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# Novel neutron detection methods for nuclear security

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# Abstract

This report presents a comparison between conventional and novel neutron detection techniques in use or planned to be used at Nordic countries as well as developed by companies. The intercomparison measurements were performed at the Metrology laboratory of the Finnish Radiation and Nuclear Safety Authority using Cf-252 and Am/Be sources. The following organizations participated in the project:

- Lund University/Swedish Radiation Safety Authority
- Icelandic Radiation Safety Authority, GR
- Norwegian Radiation Protection Authority, NRPA
- Finnish Radiation and Nuclear Safety Authority, STUK
- MARS Project, Oxford University
- Arktis Radiation Detectors Ltd.
- FinPhys Oy
- Symetrica Security Ltd.

The count rates, absolute detection efficiencies and sensitivities are presented together with descriptions of the tested detectors. Maybe the most important result is the knowledge transfer between the Nordic countries in particular and the neutron detection community in general. Measurements sessions such as this are rare and the NKS NOVE project attracted international interest.

Prior to the measurements at STUK, a seminar was organized by GR in Reykjavík, Iceland. The outcome of the seminar (including field measurements) are included in an appendix to the report.

# Key words

Neutron detection

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## Final Report from the NKS-B NOVE activity (Contract: AFT/B(13)7)

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## 1. Introduction

Society can be threatened in various ways by RN (radioactive and nuclear) substances. Spreading them out at an urban area would, for example, cause panic and a lot of economical losses. Growing international crime enhances the possibility of illicit trafficking of RN materials and terrorism relying on them. Plutonium can be detected via neutrons that are generated in spontaneous fission. Neutrons are also emitted by the neutron-generators (for example Am/Be and Pu/Be) typically used in industry.

The detection of neutrons is based on either direct or indirect methods or their combination. Direct methods include, among others, fast neutron spectrometry and thermal neutron counting. Conventionally thermal neutron counting has been based on He-3 counters. Required He-3 gas is a side product of nuclear weapons fabrication. Due to the reduced weapons production and the increased need of neutron detectors for security applications He-3 counters are nowadays expensive. This has triggered a development of novel ways to detect neutrons.

One such indirect novel approach relies on the detection of high-energy ($E > 3$ MeV) gamma-radiation emitted by a neutron source or created by the neutrons in the surroundings (Holm et al, 2012). Since the natural background above 3 MeV is low, high-energy gamma-rays are a sensitive indicator of the presence of neutrons. The same spectrometer can simultaneously be used for the regular gamma-spectrometry ($E < 3$ MeV). This method has been shown to perform well with shielded sources and is in use in Finland. Other Nordic countries have also shown interest in it.

This report presents a comparison between conventional and novel neutron detection techniques in use or planned to be used at Nordic countries as well as developed by companies. The intercomparison measurements were performed in September, 2013, at the Metrology laboratory of the Finnish Radiation and Nuclear Safety Authority using well characterized Cf-252 and Am/Be sources. The following organizations participated in the project:

- Icelandic Radiation Safety Authority, GR
- University of Lund/Swedish Radiation Safety Authority
- Norwegian Radiation Protection Authority, NRPA
- Finnish Radiation and Nuclear Safety Authority, STUK
- MARS Project, Oxford University
- Arktis Radiation Detectors Ltd.
- FinPhys Oy
- Symetrica Security Ltd.

All organizations tested their own detectors except for NRPA. The measurement results of the GR detector and of the Arktis neutron detector are not included in this public report for various reasons.

The measurement results are presented together with descriptions of the tested detectors. Prior to the measurements at STUK, a seminar was organized by GR in Reykjavík, Iceland. The seminar and the results of these measurements are presented in Appendix A.

## 2. Detector descriptions

### 2.1 MARS handheld prototype based on 6LiF:ZnS(Ag)

The device tested is a handheld prototype for early detection and identification of sources aimed at security and safeguards applications. It is based on the MARS technology developed at Oxford University[1]. The handheld is a stack of 4 detector elements (figure 1.a.) read out by Hamamatsu MPPC model S10352-33-050C. Each detector element is composed of PMMA and layers of $^{6}$LiF:ZnS(Ag) mixture. The stack of active detector element is surrounded by moderator material (High Density Poly-Ethylene) of 0.5 cm (top, bottom) and 1 cm (sides, front and back). The front face of the detector is 17 cm x 5.5 cm and the active volume 420.75 cm$^3$. A custom electronics front-end board called DEIMOS ensures voltage supply to the MPPC and pre-amplification of the four channels signal in the tens of millivolt range. Digitisation of the signal is performed by a picoscope 5000 series connected to two of the four channels at any one time. A simple OR logic and channel threshold triggering is programmed in the picoscope software to record waveforms. Counts per second are determined using a offline analysis code that use a pulse discrimination algorithm to identify neutron events. An overview of the set up is shown on Figure 1.b.

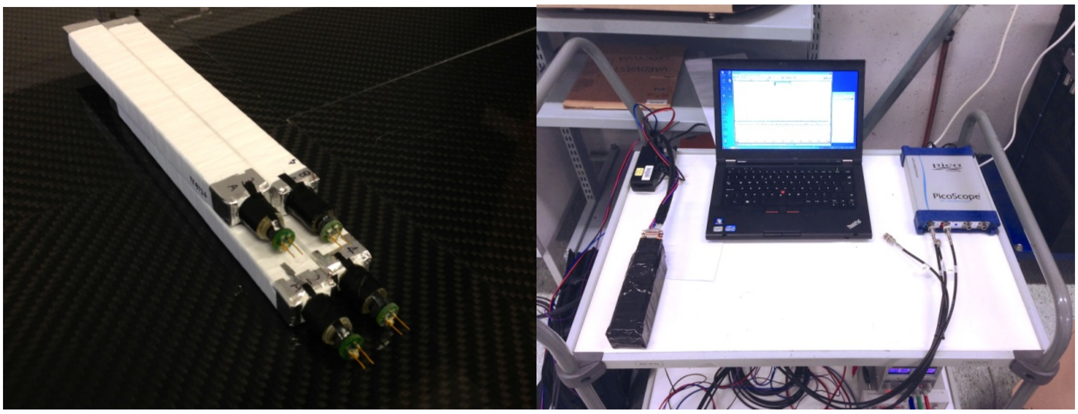

**Figure 1.a.** MARS detector elements. **1.b.** Set up used for the NOVE tests. MARS handheld is shown on the left with picoscope (right) and acquisition PC (center).

The system is at a very early stage of development and not yet in a portable format, the goal of the test is to understand better the sensitivity of the current design. An important aspect of the test is the fact that all the measurements where made without a phantom to measure the "bare" neutron efficiency. The data collected will be used to give a reliable reference in neutron efficiency for the Monte Carlo simulation and the optimisation of the next iteration on the design.

[1] http://www2.physics.ox.ac.uk/research/mars-project

### 2.2 Symetrica neutron detectors

The Symetrica neutron detectors use neutron-sensitive $^6$Li/ZnS(Ag) screens coupled to wavelength shifting plastic, as illustrated in Figure 2.

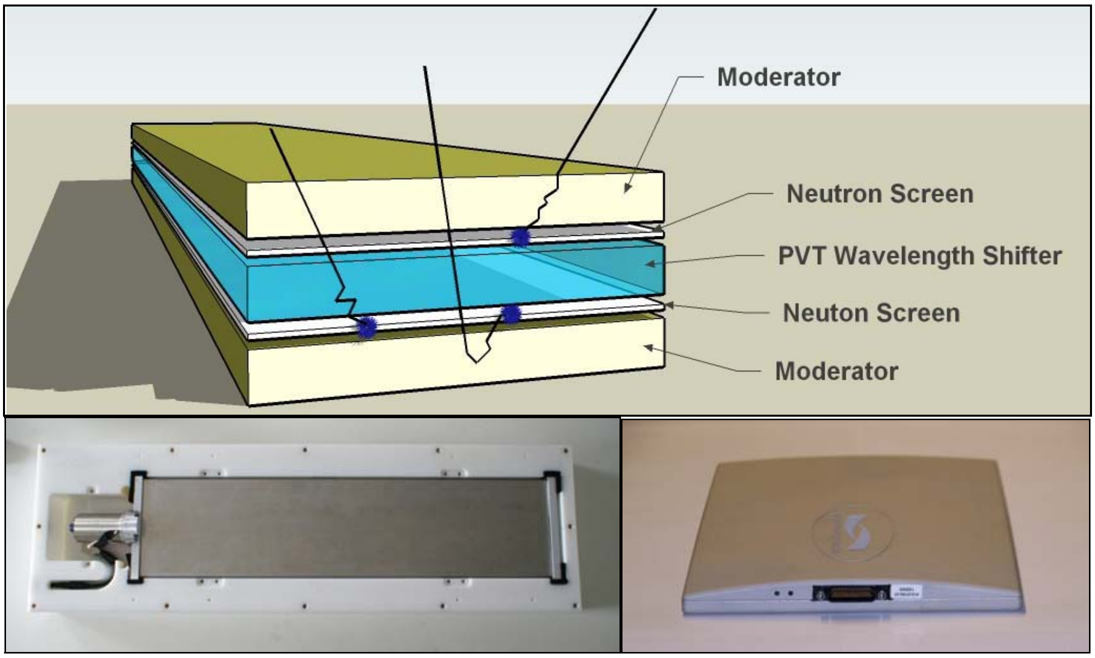


**Figure 2. a.** A schematic diagram showing the typical construction of a Symetrica neutron detector. **2.b.** The NNS:2000 neutron detector element. **2.c.** The NNS:FP miniature sensor.

