Nuclear Treaty Verification Techniques Applied to the IPNDV Measurement Campaign Data

Jennifer Schofield and Rob Hughes, July 2021

Abstract - Verification technologies can be used many ways and at many points during treaty verification, depending on the declarations made. Therefore, the use of modelling will be necessary to assess verification technology choices, as experiments will be unable to replicate exact conditions. It is imperative these models are benchmarked against well-documented data. As part of the International Partnership on Nuclear Disarmament Verification (IPNDV), during Autumn 2019, measurement data was taken by many participating nations of MOX (Mixed Oxide) nuclear fuel with varying isotopic compositions at SCK.CEN, in Belgium. The data taken during this IPNDV Measurement Campaign is an important addition to the body of experimental data for use in treaty verification. The data taken by the UK participants has been used both to validate modelling and to test verification algorithms, as shown in this paper. The benefits and challenges of extrapolating from modelled data is also discussed.

Introduction

There are a broad range of technologies that might be required by a nuclear weapons arms control treaty, all of which must be assessed. The technologies which might be most appropriate, as well as where and how those technologies are implemented, will change depending on the declarations within a particular treaty.

Whilst experiments are important in understanding the performance of a technology, they are unable to replicate the exact conditions one might find during actual treaty verification measurements. The use of modelling is, therefore, necessary to assess technology choices against the broadest possible range of scenarios. Here, the use of experiments is imperative to validate those models against well-documented data. In addition to models of technology, the most appropriate verification algorithm for a given declaration must also be evaluated for a treaty's verification system. Using good quality experimental data allows these algorithms to be developed and assessed. In addition, modelling has advantages over experiment, being cheaper, and allowing multiple technologies and environments to be assessed; it can also identify necessary measures for use in a given scenario (e.g. the need for an information barrier).

As part of the International Partnership on Nuclear Disarmament Verification (IPNDV) measurement data was taken by many participating nations of MOX (Mixed Oxide) nuclear fuel with varying isotopic compositions. The use of the IPNDV Measurement Campaign data is clear. The IPNDV considers the use of measurements important at multiple different stages in a dismantlement verification system. The objective of the UK's participation in the IPNDV Measurement Campaign was to use well-established neutron and gamma detectors with an aim to measure validation data from a well-known source. This data is then used to aid modelling for treaty verification and to allow testing of verification algorithms.

The following paper will detail not just the measurements the UK gained from this campaign, but also examples of how this data can be used to good effect for assessing technologies in verification systems.

Measurements and equipment

The IPNDV Measurement Campaign was held in 2019 in SCK.CEN, and employed detectors fielded from many different countries measuring radiation from Mixed Oxide (MOX) spent fuel pins (consisting of plutonium and uranium oxide) of varying isotopic compositions.

The UK participants chose to measure two sets of 19 fuel pins with 79% and 96% Pu-239 fuel compositions respectively. Table 1 summarises the six configurations used. The two fuel pin sets were measured with three different shielding configurations: no shielding; cadmium 2 mm thick; and a shielding of lead, 10 mm thick, over polyethylene, 50 mm thick. This choice meant that data for multiple shielding and isotopic compositions could be gathered.

79% Pu-239 Fuel Pins	96% Pu-239 Fuel Pins
No Shielding	No Shielding
Cadmium (2mm)	Cadmium (2mm)
Lead (10mm) and Poly (50mm)	Lead (10mm) and Poly (50mm)

Table 1. Six shielding configurations used by the UK during this measurement campaign.

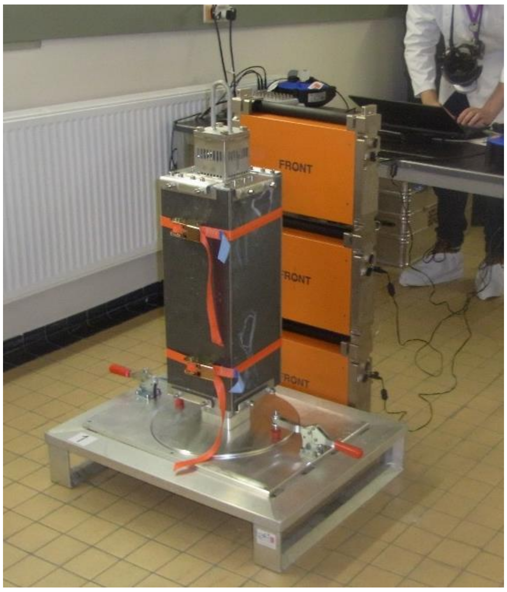

Figure 1. The $(ND)^2$ detectors in-field. Source: SCK•CEN.Used by permission.

