An Experimental Programme optimized with Uncertainty Propagation: PETALE in the CROCUS Reactor

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[2] Laboratory for Reactor Physics and Thermal-Hydraulics (LRT), Paul Scherrer Institute (PSI)

[3] Experimental Physics, Safety & Instrumentation Division (SPESI), French Alternative Energies and Atomic Energy Commission (CEA)

[4] Reactor Physics and Fuel Cycle Division (SPRC), French Alternative Energies and Atomic Energy Commission (CEA)

[5] Nuclear Energy and Safety Research Division (NES), Paul Scherrer Institute (PSI)

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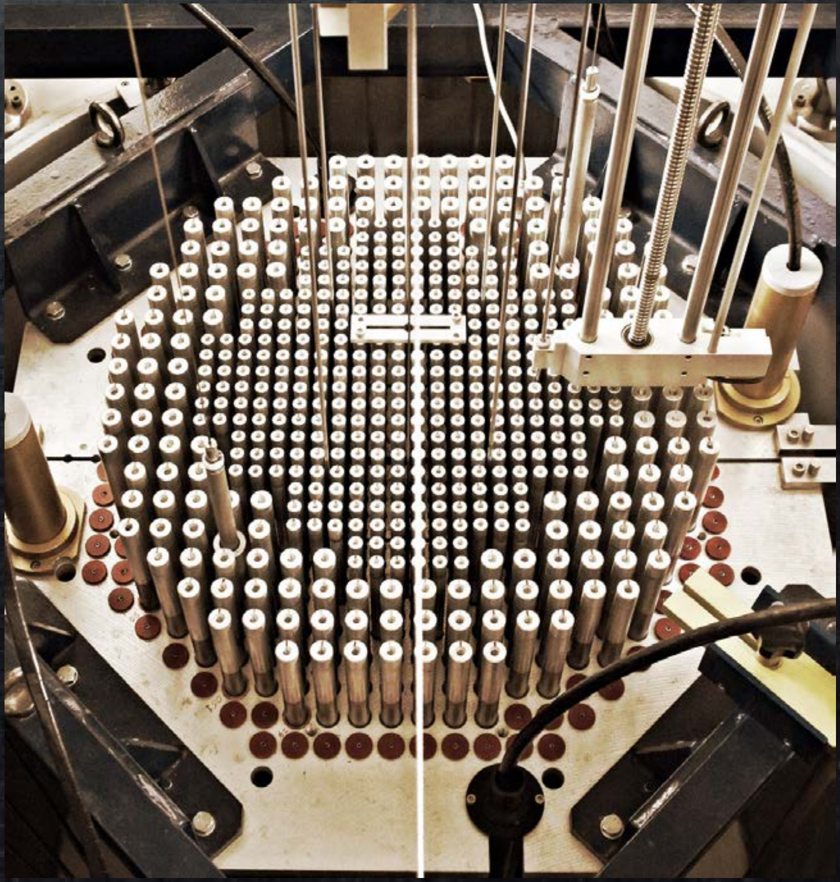
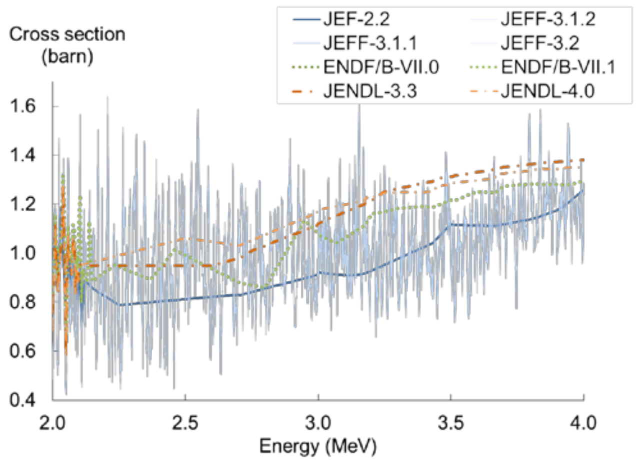


Motivation and goals

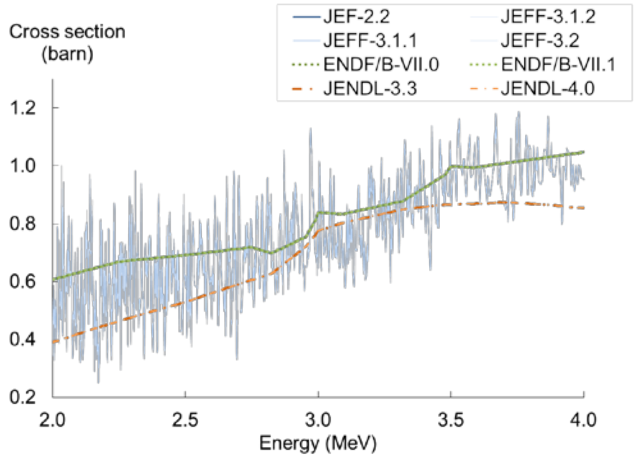
Goals

Contribute to the validation effort on the nuclear data for materials of heavy steel reflector in GEN-III PWR

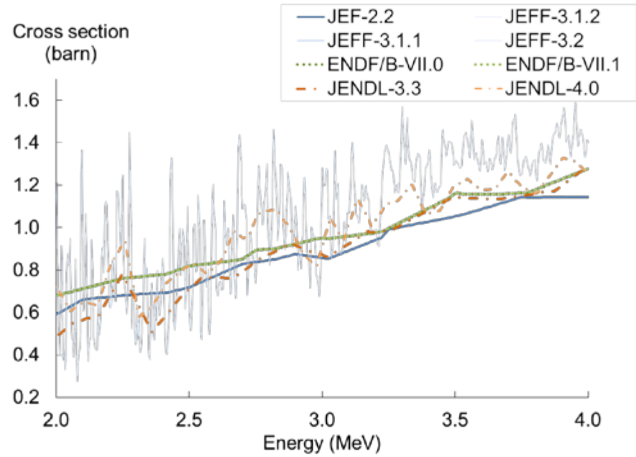
Advance the database for elemental-type integral experiments, in the prospect of data assimilation



^{56}Fe inelastic scattering cross section

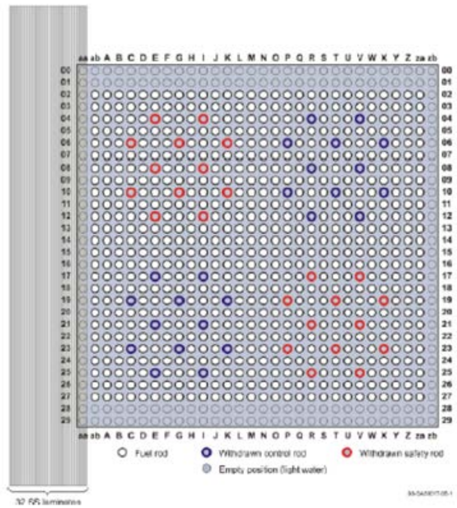


^{56}Ni inelastic scattering cross section

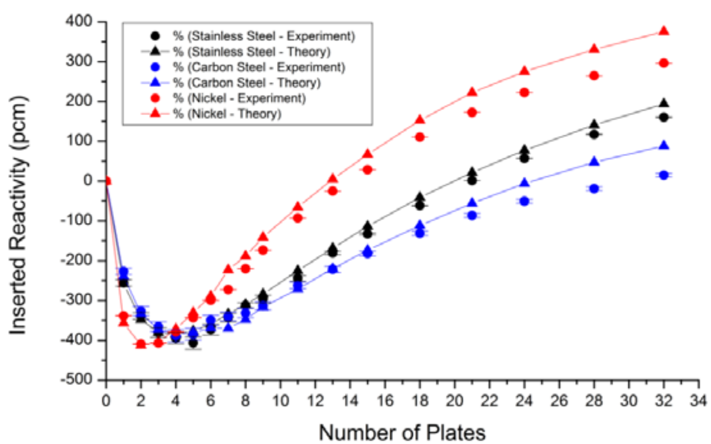


^{52}Cr inelastic scattering cross section

Motivation and goals



Cross section of the
heavy reflector core at IPEN/MB01



Theory-Experiment comparison for
the heavy reflector experiment

Previous experiments

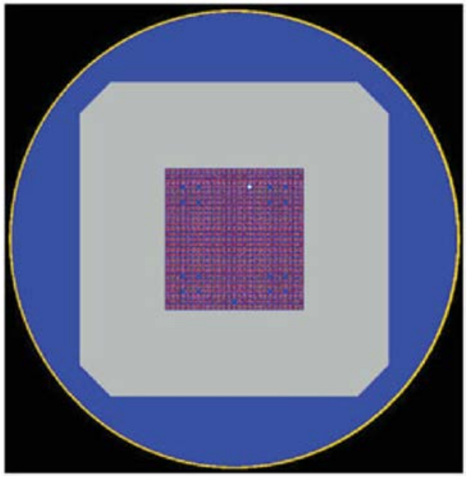
Heavy reflector in IPEN/MB-01 reactor[1]

- Varying thickness of the reflector
  - Using 3.2 mm-thick plates
  - Up to 32 plates (~10 cm)
- Elemental-oriented experiment
  - s.s., carbon steel and nickel
- Focusing on reactivity impact

