ADVANCED REACTOR SAFEGUARDS & SECURITY

Burnup-Dependent Safeguards Assessment of Sodium-Cooled Fast Reactor Fuel

PRESENTED BY

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Background

As advanced reactors move toward deployment, there is an increasing need to understand how fuel composition and operating conditions affect safeguards and security. Among the reactor types considered under the Advanced Reactor Demonstration Program (ARDP),

- Pebble-bed reactor (TRISO fuel)
  - lower heavy metal density
  - more chemically robust structure
  - more resistant to chemical separation and reprocessing
  - Easier to "divert"
- Sodium-cooled fast reactor (Metallic fuel)
  - relatively high heavy metal content
  - higher fissile material concentrations
  - material-focused safeguards challenges

Multi-Dimensional Framework

Rather than relying on a single aggregated metric, this work adopts a multi-dimensional framework that distinguishes between three functions: material attractiveness, self-protection, and monitorability.

- Material attractiveness describes the suitability of the material for use in a nuclear explosive device.
- Self-protection refers to the intrinsic radiological and thermal barriers that impede handling or misuse of nuclear material, primarily through high dose rates and decay heat.
- Monitorability refers to the extent to which the material can be observed, identified, and tracked through measurable radiation signatures.

Mapping of fuel attributes to safeguards functions

Attribute	Attractiveness	Self-Protection	Monitorability
Decay Heat	Complicates weaponization	Thermal handling barrier	Not primary
Photon Emission Rate	Not directly relevant	Contributes to dose rate	Key photon detection signature
Photon Spectrum	Not directly relevant	Contributes to dose rate	Not primary
Spontaneous Fission Rate	Degrades weapon performance (pre-initiation)	Contributes to dose rate	Key neutron detection signature
Dose Rate	Complicates handling and processing	Radiological barrier	Not primary

Objective

This work aims to establish a physics-based framework for comparing different fuel BU states, including low-burnup fuel discharged early due to operational anomalies.

By explicitly linking material composition to self-protection, attractiveness, and monitorability, the analysis is intended to inform graded physical protection strategies and safeguards approaches for advanced reactor systems.

Analysis of sodium-cooled fast reactor ⇔ typical PWR

Methodology

In the first stage, high-fidelity Serpent models are used to perform fuel depletion calculations, generating isotopic compositions as a function of burnup. The evolution of isotope inventories is then tracked as a function of cooling time following discharge. For each combination of burnup and cooling time, a set of attributes (decay heat, photon emission rate, spontaneous fission rate) is derived from the underlying isotopic composition.

In the second stage, radiation dose rates are estimated. A simplified source model is constructed in which the fuel inventory corresponding to a single assembly is homogenized and represented as an equivalent spherical source. Neutron and photon fluxes are tallied at a distance of 1 m from the source. Energy-dependent flux tallies are defined using energy group structures aligned with ICRP Publication 116

Neutronics calculations

PWR

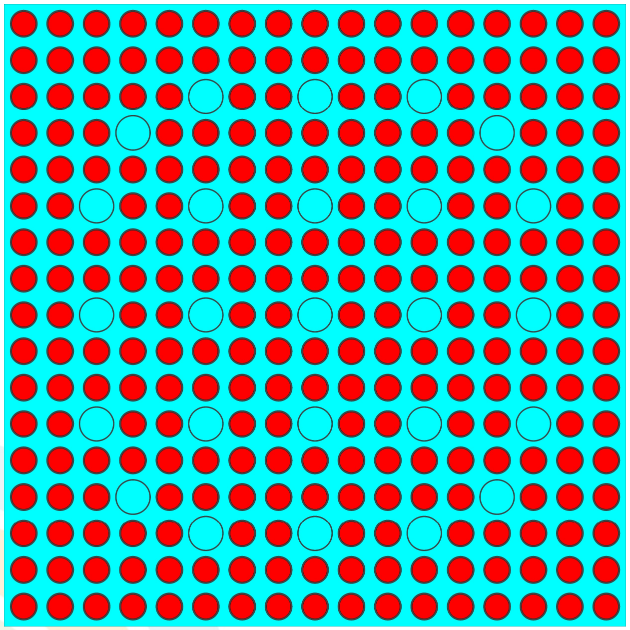


Figure 1. The x-y cross-sectional view of the AP-1000 Serpent model

Parameter	Value
Array size (-)	17 × 17
Number of fuel rods (-)	264
Number of guide/instrument tubes (-)	25
Power density (MW/MTU)	40.2
Rod pitch (cm)	1.26
Assembly pitch (cm)	21.522
Cladding outside radius (cm)	0.475
Gas gap outside radius (cm)	0.4178
Pellet outside radius (cm)	0.4096
Guide/instrument tube outside radius (cm)	0.6121
Guide/instrument tube inside radius (cm)	0.5715
Fuel volume per assembly (cm3)	50900
Initial fuel enrichment (-)	4.2%

1. Z. Wu and C. Lu, 2022. Preliminary Fuel Cycle Analysis of the -UB2 Composite Fuels in Pressurized Water Reactors. 2022 ANS Annual Meeting