The $^6$Li/ZnS(Ag) screens serve as the neutron absorber and phosphor. Thermal neutrons, captured by the $^6$Li(α,n)$^3$H reaction, generate charged particles that produce scintillation in the Zinc sulphide. This scintillation stimulates emission in the wavelength shifter and this light is conducted to a photo detector. In applications where size is not critical photomultipliers are used. In compact systems, low power solid state photo-detectors are used to enable miniaturisation.

Two detectors were submitted for testing;-

- NNS:2000 – a detector module designed for cargo and mobile applications with a detection area of 1740cm$^2$ encased in a moderator of outside dimensions 113cm x 35cm x 13cm. To provide a balanced sensitivity to differing neutron energy spectra the moderation in front and behind the detector has been set to 2.5cm and 6.5cm respectively.

- NNS:FP – a miniature planar detector module designed for wearable applications with a detection area of approximately 280cm$^2$, a solid state optical readout and no external moderator. The total thickness of the detector is approximately 15cm. The measurements were performed with the detector in front of a torso phantom.

Each detector contains an electronics module that processes the signals to provide a neutron (and gamma) count rate. These electronics packages also have the capability to provide real-time health monitoring and feedback on their intrinsic sensitivity. During performance testing the TTL pulses output by the instruments were recorded.

## 2.3 STUK's neutron detectors

### RanidPORT portal monitor

The RanidPort portal monitor (Figure 3) is a radiation detector system manufactured by Environics Oy. The detector contains a 4 l NaI(Tl) detector (4"x4"x16") surrounded on three sides with polyethylene (PE) and PVC. The energy range is up to 8 MeV, enabling neutron source detection by high-energy (>3.5 MeV) photons (Holm et al, 2012). The MCA uses 2048 channels and thus the wide energy range does not prevent normal gamma spectrometry. The PE and PVC acts as neutron moderators. The chlorine in the PVC also emits high-energy photons in neutron capture reactions ($\sigma(n,\gamma)$ for $^{35}Cl$ is 44 b at E=0.025 eV (ENDF/B-VII.1)). The detector system measures and analyses the data in real-time with an integration times of 1 s, 10 s and 100 s. The data is stored in a local LINSSI database and can also be transferred to a remote database.

**Figure 3.** RanidPort portal monitor.

### Pikkupoika and Läski

Pikkupoika and Läski (Figure 4) are gamma spectrometers with cylindrical 1 l NaI scintillators. 2048 channel Canberra Osprey MCA's are used and the detectors are operated in the same high-energy mode as the RanidPORT system. The prototype detectors are surrounded with 4 cm of PE neutron moderator. The front side is not moderated to preserve normal gamma spectrometry abilities.

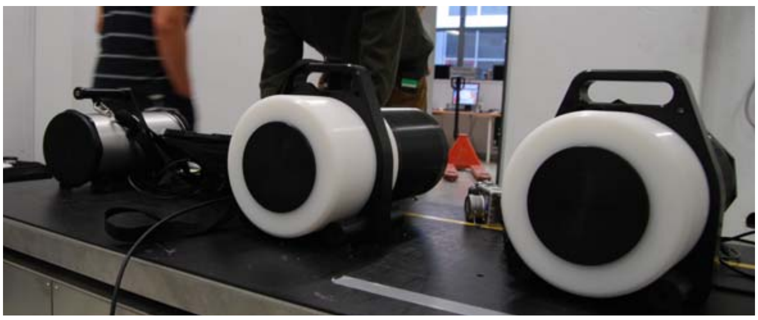

**Figure 4.** Pikkupoika and Läski NaI spectrometers on the right and BLASTER on the left.

### Vasikka backpack

The Vasikka backpack (Figure 5) is a radiation backpack developed in STUK and commercialized by Environics Oy (RanidPro200). It contains a 1.5”x1.5” $LaBr_3$ detector coupled to a 2048 channel Canberra Osprey MCA and a BC702 lithium based thermal neutron detector. The energy range of the Osprey goes up to about 5 MeV for neutron source detection. The backpack stores radiation measurement and GPS data in a local database with integration times of 4 s, 40 s and 400 s. The data is stored in a local LINSSI database and can also be transferred to a remote database.

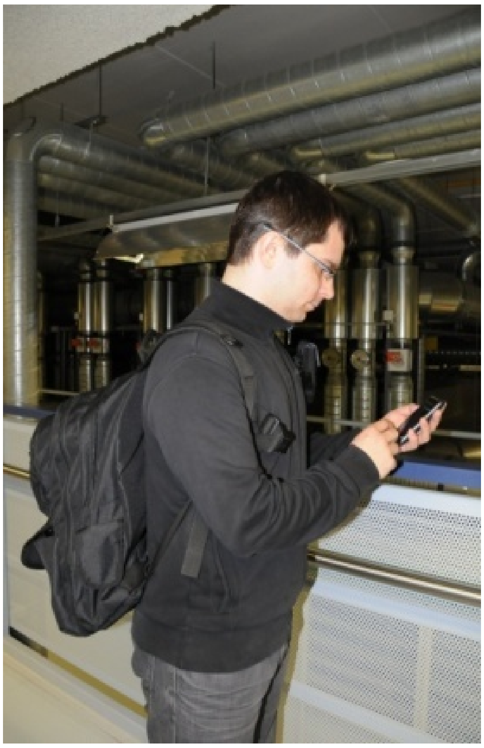

**Figure 5.** The Vasikka backpack, monitored with a smartphone.

### BLASTER

The BLASTER (Boron-Loaded Attenuated SpectromeTER) consists of a boron-loaded plastic scintillator coupled to a photomultiplier tube and a Canberra Osprey MCA (Figure 4). The MCA is operated in list-mode, and coincidence pulses are looked for. The coincidence pulses are caused by fast neutrons that thermalize by scattering with hydrogen (first pulse) and then get captured by the boron (second pulse). The scintillator is shielded with lead to minimize the amount of random coincidences caused by gamma radiation. In addition to the fast neutron coincidence signal, the detector also uses the high-energy (3.5 MeV – 5 MeV) singles spectrum and the neutron capture peak to detect neutron sources.

### 2.4 University of Lund neutron detectors

**3’’ x 3’’ NaI(Tl)**

The 76.2 mm diameter by 76.2 mm length NaI(Tl) detectors are mainly used in backpack systems for mobile measurements in the Swedish radiation protection organization. The detectors are relatively cheap and quite robust due to them being packed in aluminum tube which provides thermal and mechanical protection. Their widespread use makes it relevant to test them with regards to sensitivity to high energy gamma photons from neutron sources.

**3’’ x 3'' LaBr3:Ce**

A possible future alternative to 3’’ x 3’’ NaI(Tl) detector are LaBr3:Ce detectors with the same dimensions. They provide superior intrinsic efficiency and energy resolution. The drawback of LaBr3:Ce based detectors are their high price. Although these detectors are internally contaminated, this is not a problem when searching for high energy gamma photons from neutron sources as the pulse height distributions measured with LaBr3:Ce detectors does not have any pulses with an origin from the internal contamination above 3 MeV.

**4l NaI(Tl)**

4l NaI(Tl) detectors are mainly used in car borne and airborne measurement systems. Their large size results in a detector with excellent efficiency for measuring radioactive sources of low activity or high activity sources from long distances. This makes these detectors relatively well suited for measuring high energy gamma rays from neutron sources or prompt gammas caused by neutron radiation. To increase the sensitivity to neutron radiation, the detector was used together with a PVC moderator large enough to enclose the detector on 6 sides with up to 10 cm PVC. The electronics package used with this detector is the ORTEC DigiBASE.

**3 tube He-3 based n-detector**

This detector is intended for use in conjunction with a car or airborne gamma spectrometry survey system. It is for this reason built with high sensitivity in mind. The detector consist of 3 Helium-3 tubes of with a length of approximately 84 cm and a diameter of approximately 4.5 cm. The tubes are enclosed in a box constructed out of 1 cm thick polyethylene sheets.

As the detector is intended for mobile use, its electronics package makes 1 second long measurements which has to be summed afterwards to yield a long term measurement if used when stationary.

