.4	30.1	30.9		30.7	29.7	28.1	26.7
34.3	34.9		35.0	34.5	34.0	34.0	30.9	30.9	31.3	31.2		28.2	27.4
35.1	35.2	35.7	34.9	34.4	34.9		31.8	31.0	30.9	30.9	30.7	29.3	27.9
36.2	36.3	36.8	35.9	35.2	34.9	35.0	34.4	33.8	33.6	33.5	33.3	31.7	30.3
37.0	37.7		37.8	37.0	35.8	35.0	34.7	34.8	35.2	35.1		32.8	30.9
37.7	38.0	38.7	38.8		37.3	35.9	35.5	38.3		36.0	34.8	32.9	31.4
38.5	38.7	39.4	39.0	39.2	38.6	37.2	36.8	37.6	37.3	36.2	35.4	33.6	32.1
39.2	39.9		39.8	39.5		38.6	38.2		37.7	37.0		34.8	32.9
39.7	39.8	40.2	39.4	39.1	39.3	38.4	38.2	38.5	37.5	36.9	36.6	35.0	33.6
40.3	40.0	39.7	39.4	39.1	38.8	38.5	38.6	38.3	37.8	37.2	36.5	35.5	34.6

Pin-by-pin burnup map of a 14x14 spent fuel assembly



Neutron source distribution in the MCNP model for the CIPN detector

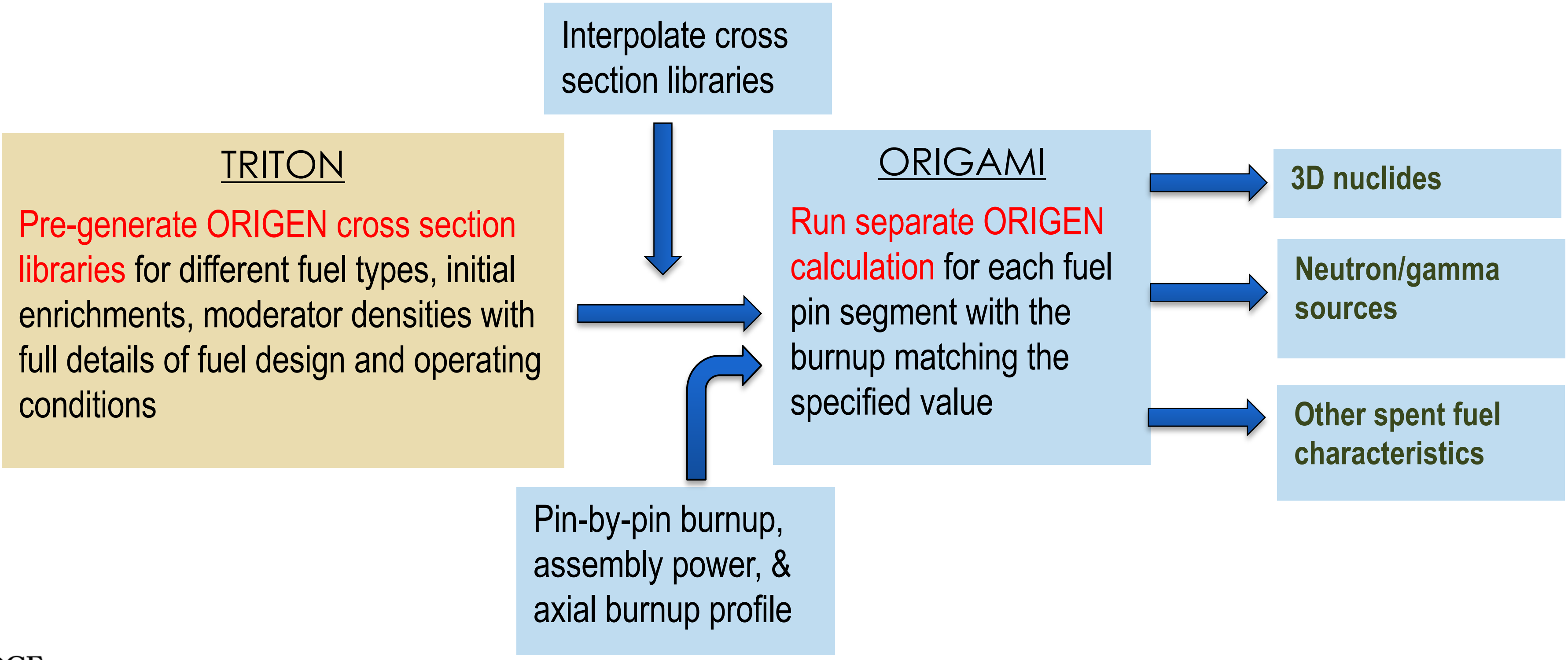


A fuel assembly [2]

[1] J. Hu, I. C. Gauld, J. Banfield and S. Skutnik, "Developing Spent Fuel Assembly Standards for Advanced NDA Instrument Calibration – NGSI Spent Fuel Project," ORNL/TM-2013/576, Oak Ridge National Laboratory, 2014.
[2]: http://modernsurvivalblog.com/nuclear/spent-nuclear-fuel-pools-are-full/

ORIGAMI: an automated ORIGEN interface for 3D fuel assembly burnup calculation

- A customized user interface of ORIGEN for 3-D assembly burnup calculations.
- Pre-generated cross-section libraries are interpolated to produce accuracies similar to full SCALE/TRITON depletion simulations.
- Can generate nuclide compositions and decay heat for each axial node of each fuel pin based on specified burnup values.
- Accepts different compositions, enrichments, burnup, cross-section libraries for each fuel rod.



[1] J. Hu, et al., "Spent Fuel Modeling and Simulation using ORIGAMI for Advanced NDA Instrument Testing," in ANS M&C 2015, Nashville, TN, 2015.

An example

```
=origami
 title= 'multi-pin; multi-library'
 options{ mtu=0.45 decayheat=yes mcnp=yes relnorm=no}
 nonfuel= [ cr=3.5 fe=6.3 ]

 fuelcomp{
  uox(fuel_2pct){ enrich=2 dens=10.42 }
  uox(fuel_4pct){ enrich=4 dens=10.45 }
  mix(1){ comps[fuel_2pct=100] }
  mix(2){ comps[fuel_4pct=97.0 Gd2O3=3.0 ]} }
 compmap=[ 1  2  1
           1  0  1
           2  1  1 ]

 libs=[ w17x17  w17x17_Gd ]
 libmap=[ 1  2  1
          1  0  1
          2  1  1 ]

 pxy=[ 0.9  1.1  0.9
       1.2  0    1.2
       0.8  1.1  0.9 ]
 pz=[ 0.6 1.0 0.5 ]
 meshz=[  0 120  240  360 ]
 modz=[ 0.75 0.73 0.71 ]

 hist[
   cycle{ power=30  burn=500  nlib=4  down=45 }
   cycle{ power=50  burn=300  nlib=4  down=45 }
   cycle{ power=25  burn=400  nlib=4  down=1825 }
 ]
 ggrp=[ 10e6 2e6 1e6 0.01]
 ngrp=[ 20e6 1e6 1e5 0.025 ]
end
```

