Performance of $^{10}\text{B} + \text{ZnS}(\text{Ag})$ neutron detectors in RPM for the detection of special nuclear materials

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ABSTRACT

In homeland security, neutron detection is used to prevent the smuggling of Special Nuclear Materials in the fight against nuclear terrorism. Thermal neutrons are normally detected with ^3He proportional counters surrounded by a polyethylene box. However, due to the ^3He shortage in the radiation portal monitors reported in 2009, new procedures are being studied. In this work, Monte Carlo methods (using the MCNP6 code) have been used to study the neutron detection features of a $^{10}\text{B} + \text{ZnS}(\text{Ag})$ under real conditions inside a radiation portal monitor. The performance of neutron detection was carried out for ^{252}Cf , HEU ^{235}U (enriched at 70% and 94%) and ^{239}Pu (enriched at 93%) under two different conditions, bare and shielded with lead and polyethylene. To mimic an actual situation occurring at border areas, when a vehicle was passing through the detection zone, a sample of Special Nuclear Materials, SNM, sited inside a cargo vehicle mixed with scrap was simulated, and the radiation portal monitors contained $^{10}\text{B} + \text{ZnS}(\text{Ag})$ neutron detectors. The responses were calculated for four different neutron detectors, two real detectors (N-15 and N-48) and two prototype detectors (N-15 plus and N-48 plus), which are based on the N-15 and N-48 geometries with an improvement in the amount of ^{10}B and a higher polymethyl methacrylate, PMMA, thickness. Measurements were reported for the actual detectors, and the response was greater than 200 cm from a neutron source of ^{252}Cf in c/s-ng of ^{252}Cf . An array of three N-15 or one array of N-48 are close to detect 2.5 c/s-ng of ^{252}Cf as required by the Pacific Northwest National Laboratory, PNNL. The PNNL is the laboratory that tests almost every alternative detector. It requires that each detector must have an absolute efficiency greater than 2.5 c/s-ng of ^{252}Cf for such a ^{252}Cf source, located 200 cm perpendicular to the geometric midpoint of the neutron sensor, complementing the ANSI recommendations that the detector must be able to detect the pass of a neutron source of ^{252}Cf of 20,000 n/s at a distance of 200 cm, to be considered an attractive alternative for the ^3He neutron detectors. The N-15 plus system reached more than 2.5 c/s-ng of ^{252}Cf . Therefore, the $^{10}\text{B} + \text{ZnS}(\text{Ag})$ detectors are an innovative and viable replacement for the ^3He detectors in the radiation portal monitor.

Keywords:

Special nuclear materials, Neutron, Radiation portal monitors, MCNP6

1. Introduction

Border protection is an important issue for governments requesting reliable prevention systems in order to provide the highest level of security. Thus, methods to detect nuclear threats are being sought (Van Liew, 2017). Terrorist acts require countries to have preventive and corrective measures in order to guarantee the safety of their citizens (Spence, 2011). Biological agents, gases, vehicles, planes, explosives and firearms have been used in acts of terrorism. The transportation of goods and commerce exchange occurs all over the world, and it is

necessary to ensure a high security level while keeping the flexibility and efficiency of the supply chain. To maintain security, it is important to recover orphan sources, as well as tightly control radioactive sources and special nuclear materials (SNMs). To dissuade the improper use of SNMs (and weapons grade nuclear materials (WGNMs)), the detection of characteristic radiations emitted by these sources, under different scenarios, is an important subject (Kouzes, 2009).

WGNMs are required for construction of nuclear weapon components. WGNMs are defined as fissile materials that contain at least 93% Pu 239 or 94% U 235 by mass and include 100% Pu 239, weapons

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Fig. 1. Internal configuration N-15 and N-48.

grade plutonium (WGP), 100% U 235, and weapons grade uranium (WGU). In the United States, WGP is defined as being composed of $> 93\%$ Pu 239, and the remainder is assumed to be mainly Pu 238 and Pu 240. WGU is defined as being composed of $> 94\%$ U 235, and the remainder is assumed to be U 234 and U 238 (DOE, 1997). Pu 239 and U 235 are considered to be the most useful weapon components due to their very low rates of spontaneous fission. Highly enriched uranium (HEU) consists of 20–90% U 235 by mass and could also be used as a nuclear device component, although larger quantities would be required than if WGU were used (Chow and Solomon, 1993; Kouzes, 2009).