Neutronics calculations

SFR

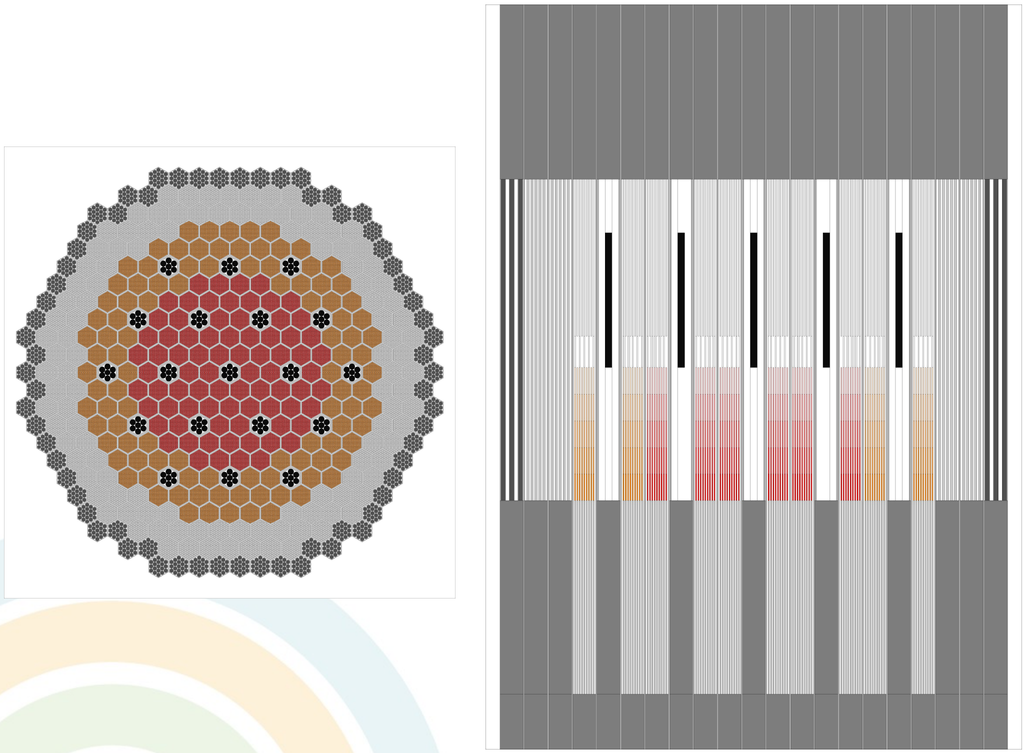


Figure 2. The x-y and y-z cross-sectional views of the 1000-MWth ABR Serpent model

Methodology demonstration – to be updated to HALEU-fueled

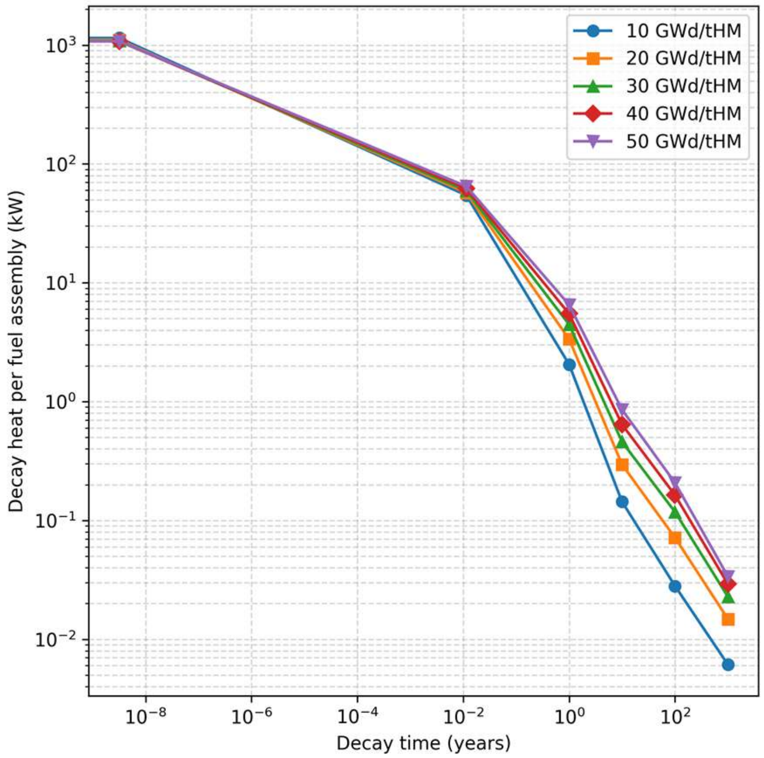
Parameter	Value	Unit
Reactor power	1,000	MWth
Cycle length	328.5	EFPD
Discharge burnup	25.0	GWd/t-iHM
Coolant temperature	432.5	°C
Average core structure temp.	432.5	°C
Average fuel temp.	534.0	°C
Fuel volume per assembly	7651	cm3

