Technology Exercise to Investigate Performance of Measurement Methods

Working Group 6: Technologies for Verification

April 2020

Introduction

At the end of Phase I in December 2017, the International Partnership for Nuclear Disarmament Verification (IPNDV, or Partnership) identified "testing and exercising potentially promising technologies and procedures" as a key next step.

In this framework, Belgium proposed and organized an international exercise at the site of the Belgian Nuclear Research Centre (SCK•CEN) in Mol, Belgium. The aim of the exercise was testing and comparing measurement techniques to be potentially used for the verification of nuclear material in the framework of the dismantlement of nuclear weapons.

The exercise was meant to complement a second nuclear disarmament verification exercise called "NuDiVe" focused on testing procedures related to a simulated nuclear weapon dismantlement, hosted in Germany jointly by German and French teams.

Although analyzing and interpreting the data is currently ongoing, this report summarizes the content of the exercise and the experimental campaign carried out between September 9–26, 2019.

Participants deployed different measurement instruments and are categorized as follows:

- Imaging devices (gamma-rays and neutrons);
- Total neutron counters;
- Neutron coincidence counters;
- High-resolution gamma-ray detectors;
- Low-/medium-resolution gamma-ray detectors.

About 30 participants representing the delegations of Australia, Belgium, Canada, the European Union, Finland, Hungary, Japan, Norway, Switzerland, and the United Kingdom, participated to the experimental campaign. The Nuclear Threat Initiative (NTI) was present as an observer at the beginning of the campaign. Germany provided support for calculations and support during the Belgian measurements.

Proposal

Objectives

The objective of the exercise was to investigate the performance of various measurement methods with respect to their capabilities to verify the presence or absence of nuclear material originating from a nuclear weapon and to distinguish weapons-grade from reactor-grade nuclear material.

The exercise was limited to non-destructive passive methods with the goal to assess the performance of the methods and the influence due to:

- The amount of nuclear material;
- The type of nuclear material;
- The type of shielding material.

The material to be assayed was unirradiated mixed oxide (MOX) fuel pins arranged in a compact hexagonal configuration. In these pins the plutonium is mixed with uranium, chemically in the form of oxide. The plutonium content in the available fuel pins is up to $14\%_{wt}$ with a relative ^{239}Pu amount up to $96\%_{wt}$.

The MOX fuel pins are well characterized in terms of composition and geometry. The design information about the set-up of the exercise was kept open and communicated beforehand to the participants. This approach allows combining the measurements with calculations for a better analysis of the results and allows testing detector prototypes that need some calibration. In addition to testing the technologies in a complex scenario, the proposed exercise provides a sound benchmark to validate developed models for the deployed technologies.

Type of Measurements

Two types of measurements were envisaged. A first type consisted of performing measurements on samples with various amounts of plutonium mass and a fixed isotopic composition. The purpose of this exercise was to determine the sensitivity of the methods to the nuclear material amount.

A second type of measurement involved samples with different isotopic compositions of plutonium. The purpose of this activity was to investigate the influence of the isotopic composition on the performance of the methods and whether they were capable to distinguish between reactor-grade and weapons-grade plutonium.

In addition, for both measurement types, measurements with shielding material such as lead, cadmium, and polyethylene were possible to study whether nuclear material could be shielded without being noticed in order to divert nuclear material during the dismantling process.

Materials

For the measurements of the plutonium mass, the material used were fuel pins with a plutonium content of $14\%_{wt}$ and with a ^{239}Pu amount of $61\%_{wt}$ and a length of 100 cm. The fuel pins were arranged in a hexagonal bundle as shown in Figures 1 and 2. The number of rods were 1, 19, or 61; these numbers allowed to keep a hexagonal arrangement and to have a ^{239}Pu mass range from 0.1 to 2.6 kg.

The hexagonal bundle was hosted in a 3 mm thick square container of stainless steel to reduce the gamma-ray dose rate and facilitate the manipulation. The dimensions of the horizontal cross-section of the container were 10 cm x 10 cm.