Radiation portal monitors (RPMs) are used in the screening of vessels, vehicles, cargo and individuals to detect the illicit trafficking of SNMs. The RPMs are deployed at ports, railways, airports and vehicle checkpoints (Weltz et al., 2015), and they are an important tool in preventing the illicit trafficking and transport of nuclear and radioactive materials (Kwak et al., 2010).

With the increase in capability and sophistication of terrorist networks worldwide, there is a growing risk of a portable radiological or nuclear device that can be used in any place; therefore, it is important to intercept the radioactive and nuclear materials during the transport of goods. Although the RPMs have some limitations in detecting nuclear materials, they still play an important role in national security (Spence, 2011). For this reason, it is important to study the response and performance of RPMs in cases of trafficking SNMs.

The RPMs have two types of radiation sensors, one is for gamma rays and another is for neutrons. To detect gamma ray, plastic scintillators of Poly Vinyl Toluene (PVT) are used, while to detect neutrons, the RPMs have neutron ^3He based proportional counters surrounded by polyethylene (Peerani et al., 2012).

Neutron detection is important for homeland security efforts, including monitoring national points of entry for the presence of SNMs, which is defined as plutonium and uranium enriched in ^{235}U and is a fissile component of nuclear weapons (Weltz et al., 2015; Kouzes et al., 2010). The U gives off 1000 times fewer neutrons than Pu.

In all cases of RPM tests, the ^{252}Cf neutron source is used. The most common source of spontaneous fission is ^{252}Cf , the fission spectrum of ^{252}Cf that is very similar to that of ^{240}Pu and ^{239}Pu , so it is often used for detection and testing because of its ease of acquisition with respect to the plutonium (Knoll, 1999).

The neutron detection systems used in nuclear security are mainly based on a ^3He proportional counter, being robust, gamma insensitive, and a proven technology for detecting efficiently thermal neutrons. However, a global shortage of ^3He has caused the price to surge,

limiting the future supply of these neutron detectors, leading to the development of alternative neutron detection technology (Weltz et al., 2015; Peerani et al., 2012).

The aim of this work was to study the neutron detection features of the $^{10}\text{B} + \text{ZnS}(\text{Ag})$ detectors using Monte Carlo methods, under real conditions inside RPMs, in border areas using a vehicle with illicit ^{252}Cf and SNMs (^{239}Pu and highly enriched uranium) as cargo.

The study includes assessing the neutron detection performance of each detector with ^{252}Cf and the two SNMs, under bare and shielded conditions. The SNMs are ^{239}Pu (WPU, ^{239}Pu (93%), ^{238}Pu (0.05%), ^{240}Pu (6.1%), ^{241}Pu (0.8%) and ^{242}Pu (0.05%)), and highly enriched uranium (HEU), where uranium is enriched in 70% and 94% in ^{235}U .

Actually, there are four different neutron detectors, two (N 15 and N 48) are constructed and commercially available. The other two neutron detectors (N 15 plus and N 48 plus) are prototypes with a design based on the external geometry of the N 15 and N 48, but with an improvement in the amount of ^{10}B and the use of a higher PMMA thickness.

