Task 2: Fuel properties characterisation and related uncertainty analysis

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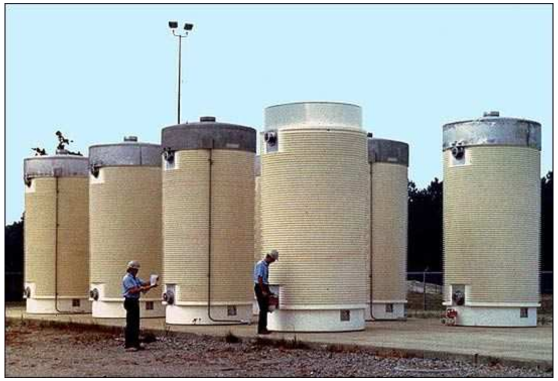
Partners:

CIEMAT, CPST, CTU (SURAO), ENRESA, ENUSA, JRC, JSI, KIT, LEI, NAGRA, PEL, PSI, SCK•CEN, SKB, SSTC NRS, TUS, VTT, UU

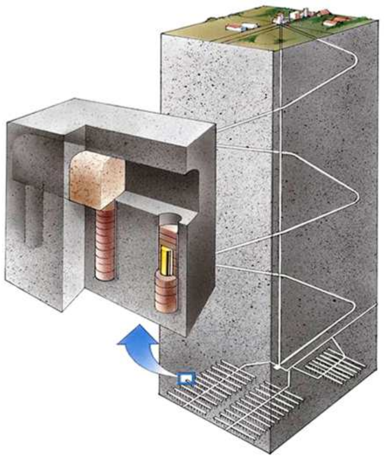
ESARDA, 6 - 7 february 2020, SCK CEN Mol (BE)

Spent Nuclear Fuel (SNF) intermediate storage or final disposal

A **safe**, **secure**, **economic** and **ecological** transport**,** storage and final disposal requires that **SNF** is **characterised** for the main source terms of interest:



- Decay heat
- Neutron emission
- γ-ray emission
- Reactivity (burnup credit)
  nuclides with high neutron absorption cross section)
- Fissile material (Safeguards)
  i.e. ^{235}U, ^{239}Pu
- Specific long-lived radionuclides (Long term safety)
  e.g. ^{14}C, ^{79}Se, ^{94}Nb, ^{99}Tc, ^{129}I, ^{226}Ra



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Neutron emission by SNF

$$S_n(t) = \sum_k S_{n,k}(t)$$

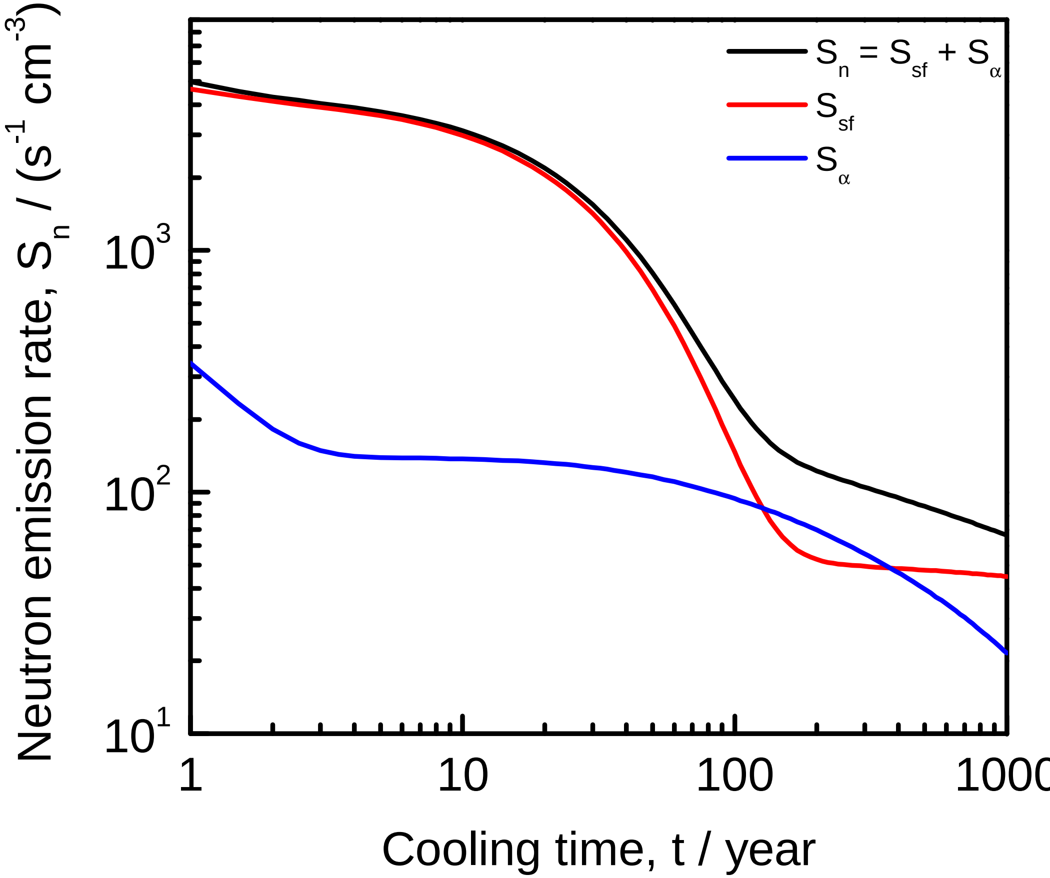
- $S_{n,k}(t)$: contribution of radionuclide k

- $S_{n,k}(t) = (s_{sf,k} + s_{\alpha n,k})\, N_k(t)$
  - $N_k(t)$: number of nuclei of nuclide k at time t
  - $s_{sf,k}$: specific neutron emission rate of nuclide k due to sf
  - $s_{\alpha,k}$: specific neutron emission rate of nuclide k due to (α,n) reactions

PWR UO_2 pellet (5 g)

