Results of the BeCamp² Measurement Campaign

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Abstract

Within the framework of the activities of Phase III of the International Partnership for Nuclear Disarmament Verification (IPNDV) and based on the lessons learned from the 2019 Belgian measurement campaign, the Belgian Nuclear Research Centre SCK CEN proposed a new measurement campaign, called BeCamp^2.

The measurement campaign was held September 11–29, 2023, with 10 measurement teams participating. Each team deployed one or more measurement technologies to verify their capabilities in the framework of their potential use in nuclear disarmament verification activities.

The goal of the measurement campaign was to carry out measurements on unknown items containing different radioactive sources (including ^{235}U and Pu) and various shielding materials. The results of the measurements were used to answer a questionnaire containing typical questions identified in IPNDV discussions, such as verifying the absence of special nuclear material and confirming whether an item is of the same class as a reference item. In addition, the participants were offered the possibility to carry out neutron active interrogation with a moderated neutron source.

We report about the content of the measurement campaign, describing first the available items and types of measurements that were carried out. We then focus on the disarmament questions that each team tried to answer. The questionnaire results are discussed for each item and in an aggregated form; in the discussion of the results, we examine what answers can be interpreted

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to be correct as well as possible limitations in the answers, given a set of available technologies. We also discuss the chosen approach to report the experimental and data analysis results.

We conclude with the lessons learned and outlook on future activities.

Introduction

In 2019, a measurement campaign was carried out on the premises of the Belgian Nuclear Research Centre in support of the IPNDV activities. Several teams tested the performance of different measurement technologies with items of known geometry and composition.[2,3]

Based on the results obtained and lessons learned from that campaign, it was envisaged that a blind measurement campaign could be carried out, where the nature of the items would not be disclosed in advance. In addition, time constraints, similar to the ones that may be present in a disarmament verification scenario, should be included. It was also noted that items containing Highly Enriched Uranium (HEU) and other radionuclide sources not containing special fissionable material could be assayed. In addition, the IPNDV plan of work and objectives for Phase III included items such as information barrier development and understanding up to which point we need measurement technology and absence measurements.

Therefore, in close collaboration with the IPNDV Technology Track Working Group, SCK CEN proposed a new measurement campaign, called BeCamp^2. The focus of BeCamp^2 was on understanding potentials and limitations of technologies in a more realistic scenario and aimed at assessing the ability to draw conclusions with limited a priori information as well as the importance of combining data from different technologies.

Main Aspects of the BeCamp^2 Measurement Campaign

BeCamp^2 took place over the course of three weeks, between September 11 and 29, 2023. In each week, up to four measurement teams were simultaneously present. Teams from Australia, Belgium, Canada, Finland, Germany, Japan, Sweden, Switzerland, United Kingdom, and the United States participated in BeCamp^2.

Measurement Setup

Unlike the 2019 measurement campaign, the nature of the items to be measured was not disclosed in advance to the participants. Each measured item was hidden behind a fabric curtain and was not discernible from other items except from an identification label that was changed at

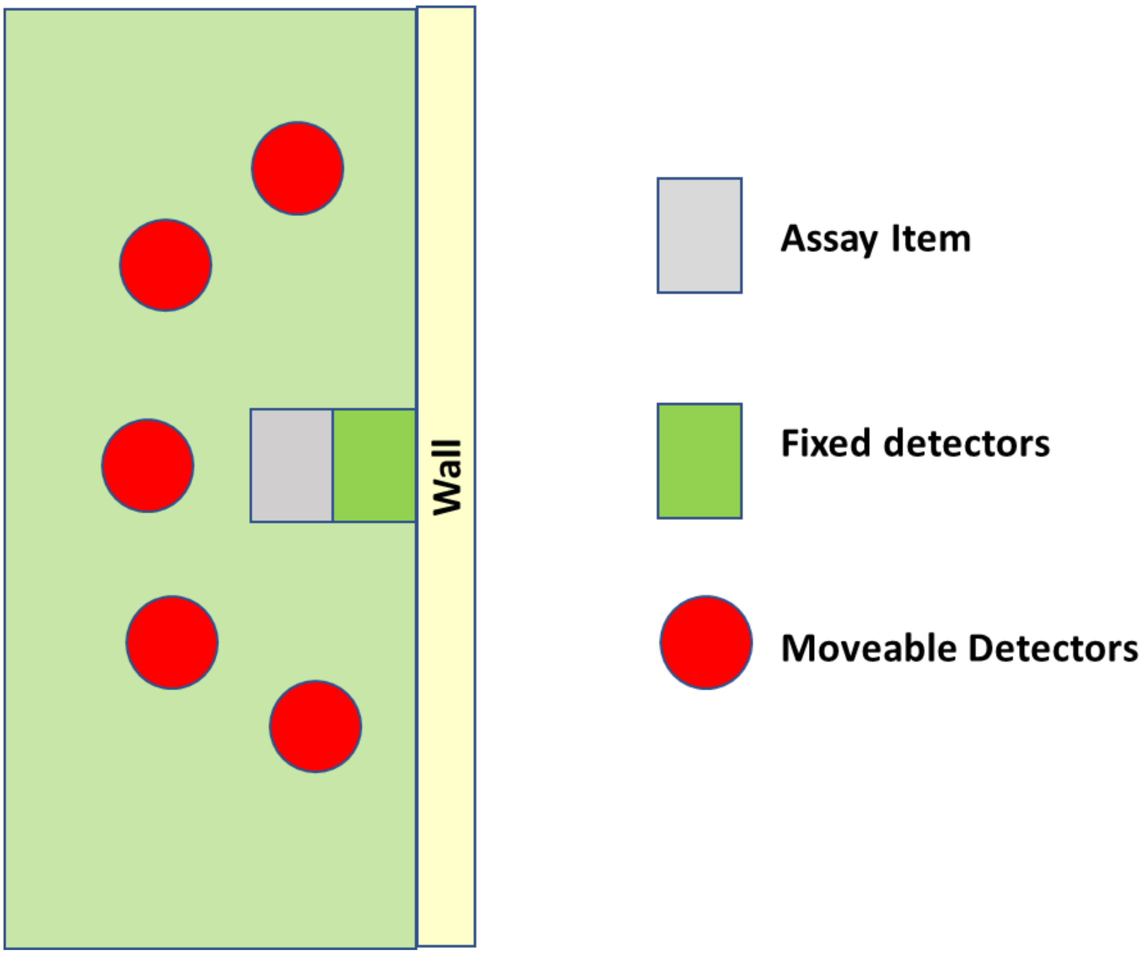
[2] A. Borella and G. Kirchner, *Results of the SCK CEN Exercise for Disarmament Verification Technologies*. IPVDV - International Partnership for Nuclear Disarmament Verification, 2021, https://www.ipndv.org/reports-analysis/results-of-the-sck-cen-exercise-for-disarmament-verification-technologies.