2. Materials and methods

2.1. Description of $^{10}\text{B} + \text{ZnS}(\text{Ag})$ neutron detectors

In this work, four $^{10}\text{B} + \text{ZnS}(\text{Ag})$ neutron detectors are known as N 15, N 48, N 15 plus and N 48 plus. The N 15 and N 48 detectors were manufactured by BridgePort Instruments, LLC (BPI, 2013; BPI, 2017). Both use a mixture of boron with a $\text{ZnS}(\text{Ag})$ scintillator, where the boron is enriched in ^{10}B ($^{10}\text{B} + \text{ZnS}(\text{Ag})$). This mixture is uniformly sprayed on polymethyl methacrylate (PMMA) plates acting as a neutron moderator and as a light guide conducting the scintillations to a photomultiplier tube. This system has a power supply and a multichannel analyzer by eMorpho[®] digital electronics. The sensitive area of each detector is formed by five opaque layers of $^{10}\text{B} + \text{ZnS}(\text{Ag})$ distributed on four PMMA $23 \times 36 \times 0.635$ cm plates (N 15) or $120 \times 15.2 \times 0.635$ cm (N 48). The PMMA is surrounded by ~ 8 μm thick aluminum Mylar as a light reflector. The internal configuration is shown in Fig. 1.

Detectors have the same internal array and different external dimensions, the N 15 detector is $23 \times 36 \times 4$ cm, and the N 48 detector is $141.5 \times 16.7 \times 6.35$ cm. Each detector has an outer moderator of high density polyethylene (HDPE) (0.94 g/cm³). For the N 15 detector the moderator thickness is 24 mm in the front and lateral faces, 36 mm in the top and bottom faces, and 48 mm thick in the back ($24 + 36 + 48$ mm). The N 48 is 25 mm thick in the front, top, bottom

Fig. 2. Configuration N-15 and N-48 detectors, bare and moderated.

and lateral faces, and 50 mm thick in the back (25 + 50 mm) as shown in Fig. 2.

Based on the characteristics of N 15 and N 48 neutron detectors (Guzman Garcia et al., 2016a,b) two new prototype neutron detectors, called N 15 plus and N 48 plus, were studied. In these detectors, the PMMA thickness was increased from 0.635 to 0.800 cm (Guzman Garcia et al., 2016c, 2016d) and the ^{10}B content in the sensitive area was increased to 30% more than N 15 and N 48. The internal configuration can be seen in Fig. 3.

2.2. Monte Carlo calculations

2.2.1. Radiation portal monitors: description of models

Models of RPMs with the four neutron detectors were designed using the MCNP6 code, version 2.6.1 (Pelowitz et al., 2014). Models include the neutron detector details, such as the sensitive layers, the PMMA, PTM and their moderators. The PTM was modeled as an empty cylinder of glass. Each neutron detection system (N 15, N 48, N 15 plus and N 48 plus) is described below.

N-15 (neutron detection system): A model was made with the configuration of the N 15 detector, this model consist of three N 15 detectors which were positioned in parallel, one on top of the other as show in Fig. 4, these detectors were defined inside an iron structure

Fig. 4. N-15, Neutron detector System.

Fig. 3. N-15 plus and N-48 plus models MCNP configuration.

Fig. 5. Radiation Portal Monitor, RPM, PVT gamma and N-48, (N-48 plus same configuration).

with dimensions $200 \times 40 \times 15$ cm and 5 cm thickness. Each detector had a moderator of $24 + 36 + 48$ mm HDPE, the first detector (N 15C) was positioned 75 cm from the midpoint of the detector with respect to the ground (Guzman Garcia et al., 2016c).

N-48 and N-48 plus (RPM): Another model was made using the N 48 detector and modeled together with a PVT gamma detector with dimensions $190 \times 41 \times 5$ cm, both were defined next to each other (Fig. 5), and they were placed inside an iron structure with dimensions $235 \times 80 \times 18$ cm. The model of the N 48 plus has the same configuration as the N 48 in Fig. 5.

N-15 plus (RPM): The N 15 plus model had extra features; three N 15 plus detectors with two PVT gamma detectors of $40 \times 60 \times 4$ cm. The PVTs were surrounded by aluminum and a lead/polyethylene shield, all inside on an iron structure with dimensions $200 \times 90 \times 15$ cm. The N 15 plus detectors were sited in parallel; the first detector was positioned 75 cm from the midpoint of the detector with respect to the ground (Fig. 6).