$^{235}U/U = 4.8$ %

burnup = 44 GWd/t



Neutron emission by SNF

$$S_n(t) = \sum_k (s_{sf,k} + s_{\alpha n,k}) N_k(t)$$

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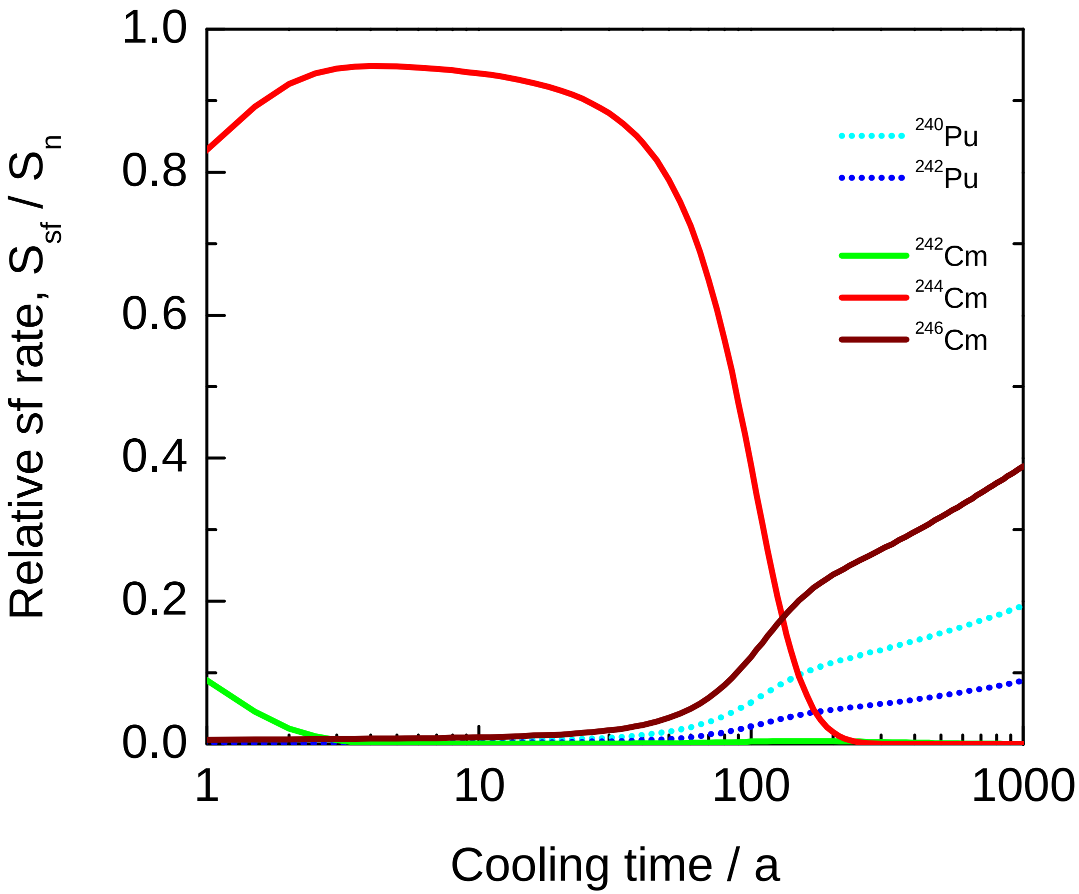

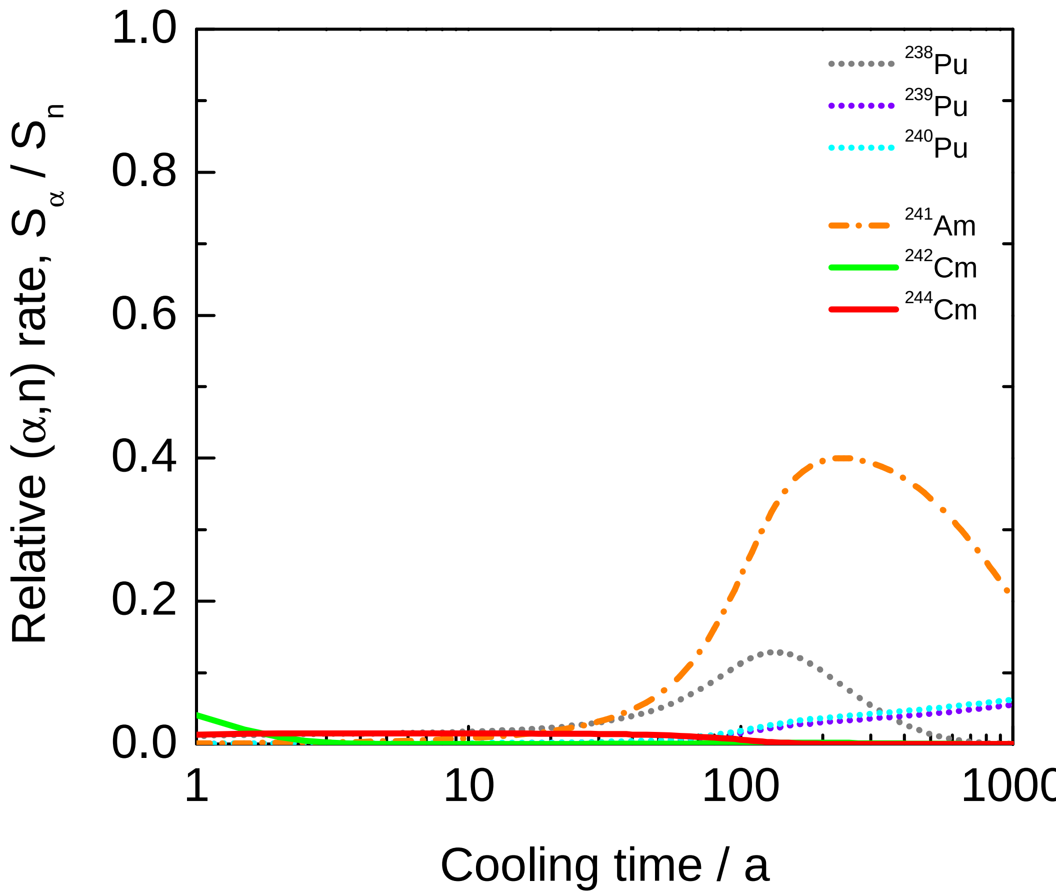

Gamma-ray emission by SNF

$$S_\gamma(t) = \sum_k S_{\gamma,k}(E_\gamma, t)$$

^{95}Nb	35.0 d
^{95}Zr	64.0 d
^{144}Ce/^{144}Pr	284.9 d
^{106}Ru/^{106}Rh	1.02 a
^{134}Cs	2.06 a
^{154}Eu	8.8 a
^{137}Cs/^{137m}Ba	30.0 a

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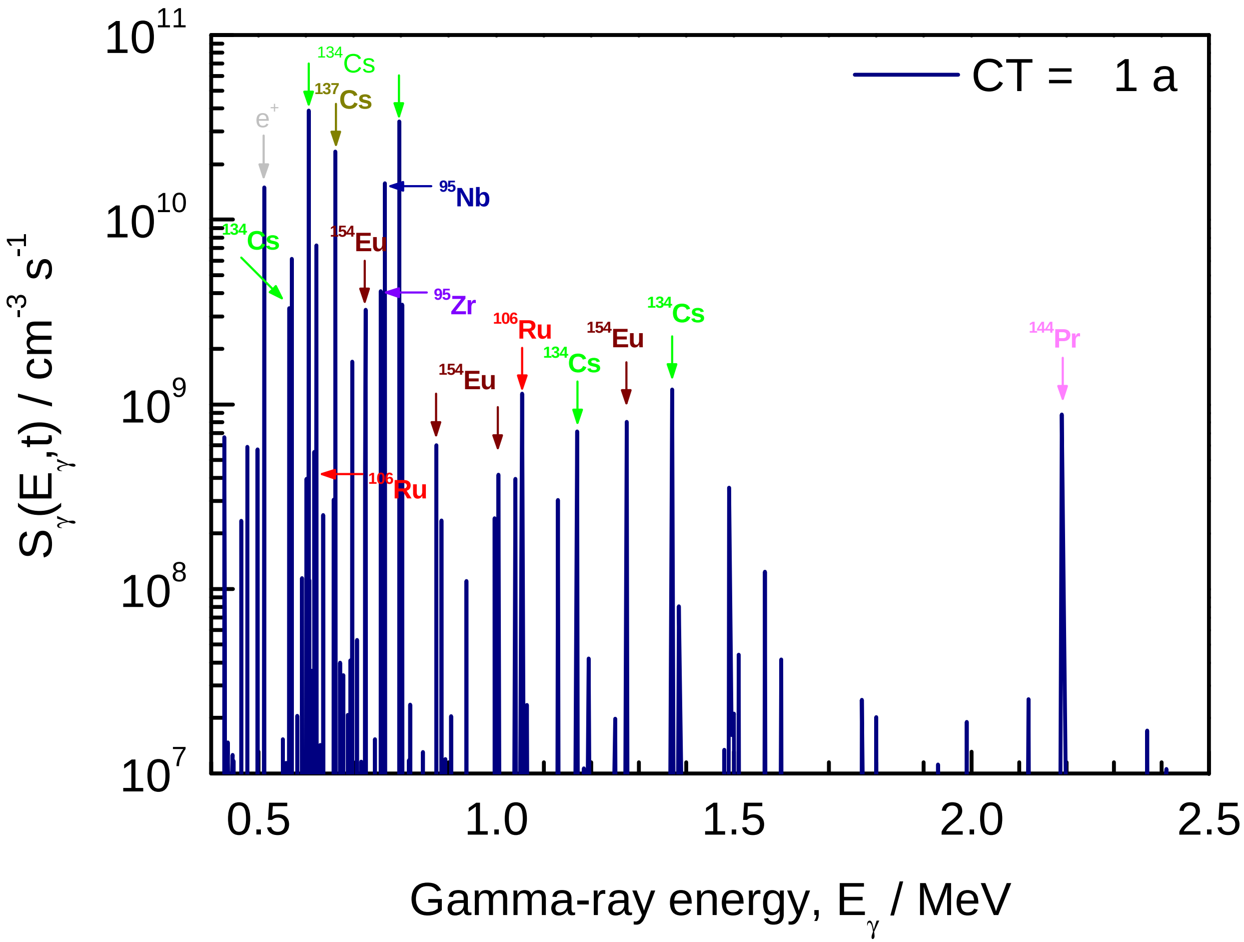