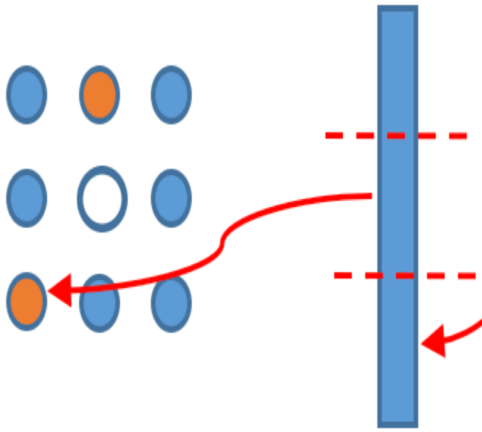
Lib1

Lib2*

Radial power/burnup profile

Axial power/burnup profile

Assembly avg. burnup:
40 GWd/MTU



Burnup on this rod segment: 40*0.8*0.6

Lib2*, not included in the SCALE package; need to be generated by the user for the Gd rods

ORIGAMI Output Files

*_AxialDecayHeat

```
2.78253E+02
5.89804E+02
2.17135E+02
```

*_ MCNP_neutron.inp

```
C  Neutron source for axial zone 03, pin 001
C  Total intensity (n/sec):  5.2826E+05
SI103          H   2.5000E-08  1.0000E-01  1.0000E+00  2.0000E+01
SP103          D   1.1249E-02  2.5571E-01  7.3304E-01
```

*_ MCNP_matls.inp

```
C  Axial zone: 03, Pin: 008
C  Zone mass (grams):  2.144858E+04
m803    1001    -8.598225E-09
             1002    -6.035635E-10
             1003    -2.526046E-08
             2003    -8.794443E-09
             2004    -3.262135E-06
             3006    -2.660487E-17
             3007    -7.905803E-18
             4009    -5.885097E-13
             5010    -6.966128E-17
             5011    -4.479028E-15
```

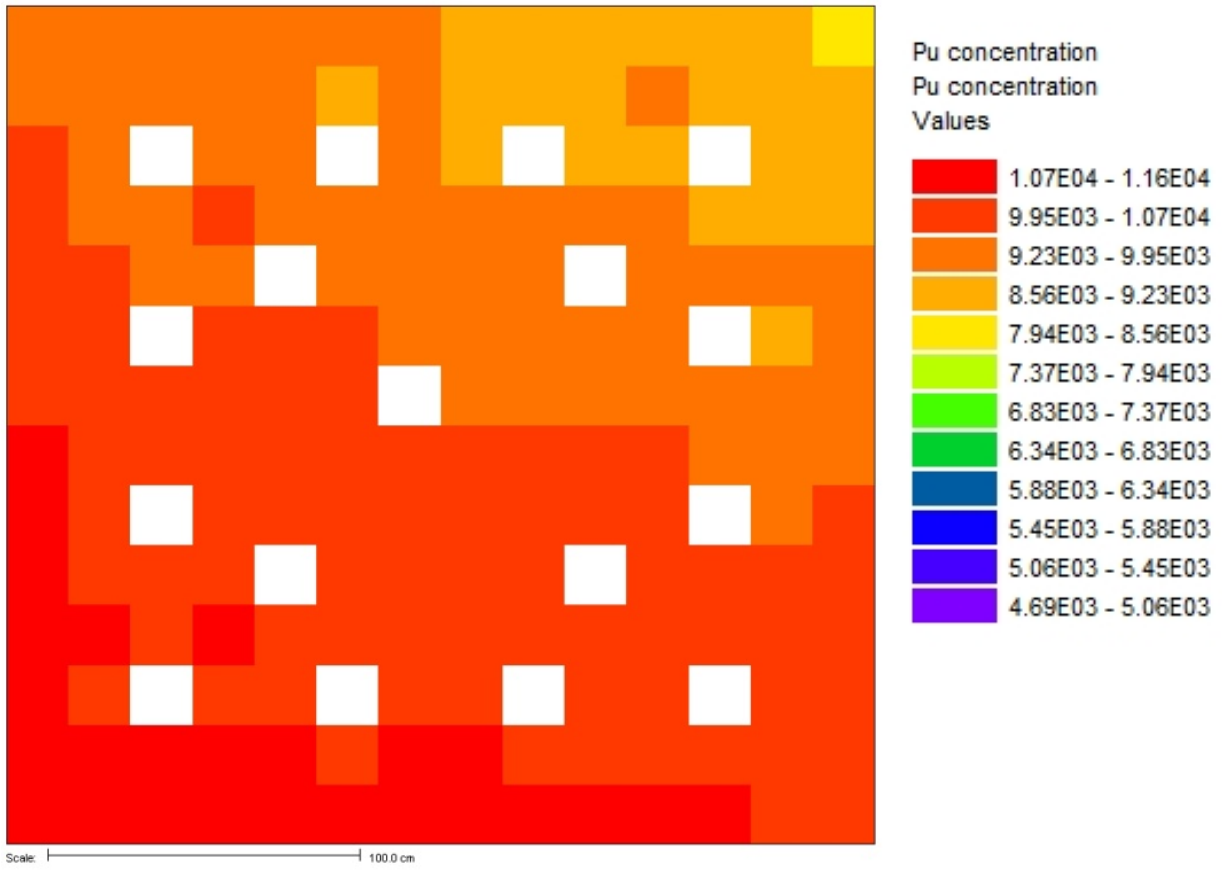
Much more info in the main output file “*.out”

```
===========================================================================================
=   Nuclide concentrations in grams, actinides for case 'axial zone: 001, pin: 03-01' (#6)
=   multi-pin; multi-library
-------------------------------------------------------------------------------------------
  (relative cutoff; integral of concentrations over time >   1.00E-04 % of integral of all
.
               1290.000d   1290.093d   1290.278d   1290.834d   1292.503d   1297.510d   131
  u-234        1.8117E+00  1.8117E+00  1.8117E+00  1.8118E+00  1.8119E+00  1.8122E+00  1.81
  u-235        6.6208E+01  6.6208E+01  6.6208E+01  6.6208E+01  6.6208E+01  6.6209E+01  6.62
  u-236        5.0132E+01  5.0132E+01  5.0132E+01  5.0132E+01  5.0133E+01  5.0133E+01  5.01
  u-238        1.7853E+04  1.7853E+04  1.7853E+04  1.7853E+04  1.7853E+04  1.7853E+04  1.78
  np-237       6.2240E+00  6.2248E+00  6.2263E+00  6.2307E+00  6.2425E+00  6.2679E+00  6.29
  pu-238       2.7486E+00  2.7491E+00  2.7500E+00  2.7527E+00  2.7589E+00  2.7694E+00  2.78
  pu-239       9.3958E+01  9.3987E+01  9.4044E+01  9.4197E+01  9.4530E+01  9.4935E+01  9.50
  pu-240       4.6659E+01  4.6659E+01  4.6659E+01  4.6659E+01  4.6659E+01  4.6659E+01  4.66
  pu-241       2.4857E+01  2.4856E+01  2.4856E+01  2.4854E+01  2.4848E+01  2.4832E+01  2.47
  pu-242       1.2514E+01  1.2514E+01  1.2514E+01  1.2514E+01  1.2514E+01  1.2515E+01  1.25
  am-241       9.5200E-01  9.5231E-01  9.5292E-01  9.5475E-01  9.6025E-01  9.7675E-01  1.02
  am-243       2.3990E+00  2.3995E+00  2.4002E+00  2.4008E+00  2.4010E+00  2.4010E+00  2.40
  cm-242       2.9934E-01  2.9937E-01  2.9941E-01  2.9925E-01  2.9771E-01  2.9156E-01  2.73
  cm-244       9.0308E-01  9.0315E-01  9.0316E-01  9.0314E-01  9.0301E-01  9.0254E-01  9.01
  cm-245       4.8234E-02  4.8234E-02  4.8234E-02  4.8234E-02  4.8234E-02  4.8234E-02  4.82
------------
  totals       1.8163E+04  1.8163E+04  1.8163E+04  1.8163E+04  1.8163E+04  1.8163E+04  1.81
```