During the IPNDV Measurement Campaign, the UK fielded three helium-3 based neutron detectors (Nuclear Diagnostics Neutron Detector, or “$(ND)^2$”) and one sodium iodide (NaI) Identifinder detector (Identifinder Ultra THG). Both of these technologies are well-developed for a range of radiation detection uses including safeguarding and arms control.

Gamma results and application

For gamma measurements, the NaI results (background subtracted) for both the 79% Pu-239 Fuel and 96% Pu-239 fuel for all configurations can be seen in Figure 2. These measurements were taken over a short time span of 5 minutes at a distance of 128 cm from the centre of the fuel bundle. The NaI measurements were taken on a table with a height of approximately 75 cm and was approximately 20 cm from a wall.

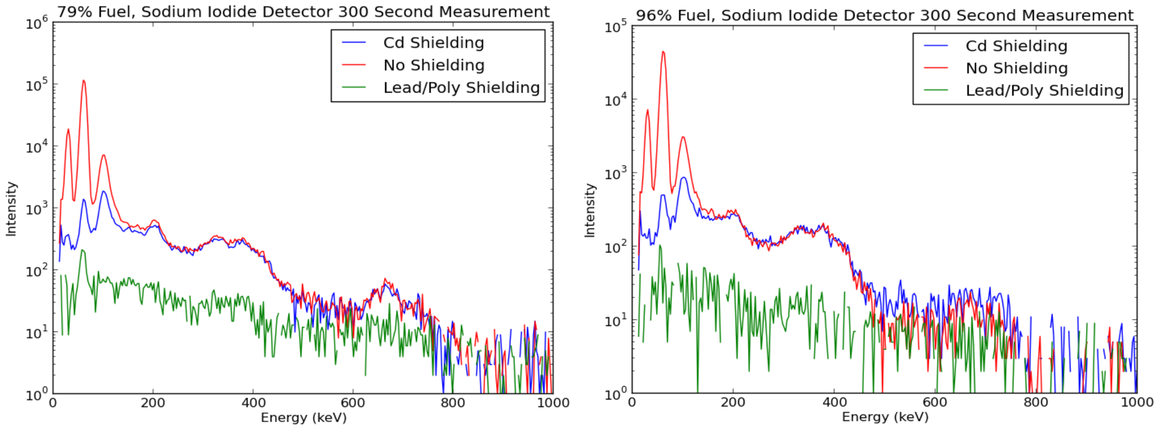

Figure 2. Results from NaI detector for the 79% Pu-239 fuel in the left figure and 96% Pu-239 fuel in the right figure. The y axis is the total counts per channel.

Although the results from the NaI detector are not as useful as high-resolution HPGe spectra for exact isotopic identification, there are other uses for lower-resolution spectral measurements such as this in a verification system. One such use could be in *radiation signature template matching*.

If a treaty defines two different classes of object (or "treaty accountable item"), then an effective verification regime will require the ability to distinguish between these two classes. For example, if a site were declared to contain objects of type "79% Pu-239" and also objects of type "96% Pu-239", how can an inspector be sure that an item declared to be one type is not, in fact, the other? What if the gamma spectrum is considered sensitive information and cannot be viewed by inspectors?

This presents an opportunity to use a template matching method, and it can be done using the low-resolution gamma data obtained during this campaign. The sodium iodide low-resolution data can be re-binned around energy groups of interest which correspond to isotopes of interest for the class of objects. A spectral measurement of a known object can then be saved as a "template" and compared against the spectra from subsequent objects, using a statistical metric to determine the likelihood of the spectra being from the same type of object. In this method, the potentially sensitive spectra of the template and the subsequent objects never need to be revealed to the inspector, only the statistical result of the comparison.

Figure 3 shows an example using two sets of NaI data taken during the campaign for this template matching. Table 3 shows the results of a comparison for all the data taken during the measurement campaign by the UK. The spectra are compared using a reduced chi-square metric, with a value less than 4 indicating a match between the template and object spectra.

This shows the ability to easily distinguish between things which are classed as a match (on the diagonal) and things which are not classed as a match to the template spectrum. It also shows that in this case the presence of shielding would affect whether something was deemed to belong to the correct class. The use of 5 minute low-resolution measurements is shown to be sufficient in this case to use this analysis method.

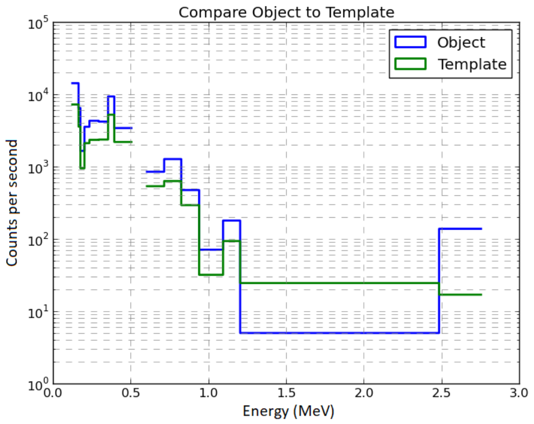

Figure 3. Example of the comparison over re-binned energy groups between a template and object.