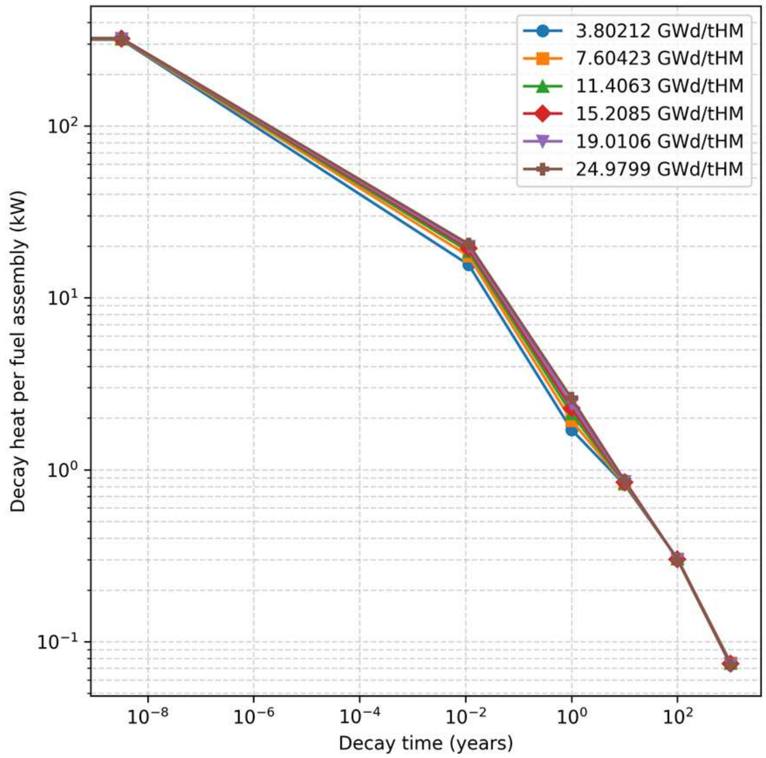
With a transuranics (TRU) conversion ratio of ~0.7, the 1000-MWth ABR is fueled with recycled discharged TRU blended with TRU feed recovered from LWR used nuclear fuel.

2. OECD/NEA, 2016. Benchmark for Neutronic Analysis of Sodium-cooled Fast Reactor Cores with Various Fuel Types and Core Sizes. Technical report. NEA/NSC/R(2015)9.