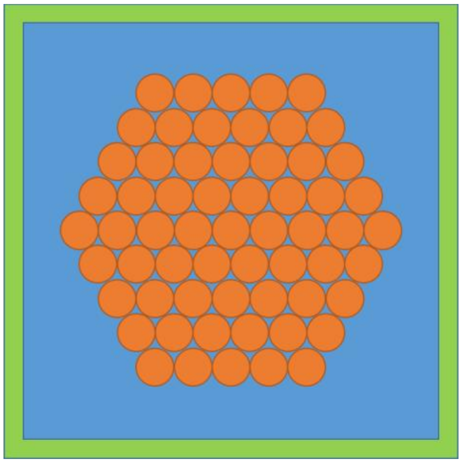


Figure 1: Horizontal cross-section of the container with 61 fuel pins

Additionally, the following individual shielding could be installed on the container:

- Lead 5 and 10 mm thick;
- Cadmium 1.1 mm thick;
- Polyethylene (PE) 50 mm thick.

A combined shielding of polyethylene (50 mm thick) and lead (10 mm thick) was also available. In this combined shielding, the polyethylene was in front of the fuel container and the lead was between the polyethylene and the detector.

Some configurations used during the measurements are shown in Figure 2.

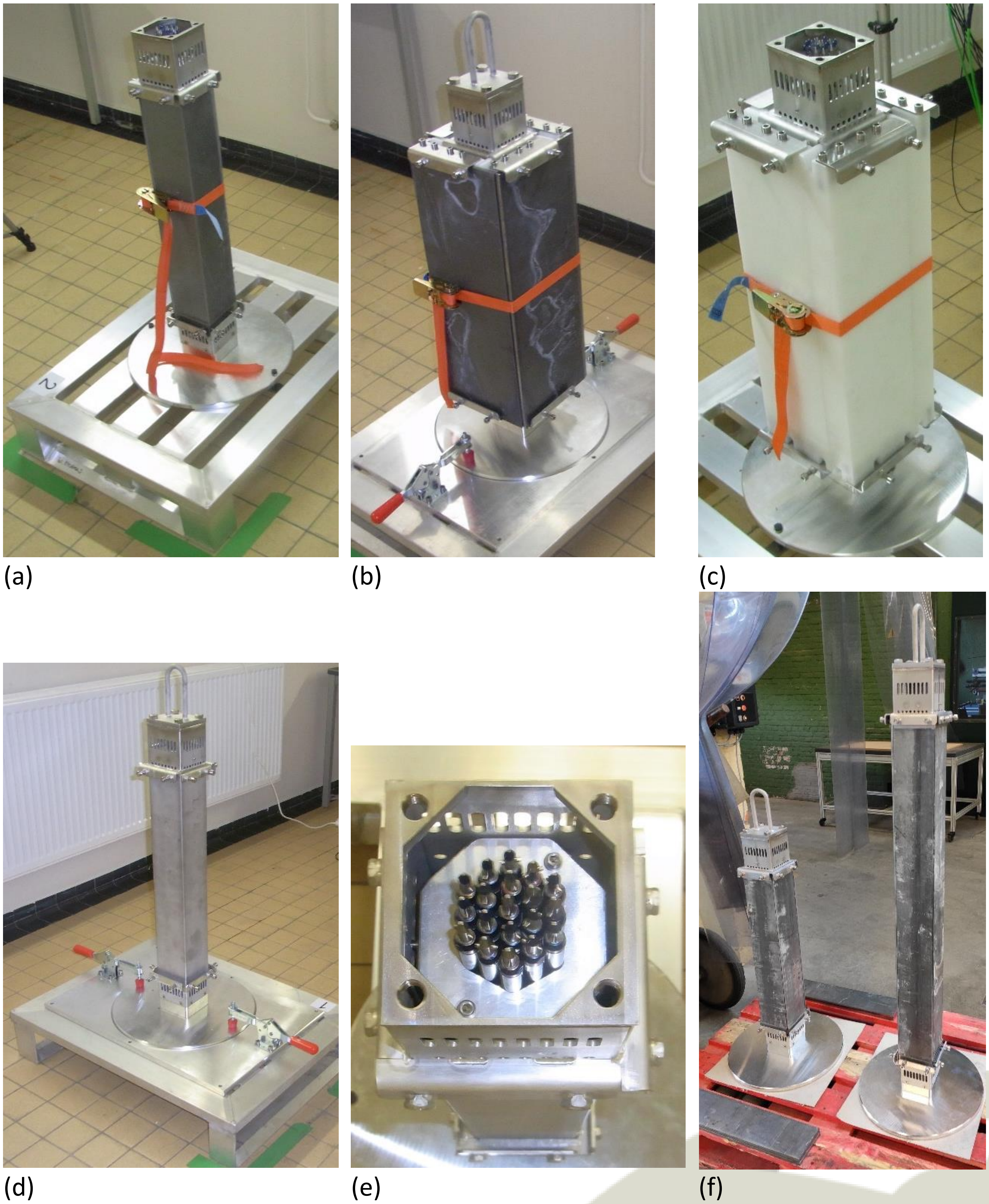


Figure 2: Examples of configurations of assemblies and shielding used during the measurement campaign. Fuel assembly with different shielding: (a) Cd; (b) PE+Pb; (c) PE; (d) bare. The top view of the 19 pins configuration is shown in (e). Figure (f) shows the comparison of 50 cm fuel assembly (left) and 100 cm fuel assembly (right).

Characteristics of the Chosen Materials

For the measurements with different isotopic composition, three fuel pin types with a ^{239}Pu content between 61%$_{wt}$ and 96%$_{wt}$ were used. The number of rods is 19 with length of either 50 cm or 100 cm. The characteristics, such as length, fissile material content and weight, and neutron and gamma emissions of the considered fuel configurations are given in Tables 1, 2, and 3.

The fuel assembly with ID 96-19 has a different isotopic composition along the axial direction. Therefore, different characteristics are included in the table depending on the axial position.

Assembly ID	Section	Length / cm cm	Pu %	U_{enr} %	^{239}Pu %$_{wt}$	# pins	Mass total kg	^{239}Pu kg
79-19		50	5.1	0.72	79	19	6.2	0.2
96-19	Top1	5	2.7	2.0	79	19	5.9	0.2
	Top2	10	3.03	2.0	79			
	Mid	20	4.37	0.72	96			
	Bottom	15	3.03	2.0	79			
62-1		100	12.6	0.4	62	1	0.5	<0.1
62-19		100	12.6	0.4	62	19	10.2	0.8
62-61		100	12.6	0.4	62	61	32.8	2.6

Table 1: ID, length, fissile material content, and weight for the considered assemblies

