DE LA RECHERCHE À L'INDUSTRIE

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LES MESURES NUCLÉAIRES NON DESTRUCTIVES POUR LE CONTRÔLE DES DÉCHETS RADIOACTIFS, L'ASSAINISSEMENT ET LE DÉMANTÈLEMENT DES INSTALLATIONS

Bertrand PEROT, CEA DEN CADARACHE

EFFMIN 4 | MARSEILLE, FRANCE | 18-21 JUILLET 2016

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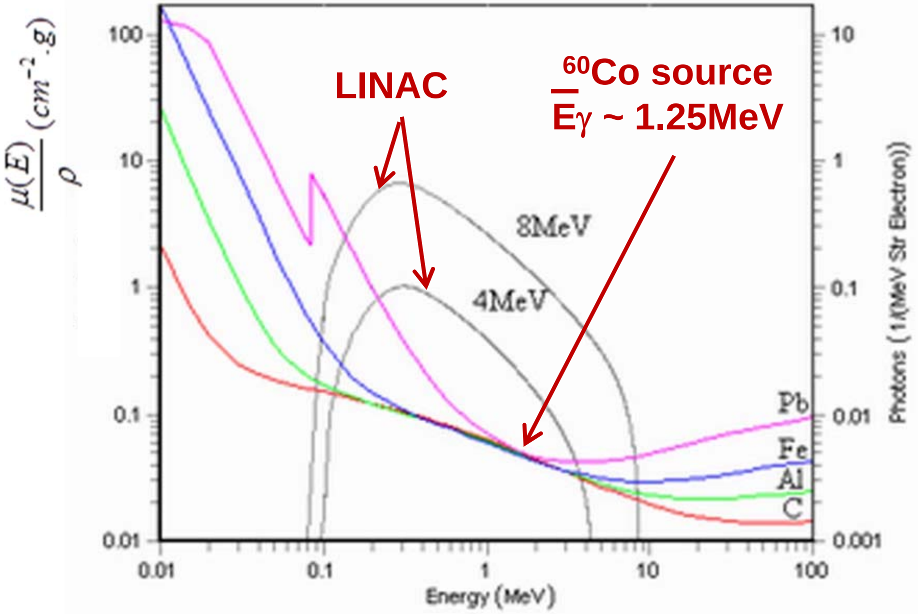
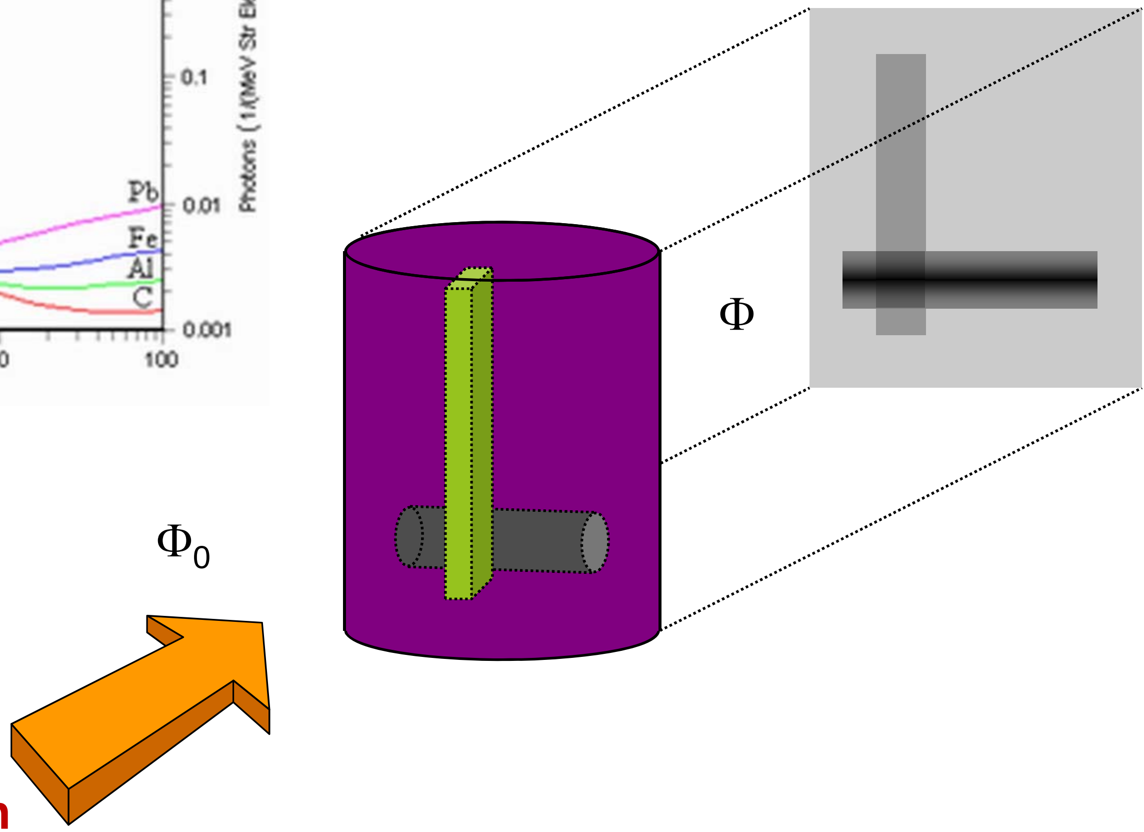
TRANSMISSION RADIOGRAPHY AND DENSITOMETRY



Detection system

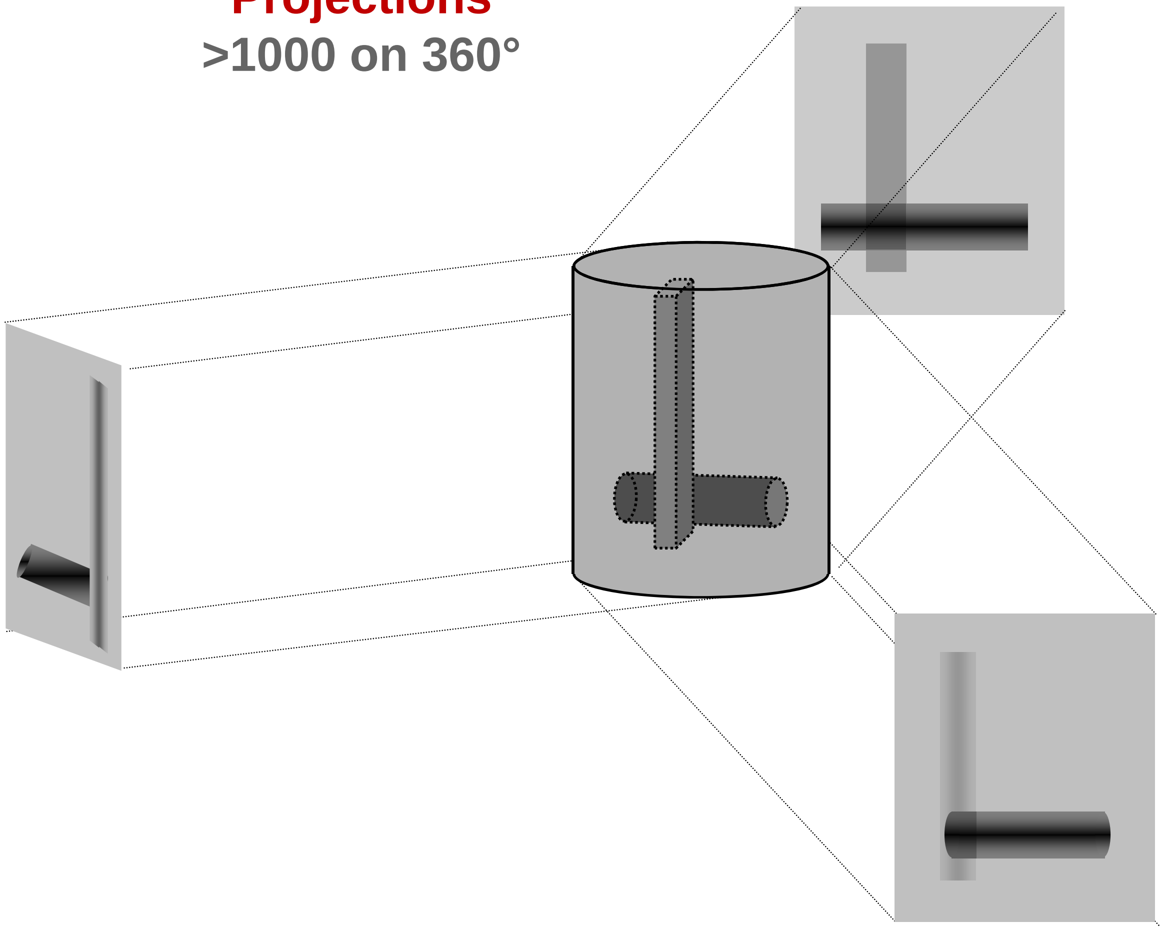


$$\rho = \frac{\ln\left(\Phi_0 / \Phi\right)}{\frac{\mu(E)}{\rho} \times L}$$

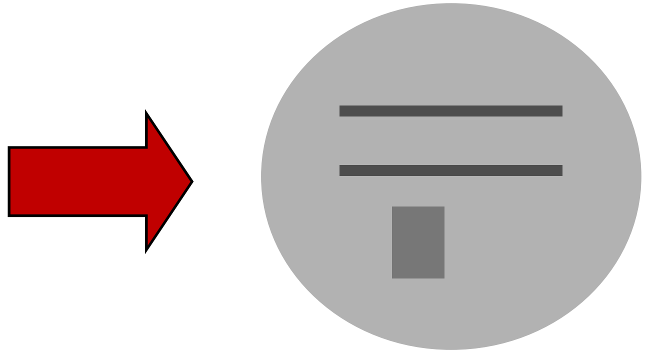
Photon source

PHOTON TRANSMISSION TOMOGRAPHY

Projections
>1000 on 360°

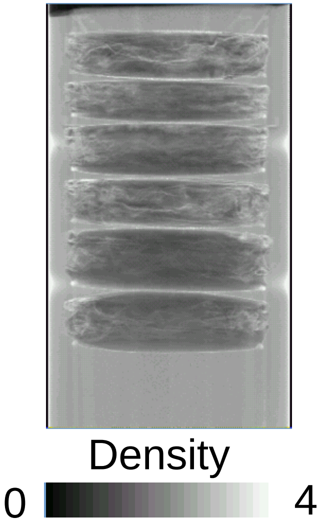


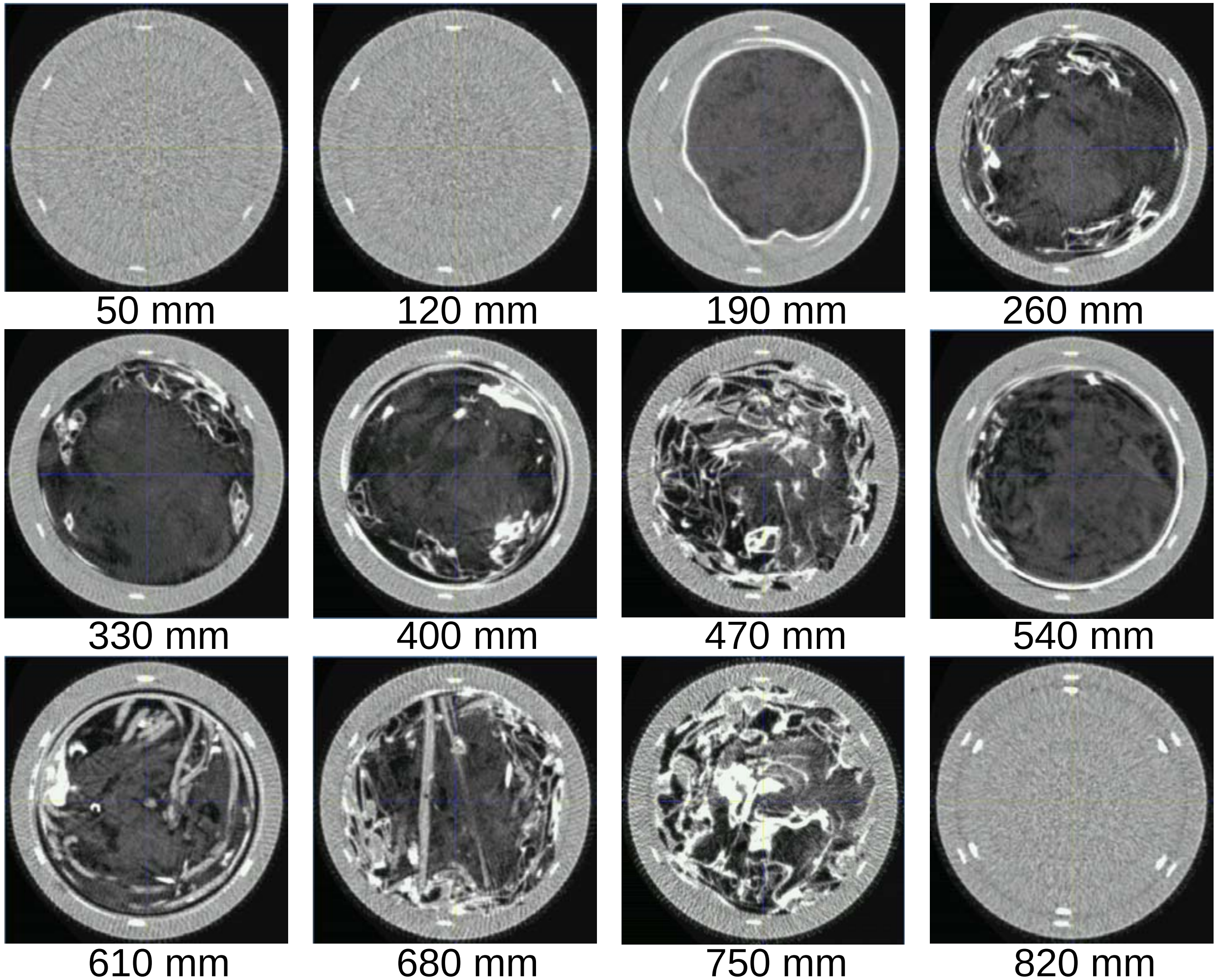
Reconstructed
2D cross sections



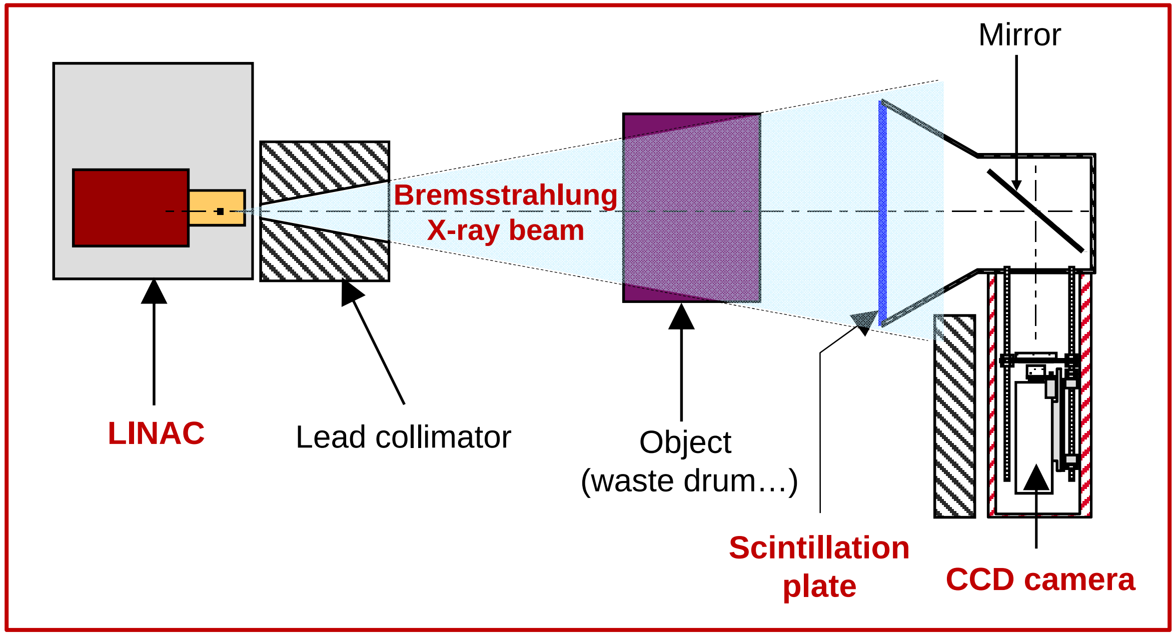
^{60}CO IMAGING: PRECISE DENSITY BUT LONG

TRANSEC: historic ^{60}Co tomography system of LMN, CEA DEN CADARACHE





HIGH ENERGY X-RAY IMAGING WITH A LINAC



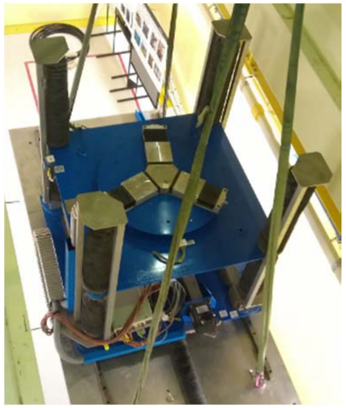
CINPHONIE: recent high energy imaging system of LMN, CEA DEN CAD

CINPHONIE Vs. TRANSEC:

- ***Radiography: 240 × faster (40 h → 10 min)***
- ***Tomography: 36 × faster (15 h → 25 min)***

9 MeV LINAC (15 Gy/min at 1m)

Moving platform (up to 2 tons)



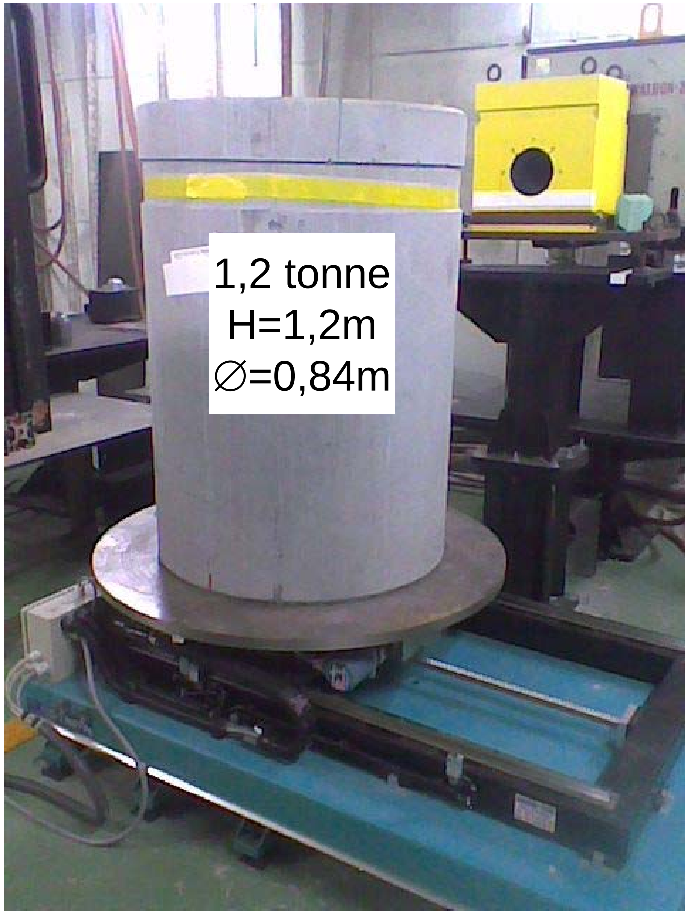
Scintillation plate (800 x 600 mm²)
Gadox Gd_2O_2S ; 1.5 mm