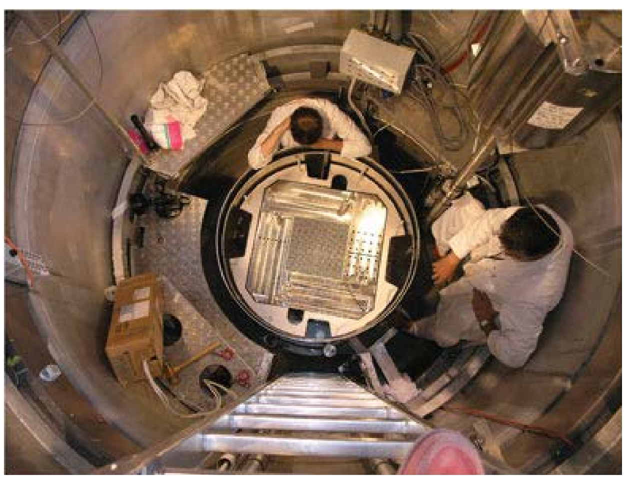
- Conclusion
  - Demonstrated competition between absorption and reflection
  - General over-prediction after 4 cm
  - Ni still under study, Cr not studied

[1] A. Dos Santos et al., "Three heavy reflector experiments in the IPEN/MB-01 Reactor: Stainless Steel, Carbon Steel, and Nickel," *Nucl. Data Sheets*, vol. 118, no. 1, pp. 568–570, 2014.

Motivation and goals



Cross section of the EOLE core for PERLE



Top view of the PERLE experiments
in the EOLE reactor

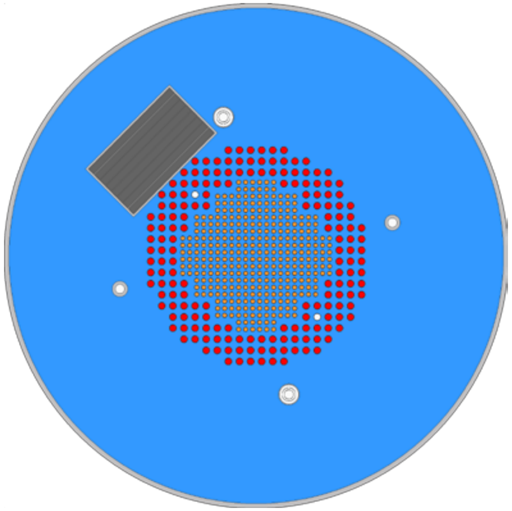
Previous experiments

PERLE[2] in CEA EOLE reactor

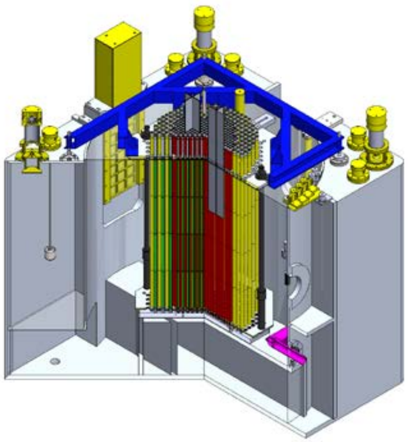
- Core Gen III PWR representative
  - Moderator ratio (1.7) and spectrum
  - 22 cm-thick stainless steel reflector
- Several types of measurements
  - residual reactivity
  - pin-by-pin power map
  - attenuation in the reflector
  - gamma heating in the reflector
- Conclusion
  - Discrepancies in residual reactivity between the libraries and with the measured value
  - Satisfactory k_{eff}
  - ^{56}Fe cross section proved globally correct using JEFF3.1.1

[2] C. Vaglio-Gaudard et al., “Interpretation of PERLE Experiment for the Validation of Iron Nuclear Data Using Monte Carlo Calculations,” *Nucl. Sci. Eng.*, vol. 166, pp. 89–106, 2010.

Motivation and goals



Section of the CROCUS vessel with the metal reflector in Serpent



Cross section of the CROCUS core and vessel

Goals

Contribute to the validation effort on the nuclear data for materials of heavy steel reflector in GEN-III PWR

Advance the database for elemental-type integral experiments, in the prospect of data assimilation

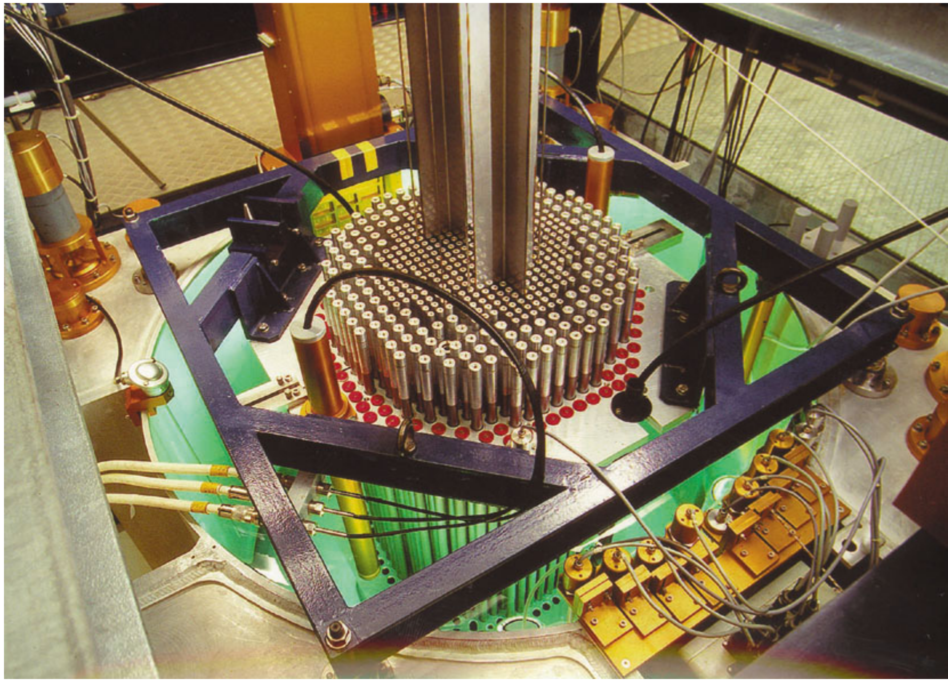
Experimental programme in CROCUS for separated elements

- s.s., and pure Fe, Ni and Cr
- Varying thickness, up to 16 cm
- Reactor experiments for extracting nuclear data in the MeV range from reactivity effects and attenuation measurements
- Project within a new collaboration between CEA and EPFL

Experimental setup

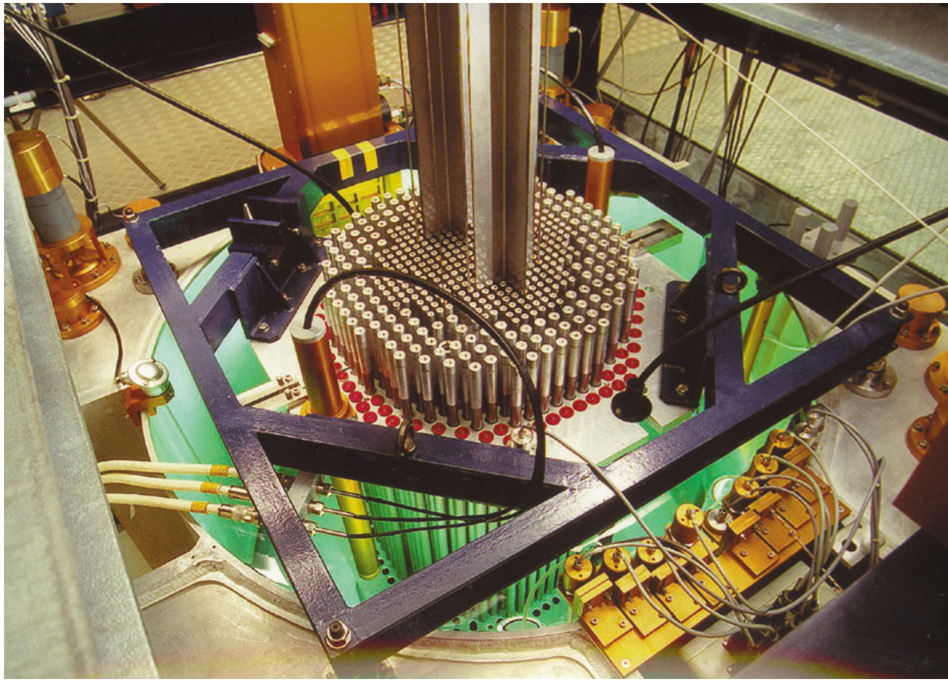
The CROCUS reactor

- Reactor type
  - LWR with partially submerged core
  - Room T (controlled) and atmospheric P
  - Forced water flow (160 l.min^{-1})

