WP5 : Active and passive neutron measurement

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CEA DES IRESNE – ENEA – CAEN

Speakers : Cyrille Eleon (CEA DES Cadarache)
Quentin Ducasse (ex CEA, now IRSN Cadarache)

WP5 project tasks overview

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Objective	• Best estimation of the nuclear material mass inside nuclear waste drums (LLW & ILW 50 L →400 L)
Challenges	• Evaluation/Reduction of nuclear material mass uncertainty due to the matrix and localization effects
Technical solution	• Design of a modular and transportable system for passive and active neutron measurements and of matrix effect corrections based on Machine Learning

1. **Neutron system design + performance assessment** — Leader: CEA DES CAD
2. **Construction of the neutron system** — Leader: CAEN; Participants: CEA - ENEA
3. **System Calibration – characterization** — Leader: CEA; Participants: CEA - ENEA
4. **Demo preparation and final demonstration (WP10)** — Leader: ENEA; Participants: all partners

Which nuclear wastes ?

Nuclear activity of the drum
- Low Level Wastes (LLW)
- Intermediate Level Wastes (ILW)

Presence of nuclear material
- 240Pu (passive measurement)
- 235U/239Pu (active measurement)

Nuclear material mass
Detection limits < 1 g

Volume of the drum
50 L – 400 L

Matrix
- Organic
- metallic
- (Homogeneous bitumized)
- No concrete
- No cement

Matrix characteristics
- Density
- chemical composition
- activity distribution
- Filling level (50%-100%)

<u>Aim</u> : Best estimation of the nuclear material mass inside nuclear waste drums

Design requirements

Technical Requirements

Simple Easy to (dis)assemble

Modular Allow both passive AND active measurements

Adjustable Allow measurement of drums with different volumes (50 L → 400 L)

Transportable Not exceed 2 tons to be easily transportable and implemented in any facility

Cost effective Use already available detectors and equipment

Performance Requirements

Performant Signal/Noise ratio as high as possible

Passive and active neutron measurements

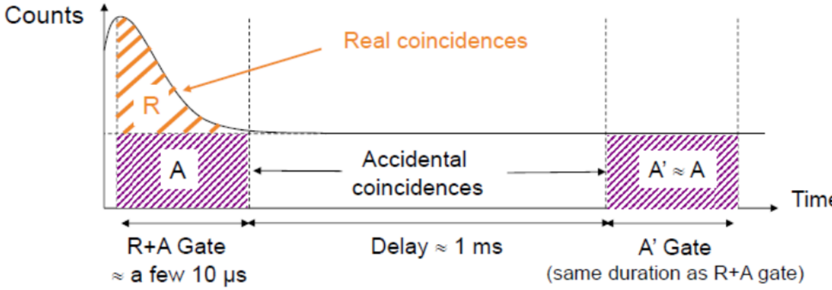
(principle and state of the art)

Nuclear material mass evaluation

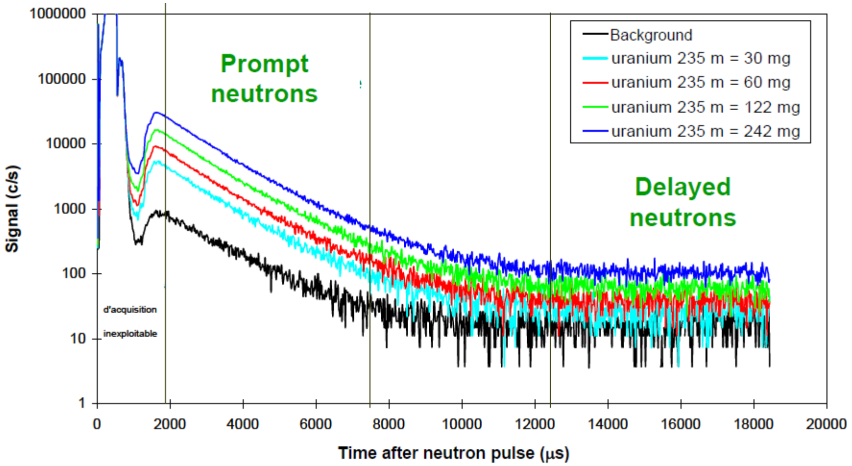
$$m_{eq}(equivalent\ mass) = \frac{S_u}{CC}$$

Su = usefull (net) signal (c/s)
CC = calibration coefficient (c/s per g)

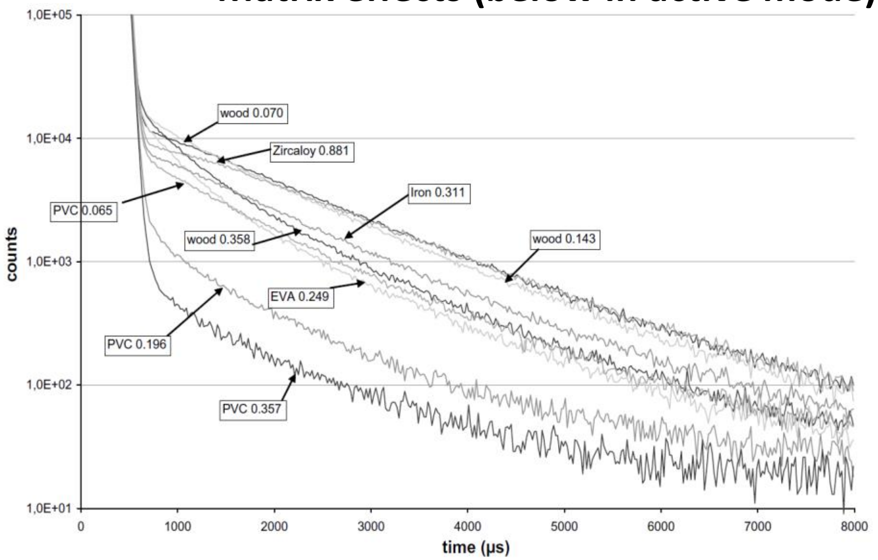
PASSIVE mode ^{238}Pu,^{240}Pu,^{242}Pu (m_{eq} ^{240}Pu)



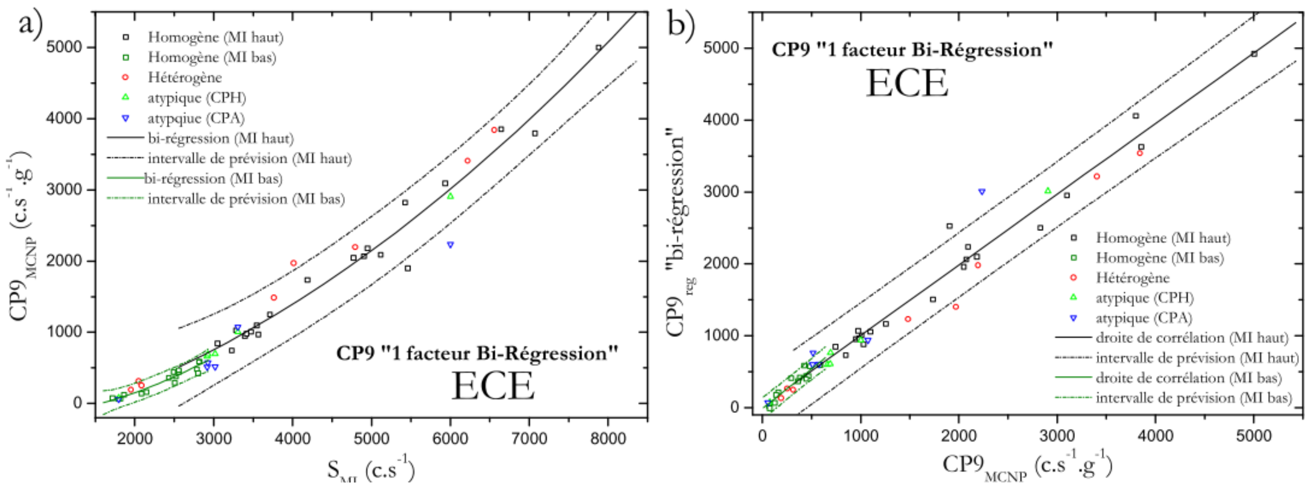
ACTIVE mode ^{235}U,^{239}Pu,^{241}Pu (m_{eq} ^{239}Pu or ^{235}U)



Matrix effects (below in active mode)



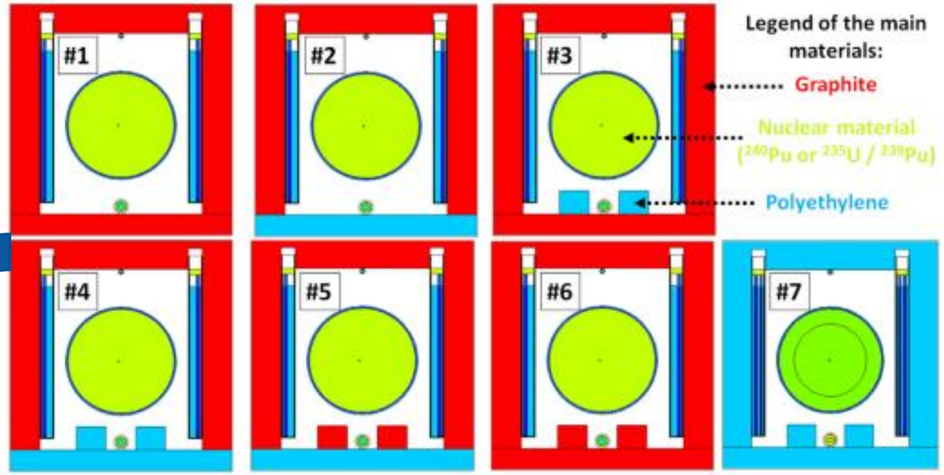
Correction method (regression model with internal monitors)

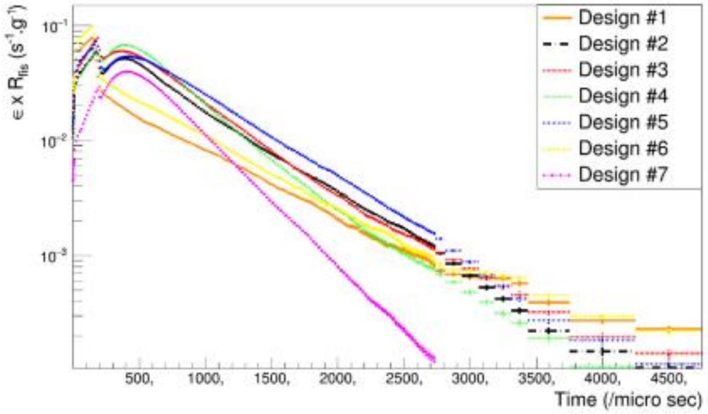


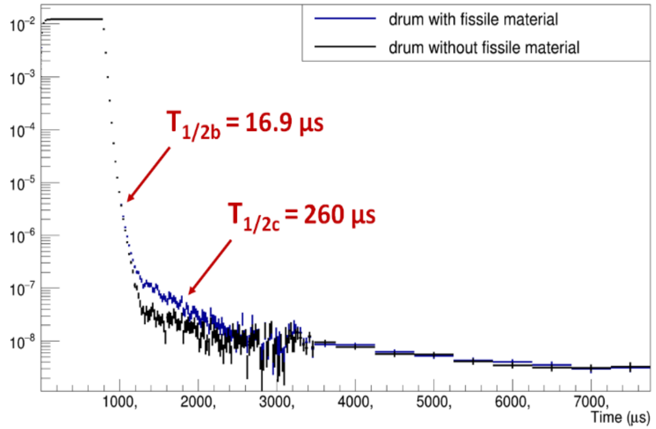
R. Antoni, "Optimisation des mesures d'interrogation neutronique active par couplage d'une méthode de correction des effets de matrice," *http://www.theses.fr*, Mar. 2014, Accessed: Sep. 02, 2021. [Online]. Available: http://www.theses.fr/2014GRENY014.