ORIGAMI results: radial Pu distribution

28.2	27.8	27.5	27.3	27.1	27.0	26.9	25.4	25.3	25.0	24.6	24.0	23.2	22.3
29.6	29.5	29.7	29.1	28.8	29.2	28.7	27.1	27.4	26.8	28.3	26.0	24.8	23.6
31.0	31.4		31.3	31.1		30.7	29.0		28.8	28.3		26.5	24.8
32.1	32.2	32.8	32.5	32.8	32.5	31.5	29.6	30.3	30.2	29.3	28.7	27.2	25.8
33.2	33.4	34.0	34.2		33.4	32.4	30.1	30.9		30.7	29.7	28.1	26.7
34.3	34.9		35.0	34.5	34.0	34.0	30.9	30.9	31.3	31.2		28.2	27.4
35.1	35.2	35.7	34.9	34.4	34.9		31.8	31.0	30.9	30.9	30.7	29.3	27.9
36.2	36.3	36.8	35.9	35.2	34.9	35.0	34.4	33.8	33.6	33.5	33.3	31.7	30.3
37.0	37.7		37.8	37.0	35.8	35.0	34.7	34.8	35.2	35.1		32.8	30.9
37.7	38.0	38.7	38.8		37.3	35.9	35.5	38.3		36.0	34.8	32.9	31.4
38.5	38.7	39.4	39.0	39.2	38.6	37.2	36.8	37.6	37.3	36.2	35.4	33.6	32.1
39.2	39.9		39.8	39.5		38.6	38.2		37.7	37.0		34.8	32.9
39.7	39.8	40.2	39.4	39.1	39.3	38.4	38.2	38.5	37.5	36.9	36.6	35.0	33.6
40.3	40.0	39.7	39.4	39.1	38.8	38.5	38.6	38.3	37.8	37.2	36.5	35.5	34.6

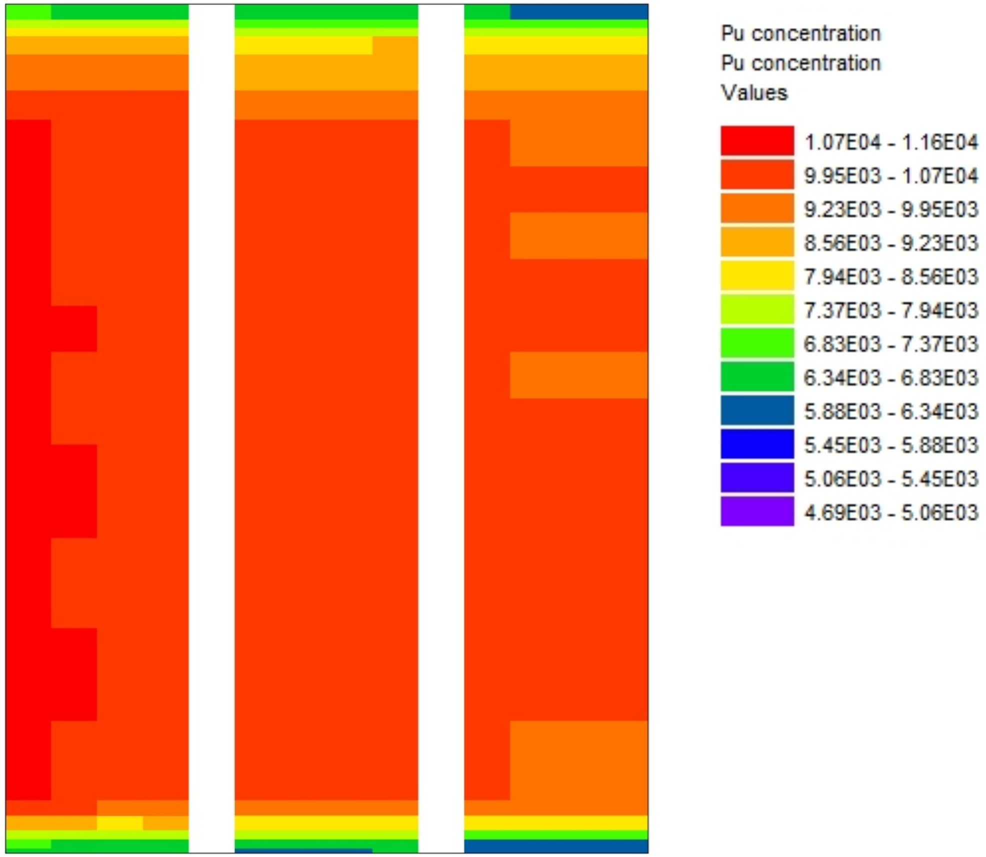
Operator-provided pin-by-pin burnup (GWd/tU) map [1]



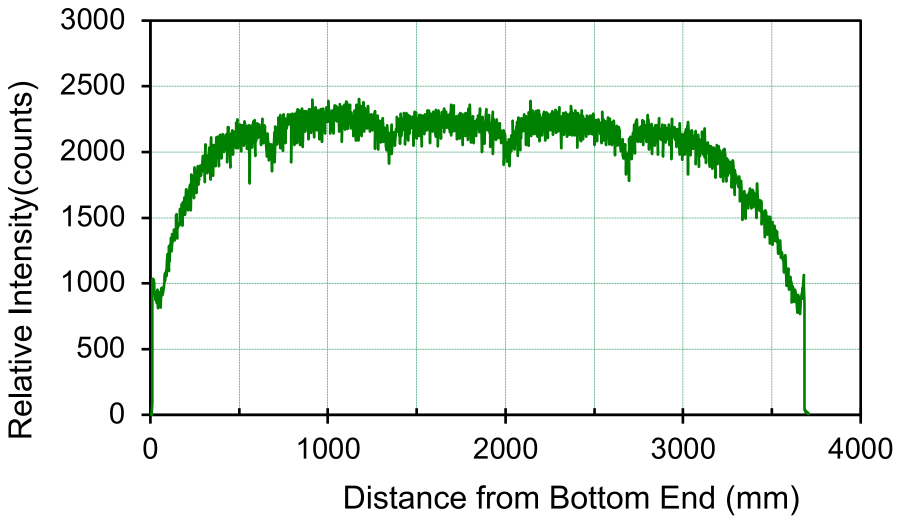
Pu content (g/MTU) in each Pin [1]

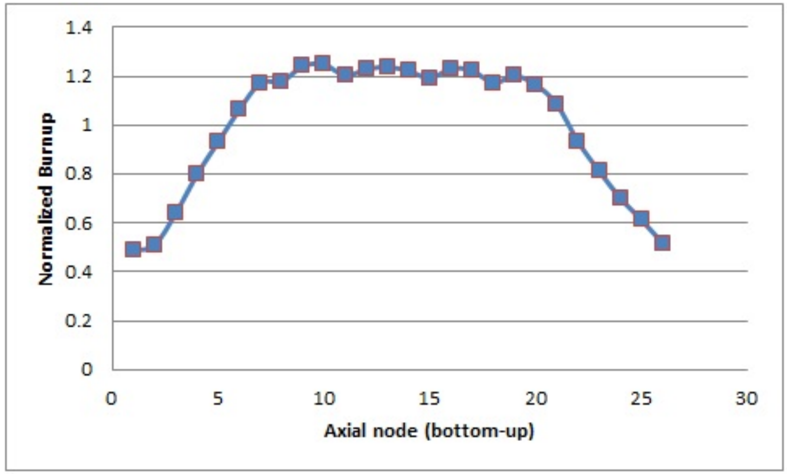
[1] J. Hu, I. C. Gauld, J. Banfield and S. Skutnik, "Developing Spent Fuel Assembly Standards for Advanced NDA Instrument Calibration – NGSI Spent Fuel Project," ORNL/TM-2013/576, Oak Ridge National Laboratory, 2014.

