Zero Knowledge Warhead Verification: System Requirements and Detector Technologies

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Abstract

We have previously proposed a "Zero-Knowledge" approach to nuclear warhead verification that avoids the need for an electronic information barrier, since sensitive information is never stored electronically. The basic concept is to use a Zero-Knowledge Protocol to make differential transmission radiographs and neutron emission measurements, comparing templates with objects presented for verification. An array of non-electronic neutron detectors are preloaded by the host with counts that complement those that will be accumulated during measurement. Here we focus on the system requirements for this approach, and particularly on the detector technology. We find that at least two detector technologies should be able to meet these requirements: superheated drop ("bubble") detectors and neutron activation imaging. Bubble detectors will require a high density of small droplets to achieve the required total counts. An appropriate chemical formulation and good temperature control will be required for controlled energy selectivity. Magnetic resonance imaging or optical tomography may be used to count the dense array of bubbles produced. For transmission neutron activation imaging with 14 MeV neutrons, the ^{90}Zr(n,2n)^{89}Zr reaction has adequate efficiency and a convenient threshold of 12.1 MeV. It has a half-life of 3.27 days and emits a 909 keV γ. We have detected the presence of ^{95}Zr from the ^{96}Zr(n,2n)^{95}Zr reaction, which will require a particular preloading procedure to preserve zero knowledge. We have begun to analyze the requirements for emission measurements. The ^{115}In(n,n')^{115m}In reaction is well suited for detection of emitted neutrons from spontaneous and actively-driven fission. It has a half-life of 4.5 hours and emits a 336 keV γ. A ~250 keV neutron source would be attractive for discriminating between fissile and fissionable material in driven emission measurements. Such a source could be provided using the ^{7}Li(p,n)^{7}Be reaction, which has a threshold at 1.88 MeV and a resonance near 2.25 MeV.

1) Introduction

We have proposed[1] a new Zero-Knowledge approach to nuclear warhead verification that avoids the need for an electronic information barrier, since sensitive information is never stored electronically. The basic concept is to use a Zero-Knowledge Protocol to make differential transmission radiographs and neutron emission measurements, comparing templates with objects presented for verification. An array of non-electronic neutron detectors is preloaded by the host with counts that complement those that will be accumulated during measurement. The desired result of the transmission measurements added to the preloads can be chosen to equal a pre-agreed number, N_{max}, for example equal to the number of counts that would be observed in the absence of any object in the neutron flux (figure 1).

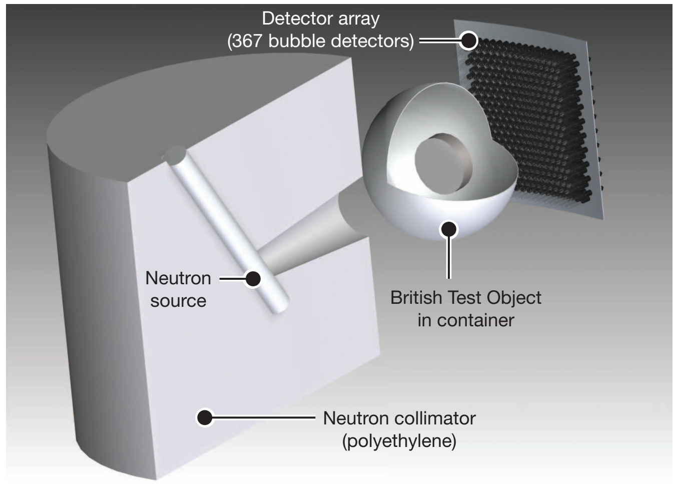

Figure 1: Configuration of 14 MeV DT neutron source, test object and transmission array. We plan to work with a "British Test Object" (BTO). (Side-located emission detectors are not shown.)