Nicolas Estre, Daniel Eck, Jean-Luc Pettier, Emmanuel Payan, Christophe Roure and Eric Simon, High-Energy X-Ray Imaging Applied to Non Destructive Characterization of Large Nuclear Waste Drums, ANIMMA 2013, 23-27 June 2013, Marseille, France

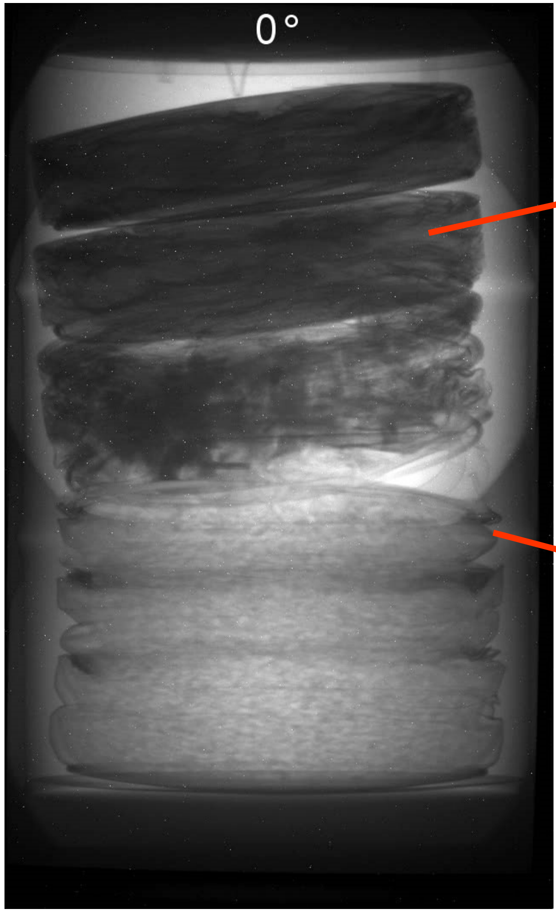
HIGH ENERGY IMAGING OF LARGE CONCRETE DRUMS

Concrete waste: density > 2

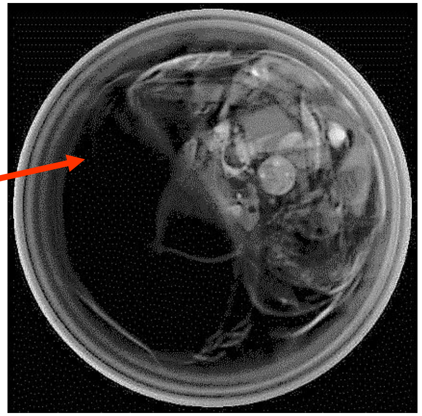
Less than 1 s per single radiography

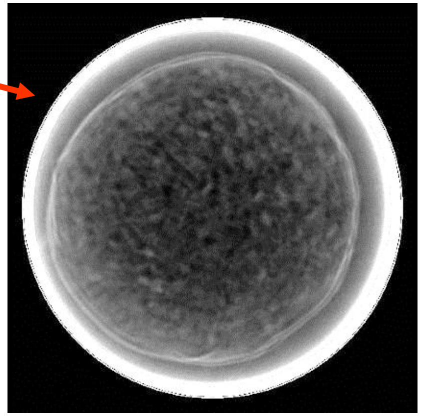


Radiography



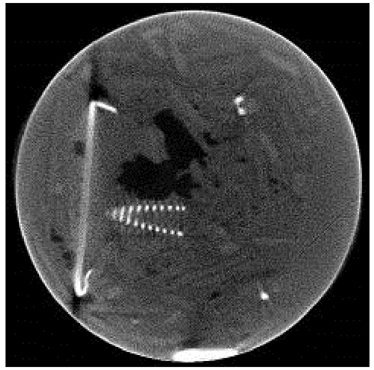
Tomography



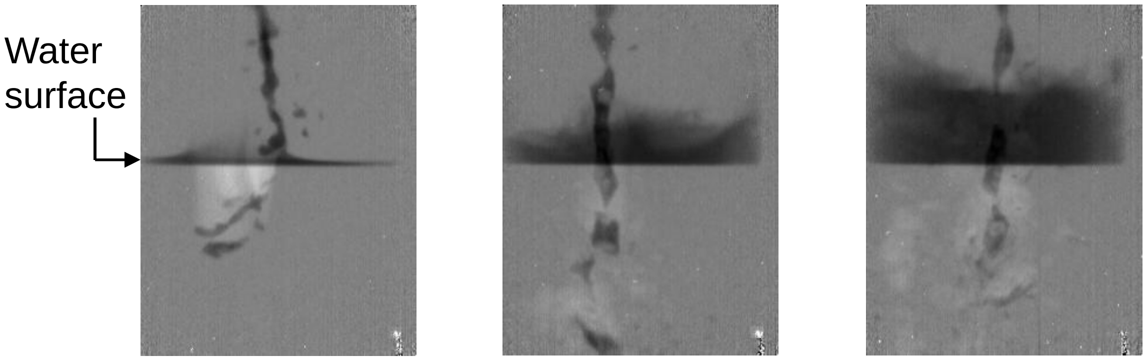


IN SITU HIGH ENERGY X-RAY IMAGING

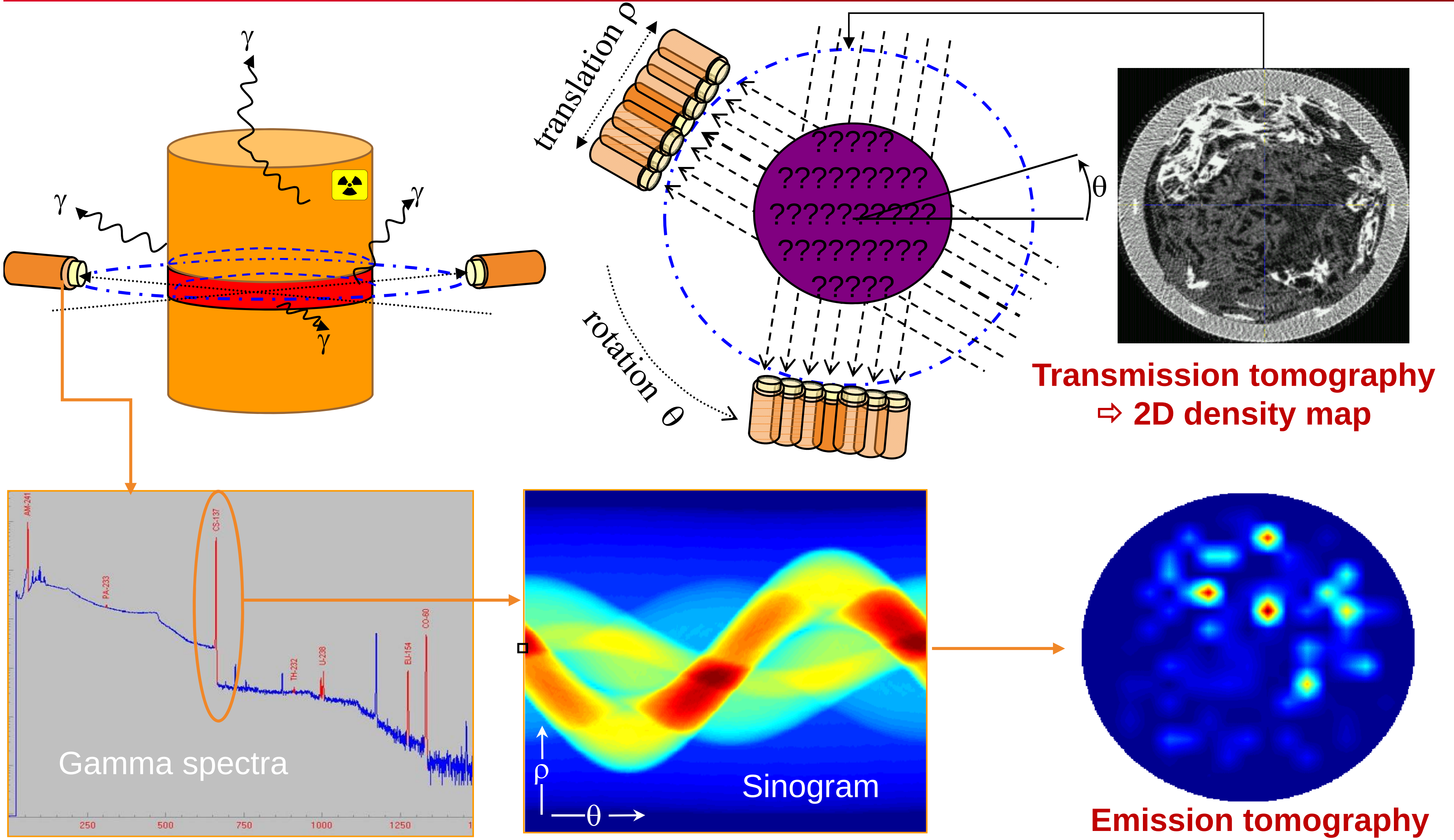
Bituminized waste drum characterization
at BELGOPROCESS facility, Belgium



Radioscopy of the corium - water interaction
Nuclear accident studies, KROTOS facility, CEA Cadarache



COMPUTED GAMMA EMISSION TOMOGRAPHY



Transmission tomography
⇨ 2D density map

Emission tomography
2D activity map

R. Thierry, J.L Pettier and L. Desbat, Simultaneous compensation for attenuation, scatter and detector response for 2D-emission tomography on nuclear waste with reduced data, 1st World Congress on Industrial Process Tomography, Buxton, Greater Manchester, April 14-17, E1 :542-551, 1999

PHOTON IMAGING

GAMMA SPECTROSCOPY

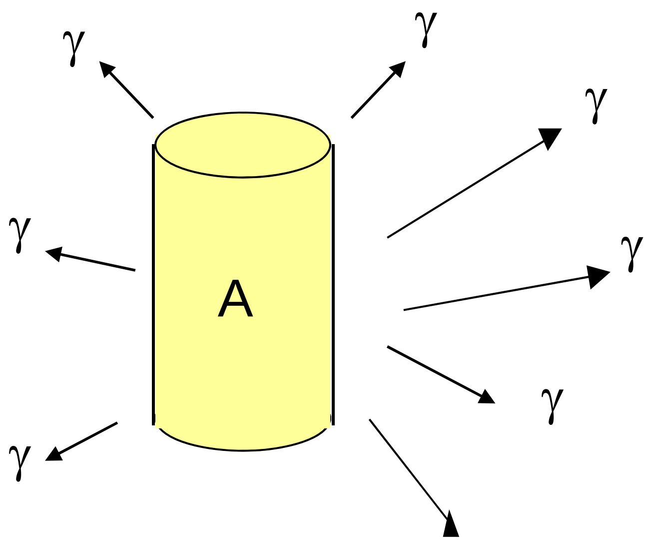
PASSIVE AND ACTIVE NEUTRON MEASUREMENTS

COMBINED MEASUREMENTS

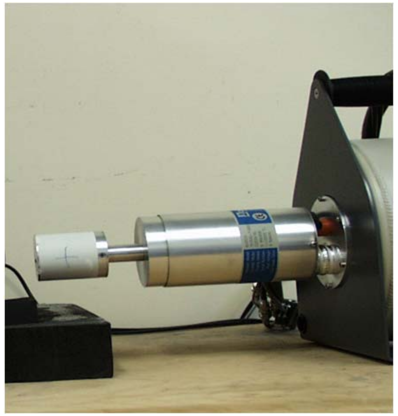
R&D

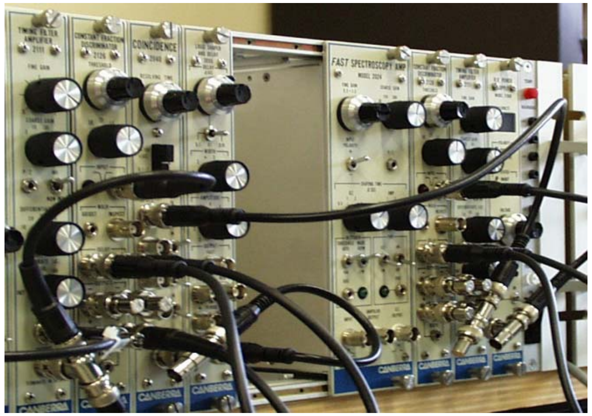
GAMMA-RAY SPECTROSCOPY

Radioactive object
(e.g. a waste package)

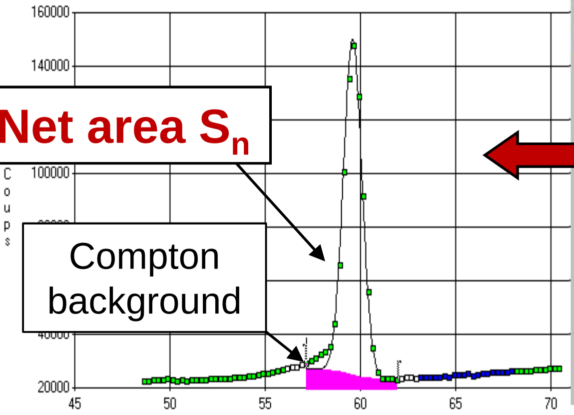


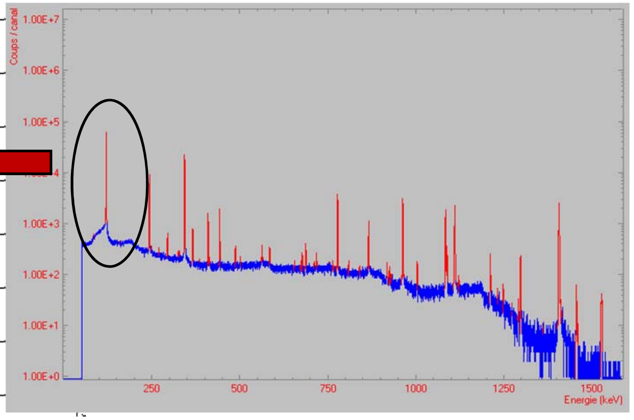
Detector and electronics





Gamma spectrum





Activity

$$A(E) = \frac{Sn(E)}{\varepsilon(E) \times I(E) \times T}$$

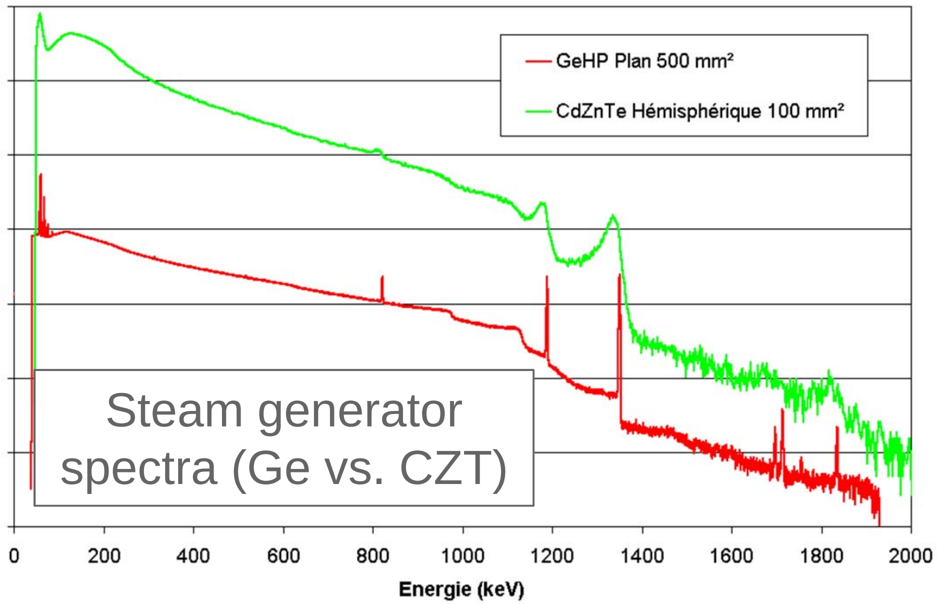
RADIOACTIVE WASTE CHARACTERIZATION

- **Specific gamma spectroscopy** stations the laboratory
- **Part of combined measurements** e.g. for ANDRA

"Super-Controls" with X-ray imaging and neutron assay

IN SITU γ SPECTROSCOPY IN NUCLEAR REACTORS

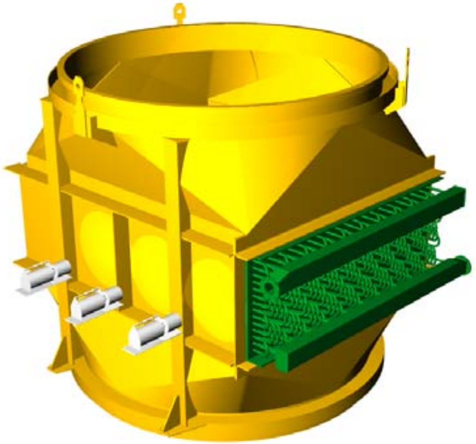
- **Historic activity** > 300 campaigns (end of 70's)
- **EDF** and foreign power plants
- **EMECC** device & software
  - Intermediate activities (1 MBq/m² → 100 GBq/m²)
  - Pipes, steam generators, heat exchangers…
  - Characterization of a whole plant (all circuits)
  - Deposited or volumetric activities (GBq / m² or m³)
  - Experimental qualification by EDF
  - Support to **OSCAR** contamination transfer code



IN SITU γ SPECTROSCOPY OF LARGE COMPONENTS

Uranium hold-up measurement in a heat exchanger

Segmented gamma spectrometry



Vessel contamination and activation

Underwater HP Ge gamma-ray spectroscopy

SFR cold trap characterization

HP Ge + CZT in inspection hall

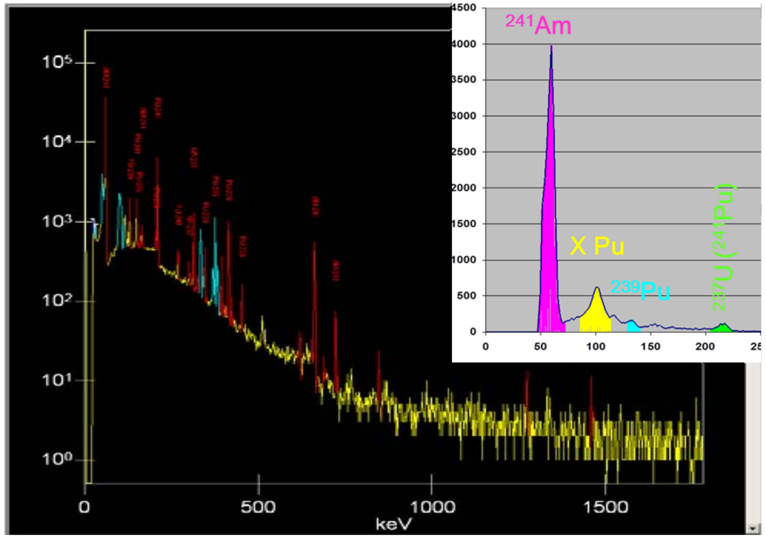
Characterization of activated components