ORIGAMI results: axial Pu distribution



XZ cross-sectional view of Pu content (the cut plane goes through 2 guide tubes) [1]

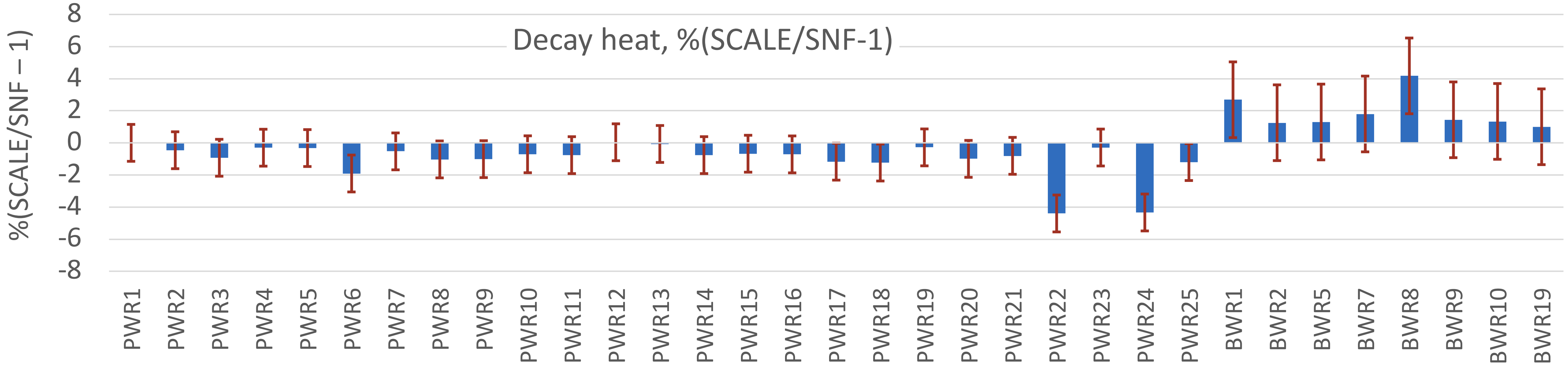


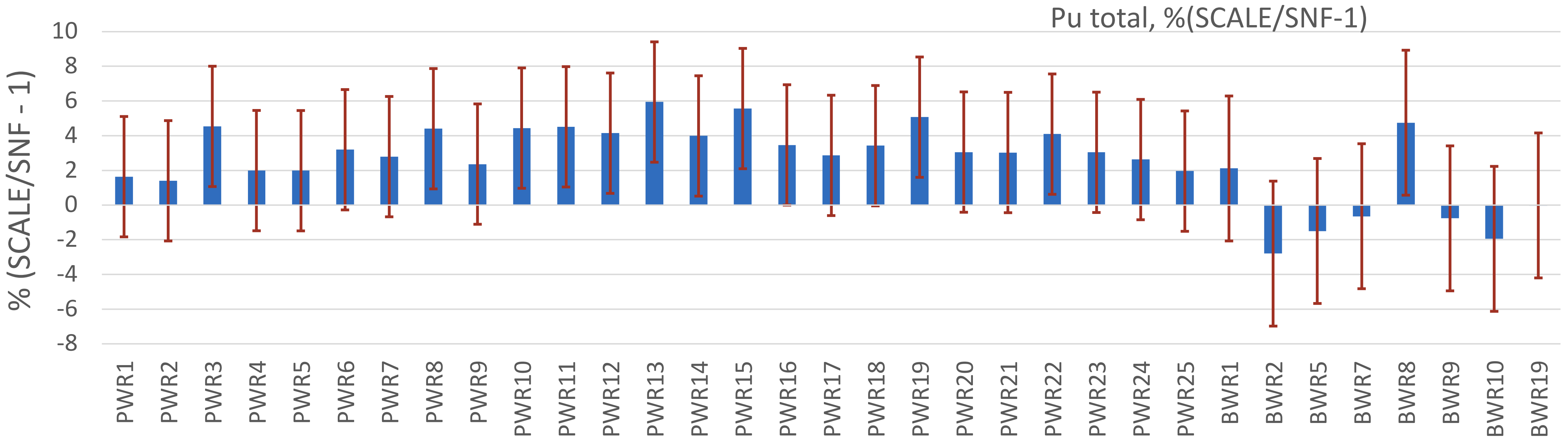


Axial burnup profile (derived from Cs-137 scans) [1]

[1] J. Hu, I. C. Gauld, J. Banfield and S. Skutnik, "Developing Spent Fuel Assembly Standards for Advanced NDA Instrument Calibration – NGSI Spent Fuel Project," ORNL/TM-2013/576, Oak Ridge National Laboratory, 2014.

Decay heat and Pu total: compared to CASMO/SIMULATE – SNF results

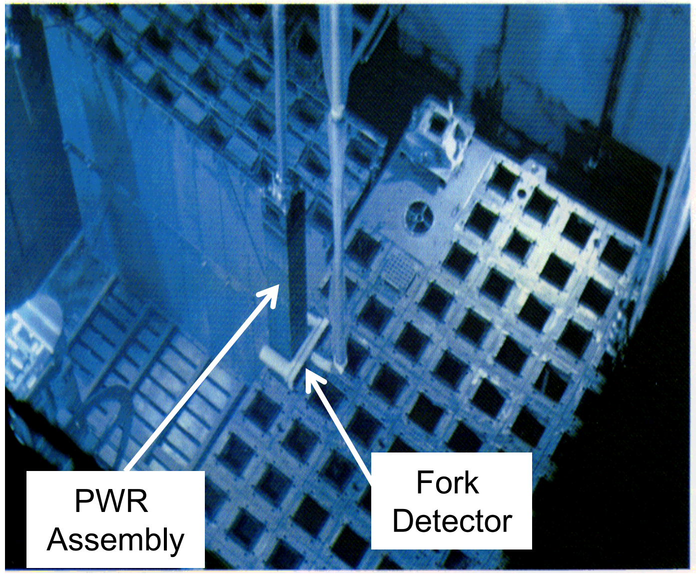




Fork Detector

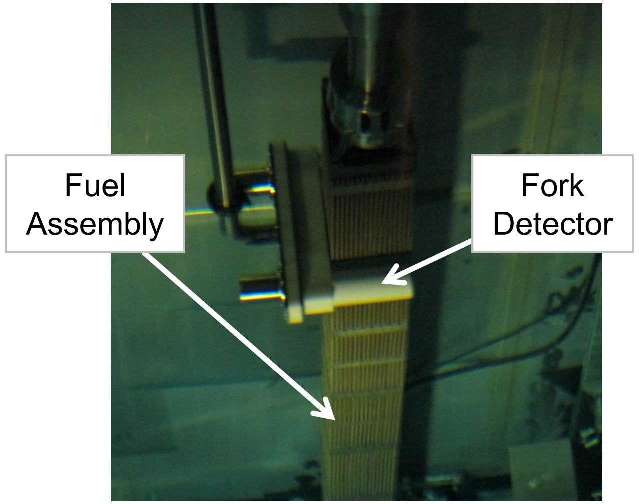
- Neutron fission chambers and gamma ion chambers.
- Measure passive neutrons primarily from curium (e.g., Cm-244) – very sensitive to burnup.
- Neutrons also multiply in the assembly due to fission (dependent on fissile nuclide content).
- Gross gamma signal comes from fission products (e.g., Cs-137); high attenuation within fuel assembly.
- 1600 assemblies have been measured using the Fork detector by IAEA and EURATOM last 3 years.