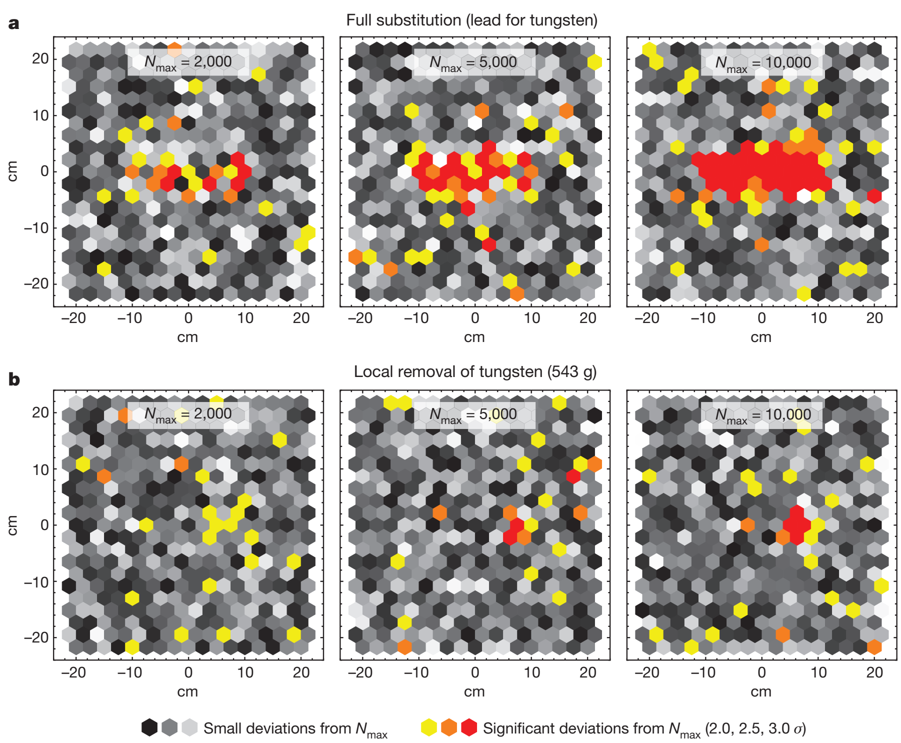

Figure 2: Increasing sensitivity of transmission measurement with larger diversion and higher number of counts per detector. BTO viewed side-on.

If the preload is provided with Poisson noise, even the noise in the final measurement will contain no information. Crucially, the inspector selects which array(s) of detectors will be placed behind the template(s) and which behind which test object(s), so a dishonest host cannot successfully cheat by preloading arrays with the complements of invalid objects.

In the case of a mismatch between the object and its preloaded array, the counts will vary from N_{max}, but this variation will potentially be lost in statistical noise unless sufficient counts are accumulated (figure 2). For one diversion scenario considered in (1) we found that 32,000 counts per detector were required to achieve false positive and false negative rates of 5% each. This was with a relatively small diversion, a 36^{o} sector of tungsten was replaced with lead in the BTO. There was also no optimization of the test for non-Poisson results, and no use of emission detectors. Nonetheless, this gives a qualitative sense that the total counts, N_{max} (= preload + transmission image) that may need to be accumulated are in the range of five thousand to tens of thousands. Since it will be a major challenge to reduce systematic variations in reproducibility substantially below 1%, this may also be an upper limit on the practical accuracy of the measurement.

2) System Requirements

There are a number of requirements on the non-electronic neutron detectors that can be used for this application. Transmission detectors located behind the test object (figure 1) are used to perform Zero-Knowledge differential neutron radiography, while emission detectors, located to the sides of the test object, are used for Zero-Knowledge differential measurement of both spontaneous and driven fission neutron production, without any attempt at imaging.

- Transmission detectors must be capable of preloading with 5 – 10’s of thousands of counts
    - The preload must persist for at least hours or days
    - The preload must be undetectable by the inspector
    - Preloaded counts must be indistinguishable from counts accumulated during irradiation of templates and test objects
- Transmission detectors should be insensitive to spurious signals
    - Energy threshold ~ 10 MeV is required to minimize effects of room-return neutrons
    - Detectors should be insensitive to γ’s to avoid fogging
- Transmission detectors should have good efficiency for neutron detection
    - For our geometry, 0.25% absolute efficiency corresponds to ~20,000 counts/hr for a 14 MeV DT neutron generator producing 3 10^{8} n/sec
- Emission detectors should be capable of preloading with counts up to thousands, since they can be ganged together, as imaging capability is not required.
    - Other preloading requirements are the same as for transmission detectors
- Emission detectors should be insensitive to spurious signals
    - ~ 500 keV threshold and local shielding to minimize effects of thermal and room-return neutrons
    - Detectors should be insensitive to γ’s
- Emission detectors should have good efficiency for neutron detection
    - More work is needed to determine the required sensitivity for both spontaneous and driven neutron emission.