Neutron system design & performance assessment

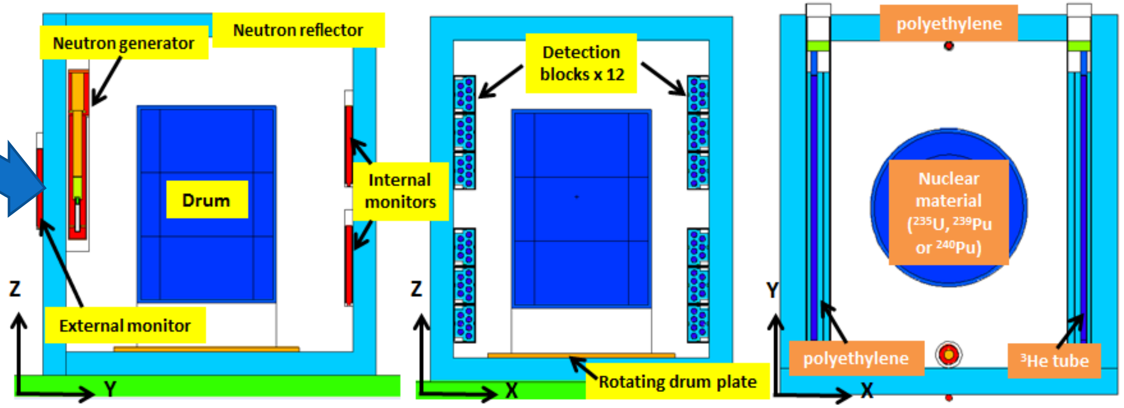
Monte Carlo simulations







Practical constraints : limited total weight ⇨ polyethylene moderator instead of graphite



MCNP model of the MICADO neutron system design

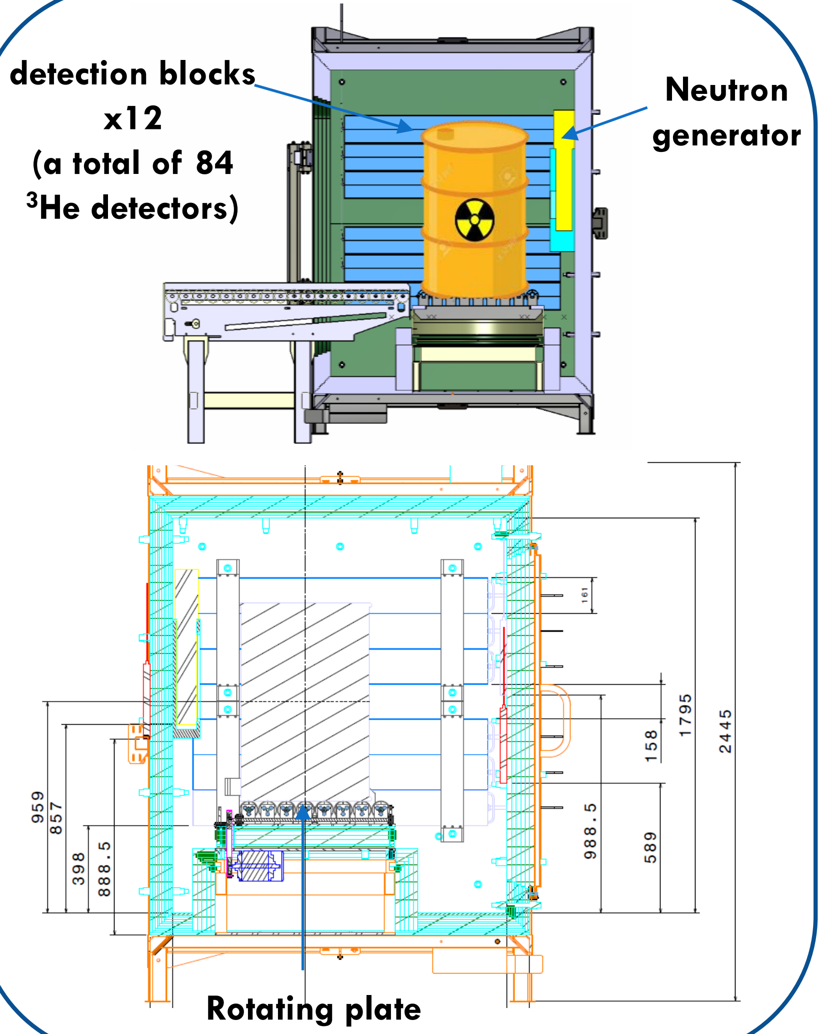
Matrix	$MDL_{passive}$ (g of ^{240}Pu)	MDL_{active} (g of ^{239}Pu)
Stainless steel	0.068	0.192
Poly 0.1	0.075	0.039
Poly 0.7	0.519	0.349
Mixed	0.119	0.116
Without matrix	0.074	0.085

Q. Ducasse, C. Eleon, B. Perot et al., Nuclear Inst. and Methods in Physics Research, A 1005 (2021) 165398

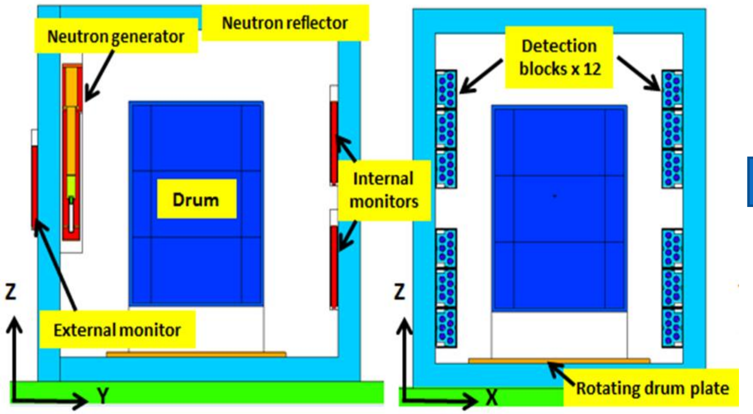
MCNP model update for performance assessment

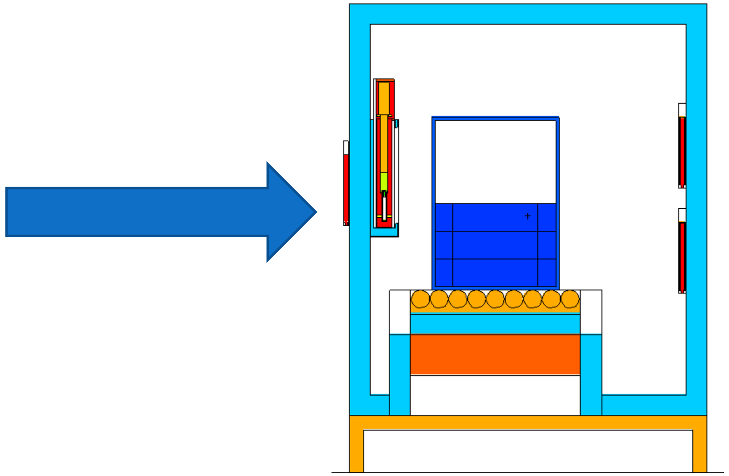
micado

Technical drawing (CAEN-CEA-ENEA)

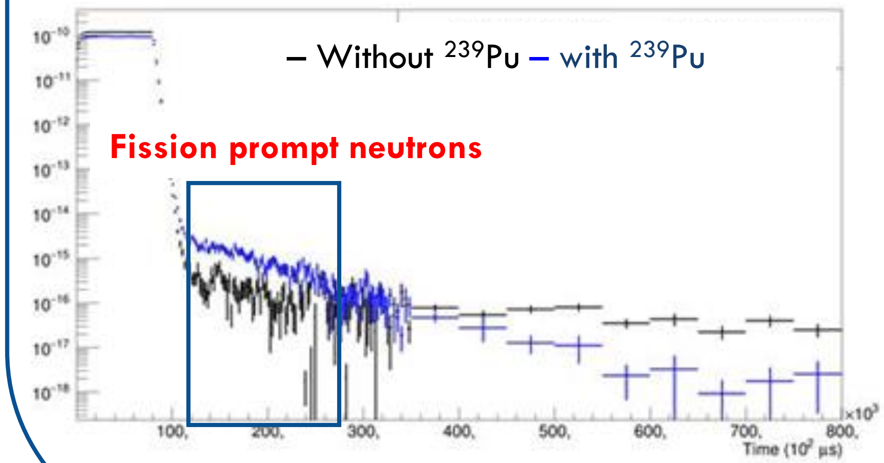


MCNP model update & performance (CEA)





Active mode (DDT method)