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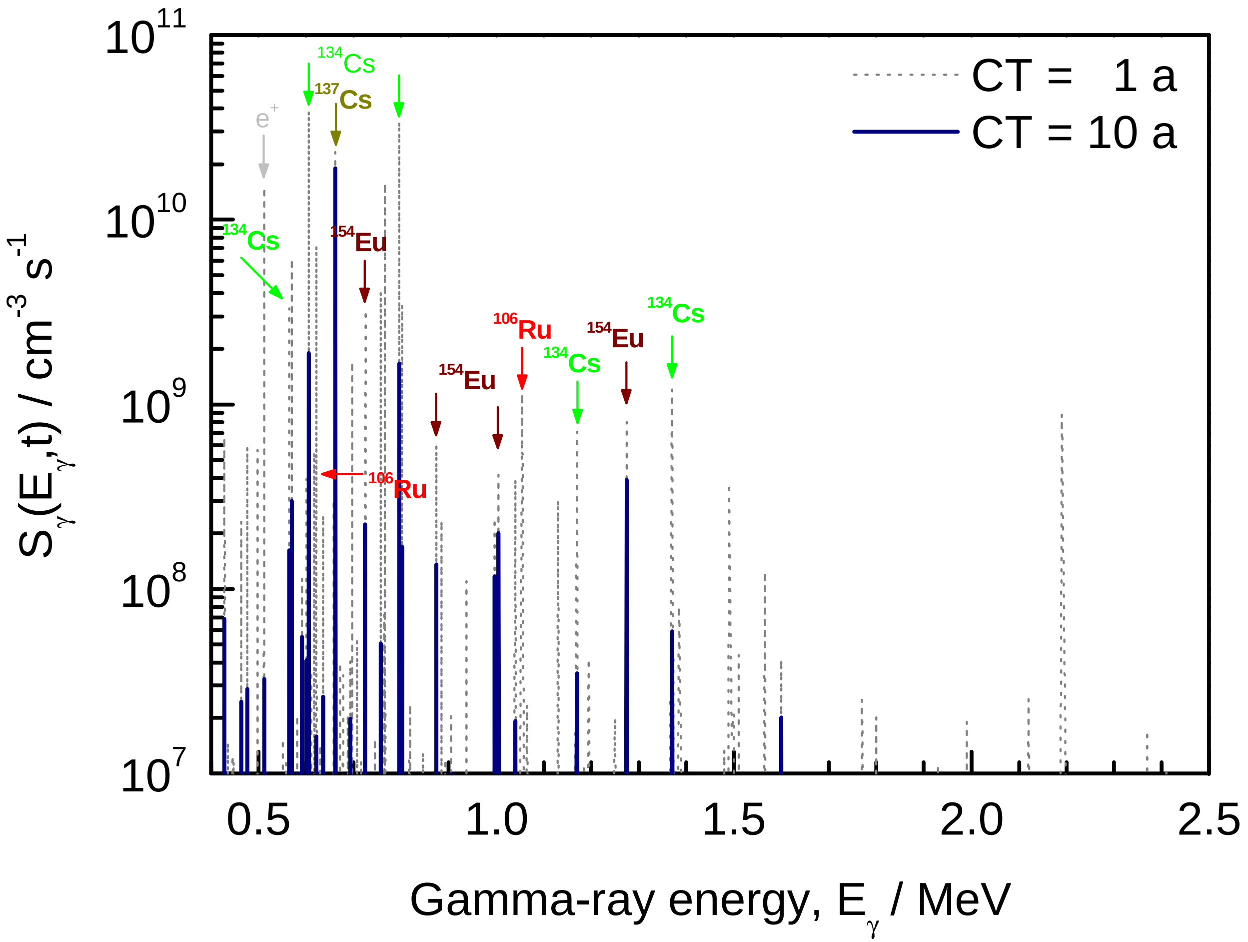

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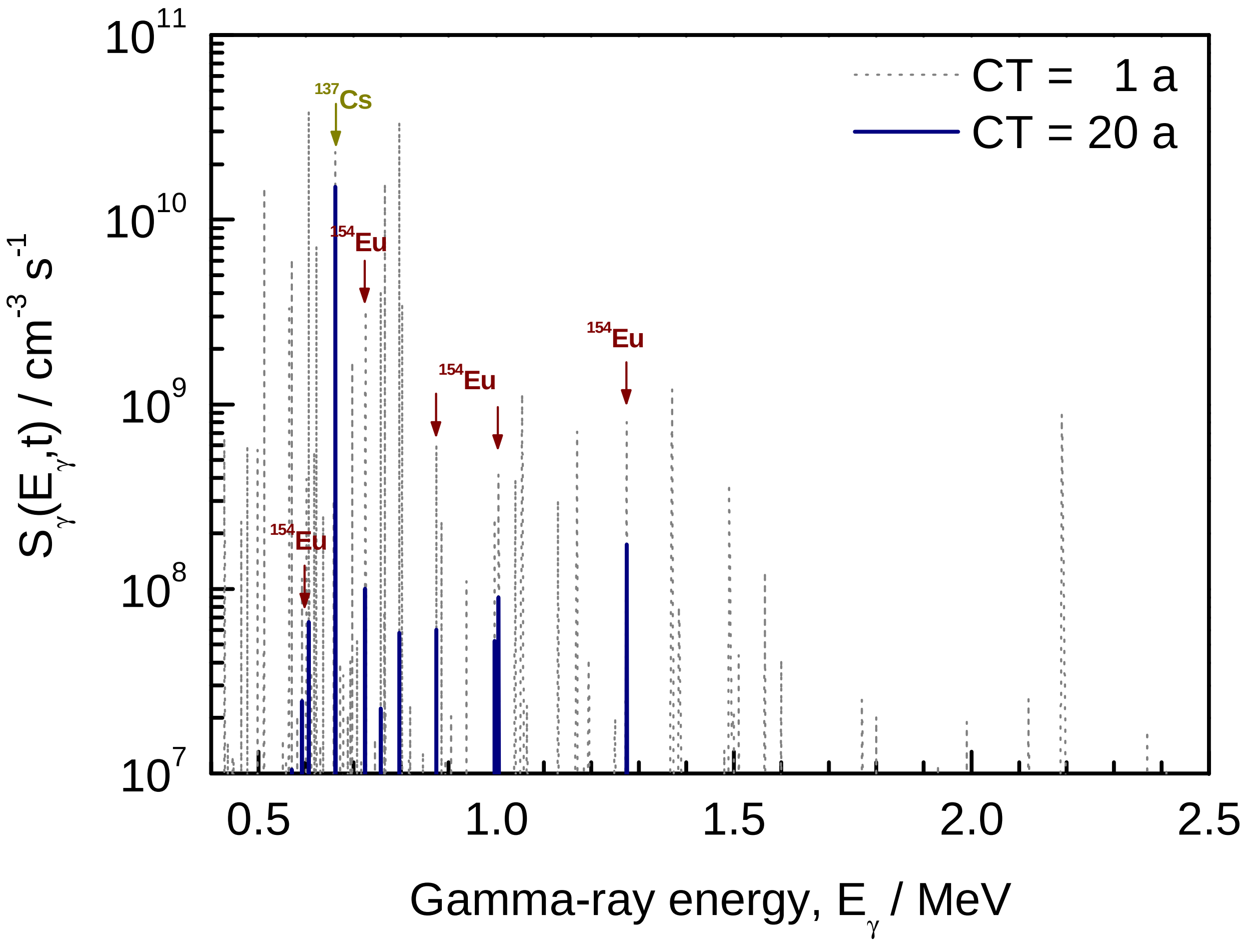