[3] A. Borella and G. Vittiglio, *Technology Exercise to Investigate Performance of Measurement Methods: Working Group 6: Technologies for Verification,* International Partnership for Nuclear Disarmament Verification, 2020, https://www.ipndv.org/wp-content/uploads/2020/04/IPNDV-Working-Group-6_Technology-Exercise-to-Investigate-Performance-of-Measurement-Methods_FINAL.pdf.

each measurement. Neutron and gamma-ray dose rates at about 1 m distance were recorded before each measurement and were communicated to the participants.

The different instruments were positioned around the measured item. Figure 1 is a layout of the measurement. The fixed position was usually dedicated for neutron coincidence counters that require being located as close as possible to the assayed item. Further details about the measurement technology and associated experimental details are given in the experimental data reports.[4]

Figure 1: Layout of the Experimental Setup



Deployed Technologies

Different technology types were deployed during the BeCamp[2] measurement campaign. They all relied on radiation detection.

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[4] IPNDV Questionnaire and data analysis reports, forthcoming.

For neutron-detection-based technologies, the following technology options were available:

- Fast neutron counting
- Thermal neutron counting
- Neutron counting (without distinction)
- Information about the neutron energy distribution
- Time correlation analysis

For gamma-detection-based technologies, the following technology options were available:

- High-Resolution Gamma-ray spectroscopy (HRGS)
- Medium-Resolution Gamma-ray spectroscopy (MRGS)
- Low-Resolution Gamma-ray spectroscopy (LRGS)
- Compton Edge Gamma-ray spectroscopy

In addition, radiation imaging capabilities were also available.

For more details on the technologies, we refer to the reports on the experimental data and data analysis produced by each team.

Table 1 summarizes the available sets of technologies during BeCamp[2]. Each line represents a combination of technologies and an "X" indicates that a given technology was available in that set. Ten combinations were available and each combination has an ID number. Each technology set received answers to the questionnaire.

Table 1: Summary of the Available Set of Technologies

Set	Neutron Counting					Gamma-Ray				Imaging
ID	Fast	Thermal	Any	Energy	Time Correlation	HRGS	MRGS	LRGS	Compton Edge	
1	X	X			X					
2								X		
3	X								X	
4		X		X			X			
5	X	X							X	X
6						X	X			
7	X	X					X			X
8						X				
9		X					X			X
10			X		X	X		X		

Note: The X marks indicate the presence of the technology in the column for the given set.

Themes

The measurement campaign focused on three themes: template measurements, absence measurements, and technology challenge.

Template Measurements

Two reference items were chosen and labeled as T001 and T002. An additional nine measurements were labeled T101 through T109. These measurements were to determine whether the technologies were capable of identifying the reference items in items T101–T109. It was assumed that any changes not identified correctly to the reference configuration would cause a verification failure. This was a choice that was made during discussion preceding the BeCamp^2 measurement campaign; however, no unanimous consensus exists on this assumption. Another option was to accept the identification of reference items when in another container or in shielded configurations.

Absence Measurements

Six absence measurements, labeled A001 through A006, were also carried out. The aim was to assess whether the technologies could confirm the absence of special nuclear material (HEU or Pu) in the measured items.

Technology Challenge

An ad hoc session was planned, which focused on active interrogation with a neutron source. In this session, measurements of an HEU reference item as well as an item without fissile material but similar scattering properties as the reference item were carried out with and without a moderated ^{252}Cf neutron source. During the Technology Challenges, the item being measured was visible to the participants.

Questionnaire

As part of the BeCamp^2 measurement campaign, a questionnaire associated to the Templates and Absence themes was developed. It contained a set of questions that the measuring teams answered based on the results of their experiments and data analysis, as follows:

Questions for the Template Theme

General Questions

- How did you verify that an item is of the same class as the reference item? What parameters did you consider (e.g., isotopics, position, statistics, repeatability of reference measurements)?
- How vulnerable is your system to spoofing?
- How did you verify the presence of HEU (or Pu)?
- How did you verify if low-z material is present?
- How did you determine if shielding is present?

Item-Specific Questions–Reference Items

- Can you confirm the presence of HEU?
- Can you confirm presence of Pu?
- Is shielding present?

- Is low-z material present in the Treaty Accountable Item (TAI)?
- Does this container have over 500g of Pu (or HEU)? Can include isotopics if the tools are available (is the ^{235}U over 20%, over 80% etc.)
- What is the confidence level on your analysis results?
- Is it a point source or an extended source, can you comment on the spatial distribution of the source?

Item-Specific Questions–Unknown Items

- Can you confirm that this item is of the same class as either of the reference items? Comment on how you reached this conclusion.
- Is shielding present? What has changed from the reference measurements?
- Is the detector able to reach a conclusion within the given time constraint? If not, what time would have been required?
- What is the confidence level on your analysis results? Do you have confidence that there is no spoofing (item that looks like one of the reference items, but it may not) in the analyzed item?
- Is it a point source or an extended source, can you comment on the spatial distribution of the source?

Questions for the Absence Theme

General Questions

- How vulnerable is your system to spoofing (based on the results of A001–A006, how suitable is for absence measurement)?
- How did you verify the absence of HEU (or Pu)?
- How did you verify if low-z material is present?
- How did you determine if shielding is present?

Item-Specific Questions

- Within the detection capabilities of your technique, can you confirm the absence of HEU?
- Within the detection capabilities of your technique, can you confirm absence of plutonium?
- Is shielding present?
- Is the detector able to reach a conclusion within the given time constraint?
- What is the confidence level on your analysis results? Do you have confidence that there is no spoofing (taking into account variation background conditions, presence of other sources, shielding) in the analyzed item?