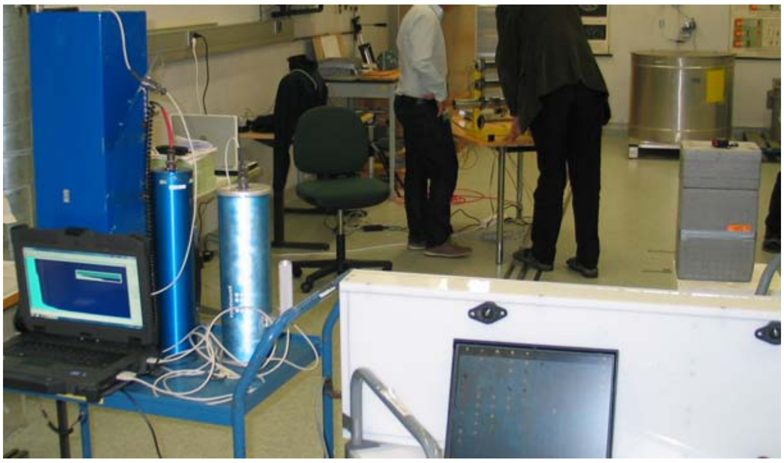

**Figure 6.** From left to right: 4 l NaI(Tl), 3”x3” detectors and He-3 based detector (white box).

## 2.5 Arktis' Extended Range Neutron Detector

Most commonly deployed neutron detectors (such as He-3, Lithium-6 or Boron-10 lined detectors) are primarily sensitive to thermal neutrons, i.e. neutrons with energies of the order of 0.025 eV. For these detectors to be sensitive to neutrons in the MeV region (the typical emission energy for neutrons coming from fission sources), the incoming neutrons need to be slowed down. During this process, called moderation, information about original neutron energy or precise time of arrival is lost. Furthermore, moderation aligns all incoming neutrons to an energy region where neutrons coming from different sources, including background, are not easy to distinguish.

Arktis' noble gas based fast neutron detectors can directly detect neutrons without the need of a moderator. This allows identification of neutron sources and reduction of the background by selection of the region of interest. In addition, when combined with fast sampling digitizers, precise timing information allows studying time correlation (specific feature to detect special nuclear material (SNM)), and time-of-flight measurements.

A new detector (Figure 7) was developed which includes a $^{6}$Li-based neutron converter layer. Applying this allowed to keep the fast neutron detection efficiency the same, while extending the sensitivity also to thermal neutron detectors.

**Figure 7.** Arktis' extended range neutron detector.

Neutrons and gammas interacting in the He-4 gas produce scintillation signals with different pulse shapes. Figure 8 shows the trace of a gamma event and a fast and thermal neutron event (amplitude versus time of arriving). While in gamma events most light arrives in the first few nanoseconds, the signals of neutron interactions are of substantially longer duration. The differentiation and clear allocation between fast and thermal neutrons, and gammas, is performed based on their different pulse shapes (See Figure 9).

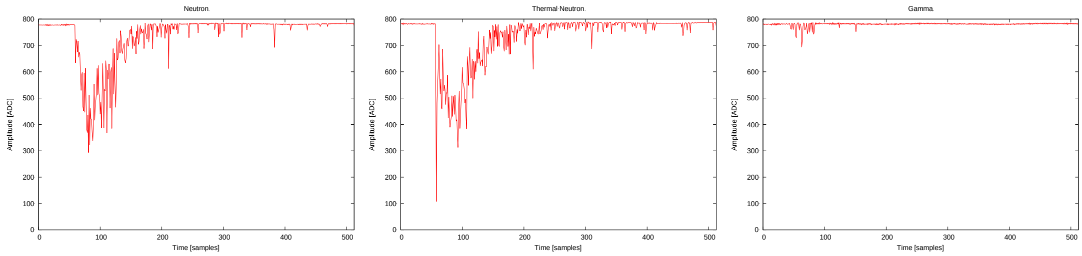


**Figure 8.** Pulse shape (amplitude vs time) of fast (left) and thermal (middle) neutron interactions as well as gamma interactions (right).

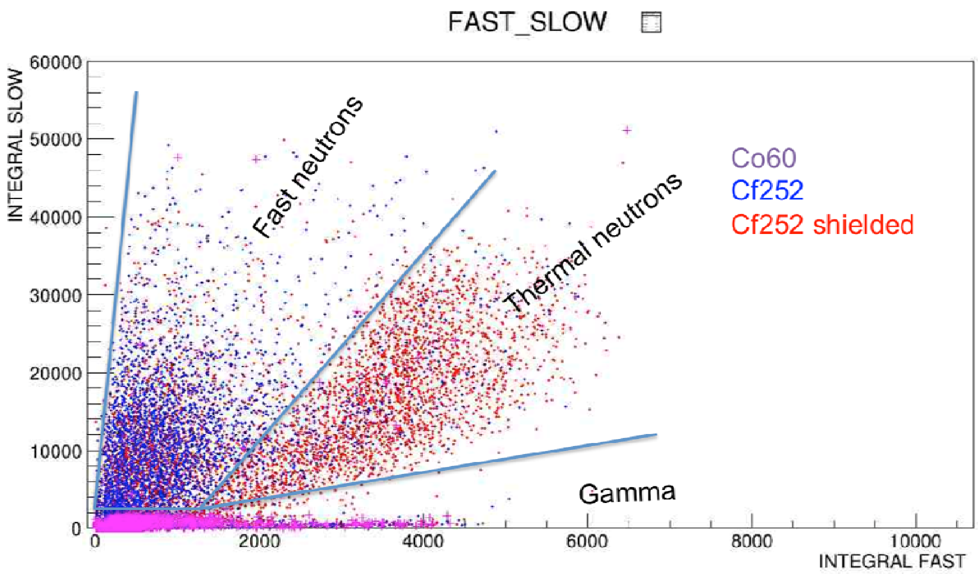


**Figure 9.** Fast neutrons, thermal neutrons, and gammas can be discriminated in the detector with a method based on their different pulse shapes.

### 2.6 Finphys Oy neutron sensor

FinPhys Oy tested a boron based solid state neutron sensor prototype with an active area of 1.0 $cm^2$. The efficiency of the sensor is improved by using a 3D structure in the sensor.

## 2.7 GR's IEMC radiation backpack

GR contributed with an IEMC radiation backpack[2] (Figure 10). The backpack contains five 5 cm x 32 cm He-3 tubes (total volume 3140 $cm^3$, pressure 2.8 atm) on one side and a NaI detector and electronics on the other side. The backpack is designed for "low profile, large area radiological searches and surveys"[2]. It measures both neutron and gamma radiation continuously with a given sample rate. The background is measured and alarms are given automatically. The detector system performed as expected from a system of this type, but the measurement results could not be published within this report.

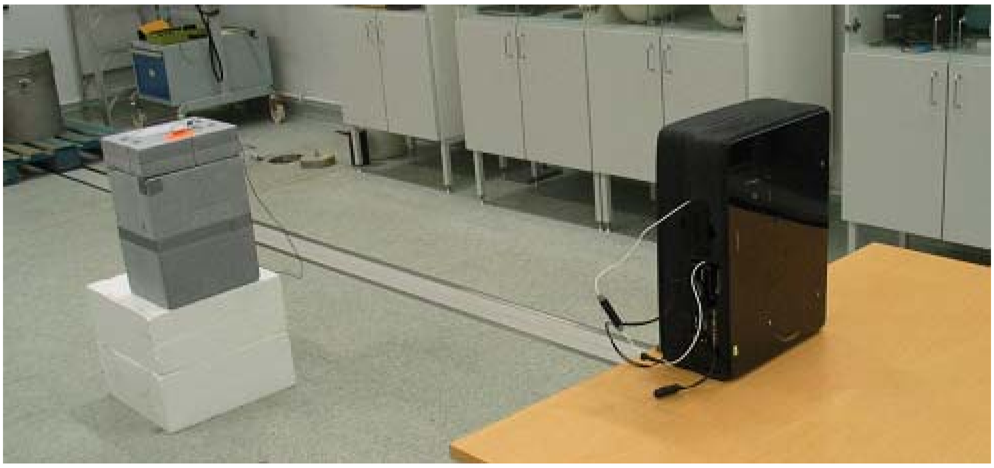

**Figure 10.** IEMC radiation detector system.

[2] Radiation Backpack User Guide, U. S. Department of Energy, International Emergency Management and Cooperation, 2012.

## 3. Experimental

The measurements were performed with the source in the centre of the measurement hall and the detectors placed around it. The measurement setups are presented in Table 1. Half-life corrected nominal neutron source emission rates given by the source manufacturers were used in the calculations. The actual emission rates may deviate from the nominal rates, however, these systematic errors are not included and not relevant in a relative comparison of the tested detectors. Several detectors were measured simultaneously and the different positions of the detectors most likely influence the result due to different amounts of scattered neutrons. The extent of this effect is not estimated in the present calculations. NaI and $LaBr_3$ scintillators are activated while in the neutron flux. This can cause a slightly higher background count rate. For this reason, background measurements were performed both before and after the measurements.