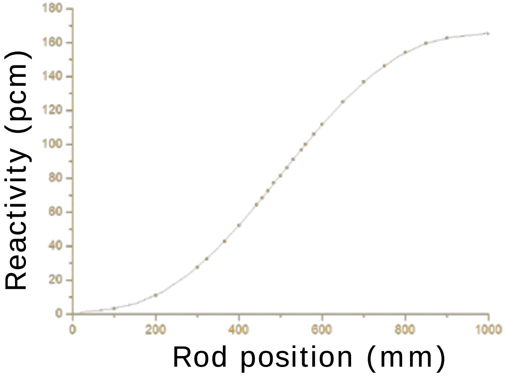


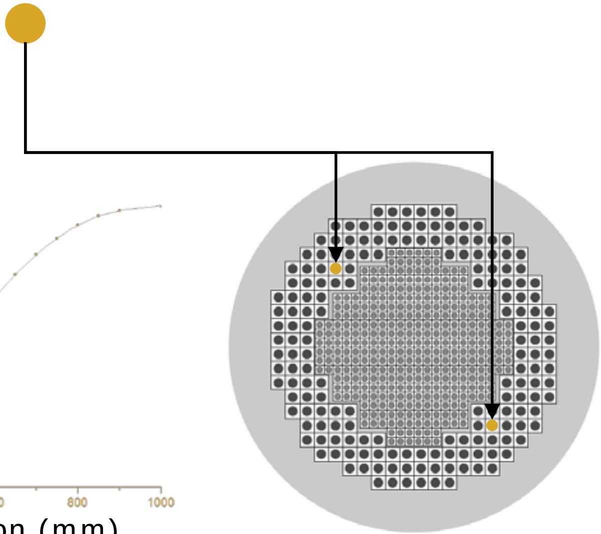
Experimental setup

The CROCUS reactor



- Reactor type
  - LWR with partially submerged core
  - Room T (controlled) and atmospheric P
  - Forced water flow (160 $l.min^{-1}$)
- Operation
  - Max. 100 W (zero-power reactor)
  - i.e. maximum 2.5×10^9 $cm^{-2}.s^{-1}$
  - Control: B_4C rods and spillway





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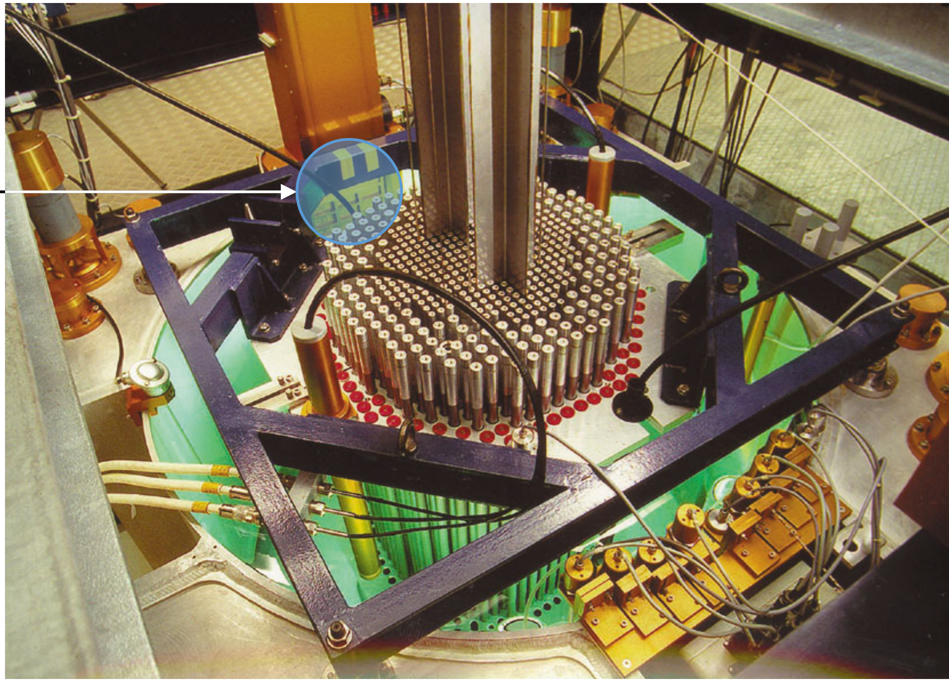

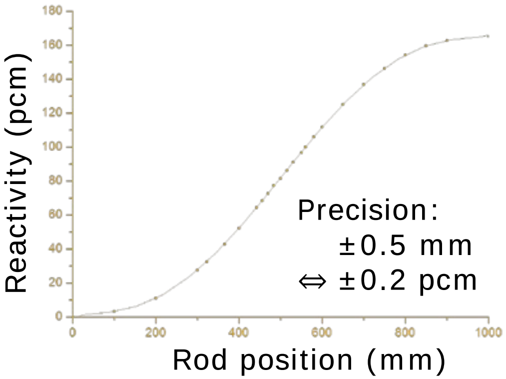

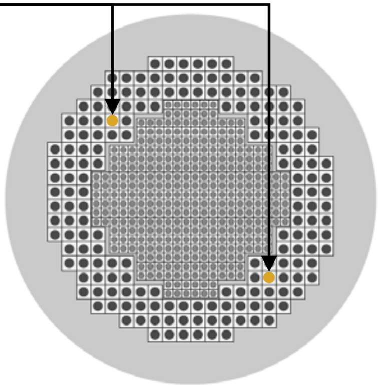

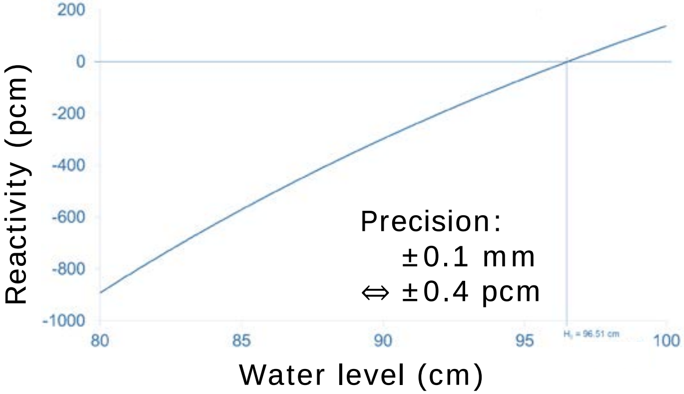

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  - LWR with partially submerged core
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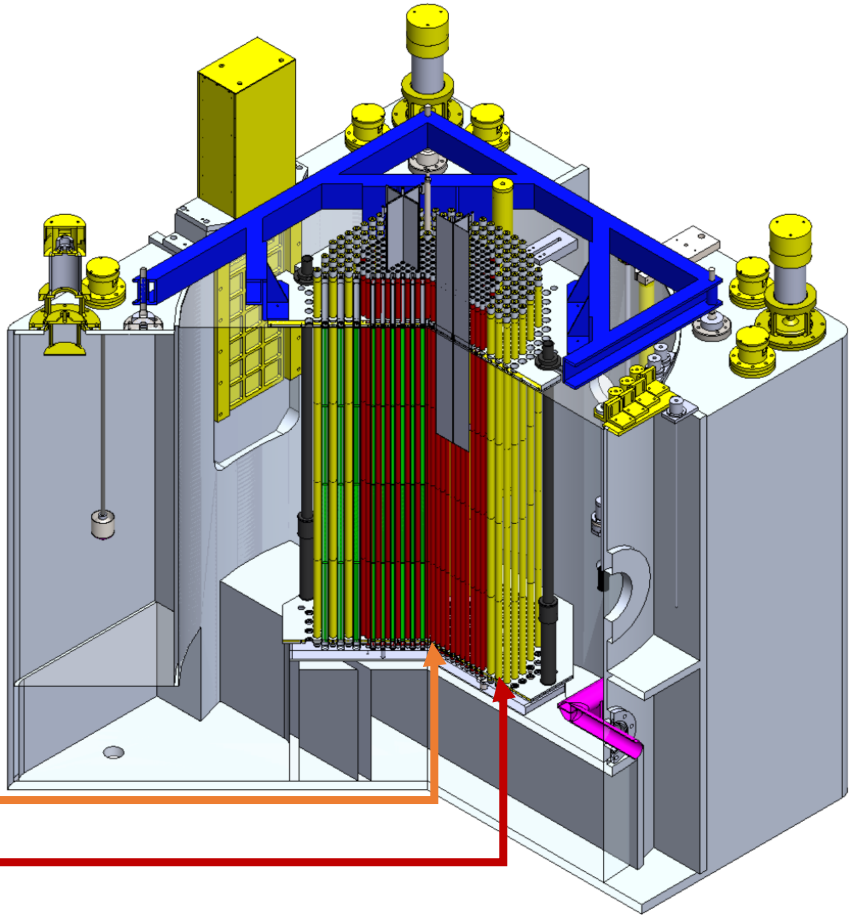
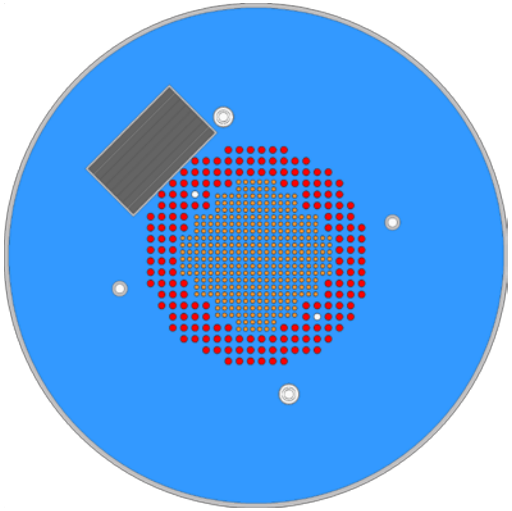
  - Forced water flow (160 $l.min^{-1}$)
- Operation
  - Max. 100 W (zero-power reactor)
  - i.e. maximum 2.5×10^{9} $cm^{-2}.s^{-1}$
  - Control: B_4C rods and spillway
- Core dimensions
  - ⌀60 cm/100 cm
- Fuel lattices
  - 2-zone (2.5 MR): 336/172-176 rods
  - Inner: UO_2 1.806 wt% 1.837 cm
  - Outer: U_{met} 0.947 wt% 2.917 cm