Preliminary results

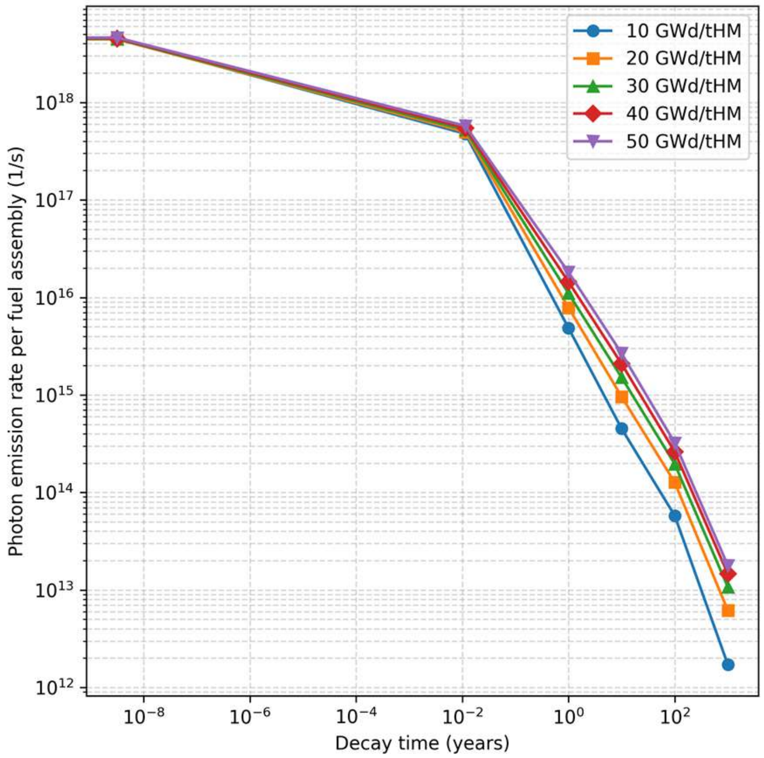
Decay heat

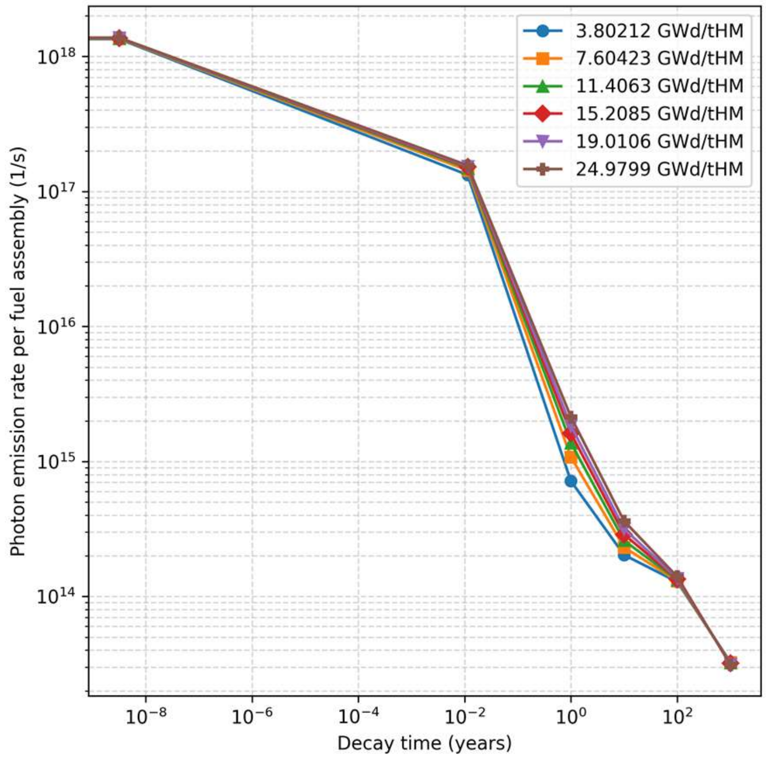




Preliminary results

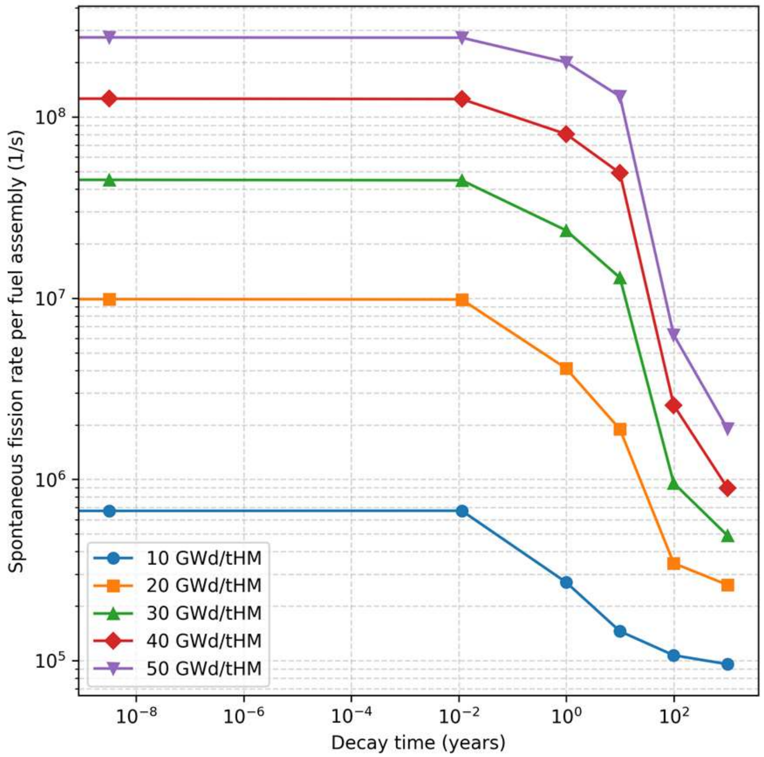
Photon emission rate

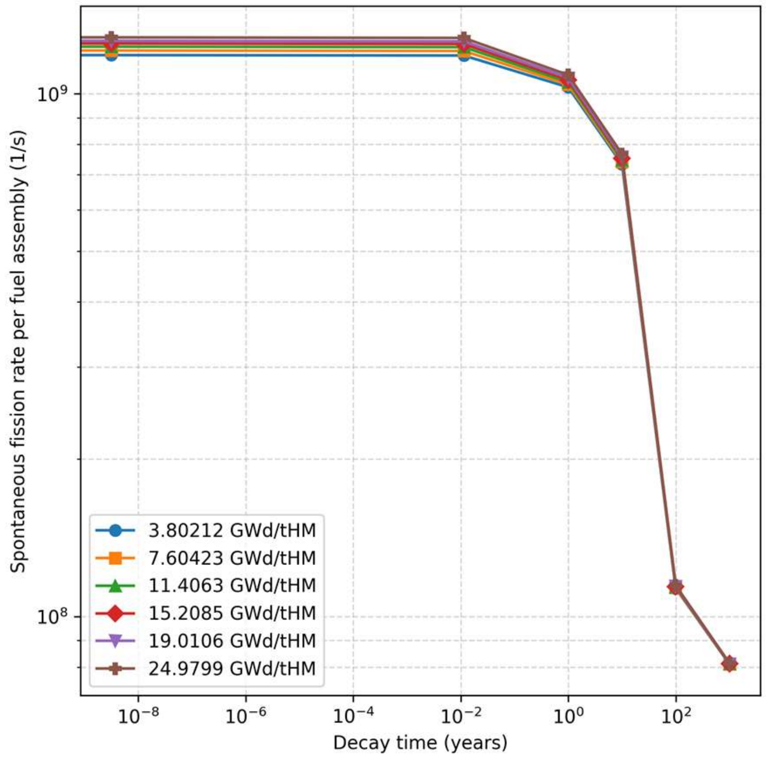




Preliminary results

Spontaneous fission rate





Path forward

- Dose analysis will be completed.
- This work demonstrated the methodology to analyze burnup-dependent safeguards attributes.
- The same methodology will be applied to other SFR designs, including the ones with fresh metallic fuels (e.g., NATRIUM)

Decay Data Sub-library

A.A. Sonzogni, A. Mattera, E.A. McCutchan

Brookhaven National Laboratory

National Nuclear Data Center (NNDC)

The NNDC is the largest and lead unit of the US Nuclear Data Program (USNDP), whose mission is to provide current, accurate, authoritative data for workers in pure and applied areas of nuclear science and engineering. This is accomplished primarily through the compilation, evaluation, dissemination, and archiving of extensive nuclear datasets. USNDP also addresses gaps in the data, through targeted experimental studies and the use of theoretical models.