For any detectors, systematic measurement errors must be very well understood, such that while one detector may be characterized by a different efficiency than another, which can be calibrated out, this efficiency must not vary between the preload and the measurement processes.

There are also a number of requirements on the neutron generators that are used for irradiation.

- 14 MeV is a desirable energy for transmission measurements, since it is highly penetrating and essentially no fission neutrons are produced at this energy range.
    - Total n/sec should equal or exceed 3 10^8/sec
    - Total neutron flux should be highly reproducible
    - Neutron source spot size and shape should be highly reproducible
    - Overall neutron field should be highly reproducible
- ~ 250 keV is a desirable energy for driving fission for emission measurements, since it would provide good penetration and strong discrimination between fissile and fissionable materials
    - More work is needed to determine the required neutron production rate
    - Total neutron flux should be highly reproducible
    - Requirements on neutron field may be relaxed compared with 14 MeV neutrons

Finally, there are requirements on the room and the "rigging" for the tests.

- Neutron scattering in the room should be minimized and reproducible – including in the sense that results must be replicable in multiple locations
    - This suggests the use of borated polyethylene wall cover
- The room should be very well temperature controlled
    - All systems, but in particular bubble detectors, are temperature sensitive
- Alignment of the neutron source, collimators, test object and detectors must be precise
    - In order to avoid shadows in differential transmission measurements, alignment must be much more precise than detector dimensions

3) Superheated drop "bubble" detectors

In superheated emulsions, neutron recoil particles trigger the formation of macroscopically observable bubbles from microscopic droplets that are dispersed in an inert matrix[2]. These detectors can be configured to have essentially any desired energy threshold from 10 keV to 10 MeV (Figure 3). However the energy threshold of the bubble detectors is sensitive to ambient temperature, so for precise control of their detection efficiency good temperature control will be required. Bubble detectors can easily be configured to be insensitive to γ's (figure 4).

Commercially available, polymer-based bubble detectors are limited to a maximum bubble count of the order of a few hundred bubbles, beyond which camera-based imaging techniques cannot resolve bubbles individually. By contrast, superheated drop detectors produced with an aqueous gel can be used up to much higher bubble counts. Either optical tomography or magnetic resonance imaging allow the counting of bubbles hidden in the depth of the fluid[3,4] (figure 4). If the highest N_{max} is desired, multiple detectors can be exposed in series. It would also be straightforward to pull back the detectors from the configuration shown in figure 1, such that the volume of each detector would grow for the same coverage of solid angle, increasing its bubble capacity.

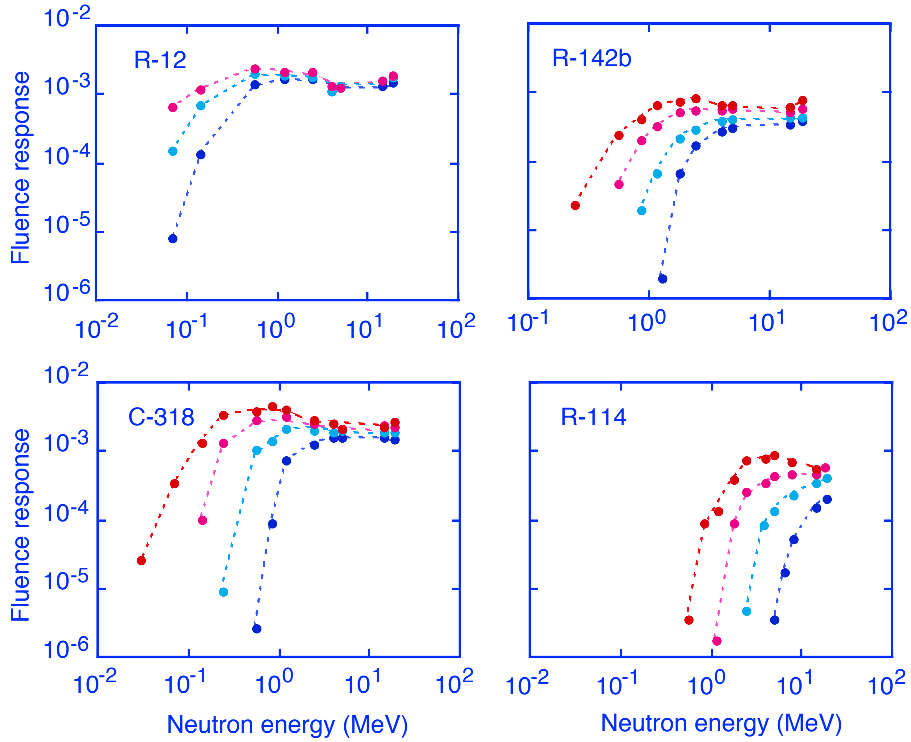

Figure 3: Fluence response of various superheated emulsions vs. temperature[2] at 25C, 30C, 35C and 40C (higher temperature gives lower energy threshold). Fluence response = bubbles/(n/cm^2). This parameter is dependent on detector geometry.