2.2.2. Performance of the RPMs for a moderated neutron source $^{252}\text{Cf}_{\text{PNNL}}$

Some models were made for each RPM described above with neutron detectors, N 15, N 48, N 15 plus and N 48 plus in order to determine the performance in c/s ng of ^{252}Cf , for a moderated neutron source. The neutron source was defined in similar conditions to the Pacific Northwest National Laboratory (PNNL) (Kouzes et al., 2010), who made the analysis for alternative studies. The neutron source used in the PNNL, to test the neutron sensitivity, is surrounded by 0.5 cm of lead to reduce the gamma ray flux and surrounded with 2.5 cm polyethylene to moderate the neutron spectrum, the model can be seen in Fig. 7.

The source was positioned 200 cm perpendicular to the geometric midpoint of the RPM and 143 cm with respect to the floor. This was to determine the efficiency for neutrons emitted by the ^{252}Cf , aiming for a result larger than 2.5 c/s ng of ^{252}Cf , the configuration can be seen in Fig. 8 (Kouzes et al., 2010).

Table 1 gives the efficiencies modeled for each RPM described above, for a moderated neutron source $^{252}\text{Cf}_{\text{PNNL}}$, to 200 cm in the

Fig. 6. Radiation Portal Monitor, RPM, two PVT gamma and three N-15 plus detectors.

Fig. 7. Moderated neutron source $^{252}\text{Cf}_{\text{PNNL}}$.

Fig. 8. Measuring the efficiency of RPM with the $^{252}\text{Cf}_{\text{PNNL}}$ source.

Table 1
Efficiencies of the RPM with three N-15 or N-15 plus detectors and with one N-48 or one N-48 plus detectors for a $^{252}\text{Cf}_{\text{PNNL}}$ neutron source.

RPM with N-15 and N-15 plus (models)		
RPM with three detectors	N-15 (manufactured) c/s-ng $^{252}\text{Cf}_{\text{PNNL}}$	N-15 plus (prototype) c/s-ng $^{252}\text{Cf}_{\text{PNNL}}$
A (superior)	0.73 ± 0.04	0.82 ± 0.04
B (centro)	0.77 ± 0.05	0.86 ± 0.05
C (inferior)	0.63 ± 0.04	0.71 ± 0.04
TOTAL	2.13 ± 0.09	2.39 ± 0.09
RPM with N-48 and N-48 plus (models)		
RPM with one detector	N-48 (manufactured) c/s-ng $^{252}\text{Cf}_{\text{PNNL}}$	N-48 plus (prototype) c/s-ng $^{252}\text{Cf}_{\text{PNNL}}$
TOTAL	1.78 ± 0.07	2.14 ± 0.09

exterior (Guzman Garcia et al., 2017). That is, the contribution by the “room return” effect is only attributed to the floor. In this section only models were produced, the measurements were not completed due to the neutron source being too dissimilar to the PNNL. In all cases, it is important to know the distance with respect to the floor, the efficiency depends directly on this due to the room return effect (Vega Carrillo

et al., 2007).

The RPM with three N 15 detectors has an efficiency of $2.13 \pm 4.22\%$ c/s ng, the efficiency increases to $2.39 \pm 3.77\%$ c/s ng by using three N 15 plus detectors. By changing the detector, the RPM efficiency increases by 12.2% with an uncertainty of 5.66%. The RPM efficiency when a single N 48 detector is used is $1.78 \pm 3.93\%$, which increases to $2.14 \pm 4.21\%$ by using the N 48 plus detector. This change increases the efficiency by 20.22% with an uncertainty of 5.77% (Guzman Garcia et al., 2016d). Using N 48 and N 48 plus detectors gives approximately 1.78 c/s ng and 2.14 c/s ng of ^{252}Cf at 200 cm with respect to the ^{252}Cf source respectively, in all cases in the exterior (Guzmán García et al., 2016b).