David Brown is the NNDC head and chair of USNDP.

The NNDC traces its roots to a group formed in 1952 by Manhattan Project alumni.

The NNDC is responsible for several foundational nuclear physics databases:

NSR: Literature

ENSDF & XUNDL: Nuclear structure and decay

ENDF: Nuclear Reactions

And we maintain a robust research portfolio in experimental and theoretical nuclear physics.

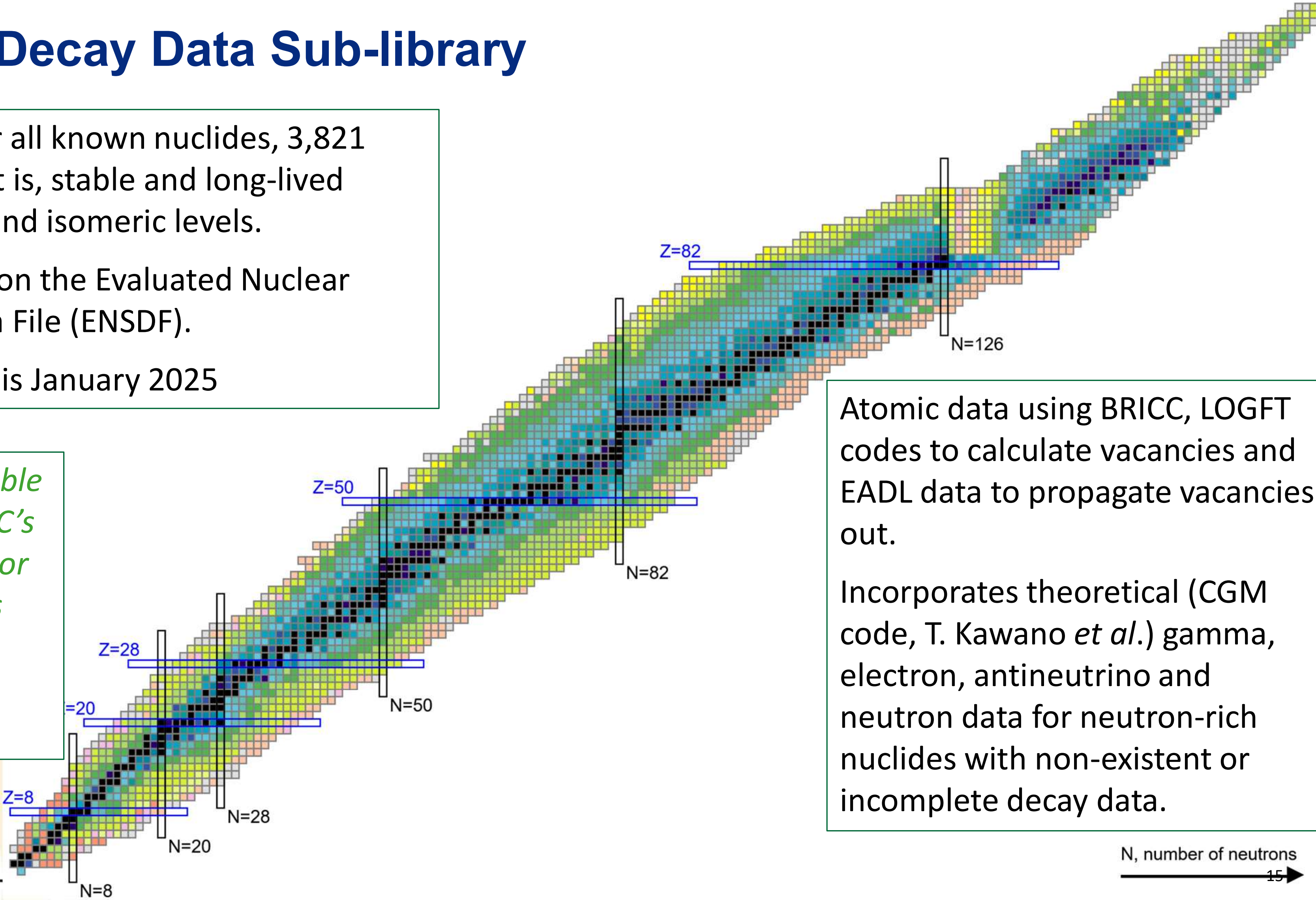
ENDF/B Decay Data Sub-library

Decay data for all known nuclides, 3,821 materials, that is, stable and long-lived ground state and isomeric levels.

Mostly based on the Evaluated Nuclear Structure Data File (ENSDF).

Latest version is January 2025

ENDF/B available from the NNDC's GitLab server, or by e-mail. It is also part of SCALE.



Atomic data using BRICC, LOGFT codes to calculate vacancies and EADL data to propagate vacancies out.