The experimental data were processed individually by the measurement teams and the answers to the questionnaire are presented as separate reports.[5] We refer to these reports for the specific answers as well as for how the concept of “confidence level” was interpreted and its values determined.

[5] Ibid.

Measurements

In this section we describe the items that were used during the measurement campaign and the configurations in which they were measured.

Measurement Items

Because the items had been irradiated in a reactor, the radiation emission from ^{137}Cs could be always observed in items containing U or Pu. For those items where ^{137}Cs was not intrinsically present, a ^{137}Cs source was added so that an item identification based on the solely presence/absence of ^{137}Cs was not possible.

Item A

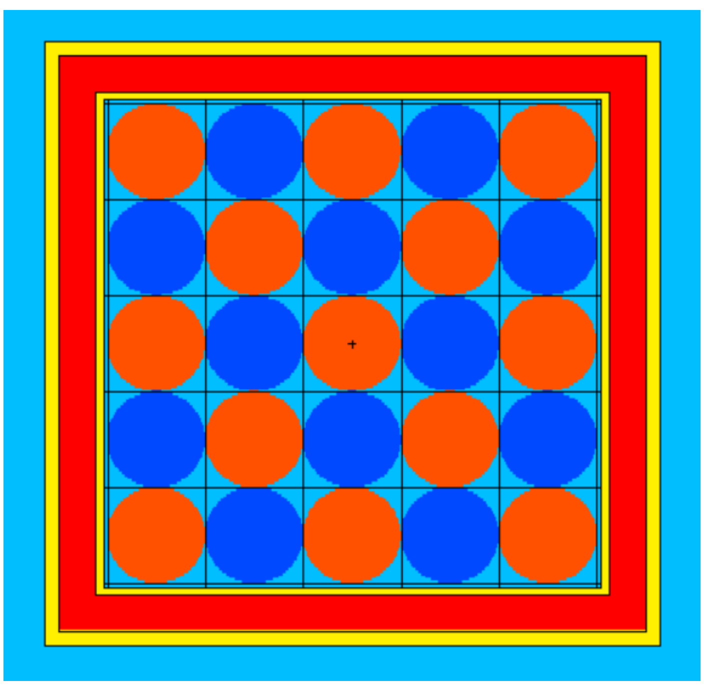
Item A is an empty transport container in aluminum. It was used for background measurements. All other items are located in such a container. The height of the transport container is about 15 cm. All items below described are mounted on such a container.

Item B

Item B contained metallic HEU with a nominal ^{235}U content of 30%. The uranium was in the form of 13 cylindrical bars 1.27 cm in diameter that were arranged in a checkered pattern together with 12 Al_2O_3 bars. The uranium bars were distributed along a length of about 61 cm.

A horizontal cross-section of the item is shown in Figure 2 (the HEU cross-sections are shown as red circles).

Figure 2: Horizontal Cross-Section of Item B



Note: The HEU cross-sections are shown as red circles and the Al2O3 cross-sections are shown as blue circles.

The total mass of U was 19.2 kg. The holder was made of stainless steel with a thickness of 3 mm and a height of about 110 cm with the HEU and Al_2O_3 bars being positioned at the bottom while the top part was empty.

The following three variants of the item were available:

- **Item B1.** As described above, but with 5 mm thick Pb shroud inside the stainless steel container.
- **Item B2.** As described above (item B).
- **Item B3.** As described above, but with Pb bars instead of U bars.

Item C

Item C is a 3 mm stainless steel square container that can be used to host 50 cm-long MOX fuel rods. It contains a 1 mm thick stainless steel cylindrical cavity to accommodate additional sources. It is available in two variants: Item C1 and Item C2.

Item C1

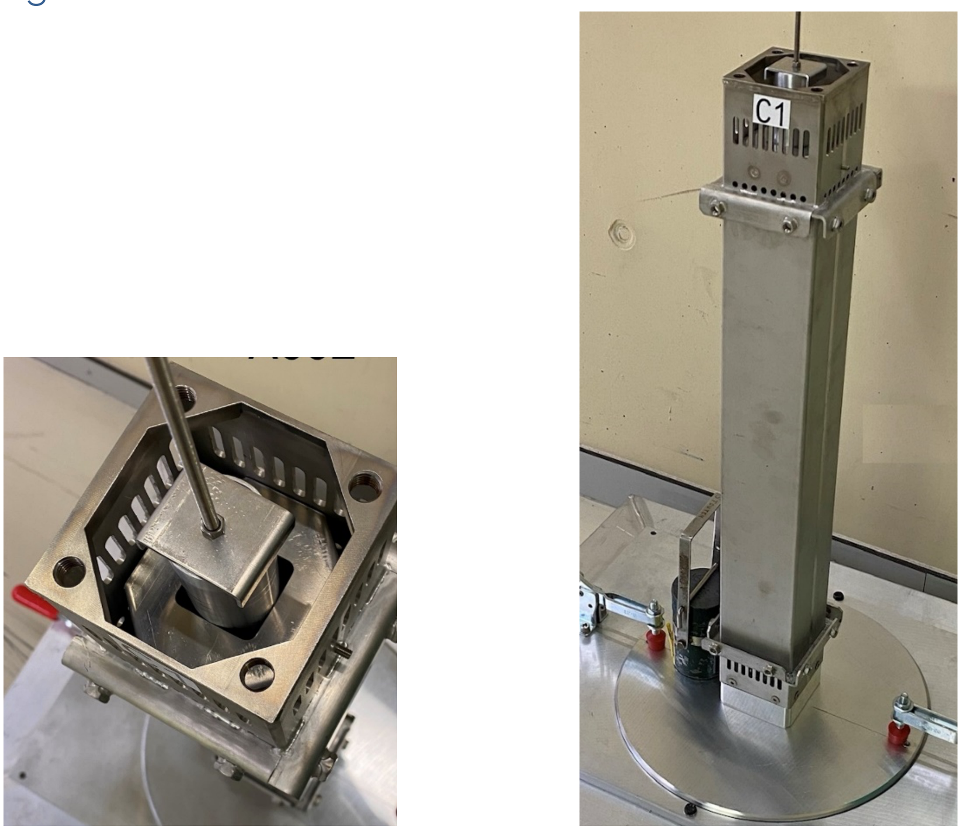
In this item (shown in Figure 3) radionuclide sources of ^{252}Cf and ^{133}Ba can be hosted in the central cavity.