OBJECT	TEMPLATE					
	79% No shielding	79% Cd shielding	79% Pb Poly shielding	96% No shielding	96% Cd shielding	96% Pb Poly shielding
79% No shielding	0.22	57.45	12631.86	91.68	309.36	52194.9
79% Cd shielding	15.54	0.25	5935.5	67.35	58.14	29942.56
79% Pb Poly shielding	82.67	79.05	0.28	71.58	65.45	150.5
96% No shielding	26	31.74	3375.32	0.23	46.73	15405.73
96% Cd shielding	32.93	19.02	1611.89	17.46	0.22	9406.58
96% Pb Poly shielding	92.33	90.8	32.9	86.35	84.26	0.41

Table 2. Template verification using low-resolution gamma spectra. The table values are the reduced chi-square statistic for the object spectrum compared to the template. Green, low values indicate a good match. Red, high values indicate a large difference between the two measurements.

The above is an example of using good quality data to assess analysis algorithms. In addition to this, as described, it is important to develop models which can be benchmarked against experimental data. This has been done using MCNP (Monte Carlo N-Particle) modelling (Werner et al, 2018). The isotopic compositions of the fuel were provided by SCK.CEN at formation, this was aged using RadSrc (Hiller et al, 2013). The ages of the 79% and 96% fuel are 52.85 and 51.91 years respectively. When the Ultra THG Identifinder is modelled in the correct environment the result is shown in Figure 4 compared to the measurements made during the campaign. The good comparison seen between the model and measured data gives confidence in using this model for future verification purposes.

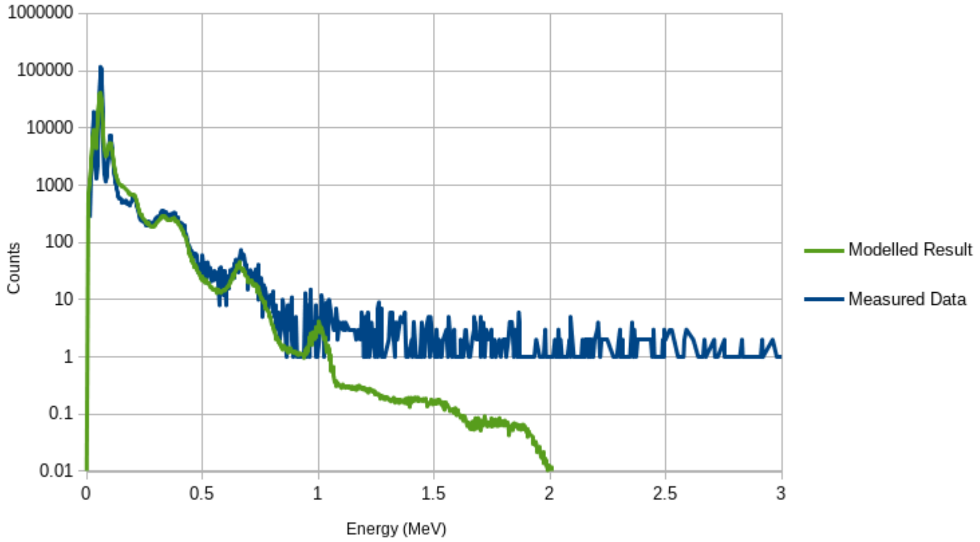

Figure 4. Comparison between MCNP modelled data and measurement for 79% bare fuel.

Neutron results and application

The $(ND)^2$ is a He^3-based, rugged, portable and established detector, developed at AWE. Each detector panel consists of four tubes of He^3 surrounded by high density polyethylene – three panels were fielded stacked vertically for the neutron measurements, as shown in Figure 1. The detector measures thermal neutrons, both gross counts and list mode data.

The gross count results from the $(ND)^2$ can be found in Table 2. The measurements were taken at 30 cm from the source with a measured background rate of 68.7 counts per second (cps). Measurement time ranged between 30 and 85 minutes. The 79% Pu-239 fuel pins have significantly more neutron counts than the 96% Pu-239 fuel pins, for any of the shielding configurations. As expected, the lead and polyethylene shielding configuration causes a significant reduction in gross counts for both fuel pin types.