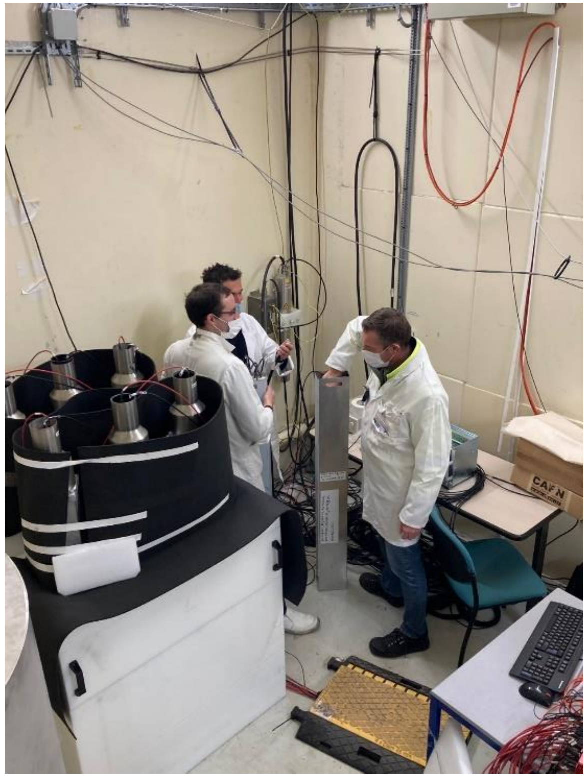
	Original design	As-built cell
Induced fission rate ^{239}Pu (fissions.s^{-1}.g^{-1})	979	1130
Detection efficiency	7%	4%
Mass detection limit (30 min measurement)	<1g	<1g

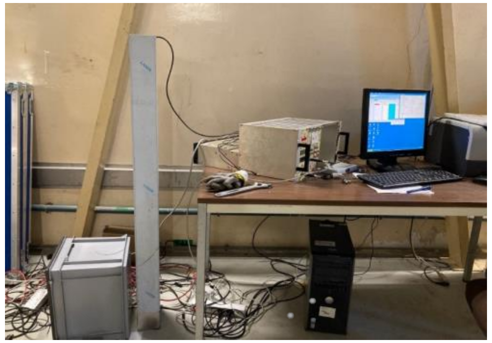
Construction and mounting (CAEN-CEA-ENEA) (1/2)

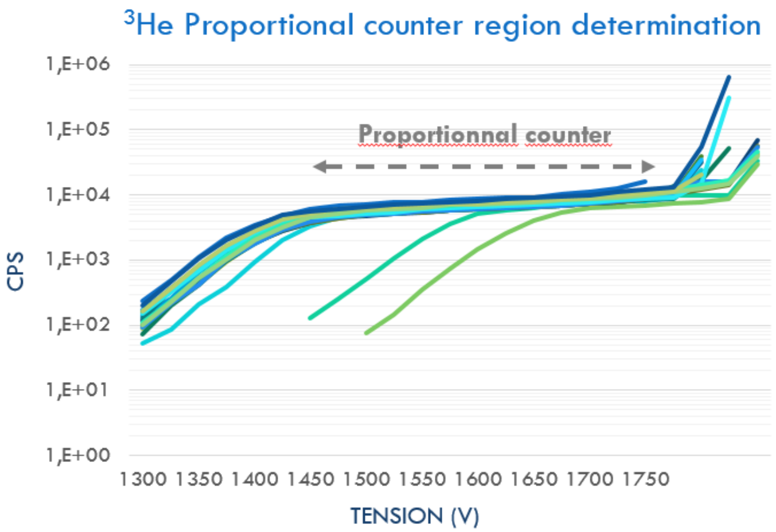
Assembly tests

(CAEN Viareggio Italy)

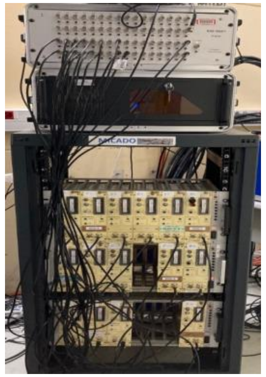
✓ **Calibration and classification of > 100 ^{3}He detectors (TOTEM facility CEA Cadarache)**





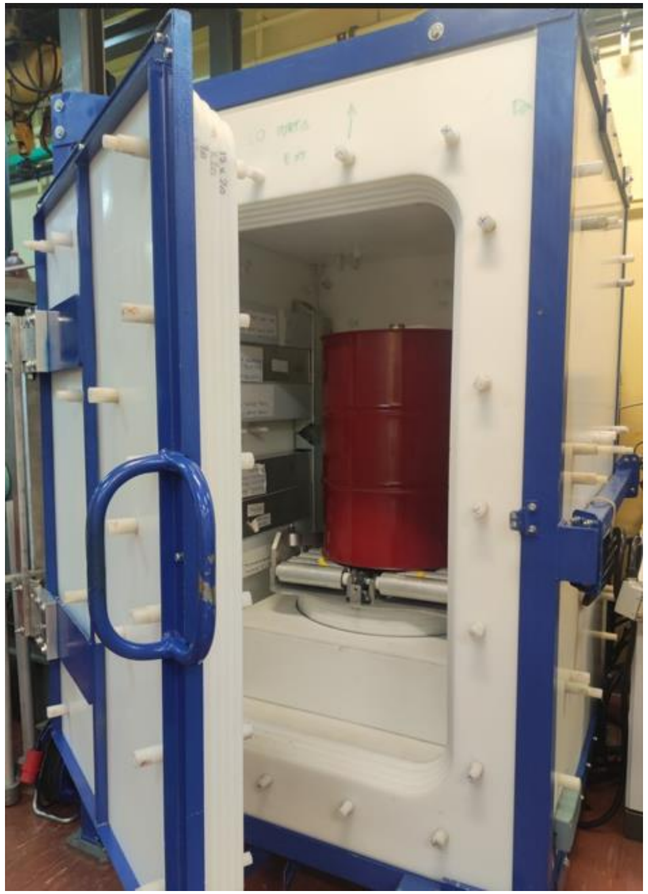


Construction and mounting (CAEN-CEA-ENEA) (2/2)



TOTEM Facility
CEA
Cadarache

Relocated in
C43 Lab
ENEA Casaccia
(within one week)



System Calibration and Characterization
DANAIDES casemate (TOTEM facility CEA Cadarache)
March to July 2022

Preliminary tests and Performance assessment for final demo
C43 Lab (ENEA Casaccia) August 2022 up to now

System Calibration – Characterization & Qualification of the MCNP model

Experimental campaign in DANAIDES (TOTEM facility CEA Cadarache)

Passive mode

- ^{252}Cf (neutron coincidence counting)
- AmBe (transmission measurement)

Active mode (neutron interrogation)

- Neutron generator (GENIE16)
- Pu sample

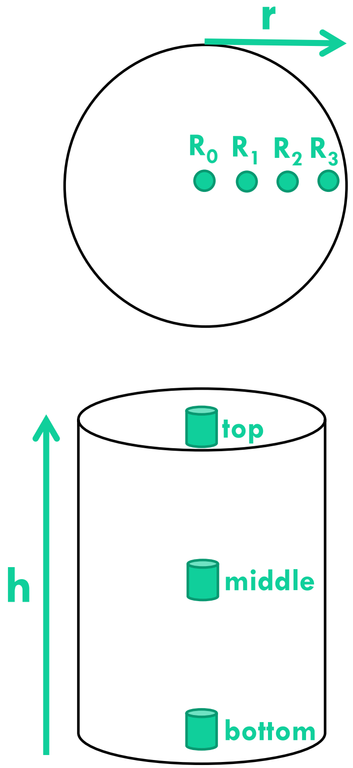
Mock-up drums (118 L)

Wood – Stainless steel – CH_2 – PVC …

Matrix name	Composition	Apparent density	Filling level
Stainless steel	Fe (70%) – Ni (18%) – Cr (8%)	0.63	82 %
Wood	$C_6H_{10}O_5$	0.35	95 %
Polyethylene	CH_2	0.5	92 %
PVC	C_2H_3Cl	0.27	91 %