Experimental setup

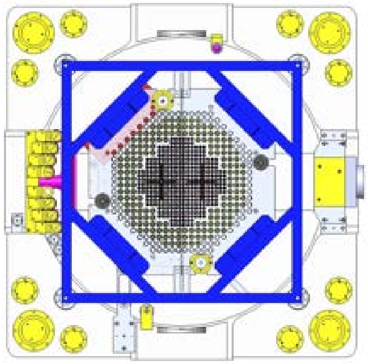
Preliminary design

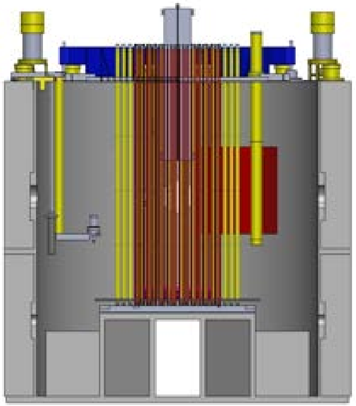


Section of the CROCUS vessel with the metal reflector in Serpent

Feasibility study[3] performed with MCNPX using ENDF/B-VII.1 libraries

- Reflector size
  - Reactivity effects below operation limit (200 pcm) for all cases
  - Reflector spectrum: in-core volume and cost vs scattered thermal neutrons



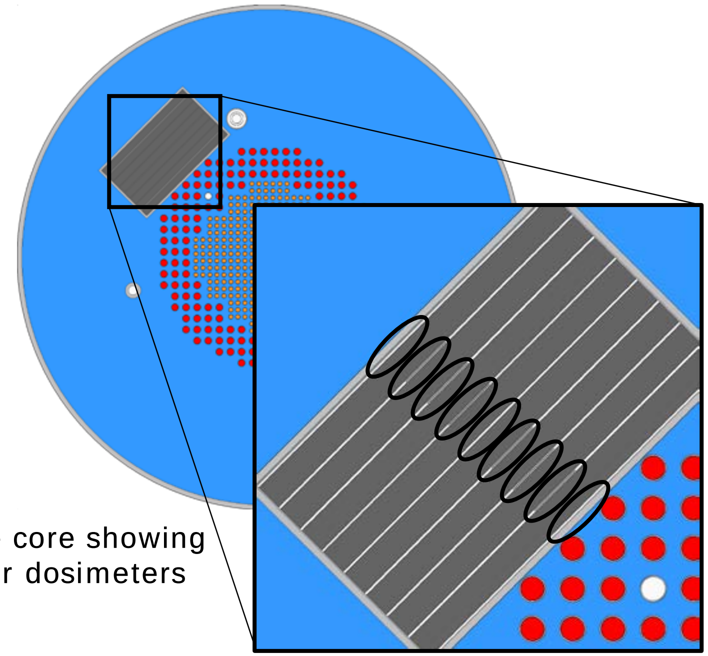


Top and side section of CROCUS with the metal reflector

[3] V. Lamirand *et al.*, "Design of Separated Element Reflector Experiments in CROCUS: PETALE," Accepted in ASTM STP1608: Reactor Dosimetry: 16th International Symposium, Santa Fe (USA), 2018.

Experimental setup

Preliminary design



Section of the core showing metal reflector dosimeters

Feasibility study[3] performed with MCNPX using ENDF/B-VII.1 libraries

- Reflector size
  - Reactivity effects below operation limit (200 pcm) for all cases
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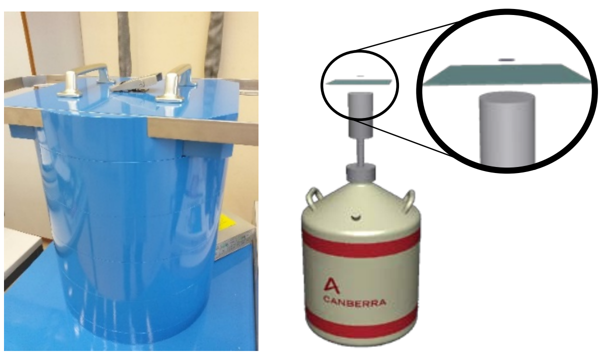
- Foils activation
  - Feasible flux levels for sufficient activation of selected dosimeters
  - Measurements at EPFL, CEA and remote low-activity laboratories

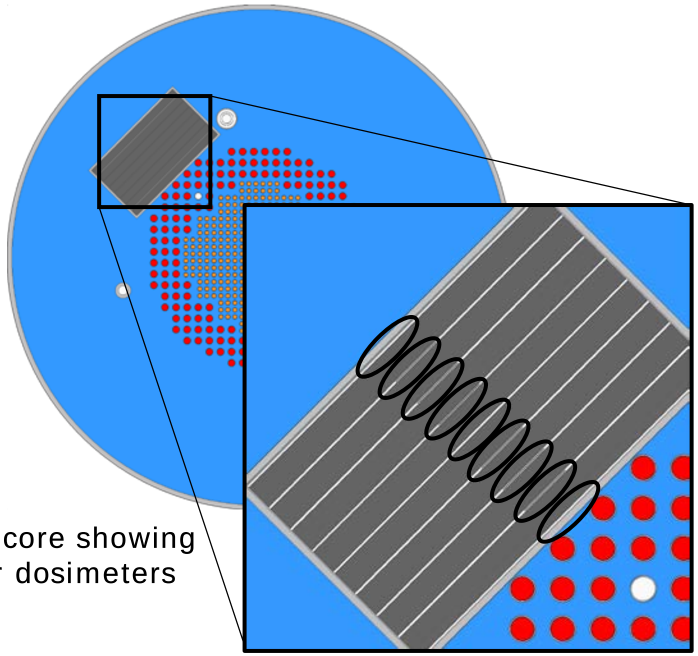


LRS high efficiency Canberra HPGe station with simulated source definition

[3] V. Lamirand *et al.*, "Design of Separated Element Reflector Experiments in CROCUS: PETALE," Accepted in ASTM STP1608: Reactor Dosimetry: 16th International Symposium, Santa Fe (USA), 2018.

Experimental setup

Preliminary design



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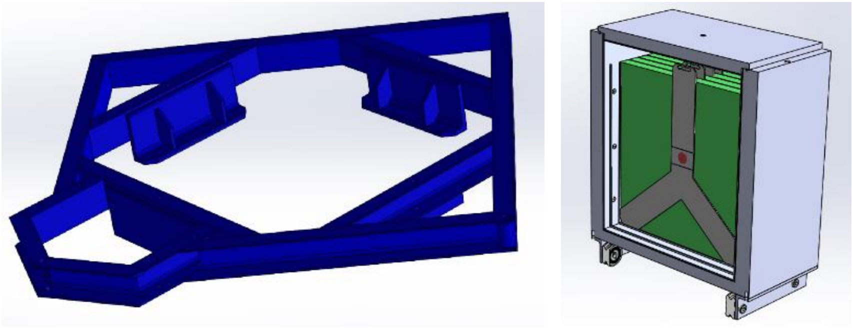


Preliminary sketches of the modified frame and the reflector positioning device

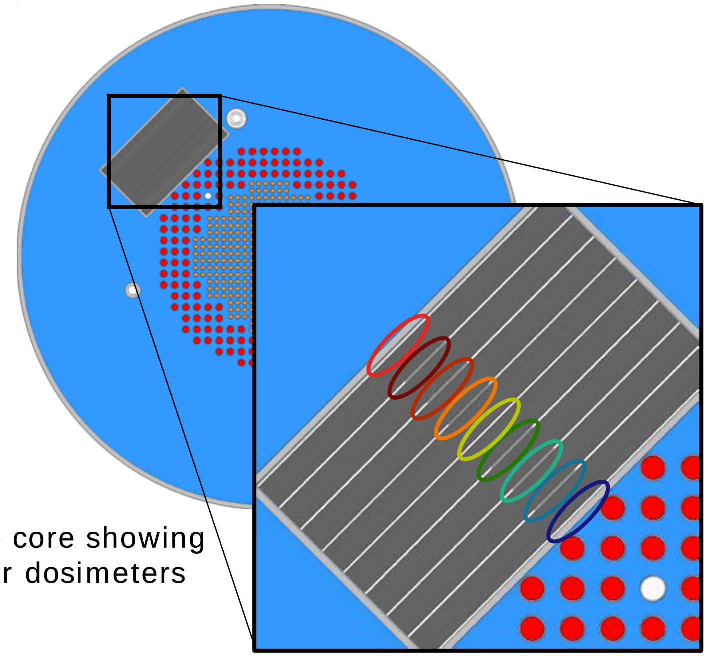
Feasibility study[3] performed with MCNPX using ENDF/B-VII.1 libraries