2.2.3. Model of vehicle with SNMs in customs

A vehicle based simulation was performed similarly to the RPM benchmark simulations. Each RPM described above was defined as an emplaced stationary detector; objects pass by the monitor, RPM, and are screened for the presence of radioactive materials. In this case, we assumed the cargo scanning scenario, and we defined a vehicle passing the RPM.

The vehicle was defined according to annex A of CEI IEC (2004), this type of vehicle is recommended in the standard “Monitors installed for the control and detection of gamma radiation contained in recyclable or non recyclable materials transported by vehicles” used for the alarm test. The dimensions of the vehicle cargo box are $530 \times 270 \times 200$ cm, and the cab is $120 \times 250 \times 170$ cm. In the cargo box, different materials were defined as scrap with mass of ~ 730 kg. These scrap materials were steel, copper, bronze, lead, zinc, aluminum, brass and iron, whose features are shown in Table 2. They were defined in an arbitrary position as in a real situation where the materials are mixed and in an arbitrary position, for example, this is the case in the metal sector industry where scrap cargo is largely made up of metals.

In the scrap midpoint, the SNMs (HEU and ^{239}Pu) and ^{252}Cf neutron source were included. The sources in the models were selected because firstly, the ^{252}Cf is the principal source for the tests of the RPMs, and secondly, plutonium (SNM) is the most important for the neutron detectors in the RPMs, since it is a material used for nuclear weapons and is a significant source of fission neutrons (Kouzes et al., 2010).

The first case considered was a 1.87 cm radius sphere, ~ 500 g of HEU (70% or 94% ^{235}U enriched) in two scenarios: bare source, and shielded with polyethylene and lead concentric spheres, with 0.6 cm thick lead and 4 cm thick borated polyethylene. The second case was a 1.87 cm radius sphere, ~ 543 g of ^{239}Pu in two scenarios: bare, and shielded with polyethylene and lead concentric spheres with 0.6 cm thick lead and 4 cm thick borated polyethylene. Another case was a neutron source of ^{252}Cf moderated with 0.7 cm of HDPE, similar to the UPM sources $^{252}\text{Cf}_{\text{UPM}}$ and the other case with 2.8 cm thick lead and 4 cm thick borate polyethylene. Table 3 shows the number of cases calculated.

The different materials in the container, that were defined in

Table 2
Materials used to model the scrap in the cargo.

Material	Density [g/cm ³]	Weight [kg]
Steel 304	7.8700	78.70
Steel	8.0000	104.00
Copper	8.9600	116.48
Bronze	8.4000	75.60
Lead	11.3500	79.45
Zinc	7.1330	135.53
Aluminum	2.6989	29.69
Brass	8.0700	56.49
Iron	7.8740	55.12
Total	–	731.05

Table 3
Monte Carlo cases.

Position 1	Position 2	Position 3
Just in front of N-15	Just in front of N-48 and N-48 plus	Just in front of N-15 plus
²³⁹ Pu-WPU bare	²³⁹ Pu-WPU bare	²³⁹ Pu-WPU bare
²³⁹ Pu-WPU shielded	²³⁹ Pu-WPU shielded	²³⁹ Pu-WPU shielded
HEU 70% bare	HEU 70% bare	HEU 70% bare
HEU 70% shielded	HEU 70% shielded	HEU 70% shielded
HEU 94% bare	HEU 94% bare	HEU 94% bare
HEU 94% shielded	HEU 94% shielded	HEU 94% shielded
²⁵² Cf _{UPM}	²⁵² Cf _{UPM}	²⁵² Cf _{UPM}
²⁵² Cf _{UPM} shielded	²⁵² Cf _{UPM} shielded	²⁵² Cf _{UPM} shielded

randomly positions, and the different SNM or ²⁵²Cf, bare or shielded, can see in the Fig. 9.