Figure 4: CT scan of detector exposed to 1 Gy of 6 MeV γ rays (left). CT scan of same detector exposed to 2.5 mSv of AmBe neutrons (right).

Commercial bubble detectors exhibit visible increase in bubble size over even short periods of time ~24h. By the proper choice of a compliant matrix visible growth of bubbles can be eliminated. In order to assure the Zero-Knowledge feature of this technique, it will be necessary to perform further research to demonstrate that information about bubbles that will be measured and stored electronically in the bubble counting process will reveal no information about bubble age, through subtle effects. The bubble detectors themselves can be verifiably destroyed after they have been read out.

Net detection efficiency greater than 1% can be easily achieved. The emulsions can be contained in opaque containers so that a preload is not visible to the inspector.

4) Neutron activation imaging

An alternative approach for 14 MeV neutron imaging is to deploy an array of activation "slugs", such as short cylinders made of zirconium[5] at the image plane. ^{90}Zr has a neutron activation threshold of 12.1 MeV through an (n,2n) reaction, providing excellent discrimination against room return. The resulting ^{89}Zr has a half-life of 3.27 days, which must be taken into account to determine the required level of preloading. Counting the γ-rays from ^{89}Zr decay in high-purity germanium well detectors is estimated to give an absolute detection efficiency of about 0.24% for 14 MeV neutrons impinging on the front surface of the detectors. For 3 cm long cylinders, with diameter of 1.6 cm, this would provide an N_{max} in the range of 20,000 per hour, for a commercially available DT neutron generator producing 3 10^8 n/sec[6] at a distance of 1.5m.

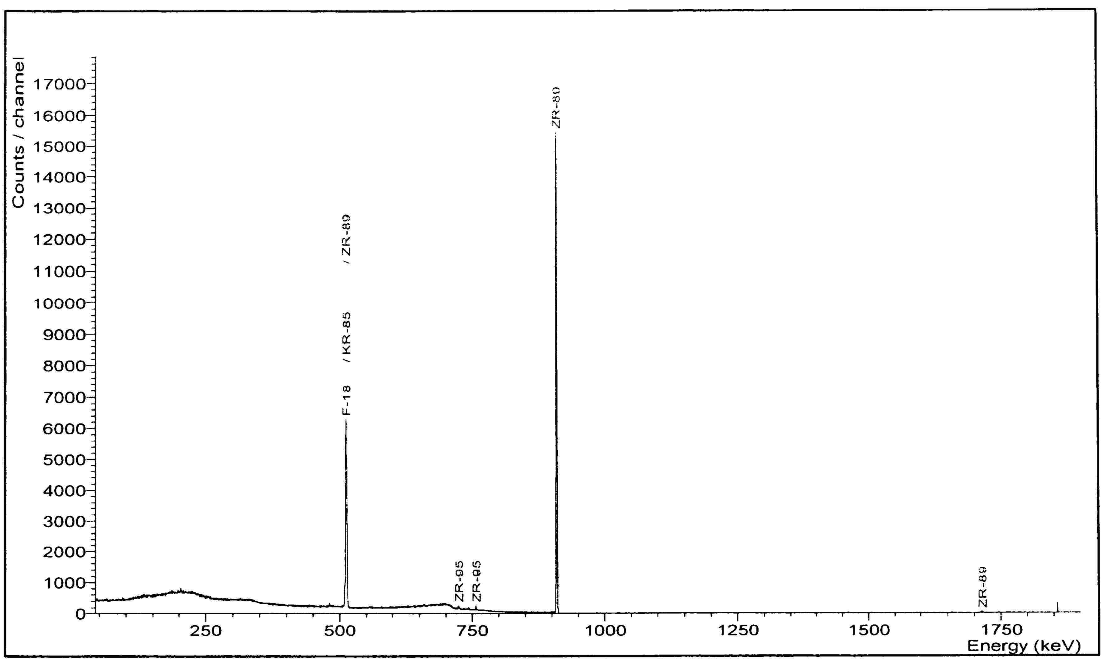

Figure 5. HPGe γ spectrum from Zr slug exposed close to 14 MeV neutron source. Total counts above background in uniquely identified ^{89}Zr lines = 1.27 10^5. Total counts above background in ^{95}Zr lines = 1.32 10^3. Exposure time ~ 2.5 days, measurement time ~ 18 hours.