During the measurement, the ^{133}Ba source had a distance of approximately 48 cm from the floor, whereas the ^{252}Cf source was positioned about 15 cm above the ^{133}Ba source.

The intensity of the ^{252}Cf source was 3.959 GBq (107 mCi) on October 16, 1993, and the intensity of the ^{133}Ba source was 8.8 MBq on August 2022.

During the measurement, an additional ^{137}Cs source was present in a Pb container positioned outside the outer stainless steel container 23 cm below the ^{133}Ba source.

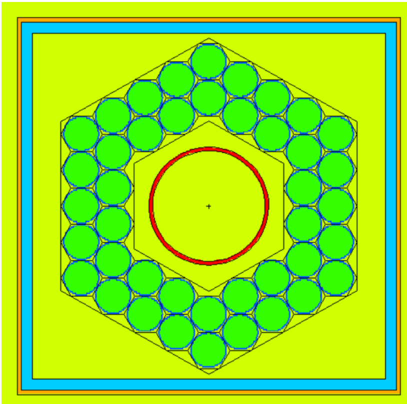
Figure 3: Pictures of Item C1

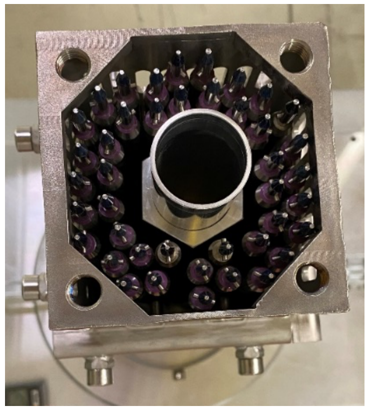


Item C2

This item contains 42 MOX pins arranged as indicated in Figure 4. The item contains a 1 mm thick stainless steel cylindrical cavity with a hexagonal spacer to allow a correct positioning of the fuel pins.

Figure 4: Illustration of a Horizontal Cross-Section and Picture of Item C2





The MOX composition of this item, corrected for decay to September 2023, is given in Table 2.

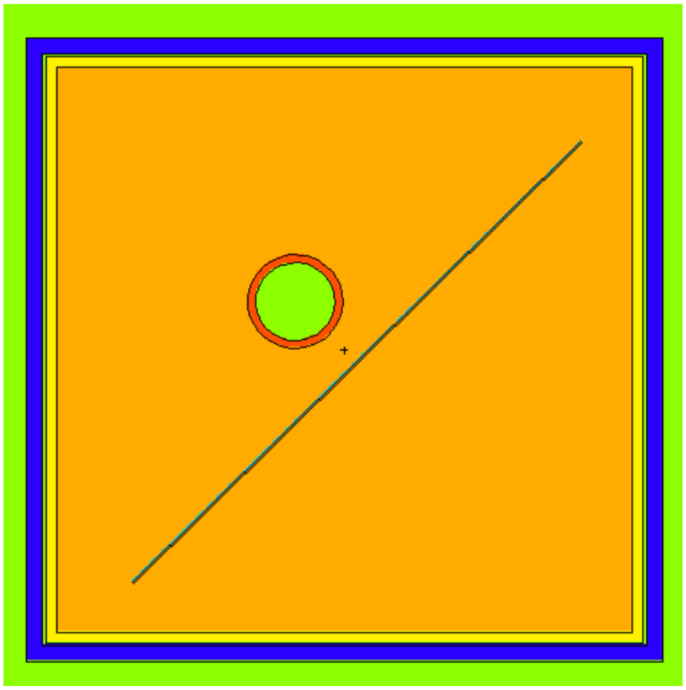
Table 2: Radionuclide Composition of the MOX in Item C2

Item	Mass / g	Item	Mass / g
^{238}Pu	0.26	^{241}Am	17.25
^{239}Pu	483.59	^{235}U	82.56
^{240}Pu	104.94	^{238}U	11383.93
^{241}Pu	1.19	Oxygen	1606.80
^{242}Pu	2.72	Total	13683.52

Item D

This item contained two ~0.5 mm thick metallic plates of HEU with a total mass of uranium of 113 g. The ^{235}U enrichment is 93%. The plates are vertically placed next to each other and inside a polyethylene block (72.5 mm x 72.5 mm) as shown in Figure 5. The plates are 2 mm away from the diagonal of the polyethylene. The polyethylene includes a cavity to host instrumentation. Both plates have a length of 185 mm along their vertical and 80 mm along their diagonal axis. The vertical center of gravity of the HEU is about 31 cm from the bottom of the container.

Figure 5: Horizontal Cross-Section of Item D



The polyethylene is wrapped in a 1.3 mm thick Cd liner. The container is made of 2 mm thick stainless steel.

Measurement Configurations

The measurement sequences of the aforementioned items are detailed below for the three themes of the measurement campaign. The planned duration of the measurements was 30 minutes unless indicated otherwise. For each measurement, a picture was taken and shown in the results section.

Template Measurements

A facility background measurement was carried out first to assess the background conditions (T000). The reference items containing fissile material were then measured (T001, T002). Subsequent measurements, T101–T109, were repeated as follows:

- With the reference items (T103, T106)
- With additional measurements of the reference items with shielding material (T102, T104, T105, T109)
- With other items containing fissile material but with a different composition (T101, T107)

In addition, we measured radionuclide sources that could mimic the presence of fissile material (T108). Table 3 describes each measurement.