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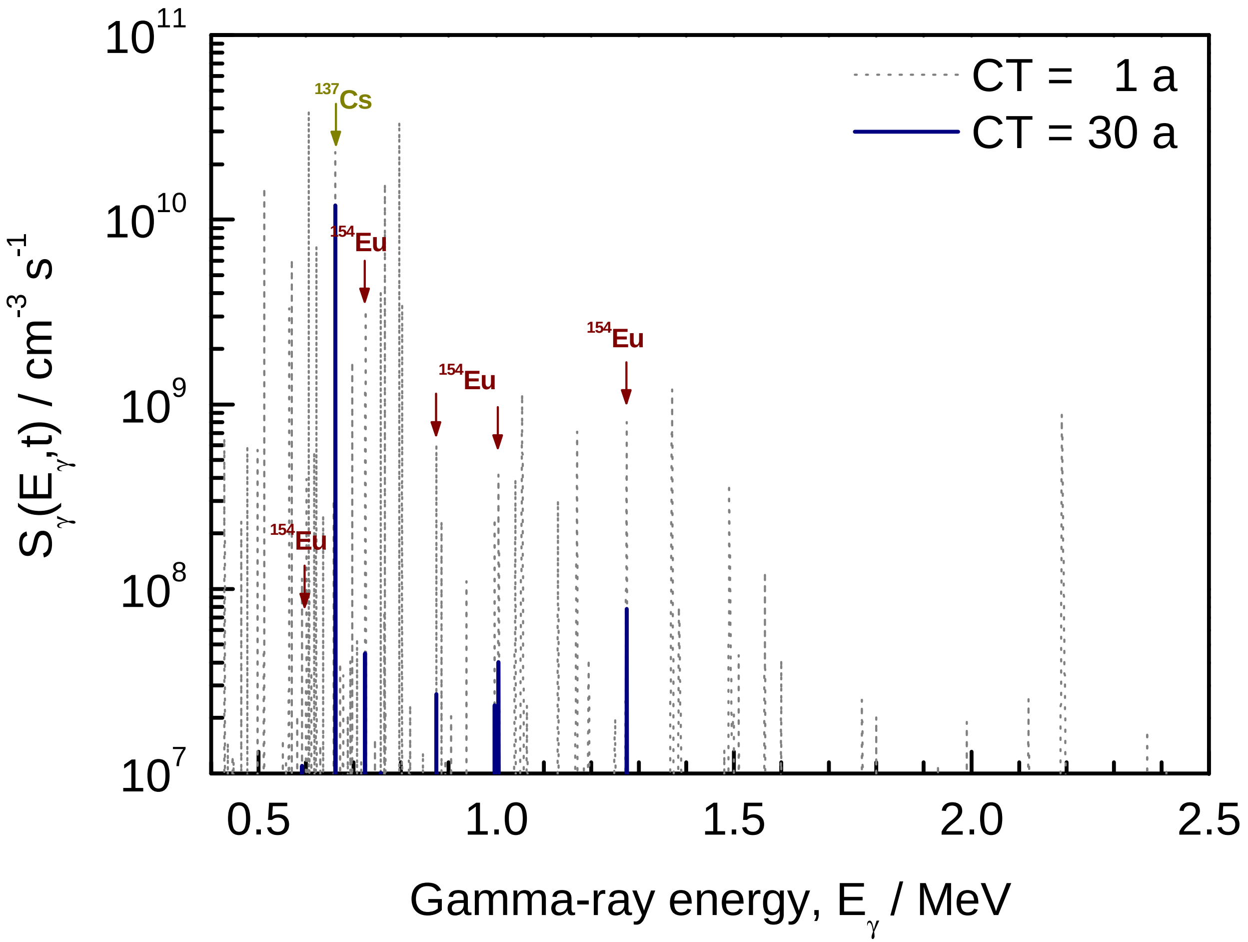
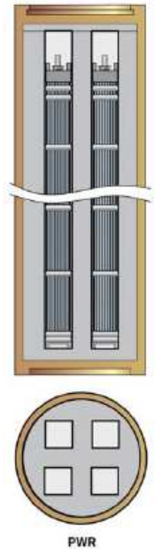
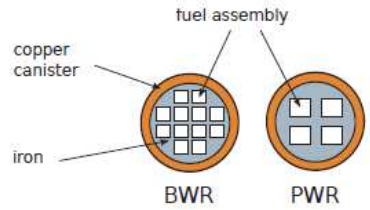


Characterisation of SNF

Main **source terms** of interest:

- Decay heat : H
- Neutron emission : S_n
- γ-ray emission : S_γ
- Reactivity : ^{235}U, ^{239}Pu, ^{241}Am, Fission Products (BUC)
- Fissile material : ^{235}U, ^{239}Pu
- Long-term safety : e.g. ^{14}C, ^{79}Se, ^{94}Nb, ^{99}Tc, ^{129}I, ^{226}Ra





Contributions of nuclides with different characteristics

Difficult to be measured directly, in particular during industrial operation

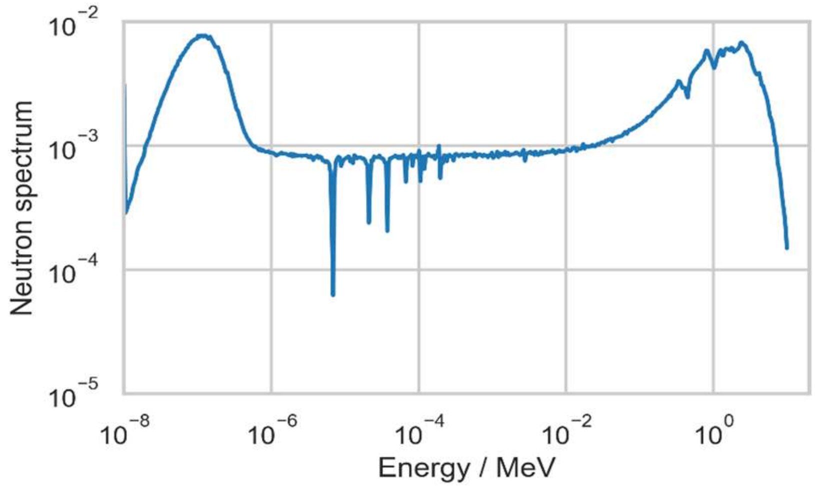
e.g. decay heat by calorimetry at CLAB: accurate but long measurement times