We have found that a small signal associated with ^{95}Zr arising from the ^{96}Zr(n,2n)^{95}Zr reaction is visible in the spectrum of a Zr slug exposed to 14 MeV neutrons, at about 1% of the activity level of ^{89}Zr (figure 5). ^{90}Zr is 51% of natural zirconium, while ^{96}Zr is 2.8%. Since the

64 day half-life of ^{95}Zr is much longer than the 3.27 day half-life of ^{89}Zr, one could be concerned that the ^{95}Zr signal could serve as an indicator for the amount of preloaded ^{89}Zr, if the inspector can estimate the time of preloading. However this can be avoided: the host and inspector can agree in advance to accept a preload with sufficient ^{95}Zr that it would provide, for example, twice the ^{95}Zr counts that would be expected to correlate with N_{max} ^{89}Zr counts accumulated during irradiation. This can be accomplished by over-exposing the activation slug by a factor of ~2 and then allowing the ^{89}Zr to decay to its originally desired initial value over ~3.3 days, while the ^{95}Zr decays much less to its new desired initial value.

In order to minimize the complexity associated with small features, we have begun to investigate activation using mono-nuclidic elements. In particular we find the reaction of mono-nuclidic niobium, $^{93}Nb(n,2n)^{92m}Nb$ (10.15d half-life, 934 keV γ, E_{th} = 9 MeV) reaction to be interesting[7]. The reaction $^{93}Nb(n,n')^{93m}Nb$ is competitive, but the half-life of ^{93m}Nb is 16.1 years, so its signal level should be negligible. Nb is calculated to provide ~ 2x greater absolute efficiency than Zr, compensating for the inconvenience of its greater half life.

The $^{115}In(n,n')^{115m}In$ reaction is well suited for detection of emission of neutrons due to spontaneous and actively-driven fission, using detectors located to the sides of the test object. It has a threshold of about 350 keV with reduced sensitivity in the range of 14 MeV. It has a half-life of 4.49 hours and emits a 336 keV γ. The parallel reaction in ^{113}In (a 4.3% component of indium), $^{113}In(n,n')^{113m}$, has a half-life of 1.66 hours and emits a 392 keV γ. The procedure described above for Zr slugs could be used in this case as well. However, because of its larger cross-section at low energy (figure 6)[8], ^{113}In may also be able to be "overcharged" into ^{113m}In using low energy neutrons to compensate for its shorter decay time. The same neutron generator that could provide these neutrons would also be an appropriate probe beam to stimulate fission in fissile, but not fissionable, isotopes providing a sensitive test for substitution of such materials. (See section 5.)