**Table 1.** Measurement setups.

| Setup name | Description |
|---|---|
| Setup 1a | No source shield. Source height from floor 94 cm. |
| Setup 1b | 3 mm Pb source shield. Source height from floor 94 cm. |
| Setup 1c | 8 mm Pb source shield. Source height from floor 94 cm. |
| Setup 2 | 3 cm Pb source shield. Source height from floor 94 cm. |
| Setup 3 | 10 cm Pb source shield. Source height from floor 33 cm. |
| Setup 4a | 14 cm PE source shield. Source height from floor 94 cm. |
| Setup 4b | 3 mm Pb and 14 cm PE source shield. Source height from floor 94 cm. |
| Setup 5a | 50 cm borated PE source shield. Source height from floor 46 cm. |
| Setup 5b | 3 mm Pb and 50 cm borated PE source shield. Source height from floor 46 cm. |
| Background 1 | Laboratory background |
| Background 2 | Laboratory background (after measurements) |
| Background 3 | Control room background |

**Table 2.** Neutron sources.

| Source | Activity [Bq] | Neutron emission rate [1/s] |
|---|---|---|
| $^{252}Cf$ 1 | $2.44 \cdot 10^{6}$ | $2.79 \cdot 10^{5}$ |
| $^{252}Cf$ 2 | $1.44 \cdot 10^{7}$ | $1.67 \cdot 10^{6}$ |
| AmBe 1 | $1.05 \cdot 10^{10}$ | $7.95 \cdot 10^{5}$ |
| AmBe 2 | $3.49 \cdot 10^{10}$ | $2.25 \cdot 10^{6}$ |
| AmBe 3 | $1.75 \cdot 10^{11}$ | $1.39 \cdot 10^{7}$ |

## 4. Results

### 4.1 Neutron source measurements

The measurement data is presented detector wise in the following tables. The net signals are dead time and background corrected. The count rate uncertainty consists of one sigma statistical uncertainty. In addition to the statistical uncertainty, a source-detector distance uncertainty of ±2.5 cm is assumed in the absolute efficiency uncertainty calculation. The uncertainties are given in parentheses containing the uncertainty of the last digit. The background count rates marked with bold text were subtracted from the gross signals.

**Table 3.** STUK RanidPORT (4 l NaI) measurement data.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 1.276(5) | | |
| Background 2 | **1.63(6)** | | |
| Background 3 | 1.872(6) (Detector activated) | | |
| Setup 1a ($^{252}$Cf 1) | 104.8(4) | $3.8(1)\cdot10^{-4}$ | 0.87(2) |
| Setup 2 ($^{252}$Cf 1) | 104.4(5) | $3.7(1)\cdot10^{-4}$ | 0.87(2) |
| Setup 3 ($^{252}$Cf 1) | 98.8(5) | $3.5(1)\cdot10^{-4}$ | 0.82(2) |
| Setup 4a ($^{252}$Cf 1) | 31.2(2) | $1.12(3)\cdot10^{-4}$ | 0.258(7) |
| Setup 5a ($^{252}$Cf 2) | 16.5(1) | $9.9(3)\cdot10^{-6}$ | 0.0229(7) |
| Setup 1a ($^{252}$Cf 2) | 637(1) | $3.8(1)\cdot10^{-4}$ | 0.88(2) |
| Setup 1b (AmBe 1) | 395.1(8) | $5.0(1)\cdot10^{-4}$ | |
| Setup 2 (AmBe 1) | 308(1) | $3.9(1)\cdot10^{-4}$ | |
| Setup 3(AmBe 1) | 254.5(7) | $3.20(8)\cdot10^{-4}$ | |
| Setup 4b (AmBe 1) | 230.3(7) | $2.90(7)\cdot10^{-4}$ | |
| Setup 5a (AmBe 1) | 49.2(4) | $6.2(2)\cdot10^{-4}$ | |

**Table 4.** STUK Läski (1 l NaI) measurement data.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 0.516(3) | | |
| Background 2 | 0.48(4) | | |
| Background 3 | **1.102(4)** | | |
| Setup 1a ($^{252}$Cf 2) | 122.02(4) | $7.3(2)\cdot10^{-5}$ | 0.169(4) |
| Setup 2 ($^{252}$Cf 2) | 130.4(4) | $7.8(2)\cdot10^{-5}$ | 0.181(5) |
| Setup 3 ($^{252}$Cf 2) | 139.1(4) | $8.3(2)\cdot10^{-5}$ | 0.193(5) |
| Setup 4a ($^{252}$Cf 2) | 39.8(2) | $2.38(6)\cdot10^{-5}$ | 0.055(1) |
| Setup 1c (AmBe 3) | 1592(2) | $1.15(3)\cdot10^{-4}$ | |
| Setup 2 (AmBe 3) | 1233(1) | $8.9(2)\cdot10^{-5}$ | |
| Setup 3(AmBe 3) | 1126(1) | $8.1(2)\cdot10^{-5}$ | |
| Setup 4b (AmBe 1) | 56.6(2) | $7.1(2)\cdot10^{-5}$ | |

**Table 5.** STUK Pikkupoika (1 l NaI) measurement data.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 0.484(3) | | |
| Background 2 | 0.49(3) | | |
| Background 3 | **0.798(4)** | | |
| Setup 1a ($^{252}$Cf 2) | 104.4(3) | $6.3(2)\cdot10^{-5}$ | 0.145(4) |
| Setup 2 ($^{252}$Cf 2) | 109.7(4) | $6.6(2)\cdot10^{-5}$ | 0.152(4) |
| Setup 3 ($^{252}$Cf 2) | 107.7(4) | $6.5(2)\cdot10^{-5}$ | 0.149(4) |
| Setup 4a ($^{252}$Cf 2) | 35.5(2) | $2.13(6)\cdot10^{-5}$ | 0.049(1) |
| Setup 1c (AmBe 3) | 1373(2) | $9.9(2)\cdot10^{-5}$ | |
| Setup 2 (AmBe 3) | 1030(1) | $7.4(2)\cdot10^{-5}$ | |
| Setup 3(AmBe 3) | 838(1) | $6.0(2)\cdot10^{-5}$ | |
| Setup 4b (AmBe 1) | 52.8(2) | $6.6(2)\cdot10^{-5}$ | |

**Table 6a.** STUK BLASTER measurement data coincidence signal. The calculated random coincidence rate was used in the background subtraction.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] | Random coincidenc e [cps] |
|---|---|---|---|---|
| Background 1 | 0.0049(3) | | | 0.0023(1) |
| Background 3 | 0.0065(4) | | | 0.00181(9) |
| Setup 1a ($^{252}$Cf 2) | 8.5(1) | $5.1(2)\cdot10^{-6}$ | 0.0118(4) | **0.26(2)** |
| Setup 2 ($^{252}$Cf 2) | 9.7(1) | $5.8(2)\cdot10^{-6}$ | 0.0134(4) | **0.24(2)** |
| Setup 3 ($^{252}$Cf 2) | 9.3(1) | $5.6(1)\cdot10^{-6}$ | 0.0129(4) | **0.25(2)** |
| Setup 4a ($^{252}$Cf 2) | 0.871(3) | $5.2(2)\cdot10^{-7}$ | 0.00121(5) | **0.045(3)** |
| Setup 1c (AmBe 3) | 53.0(5) | $3.8(1)\cdot10^{-6}$ | | **7.9(4)** |
| Setup 2 (AmBe 3) | 57.7(5) | $4.2(1)\cdot10^{-6}$ | | **8.4(4)** |
| Setup 3(AmBe 3) | 64.9(6) | $4.7(1)\cdot10^{-6}$ | | **10.4(5)** |
| Setup 4b (AmBe 1) | 0.79(3) | $9.9(4)\cdot10^{-7}$ | | **0.020(2)** |

**Table 6b.** STUK BLASTER measurement data high-energy singles signal.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 0.078(1) | | |
| Background 3 | **0.099(2)** | | |
| Setup 1a ($^{252}$Cf 2) | 0.66(4) | $4.0(2)\cdot10^{-7}$ | 0.00092(6) |
| Setup 2 ($^{252}$Cf 2) | 0.48(3) | $2.9(2)\cdot10^{-7}$ | 0.00067(5) |
| Setup 3 ($^{252}$Cf 2) | 0.43(3) | $2.6(2)\cdot10^{-7}$ | 0.00060(4) |
| Setup 4a ($^{252}$Cf 2) | 0.38(2) | $2.3(1)\cdot10^{-7}$ | 0.00053(3) |
| Setup 1c (AmBe 3) | 29.7(2) | $2.14(6)\cdot10^{-6}$ | |
| Setup 2 (AmBe 3) | 16.6(2) | $1.19(3)\cdot10^{-6}$ | |
| Setup 3(AmBe 3) | 6.3(1) | $4.6(1)\cdot10^{-7}$ | |
| Setup 4b (AmBe 1) | 1.43(4) | $1.80(7)\cdot10^{-6}$ | |

**Table 7.** STUK Vasikka 1.5”x1.5” $LaBr_3$ measurement data. The measurements were performed later than the other measurements (Cf-252 activity about 4 % smaller).