$\Rightarrow$ Estimated by **theoretical calculations** using a burnup code

$(N_k(t_0), k = 1, \ldots, n)$: by theoretical calculations

Coupled neutron transport – nuclide depletion/creation calculation

Neutron transport



Bateman equation

$$\frac{dN_k}{dt} = Y\, N_f\, \sigma_f\, \varphi + \sum_i \lambda_i N_i + \sum_j \sigma_j N_j\, \varphi - (\lambda_k + \sigma_{k,a}\varphi) N_k$$

Update nuclide vector

SFC – Task 2 (structure)

2.1 Theory

2.2 NDA

2.3 Cladding

2.4 Define/recommend **validated procedures** to estimate **SNF source terms** in **industrial conditions** with **realistic confidence limits** based on:

- Best practice **industrial code**
- **Realistic NDA** measurements (time, industrial environment)

SFC- Task 2: Code comparison

• CIEMAT	:	EVOLCODE (MCNP)
• JRC Geel	:	SERPENT, SCALE
• JSI	:	SCALE, DRAGON
• KIT	:	MCNP-CINDER
• NAGRA	:	SCALE
• PSI	:	CASMO
• SCK CEN	:	ALEPH-2 (MCNP)
• VTT	:	SERPENT

Sensitivity and Uncertainty (S/U) analysis

- Input data:
  - **Nuclear Data (ND)**
    - Cross sections (neutron interactions)
    - Fission yields
    - Neutron emission probabilities
    - Decay data
  - **Fuel History (FH)**
    - Fuel properties (design, composition)
      e.g. Initial enrichment (IE)
    - Reactor operation and irradiation conditions
      e.g. Burnup (BU)
    - Cooling time (CT)

BurnUp (BU):
time integrated power per mass of initial fuel (MWd/kg)
$\propto$ *total number of fission x energy per fission event*

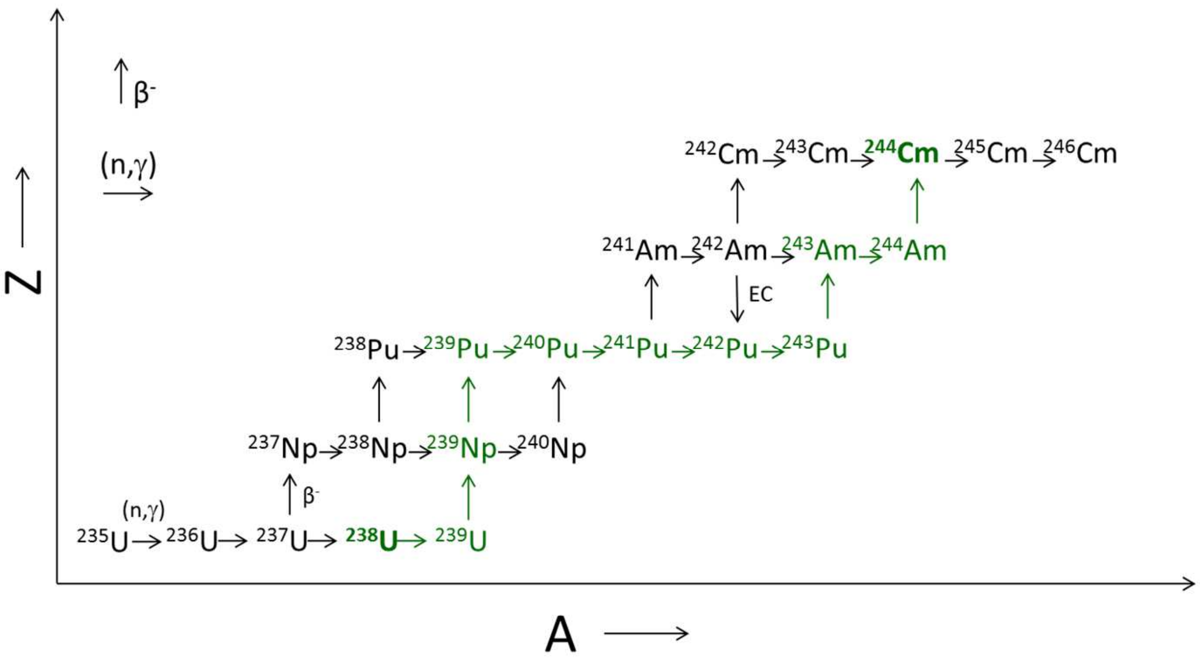
- Computational
  - Method: stochastic/deterministic
  - Model (2D/3D, boundary conditions, …)
  - Numerical approximations (depletion time steps, depletion zones, …)

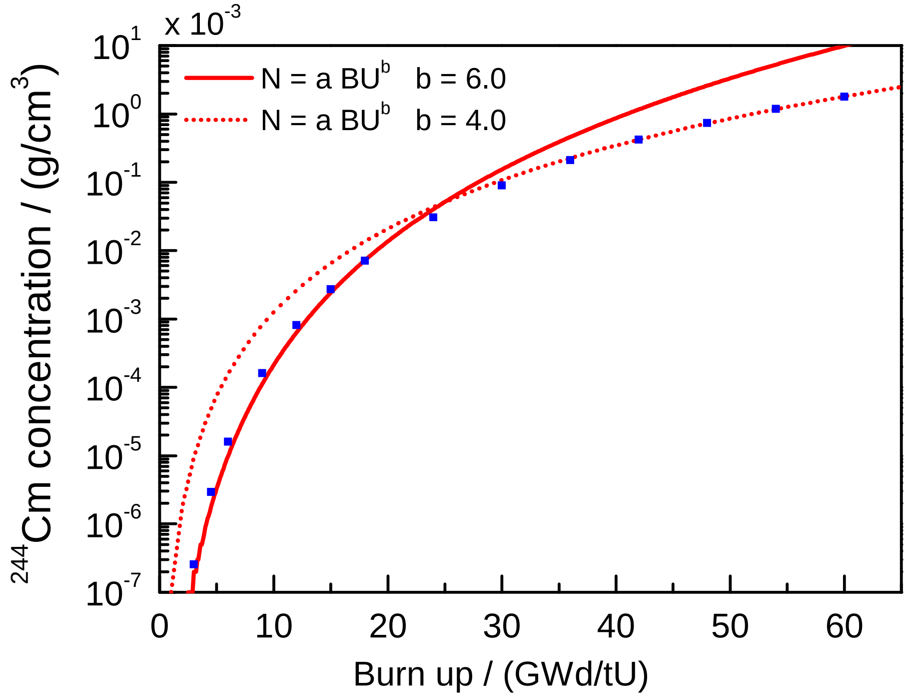
S/U analysis: ^{244}Cm production

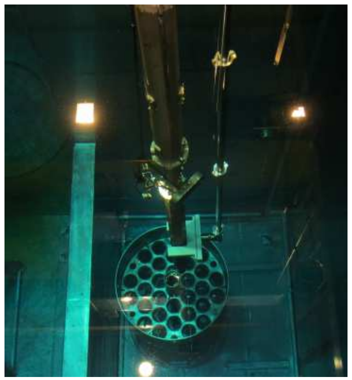
$$\frac{dN_k}{dt} = Y\,N_f\,\sigma_f\,\varphi + \sum_i \lambda_i N_i + \sum_j \sigma_j N_j\,\varphi - (\lambda_k + \sigma_{k,a}\varphi)N_k$$

$N = aBU^b$

b = 6 for BU < 20 GWd/t







⇒ ^{244}Cm : burnup indicator

⇒ Neutron emission rate : burnup indicator

S/U analysis: estimation of ^{244}Cm inventory

$$\frac{dN_k}{dt} = Y N_f \sigma_f \varphi + \sum_i \lambda_i N_i + \sum_j \sigma_j N_j \varphi - (\lambda_k + \sigma_{k,a}\varphi) N_k$$