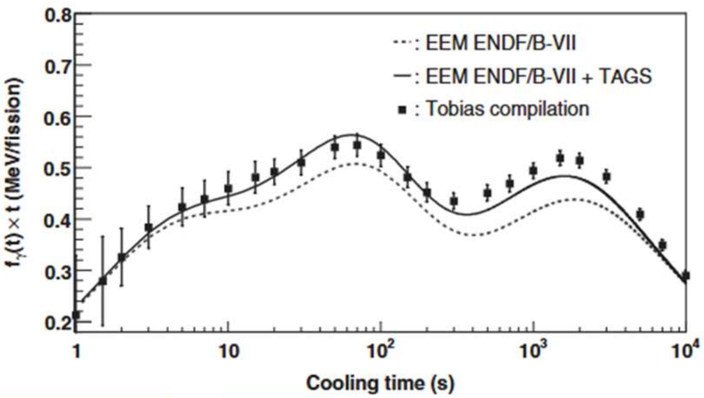
Incorporates theoretical (CGM code, T. Kawano *et al*.) gamma, electron, antineutrino and neutron data for neutron-rich nuclides with non-existent or incomplete decay data.

We are both, producers and users of the decay data sub-library

Selected for a Viewpoint i
PRL 105, 202501 (2010) PHYSICAL REVIEW

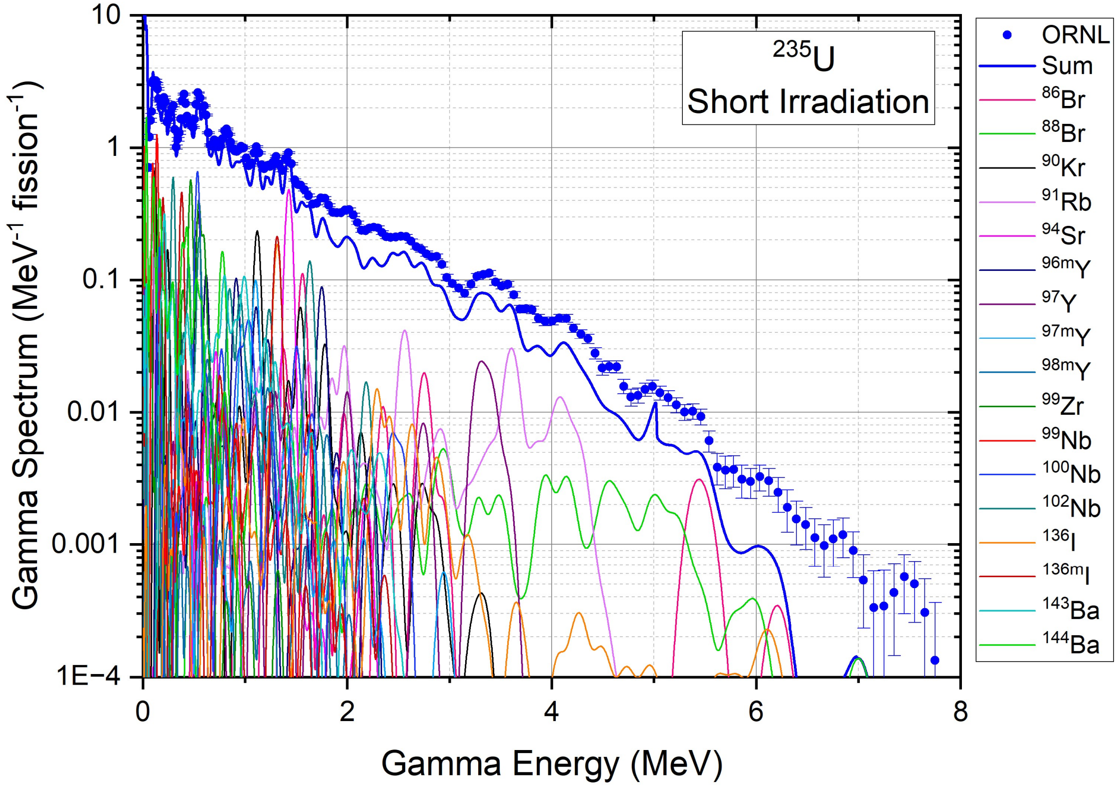
Reactor Decay Heat in ^{239}Pu: Solving the γ Discrep

A. Algora,[1,2,*] D. Jordan,[1] J.L. Taín,[1] B. Rubio,[1] J. Agramunt,[1] A. B. Perez-Cerd
E. Nácher,[1] A. Krasznahorkay,[2] M. D. Hunyadi,[2] J. Gulyás,[2] A. Vitéz,[2] M. Csatlós,[2]
I. D. Moore,[3] T. Eronen,[3] A. Jokinen,[3] A. Nieminen,[3] J. Hakala,[3] P. Karvonen,[3] A.
J. Rissanen,[3] T. Kessler,[3] C. Weber,[3] J. Ronkainen,[3] S. Rahaman,[3] V. Elomaa,[3] S. Ri
K. Burkard,[4] W. Hüller,[4] L. Batist,[5] W. Gelletly,[6] A. L. Nichols,[6] T. Yoshida,[7] A.



Beta-delayed gamma spectra compilation and analysis following the thermal-neutron induced fission of ^{235}U, ^{239,241}Pu

Z. Harris,[1] B. Hill,[2,3] S. Kim,[4] A. Mattera,[4] E.A. McCutchan,[4] O. Palaguachi,[5] M. Seeley,[6] and A.A. Sonzogni[7,*]



Data is provided in the ENDF-6 format

Must have a code to interpret it.