Neutron system measurements in passive mode

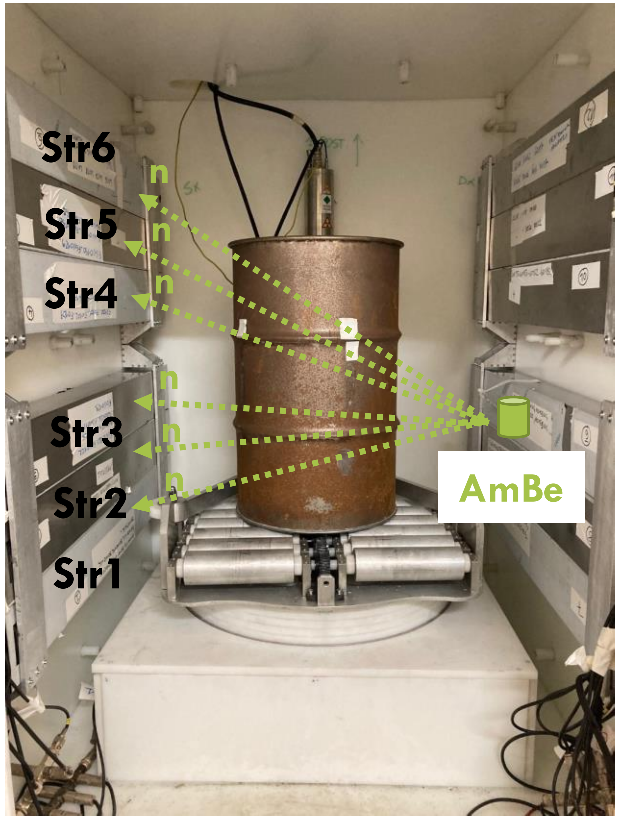
Coincidence measurements



Measurements with ^{252}Cf in 12 different positions

- ➢ **Real (R) neutron coincidences**

Transmission measurement



One measurement per drum

- ➢ **In view of matrix effect correction**

→ Comparison with MCNP simulations

Neutron system calibration in passive mode

Mock-up DRUM
Volume : 118L *Matrix* : None *Density* : N/A *Filling level* : N/A

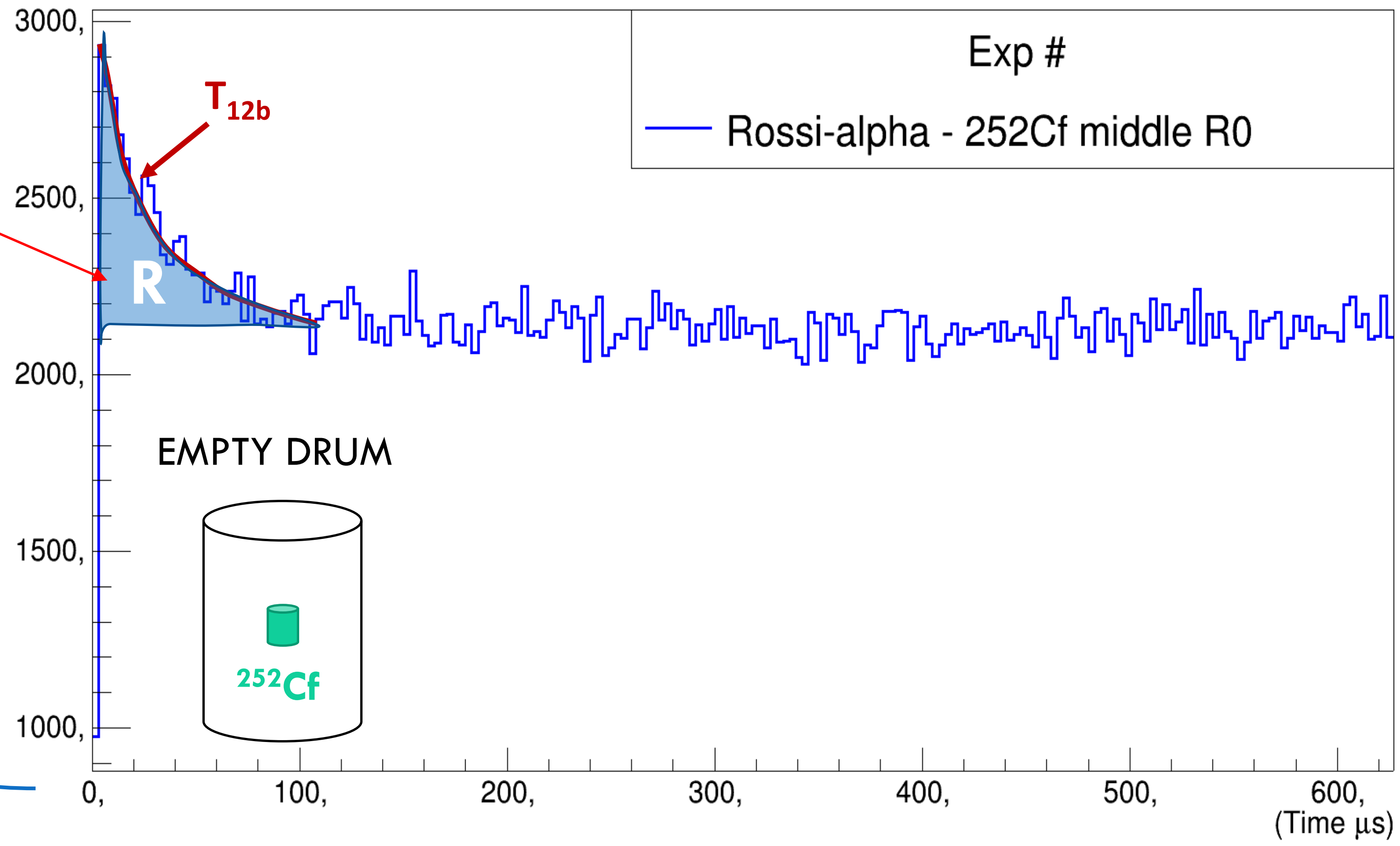
Real coincidences

$$m^{252_{Cf}}_{estimated} = \frac{R}{CC}$$

MCNP6

Key physical quantities
Neutron efficiency (ε) = 3.7% T_{12b} = 17,9 µs Detection limit < 0,5 g (^{240}Pu,eq)

COINCIDENCE - calibration



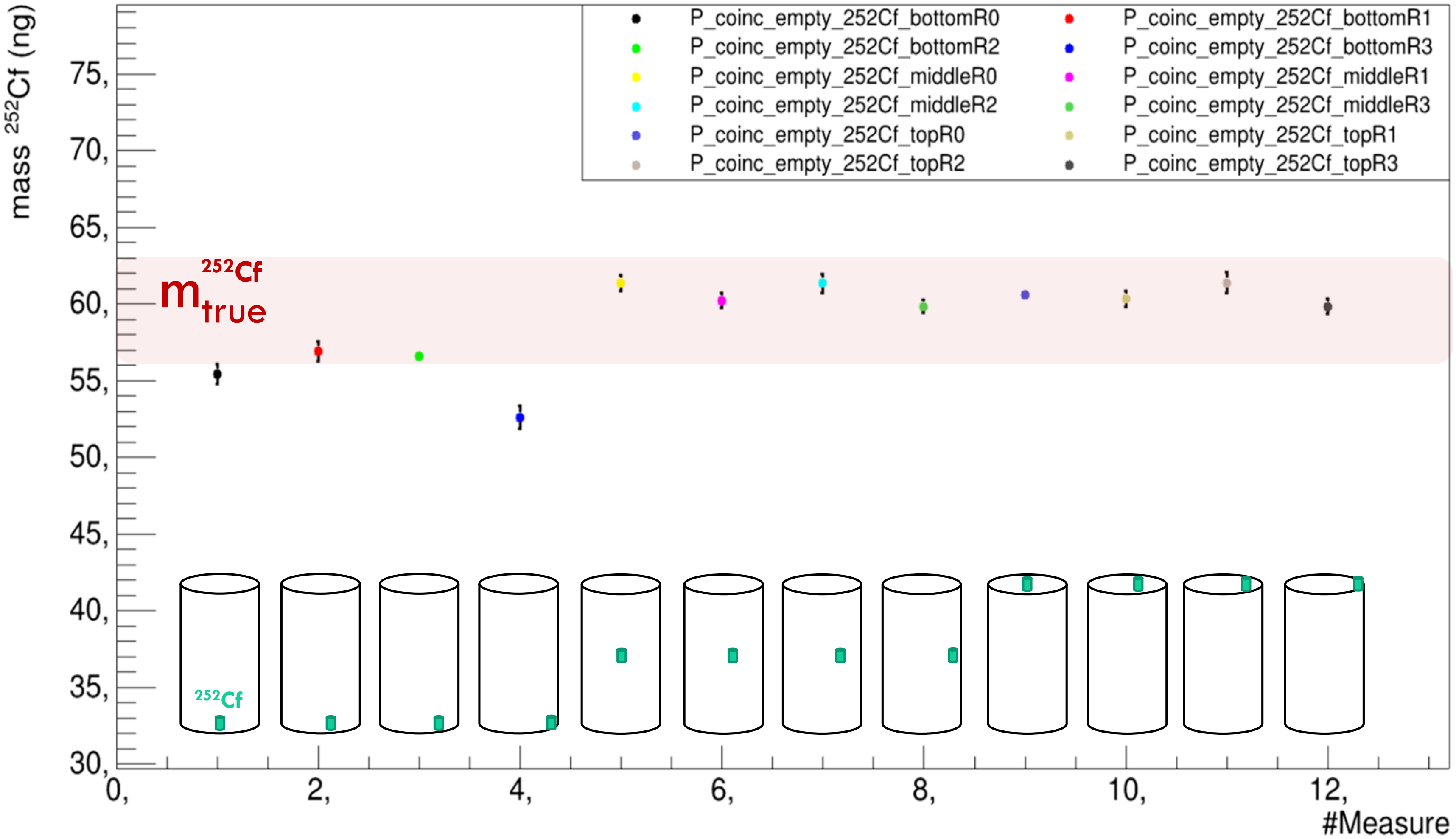
Neutron system calibration in passive mode

Mock-up DRUM
Volume : 118L
Matrix : None
Density : N/A
Filling level : N/A

m_{true}^{252Cf} = 60 ng +/- 6%

$$0\% \leq \frac{<m_{true}^{252Cf}>}{m_{estimated}^{252Cf}} \leq 13\%$$

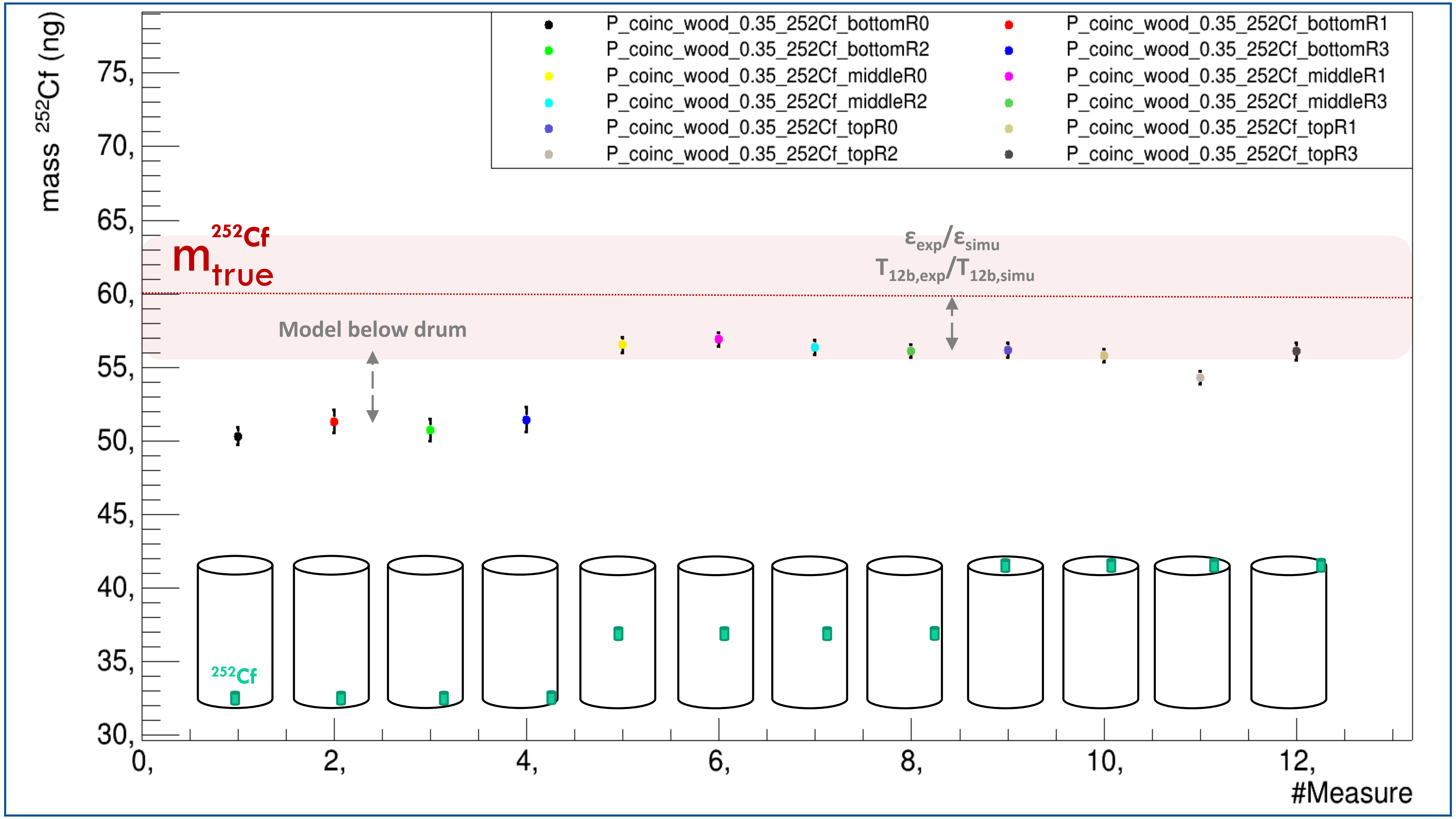
COINCIDENCE - qualification



Neutron system qualification in passive mode

Mock-up DRUM
Volume : 118L *Matrix* : Wood *Density* 0.35 *Filling level* : 95 %

COINCIDENCE - qualification



$$5\% \leq \frac{\langle m_{true}^{252Cf} \rangle}{m_{estimated}^{252Cf}} \leq 16\%$$