Ref.	Library	Reactor	Fuel	BU GWd/t	IE wt%	^{244}Cm
Rochman	ENDF/B-VII.0	PWR	UO_2	10	4.1	18.7 %
	ENDF/B-VII.0	PWR	UO_2	20	4.1	16.9 %
	ENDF/B-VII.0	PWR	UO_2	30	4.1	15.5 %
	ENDF/B-VII.0	PWR	UO_2	40	4.1	14.1 %
Zwermann	SCALE-6.1	PWR	UO_2	40	4.1	8.5 %
Leary	ENDF/B-VII.1	PWR	UO_2	54	3.4	9.6 %
Rochman	ENDF/B-VII.1	PWR	UO_2	54	3.4	9.1 %
Rochman	ENDF/B-VII.1	PWR	UO_2	40	4.1	9.7 %

^{244}Cm inventory prediction production

- uncertainty due to nuclear data : ~10%
- due to ^{242}Pu(n,γ), ^{243}Am(n,γ)

⇒ Systematic study for key nuclides

⇒ Improve nuclear data

- Input HPRL NEA/OECD
- Input to SANDA (DG-RTD)
  https://cordis.europa.eu/project/id/847552
  Supplying Accurate Nuclear Data for energy and non-energy Applications

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Innovative NDA methods/systems for SNF characterisation

- **Innovative NDA** methods to characterise **pin segments**
  - **Validate codes** (alternative to radiochemical analysis)
  - Production of a reference pellet

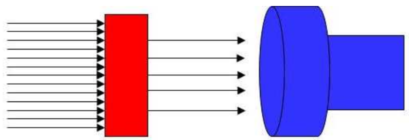
- **NDA** methods to characterise **fuel assemblies** (SKB-50)
  - Improve theoretical source term predictions during industrial routine operation **Improve fuel history** data: e.g. BU
  - Validate codes

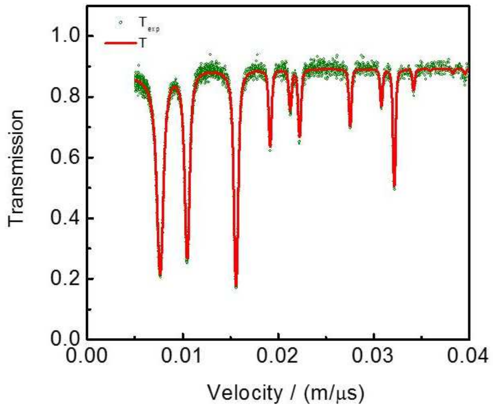
- Study **new detectors**
  - CLYC, *CVD*

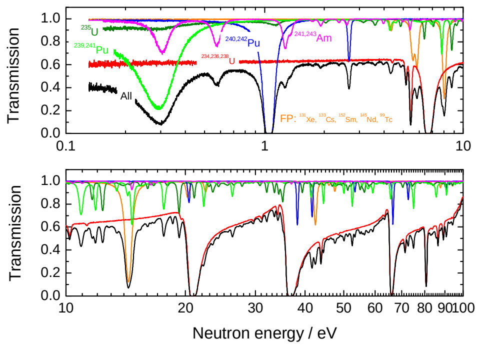
NDA methods to characterise pin segments

- **Neutron emission rate** of a SNF pin segment
  (collaboration SCK CEN – JRC Geel, Ispra)
  - Non-destructive method to determine ^{244}Cm content
  - Measurements in conventional controlled area conditions
    Hage's point model, JRC Ispra (B. Pedersen)

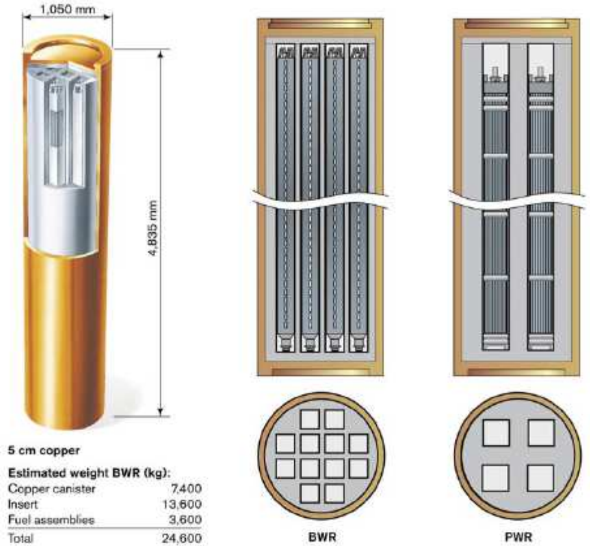
- **Nuclide vector** of SNF pin segment by **NRTA**
  (collaboration SCK CEN – JRC Geel)
  - **Non-destructive**; no chemical analysis
  - **Absolute** measurement (no calibration)
  - Measurements at **GELINA** facility of JRC Geel







Experiments at CLAB: SKB-50



Installed systems

- Calorimeter
- Gamma-ray spectroscopic scanner

Testing of advanced systems (LANL)

- Differential Die-Away Self-Interrogation (DDSI)
- Differential Die-Away (DDA)