Assembly ID	^{240}Pu 160 keV	^{235}U 186 keV	^{239}Pu 413 keV	^{239}Pu 646 keV	^{240}Pu 642 keV	^{241}Am 662 keV	^{238}U 1001
79-19	1605	161	7482	75	50	3567	386
96-19	660	319	5598	56	20	1345	373
62-1	539	7	1436	14	17	2364	30
62-19	10243	134	27292	273	318	44907	576
62-61	32887	430	87621	876	1022	144174	1850

Table 2: Emission rate for most intense gamma rays for the considered assemblies. Values are expressed in 10^3 gamma/s.

Assembly	Spontaneous Fission			(α,n) Reaction		
ID	Pu	U	Am	Pu	U	Am
7919	51	0.1	<0.1	17	0.5	21
96-19	21	0.1	<0.1	10	0.5	8
62-1	23	<0.1	<0.1	13	<0.1	14
62-19	439	0.1	<0.1	241	0.7	262
62-61	1410	0.3	<0.1	774	2.1	841

Table 3: Neutron emission rate for the considered assemblies. Values are expressed in 10^3 neutron/s

Significance of the Chosen Materials

The plutonium used in the exercise is in a form that is different from the envisaged material in a nuclear explosive device for the aspects outlined in Table 4.

	Exercise	Weapon
Material	Civil-/weapons-grade Pu and depleted/natural/low-enriched uranium	Weapons-grade Pu metal (+depleted uranium as reflector)
Chemical Form	Oxide	Metal
Geometry	Hexagonal bundle of pins	spherical
Impurities	^{241}Am from ^{241}Pu decay (30 ÷ 85 mg/g_{Pu})	^{241}Am from ^{241}Pu decay (0 ÷ 30 mg/g_{Pu})

Table 4: Characteristics of the materials measured in the exercise and in a nuclear weapon.

These differences have the following consequences on the emission of gamma rays and neutrons and their detection, considering gamma-ray spectroscopy and neutron coincidence counting systems.

Gamma Rays

The gamma-ray emission of plutonium does not depend on the chemical form, while its density, composition and geometry affects the degree of attenuation to which the gamma radiation undergoes.

Table 2 reveals that gamma lines from both uranium and ^{241}Am should be visible in the spectra and this would complicate the spectral analysis, when compared to the one associated with a real weapon.