TORE SUPRA wastes – HP Ge

IN SITU γ SPECTROSCOPY OF NUCLEAR MATERIALS

- **Dismantling operations**
  Fuel fabrication and reprocessing units
- **HP Ge detector**
  ⇨ isotopic composition, activity or mass
- **CZT** probe introduced in glove boxes
  ⇨ localization

Fissile mass estimation in a reprocessing unit



HP Ge detector

CZT probe

Characterization of Pu in glove boxes of a Pu fuel fabrication facility

IN SITU γ SPECTROSCOPY FOR BUILDINGS

Inside
After removing all components

Outside
Walls control

High efficiency HP Ge with tungsten shield

PHOTON IMAGING

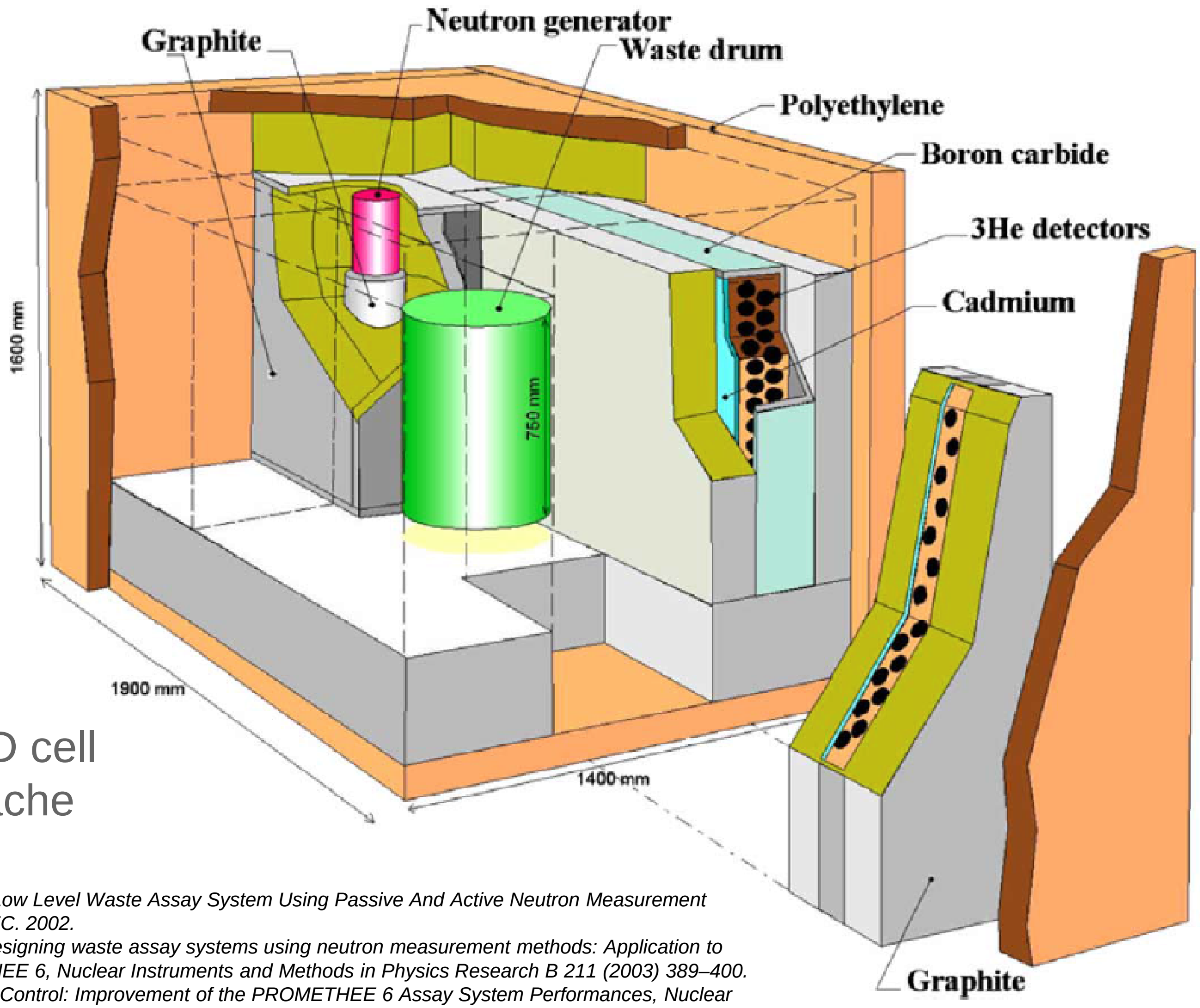
GAMMA SPECTROSCOPY

PASSIVE AND ACTIVE NEUTRON MEASUREMENTS

COMBINED MEASUREMENTS

R&D

MIXED PASSIVE & ACTIVE NEUTRON CELL (R&D)



"PROMETHEE VI" R&D cell
LMN, CEA DEN Cadarache

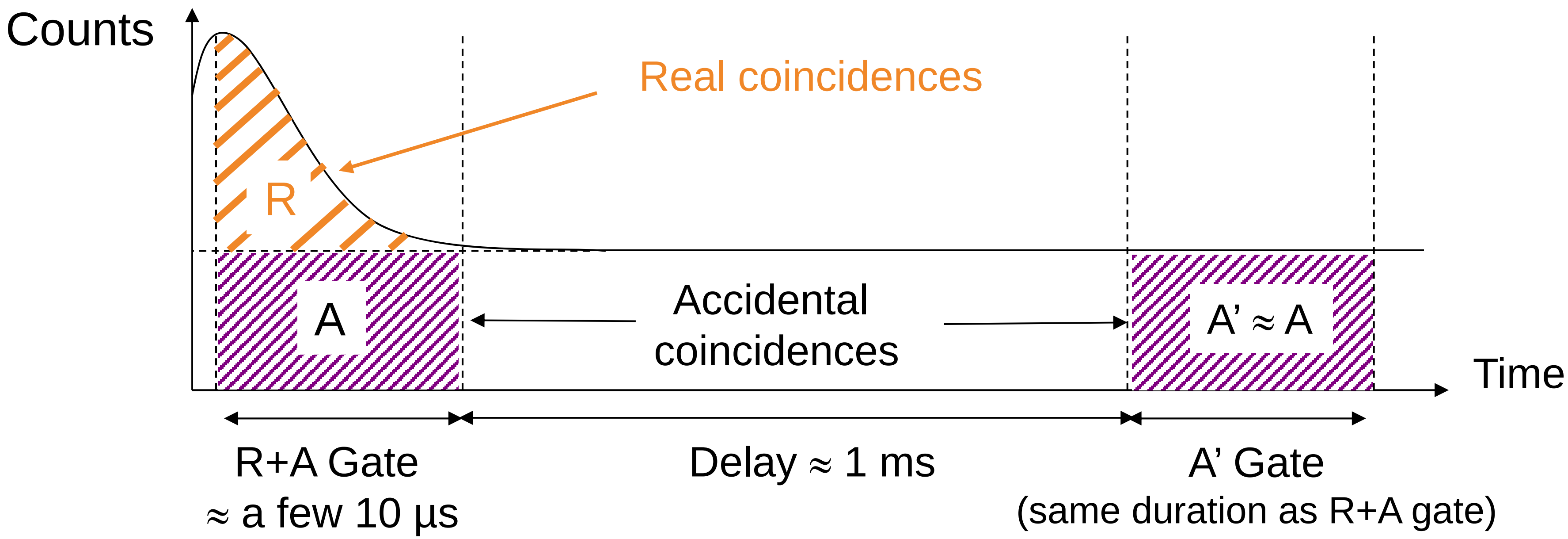
- *Christian Passard et al., PROMETHEE: An Alpha Low Level Waste Assay System Using Passive And Active Neutron Measurement Methods, NUCLEAR TECHNOLOGY VOL. 140 DEC. 2002.*
- *A. Mariani et al., The help of simulation codes in designing waste assay systems using neutron measurement methods: Application to the alpha low level waste assay system PROMETHEE 6, Nuclear Instruments and Methods in Physics Research B 211 (2003) 389–400.*
- *Fanny Jallu et al., Alpha-Particle Low-Level Waste Control: Improvement of the PROMETHEE 6 Assay System Performances, Nuclear Technology Vol. 153 Jan. 2006.*

❑ Total counting

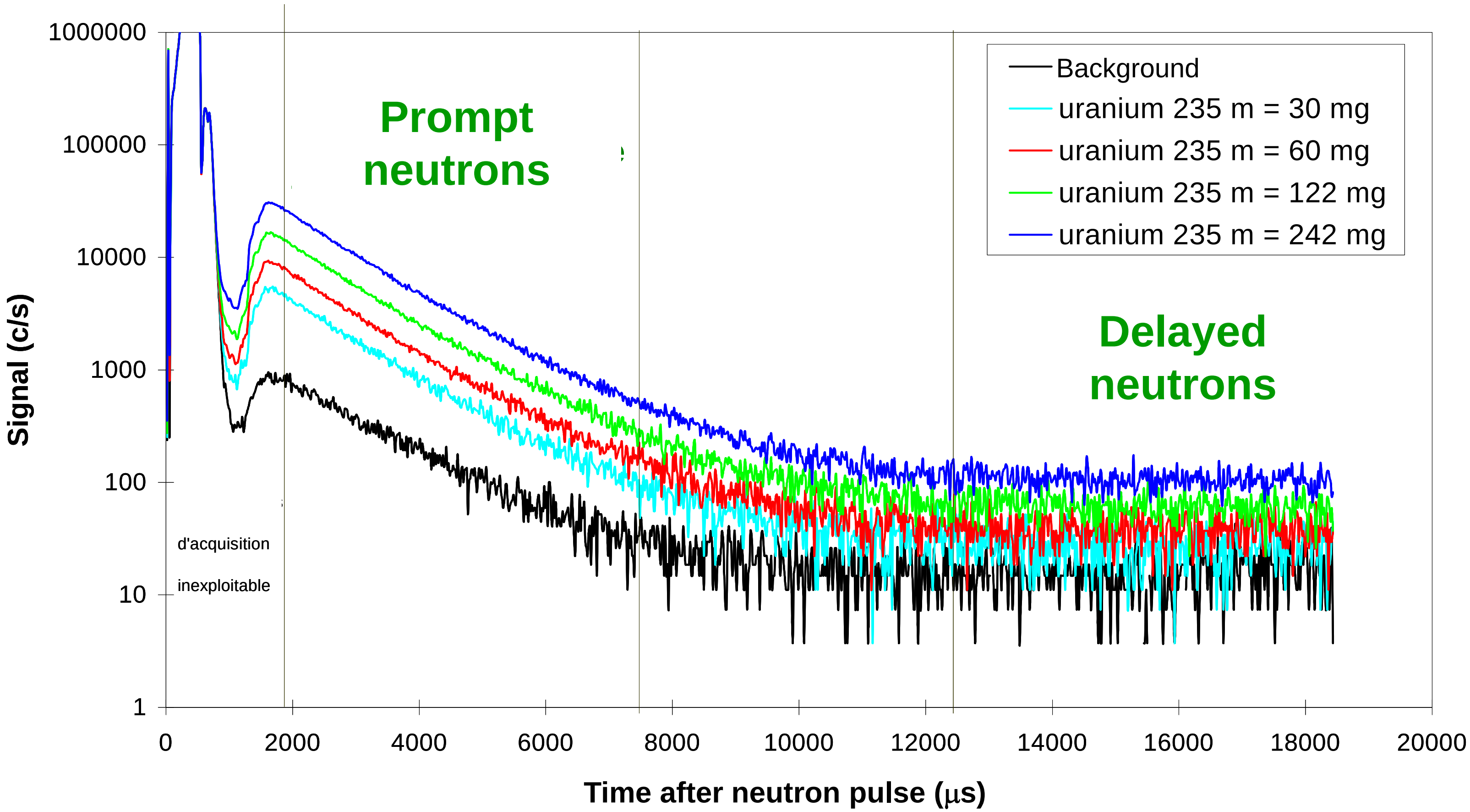
Spontaneous fission + (α,n) neutrons ⇨ $^{242 \text{ and } 244}Cm$, $^{238, 240 \text{ and } 242}Pu$, ^{241}Am (+ ^{238}U if mass > kg)

❑ Coincidence counting

Spontaneous fission neutrons only ⇨ $^{242 \text{ and } 244}Cm$, $^{238, 240 \text{ and } 242}Pu$ (+ ^{238}U)



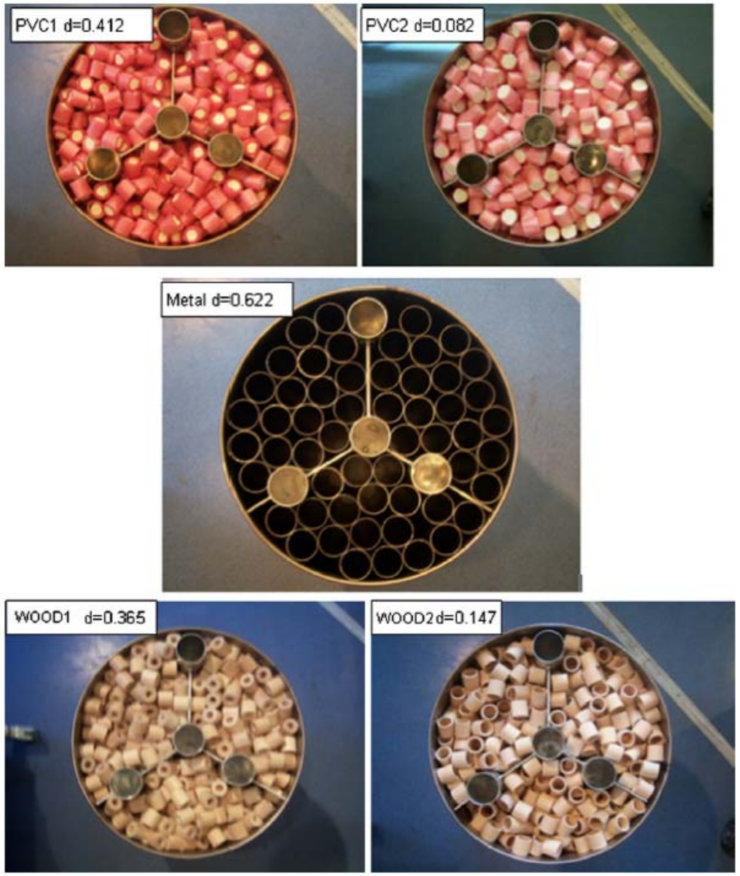
ACTIVE "DIFFERENTIAL DIE AWAY TECHNIQUE"



Prompt and delayed neutron signals ⇨ ^{235}U and ^{239}Pu discrimination

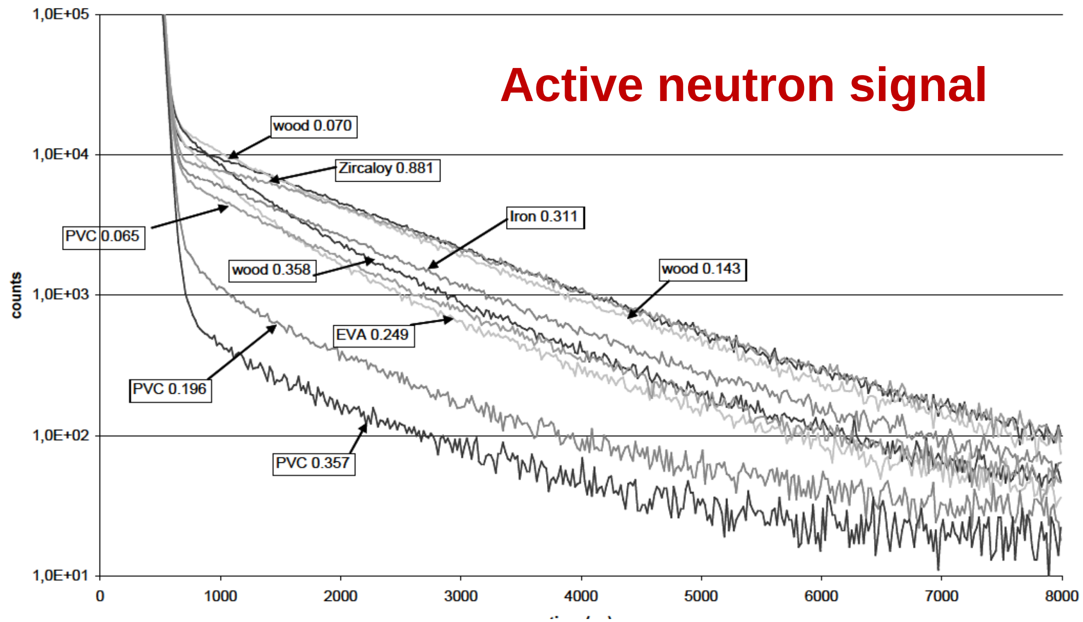
- **Prompts neutrons** ⇨ ^{235}U, $^{239 \text{ and } 241}Pu$
- **Delayed neutrons** ⇨ ^{235}U, $^{239 \text{ and } 241}Pu$ + ^{238}U and ^{232}Th