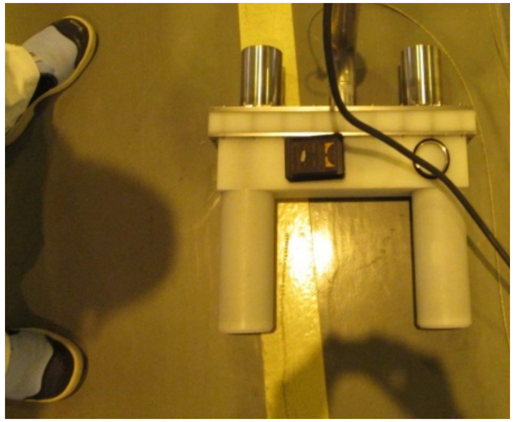
Neutron/Gamma Detectors

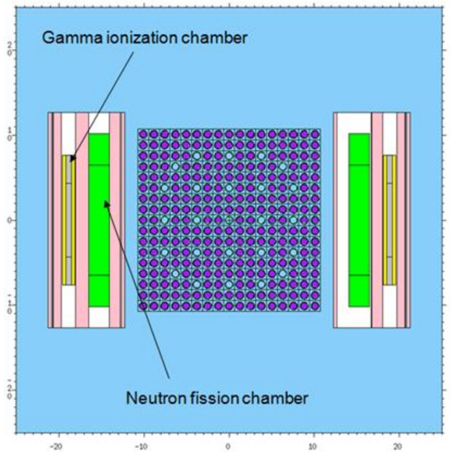


Technical Approach: ORIGEN for Fork

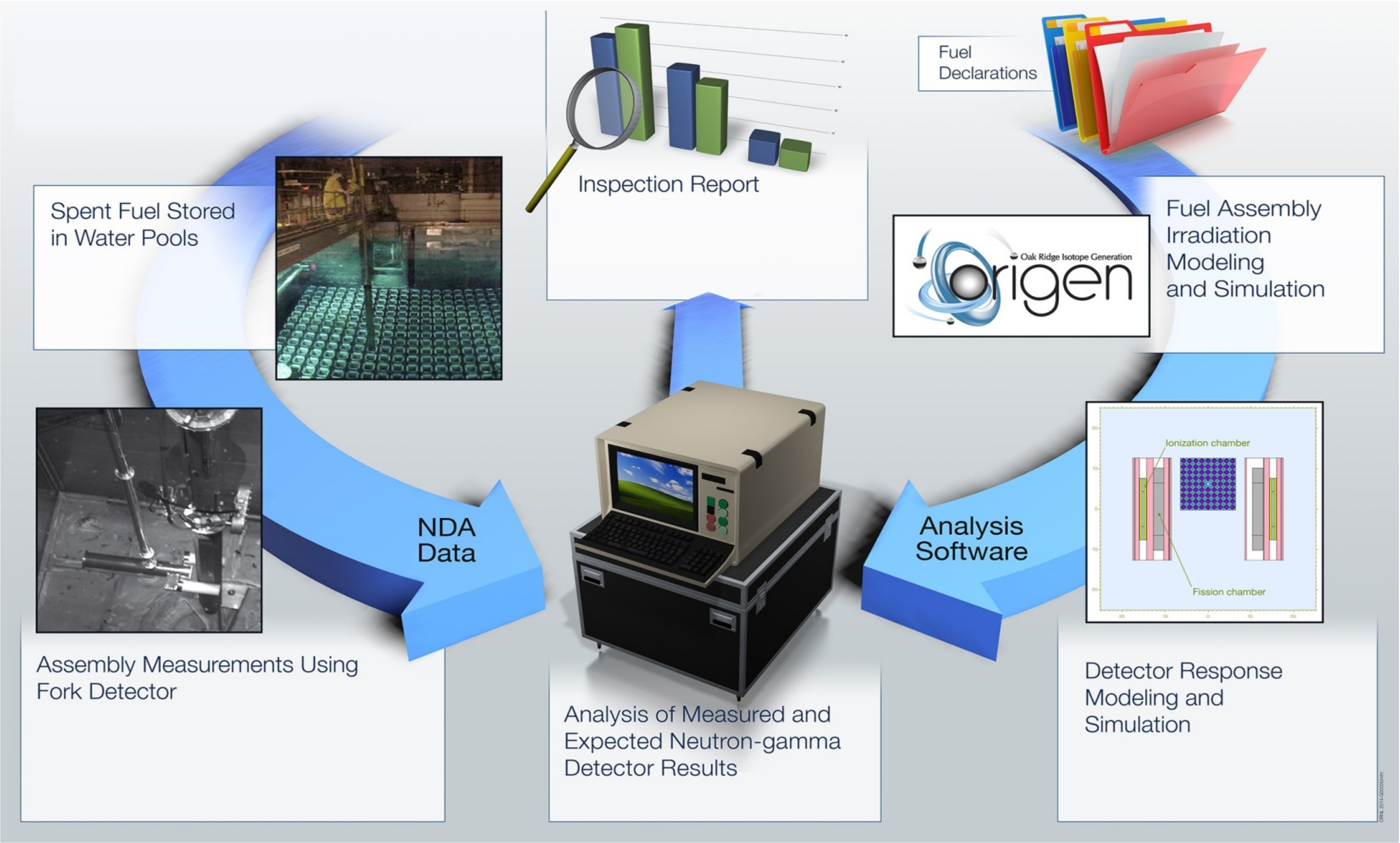
- ORNL developed a spent fuel data module for iRAP using the burnup code ORIGEN to predict the expected Fork detector count rates.
- ORIGEN spent fuel module:
  - Performs fully automated fuel burnup simulation based on operator declarations,
  - Calculates isotopics and associated neutron and gamma ray emission rates,
  - Combines emission rates with pre-determined neutron/gamma response functions (MCNP) and calibration factors to predict both neutron and gamma signals,
  - Module provides immediate (< 5 seconds) indication of declaration inconsistencies.
- Implemented in the safeguards data review and analysis program iRAP, developed jointly by Euratom and IAEA