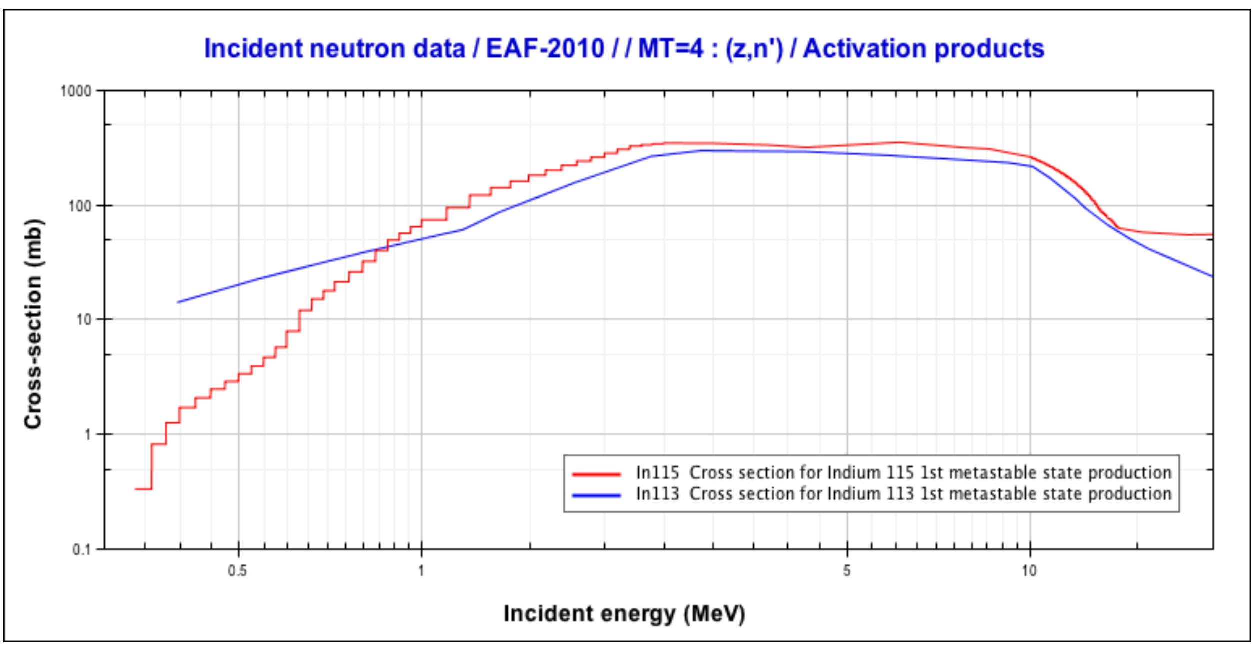

Figure 6. ^{115}In and ^{113}In neutron excitation cross-sections. (Graphics by JANIS, OECD-NEA)

It will be important to ensure that unshielded, preloaded activation slugs are not in the presence of γ-ray detectors before their final exposure, in order to avoid providing the inspector with any information about the preloads. Note that neutron activation imaging requires a large bank of γ detectors for each measurement "rig", and has certain intrinsic time constraints, since the preloads must be prepared with a specific time of use in mind. Thus this detector technology may not lend itself well to large-scale parallel testing such as envisioned by Kutt et al.[9], particularly if many preloads must be committed in parallel for use at different times.

5) Neutron generators (14 MeV and ~ 250 keV)

We find that a commercial 14 MeV DT neutron generator[6] which can produce 3 10^8 n/sec is quite compact and should be adequate for our experiments. However research will be required to determine the best means to achieve reproducibility of the total fluence, neutron field and originating spot size, as discussed in section 2.

It is interesting to consider the possibility of using ~ 250 keV neutrons to drive fission in test objects. Bubble detector energy thresholds can be set above this value, while still being sensitive to fission neutrons. Indium activation detectors can perform similar discrimination. What could be ground-breaking about this approach is that neutrons at this energy are quite penetrating, and at the same time are greatly more effective at driving fission in fissile than in fertile material (figure 7). The most efficient means to generate neutrons in this energy range is by the $^7Li(p,n)^7Be$ reaction. This reaction has a threshold at 1.88 MeV and a resonance at about 2.25 MeV. If 2.3 MeV protons are directed at a thick lithium target[10], the maximum energy neutron that can be produced is 573.1 keV and the mean neutron energy is 233.1 keV. 5.78 10^{11} neutrons are produced per mC of beam. The neutrons are somewhat forward directed, with mean angle 66.3^o.