CALIBRATION WITH DIFFERENT MATRIX MATERIALS



Passive detection

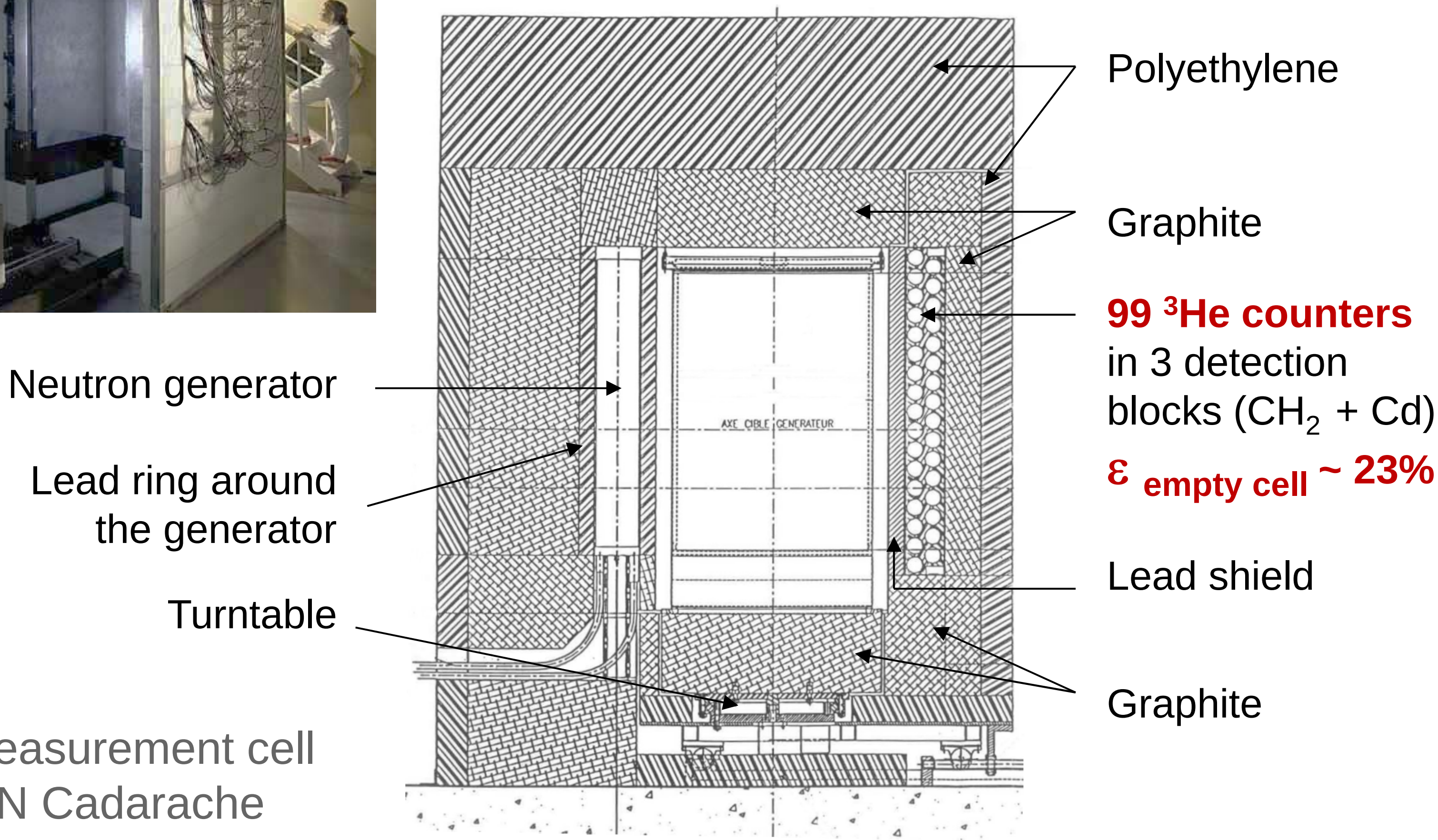
Matrix	Detection efficiency (%)	
	Measured	Calculated
Empty cavity	10.13 ± 0.22	10.27 ± 0.01
PVC1 ($d = 0.412$)	9.05 ± 0.20	9.19 ± 0.01
PVC2 ($d = 0.082$)	10.37 ± 0.23	10.54 ± 0.01
WOOD1 ($d = 0.365$)	8.92 ± 0.20	8.88 ± 0.01
WOOD2 ($d = 0.147$)	10.44 ± 0.23	10.65 ± 0.01
Metal ($d = 0.622$)	10.49 ± 0.23	10.67 ± 0.05



- F. Jallu et al. / Nuclear Instruments and Methods in Physics Research B 271 (2012) 48-54
- A.-C. Raoux et al. / Nuclear Instruments and Methods in Physics Research B 266 (2008) 4837-4844
- R. Antoni et al. Matrix effect correction with internal flux monitor in radiation waste characterization with the Differential Die-away Technique, IEEE Transactions on Nuclear Science, Vol. 61, No. 4 (2014) 2155-2160

PASSIVE & ACTIVE NEUTRON CELL

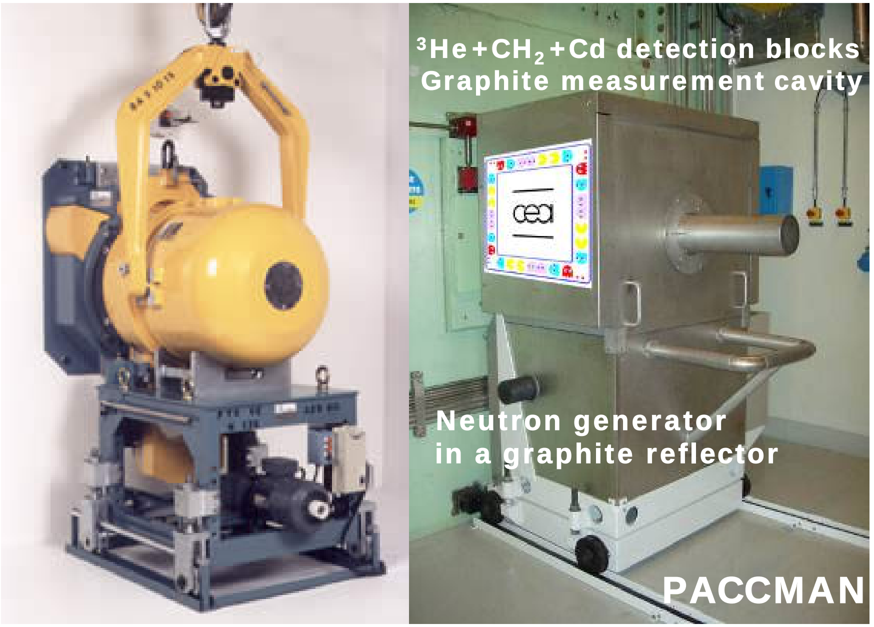
Pulsed DT neutron generator
GENIE 36 SODERN, **2.10^9 n/s**

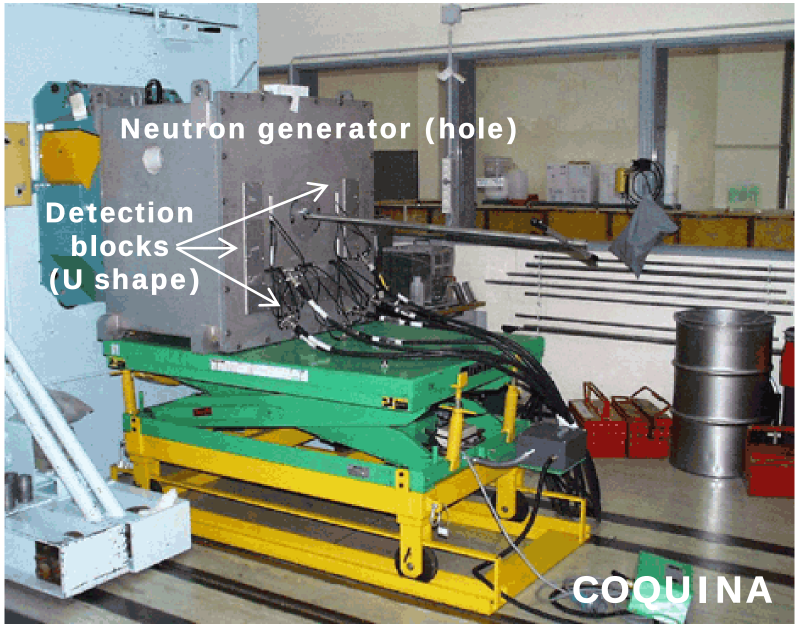


SYMETRIC measurement cell
LMN, CEA DEN Cadarache
ANDRA -CEA “Super-controls”

IN SITU PASSIVE / ACTIVE NEUTRON SYSTEMS

PACCMAN, COQUINA: active neutron interrogation systems plugged to hot cells to assess Pu and U in high level wastes





LMN, CEA DEN CADARACHE

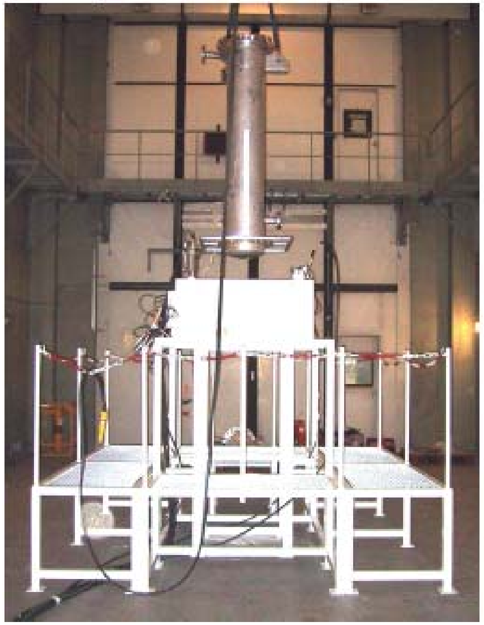
ATALANTE, CEA DEN MARCOULE

IN SITU NEUTRON MEASUREMENTS

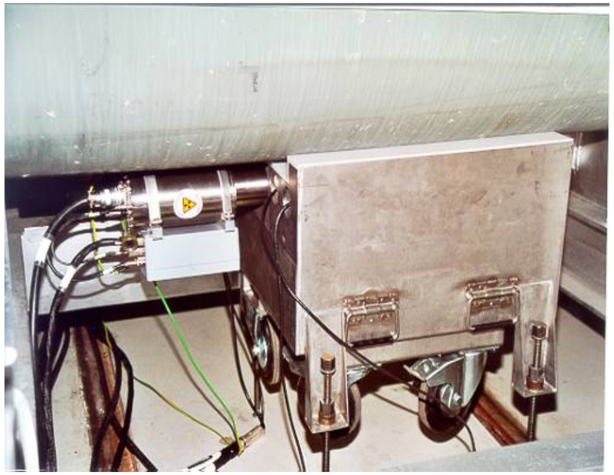
Characterization of large components in uranium enrichment facilities

(UF_6 gas diffusion technology)

Passive neutron measurement of the uranium hold-up in UF_6 compressors



Passive (and active) neutron measurements of uranium hold-up in an UF_6 crystallizer



Measurement of the uranium enrichment in an UF_6 container by active neutron interrogation

F. Jallu et al., Dismantling and decommissioning: The interest of passive neutron measurement to control and characterise radioactive wastes containing uranium, Nuclear Instruments and Methods in Physics Research B 271 (2012) 48–54

PHOTON IMAGING

GAMMA SPECTROSCOPY

PASSIVE AND ACTIVE NEUTRON MEASUREMENTS

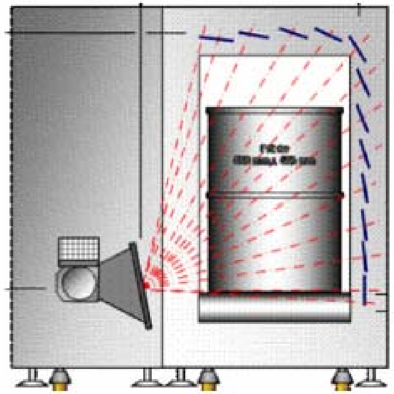
COMBINED MEASUREMENTS

R&D

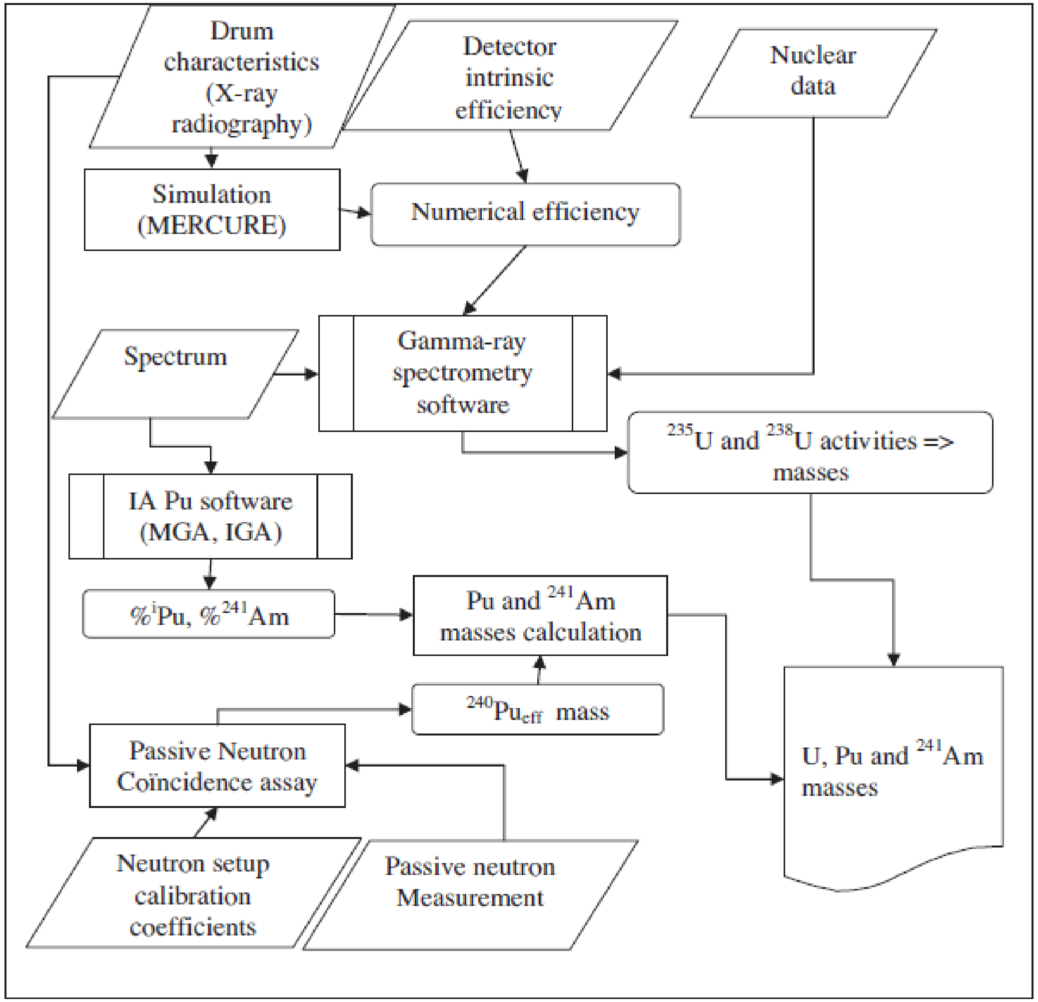
RADIOACTIVE WASTE CARACTERISATION

X-RAY RADIOGRAPHY + γ SPECTROSCOPY + PASSIVE NEUTRON COUNTING

X-ray radiography

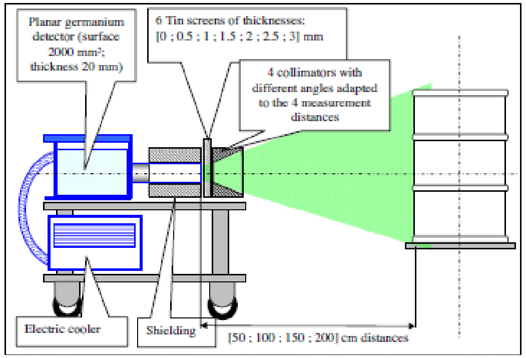


PEGAZE 100 L historic waste drums, CEA DEN CADARACHE



F. Jallu et al. / Nuclear Instruments and Methods in Physics Research B 271 (2012) 48–54

γ-ray Spectro.



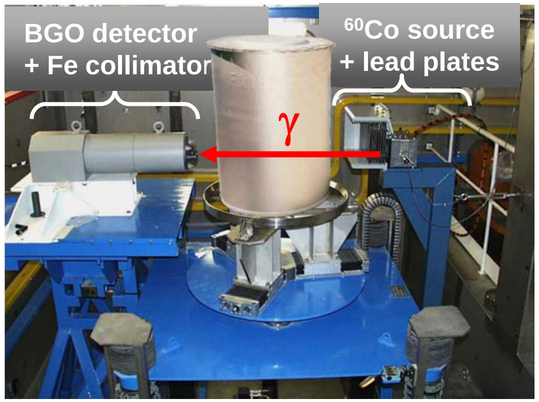
Passive Neutron Coinc. Counting

COMBINED MEASUREMENT SYSTEM

γ RADIOGRAPHY + γ SPECTROSCOPY + ACTIVE & PASSIVE NEUTRON CELL

> 60,000 historic 225 L bituminized waste drums (Marcoule, France) ➡ **Non Destructive Assay** performance study

Low resolution gamma radiography (^{60}Co)

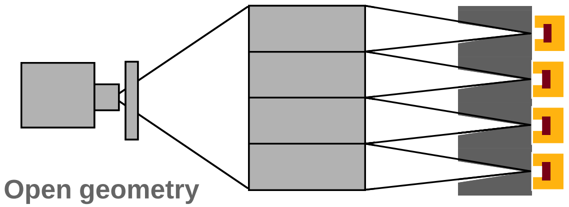


Gamma spectroscopy

⇨ β,γ radionuclides ⇨ ^{241}Am α activity

Coaxial HP Ge (100% rel. eff.)