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 0.013(3) | | |
| Background 2 | **0.021(3)** | | |
| Setup 1a ($^{252}$Cf 2) | 1.60(4) | $9.6(4)\cdot 10^{-7}$ | 0.00222(8) |
| Setup 2 ($^{252}$Cf 2) | 1.36(4) | $8.1(3)\cdot 10^{-7}$ | 0.00188(7) |
| Setup 4a ($^{252}$Cf 2) | 0.75(6) | $4.5(4)\cdot 10^{-7}$ | 0.00104(8) |
| Setup 1c (AmBe 3) | 35.1(2) | $2.53(7)\cdot 10^{-6}$ | |
| Setup 2 (AmBe 3) | 19.8(2) | $1.42(4)\cdot 10^{-6}$ | |
| Setup 4b (AmBe 1) | 1.96(3) | $2.46(7)\cdot 10^{-6}$ | |

**Table 8.** STUK Vasikka neutron detector measurement data. The measurements were performed later than the other measurements (Cf-252 activity about 4 % smaller).

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 0.12(1) | | |
| Background 2 | **0.102(7)** | | |
| Setup 1a ($^{252}$Cf 2) | 6.36(9) | $3.8(1)\cdot 10^{-6}$ | 0.0088(3) |
| Setup 2 ($^{252}$Cf 2) | 6.70(9) | $4.0(1)\cdot 10^{-6}$ | 0.0093(3) |
| Setup 4a ($^{252}$Cf 2) | 2.21(4) | $1.32(4)\cdot 10^{-6}$ | 0.0031(1) |
| Setup 1c (AmBe 3) | 43.9(3) | $3.16(8)\cdot 10^{-6}$ | |
| Setup 2 (AmBe 3) | 46.4(3) | $3.34(9)\cdot 10^{-6}$ | |
| Setup 4b (AmBe 1) | 1.48(2) | $1.86(6)\cdot 10^{-6}$ | |

**Table 9.** FinPhys Semiconductor detector measurement data. Note that all but one of the measurements were performed at a source-detector distance of 1 m instead of 2 m. The measurement at 2 m distance was also performed with the detector moderator facing the source instead of being behind the detector.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | **0** | | |
| Background 3 | 0 | | |
| Setup 1a ($^{252}$Cf 2)@2 m | 0.019(5) | $1.2(3)\cdot 10^{-8}$ | $2.7(8)\cdot 10^{-5}$ |
| Setup 1a ($^{252}$Cf 2)@1 m | 0.026(6) | $1.5(4)\cdot 10^{-8}$ | $3.6(9)\cdot 10^{-5}$ |
| Setup 2 ($^{252}$Cf 2)@1 m | Measurement error | | |
| Setup 3 ($^{252}$Cf 2)@1 m | 0.053(9) | $3.2(5)\cdot 10^{-8}$ | $7(1)\cdot 10^{-5}$ |
| Setup 4a ($^{252}$Cf 2)@1 m | 0.027(6) | $1.6(4)\cdot 10^{-8}$ | $3.7(9)\cdot 10^{-5}$ |
| Setup 1c (AmBe 3)@1 m | 0.31(2) | $2.2(2)\cdot 10^{-8}$ | |
| Setup 2 (AmBe 3)@1 m | 0.33(2) | $2.4(2)\cdot 10^{-8}$ | |
| Setup 3(AmBe 3)@1 m | 0.27(2) | $2.0(2)\cdot 10^{-8}$ | |
| Setup 4b (AmBe 1)@1 m | 0.025(6) | $3.1(8)\cdot 10^{-8}$ | |

**Table 10.** Oxford MARS measurement data.

| Measurement | Net signal [cps] | Absolute efficiency | Sensitivity |
|---|---|---|---|

| | | | |
|---|---|---|---|
| | | [counts/neutrons] | [cps/ng] |
| Background 1 | **0.0030(4)** | | |
| Setup 1a ($^{252}$Cf 2) | 8.7(1) | $5.2(2)\cdot10^{-6}$ | 0.0120(4) |
| Setup 2 ($^{252}$Cf 2) | 8.4(2) | $5.1(2)\cdot10^{-6}$ | 0.0117(4) |
| Setup 3 ($^{252}$Cf 2) | 9.8(2) | $7.0(2)\cdot10^{-7}$ | 0.00163(5) |
| Setup 4a ($^{252}$Cf 2) | 4.05(9) | $2.42(8)\cdot10^{-6}$ | 0.0056(2) |
| Setup 1c (AmBe 3) | 30.2(4) | $2.17(6)\cdot10^{-6}$ | |
| Setup 2 (AmBe 3) | 30.7(4) | $2.21(6)\cdot10^{-6}$ | |
| Setup 3(AmBe 3) | 35.7(5) | $2.57(7)\cdot10^{-6}$ | |
| Setup 4b (AmBe 1) | 2.89(7) | $3.6(1)\cdot10^{-6}$ | |

**Table 11.** Symetrica NNSFP measurement data.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 0.200(2) | | |
| Background 2 | **0.198(2)** | | |
| Setup 1a ($^{252}$Cf 2) | 224.2(6) | $1.35(4)\cdot10^{-4}$ | 0.312(8) |
| Setup 2 ($^{252}$Cf 2) | 262.7(7) | $1.58(4)\cdot10^{-4}$ | 0.37(1) |
| Setup 3 ($^{252}$Cf 2) | 257.2(7) | $1.55(4)\cdot10^{-4}$ | 0.36(1) |
| Setup 4a ($^{252}$Cf 2) | 123.2(5) | $7.4(2)\cdot10^{-5}$ | 0.171(5) |
| Setup 1c (AmBe 3) | Measurement error | | |
| Setup 2 (AmBe 3) | 1449(2) | $1.07(4)\cdot10^{-4}$ | |
| Setup 3(AmBe 3) | 1757(2) | $1.31(5)\cdot10^{-4}$ | |
| Setup 4b (AmBe 1) | 72.3(4) | $9.1(2)\cdot10^{-5}$ | |

**Table 12.** Symetrica NNS2000 measurement data.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | 0.829(4) | | |
| Background 3 | **0.631(3)** | | |
| Setup 1a ($^{252}$Cf 1) | 358(1) | $1.38(4)\cdot10^{-3}$ | 3.20(8) |
| Setup 2 ($^{252}$Cf 1) | 387(1) | $1.50(4)\cdot10^{-3}$ | 3.48(9) |
| Setup 3 ($^{252}$Cf 1) | 380(1) | $1.47(4)\cdot10^{-3}$ | 3.41(9) |
| Setup 4a ($^{252}$Cf 1) | 62.7(5) | $2.28(6)\cdot10^{-4}$ | 0.53(1) |
| Setup 5a ($^{252}$Cf 2) | 25.2(2) | $1.51(4)\cdot10^{-5}$ | 0.0350(9) |
| Setup 1a ($^{252}$Cf 2) | 1428(1) | $1.20(3)\cdot10^{-3}$ | 2.77(7) |
| Setup 1b (AmBe 1) | 685(2) | $1.00(3)\cdot10^{-3}$ | |
| Setup 2 (AmBe 1) | 779(2) | $1.16(3)\cdot10^{-3}$ | |
| Setup 3(AmBe 1) | 820(2) | $1.23(3)\cdot10^{-3}$ | |
| Setup 4b (AmBe 1) | 290(2) | $3.9(1)\cdot10^{-4}$ | |
| Setup 5a (AmBe 1) | 39.1(2) | $5.0(1)\cdot10^{-5}$ | |

**Table 13.** Lund 3”x3” $LaBr_3$ (flat side down) measurement data.

| Measurement | Net signal [cps] | Absolute efficiency | Sensitivity |
|---|---|---|---|

| | | [counts/neutrons] | [cps/ng] |
|---|---|---|---|
| Background 1 | **0.261(2)** | | |
| Background 2 | 0.27(2) | | |
| Setup 2 ($^{252}$Cf 1) | 4.2(1) | $1.52(6)\cdot10^{-5}$ | 0.035(1) |
| Setup 3 ($^{252}$Cf 1) | 4.7(1) | $1.69(6)\cdot10^{-5}$ | 0.039(1) |
| Setup 4a ($^{252}$Cf 1) | 2.26(8) | $8.1(4)\cdot10^{-5}$ | 0.0188(8) |
| Setup 5a ($^{252}$Cf 2) | 1.42(3) | $5.1(2)\cdot10^{-6}$ | 0.0118(5) |
| Setup 1b (AmBe 1) | 27.2(2) | $3.43(9)\cdot10^{-5}$ | |
| Setup 2 (AmBe 1) | 15.8(2) | $1.99(6)\cdot10^{-5}$ | |
| Setup 3(AmBe 1) | 12.3(1) | $1.55(4)\cdot10^{-5}$ | |
| Setup 4b (AmBe 1) | 21.4(2) | $2.69(7)\cdot10^{-5}$ | |
| Setup 5a (AmBe 1) | 5.05(6) | $6.4(2)\cdot10^{-6}$ | |

**Table 14.** Lund 3”x3” LaBr$_3$ measurements with phantom. The measurements were performed with source $^{252}$Cf 1, detector distance 2 m and with different PVC booster configurations. The measurements results are averages of measurements with the phantom behind, in front, and on the side of the detector. One measurement result with the phantom only on the backside is also included for comparison (marked with an asterix).