	96% Pu-239 Fuel (cps)	79% Pu-239 Fuel (cps)	MCNP Model of 79% Fuel	Error (%)
No shielding	395.74	958.36	1070.56	11.71
Cadmium shielding	414.33	968.01	1096.74	13.30
lead and poly shielding	319.48	769.6	799.83	3.93

Table 3. Background subtracted simple neutron count results obtained using the $(ND)^2$ and MCNP modelled results for 79% Pu-239 fuel with difference to the experimental value (%).

The use of modelling is inevitable when planning for treaty verification. By using a detector response function for the $(ND)^2$, the IPNDV Measurement Campaign set-up can be modelled. Using well-documented data, such as that from this campaign, for validation gives confidence in models which may be used for verification purposes in future. Table 2 shows the good comparison found between a model using MCNP and experimental data for the 79% Pu-239 fuel pins.

In order to allow flexibility, the model can be split into two, allowing the detector and environment to be modelled separately. This is done by forming a detector response function for the technology being used and, once this has been validated against measured data, allows predictions to be made of measurements in other treaty scenarios.

For example, if the IPNDV measurement campaign represented a real environment for a treaty, different detector positions could be evaluated. The counts per second for the detector, shown in Table 3, allows decisions to be made about how long measurements should be undertaken at 30 cm to achieve a certain level of certainty in a measurement. But if the host says that the detector must in fact be further away, at 2.5 m away, then how does that change the result. In the case of the IPNDV measurement campaign the effect of large objects in the room, such as the Sigma pile (a large construction of graphite bricks) might be expected to affect the result depending on where the detector and fuel are placed. Whilst back of the envelope calculations can be made, in order to have certainty modelling will be necessary as the effect of walls and other objects may well modify the neutron results.

	Normal Distance (cps)	**Detector 2.5m away (cps)**	**Corner of the room (cps)**
No shielding	1070.56	108.26	101.40
Cadmium shielding	1096.74	109.61	103.01
lead and poly shielding	799.83	60.11	56.20

Table 4 Prediction of effect of moving detector 2.5 m directly, as well as moving it the nearest corner of the room.

Table 4 shows the result of modelling these two new scenarios using the same MCNP environment. They would give those constructing a verification system a concrete prediction of how to proceed, deciding how long, for example, a measurement for bare 79% fuel should be made for if the distance is increased from 30 cm to 2.5 m. In this case to get the same counts as a 30 minute measurement at 30 cm would take almost 5 hours, a significant increase that would have implications for inspectors and hosts alike.

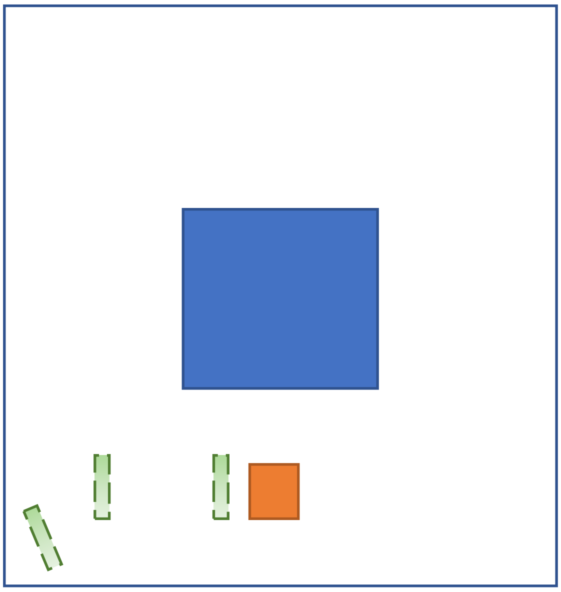

Figure 5. Simplified diagram of the IPNDV measurement campaign environment. The fuel assembly is in orange, with the three possible detector sites shown in green. The Sigma pile is shown in blue (not to scale).

Conclusion

Having good quality data, such as that gathered during this campaign, is useful in a plethora of ways to arms control. It can be used to assess the technologies being implemented, but also any analysis algorithms which may be required in a particular treaty scenario, as well as benchmarking modelling efforts to allow for flexibility in verification systems. The well-developed technologies explored in this paper of low-resolution gamma and gross neutron counts have been shown to be appropriate to certain verification systems. The possibility of using low-resolution gammas in a manner which gives confidence whilst also protecting information is shown using a radiation signature template matching method. Models for both gamma and neutron measurements have been benchmarked against this data and the consequences of limitations on the detector siting for neutrons has been explored.

References

C.J. Werner, et al., "MCNP6.2 Release Notes", Los Alamos National Laboratory, report LA-UR-18-20808 (2018).

Larry Hiller, Tom Gosnell, Jeff Gronberg, Doug Wright, “RadSrc Library and Application Manual”, Lawrence Livermore National Laboratory, report UCRL-TM-229497 (2013).