Planar HP Ge + BGO Compton suppression

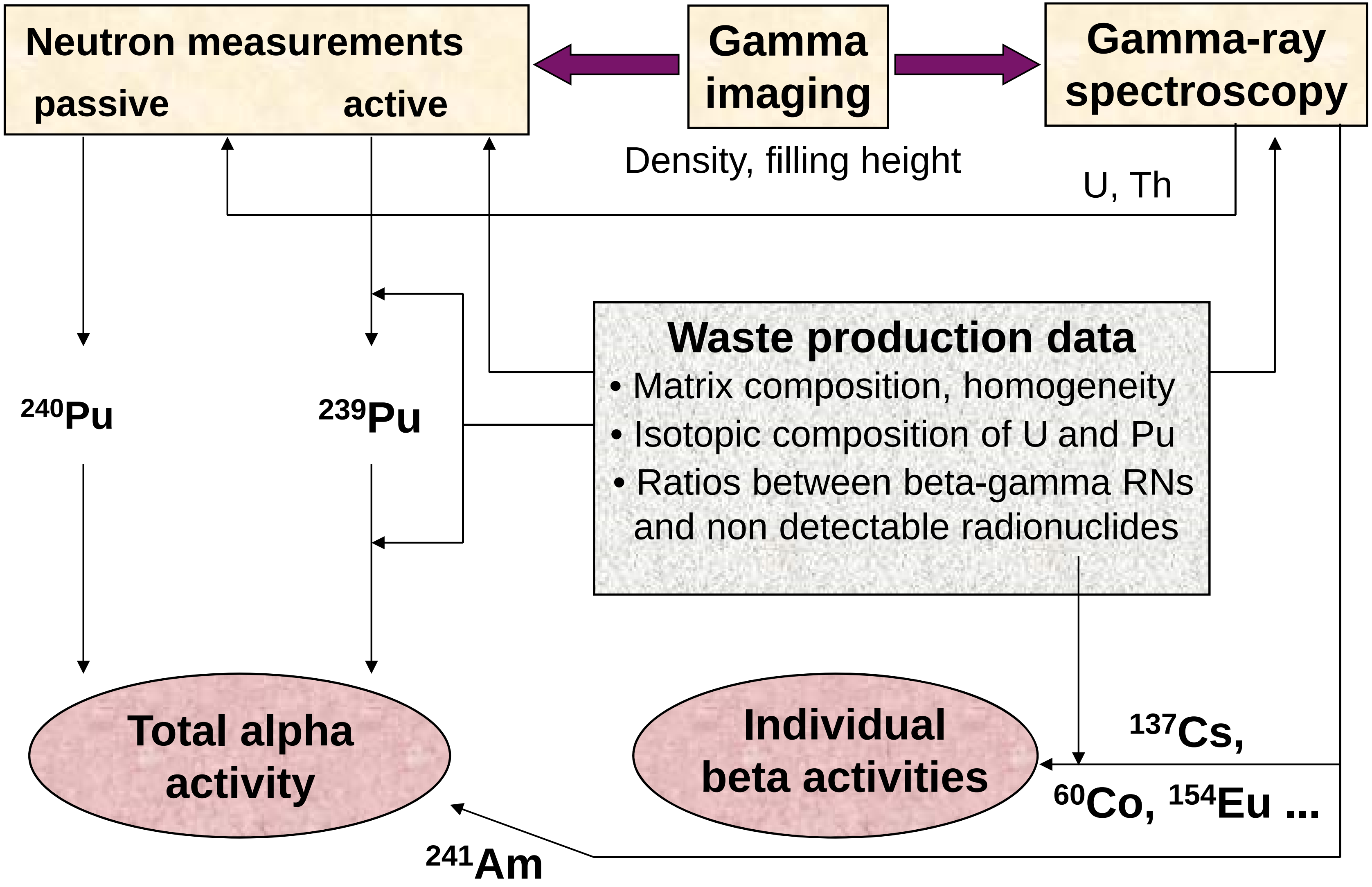


Passive & active neutron cell ⇨ Pu, U

- Graphite and polyethylene cell
- 99 ^{3}He counters + Pb and Cd shields
- Pulsed 2.10^{9} n/s neutron generator

B. Pérot, J.-L. Artaud, C. Passard, A.-C. Raoux, Experimental Qualification With a Scale One Mock-Up of the "Measurement and Sorting Unit" for Bituminized Waste Drums, http://dx.doi.org/10.1115/ICEM2003-4597

COUPLING MEASUREMENT RESULTS



PHOTON IMAGING

GAMMA SPECTROSCOPY

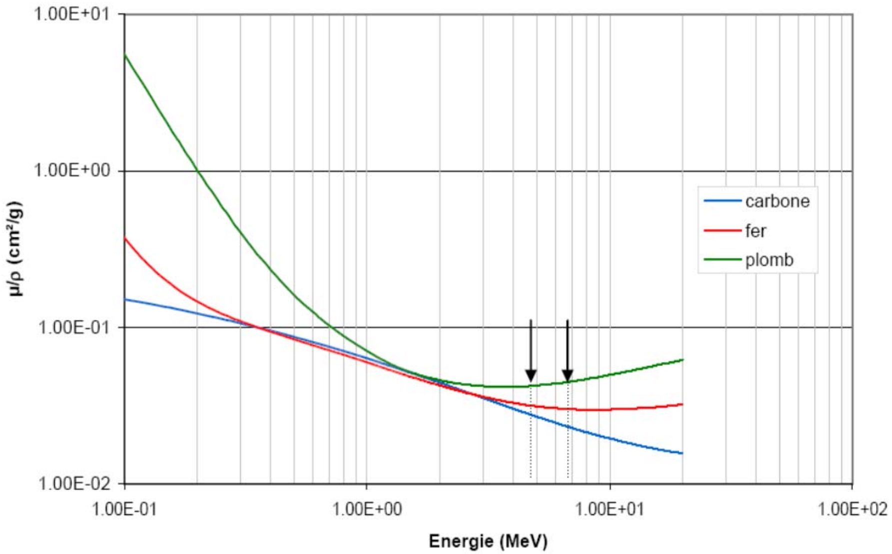
PASSIVE AND ACTIVE NEUTRON MEASUREMENTS

COMBINED MEASUREMENTS

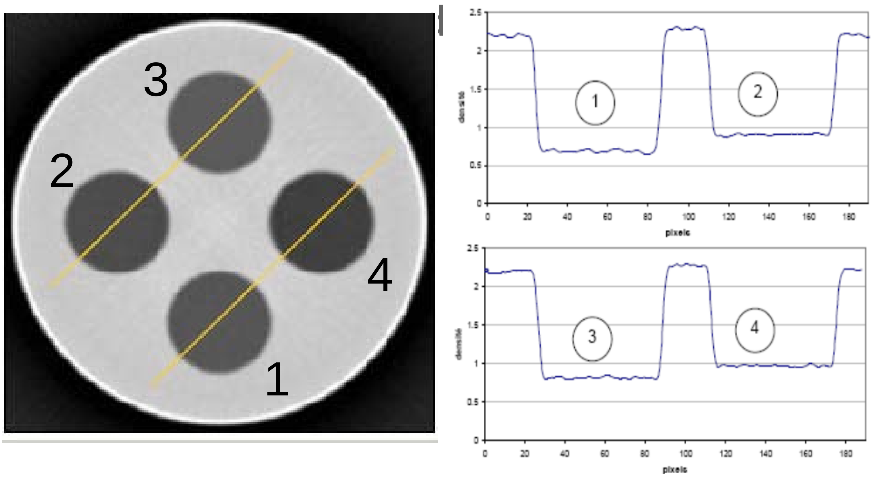
A FEW R&D TOPICS

DUAL ENERGY IMAGING (SATURNE LINAC PROJECT)

Mass attenuation coefficient μ/ρ



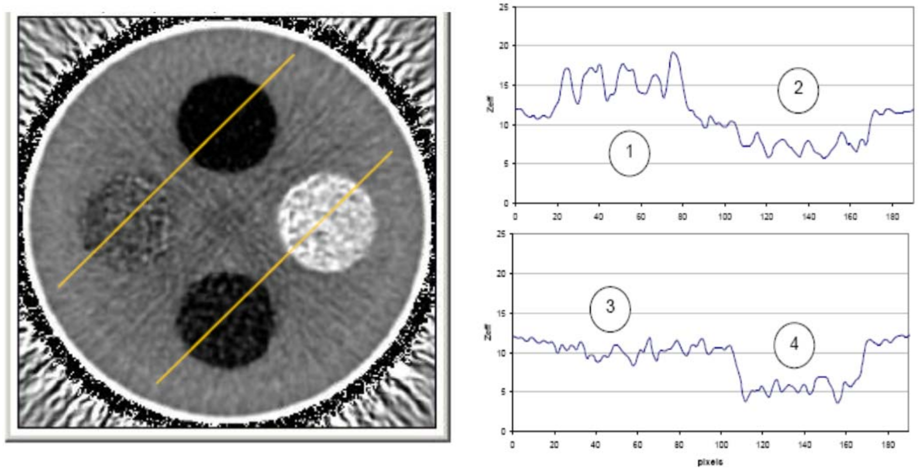
Density (simulation of a 870 L



LINAC acquisitions at 15 MeV and 9 MeV

μ_{15MeV} ($\bar{E}$~ 6 MeV) / μ_{6MeV} ($\bar{E}$~4 MeV)

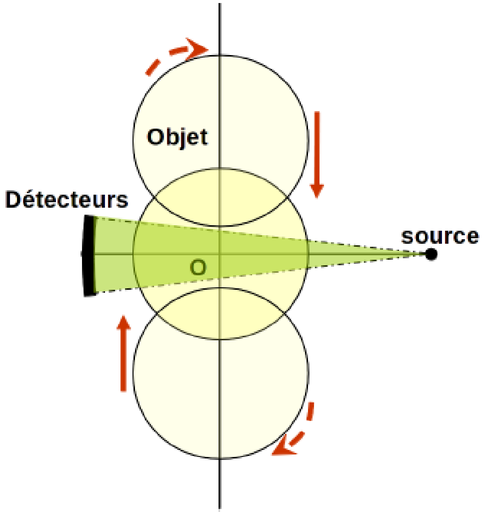
Atomic number Z (simulation of a 870 L drum)



N° insert	matériau	Z_{eff} théorique	Z_{eff} calculé
1	PVC	12	15.90 ± 11.3%
2	Cellulose	6.68	7.05 ± 15%
3	plastique	9.3	9.96 ± 11.1%
4	CH_2	5.28	5.46 ± 15.5%

HIGH ENERGY X-RAY TOMODENSITOMETRY

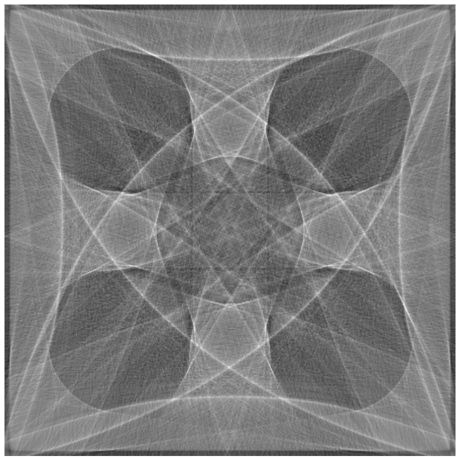
- **Attenuation up to 5 decades (40 cm steel)**
- Radiography and 2D plane tomography
- 3D helicoidally tomography
- **0.5 to 2 mm spatial resolution**
- 1 h (2D) to several days (3D) acquisitions



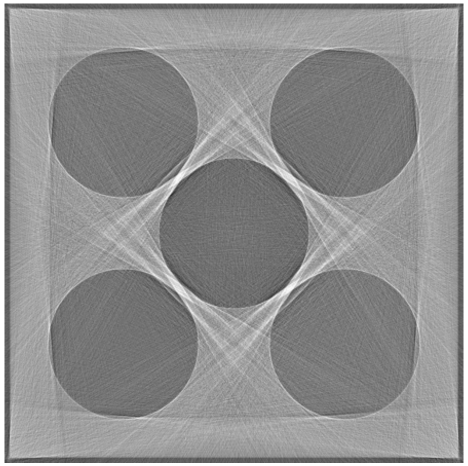
Collimated CdTe detectors

Simulations of a 5 m³ concrete waste package

9 MeV LINAC



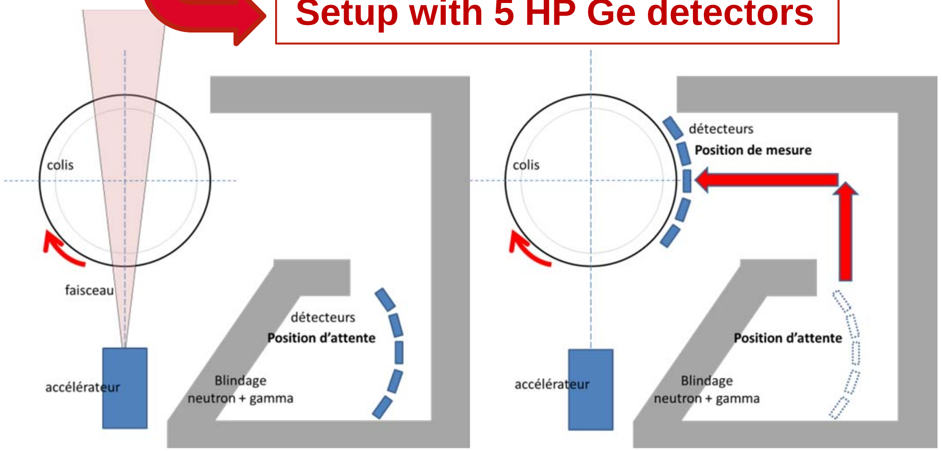
15 MeV LINAC

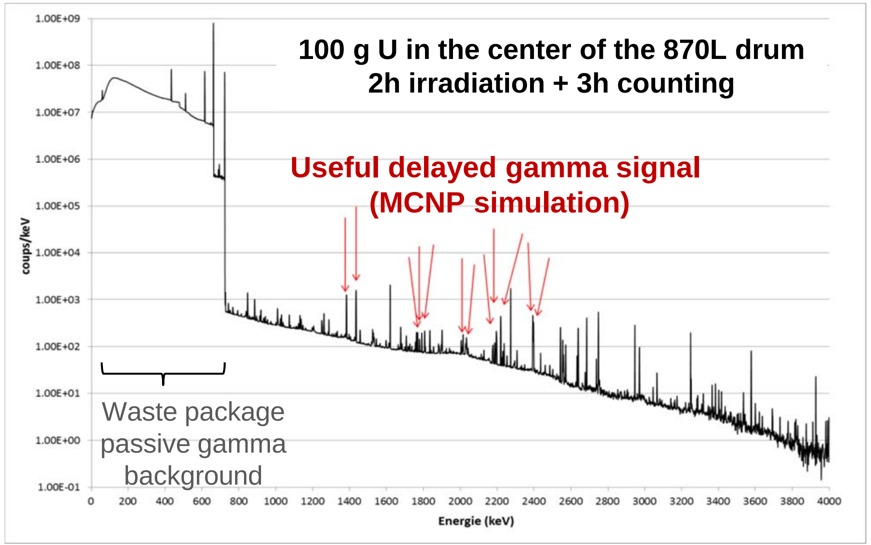


ACTIVE PHOTON INTERROGATION: PHOTOFISSION

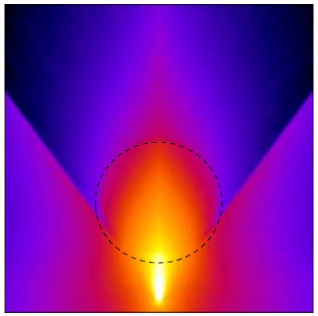
- **U and Pu** measurement in **large concrete waste packages**
- **High energy X rays** produced by an electron LINAC (photofission threshold ~ 6 MeV)
- **Delayed neutron counting** between the pulses
- **Delayed gamma-ray spectroscopy** after stopping irradiation

Setup with 5 HP Ge detectors





15 MV Linac beam
(870 L drum)

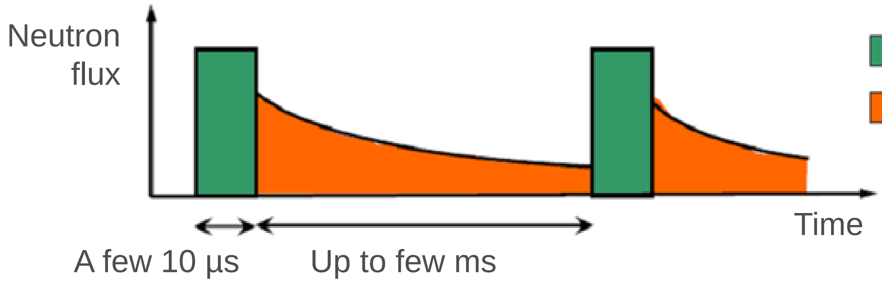


U in the center	Background & detection limit - 1 detector			Backgr. & detection limit - 5 detector cluster		
γ ray (keV)	B (counts)	L_D (counts)	L_D (g ^{235}U)	B (counts)	L_D (counts)	L_D (g ^{235}U)
1384	80	44	0,92	240	75	0,312
1436	116	53	0,84	580	115	0,36
1768	64	40	7,98	320	86	3,43
1791	64	40	7,98	320	86	3,43
1807	60	39	6,45	300	83	2,78
2016	96	48	9,66	480	105	4,18
2032	100	49	8,21	500	107	3,56
2176	34	30	9,94	170	63	4,22
2196	32	29	2,89	158	61	1,22
2218	34	30	1,74	168	63	0,74
2392	36	31	1,70	180	65	0,72
2398	36	31	2,35	180	65	1,00

E. Simon, F. Jallu, B. Pérot, S. Plumeri, Feasibility study of fissile mass quantification by photofission delayed gamma rays in radioactive waste packages using MCNPX, submitted to Nuclear Instruments and Methods in Physics Research A

NEUTRON ACTIVATION ANALYSIS

- **Toxic chemical or matrix material** characterization in radioactive wastes
- **PGNAA** Prompt Gamma Neutron Activation Analysis
- **Pulsed neutron generator** + **HP Ge gamma-ray detector**

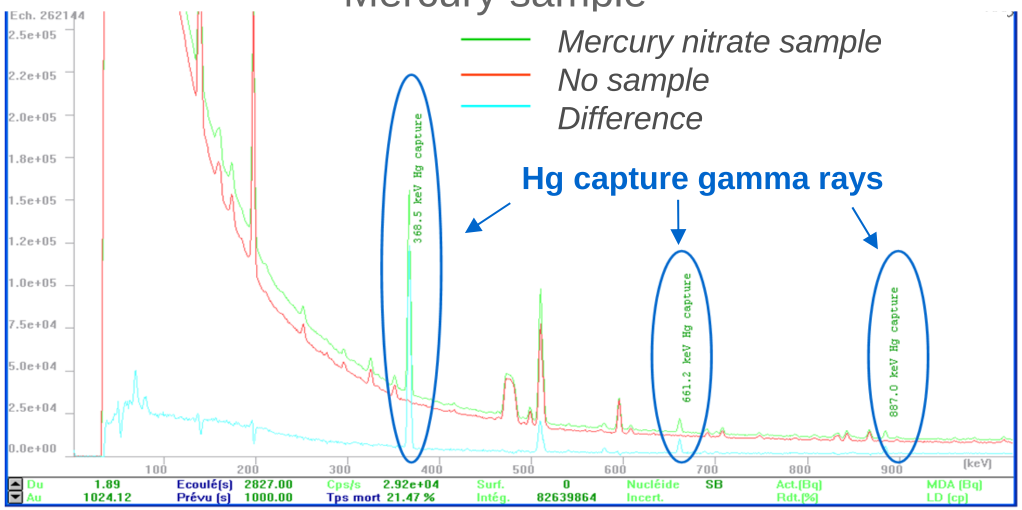


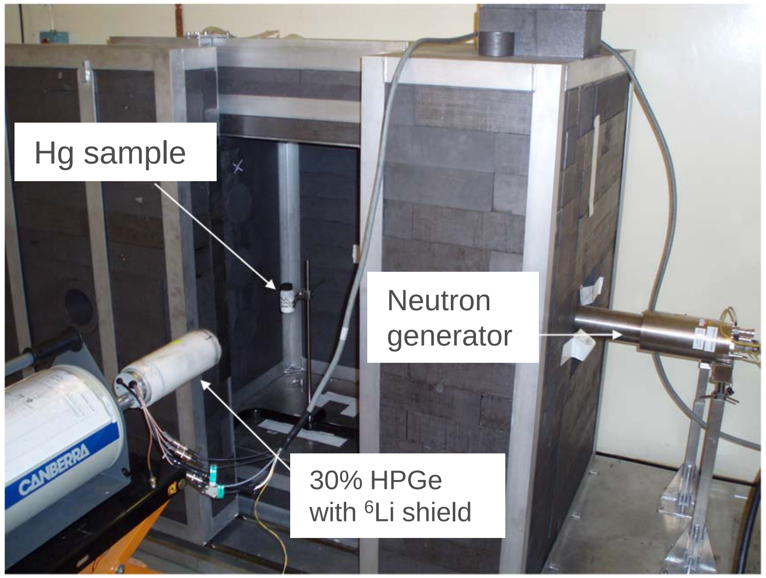
Fast neutrons during the pulses ⇨ (n,n'γ)