- Reflector size
  - Reactivity effects below operation limit (200 pcm) for all cases
  - Reflector spectrum: in-core volume and cost vs scattered thermal neutrons
- Foils activation
  - Feasible flux levels for sufficient activation of selected dosimeters
  - Measurements at EPFL, CEA and remote low-activity laboratories
- Reflector design
  - Metal sheets purchased in 2015: 8 sheets of 30 x 30 cm^2, 2 cm-thick
  - Optimized for operation constraints
  - Ongoing final update of the design for uncertainty reduction[4], in preparation of manufacture

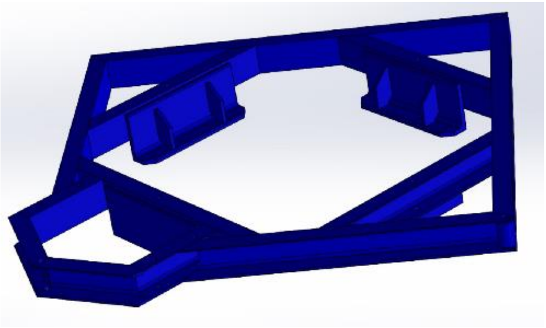
[4] V. Lamirand and A. Laureau, “Elemental reflector experiments in CROCUS: PETALE,” in Nuclear Data Week - JEFF meetings, NEA Headquarters, Paris (France), 2017.

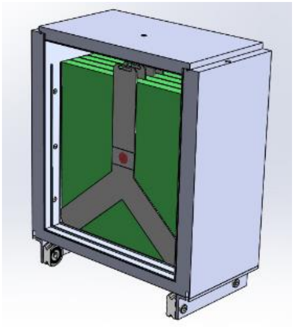
Experimental setup

Preliminary design



Section of the core showing metal reflector dosimeters





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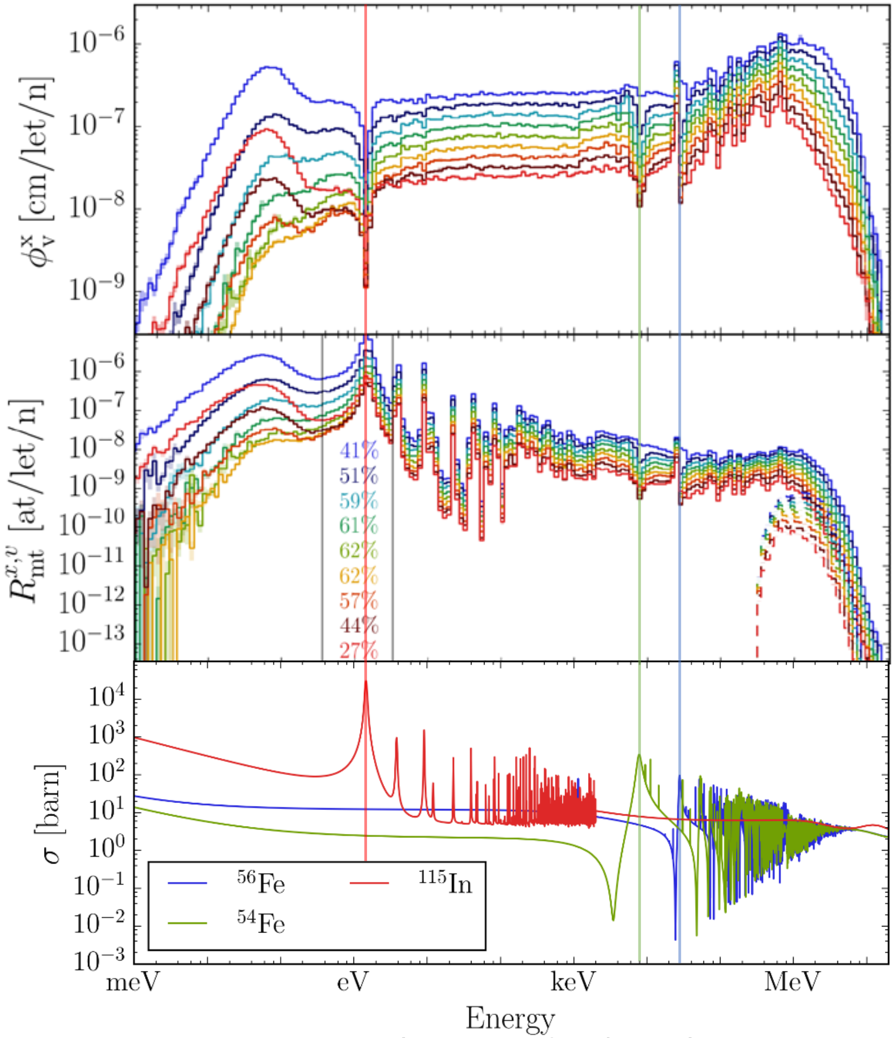


Integrated neutron flux/reaction rate in the indium dosimeters for the iron reflector

[4] V. Lamirand and A. Laureau, “Elemental reflector experiments in CROCUS: PETALE,” in Nuclear Data Week - JEFF meetings, NEA Headquarters, Paris (France), 2017.

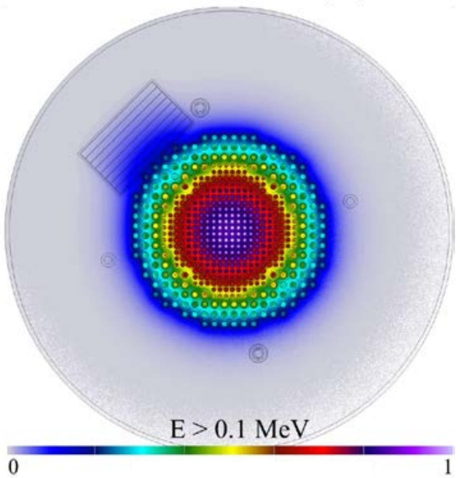
Optimization of the programme

Motivation

- Limited neutron flux

  Max. 100 W, i.e. total flux:

  - 2.5×10^{9} $cm^{-2}.s^{-1}$ at core centre
  - 1.0×10^{9} $cm^{-2}.s^{-1}$ at periphery



Fast neutron flux in CROCUS (a.u.)

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  - 2.5×10^{9} $cm^{-2}.s^{-1}$ at core centre
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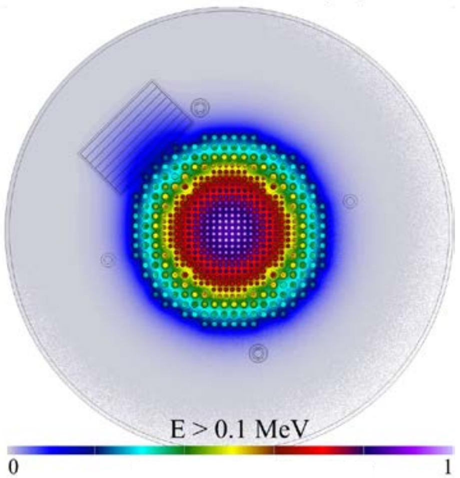
- Limitation on core activation

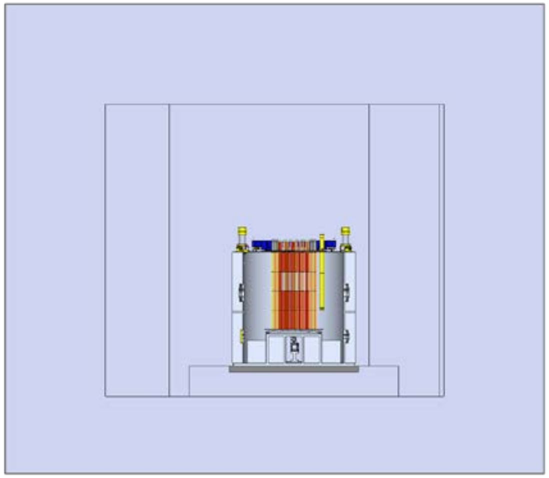
  Academic year: teaching 2-3 days/week

  Vacation time: shared with maintenance

  ➡ Management of the cavity accessibility



Fast neutron flux in CROCUS (a.u.)