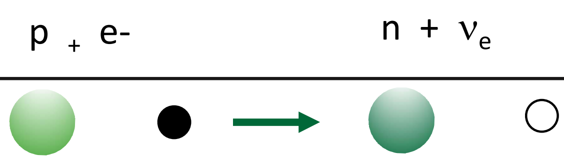
Showing the first 23 lines for 239-Plutonium out of 2392 lines.

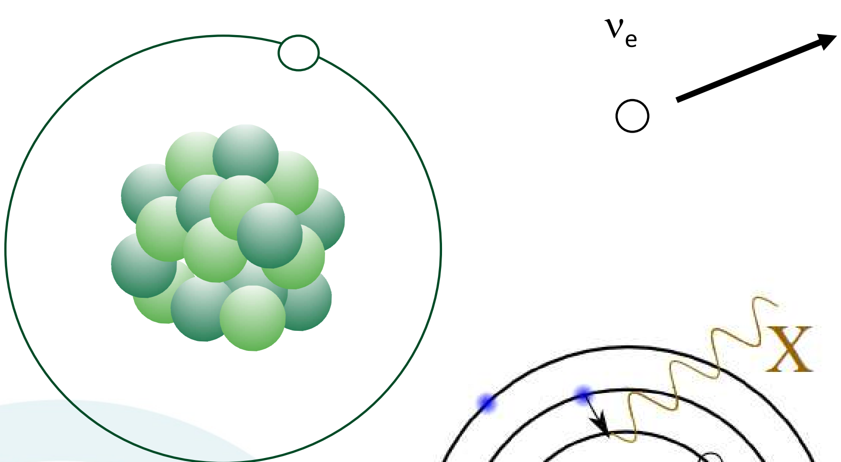
```
9.423900+4 2.369986+2          0          0          0          63559 8457    1
7.60854+11 9.467280+8          0          0          6          03559 8457    2
5.765401+3 5.928601+1 3.669624+2 2.755905+1 5.237127+6 1.085203+43559 8457    3
5.000000-1 1.000000+0          0          0         18          33559 8457    4
6.000000+0 0.000000+0 1.843000+8 3.600000+6 3.10000-12 6.00000-133559 8457    5
4.000000+0 0.000000+0 5.244430+6 1.400000+2 4.626700-4 3.787687-53559 8457    6
4.000000+0 1.000000+0 5.244354+6 1.400006+2 9.995373-1 3.787687-53559 8457    7
0.000000+0 0.000000+0          0          0          6        1683559 8457    8
1.000000+0 0.000000+0 6.339737+1 2.759025-1 0.000000+0 0.000000+03559 8457    9
1.297500+4 1.000000+1          0          0         12          03559 8457   10
4.000000+0 0.000000+0 3.694779-4 6.024100-6 0.000000+0 0.000000+03559 8457   11
4.970000+2 9.002005-3 0.000000+0 0.000000+0 0.000000+0 0.000000+03559 8457   12
3.004000+4 2.000000+1          0          0         12          03559 8457   13
4.000000+0 0.000000+0 2.170000-6 6.000000-8 0.000000+0 0.000000+03559 8457   14
1.567000+2 0.000000+0 0.000000+0 0.000000+0 1.180000+2 1.700000+03559 8457   15
3.866100+4 2.000000+0          0          0         12          03559 8457   16
4.000000+0 0.000000+0 1.044000-4 1.300000-6 0.000000+0 0.000000+03559 8457   17
2.980000+2 2.400000+1 0.000000+0 0.000000+0 2.190000+2 1.700000+13559 8457   18
4.193000+4 5.000000+1          0          0         12          03559 8457   19
4.000000+0 0.000000+0 1.460000-6 1.500000-7 0.000000+0 0.000000+03559 8457   20
7.000000+1 3.000000+1 0.000000+0 0.000000+0 5.500000+1 2.100000+13559 8457   21
4.621000+4 5.000000+1          0          0         12          03559 8457   22
4.000000+0 0.000000+0 7.210000-7 1.100000-8 0.000000+0 0.000000+03559 8457   23
```

Developments:

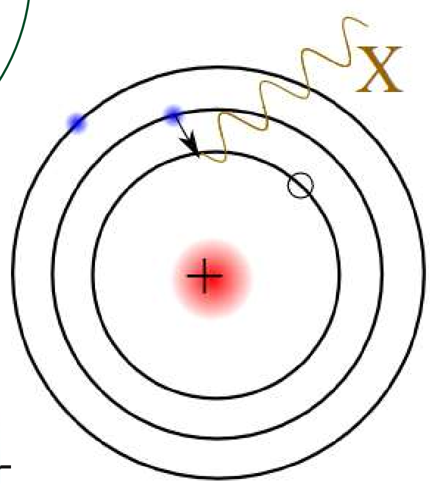
- A JSON version that would be easier to read and interpret, by humans and LLMs.
- Level information to reconstruct a level scheme.
- Radiation coincidence matrices.
- Improved Atomic Radiation.
- Feel free to suggest one, and to **point out errors**.