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | **0.22** | | |
| No PVC | 32(1) | $1.16(5)\cdot10^{-4}$ | 0.27(1) |
| 5 cm PVC around detector | 43(1) | $1.53(6)\cdot10^{-4}$ | 0.35(1) |
| 10 cm PVC around detector | 45(1) | $1.61(6)\cdot10^{-4}$ | 0.37(1) |
| 5 cm PVC under detector | 40(1) | $1.44(6)\cdot10^{-4}$ | 0.33(1) |
| 5 cm PVC between detector and phantom | 37(1) | $1.32(5)\cdot10^{-4}$ | 0.31(1) |
| No PVC, phantom behind detector* | 35.2(8) | $1.26(4)\cdot10^{-4}$ | 0.29(1) |

**Table 15.** Lund 3”x3” NaI (flat side down) measurement data

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | **0.275(2)** | | |
| Background 2 | 0.29(2) | | |
| Setup 2 ($^{252}$Cf 1) | 2.66(9) | $9.5(4)\cdot10^{-6}$ | 0.0220(9) |
| Setup 3 ($^{252}$Cf 1) | 2.75(9) | $9.9(4)\cdot10^{-6}$ | 0.023(1) |
| Setup 4a ($^{252}$Cf 1) | 1.44(6) | $5.2(3)\cdot10^{-6}$ | 0.0119(6) |
| Setup 5a ($^{252}$Cf 2) | 0.98(3) | $5.9(3)\cdot10^{-7}$ | 0.00136(6) |
| Setup 1b (AmBe 1) | 18.0(2) | $2.26(6)\cdot10^{-5}$ | |
| Setup 2 (AmBe 1) | 9.8(2) | $1.24(4)\cdot10^{-5}$ | |
| Setup 3(AmBe 1) | 7.1(1) | $9.0(3)\cdot10^{-6}$ | |
| Setup 4b (AmBe 1) | 14.3(2) | $1.80(5)\cdot10^{-5}$ | |
| Setup 5a (AmBe 1) | 3.41(5) | $4.3(1)\cdot10^{-6}$ | |

**Table 16.** Lund 3”x3” NaI measurements with phantom. The measurements were performed with $^{252}$Cf 1, detector distance 2 m and with different PVC booster configurations. The measurements results are averages of

measurements with the phantom behind, in front, and on the side of the detector. One measurement result with the phantom only on the backside is also included for comparison (marked with an asterix).

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | **0.32** | | |
| No PVC | 16.6(8) | $6.0(3)\cdot10^{-5}$ | 0.138(7) |
| 5 cm PVC around detector | 29(1) | $1.03(4)\cdot10^{-4}$ | 0.24(1) |
| 10 cm PVC around detector | 32(1) | $1.16(5)\cdot10^{-4}$ | 0.27(1) |
| 5 cm PVC under detector | 23.5(9) | $8.4(4)\cdot10^{-5}$ | 0.195(9) |
| 5 cm PVC between detector and phantom | 21.6(9) | $7.8(4)\cdot10^{-5}$ | 0.180(9) |
| No PVC, phantom behind detector* | 18.5(6) | $6.6(3)\cdot10^{-5}$ | 0.153(6) |

**Table 17.** Lund He-3-tube measurement data. Because of the high efficiency of the detector, it had to be moved to a distance of 3 m in part of the measurements. The source-detector distance is included in the table.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| Background 1 | **0.356(2)** | | |
| Background 2 | | | |
| Background 3 | 0.332(2) | | |
| Setup 1a ($^{252}$Cf 1)@2 m | 109.5(6) | $3.9(1)\cdot10^{-4}$ | 0.91(2) |
| Setup 2 ($^{252}$Cf 1)@3 m | 81.6(6) | $2.93(5)\cdot10^{-4}$ | 0.68(1) |
| Setup 3 ($^{252}$Cf 1)@2 m | 126.8(9) | $4.6(1)\cdot10^{-4}$ | 1.05(3) |
| Setup 4a ($^{252}$Cf 1)@2 m | 30.4(3) | $1.09(3)\cdot10^{-4}$ | 0.252(7) |
| Setup4a ($^{252}$Cf 1)@3 m | 17.7(2) | $6.4(2)\cdot10^{-5}$ | 0.147(4) |
| Setup 5a ($^{252}$Cf 2)@2 m | 8.41(8) | $5.0(3)\cdot10^{-6}$ | 0.0116(6) |
| Setup 1b (AmBe 1)@3 m | 146(1) | $1.83(4)\cdot10^{-4}$ | |
| Setup 2 (AmBe 1)@3 m | 169(2) | $2.13(4)\cdot10^{-4}$ | |
| Setup 3(AmBe 1)@2 m | 255(5) | $3.2(1)\cdot10^{-4}$ | |
| Setup 4b (AmBe 1)@2 m | 116.7(7) | $1.47(4)\cdot10^{-4}$ | |
| Setup 5a (AmBe 1)@2 m | 11.49(9) | $1.45(6)\cdot10^{-5}$ | |

**Table 18.** Lund 4 l NaI measurement data.

| Measurement | Net signal [cps] | Absolute efficiency | Sensitivity |
|---|---|---|---|

| | | [counts/neutrons] | [cps/ng] |
|---|---|---|---|
| Background 1 | **1.666(5)** | | |
| Background 2 | 1.67(5) | | |
| Background 3 | 2.620(7) (activated) | | |
| Setup 1a ($^{252}$Cf 1) | 42.1(3) | $1.51(4) \cdot 10^{-4}$ | 0.35(1) |
| Setup 2 ($^{252}$Cf 1) | 40.7(3) | $1.46(4) \cdot 10^{-4}$ | 0.338(9) |
| Setup 3 ($^{252}$Cf 1) | 44.1(4) | $1.58(4) \cdot 10^{-4}$ | 0.37(1) |
| Setup 4a ($^{252}$Cf 1) | 19.9(2) | $7.1(2) \cdot 10^{-5}$ | 0.165(5) |
| Setup 5a ($^{252}$Cf 2) | 11.7(1) | $7.0(2) \cdot 10^{-6}$ | 0.0162(5) |
| Setup 1b (AmBe 1) | 241.3(6) | $3.04(8) \cdot 10^{-4}$ | |
| Setup 2 (AmBe 1) | 143.4(7) | $1.80(5) \cdot 10^{-4}$ | |
| Setup 3(AmBe 1) | 116.0(5) | $1.46(5) \cdot 10^{-4}$ | |
| Setup 4b (AmBe 1) | 186.6(7) | $2.35(6) \cdot 10^{-4}$ | |
| Setup 5a (AmBe 1) | 39.7(2) | $5.0(1) \cdot 10^{-5}$ | |

**Table 19.** Lund 4 l NaI measurement data with PVC booster. The measurements were performed with source $^{252}$Cf 2 with a source-detector distance of 2 m.

| Measurement | Net signal [cps] | Absolute efficiency [counts/neutrons] | Sensitivity [cps/ng] |
|---|---|---|---|
| No PVC | 248 | $1.48(4) \cdot 10^{-4}$ | 0.343(9) |
| 5 cm PVC on two sides (under and over) | 358 | $2.15(5) \cdot 10^{-4}$ | 0.50(1) |
| 10 cm PVC on two sides (over and under) | 406 | $2.43(6) \cdot 10^{-4}$ | 0.56(1) |
| 5 cm PVC on four sides | 420 | $2.52(6) \cdot 10^{-4}$ | $0.58(1) \cdot 10^{-4}$ |

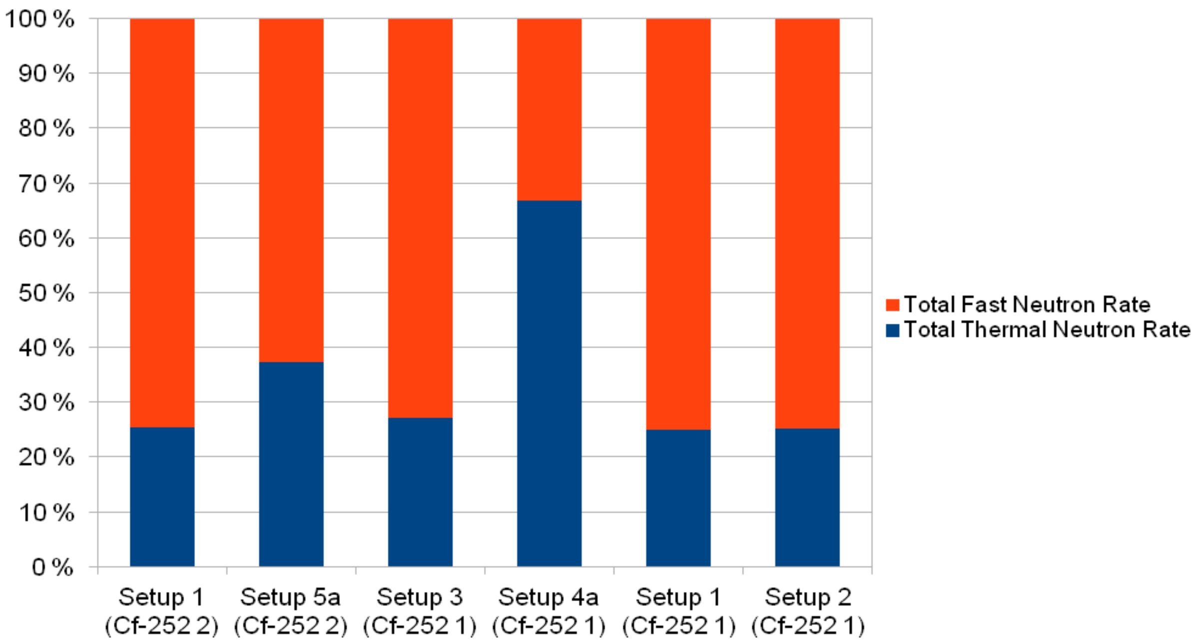


**Figure 11.** Arktis' extended range neutron detector fast and thermal neutron rates for different measurement setups. The 14 cm PE shielding results in an increase in the thermal flux, while the lead shielding has hardly any effect on the thermal versus fast neutron ratio. For the chosen settings, a gamma rejection of $7.5 \cdot 10^{-8}$ was obtained. The absolute values are not included in this report, but can be provided from the manufacturer upon request.

