Novel Technologies for Nuclear Safeguards, Security, and Nonproliferation: Improving Resilience to Radiological Threats

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Erice International Seminars on Planetary Emergencies

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A new kind of fire

December 1938: Fritz Straßmann, Otto Hahn, and Lise Meitner discover nuclear fission

January 1931: Ernest O. Lawrence invents the cyclotron


\[
\begin{align*}
\frac{238}{92} U + \frac{2}{1} D & \rightarrow \frac{238}{93} Np + 2 \frac{1}{0} n; \\
\frac{238}{93} Np & \rightarrow \frac{239}{94} Pu \\
\frac{239}{93} Np & \rightarrow \frac{239}{94} Pu
\end{align*}
\]
A new kind of fire

December 2\textsuperscript{nd}, 1942: CP1 first goes critical

The nuclear fire, allowing one to extract \(\sim\)10 TJ from 1 gram of matter, is tamed.

July 16th, 1945: Trinity test
Highly-enriched uranium (HEU): the material with the greatest ease of use in an improvised nuclear explosive

Global stockpile: ~1345 metric tonnes
  ~27600 first-generation fission bombs

Plutonium:

Global stockpile: ~499 metric tonnes
  ~99000 first-generation fission bombs

5 kg Pu

50 kg U

Football ball
Spent fuel: $\sim 10^{10}-10^{11}$ TBq

Radioactive sources for medical treatments: $\sim 10^3$ TBq

$\sim 10^4$ hospitals worldwide use radioisotopes for *in vivo* diagnosis or treatment of about 35 million patients every year

Dispersion of such a material in a city would result in massive disruption and huge economic consequences

Substantial progress is needed to secure vulnerable nuclear and radiological materials around the world and reduce the risks of nuclear and radiological terrorism.

The concerted work of all Nations is necessary to prevent these terrorist acts from happening.
A directorate of the European Commission's Joint Research Centre with establishments in Germany, Italy, The Netherlands, and Belgium.

**Fundamental properties and Applications of Nuclear Materials**

- Safety of nuclear fuel cycle, waste management & decommissioning, environment
- Nuclear safeguards, non-proliferation, security & forensics
Nuclear safeguards, non-proliferation, security & forensics

UN agency
Safeguards & Verification
Non proliferation
Additional protocol
Nuclear Security / IEC

EURATOM
Rome treaty 1957
Chapter VII on nuclear safeguards

DG-ENERGY
Nuclear Energy and Safeguards

DG HOME
EU CBRN action plan

EEAS

DG DEVCO
Instrument for Stability and Nuclear Safety

TRADE TAXUD ENTR
Effective and Efficient Safeguards
- Nuclear material measurements
- Reference materials
- Containment & Surveillance
- Process monitoring
- Safeguards by Design
- On-site laboratories

Verification Absence of Undeclared Activities
- Trace & particle analysis
- In-field tools for investigative inspector
- Reference materials

Nuclear Non-Proliferation
- Proliferation Resistance & Physical Protection
- Export control
- Trade analysis
- Non-proliferation studies

Combating Illicit Trafficking
- Equipment development
- Testing & validation
- Nuclear forensics
- Nuclear preparedness
- National response plan
- CBRN, IfS, ...
Non-destructive assay of nuclear materials

Monte Carlo neutron detector modelling

New nuclear detector technologies

Coincidence counting of Cm-244 spontaneous fission neutrons for Pu content determination in undissolved materials (from Cm/Pu ratio)

Replacing He-3 for neutron coincidence
Unmasking hidden nuclear materials

Pulsed Neutron Interrogation Test Assembly: detection of fission signatures (prompt and delayed $\gamma$ and n) following exposure to an external neutron source

Nuclear Safeguards Applications
Mass determination of small quantities of fissile materials in huge drums

Nuclear Security Applications
Detection of special nuclear materials by fission signatures in large containers

Pulse shape discrimination (PSD) = charge integral in the tail/charge integral for the whole pulse allows discrimination between $\gamma$ and fast neutrons
Non-destructive assay of nuclear materials

Development of gamma/neutron detection devices

R&D for EURATOM Inspectors
measurements of $^{235}$U mass of HEU fuel plates

Tomography on spent nuclear fuels
for final storage or analysis of molten cores

Tomography with cosmic muons
Microparticle analysis

U/Pu microparticle analysis in fuel cycle installations

- Monitor declared activities (for DG ENER, Euratom)
- Verify undeclared activities (for IAEA)

Analysis of particles of nuclear materials within millions of others

Uranium-235 enrichment measurements
Microparticle analysis with SIMS/SEM techniques

One particle of weapon grade material hidden in a large amount of other uranium particles.
Nuclear security

Stakeholders:
- DG DEVCO, HOME, ENER, ..
- IAEA
- EU Member States

Partners:
- Research organizations
- Law enforcement
- US DOE, DOS

Platforms:
- Border Monitoring Working Group (BMWG)
- Nuclear Forensics International Technical Working Group (ITWG)
- Global Initiative to Combat Nuclear Terrorism (GICNT)

Confirmed incidents as Reported to the IAEA

- Illicit trafficking
- Proliferation
- Malicious use
- Nuclear Terrorism
Nuclear forensics

Aims at identifying linkages between things, people, places and events

Provide hints on the origin of (illicit) material in order to

• Prevent future thefts or diversion

• Deter unlawful or criminal use of nuclear material

Contaminated scrap metal, Rotterdam, April 2010

Natural uranium, coming from a sandstone-type U ore deposit, produced in Nigeria in 1978, imported from Niger
Nuclear forensics