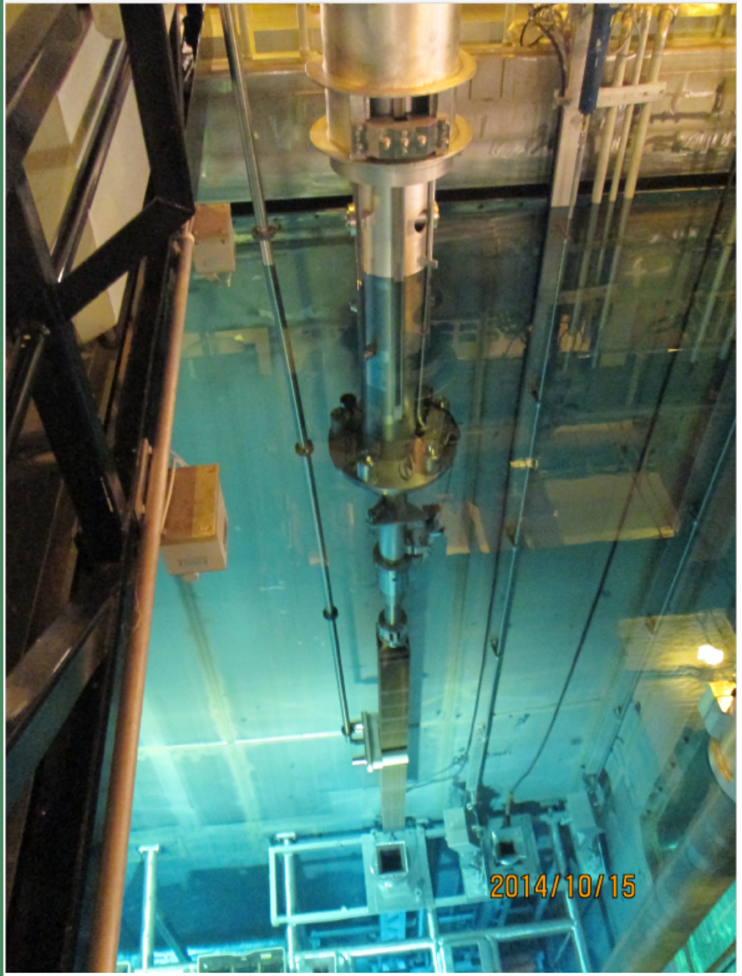


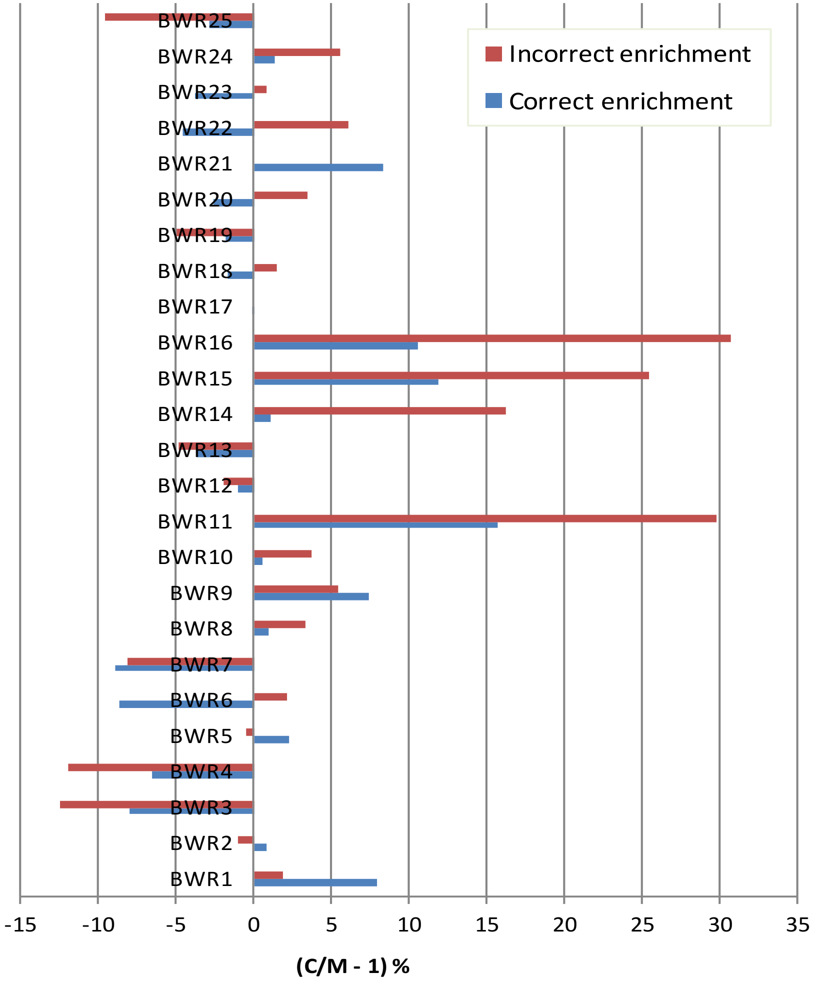


ORIGEN module for the Fork detector

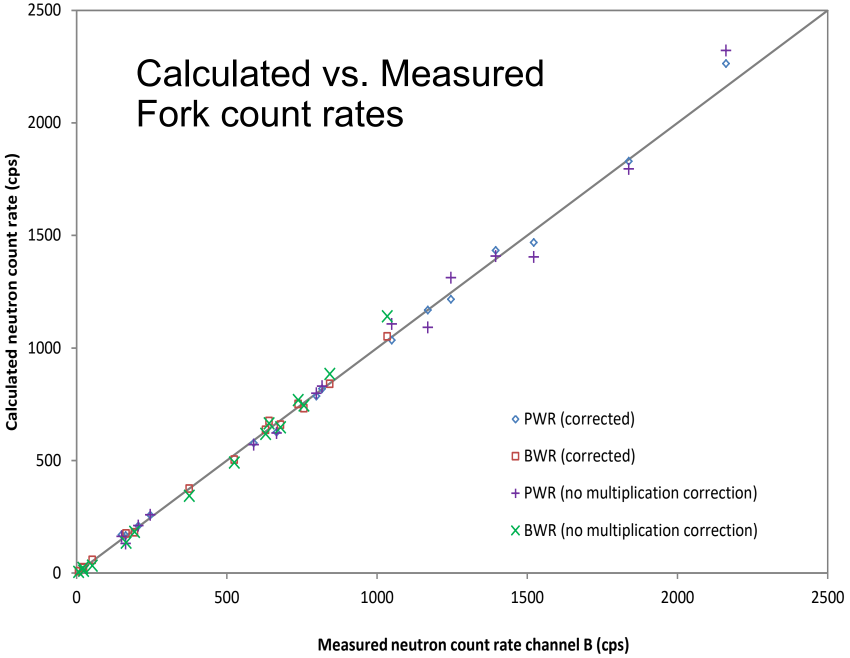


Fork measurements in Sweden





Outlier assemblies were identified using Fork detector and were later confirmed.



[1] I. Gauld, J. Hu, P. DeBaere, and et al., "In-Field Performance Testing of the Fork Detector for Quantitative Spent Fuel Verification," in *Proceedings of ESARDA*, Manchester, UK, ISBN 978-92-79-49495-6 (2015).

Summary

- Spent fuel safeguards becomes more important due to increased activities associated with spent fuel disposal worldwide.
- Modeling and simulation is essential for advanced NDA testing.
- ORIGAMI provides an efficient interface for fuel assembly burnup calculations to account for the complex radial and axial variations in the assembly.
- ORIGAMI results have been compared to the ones from an industry code. Good agreements have been observed.
- The ORIGEN Module has been developed to predict Fork detector count rates and validated using experimental data.
- SCALE has proved to be a very useful tool for international spent fuel safeguards.

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  - Office of Nonproliferation and Arms Control (NPAC), National Nuclear Security Administration (NNSA)
  - International Safeguards Engagement Program (INSEP), National Nuclear Security Administration (NNSA)

Questions?