## 4.2 Gamma source measurements

The gamma insensitivity of part of the detectors was tested by exposing the detectors to large gamma dose rates using a 120 GBq Co-60 and a 21 GBq Cs-137 source. The distance to the gamma source was large (7-9 m), so the dose rate was evenly distributed over the detectors. The uncertainty of the dose rate is ±5 %.The background has been subtracted to obtain the neutron signal counts caused by the gamma source.

**Table 20.** FinPhys Semiconductor detector gamma insensitivity.

| Source (H*(10) dose rate) | Neutron signal count rate [cps] |
|---|---|
| Background | 0 |
| Cs-137(100 μSv/h) | 0 |
| Co-60(500 μSv/h) | 0 |

**Table 21.** Oxford MARS detector gamma insensitivity.

| Source (H*(10) dose rate) | Neutron signal count rate [cps] |
|---|---|
| Background | 0.0030(4) |
| Cs-137(100 μSv/h) | 0.12(2) |
| Co-60(500 μSv/h) | 0.49(4) |

**Table 22.** Symetrica NNSFP detector gamma insensitivity.

| Source (H*(10) dose rate) | Neutron signal count rate [cps] |
|---|---|
| Background | 0.198(2) |
| Cs-137(100 μSv/h) | 0.356(1) |
| Cs-137(175 μSv/h) | 0.369(1) |
| Co-60(500 μSv/h) | 0.994(2) |

**Table 23.** Symetrica NNS2000 detector gamma insensitivity.

| Source (H*(10) dose rate) | Neutron signal count rate [cps] |
|---|---|
| Background | 0.631(3) |
| Cs-137(100 μSv/h) | 1.34(1) |
| Cs-137(175 μSv/h) | 14.66(5) |
| Co-60(500 μSv/h) | Neutron rate saturated. |

## 5. Conclusions

A large number of novel and conventional neutron detector methods were tested under the same experimental conditions at STUK. This report presents both the different techniques used as well as the quantitative measurement results. Maybe the most important result is the knowledge transfer between the Nordic countries in particular and the neutron detection community in general. Measurements sessions such as this are rare and the NKS NOVE project attracted international interest. The number of detectors tested grew significantly larger with Arktis Radiation Detectors Ltd, Symetrica Security Ltd, Oxford University and FinPhys joining without receiving NKS funding. Many alternatives to He-3 counters with different possible field applications were demonstrated. Because of the large amount of data, detailed data analysis is not possible within the scope of this report, but left to the reader.

During the Reykjavík seminar, the neutron detection capabilities of the participating Nordic authorities were presented. In addition, measurements were performed in special field environments, such as a cargo ship harbour and under-sea tunnel. The seminar thus contributed both to the knowledge transfer and experimental results. The results of the seminar are presented in Appendix A.

Funding has been applied for a continuation of the present project. The possible future project will include neutron measurements with moving sources simulating e.g. border control or other security applications.

## 6. References

Holm, P et al.2012. Neutron detection with a NaI spectrometer using high-energy photons. Nucl. Instrum. and Methods in Phys. Res. A. 697: 59-63. http://dx.doi.org/10.1016/j.nima.2012.09.010.

ENDF/B-VII.1 library, retrieved from http://www.nndc.bnl.gov/ on 19.12.2013.

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The views expressed in this document remain the responsibility of the authors and do not necessarily reflect those of NKS. In particular, neither NKS nor any other organisation or body supporting NKS activities can be held responsible for the material presented in this report.

## APPENDIX A: Minutes of NKS NOVE Seminar 13. – 16.5. 2013

### Participants

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### 13 – 14.5.2013, Measurements

*Measurements at GR irradiation hall*

A 1 Ci AmBe source was measured with the following detectors:

- IEMC backpack containing $^{3}$He-tubes (GR)
- 3"x3" NaI and 3"x3" $LaBr_3$ (Lund/SSM)
- Moderated 5"x5" NaI detector (STUK)
- BLASTER neutron spectrometer (STUK)
- Vasikka backpack containing 1.5"x1.5" $LaBr_3$ and BC-702 thermal neutron detector (STUK)
- Germanium detector (GR)

The measurement campaign proved to be very interesting, since the neutron detection efficiency of NaI and $LaBr_3$ can be directly compared with the same-sized detectors. Without any boosters, the neutron signal of the $LaBr_3$ detector was about 60% higher as compared to the same sized NaI detector for the wax-shielded 1 Ci AmBe source. The background count rates were similar for both detectors. This prompts for further studies in the planned measurement session in STUK. In later measurements at Iceland, the Swedish $LaBr_3$ detector was occasionally boosted with PVC. Figure 1 shows unshielded AmBe spectra measured with the $LaBr_3$ detector. The good resolution of $LaBr_3$ (3% at 662 keV) makes the peaks caused by neutron reactions with chlorine easily distinguishable. Figure 2 presents the same spectra for the neutron-shielded AmBe source. In this case the effect of the booster is much smaller. Note that in the used measurement configurations, the booster material was always also in between the detector and the source.

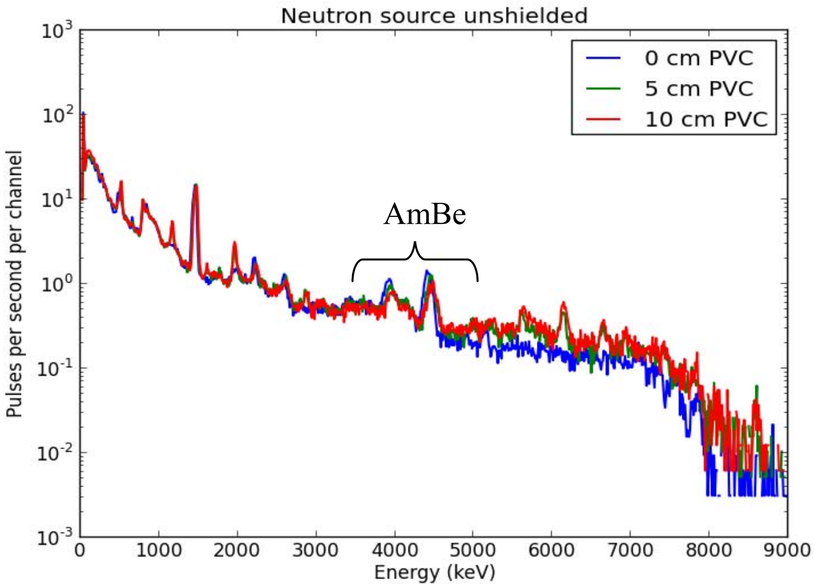


**Figure 1**. 1 Ci AmBe spectrum measured with a 3”x3” $LaBr_3$ detector with and without a PVC booster. High energy (> 3.5 MeV) peaks visible in the boosted spectra are presumably caused by chlorine, however, there are also some low energy peaks most likely caused by chlorine (at around 1 MeV and 1.9 MeV). Source to detector distance was 2 m and the 59.5 keV gamma-rays were removed using a lead shield around the source.

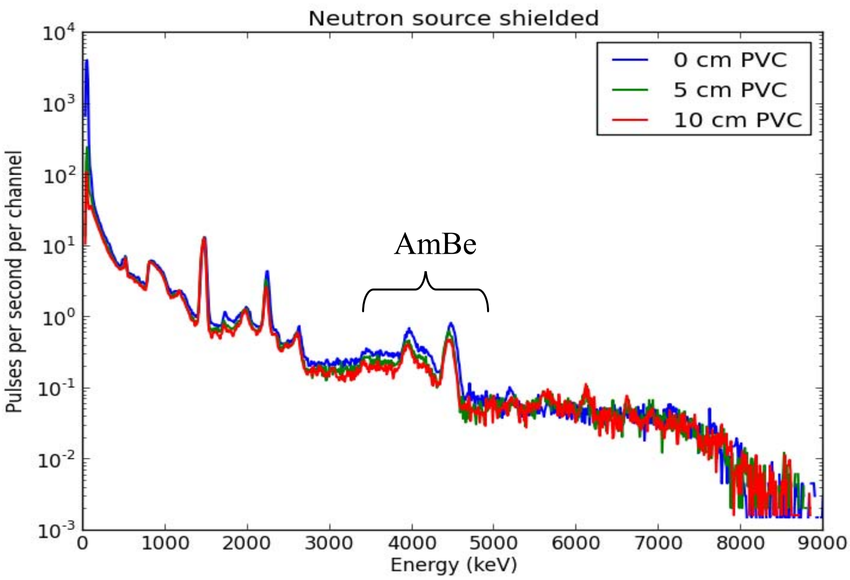


**Figure 2**. Spectrum of 1 Ci AmBe source shielded with wax and measured with a 3”x3” $LaBr_3$ detector with and without a PVC booster. Source to detector distance was 2 m.