Table 3: Summary of the Measurements Carried Out in the Template Theme

ID	Item	Description
T000	**A**	Facility background
T001	**D**	First reference item
T002	**C2**	Second reference item including a 1 Cd liner around
T101	**B2**	HEU 30%
T102	**C2**	As T002 but Cd was removed and 5 cm thick high-density polyethylene (HDPE) was added
T103	**D**	Same as T001
T104	**C2**	5 mm Pb was added outside the container
T105	**D**	5 mm Pb was added outside the container (90’)
T106	**C2**	Same as T002
T107	**B1**	HEU 30% with 5 mm Pb
T108	**C1**	^{137}Cs + ^{133}Ba + ^{252}Cf bare
T109	**B2**	As T101 but with an additional 1 mm Cd liner around

Absence Measurements

A facility background measurement was carried out first to assess the background conditions (A000). The first four measurements (A001–A004) did not contain fissile material but gamma and neutron sources in bare or shielded configurations. In the last two measurements (A005, A006) we used an item with HEU in bare and shielded configurations. We chose HEU because it should be more difficult to identify in an absence measurement than an item with Pu. Table 4 describes each measurement.

Table 4: Summary of the Measurements Carried Out in the Absence Theme

ID	Item	Description
A000	**A**	Facility background
A001	**A**	^{137}Cs in Pb container + ^{133}Ba in Pb container + ^{252}Cf in Polyethylene container
A002	**C1**	^{133}Ba bare + ^{252}Cf bare in stainless steel container. ^{137}Cs in Pb container outside the stainless steel container. Same as T108.
A003	**B1**	5 mm Pb was added outside the container. Total Pb thickness is 10 mm.
A004	**C2**	5 cm Polyethylene and 10 mm Pb were added outside the stainless steel container
A005	**D**	10 mm Pb was added outside the stainless steel container
A006	**D**	Same as T001

Technology Challenges

Table 5 summarizes the measurements from the Technology Challenges.

Table 5: Summary of the Measurements Carried Out in the Technology Challenge

ID	Item	Description
C000	**A**	Facility background
C001	**B2**	Background due to B2 item
C002	**B2**	^{252}Cf in Polyethylene block and B2 item
C003	**B3**	^{252}Cf in Polyethylene block and B3 item
C004	**B3**	Background due to B3 item

Results

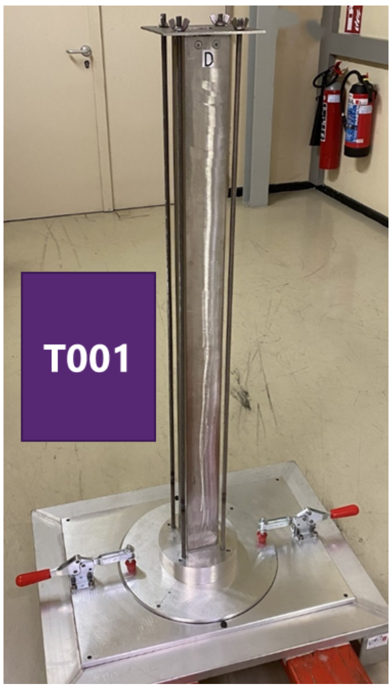
In this section we report a summary of the results obtained for each measured item for the template and absence themes. For each item we look at all answers received and look for a correlation between the correctness of the answers and the available technologies. We then explain in more detail the measurements related to the technology challenge theme. Afterward, in the Technologies Assessment section, we evaluated the performance of the available sets of the technologies with respect to their capabilities of sample characterization, class assignment, absence verification, and shielding identification.

For detailed results we refer to the appendix or to the individual team reports.[6]

Template Measurements

A measurement time of 30 minutes was generally sufficient for template verification measurements. The imagers could determine a rough image of the item and distinguish between an axially extended source and a point source.

Item T001



The presence of HEU could be confirmed only when HRGS or MRGS (such as CLLBC) were deployed.

Item T001 contains HDPE and Cd and most of the techniques could not determine with a good level of confidence the presence and/or the nature of the shielding material.

The enrichment could be determined with high confidence with HRGS, but with less confidence only with MRGS.

The mass of HEU could not be determined except when combining different technologies (HRGS and coincidence neutron counting) and with ad hoc data analysis software. This result, however, strongly depends on assumptions made about the spatial distribution of the source.

[6] Ibid.

Item T002

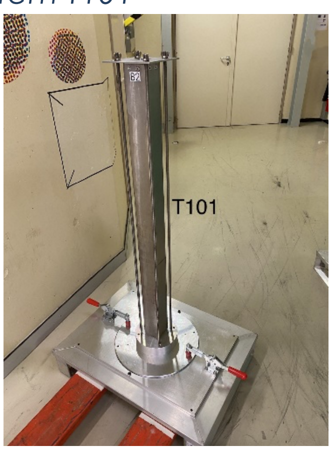
The presence of Pu could be confirmed when HRGS or MRGS were deployed.

Item T002 contains Cd. The presence of light gamma shielding could be identified with all gamma detectors. When also measuring neutrons, a thermal neutron shield could be identified. However, it was often mistaken as a hydrogenous moderator rather than a neutron absorber.

The radionuclide composition could be determined with good accuracy only when HRGS were used.

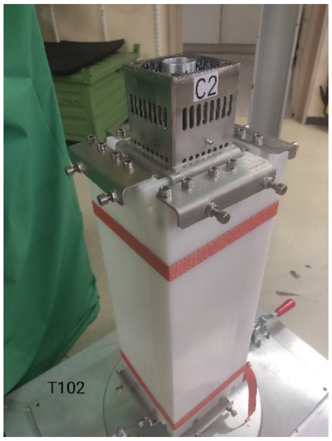
When the Pu mass estimation was attempted, the mass was in a different range than the actual mass. Neutron time correlation measurements and associated data analysis can potentially address the question but require information on the composition of the item.

Item T101



T101 includes HEU with comparably lower enrichment and larger mass than item T001. There were no misclassifications for this item and the associated level of confidence was high. When HRGS was used, the uranium enrichment levels could be determined.

Item T102



In Item T102, the Cd shroud was removed and replaced by 5 cm HDPE. In some cases, this item was misclassified as T002 although with a lower confidence level. These misclassifications were not correlated with the deployed technology and are probably due to the analysis approach used.