Neutron system qualification in passive mode

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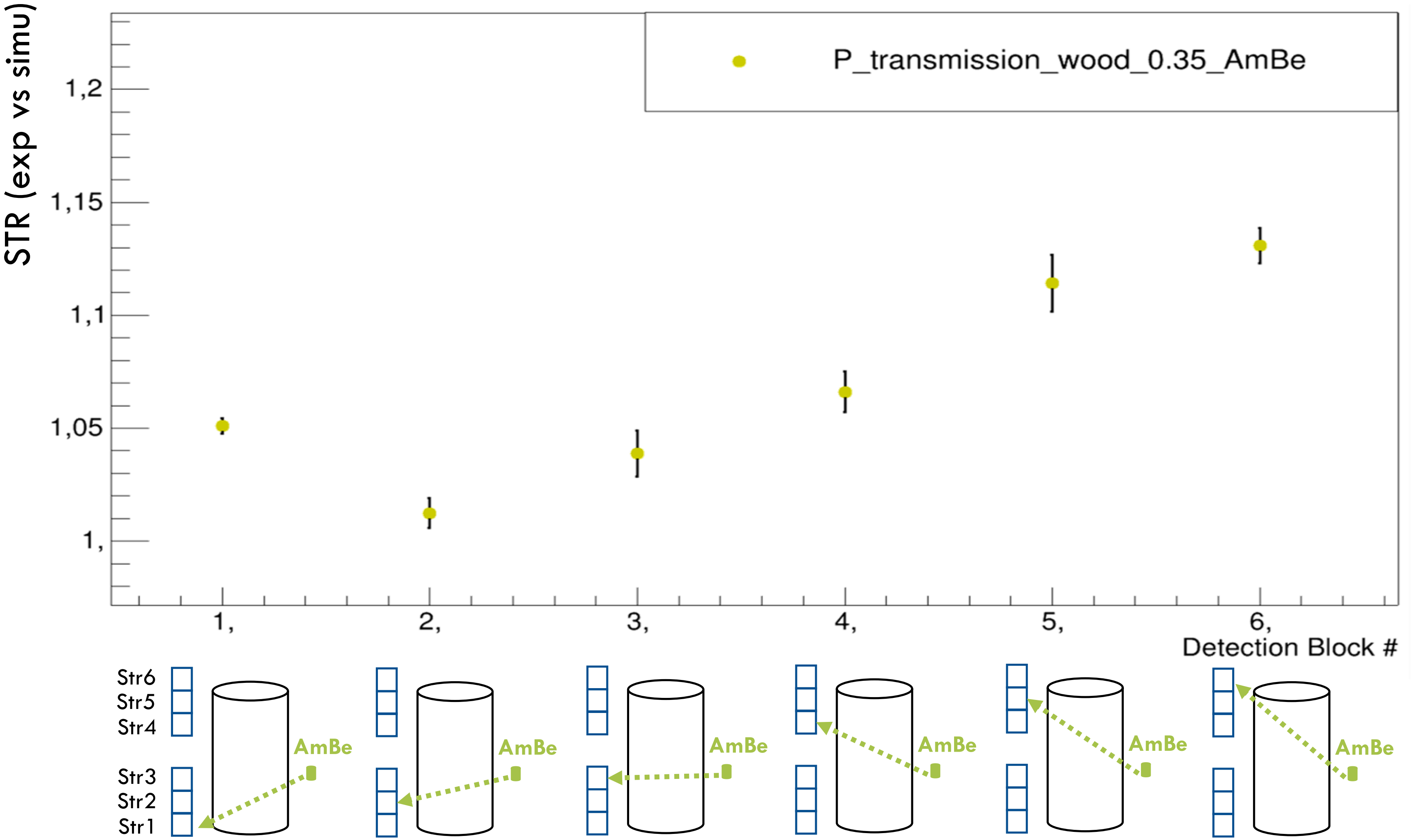
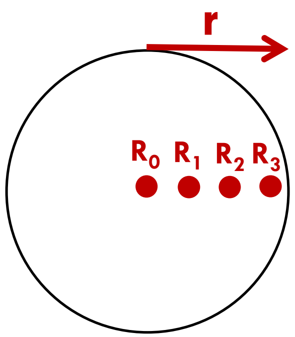
Mock-up DRUM
Volume : 118L *Matrix* : Wood *Density* 0.35 *Filling level* : 95 %

TRANSMISSION - qualification

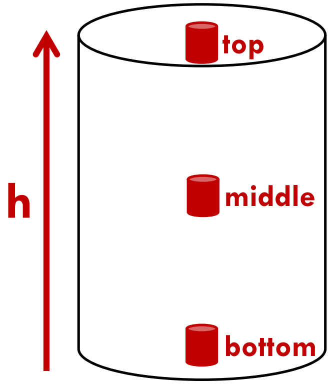


- Transmission signal agreement between 1-15%
- Similar observations for the other matrices

Neutron system measurements : active mode



12 measurements per matrix



Neutron generator

Pulse Frequency = 125 Hz

Pulse length = 800 µs

(10% duty cycle)

En ≈ 2.5 x 10^8n/s

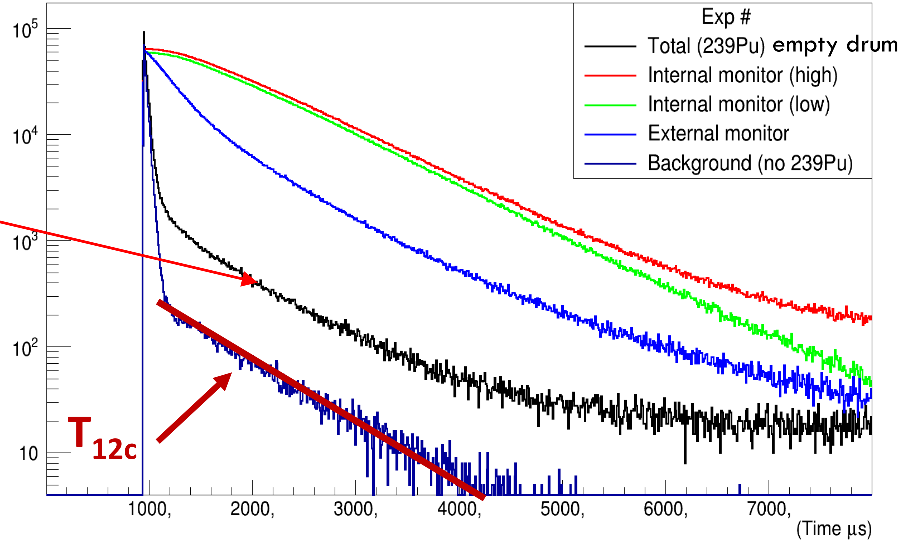
→ Comparison with MCNP simulations

Neutron system qualification in active mode

Useful signal (prompt fission neutrons)

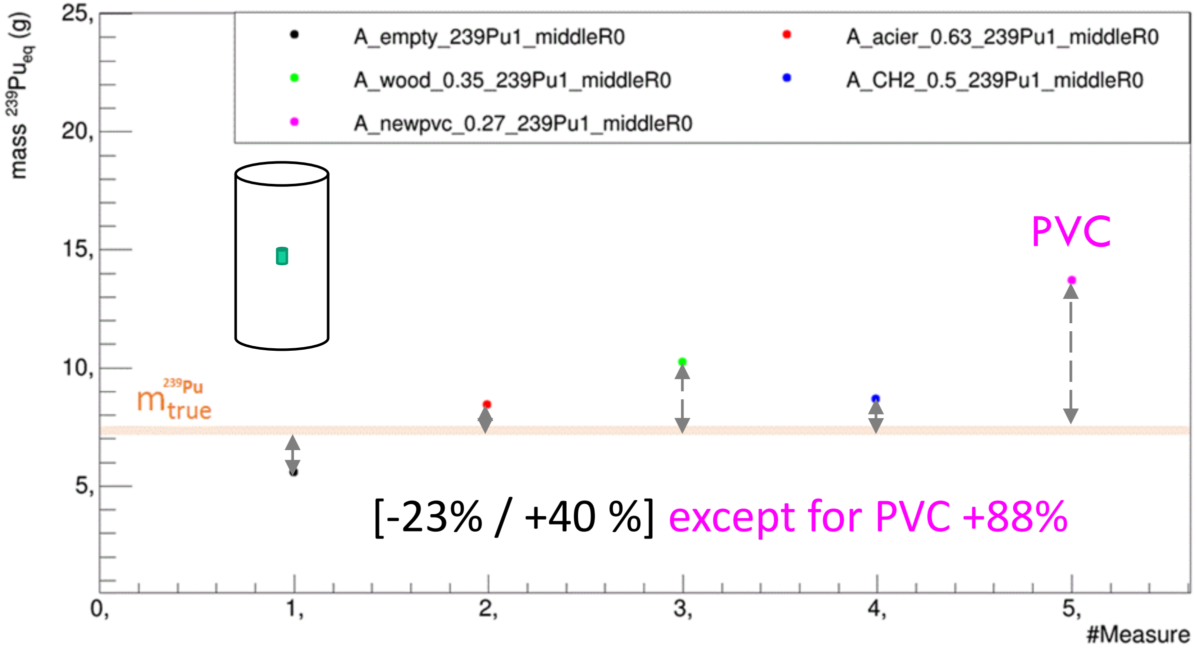
$$m^{239}_{estimated} = \frac{S_{up}}{CC}$$