Neutrons

The neutron emission due to spontaneous fission does not depend on the chemical form. However, due to the oxide form, a contribution to the neutron emission from the (α,n) reaction is expected; this contribution is estimated to be comparable to the contribution from spontaneous fission as indicated in Table 3. The total neutron emission therefore depends on the chemical form.

The density, composition, and geometry effects the degree of attenuation and multiplication to which the neutron radiation undergoes. The (α,n) contribution has to be considered when accounting for the multiplication factor.

According to the data in Table 3, the presence of uranium results in a negligible neutron emission, both spontaneous fission and (α,n), whereas ^{241}Am results in a contribution of the (α,n) term in the same order of magnitude as the plutonium.

For a system based on neutron coincidence counting, we expect therefore that the time uncorrelated component associated to the (α,n) reaction makes the measurements and interpretation of the data more difficult when compared to a plutonium in metal form. Conversely, the time-correlated component (due to spontaneous fission and multiplication) is only affected by degree of attenuation and multiplication due to the density, composition, and geometry.

Conclusions

Given these considerations, the verification of well characterized MOX fuel may even be more challenging than the one of a nuclear explosive device. In addition to testing the technologies in a complex scenario, the proposed exercise provides a sound benchmark to validate developed models for verification devices based on the deployed technologies.

Measurement Campaign

Preparation

After several informal discussions, Belgium presented the exercise at the London IPNDV Plenary meeting in December 2018.

In the first half of 2019, the candidate participants were invited to present a measurement plan as well as documents needed to access the site and the area were the measurements took place. At SCK•CEN, the necessary materials to carry out the measurement campaign were prepared, and the necessary permissions were obtained without delay.

From an organizational point of view, the procedures were, as expected, time consuming because in some cases it was not straightforward to obtain the required medical forms completed as requested, the right documents in compliance with one's own national regulations and privacy laws, and translation of documents.

Eventually a measurement schedule to accommodate the requests within a three-week period was developed. Ten measurement teams attended the measurement campaign during September 9–26, 2019.

About 30 participants representing the delegations of Australia, Belgium, Canada, the European Union, Finland, Hungary, Japan, Norway, Switzerland, and the United Kingdom, participated in the experimental campaign. The Nuclear Threat Initiative (NTI) was present as an observer at the beginning of the campaign. Germany provided support for calculations and support during the Belgian measurements.

Results

Participants deployed different measurement instruments, categorized as follows:

- Imaging devices (gamma-rays and neutrons);
- Total neutron counters;
- Neutron coincidence counters;

- High-resolution gamma-ray detectors;
- Low-/medium-resolution gamma-ray detectors.

In the following tables, we overview the assembly and shielding configurations that were measured by the different teams, per category of instrument.

The measurement campaign covered the possible scenarios well. Given the limited amount time, only a few measurements in the 1 pin configuration (62-1) could be carried out.

For a more detailed description of the devices that were deployed during the campaign, the chosen configurations, and the obtained results, please refer to the WG6 experimental technology data sheets.

Additional Comments

As expected, the on-site safety quiz was relatively time consuming although informative videos were made available to the participant in advance. However, the simplified access procedure went smoothly and did not cause delay to the schedule.

During the measurement campaign several events put the measurement schedule at risk, such as equipment arriving late, equipment malfunctioning , and flight delays. However, thanks to careful planning that included a very clear sequence of operations, additional time allowance for unexpected events, good on-site coordination between different units, and open attitude of the personnel, all foreseen measurements were performed with few changes to the original schedule.

Some participants asked whether it was possible to perform measurements on more than one fuel container simultaneously. This request could not be accommodated because it was not planned in the safety assessment. This shows the importance of knowing in advance the wishes of the measurement teams.

Performing the measurement campaign stressed the importance of a timely preparation. Although not everything could be foreseen, we were prepared to deal with unexpected events. For future measurement campaigns, we emphasize the importance of shipping the equipment in a timely manner and having a margin in travel schedule.

Conclusions

The exercise provided a unique opportunity to measure material containing weapons-grade plutonium.

The measurement on assemblies with material containing weapons-grade plutonium turned out to be very informative and drastically different from the ones with old civilian plutonium, where the relatively large Am content potentially made the interpretation of the results more difficult. The experience gathered in the measurement campaign suggested that having an additional compound shielding of polyethylene and cadmium would have been beneficial. In addition, measurements with 7 and 37 pins configuration would be beneficial to better define the trend of the measurements when changing the sample mass.