Item T103

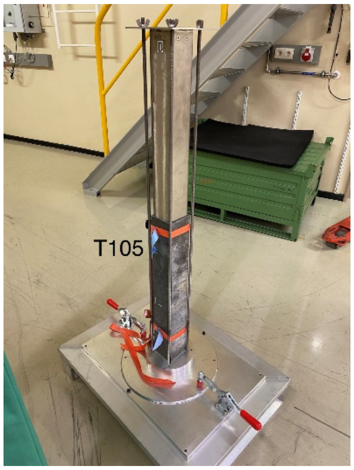
Item T103 is identical to T001. It was generally correctly classified with a high level of confidence. Measuring gamma radiation is important as well as correct positioning.

Item T104

In Item T104, the Cd shroud was removed and replaced with 5 mm Pb. In some cases, it was misclassified as T002 although with a lower confidence level. However, the presence of shielding and its nature (high atomic number) could usually be identified.

Both the misclassifications and the ability to determine the presence of the shielding are not correlated with specific technologies but may be caused by the data analysis procedure used.

Item T105



In Item T105, 5 mm of Pb was added on the outside of item T001. The item was generally correctly classified with varying levels of confidence. Measuring gamma radiation was necessary. With the appropriate analysis, the presence of shielding and its nature (high atomic number) could be identified. Due to the presence of shielding, the time was only sufficient for class assignment.

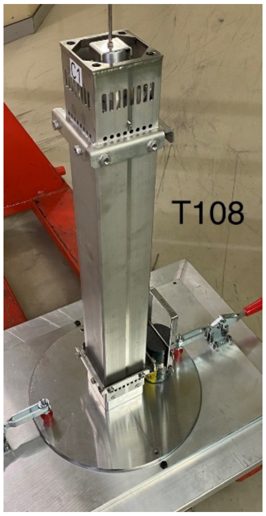
Item T106

Item T106, which is identical to T002, was generally correctly classified with a high level of confidence. The results stressed the importance of monitoring the background due to its fluctuations during facility operations.

Item T107

Item T107 is similar to T101, but with 5 mm of Pb inside the walls of the container. It was generally correctly classified with varying levels of confidence. Measuring gamma radiation is necessary. With the appropriate analysis, the presence of shielding and its nature (high atomic number) could be identified. Due to the presence of shielding, the fixed measurement time was only sufficient for class assignment.

Item T108



Item T108 was generally correctly classified with a high level of confidence with gamma-ray measurements. With HRGS, the nature of the sources could be determined. The analysis of neutron time correlations could distinguish this item (^{252}Cf) from T002 (Pu).

The spatial resolution of the imagers was not sufficient to resolve the position of the sources. With some imagers it was mistaken for an axially distributed source.

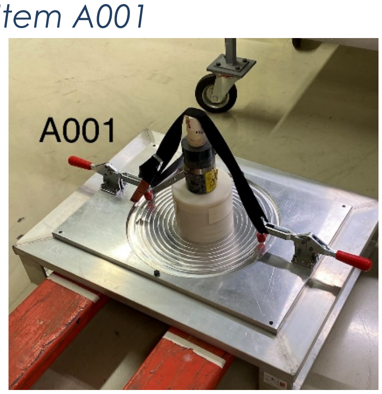
Item T109

A 1 mm Cd shroud was added to item T101. Item T109 was generally correctly classified with varying levels of confidence when gamma radiation was measured. The presence of shielding and its nature could not be identified.

Absence Measurements

As a general result, the 30-minute measurement time was not always considered sufficient to achieve high confidence, irrespective of the technology used.

Item A001



For Item A001, both the absence of HEU and Pu could be confirmed with high- and medium-resolution gamma detectors, but not with other technologies.

The presence of HDPE could be identified with neutron detectors. The presence of Pb could not be determined.

Item A002

Similarly to A001, for A002, the absence of HEU and Pu was confirmed with high- and medium-resolution gamma detectors only.

The presence of Pb could not be determined.

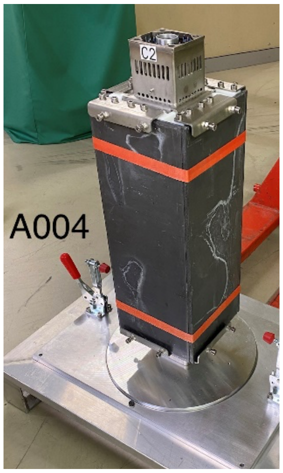
Item A003

Item A003 included HEU shielded by 10 mm of Pb. The absence of Pu could usually be confirmed, as well as the presence of the Pb shielding, with high- or medium-resolution gamma spectrometry.

When the presence of Pb was determined, the absence of HEU was not confirmed. In this case, the absence of low-energy gamma-rays of ^{235}U was attributed to the presence of Pb rather than to the absence of ^{235}U.

When the presence of Pb was not determined, the absence of HEU was wrongly confirmed. Now, the absence of low-energy gamma-rays of ^{235}U was attributed to the absence of ^{235}U. It is possible that the presence of a Pb collimator did not allow a proper assessment of the Pb shielding.

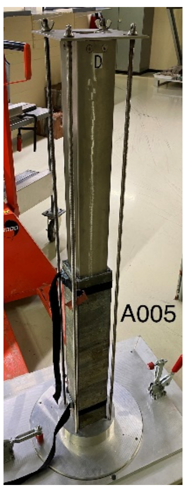
Item A004



In Item A004 Pu was present, shielded by 5 cm of HDPE and 10 mm of Pb. The absence of Pu was never confirmed. In most of the cases, the absence of HEU was not confirmed. As with Item A003, a correct assessment of the shielding is important.

The presence of significant shielding was not always identified even with high-resolution gamma detectors. It is possible that the presence of a Pb collimator did not allow a proper assessment of the Pb shielding.

Item A005



Item A005 differs from A003 only in the mass of HEU (lower) and its enrichment (higher). There was higher consensus about the absence of Pu for this item than for A003. Due to the high ^{235}U content, the ^{238}U lines were not observed and this made it easier to confirm the absence of Pu. The absence of HEU was not always correctly answered irrespective of the technology and the ability to identify the presence of shielding.

Item A006

This is the same item as T001.

The question about the absence of HEU was always correctly answered if a gamma-ray measurement technology was used. The absence of Pu was confirmed except in case when an insufficient confidence was achieved.