MCNP6



Key physical quantities

Neutron efficiency (ε) = 3.7%
T_{12c} = 499 µs
Detection limit < 1 g (^{239}Pu,eq)



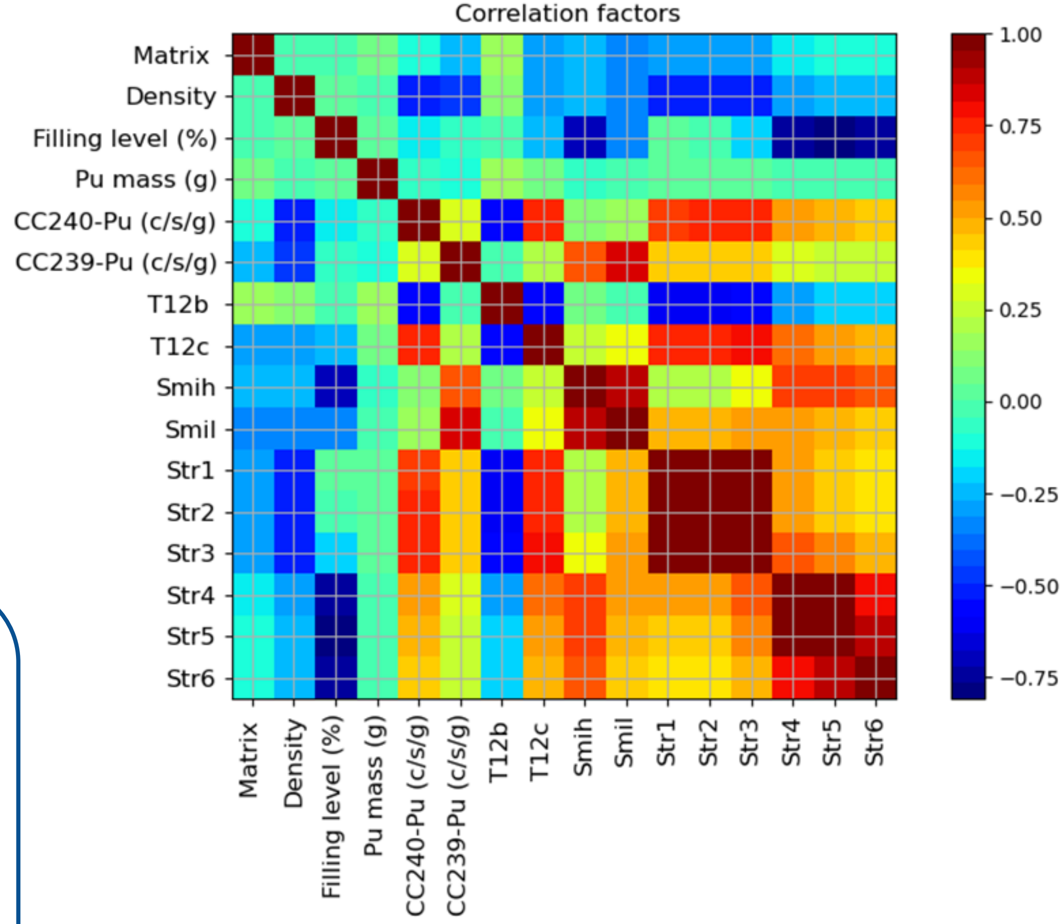
Matrix effect correction (1/3)

Experimental design with 104 Monte Carlo simulations

(Taguchi L72 & L32)

L72		L32	
Parameters	Levels	Parameters	Levels
Matrix (homogeneous distribution)	Metallic- Zircaloy – MELOX – WOOD/CH_2– PVC – SiC	Matrix (homogeneous distribution)	100% CH2– 100% Stainless steel– mixed 33/67 – mixed 67/33
Density	0.1 – 0.2 – 0.35 – 0.45 – 0.6 – 0.7	Density	0.1 – 0.3 - 0.5 - 0.7
Filling level (%)	50 – 65 – 80 – 100	Filling level (%)	50 – 65 – 80 – 100
Nuclear material mass (g) (homogenous distribution)	1. - 10 - 100	clear material mass (g) mogenous distribution)	0.1 – 1 – 10 - 50

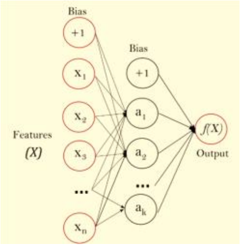
Correlation between Pu signal and matrix indicators (internal monitors & transmission measurements)



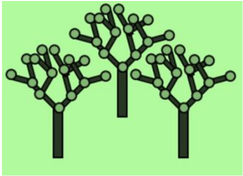
Machine learning algorithms for regression models

Artificial Neural Networks

MLP (Multilayer Perceptron)

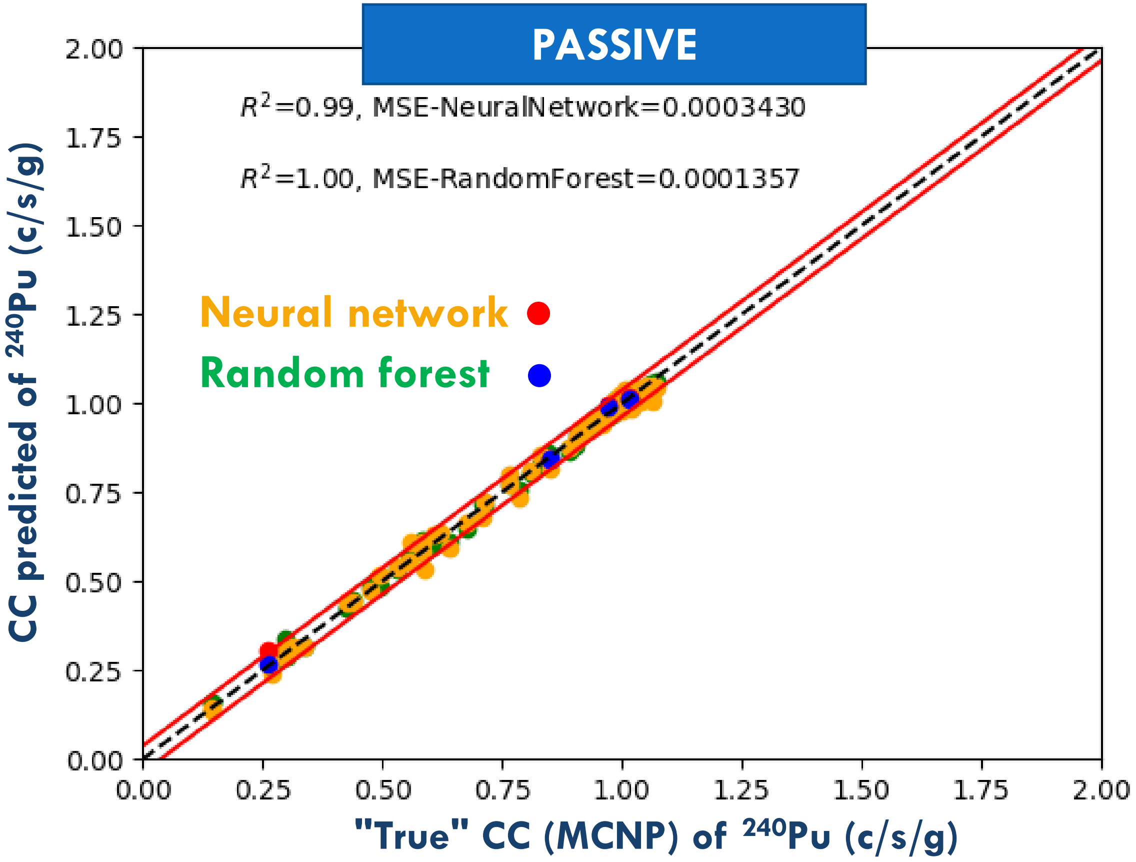


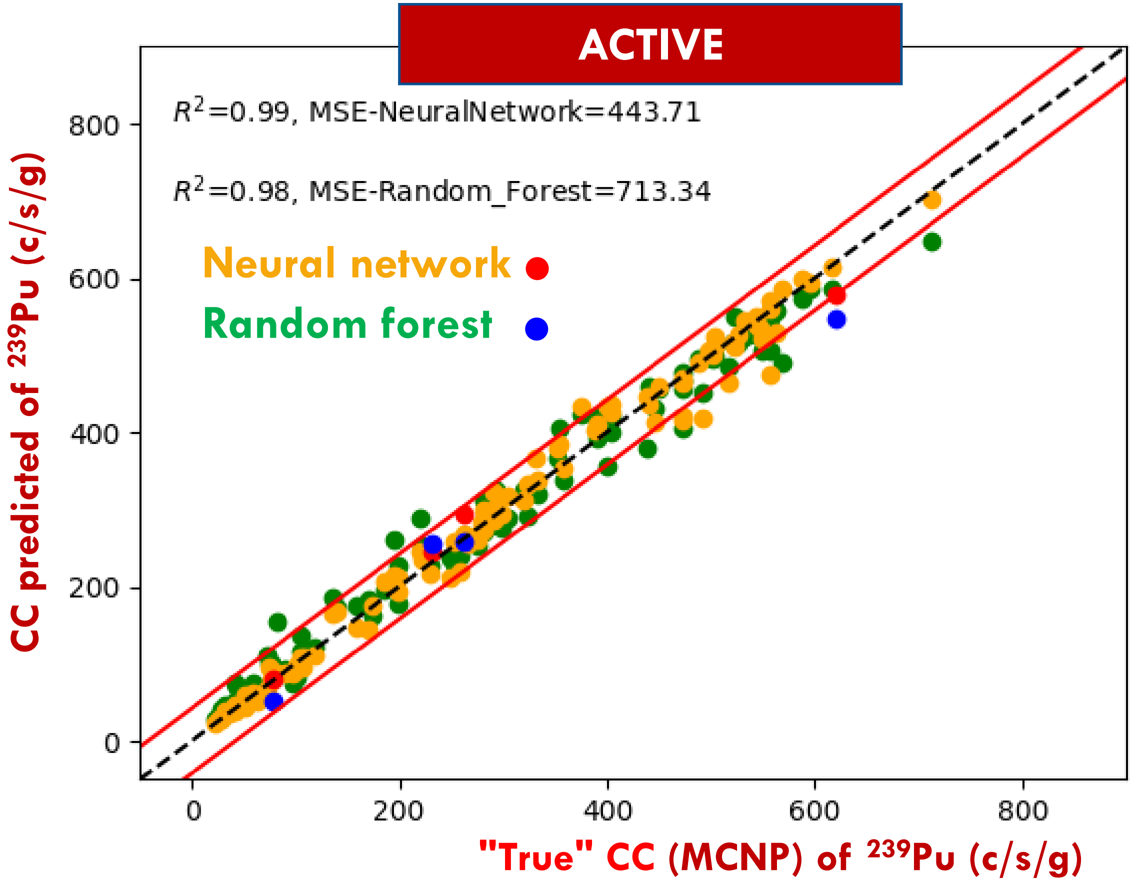
Random Forest



Matrix effect correction (2/3)