Thermal neutrons between pulses ⇨ (n,γ)

(+ deactivation gamma rays after irradiation)

Mercury sample





REGAIN cell, CEA DEN CAD, LMN

J.-L. Ma et al., Prompt Gamma Neutron Activation Analysis of toxic elements in radioactive waste packages, Applied Radiation and Isotopes 70 (2012) 1261

CEA- FZJ COLLABORATION ON PGNAA

- ❑ **MEDINA PGNAA cell**
  FZJ, Germany, GENIE 16 neutron generator and ~ 100% HP Ge
- ❑ **EXP / MCNP** comparisons
- ❑ **MCNP performance** optimization
- ❑ **Fission delayed** γ (see next slide)

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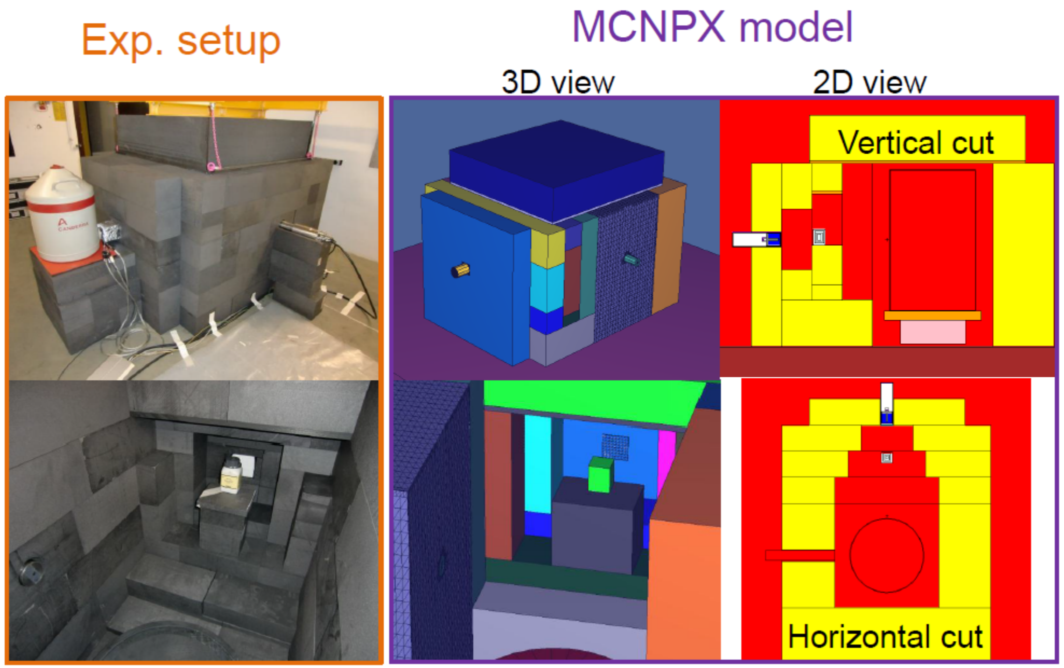
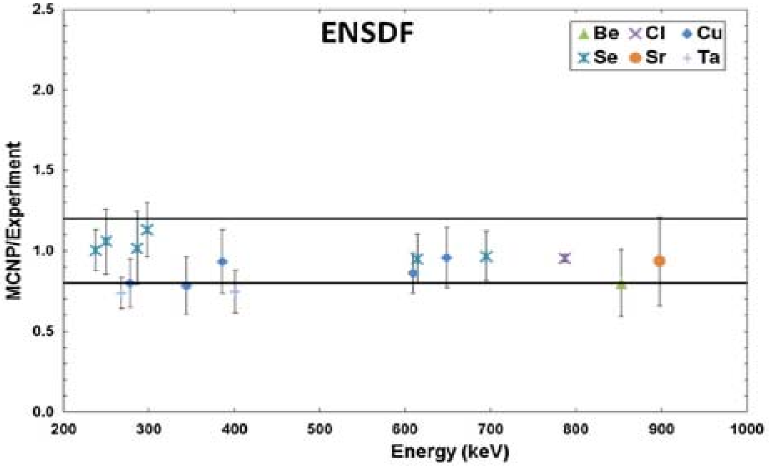
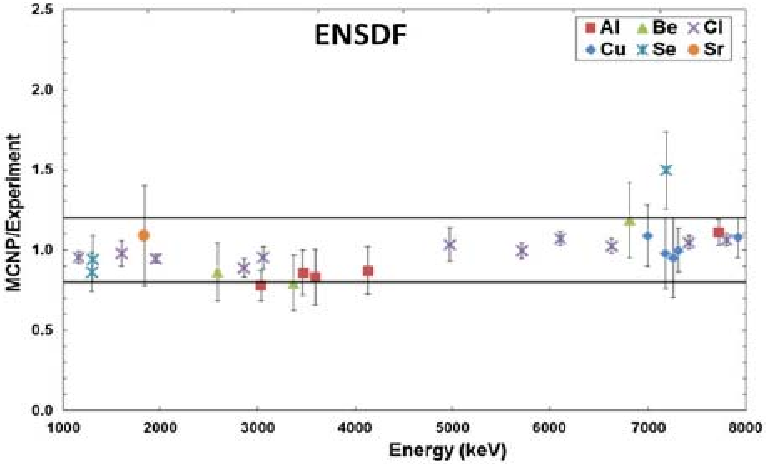


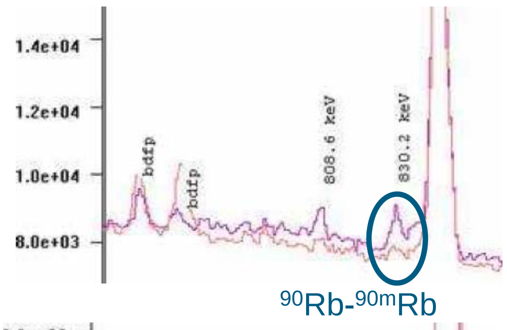


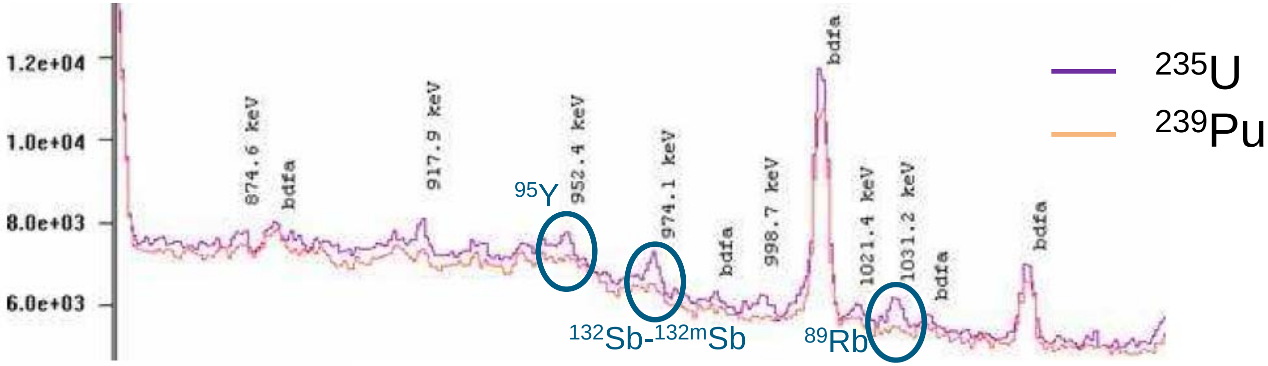


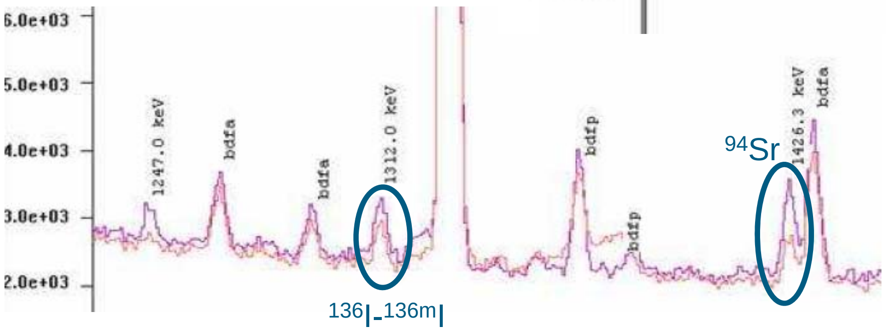
T.Nicol, C. Carasco, B. Perot, J.L. Ma, E. Payan et al., Quantitative comparison between PGNAA measurements and MCNPX simulations, Journal of Radioanalytical and Nuclear Chemistry, DOI 10.1007/s10967-015-4451-4

NEUTRON-INDUCED FISSION DELAYED γ-RAY YIELDS

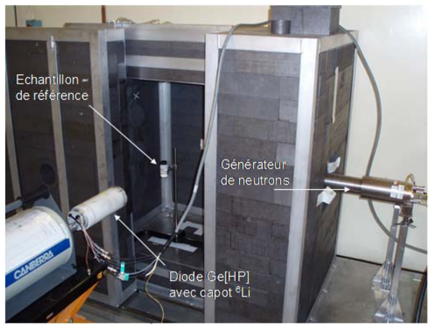
❑ Gamma spectra of ^{235}U and ^{239}Pu samples measured in REGAIN between neutron pulses

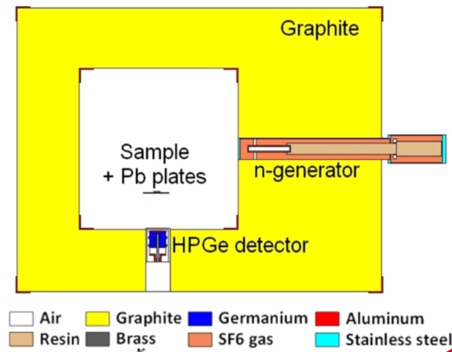






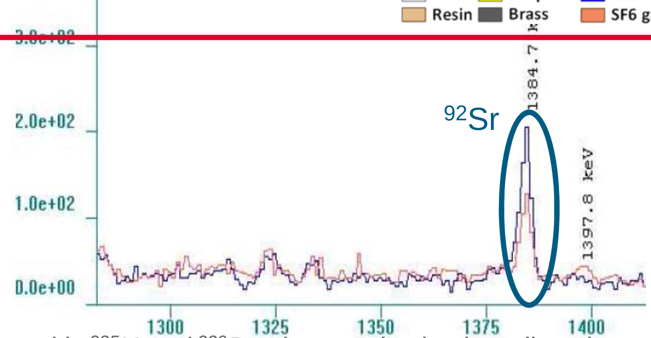
REGAIN and its MCNP model





❑ Gamma spectra after irradiation

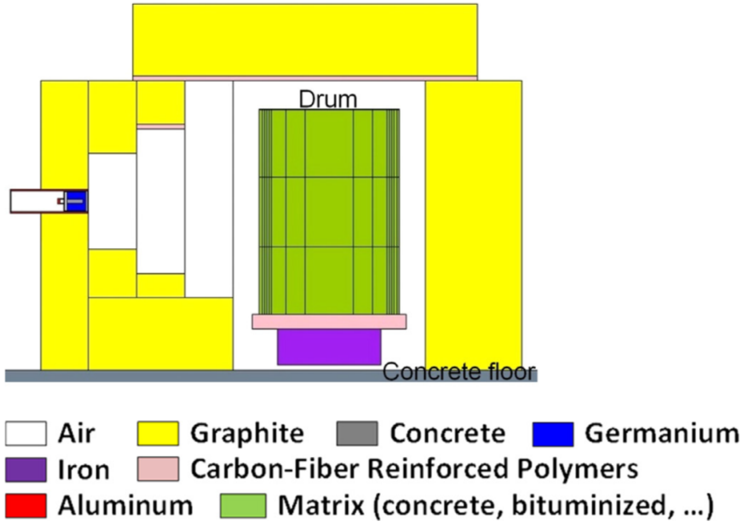
Low background γ-spectroscopy lead shelter

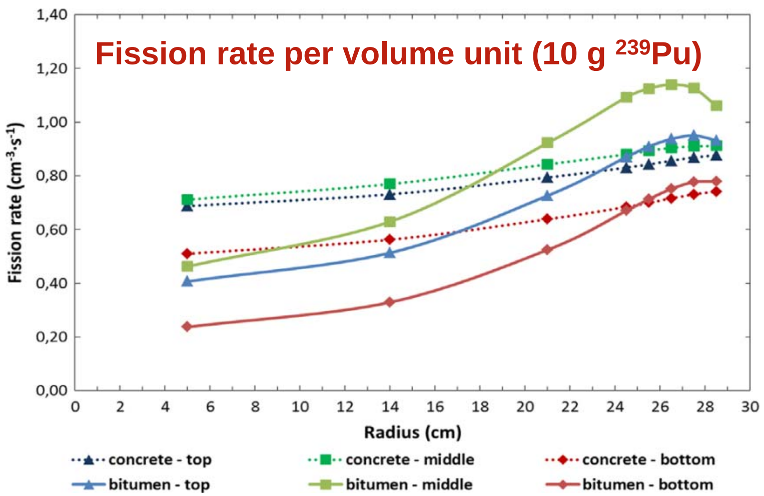


T. Nicol, B. Pérot, C. Carasco, E. Brackx, A. Mariani, C. Passard, E. Mauerhofer, A. Havenith, ^{235}U and ^{239}Pu characterization in radioactive waste using neutron-induced fission delayed gamma rays, Nuclear Instruments and Methods in Physics Research A 832 (2016) 85-94

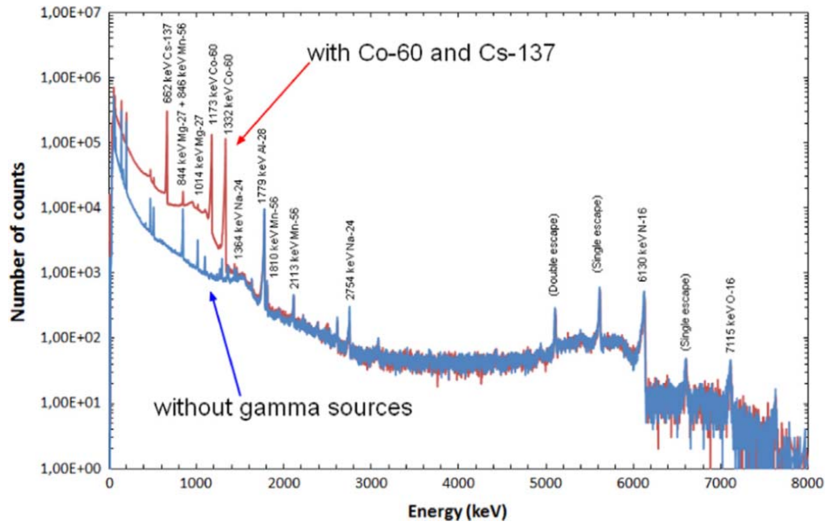
FISSION DELAYED γ-RAY DETECTION LIMITS

- **MCNP calculations** (MEDINA, 225 L drums)





- **Active background** (MEDINA, 225 L concrete mockup drum, measurement between pulses)



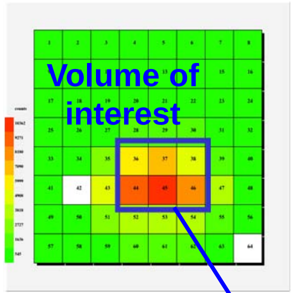
- **Detection limits** in a 225 L concrete drum, with a $2 \cdot 10^8$ n/s emission, 7200 s irradiation, 900 s post irradiation counting

E (keV)	Precursor	$T_{1/2}$ (s)	DL ^{239}Pu (g)	DL ^{235}U (g)
830	^{90}Rb-^{90m}Rb	156-258	154.2	71.3
952	^{95}Y	618	192.2	197.2
973	^{132}Sb-^{132m}Sb	168-252	66.3	86.7
1032	^{89}Rb	924	287.3	202.3
1312	^{136}I-^{136m}I	84-47	67.9	84.2
1384	^{92}Sr	9756	**24.1**	**19.0**
1427	^{94}Sr	75	**21.5**	**18.7**
1614	^{104}Tc-^{134}I	1092-3156	54.8	108.5

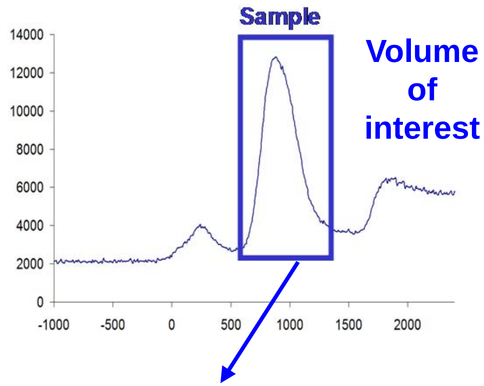
T. Nicol, B. Pérot, C. Carasco, E. Brackx, A. Mariani, C. Passard, E. Mauerhofer, A. Havenith, ^{235}U and ^{239}Pu characterization in radioactive waste using neutron-induced fission delayed gamma rays, Nuclear Instruments and Methods in Physics Research A 832 (2016) 85-94

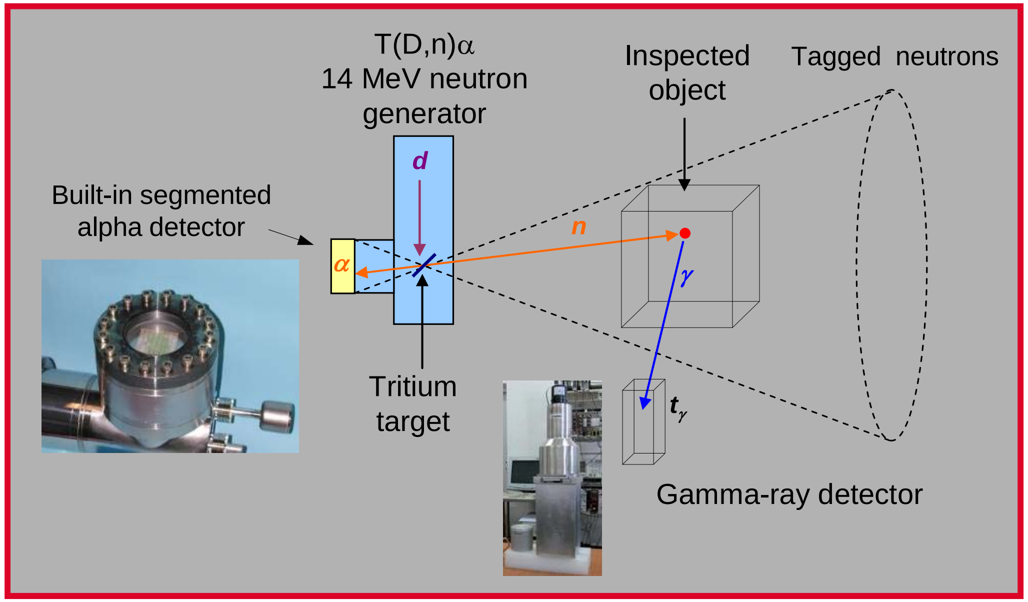
THE ASSOCIATED PARTICLE TECHNIQUE (APT)