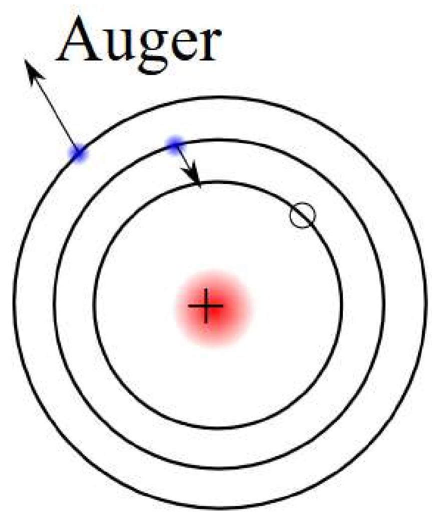
Atomic Radiation: X-rays, Conversion electrons, Auger electrons





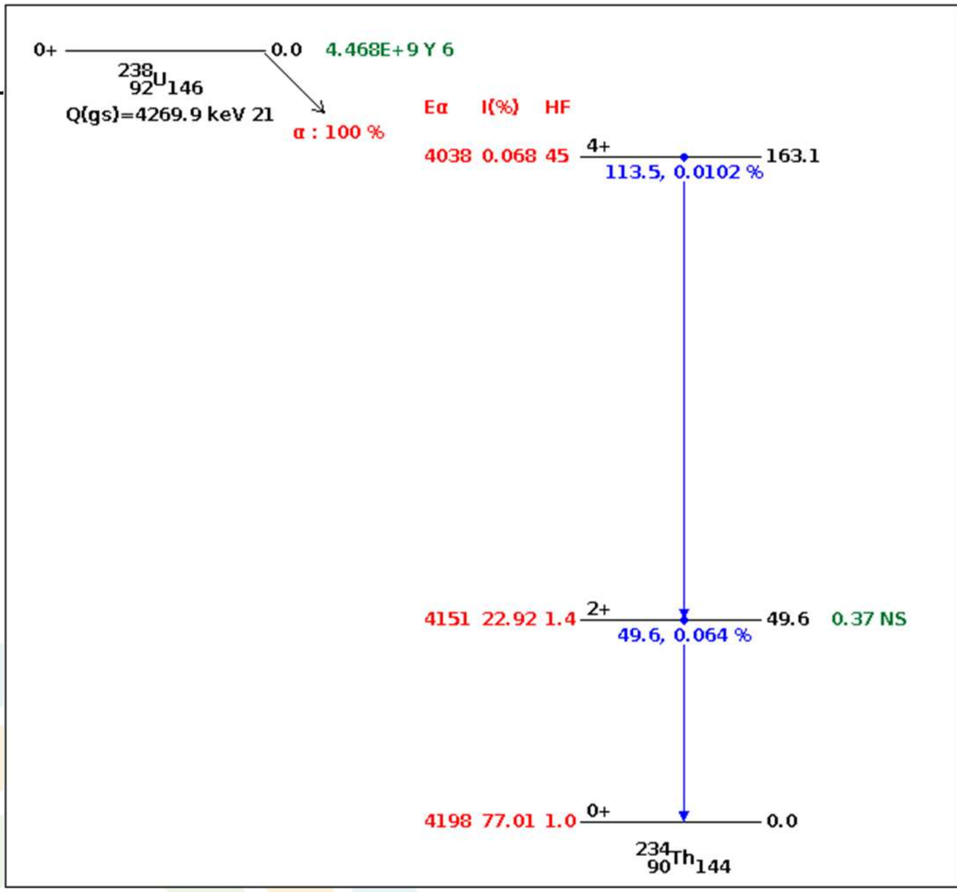
Electron capture, an electron from the inner shells (K, L) is captured, creating a vacancy, which is filled by electrons from the outer shells producing X-rays and/or Auger electrons.





De-excitation of excited levels by electron conversion will also produce vacancies.

^{238}U alpha decay



Radiation Type	Energy (keV)	Absolute Intensity
γ M XR	3.1 *4*	1.08 *14*
γ L α XR	13.0 *17*	3.0 *4*
γ Other L XRs	13.4 *11*	0.40 *3*
γ L β XR	16.2 *21*	3.7 *5*
γ L γ XR	19 *3*	0.82 *11*
γ 1	49.55 *6*	0.064 *8*
γ K-L2 ($K_{\alpha 2}$) XR	90.3 *9*	6.7E-4 *12*
γ K-L3 ($K_{\alpha 1}$) XR	93.8 *9*	0.00111 *20*
γ K-M2 ($K_{\beta 3}$) XR	105.3 *11*	1.29E-4 *23*
γ K-M3 ($K_{\beta 1}$) XR	106.1 *11*	2.5E-4 *5*
γ K-M4 ($K^{II}_{\beta 5}$) XR	106.6 *11*	4.3E-6 *8*
γ K-M5 ($K^{I}_{\beta 5}$) XR	106.8 *11*	5.0E-6 *9*
γ K-N2 ($K^{II}_{\beta 2}$) XR	108.9 *11*	3.2E-5 *6*
γ K-N3 ($K^{I}_{\beta 2}$) XR	109.2 *11*	6.5E-5 *12*
γ K-N4 ($K^{II}_{\beta 4}$) XR	109.4 *11*	1.25E-6 *22*
γ K-N5 ($K^{I}_{\beta 4}$) XR	109.4 *11*	1.4E-6 *3*
γ 2	113.5 *1*	0.0102 *15*

Gamma intensities from a 1984 measurement using a single Ge detector. X-rays from theory.
$I\gamma$ and I_{xr} not consistent!
New measurements from microCalorimeters.