Performance assessment with the MCNP models of the mock-up drums (118L) used for qualification



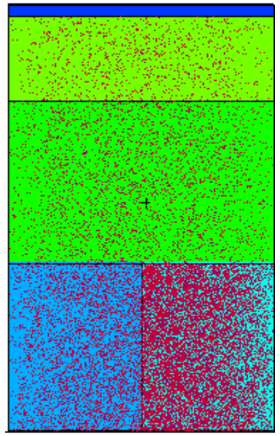


Matrix effect correction (3/3)

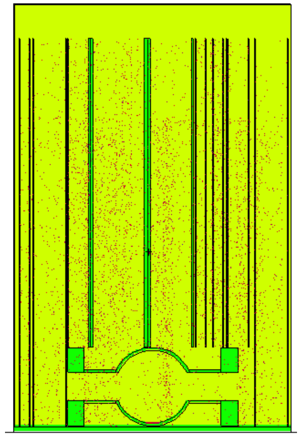
WP2 ORANO

⇨ **Realistic but heterogenous drums MCNP models**

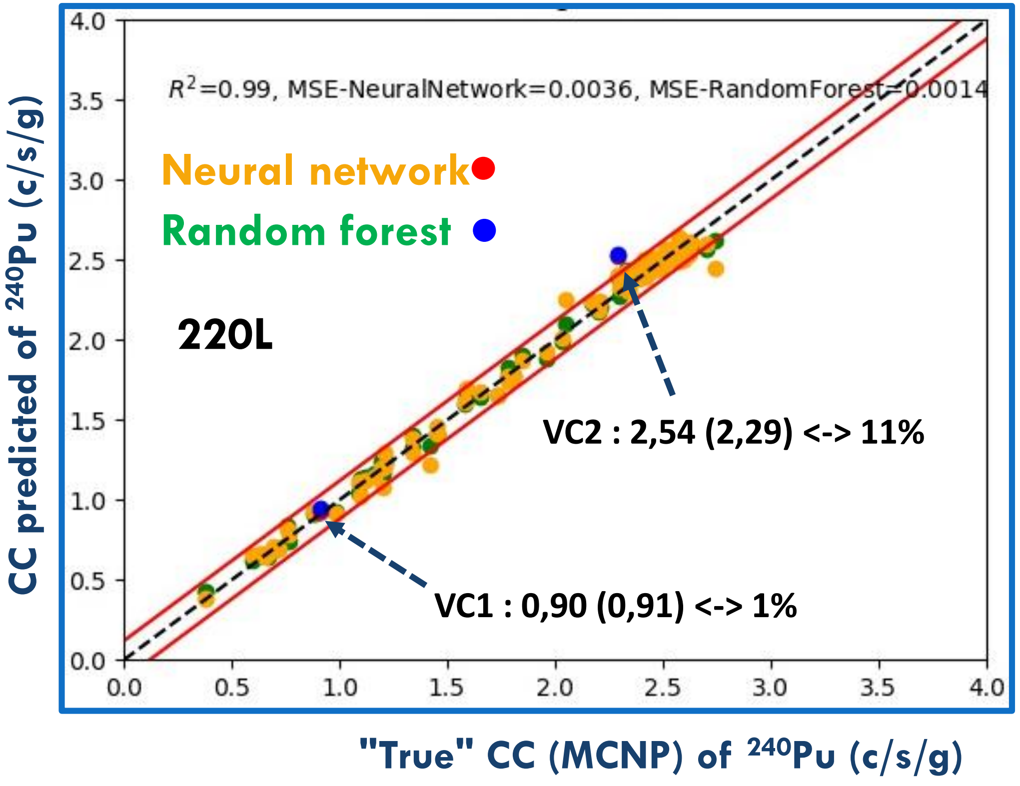
VC1 : Organic



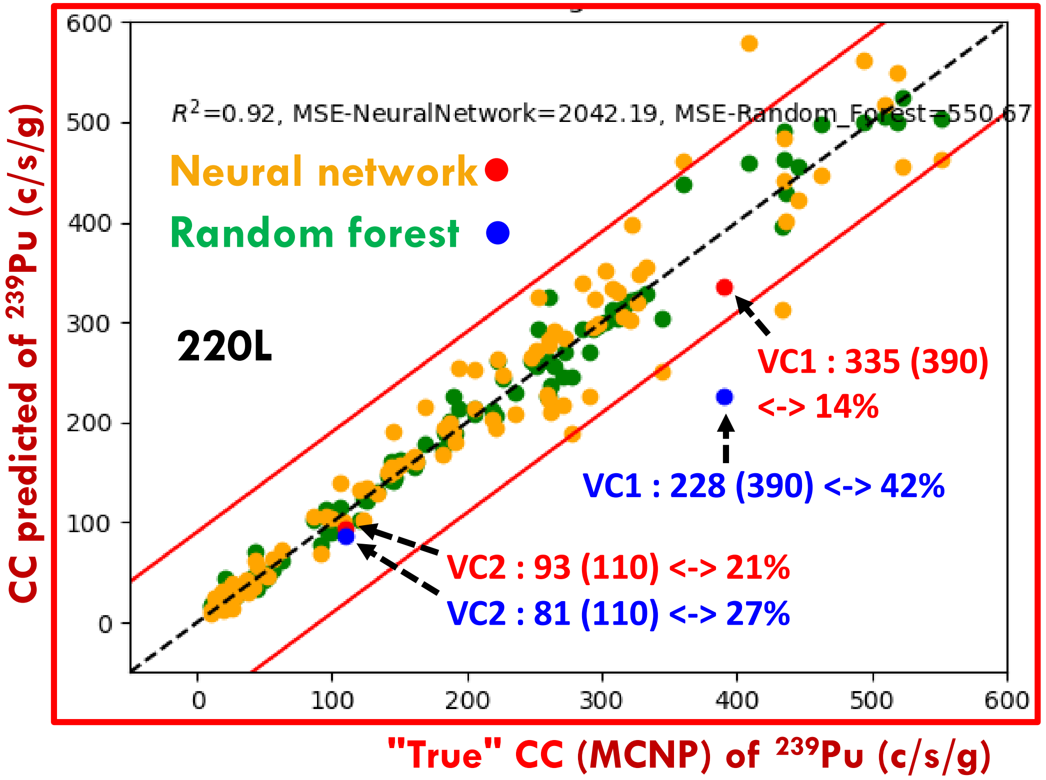
VC2 : Metallic rods



PASSIVE



ACTIVE



Experimental results in passive mode (ENEA C43 Lab)

200 L mockup-drum with cotton matrice
(d=0,16 & FL=100%)

Point source in the middle of the matrix
⇨ larger uncertainty

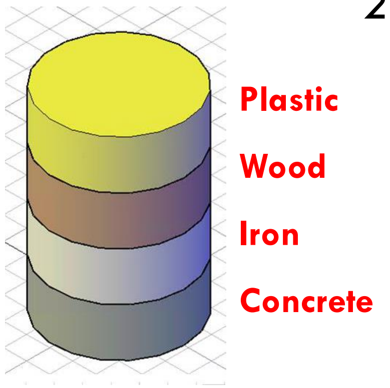
Meq ^{240}Pu predicted with ANN (for an homogeneous distribution whereas Pu was placed in only one position):
2.30 g ± 0,60 g (1σ) Vs. true M($^{240}Pu_{eq}$) = 2.01 g
(detection limit in 10 min = 0,260 g of $^{240}Pu_{eq}$)

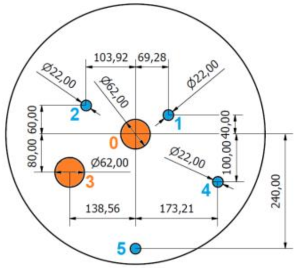
200 L mockup-drum with plastics matrice
(d=0,37 & FL=80%)

12 Pu positions
⇔ ≈ homogeneous distribution

Meq ^{240}Pu predicted with ANN (for an homogeneous distribution):
1,74 g ± 0,07 g (1σ) Vs. true M($^{240}Pu_{eq}$) = 2.01 g
(detection limit in 10 min = 0,274 g of $^{240}Pu_{eq}$)

200 L mockup-drum with 4 multi-material matrices (wood, plastic, iron & concrete)
(d=0,8 & FL = 100%)





8 Pu positions
⇔ ≈ homogeneous distribution

Meq ^{240}Pu predicted with ANN (for an homogeneous distribution):
2,17 g ± 0,60 g (1σ) Vs. true M($^{240}Pu_{eq}$) = 2.01 g
(detection limit in 10 min = 0,300 g of $^{240}Pu_{eq}$)

Heterogeneous matrix ⇨ larger uncertainty

Experimental results in active mode (CEA Cadarache TOTEM Facility)

118 L mockup-drum with wood matrice
(d=0,35 & FL=95%)

Meq ^{239}Pu predicted with ANN
(for an homogeneous distribution):
7,24 g ± 0,70 g (1σ) Vs. true M($^{239}Pu_{eq}$) = 7,3 g
(detection limit in 5 min = 0,02 g of $^{239}Pu_{eq}$)

118 L mockup-drum with stainless steel matrice
(d=0,63 & FL=82 %)

Meq ^{239}Pu predicted with ANN
(for an homogeneous distribution):
7,51 g ± 0,70 g (1σ) Vs. true M($^{239}Pu_{eq}$) = 7,3 g
(detection limit in 5 min = 0,04 g of $^{239}Pu_{eq}$)