Identification of characteristic parameters
- Impurities
- Decay products
- Isotope ratios
- Morphology

Development of analytical methods
- Trace and ultra-trace analysis
- High accuracy isotope ratios
- Reference materials

Data interpretation
- Compilation of reference data
- Comparative evaluation

2.4-kg natural U metal cube, found in 1965 in the river Loisach near W. Heisenberg summer cottage in Urfeld. Raw material extracted in Joachimstal; cube produced in September 1943 (±0.5 year). Used for the "B-8" experiment at Heigerloch during the winter of 1945.
Training of inspectors, custom officers and police officials


About 300 participants per year from more than 70 Countries
**Aim:** development of novel technologies for nuclear safeguards, security and forensics to counteract illicit activities involving nuclear and radiological materials; to enhance border security and frontline response against diversion of materials from declared activities.

**Coordinators, Organization names and Countries:**

*RC*, European Commission, Joint Research Centre (JRC), Directorate for Nuclear Safety and Security, Postfach 2340 Karlsruhe (Germany).

*Klaus Mayer*, European Commission, Joint Research Centre (JRC), Directorate for Nuclear Safety and Security, Postfach 2340 Karlsruhe (Germany).

*Carla Andreani*, Università degli Studi di Roma Tor Vergata, Via Orazio Raimondo, 18, 00173 Roma, Italy

*Giuseppe Gorini*, Università degli Studi di Milano Bicocca, Piazza dell'Ateneo Nuovo, 1, 20126 Milano, Italy

*Itzhak Halevy*, Ben-Gurion University of the Negev, Israel
1) Design, construction and test of Boron Array Neutron Detectors Gas Electron Multiplier (BANDGEM)

Radiation portal monitors for screening people, vehicles, and cargo. Measuring neutrons streaming from enriched uranium and weapons-grade plutonium.

Detector networks for continuous monitoring of radiation in cities.

Challenge of replacing $^3\text{He}$ in proportional counters.

Coordinator: Giuseppe Gorini

Task duration: 12 months for construction of a prototype; 4 months for testing at GELINA neutron source in Geel
Gas Electron Multiplier (GEM)

GEM is used as a proportional amplifier of the ionization charge released in a gas detector.

Perforated 50 µm thick kapton foil, copper clad (5 µm thick)

80-100 kV/cm

Triple GEM detector constructed with standard 10 x 10 cm².
Detection of shielded special nuclear materials in transport vehicles and cargo containers.

Neutron emission from fissile, fertile materials (N-GEM detector)

Prompt and delayed $\gamma$ emission (HpGe detector) with $\mu$s time-resolved acquisition (TPGAA)

Collaboration with a team working on a cosmic muon scattering tomography device for similar application.

The prototype will be commissioned at the GELINA neutron source operated by the JRC in Geel

**task duration:** 12 months for design, 10 months for assembling the prototype, 2 months for commissioning.

**Coordinators:** Carla Andreani, Roberto Senesi.
Optimization of the neutron generator

\[ D + T \Rightarrow ^4\text{He} + n + 17.6 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Neutron Yield</th>
<th>$10^8 \text{ n/s}$</th>
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<tr>
<td>Neutron Energy</td>
<td>$14\text{MeV}$</td>
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Time resolved acquisition to measure neutron and $\gamma$ emission during neutron pulses as well as between neutron pulses.
Design of the spectrometer:
Combined fast neutron analysis and thermal neutron analysis
for dual-energy neutron inspection

Incident n-beam → Scattered n-beam → GEM detector
→ Trasm. n-beam
→ γ emission (Ge Detector)

Time Resolved PGAA tests at pulsed neutron source

Example of PGAA during pulses (blue) and between pulses (red)

Aim: sensitivity to $^{235}\text{U}$, $^{239}\text{Pu}$, fertile $^{238}\text{U}$, C, N, O, H
Design of the spectrometer

Using the pulsed nature of the neutron source
Measure bi-parametric map of $\gamma$ energy spectrum vs neutron time of flight

Isotopic contrast enhancement by measuring PGAA from epithermal (resonance) and thermal neutrons
Development of image reconstruction algorithms

Prototype will be commissioned at GELINA neutron source operated by the JRC in Geel

Localization of inclusion volumes using attenuation correction algorithms.

Integration of neutron and $\gamma$ ray reconstruction algorithms.

Successfully applied to Neutron Resonance Transmission on metallic samples

Cu (green), Fe (red), Au (yellow), Ag (blue)
Development and validation of Gas chromatography and Mass spectrometry techniques for ultra-traces measurements of solvents, extractants, and reagents in uranium ore concentrates for identifying origin and intended use of illicit nuclear materials.

Coordinator: Klaus Mayer

Task duration: 12 months for validation phase, 6 months for optimization of a device for routine analysis measurements.
4) Optimization of aerial survey of radiation in outdoor environments

Aerial Radiation Survey for first response to a major nuclear incident.

• Registration of real time data for enabling on line risk assessment and situation awareness.

• Employment of small scale drones with high levels of autonomy for automatic operation and smart survey patterns

• Parametric selection function for the survey system

• Optimization of the sensor and the flying platform.

• Real world demonstration of aerial survey system of radiological contamination in outdoor environments

Coordinator: Itzhak Halevy
Task duration: 24 months