Technology Challenge

The goal of this session was to carry out measurements with a thermalized neutron (^{252}Cf) source to observe the induced fission radiation with the available detector technologies. The session consisted of four measurements each allowing assessment of different aspects of the radiation field.

The four available measurements are as follows and allow assessment of:

- **C001.** The intrinsic background of the B2 item (i.e., the passive gamma and neutron emission rates of the item with fissile material).
- **C002.** The response due to the presence of fissile material (B2 item) and a moderated ^{252}Cf source. This includes radiation from the source itself and induced radiation in the fissile material due to the presence of the external source.
- **C003.** The response due to the presence of material (B3 item) with similar scattering properties as the item with fissile material and a moderated ^{252}Cf source. This includes radiation from the source itself and induced radiation due to the presence of the external source.
- **C004.** The intrinsic background due to the presence of material with similar scattering properties (B3 item) as the item with fissile material.

If we denote the response from measurement *i* as R_i , it is expected that the induced fission signal can be derived by computing:

$(R_{C002} - R_{C001}) - (R_{C003} - R_{C004})$

Pictures taken during measurements of the C001 and C002 items are shown in Figure 6.

The results of the active interrogation measurements are still to be analyzed and will be reported separately.

Figure 6: Pictures of Measurement Items During the Technology Challenge

Technology Assessment

We analyzed the answers received for each of these sets of technologies and evaluated them with respect to their capabilities of:

- Sample characterization (using the questionnaire answers for measurements of T001 and T002)
- Class assignment (using the questionnaire answers for measurements of T101 and T109)
- Absence verification (using the questionnaire answers for measurements of A001 and A006)
- Shielding identification, presence, and type (using all questionnaire answers).

The sample characterization was not per se a goal of the campaign. However, the answers to the questionnaire also allowed assessment of this aspect, which we believe to be important when considering aspects related to the information barrier.

The results are summarized in Table 6, according to the qualitative color coding indicated in the key, and discussed in the following subsections.

Sample Characterization

Here we assessed the capabilities to identify the type of nuclear material, its mass, its radionuclide composition, and shielding material (presence and type) in the two reference items of the Template theme.

With the caveat that only two items were considered, the results indicate that none of the technologies considered allowed an excellent characterization on all the capabilities considered. The results stress that when HRGS is available, the quality of the result improves.

Some technologies, such as the ones based on neutron counting or Compton scattering, show a potential for an intrinsic information barrier because their results may not be considered as sensitive by a nuclear-weapon state. These showed worse performance than other detector types (e.g., HRGS or MRGS).

6: Summary of the Results for the Sample Characterization, Class Assignment (Template Verification), Absence Verification, and Shielding Identification

Neutron Counting: Fast	Neutron Counting: Thermal	Neutron Counting: Any	Neutron Counting: Energy Distribution	Neutron Counting: Time correlated	Gamma-ray Spectroscopy Resolution: High	Gamma-ray Spectroscopy Resolution: Medium	Gamma-ray Spectroscopy Resolution: Low	Gamma-ray Spectroscopy Resolution: Compton Edge	Imaging	Characterization: HEU	Characterization: Pu	Template Matching: HEU	Template Matching: Pu	Absence Verification: HEU	Absence Verification: Pu	Shielding Identification: Presence and type
X	X			X						Poor	Fair	Poor	Good	N/A	Average	Fair
							X			N/A	N/A	Excellent	Excellent	N/A	N/A	N/A
X								X		Fair	Poor	Good	Average	N/A	Average	Fair
	X		X			X				Average	Average	Good	Excellent	Fair	Fair	Average
X	X							X	X	Poor	Average	Excellent	Good	Average	Poor	Fair
					X	X				Good	Good	Excellent	Good	Good	Excellent	Good
X	X					X			X	Fair	Average	Good	Average	Fair	Poor	Excellent
					X					Average	Good	Excellent	Excellent	Fair	Excellent	Fair
	X					X			X	Average	Average	Good	Excellent	Average	Average	Good
		X		X	X		X			Good	Average	Excellent	Excellent	Fair	Excellent	Average

Key:
- Excellent
- Good
- Average
- Fair
- Poor
- N/A

Class Assignment

Within the Template theme, two classes were considered and nine unknown samples were measured. We assessed the capabilities to identify the class of an unknown sample.

The results in Table 6 indicate that even with LRGS, excellent class assignment results were achieved. The results obtained seem to indicate that gross neutron flux density measurements do not provide substantial added value for class assignment.

Absence Verification

Within the Absence theme, six items were measured. We assessed the capabilities to correctly determine the questions related to absence of either HEU or Pu in a given item. False negatives (declared absent when present) and false positives (declared present when absent) were more penalized that the inability to confirm the absence.

The results reveal that better results are obtained for Pu absence verification than for HEU. The best results were achieved when HRGS was available.

Shielding Identification, Presence, and Type

We assessed the capabilities to identify the presence and type of additional material, such as gamma-ray shielding, neutron moderator, and thermal neutron shielding. A more detailed and accurate answer (e.g., containing the information about the type of material) was valued more than, for example, a yes/no answer about the presence of shielding.

The results reveal that the best results were achieved with HRGS in combination with thermal and fast neutron detection.

Experimental and Data Analysis Results

In addition to the responses to the questionnaire, we also documented the experimental and data analysis results that were obtained with the different deployed technologies for all measured items. The results may be used in combination to better address, for example, the questionnaire. Another example is that one could combine a gamma-ray spectroscopic measurement with neutron coincidence data; knowing the spatial distribution of the source is important for a better determination of the item mass, knowing whether there is a neutron moderator or a gamma-ray attenuator may also be important in the framework of absence measurements. In addition, the results can be used to address future technical disarmament verification questions.

Dose Rates During the Three Weeks

The gamma and neutron dose rates were measured with a dose rate meter from Automess and a LB 6411 Neutron Probe from Berthold Technologies. They are given in Table 7 for the items during the template and absence measurements. The detector was positioned at an angle of 180 degrees in position 4, as outlined in Figure 7. The distance was 150 cm from the center of the items, except during week 3 when the distance was 100 cm.