*Ship effect studies at Reykjavík harbour*

Earlier measurements by other scientists have shown that the neutron background may increase near large objects containing heavy elements, like in a vicinity of container ship. This is called the ship effect and it was studied by measuring the background at the dock of a bay with and without a large container ship (Godafoss).

The ship decreased the high energy count rate of the gamma spectrometers (3”x3” $LaBr_3$, 3”x3” NaI and moderated 5”x5” NaI), indicating a shadow effect instead of a ship effect. The direct neutron detectors (IEMC Backpacks, Vasikka BC-702 and BLASTER, see seminar presentations) detected no significant change in the count rate. The conclusion was that although the ship effect may be real, the integration times of the detectors were too long in order to see it (the ship effect neutrons come in bursts). For the gamma-spectrometers the shadow effect is more important.

*Measurements in the Hvalfjörður tunnel*

Background measurements were performed in the Hvalfjörður tunnel 165 m below sea level. For comparison, measurements were also performed outside the tunnel on sea level. The low-energy (< 3.5 MeV) singles background was roughly the same in the tunnel compared to sea level. The high-energy background count rate of the gamma spectrometers (including the BLASTER singles spectrum) dropped with factors of about 10-100, experimentally confirming that the high-energy singles background counts are caused by cosmic radiation. The BLASTER and BC-702 neutron detectors also measured a significant drop in the background count rate: 8 fast neutrons compared to 0 in 1000 seconds (BLASTER) and 0.03 thermal neutron cps compared to 0.002 cps (BC-702).

**15.5. 2013, Seminar day 1**

The neutron detection capabilities of the participating organizations were presented.

*NRPA*

NRPA gave an overview on their neutron detection capability. In addition to conventional methods, indirect neutron detection with NaI detectors has been tested.

*GR*

GR has primarily $^3$He-tubes in use for neutron detection. IEMC Backpack was introduced.

*Lund University / SSM*

The Swedish radiation protection organization has access to a few different neutron sensitive instruments. These include the GR100 personal radiation detector and the GR135 handheld radioisotope identifier which both include a small neutron sensitive detector. These detectors however, are only useful when the neutron fluence is relatively high as their limited sensitive volume is not very helpful when searching for neutron sources.

Besides the above mentioned instruments, the Swedish radiation protection organization includes 4 car borne mobile gamma spectrometry systems, operated by the Swedish customs, that are equipped with 3 He-3 tubes each. These systems are the only ones specifically designed to search for neutron sources.

Based on the idea presented by STUK, a very preliminary comparison between using the He-3 based neutron detector, a 4L NaI(Tl) detector surrounded by a 10 cm PVC booster and a 123% HPGe detector to locate a neutron source were presented. The results indicated that the sensitivity of the 4L NaI(Tl) detector surrounded by 10 cm PVC in detecting neutrons approached the sensitivity of the He-3 tubes. Using the 4L NaI(Tl) or 123% HPGe detectors to study the pulse rate in the 2.2 MeV peak produced from the prompt gamma emitted by deuterium appeared to be far less useful than using the He-3 tubes or the PVC boosted NaI(Tl) detector.

*STUK*

The neutron detection method using high-energy gamma spectrometery with NaI detectors was presented. Neutron sources can be detected by their emitted and induced high-energy (> 3.5 MeV) photons. The detection method is in operative use in Finland. Measurements show that the detection efficiency is comparable to that of a $^3$He-tube of similar dimensions. The indirect NaI method has advantages especially when the neutron sources are shielded with neutron shields.

A new, portable neutron spectrometer designed and built in STUK was presented. The spectrometer is named BLASTER (Boron-Loaded Attenuated SpectromeTER). The detector consists of a borated plastic scintillator coupled to a Canberra Osprey MCA acquiring data in event mode. Neutrons are identified by analysing the event list and looking for scattering and capture coincidence pulse pairs. Neutrons can simultaneously be indirectly detected using the high-energy singles events.

The Vasikka backpack, LINSSI database and SNITCH reach back systems developed by STUK were presented. The Vasikka backpack contains a 1.5”x1.5” $LaBr_3$ gamma spectrometer and a BC-702 Zinc Sulfide thermal neutron detector. The energy region of the gamma spectrometer is 0 – 5 MeV to also enable indirect neutron detection. Similarly, the NaI detectors in the mobile laboratory car SONNI are set to cover 0 – 8 MeV. Measurement data of all mobile measurement systems are stored in a LINSSI database continuously both locally and on-line on a STUK SNITCH server.

STUK also presented results from the preliminary detector comparison. A large number of gamma spectrometers and traditional neutron detectors have been tested in the past.

Preliminary results of measurements performed by the seminar participants in Iceland were presented. See pages 1-3 of this document.

**16.5. 2013, Seminar day 2**

Presenting the results from the measurements performed in Iceland was continued.

Introduction of commercialized NaI portal monitor which has recently been taken into operational use in Finland.

The upcoming Nordic detector comparison exercise to be performed in STUK at autumn 2013 was discussed. The measurement facilities (radiation metrology laboratory) and sources ($^{252}$Cf and AmBe) available were introduced. It was decided that Lund University brings an additional 4.6 MBq $^{238}$PuO source to the tests.

The dates were set preliminary to 23.9 – 26.9.3013. The nights between 23.9 and 25.9 will be used for background measurements. The following detectors will be brought to the measurements:

- Icelandic IEMC backpack ($^{3}$He-tubes)
- 3”x3” NaI and 3”x3” $LaBr_3$ (Lund/SSM) with boosters
- 4 l NaI (Lund/SSM)
- $^{3}$He tubes (tube length 50 cm and diameter 5.8 cm) and exploranium system for data taking, 1 s acqs (Lund)
- Detective (Lund)
- NaI detectors from Norway
- Moderated 5”x5” NaI detector (STUK)
- BLASTER neutron spectrometer (STUK)
- Commercialized NaI portal monitor (STUK)
- Vasikka backpack containing 1.5”x1.5” $LaBr_3$ and BC-702 thermal neutron detector (STUK)
- Some companies may also bring their prototype detectors to the tests.

Lund University will need a garage for their car.

To facilitate the measurement analysis, it was decided that a result template will be written for every participant to fill. STUK will prepare the first draft of the template. Different properties that could be compared were discussed (detection efficiency, signal-to-noise ratio, minimum detectable activities, background count rate etc). Preliminary information on the detection systems such as, approximate absolute neutron detection efficiency and need for electricity for your detectors during the measurements, should be provided beforehand to Philip Holm and Kari Peräjärvi so that the measurements can be planned thoroughly.

Possible measurements include:

- Measurements comparing detection efficiencies with shielded and bare sources ($^{252}$Cf, AmBe, $^{238}$PuO).

- Measurements with phantoms (some preliminary measurements can be performed "at home").

- Further ship effect studies, in case that measurements in STUK and/or Lund ($^{3}$He-tubes) show a measureable effect.

- Background measurements will be performed during the nights. At least one background measurement should be performed outside the radiation metrology laboratory because of its higher background.

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|---|---|
| Title | Novel neutron detection methods for nuclear security |
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| Abstract<br>max. 2000 characters | This report presents a comparison between conventional and novel neutron detection techniques in use or planned to be used at Nordic countries as well as developed by companies. The intercomparison measurements were performed at the Metrology laboratory of the Finnish Radiation and Nuclear Safety Authority using Cf-252 and Am/Be sources. The following organizations participated in the project:<br>- Lund University/Swedish Radiation Safety Authority<br>- Icelandic Radiation Safety Authority, GR<br>- Norwegian Radiation Protection Authority, NRPA<br>- Finnish Radiation and Nuclear Safety Authority, STUK<br>- MARS Project, Oxford University<br>- Arktis Radiation Detectors Ltd.<br>- FinPhys Oy |

- Symetrica Security Ltd.

The count rates, absolute detection efficiencies and sensitivities are presented together with descriptions of the tested detectors. Maybe the most important result is the knowledge transfer between the Nordic countries in particular and the neutron detection community in general. Measurements sessions such as this are rare and the NKS NOVE project attracted international interest.

Prior to the measurements at STUK, a seminar was organized by GR in Reykjavík, Iceland. The outcome of the seminar (including field measurements) are included in an appendix to the report.

Key words Neutron detection

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