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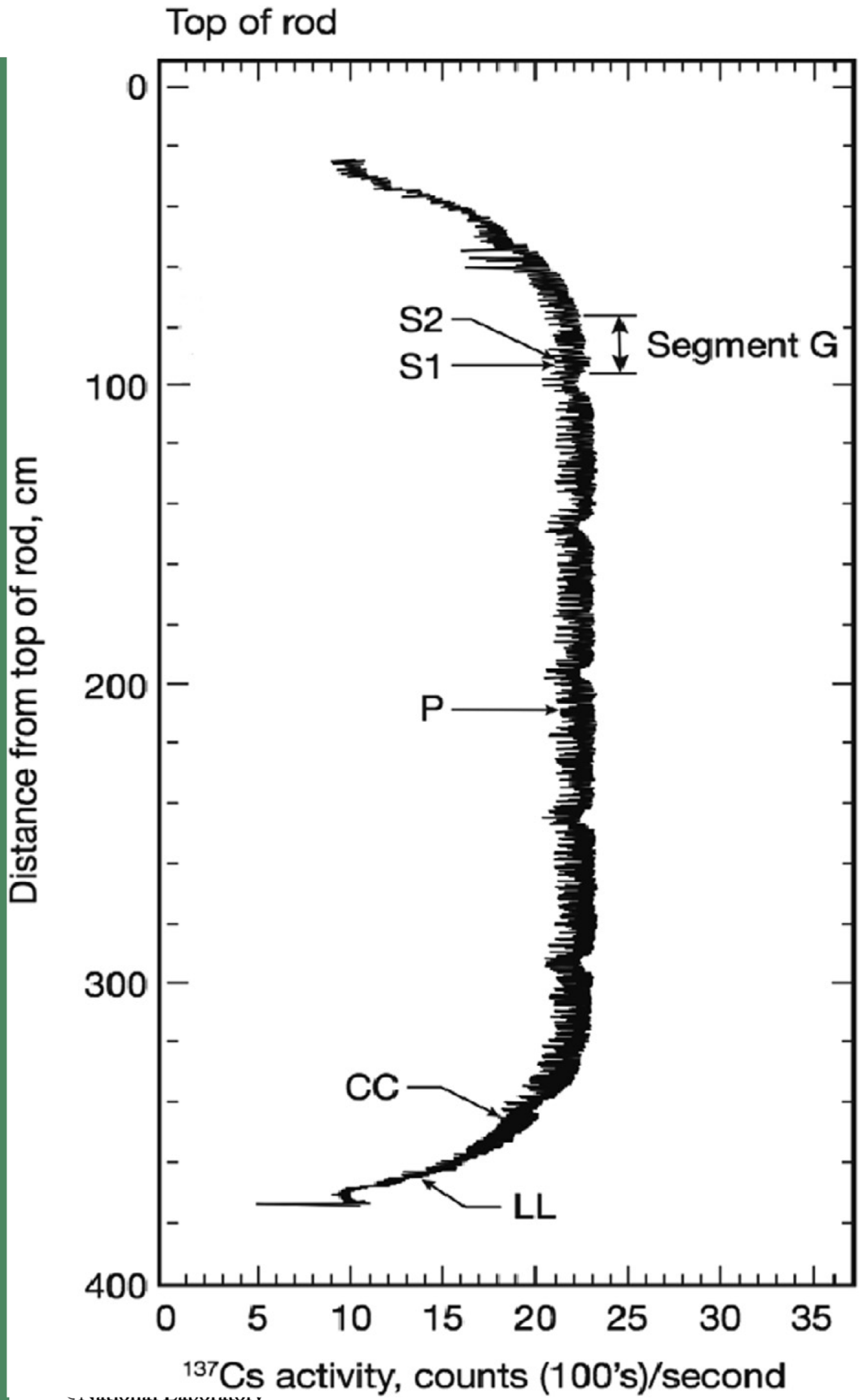
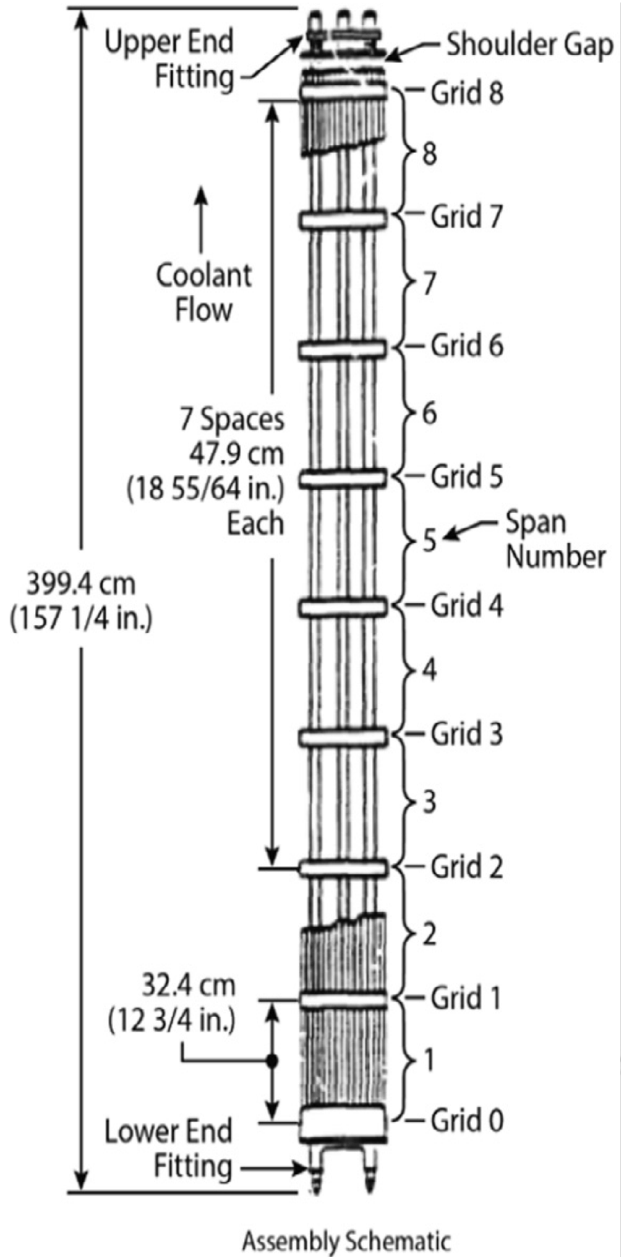
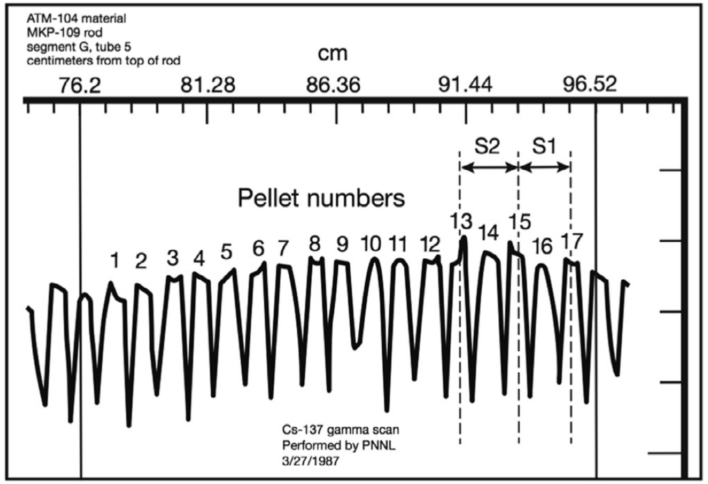
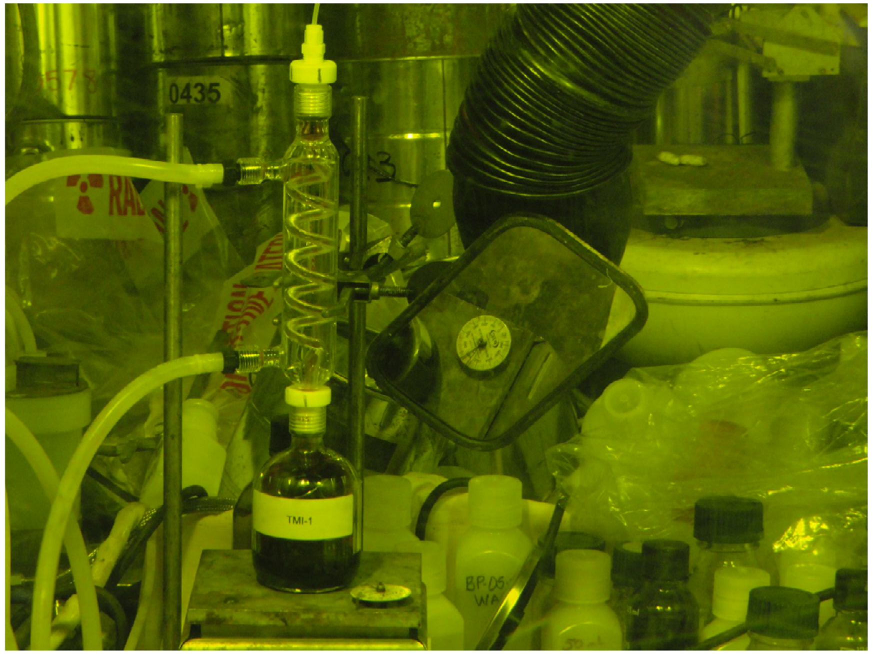
Backup slides