Alpha detector
(position sensitive)

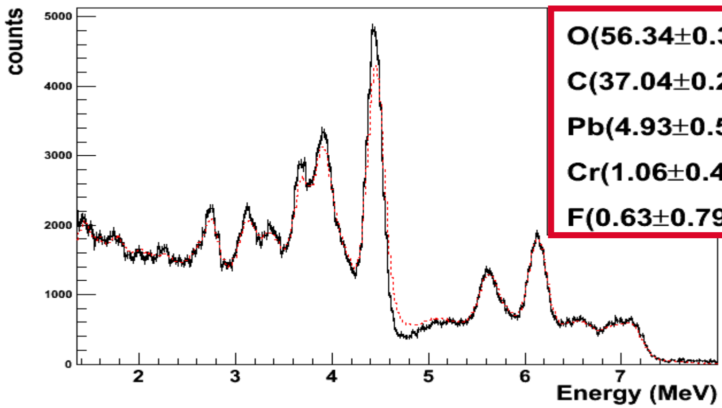


Neutron TOF
(alpha-gamma coincidence)



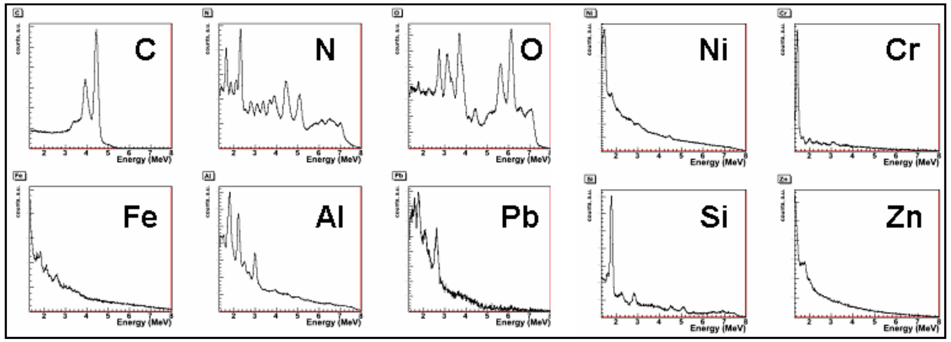


Gamma spectrum (selected volume)



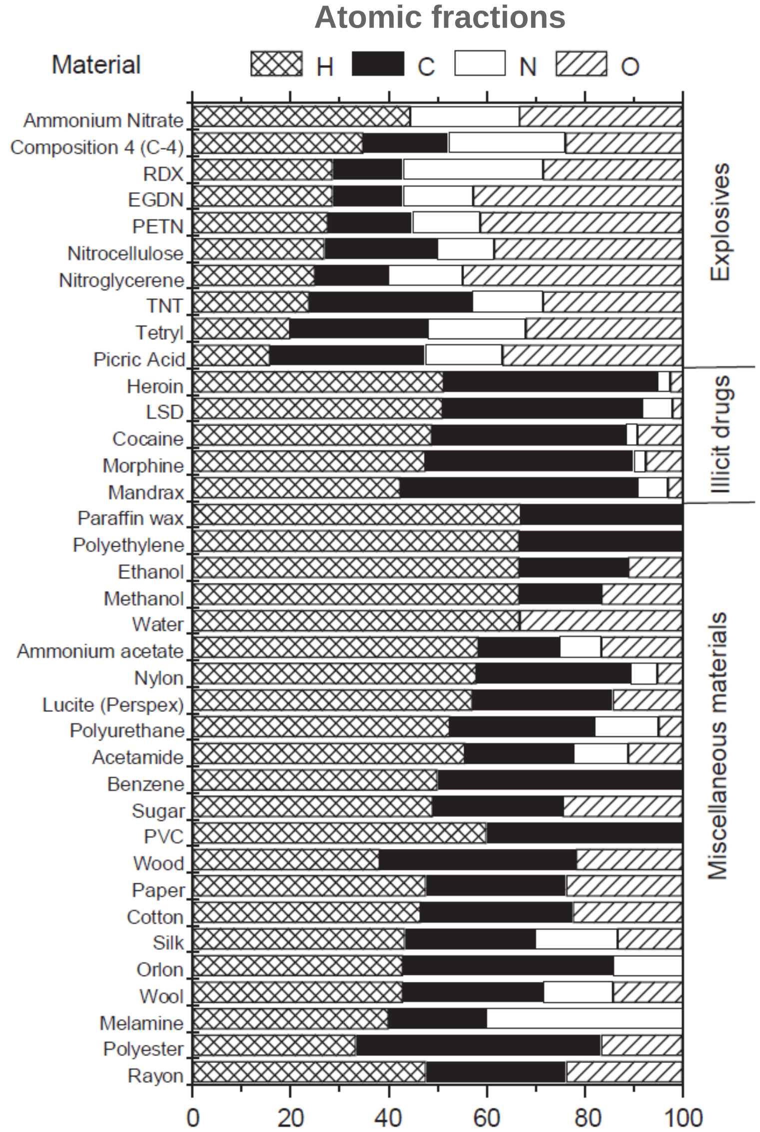
O(56.34±0.31)%
C(37.04±0.22)%
Pb(4.93±0.54)%
Cr(1.06±0.46)%
F(0.63±0.79)%

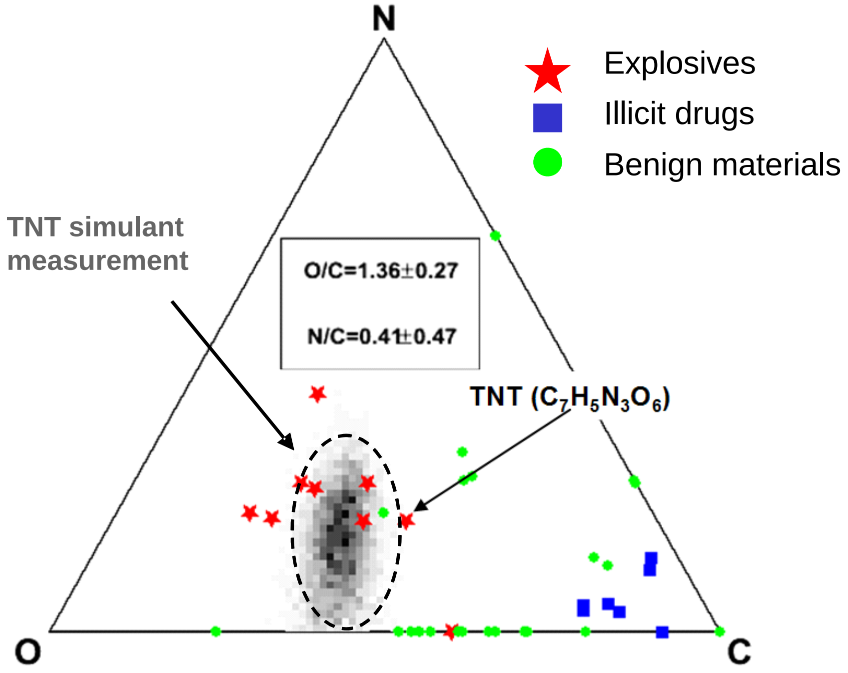
Unfolding (with a calibration database)



B. Pérot, G. Sannié, Détection neutronique de matières illicites avec la technique de la particule associée, Editions Techniques de l'Ingénieur, RE 177, février 2015

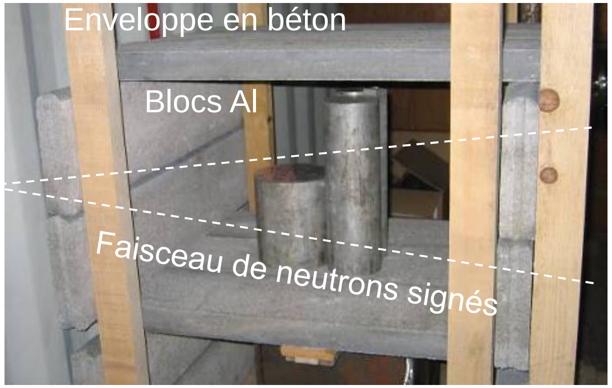
ORGANIC MATERIALS IDENTIFICATION (SECURITY)



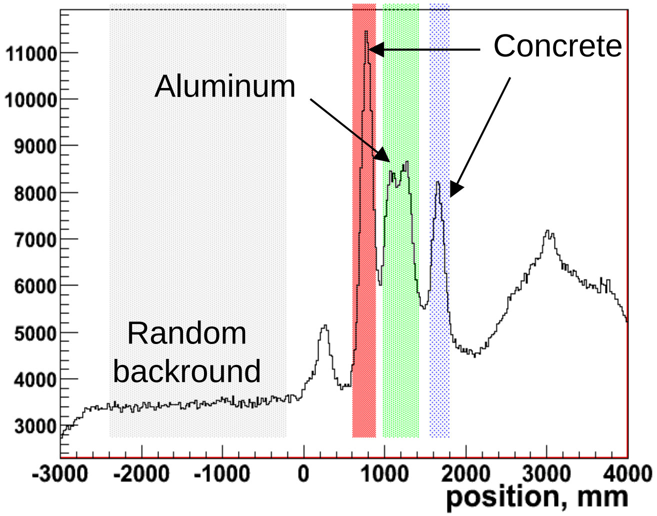


A. Buffler, http://dx.doi:10.1016/j.radphyschem.2004.04.110

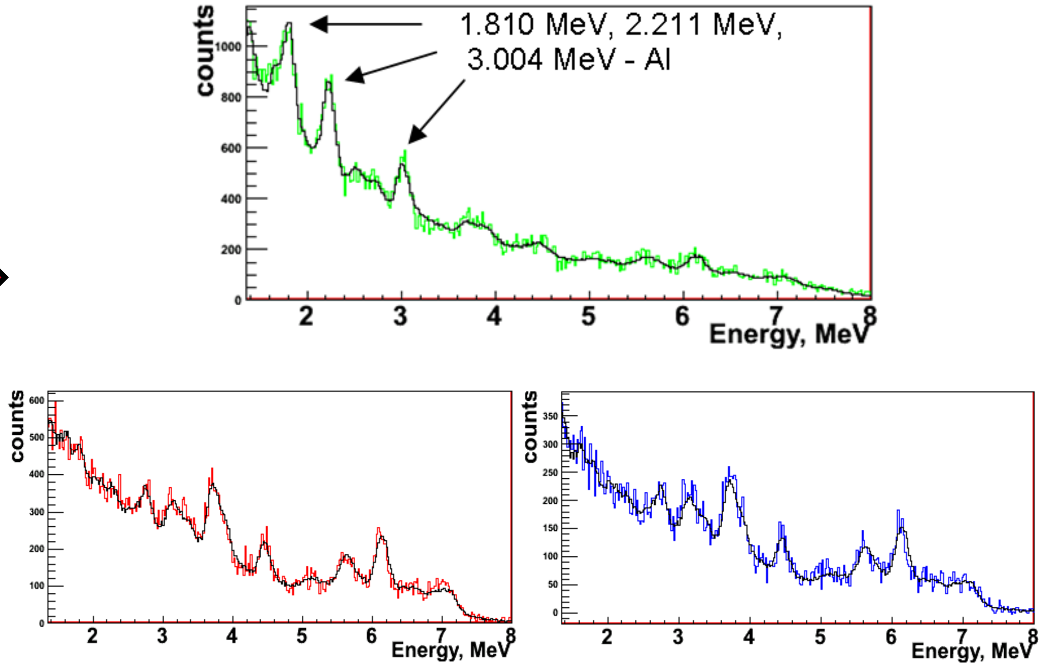
❑ Feasibility study on non-radioactive materials (experiments)



Time-of-flight (TOF) spectrum



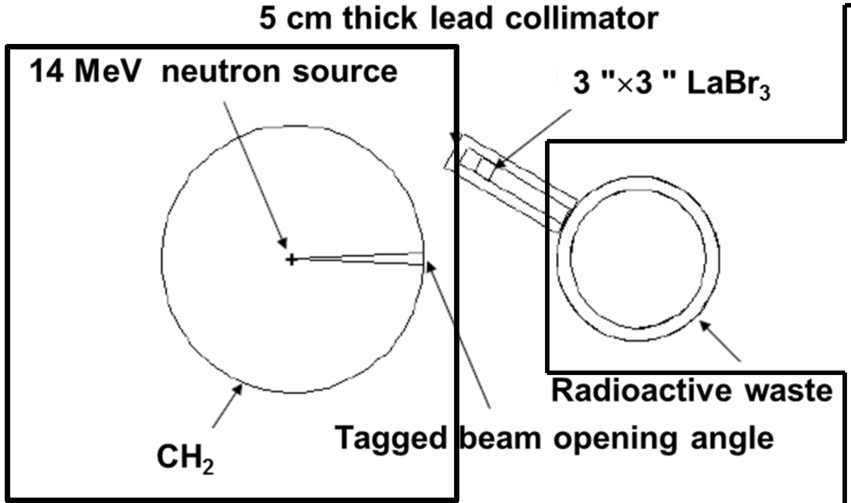
Gamma spectra for different TOF windows



C. Carasco, B. Pérot, A. Mariani, W. El Kanawati, V. Valkovic, D. Sudac, J. Obhodas, Material characterization in cemented radioactive waste with the associated particle technique, Nuclear Instruments and Methods in Physics Research A 619 (2010) 432-435.

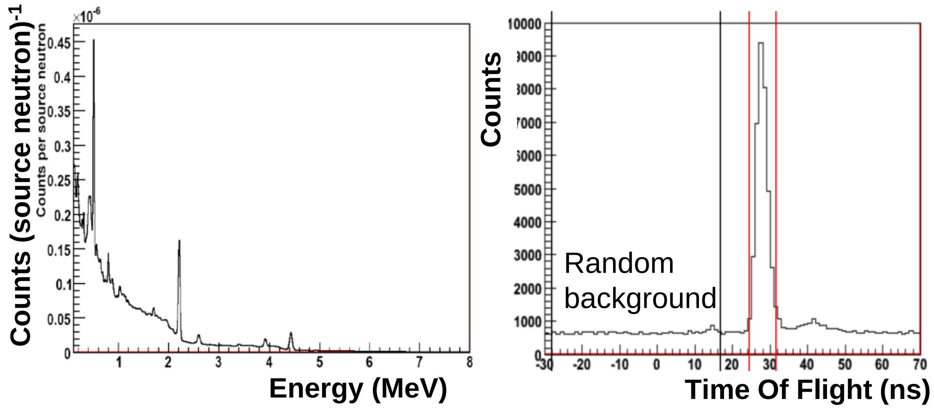
PERFORMANCES FOR RADIOACTIVE WASTE PACKAGES

- MCNP simulations for 225 L bituminized waste drums (~ 1 TBq ^{137}Cs)

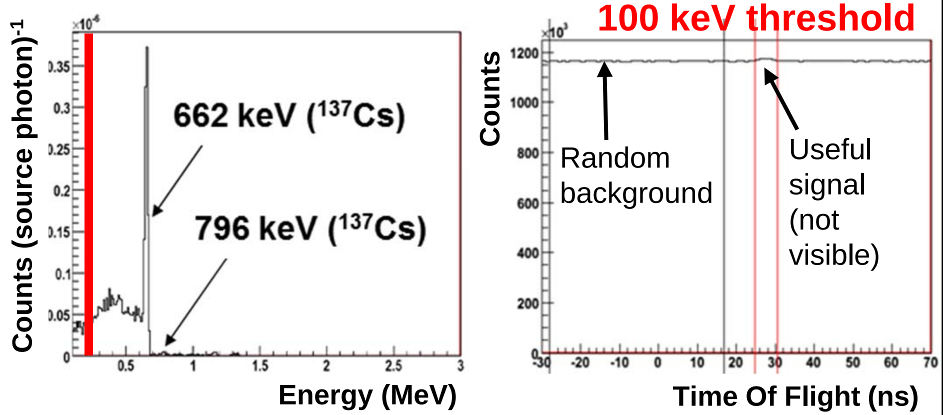


Isotopes	Energy (keV)	Emission ($\gamma.s^{-1}$)
^{137}Cs	662	~10^{12}
^{60}Co	1332	~10^{10}
^{60}Co	1173	~10^{10}
^{134}Cs	605	~10^{10}
^{134}Cs	796	~10^{10}
^{241}Am	59	~$2 \cdot 10^{9}$

Neutron generator background ($2 \cdot 10^8$ n/s)



Radioactive waste background



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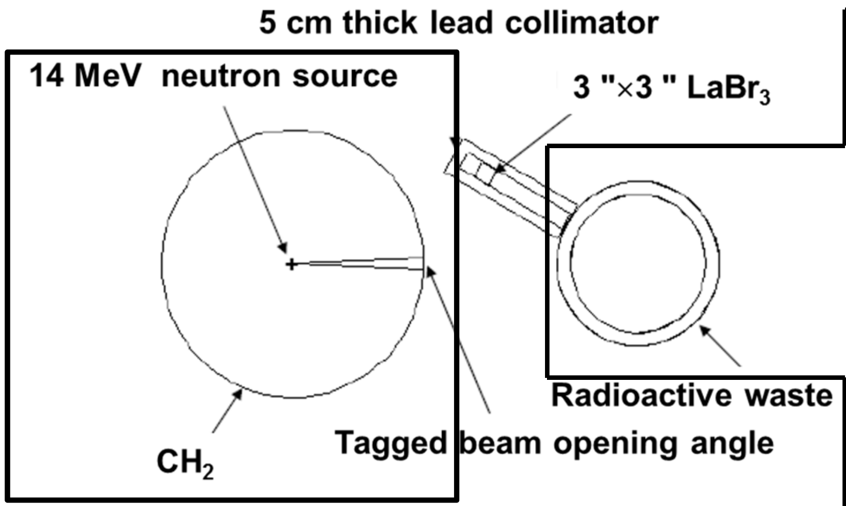