CROCUS in its cavity

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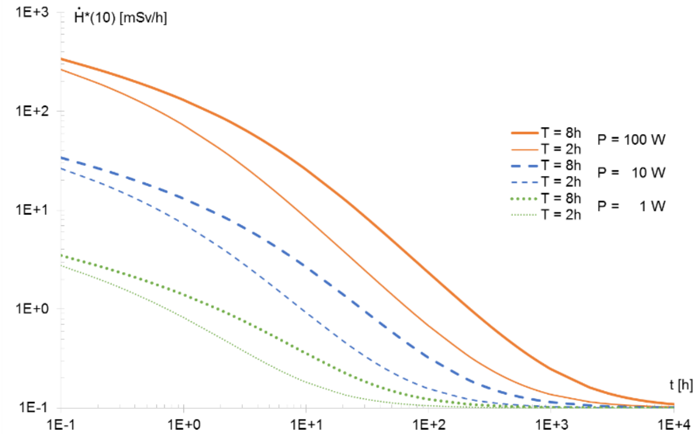
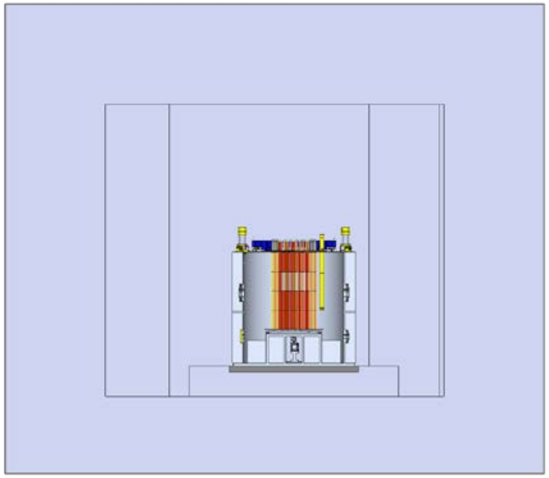


Dose equivalent at CROCUS contact, mid-height, after irradiation



CROCUS in its cavity

Optimization of the programme

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- Limitation on core activation

  Academic year: teaching 2-3 days/week

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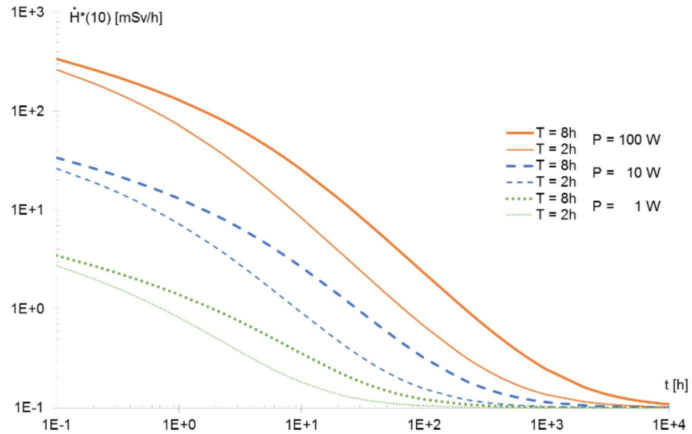
  ➡ Management of the cavity accessibility

- How useful are we?

  ➡ Measuring dosimeters is not constraining nuclear data

➡ <u>Optimization required</u>



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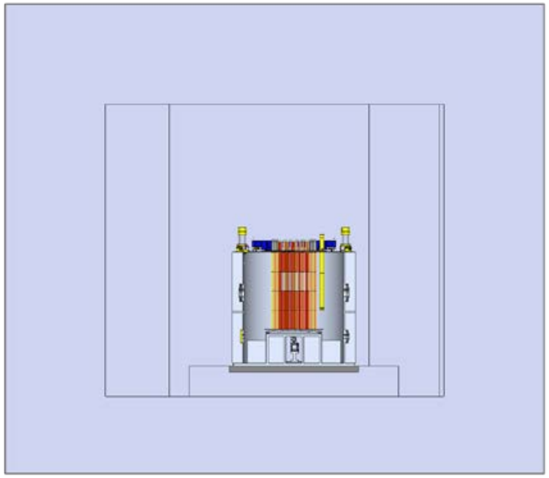


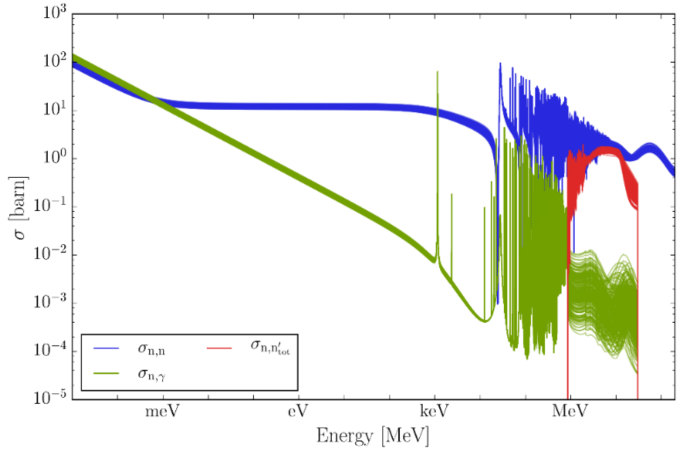
CROCUS in its cavity

Optimization of the programme

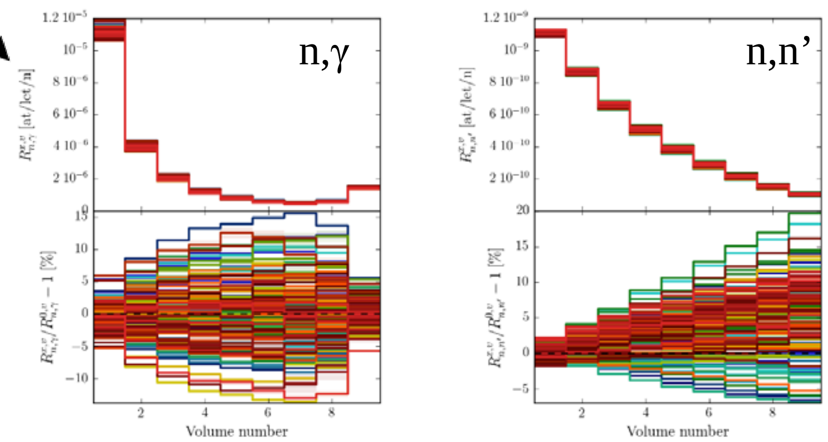
Uncertainty propagation

Relating cross sections uncertainty distribution with reaction rates

- Nuclear data uncertainty propagation by Total Monte Carlo (TMC) approach
- Correlated Sampling used to estimate the flux/reaction rate associated to different ACE files[5]



^{56}Fe cross sections dispersion in TENDL 2017 library



Reaction rate distributions with indium in the iron metal reflector (128 ACE files)

Optimization of the programme

Uncertainty propagation

Relating cross sections uncertainty distribution with reaction rates

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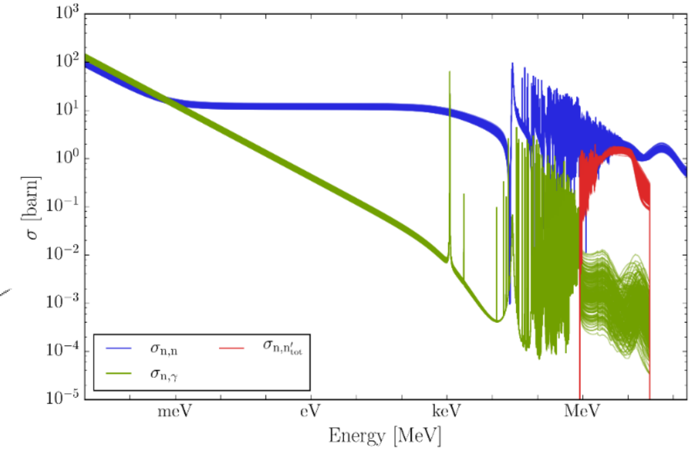


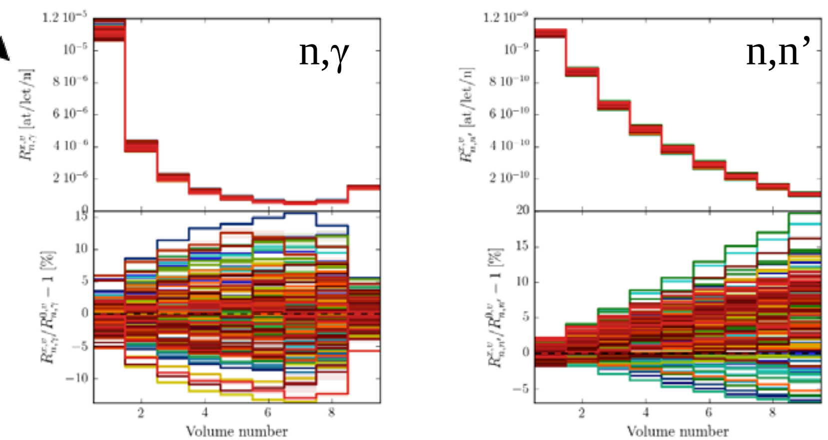
^{56}Fe cross sections dispersion in TENDL 2017 library

Why TMC-CS?