SNF Destructive assay









Ref: J.Hu, et al., Analysis of new measurements of Calvert Cliffs spent fuel samples using SCALE6.2, Annals of Nuclear Energy, 106, 2017

Accuracy of SCALE/ORIGEN: nuclides

Isotope	Number of measurements	SCALE 6.1 ENDF/B-VII		Application
		$(C/E-1)_{avg}$ (%)	σ (%)	
^{234}U	55	12.4	17.6	Nuclear Safeguards subjects
^{235}U	92	1.2	3.5	
^{236}U	77	-1.9	3.5	
^{238}U	92	-0.1	0.4	
^{238}Pu	77	-11.7	5.9	
^{239}Pu	92	4.1	3.5	
^{240}Pu	92	2.2	3.4	
^{241}Pu	92	-1.4	4.5	
^{242}Pu	91	-5.9	6.1	
^{241}Am	39	10.2	20.7	Neutron absorber
^{244}Cm	57	-4.4	11.1	Main neutron emitter
^{106}Ru	31	7.9	22.7	Gamma emitter
^{103}Rh	8	9.1	10.9	Gamma emitter
^{134}Cs	59	-7	7.1	Gamma emitter
^{137}Cs	73	-0.7	3.1	
^{148}Nd	77	0.6	1.4	burnup indicator used by DA
^{144}Ce	32	-2.1	8.1	Gamma emitter
^{149}Sm	20	1.9	6.2	Neutron absorber
^{151}Sm	24	-2.1	4.4	
^{154}Eu	44	4.2	10.4	Gamma emitter
^{155}Gd	19	-8.4	14.4	Neutron absorber

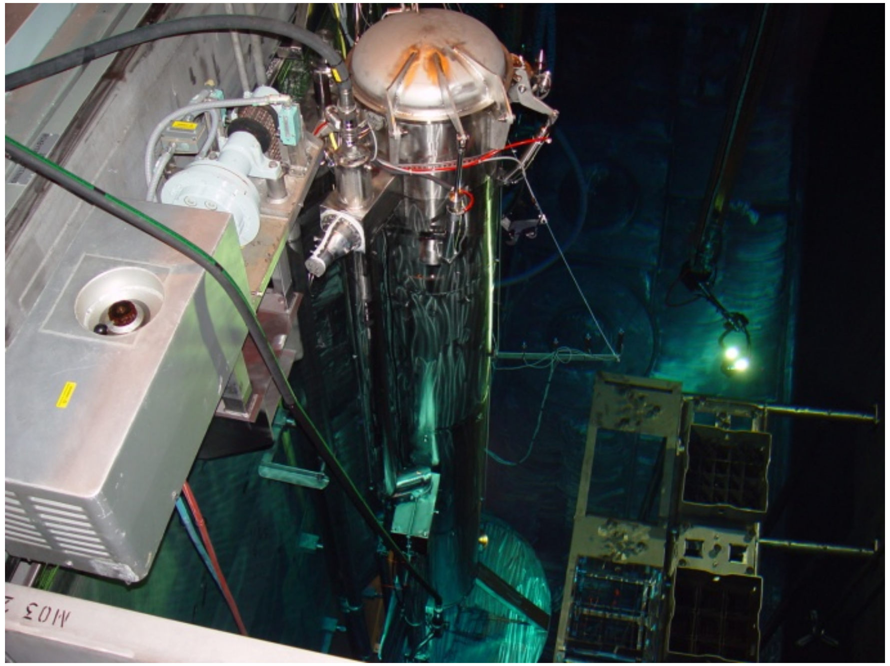
Note: these results were based on PWR DA data on small spent fuel samples (of fuel pellet size). Accuracies on assembly average are expected to be better because average operating conditions are better known than that of a small region.

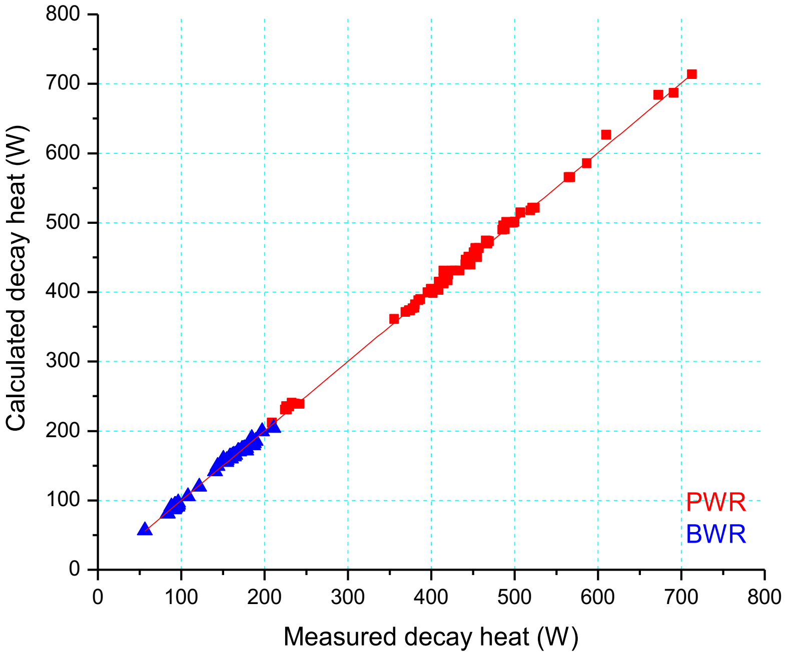
Ref: G. Ilas, I. C. Gauld and G. Radulescu, "Validation of new depletion capabilities and ENDF/B-VII data libraries in SCALE," Annals of Nuclear Energy, vol. 46, pp. 43-55, 2012.

Accuracy of SCALE/ORIGEN: decay heat

- Analysis of 121 spent fuel assemblies at Clab

Reactor name	Reactor type	Number of measurements	C/E[a]		R(W)[b]	
			mean	σ	mean	σ
Ringhals 2	PWR	33	0.998	0.012	-0.96	5.11
Ringhals 3	PWR	38	1.005	0.011	1.89	4.36
Ringhals 1	BWR	45	0.999	0.024	-0.02	3.43
Oskarshamn 2	BWR	5	0.975	0.020	-2.35	1.66





Reference: Nuclear Engineering and Design, vol.273, p. 58, 2014