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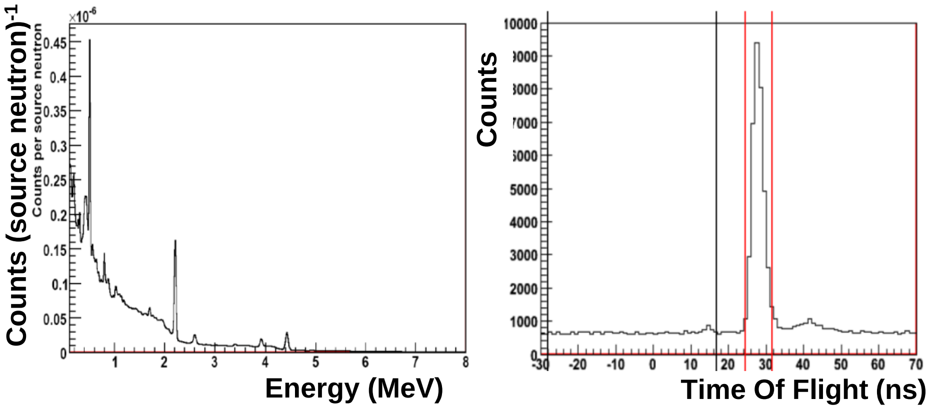
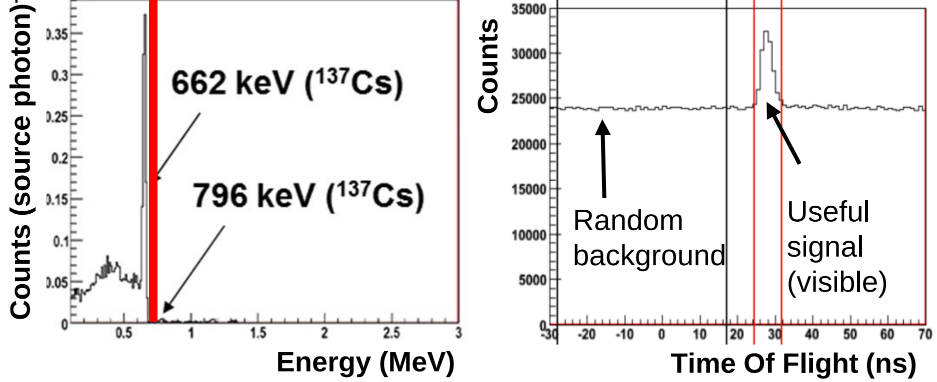
Neutron generator background ($2 \cdot 10^8$ n/s)

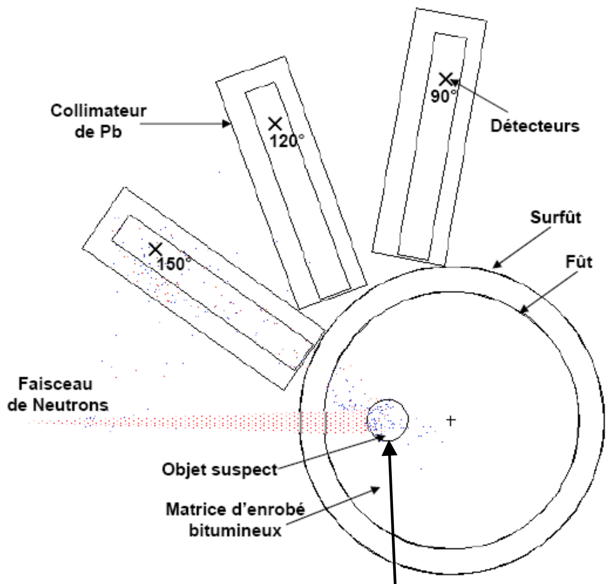


Radioactive waste background

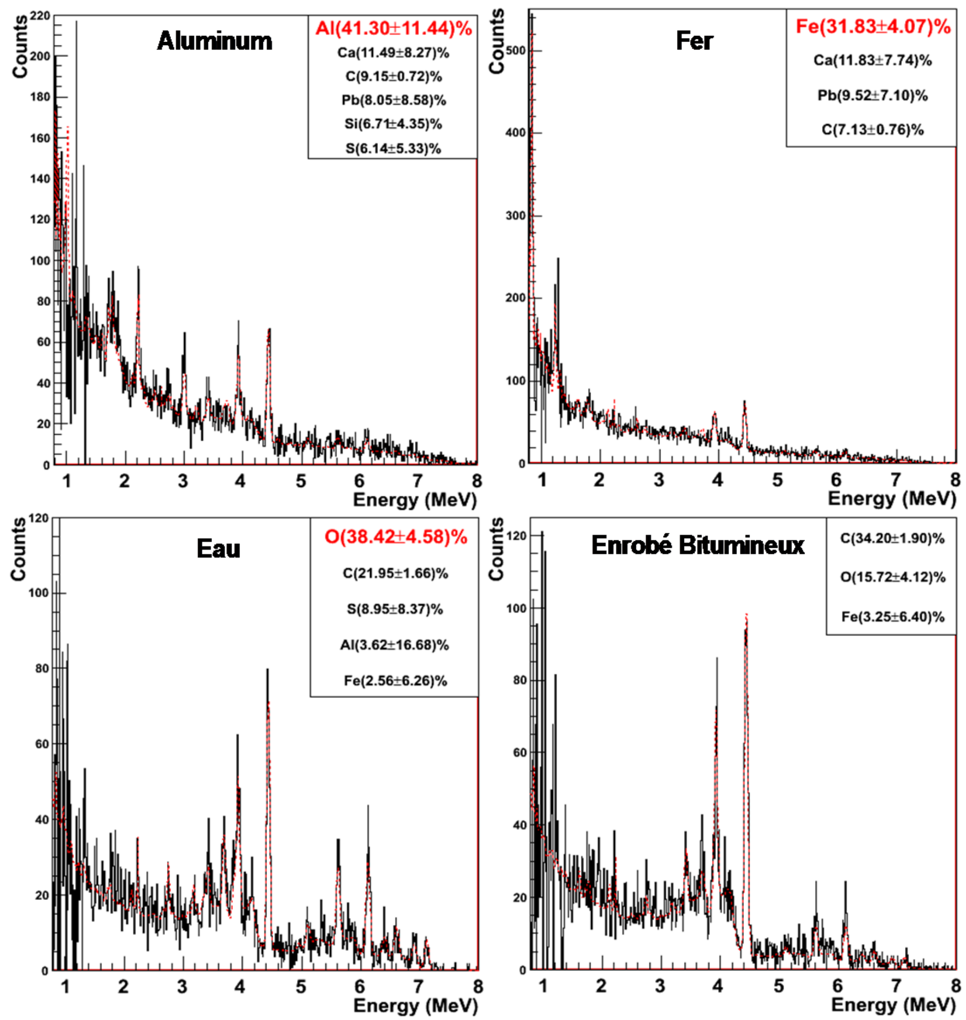
790 keV threshold



SIMULATION OF OBJECTS IN THE 225 L BITUMINIZED DRUM

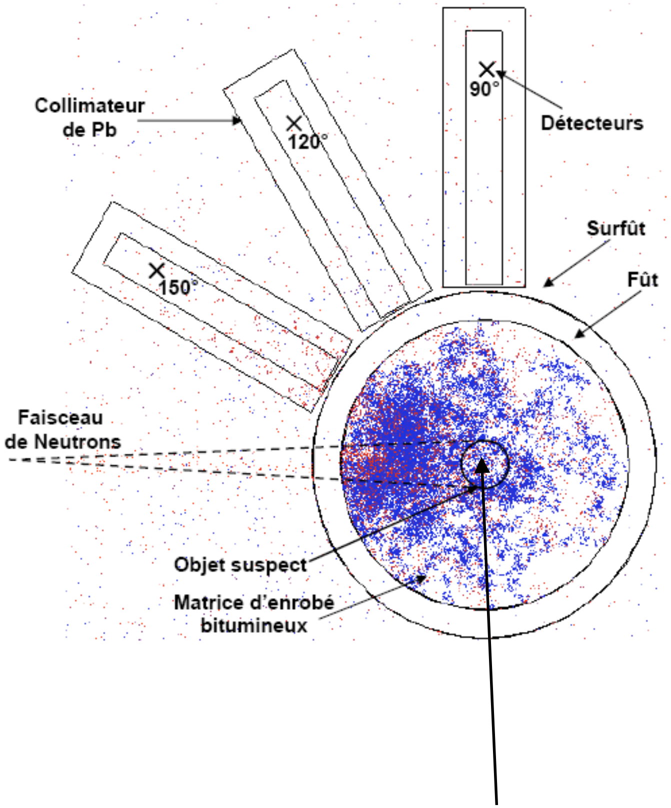


Object of interest



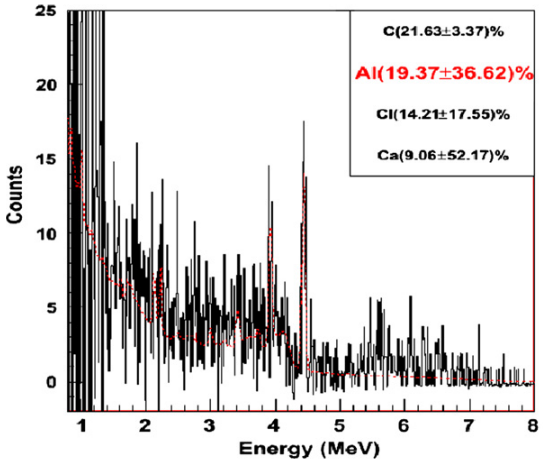
W. El Kanawati, B. Perot, C. Carasco, Monte Carlo Simulation of High-Level Radioactive Waste Characterization with the Associated Particle Technique, Nuclear Instruments and Methods in Physics Research A 705 (2013) 61–73.

OBJECT IN THE CENTER OF THE BITUMINIZED DRUM (MCNP)

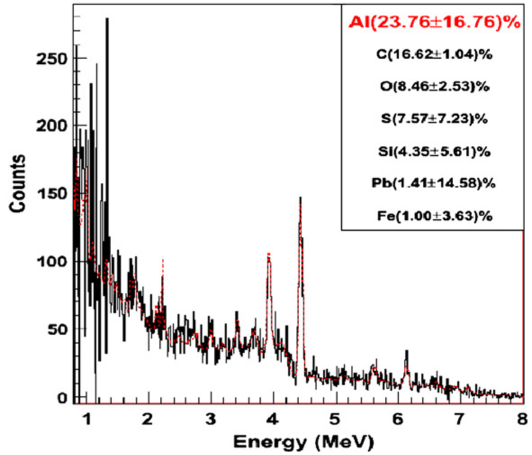


Object of interest

1 detector, 60 min



10 times more counts
(10 detectors or 600 min)



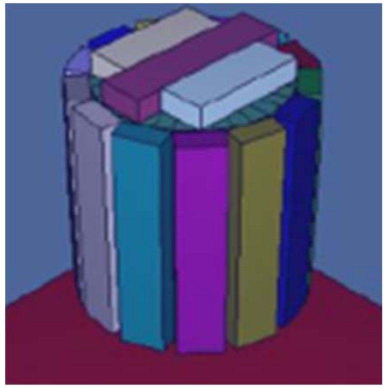
W. El Kanawati, B. Perot, C. Carasco, Monte Carlo Simulation of High-Level Radioactive Waste Characterization with the Associated Particle Technique, Nuclear Instruments and Methods in Physics Research A 705 (2013) 61–73.

SCINTILLATORS TO REPLACE ^{3}HE DETECTORS

^{3}He proportional counters	Plastic Scintillators
	
GOOD EFFICIENCY	GOOD EFFICIENCY
EXPENSIVE (since 09/11/2001)	CHEAP (~ factor 5 wrt. ^{3}He)
SLOW RESPONSE (~ µs) (thermalization needed)	FAST RESPONSE (~ ns) (recoil proton)
UNSENSITIVE TO γ RAYS AND CROSS TALK	VERY SENSITIVE TO γ RAYS AND CROSS-TALK

Passive neutron coincidence counting for radioactive waste drums - MCNP PoliMi simulation

- 118 L waste drums
- 10 cm thick plastic detectors (with lead shields)
- ~ 0.5 g of $^{240}Pu_{eq}$
- 1500 s acquisition time



0.2 g/cm^3 organic matrix

Multiplicity	Pu only	Am only	Mix (Am, Pu)
0	178,516 ± 423	299,817 ± 548	478,372 ± 692
1	11,744 ± 108	2,795 ± 53	14,777 ± 122
2	372 ± 19	12 ± 3	365 ± 19

→ Triples (multiplicity 2 coincidences)

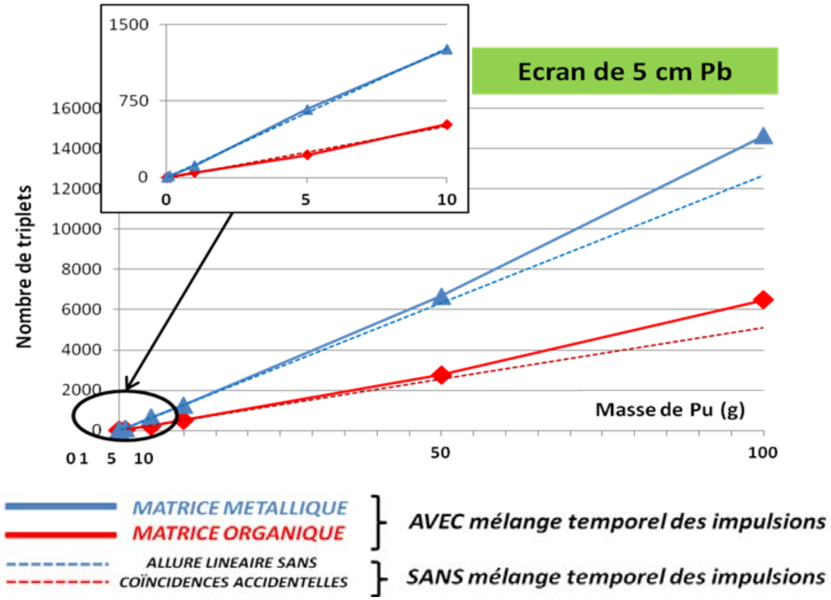
0.5 g/cm^3 metallic matrix

Multiplicity	Pu only	Am only	Mix (Am, Pu)
0	232,383 ± 482	450,562 ± 671	684,157 ± 827
1	32,356 ± 180	3,675 ± 61	36,287 ± 190
2	2,400 ± 49	9 ± 3	2,365 ± 49
3	66 ± 8	0	66 ± 8

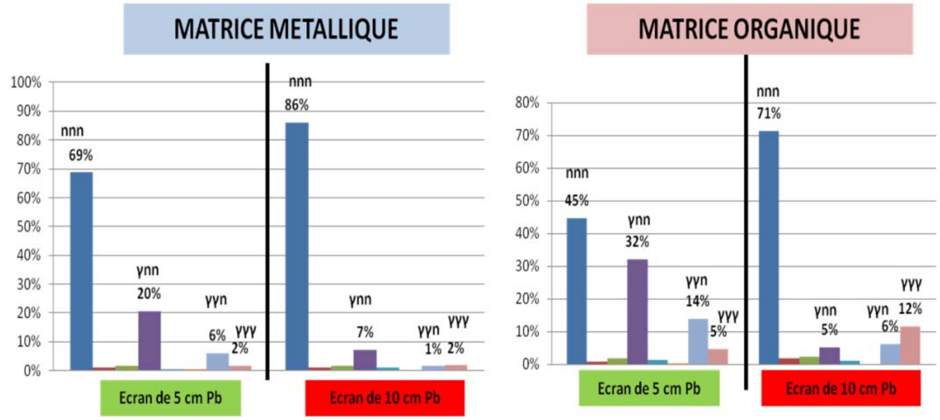
B. Simony, C. Deyglun, B. Pérot, C. Carasco, N. Saurel, S. Colas, J. Collot, Cross-talk characterization in passive neutron coincidence counting of radioactive waste drums with plastic scintillators, IEEE Transactions on Nuclear Science, Vol. 63, No. 3, June 2016

SIMULATED PERFORMANCES (TRIPLES)

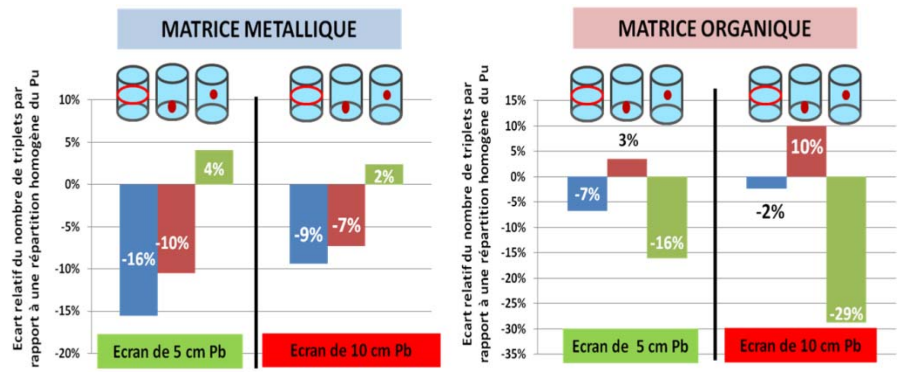
- Few accidental coincidences up to 10 g of Pu



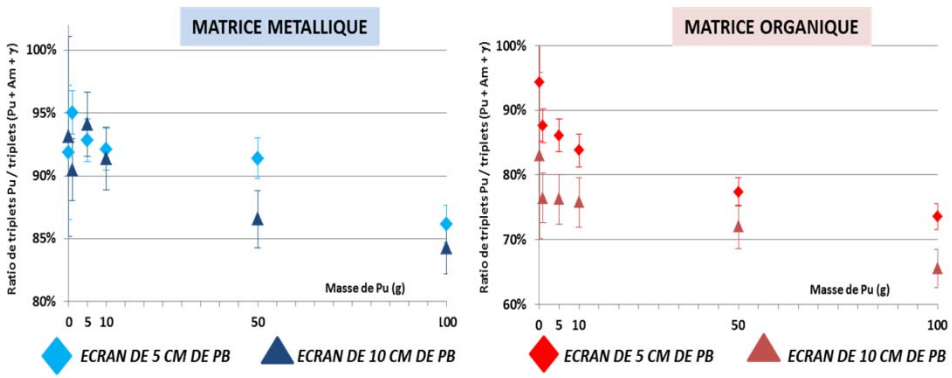
- Neutron vs. gamma events in the triples



- Plutonium localization effect



- Good signal to noise ratio (Pu/Total)



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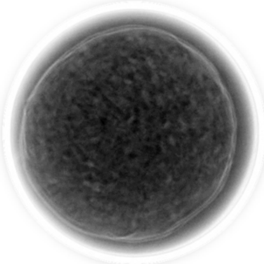
CONCLUSION

- **Radioactive and nuclear material characterization**
  - Gamma-ray spectroscopy
  - Passive neutron counting
  - Neutron and photon interrogation

- **Physical and elemental characterization**
  - Imaging techniques: gamma, X-ray
  - Neutron activation analysis

- **NDA for D&D and radioactive waste characterization**
  - Complementary to sampling & analytic methods
  - Sensitivity, precision, accuracy Vs. complexity, acquisition time, cost

⇨ The "dream team" = historic operators + NDA experts + D&D operators



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THANK YOU !

bertrand.perot@cea.fr

CEA International Expert

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Direction de l'Energie Nucléaire
Département de Technologie Nucléaire
Service Mesures et Modélisation des
Transferts et des Accidents Graves