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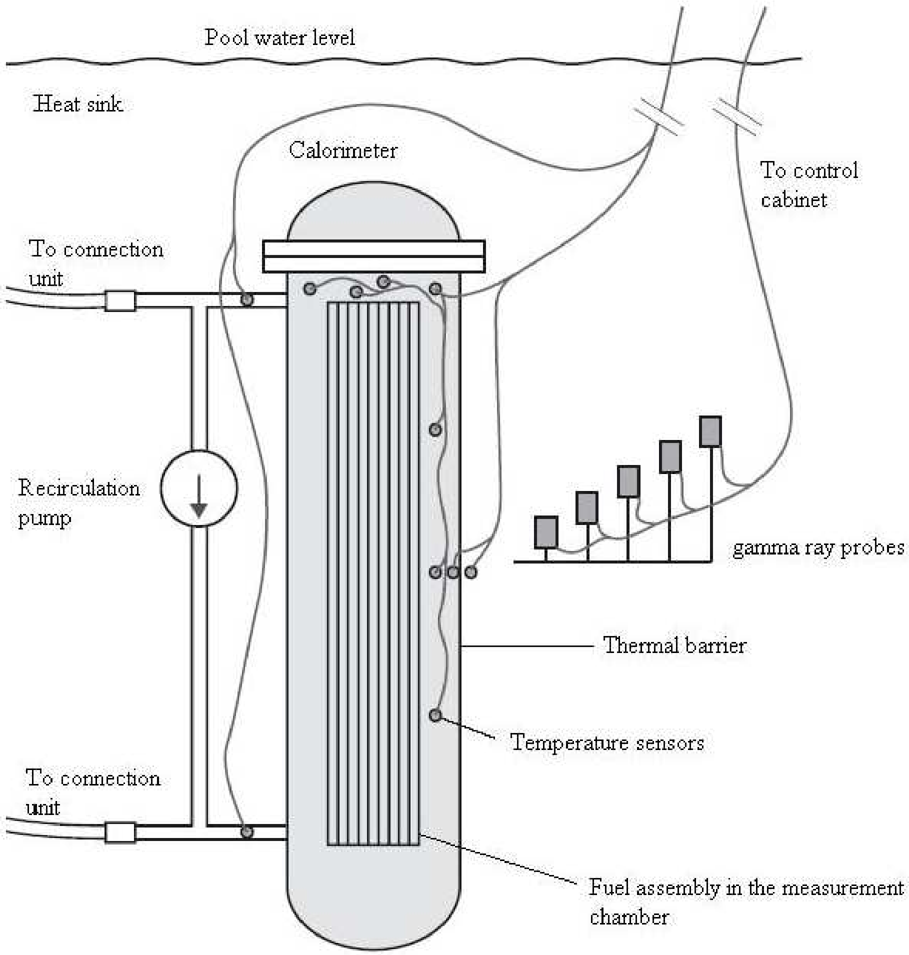
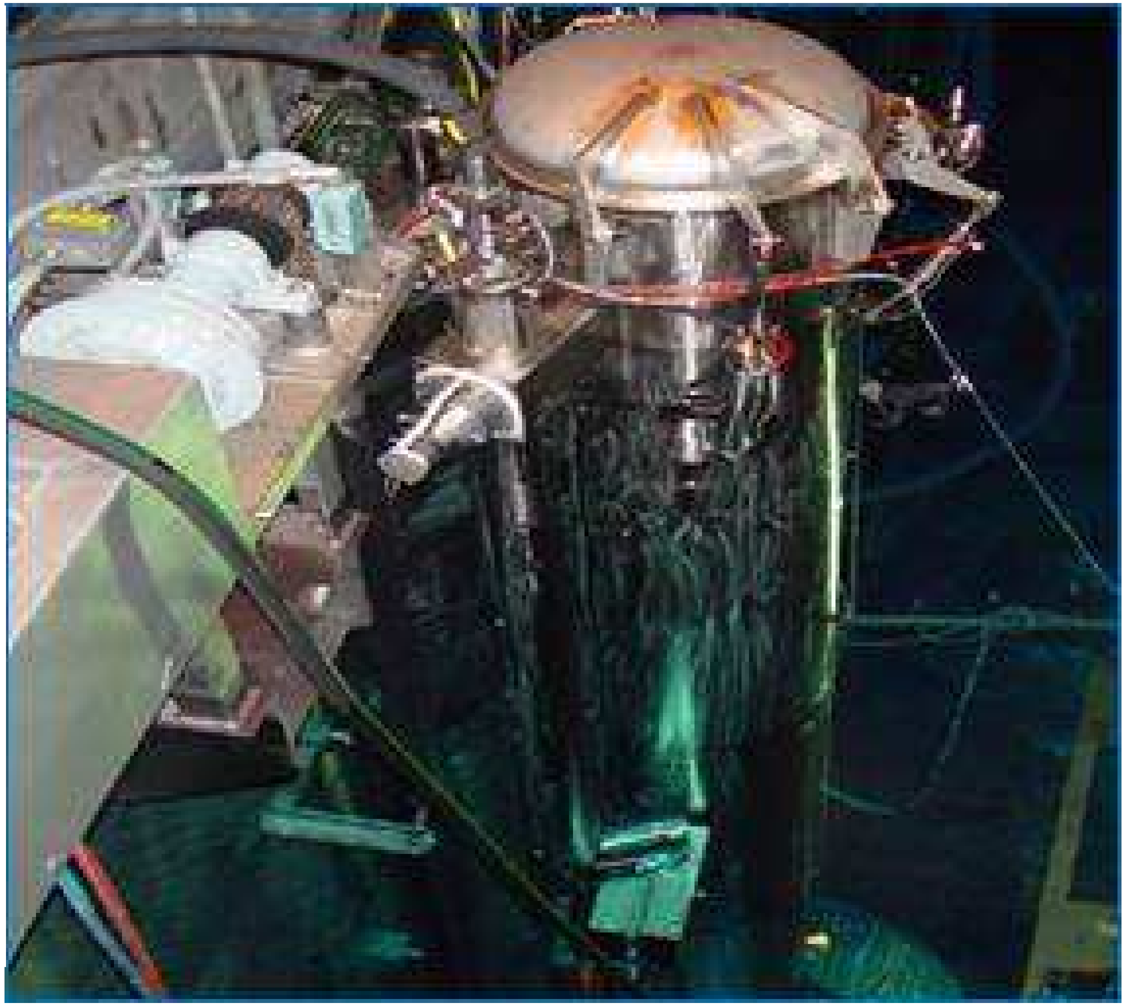
Calorimeter at CLAB

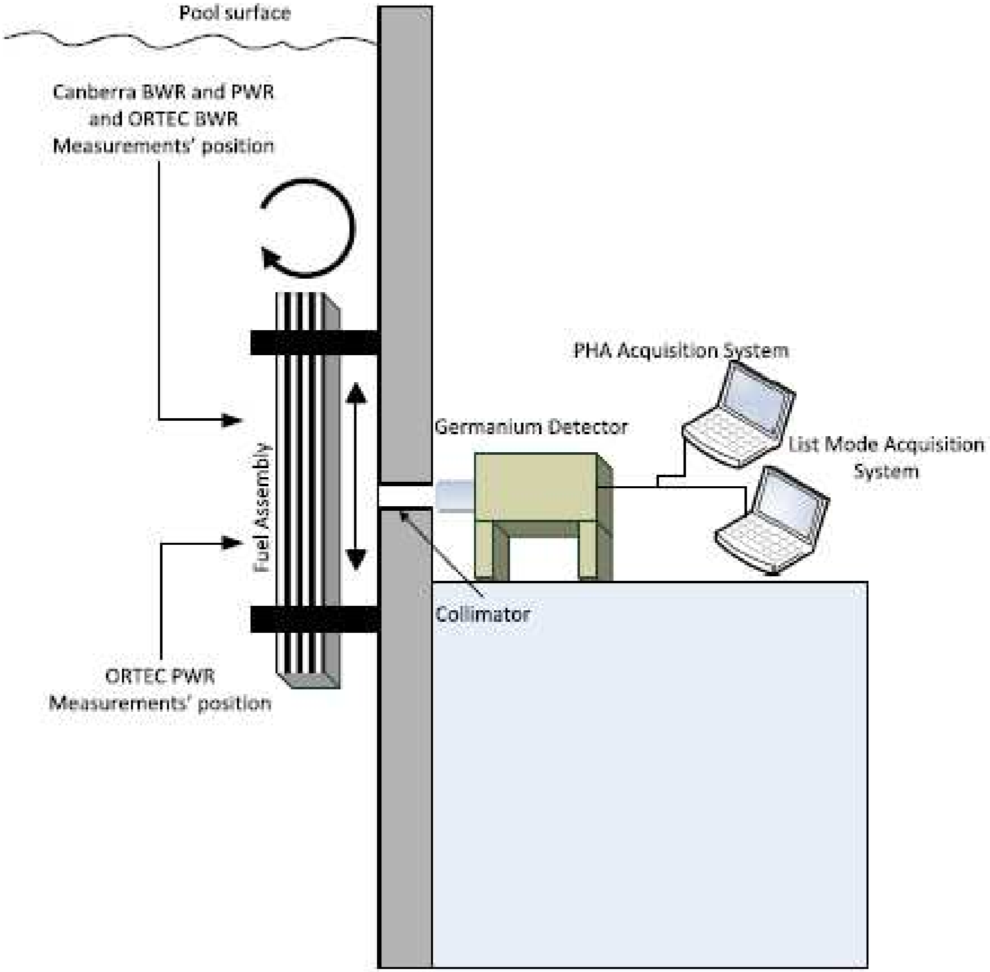




⇒ Target value uncertainty ≤ 2%

⇒ Reference instrument for decay heat of SNF

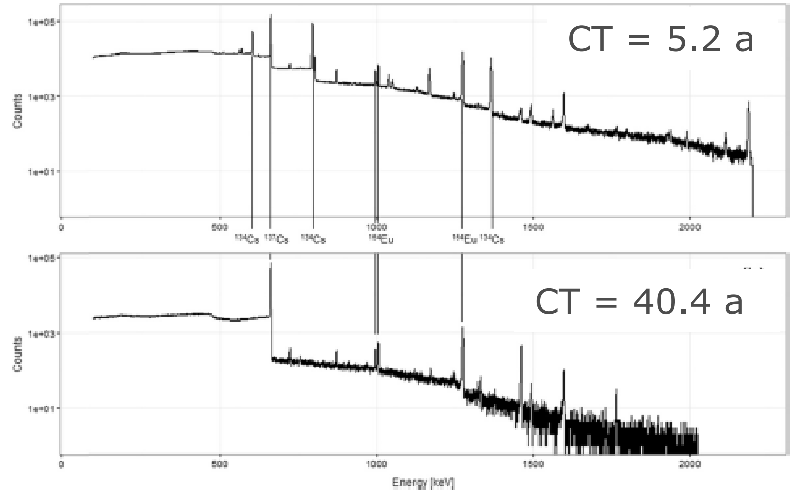
Gamma-ray spectroscopic scanning system at CLAB