Figure 7: Layout of the Experimental Setup with Respect to Dose Rate Measurements

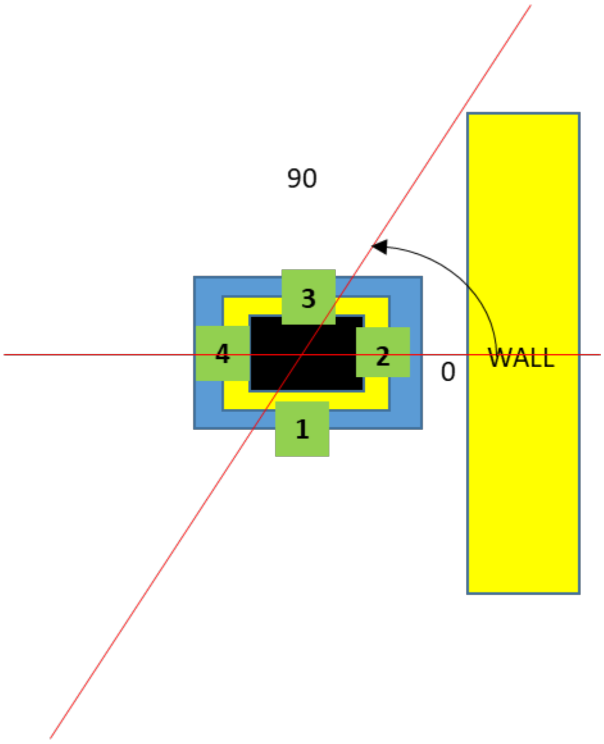


Table 7: Neutron and Dose Rate Measurements for Each Item Measured in the Three Weeks of the BeCamp^{2} Measurement Campaign

		Week 1				Week 2				Week 3	
Item	Berthold	Berthold	Automess		Berthold	Berthold	Automess		Berthold	Berthold	Automess
	µSv/h	cps	µSv/h		µSv/h	cps	µSv/h		µSv/h	cps	µSv/h
T000	<0.05	0.02	<0.1		---	---	---		<0.05	0.01	<=0.1
T001	<0.05	0.03	<0.1		<0.05	0.013	0.2-0.3		<0.05	0.015	0.3-0.5
T002	1.7-1.8	1.4-1.5	0.7		1.65	1.3	0.5-0.7		3.4	2.7	1.6-1.7
T100	<0.05	0.02-0.03	<0.1		---	---	---		---	---	---
T101	<0.05	0.02	0.3		<0.05	0.01	0.2-0.4		0.06	0.05	0.9+-0.1
T102	0.9	0.6	1		1	0.6	1		1.4	1.1	2.4+-0.3
T103	<0.05	0.02	0.2		0.05	0.04	0.2		<0.05	0.01	0.3
T104	1.7	1.3	0.2		1.4	1.2	0.3		3+-0.1	0.01	0.15
T105	0.2	0.15-0.20	0.15-0.20		<0.05	0.013	0.1		<0.05	0.011	0.3
T106	1.6	1.3	0.8		1.25	1.2	0.7-0.8		3+-0.1	2.4+-0.1	1.7+-0.3
T107	<0.1	0.02	0.4		<0.05	0.03	0.1-0.2		<0.05	0.011	0.3
T108	2.8	2.3	0.4-0.6		2.5	2	0.5		4.3	3.4	0.9+-0.2
T109	<0.05	0.012	0.2		<0.05	0.015	0.2		<0.05	0.03	0.6+-0.2
A000	0.19	0.15	<0.1		---	---	---		---	---	---
A001	1.1	0.9	0.5		1.1	0.9	0.4-0.6		1.7	1.5	0.9+-0.1
A002	2.7	2.1	0.4		2.4	2.1	0.4-0.6		4.8	4	1.0+-0.1
A003	0.07	0.06	<=0.1		<0.05	0.03	0.2		<0.05	0.02-0.03	0.1-0.2
A004	0.6	0.5	0.2		0.9	0.7	0.2		1.6	1.3	0.5+-0.1
A005	0.07	0.05	<0.1		<0.05	0.015-0.02	<0.1		<0.05	0.02	<=0.1
A006	0.05	0.03	0.2		<0.05	0.03	0.15		<0.05	0.017	0.3-0.4

Conclusion and Future Work

A blind measurement campaign to assess the suitability of different technologies in view of their deployment for disarmament verification was carried out in September 2023 on the premises of the Belgian Nuclear Centre SCK CEN. We have reported the main aspects and results of the measurement campaign called $BeCamp^2$. The focus is on aspects related to template verification and absence measurements. From the analysis of the answers to a predefined questionnaire, we can draw some general conclusions:

- For the template measurement, the results obtained indicate that with low-resolution gamma detectors excellent class assignment results were achieved.
- Absence measurements are challenging, and the results reveal that better results are obtained for the verification of absence of Pu than of HEU. The best results were achieved with HRGS.

The data obtained also allowed us to draw conclusions with respect to sample characterization, although these are based on a limited sample size.

The results indicate that none of the technologies considered allowed a full characterization. In particular, the mass assessment, even approximate, was always challenging. The results stress that the quality of the result improves when HRGS is available. Because a sample characterization is not desirable in disarmament, these results are interesting with respect to assessing the potential of technologies with an intrinsic information barrier.

With respect to detecting the presence of shielding material, such as gamma-ray attenuators and neutron moderator and absorbers, the results reveal that the best results were achieved with medium-resolution gamma detectors in combination with thermal and fast neutron detection.

The $BeCamp^2$ measurement campaign was useful to assess the performance of measurement technologies with respect to a close-to-realistic disarmament measurement scenario. Future work may focus on processing the results of the technology challenge and address the problem of information barriers. An important aspect of $BeCamp^2$ is that the experimental and data analysis results obtained are documented in a way that they can be further used in case additional disarmament related questions arise in the future.

About IPNDV the International Partnership for Nuclear Disarmament Verification

The International Partnership for Nuclear Disarmament Verification (IPNDV) convenes countries with and without nuclear weapons to identify challenges associated with nuclear disarmament verification and develop potential procedures and technologies to address those challenges. The IPNDV was founded in 2014 by the U.S. Department of State and the Nuclear Threat Initiative. Learn more at www.ipndv.org.