- To use methods developed in-house

- in preparation of data assimilation

- complementing CEA’s methods



Reaction rate distributions with indium in the iron metal reflector (128 ACE files)

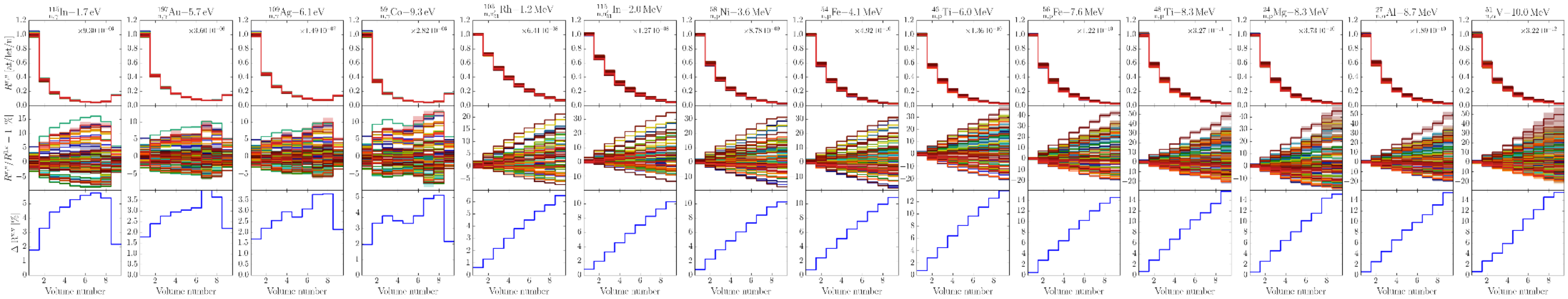
[5] A. Laureau *et. al*, “Total Monte Carlo acceleration for the PETALE experimental programme in the CROCUS reactor”, this conference

Optimization of the programme

Application to all cases

Calculations performed for:

- All reflector materials: Fe, Ni, Cr
- All dosimeters and their reactions of interest, with self-shielding
- For reasonable irradiations (1-3h at 50 W) and measurements (1-24h)



Reaction rate distributions in the iron metal reflector for all considered dosimeters

Optimization of the programme

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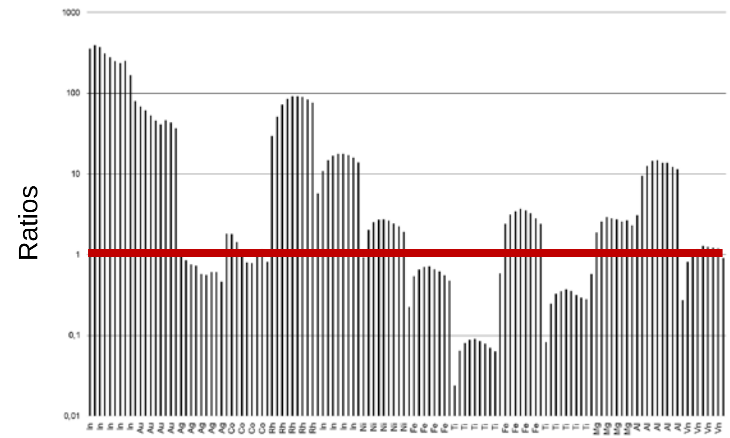
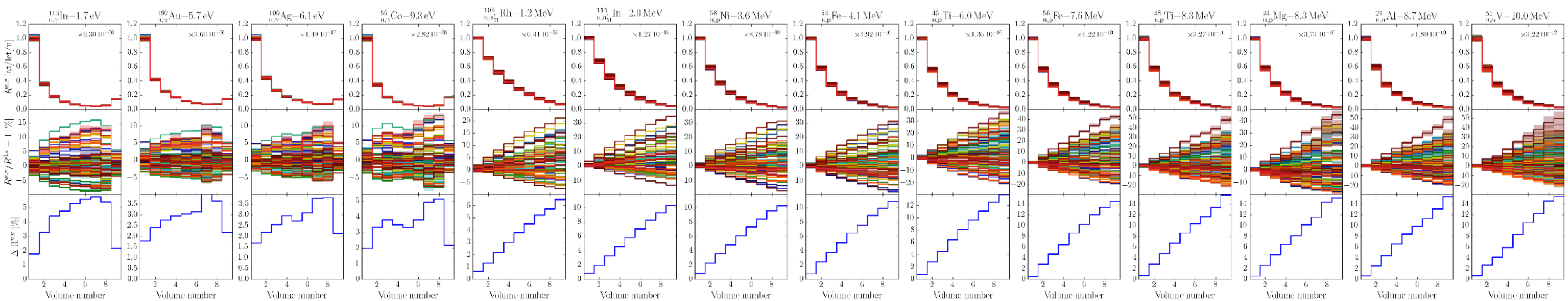
➡ Comparison of RR distributions and activity uncertainties



Ratios between RR distributions and activity uncertainties for the iron reflector



Reaction rate distributions in the iron metal reflector for all considered dosimeters

Selection of dosimeters

Calculations performed for:

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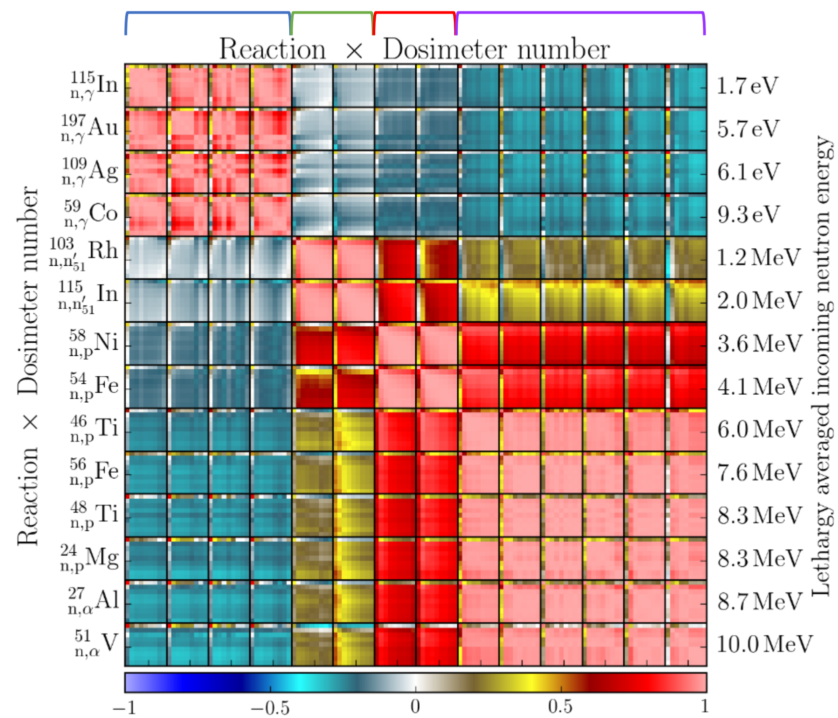
➡ Comparison of RR distributions and activity uncertainties

➡ Quantification of correlations between reactions' outputs

4 independent groups



Correlations between reactions for each dosimeters' locations, in the case of the iron reflector

Optimization of the programme

Selection of dosimeters

Calculations performed for:

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- For reasonable irradiations (1-3h at 50 W) and measurements (1-24h)

➡ Comparison of RR distributions and activity uncertainties

➡ Quantification of correlations between reactions' outputs

➡ Definition of dosimeters' choice and target uncertainties

List of dosimeters pre-selected based on ratios and correlations for iron

Reaction	Half-life	σ(RR)/U(A) Max. Ratio	Position of Max.
^{115}In(n,γ)	54.29 min	40	2
^{197}Au(n,γ)	2.7 d	79	1
^{115}In(n,n')	4.49 h	18	5
^{58}Ni(n,p)	71 d	2.7	4
^{54}Fe(n,p)	312 d	0.7	5
^{56}Fe(n,p)	2.58 h	3.7	5
^{27}Al(n,α)	14.96 h	15	4

Optimization of the programme

Discussion

- Dosimeters
  - Interest of double reaction dosimeters
  - Ti out, Fe complementary
  - Globally cheap materials
- Irradiation optimization
  - Ok for all, to be lowered for high ratios
  - Possibility of mixed irradiations
- Spectrometry optimization
  - Low ratios with long half-lives to be measured in low-activity labs (Ni, Fe)
- Reflector sheets of iron and nickel are optimal massive dosimeters
  - Confirmed interest of 2D-mapping

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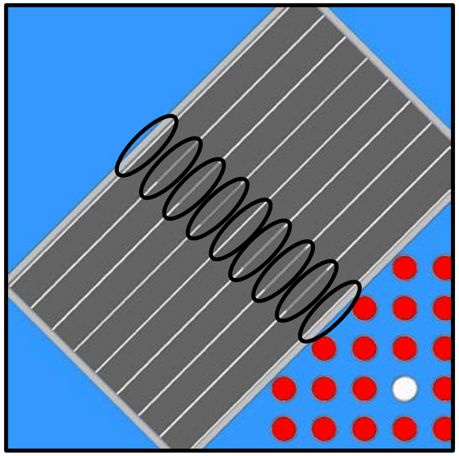

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[6]All these dosimeters (but Al and ^{54}Fe) were tested in-core for a 1^{st} validation of:

- *calculation methodologies*
- *spectrometry techniques*
- *calculated in-core spectra*

→

<u>Consistent results</u>

- *Au and Ni* ✓
- *In(n,γ)* ✗
- *In(n,n'), $^{56}Fe(n,p)$* ✗

[6] Y. Jiang, A. Laureau and V. Lamirand, "Characterization of Neutron Spectra in the EPFL CROCUS Reactor by Foil Activation Dosimetry and Monte Carlo Calculations", INSTN Master thesis, 2018

Conclusion & Prospects

A new methodology based on TMC-CS was applied for optimizing integral experiments dedicated to the study of s.s. nuclear data

- Selection of dosimetry reactions based on the feedback they provide
- Quantification of the uncertainties requirements for optimizing the programme

The next steps are:

- Propagation of the nuclear data uncertainties on the dosimetry reactions
- Application to the technological uncertainties for the finalisation of the setup
- Design of a gamma scanning system
- Start of the experimental program!