Vaccaro et al. NIMA 830 (2016) 325

^{134}Cs, ^{137}Cs, ^{154}Eu

PWR



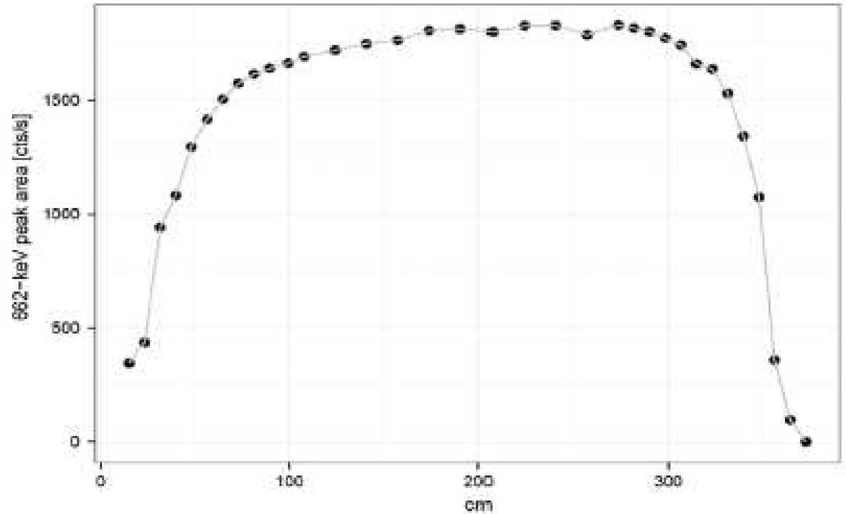
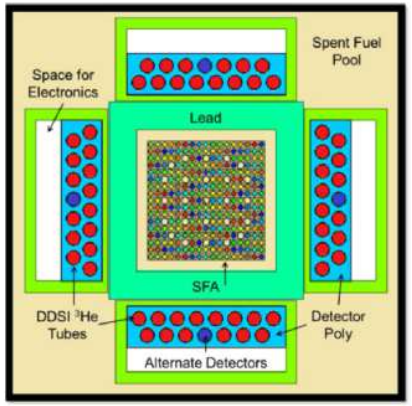


Fig. 8. Count rate for the 662-keV 137Cs net peak area as a function of axial location along BWR9. These data were measured with the ORTEC GMX detector and Canberra Lynx MCA from the 45° corner. The axial location is specified as downward along the uranium containing portion of the fuel (The indicated absolute positions are accurate to ± 10 cm, the error bars are much smaller than the data points).

Fuel assemblies: DDSI and DDA at CLAB (LANL development, NGSI)

- Differential Die Away Self-Interrogation (DDSI, passive)

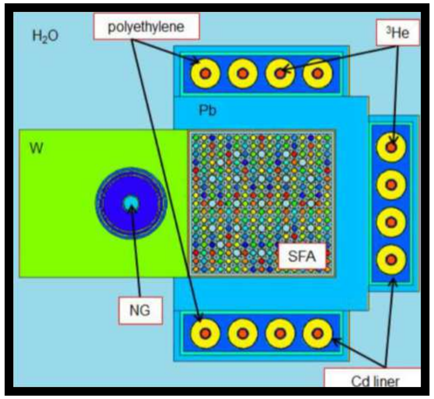
A.C. Trahan, LA-UR_16_20026   Kaplan et al., NIMA 764 (2014) 347 - 351



⇒ Optimise data analysis procedures for source term determination (not only safeguards)

- Differential Die Away (DDA, active)

V. Henzl, LANL-UR-123025



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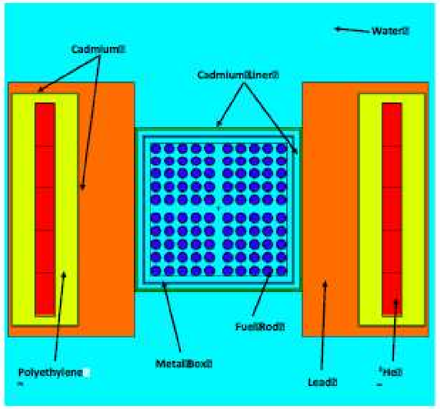
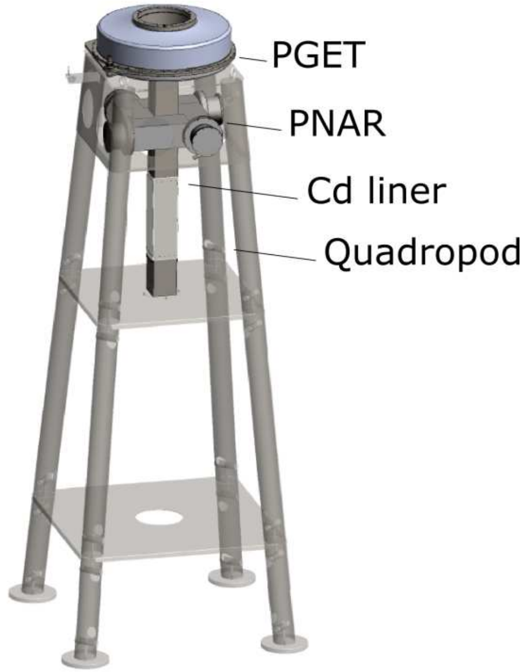
Fuel assemblies: Finland

- Passive Neutron Albedo Reactivity (PNAR, NGSI)

LANL development, Tobin et al., NIMA 897 (2018) 32 - 37

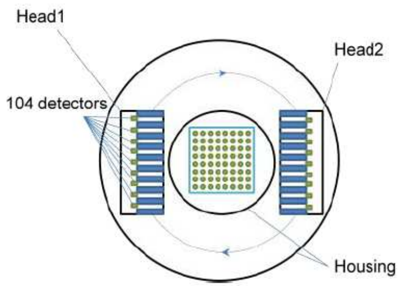
Tobin et al., ESARDA bulletin 56 (2018) 12 - 18





- Passive Gamma Ray Emission Tomography (PGET)

IAEA development, Honkamaa et al., Symp. Int. Safeguards, IAEA Vienna 2014



EURAD-SFC (4 years project)

Define/recommend **validated procedures** to estimate **SNF source terms** (including fissile material) in **industrial conditions** with **realistic confidence limits** based on:

- Best practice **industrial code**
- **Realistic NDA** measurements (time, industrial environment)

- EURAD project (SNF characterisation)
  - https://www.ejp-eurad.eu/about-eurad
  - NUGENIA, http://nugenia.org/call-for-mobility-grants-open/
- ARIEL
  support for open access, scientific visits, training early researchers, …
  - www.ariel-h2020.eu
- JRC Geel open access
  - https://ec.europa.eu/jrc/en/research-facility/open-access

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