Further conclusions will be elaborated as the data analysis and interpretation is carried out.

Overall

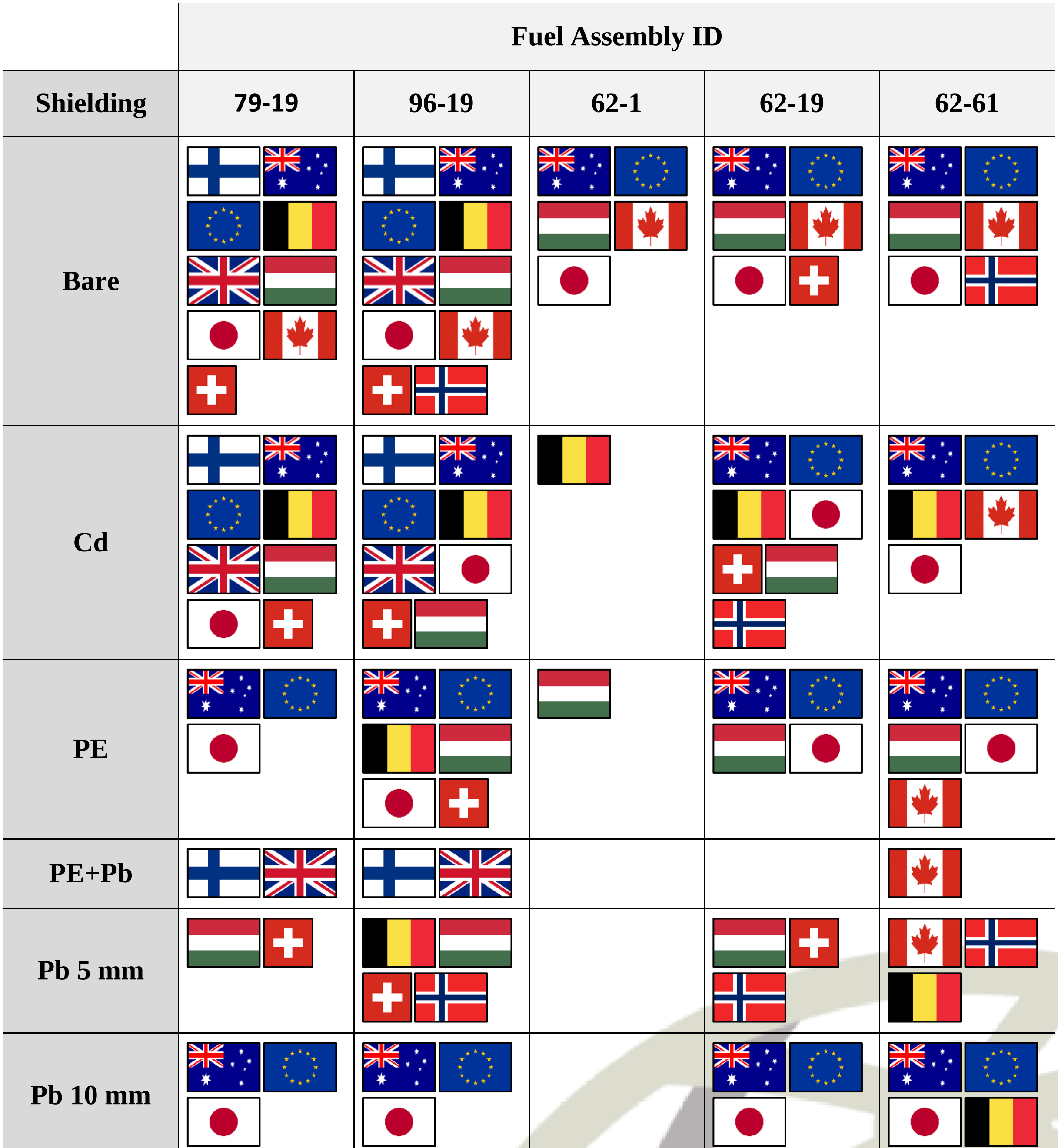


Table 5: Overview of the assembly and shielding configurations measured by the different teams (all devices)