Thanks for your attention!

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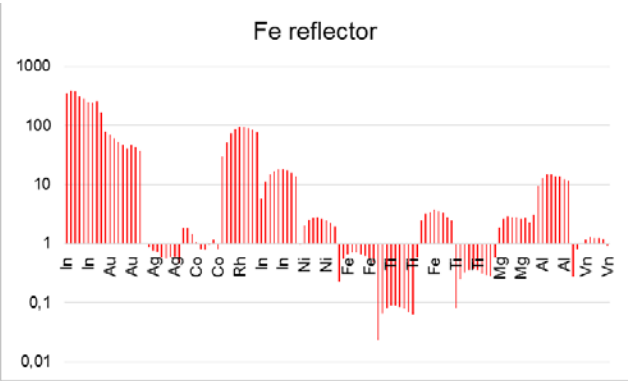
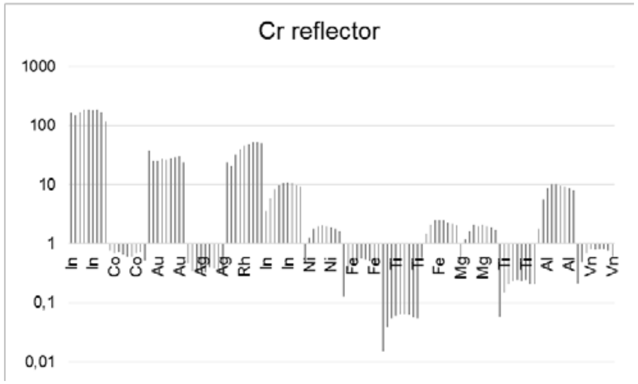
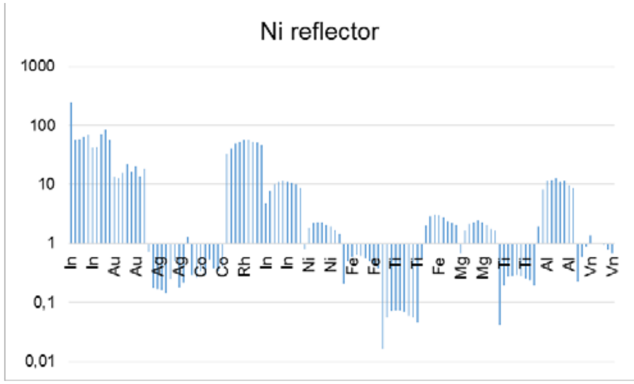
Axel Laureau axel.laureau@epfl.ch LRS postdoctoral fellow on PETALE

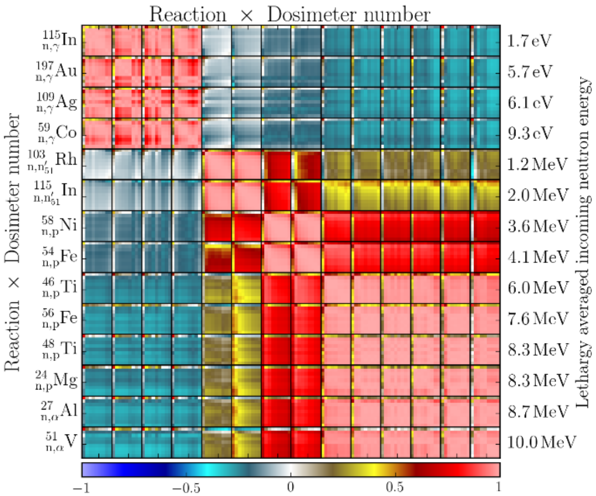
Optimization of the programme

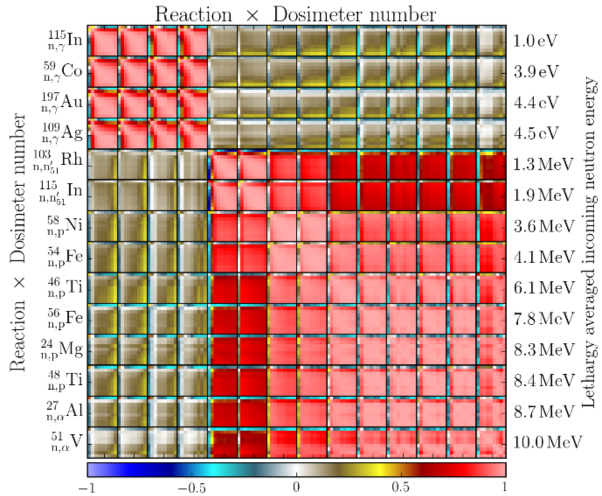
Selection of dosimeters

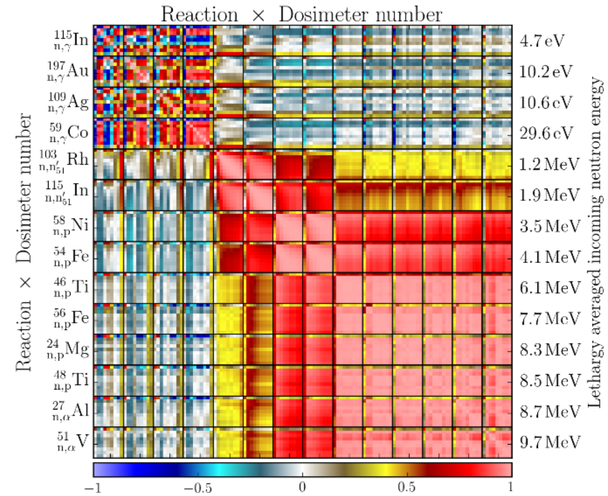






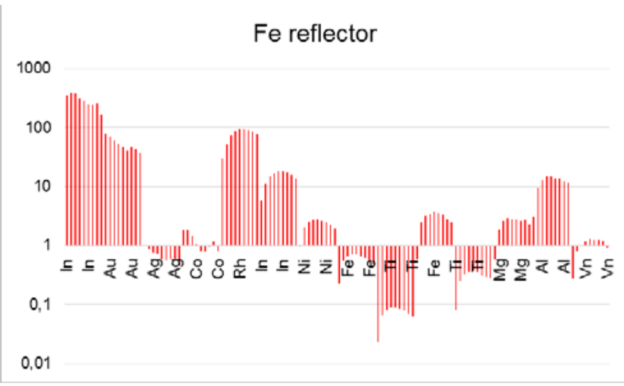


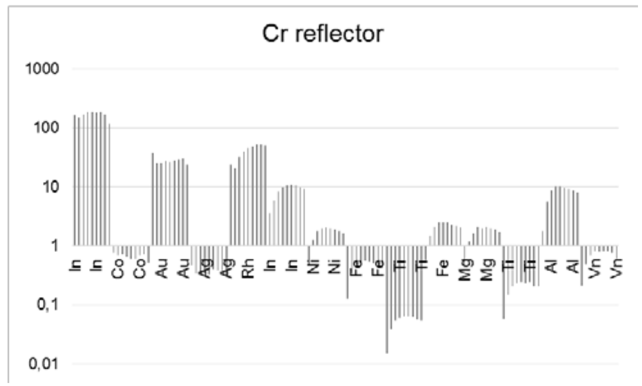


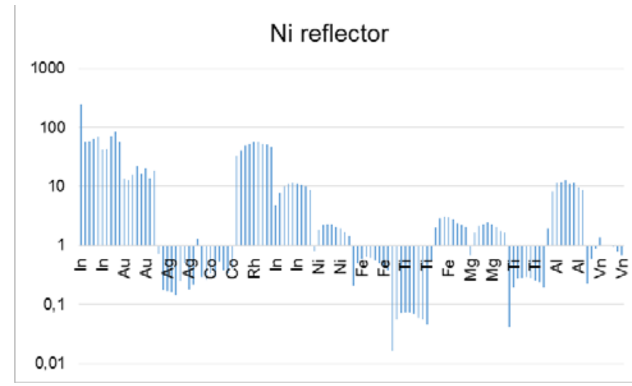


Optimization of the programme

Selection of dosimeters







Reaction	Half-life	Iron		Chromium		Nickel	
		σ(RR)/U(A) Max. Ratio	Position of Max.	σ(RR)/U(A) Max. Ratio	Position of Max.	σ(RR)/U(A) Max. Ratio	Position of Max.
^{115}In(n,γ)	54.29 min	40	2	188	7	245	1
^{197}Au(n,γ)	2.7 d	79	1	38	1	56	1
^{115}In(n,n’)	4.49 h	18	5	11	6	12	5
^{58}Ni(n,p)	71 d	2.7	4	2.1	5	2.3	4
^{54}Fe(n,p)	312 d	0.7	5	0.6	5	0.6	4
^{56}Fe(n,p)	2.58 h	3.7	5	2.5	5	3.0	4
^{27}Al(n,α)	14.96 h	15	4	10	4-5	12.4	5