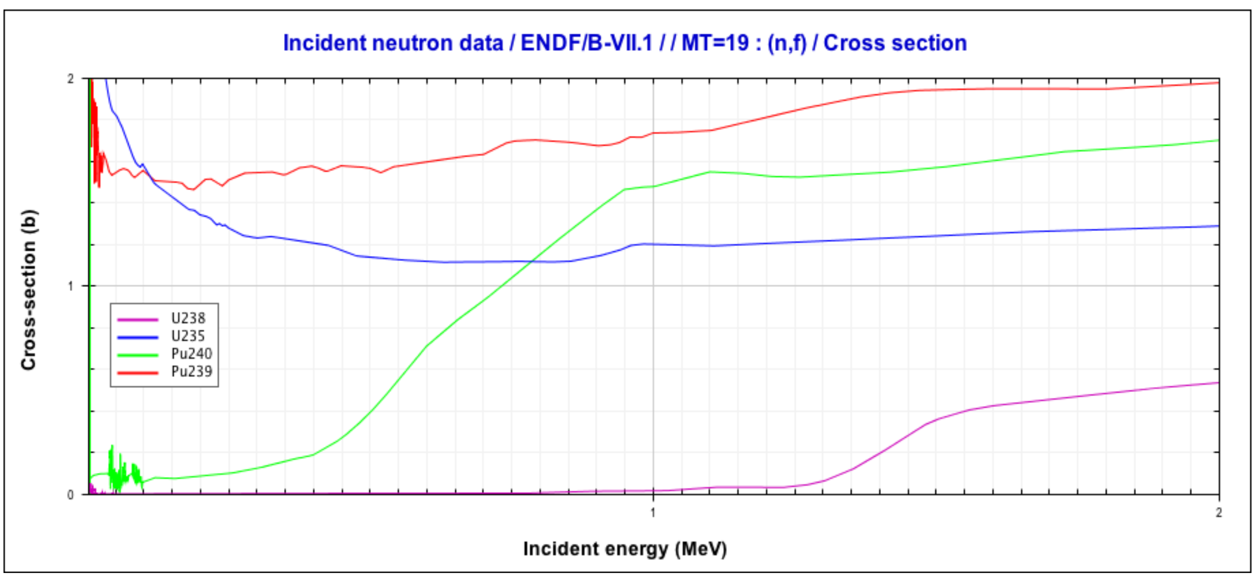

Figure 7: Fission cross-sections vs. energy in the low energy region, illustrating that ~ 250 keV neutrons are very sensitive to fissile vs. fertile materials. (Graphics by JANIS, OECD-NEA)

We are examining a number of options to produce 2.3 MeV protons including radio frequency quadrupoles, tandem electrostatic accelerators and small cyclotrons. Since work is only starting on examining means to measure spontaneous fission (which should be very sensitive to Pu-240) and to measure driven fission, the precise specifications for detectors and neutron sources are still being developed.

6) Room design

Room return neutrons may play a role in both transmission and emission measurements. While some room return is acceptable, it should not "fog" the transmission measurements making them insensitive to signal from the test object, nor should it direct too much probe beam into emission detectors. In general, it should not affect either transmission or emission measurements in an irreproducible manner.

It is not clear that load-bearing construction materials can be fully reproduced from one location to another, but it is clear that the host and inspector must have functionally identical systems – including the full neutron-reflecting environment. It seems attractive therefore to cover the walls of the test chamber with borated polyethylene to a depth that is sufficient to reduce any sensitivity to the underlying construction materials to low levels. Polyethylene itself should not vary in moisture content like construction materials. To understand the depth of coverage that may be required, we have calculated the reflection of 14 MeV neutrons from a borated concrete wall, covered with differing depths of borated polyethylene (Table 1).

5%-borated PE thickness (inches)	Fraction of incident neutrons reflected at >1 MeV	Fraction of incident neutrons reflected at >10 MeV
0	17.7%	3.4%
2	10.5%	1.9%
4	8.2%	1.6%
6	7.6%	1.6%
8	7.5%	1.5%

Table 1: Fraction of incident 13.7 MeV neutrons reflected from a borated concrete wall, shielded with varying thicknesses of 5%-borated polyethylene, above threshold energies of 1 MeV and 10 MeV.

As the borated polyethylene sheeting approaches 8" depth, "memory" of the underlying borated concrete wall is lost. Polyethylene is quite flammable, so special precautions will be needed in a room lined with this material, but this appears to be a viable first step toward providing a reproducible environment. Tests will required to demonstrate this.

7) Conclusions

Progress is being made in a number of areas towards defining the practical requirements for a Zero-Knowledge Protocol warhead verification system: neutron transmission detectors, neutron emission detectors, neutron generators both 14 MeV and ~250 keV, and environmental conditions. Bubble detectors will need to be improved compared to those that are commercially available, but they have high potential for this application. They bring with them necessity for precise temperature control. Neutron activation imaging is affected for this application by reactions that are present with decay times that differ from the reaction of interest. Good solutions appear available for both transmission and emission detectors, although more analysis and measurements will be required. An intriguing idea is being developed to use a ~250 keV neutron probe beam to discriminate between fissile and fissionable material. This has the further advantage that threshold neutron detectors can distinguish well between the probe neutrons and fission neutrons. Finally, we are making progress towards specifying the appropriate room environment to support the required reproducibility of results.

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