Imaging Devices

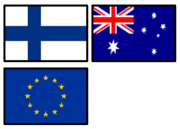
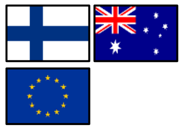
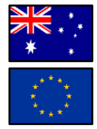
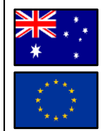
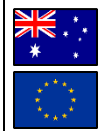
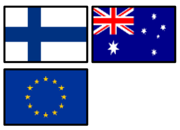
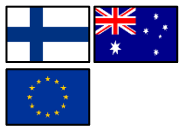
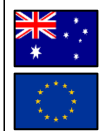
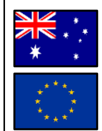
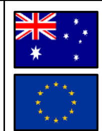
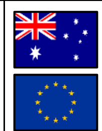
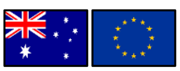
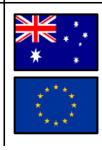
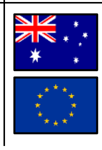
	Fuel Assembly ID				
Shielding	**79-19**	**96-19**	**62-1**	**62-19**	**62-61**
Bare					
Cd					
PE					
PE+Pb					
Pb 5 mm					
Pb 10 mm					

Table 6: Overview of the assembly and shielding configurations measured by the different teams (imaging devices)

Total Neutron Counting

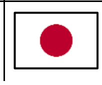
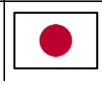
	Fuel Assembly ID				
Shielding	**79-19**	**96-19**	**62-1**	**62-19**	**62-61**
Bare					
Cd					
PE					
PE+Pb					
Pb 5 mm					
Pb 10 mm					

Table 7: Overview of the assembly and shielding configurations measured by the different teams (total neutron counters)

Neutron Coincidence Counting

	Fuel Assembly ID				
Shielding	**79-19**	**96-19**	**62-1**	**62-19**	**62-61**
Bare	   	   	 	 	 
Cd	  	 			 
PE		 			
PE+Pb					
Pb 5 mm					
Pb 10 mm					

Table 8: Overview of the assembly and shielding configurations measured by the different teams (neutron coincidence counters)

High Resolution Gamma-Ray Detectors

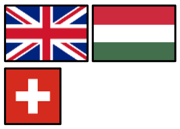
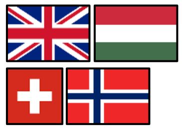
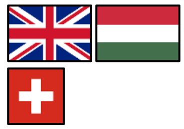
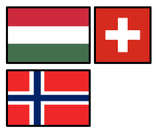
	Fuel Assembly ID					
Shielding	**79-19**	**96-19 mid**	**96-19 bottom**	**62-1**	**62-19**	**62-61**
Bare						
Cd						
PE						
PE+Pb						
Pb 5 mm						
Pb 10 mm						

Table 9: Overview of the assembly and shielding configurations measured by the different teams (High resolution gamma-ray detectors)

Low- and Medium-Resolution Gamma-Ray Detectors

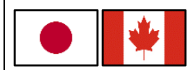
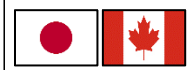
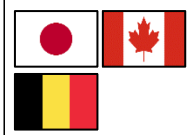
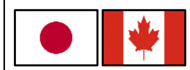
	Fuel Assembly ID					
Shielding	**79-19**	**96-19 mid**	**96-19 bottom**	**62-1**	**62-19**	**62-61**
Bare						
Cd						
PE						
PE+Pb						
Pb 5 mm						
Pb 10 mm						

Table 10: Overview of the assembly and shielding configurations measured by the different teams (low- and medium-resolution gamma-ray detectors)

This is a product of the IPNDV Working Group 6: Technologies for Verification. For more information on the IPNDV Working Groups, please see www.ipndv.org/working-groups.

About the IPNDV:

The IPNDV is an ongoing initiative that includes more than 25 countries with and without nuclear weapons. Together, the Partners are identifying challenges associated with nuclear disarmament verification and developing potential procedures and technologies to address those challenges.

The IPNDV is working to identify critical gaps and technical challenges associated with monitoring and verifying nuclear disarmament. To do this, the Partnership assesses monitoring and verification issues across the nuclear weapon lifecycle.

The IPNDV is also building and diversifying international capacity and expertise on nuclear disarmament monitoring and verification. Through the Partnership, more countries understand the process, as well as the significant technical and procedural challenges that must be overcome. At the same time, the Partnership is highlighting the importance of verification in future reductions of nuclear weapons.