118 L mockup-drum with CH_2 matrice
(d=0,50 & FL=92%)

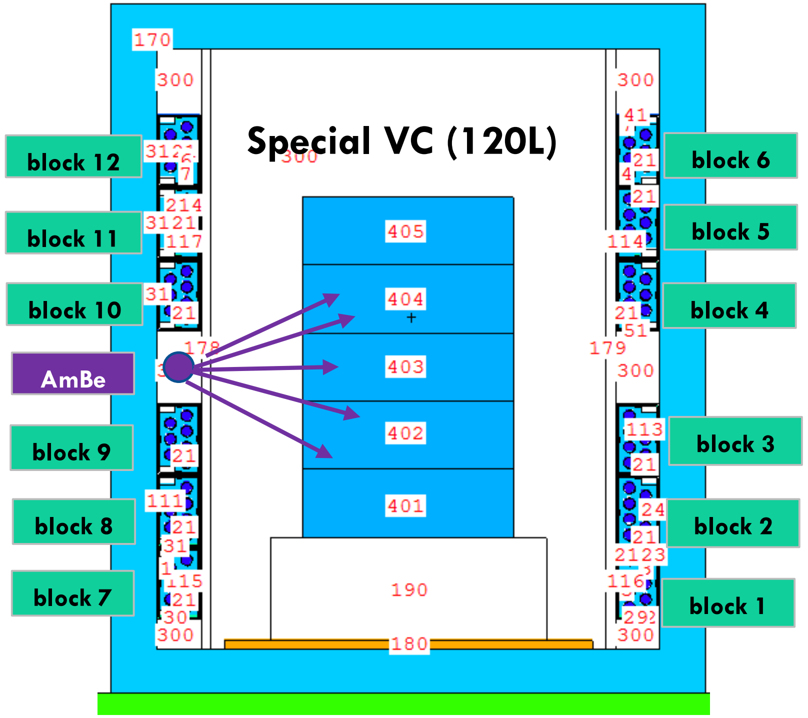
Meq ^{239}Pu predicted with ANN
(for an homogeneous distribution):
6,05 g ± 0,80 g (1σ) Vs. true M($^{239}Pu_{eq}$) = 7,3 g
(detection limit in 5 min = 0,05 g of $^{239}Pu_{eq}$)

118 L mockup-drum with PVC matrice
(d=0,27 & FL=91%)

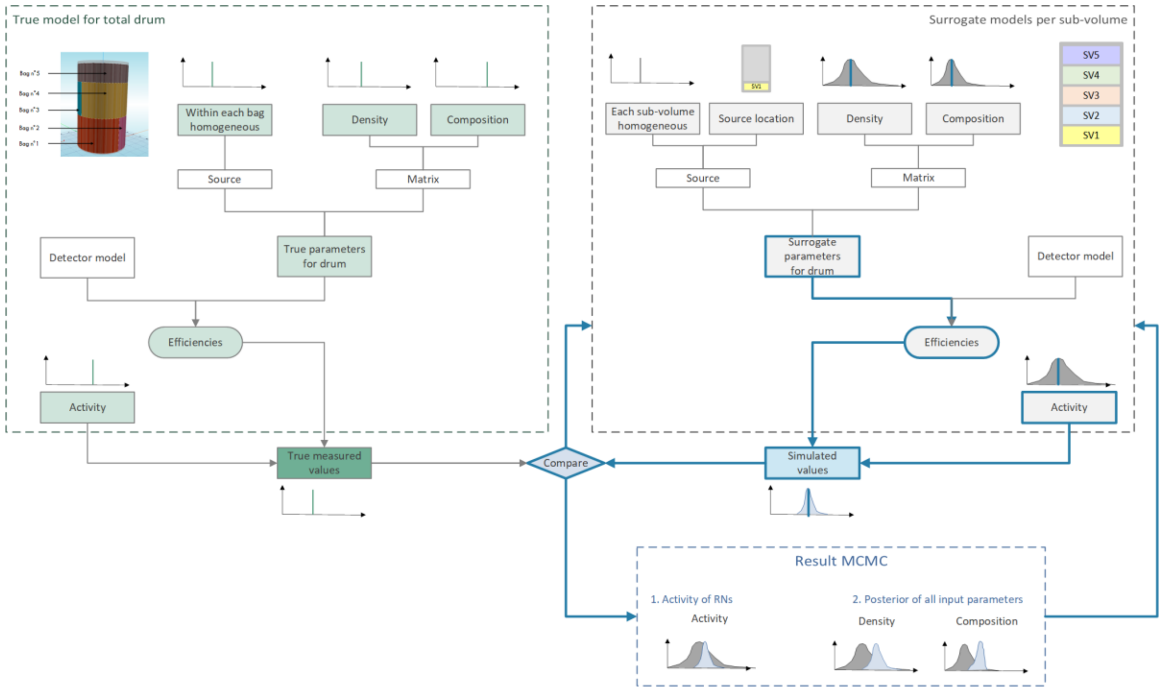
Meq ^{239}Pu predicted with ANN
(for an homogeneous distribution):
3,32 g ± 0,50 g (1σ) Vs. true M($^{239}Pu_{eq}$) = 7,3 g
Deviation = -55% (large relative uncertainty of the Machine Learning model for small CC in active mode)

Collaboration with WP8 (SCK-CEN)

WP8 (SCK-CEN): uncertainty analysis from bayesian method



Global uncertainty propagation scheme (WP8)



MCNP Calculations in active and passive modes for :

- **Matrices [$C_3H_6(H_2O)_8$; $C_3H_6(H_2O)_{12}$]**
- **Densities [0.25 ; 0.60]**

→ 16 MCNP calculations

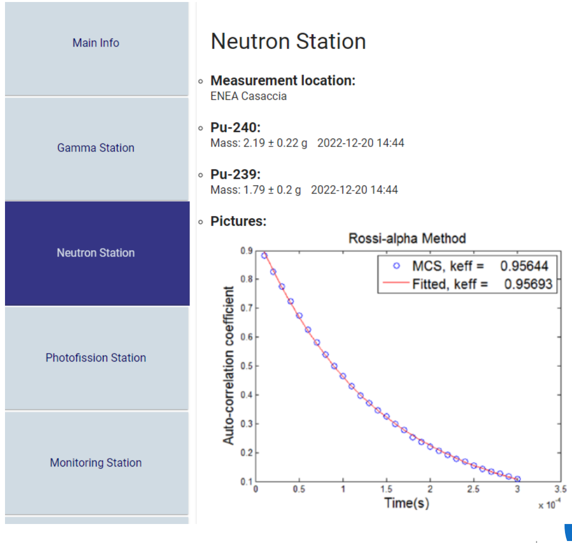
Data integration in the RCMS DigiWaste Platform (WP9, CAEN)

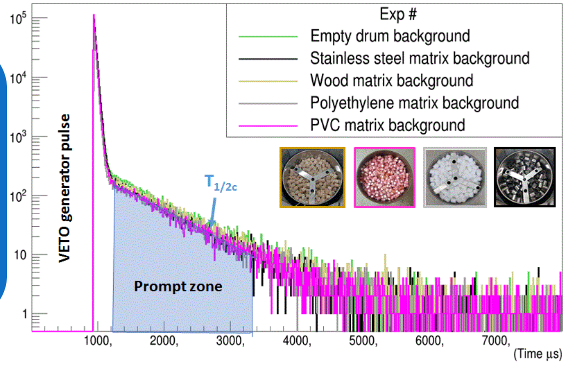
Data taking/measurement

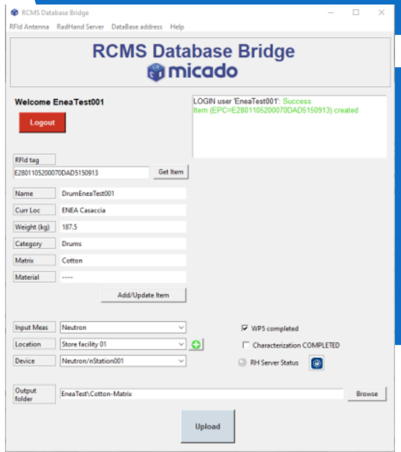
Data available on the RCMS DigiWaste Software for all users

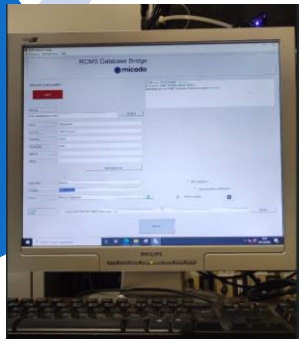
Offline analysis

Data upload









Final demo test results (WP10, ENEA)

- **MOCK-UP DRUM "A":** simulating drum from a **Reprocessing Plant/MOX Fuel production facility**
  - Waste matrix: metal, burnable materials
  - → *mock-up MULTIMATERIAL REFERENCE DRUM*
  - *Radiological content : Pu & U*

- **MOCK-UP DRUM "C": LEGACY WASTE**
  - Waste matrix: metal, burnable → *mock-up MULTIMATERIAL REFERENCE DRUM*
  - *Radiological content : Pu , U & Cs-137, Co-60 & Eu-152*

Mock-up drum A
Meq ^{240}Pu predicted with ANN
4,58 g (15 g of Pu-total) ± 0,19 g (1σ)
Vs. Mequ ^{240}Pu true 3.36 g (11 g of Pu-total)
(detection limit in 10 min = 0,550 g of $^{240}Pu_{eq}$)

Mock-up drum C :
Meq ^{240}Pu predicted with ANN
4,55 g (15 g of Pu-total) ± 0,20 g (1σ)
Vs. Meq ^{240}Pu true 3.36 g (11 g of Pu-total)
(detection limit in 10 min = 0,560 g of $^{240}Pu_{eq}$)

Deviation of + 35% due to the heterogeneity of both the matrix and Pu distributions

Summary

CEA DES/CAEN/ENEA

- Calibration of the neutron system in Danaides casemate (CEA Cadarache, IRESNE)
- Demonstration in active mode in Danaides casemate
- Demonstration in passive mode at ENEA Casaccia on mock-up drums

CEA DES IRESNE CADARACHE

- MCNP simulations for performance assessment and database for Machine Learning
- Exploration of Machine Learning methods for regression modeling and better estimation of the nuclear material mass (ANIMMA 2023 conference)
- Finalizing the matrix effect correction model in passive / active mode using artificial neural networks

CEA DES / CAEN / SCK.CEN

- Measurement combination including WP5 simulations (WP8)
- Integration of WP5 measurements in DigiWaste platform (WP9)

This project has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement No 847641. This text reflects only the author's views and the Commission is not liable for any use that may be made of the information contained therein.

Thanks for your attention