The sources produce neutrons whose energy distribution is defined by Watt fission, as shown in Equation (1).

$$n(E) = Ce^{-\frac{E}{a}} \sinh(\sqrt{bE}) \quad (1)$$

Here, $n(E)$ are the fission neutrons with energy between E and $E + dE$, C is the normalization factor, a and b are parameters whose values depend on the isotope suffering spontaneous fission.

Calculations were carried out using three positions of the SNM with respect to the neutron detectors: firstly in front of the N 15 detection systems, then in front of the RPM N 48 and RPM N 48 plus, and finally in the RPM N 15 plus, these entire models are shown in Fig. 10.

In all Monte Carlo calculations, the number of histories was large enough to obtain uncertainties of less than 5%. For the calculations, the cross sections were taken from the ENDF/B VI library, where the $S(\alpha, \beta)$ treatment was included to take into account the thermalized neutron interactions (Vega Carrillo et al., 2014).

The efficiency of the N 15 and N 48 detectors to ²⁵²Cf fission neutrons was measured, this is in counts per second per nanogram of ²⁵²Cf (c/s ng) (only detectors outside a RPM system, see Fig. 11). To qualify as a neutron detector for use in the RPMs, the PNNL used with the requirements of the ANSI (2006) (Kouzes et al., 2010) recommends that, to 200 cm, the efficiency must be at least 2.5 c/s ng of ²⁵²Cf. Measurements were made in the Laboratorio de Mediciones Neutronicas at the UPM (LMN UPM) on a bench up to 200 cm from the ²⁵²Cf neutron source moderated with 0.7 cm HDPE thickness, differing from the PNNL neutron source, ²⁵²Cf_{UPM}. In Fig. 11 the experimental setup is shown.

The efficiency of the N 48 detector (inside a RPM system, see Fig. 12) was measured in the Laboratorio de Ingenieria Nuclear at the UPM (LIN UPM). In this measurement, the detector was set in the RPM together with a PVT gamma detector, as shown in Fig. 12.

Allocating the ²⁵²Cf_{UPM} 200 cm from the detector, the efficiency of the N 15 detector is 0.77 ± 0.17 c/s ng and 1.78 ± 0.19 c/s ng. Table 4 shows the measured efficiencies as well as the efficiency reported by the manufacturer.

According to the manufacturer of the detectors, the efficiency is approximately 0.77 c/s ng and 1.78 c/s ng for N 15 and N 48 detectors respectively, with a neutron source moderated with 0.7 cm HDPE thickness, ²⁵²Cf_{UPM} (Guzman Garcia et al., 2016a, b; BPI, 2013).

For the measurements shown in Fig. 12, the efficiency reported in the measurements inside the RPM and allocated near to a wall, is 1.92 c/s ng (Guzmán Garcia et al., 2016b). The difference between the efficiency given by the manufacturer and the efficiency measured in the LIN, is probably due to the room return (Vega Carrillo et al., 2007). Neutrons are backscattered in the wall near the RPM, increasing the number of neutrons reaching the RPM.

3. Results

Tables 5 and 6 show the calculated response of N 15, N 48, N 15 plus and N 48 plus neutron detectors for each source/SNM (bare and shielded), in the three positions. Response is the number of ¹⁰B(n, α)⁷Li reactions per second.

The MCNP results are per neutron emitted by the source term, therefore, each result was multiplied by the source strength. In the case of ²⁵²Cf, it emits 2340 n/s per ng of ²⁵²Cf (Profio, 1979; Vega Carrillo, 1988). For ~500 g of 70% HEU (metal) 2.09 n/s is emitted, ~500 g of 94% HEU (metal) emits 0.27 n/s, and ~500 g of ²³⁹Pu (WGP) enriched at 93% emits 99455.77 n/s (yield based on a composition of Pu 239 (93%), Pu 238 (0.05%), Pu 240 (6.1%), Pu 241 (0.8%) and Pu 242 (0.05%), total neutron specific yield 194 n/s g) (Relly et al., 1991; DOE, 2000; Bias, 2002). The results are represented by the reactions occurring in the ¹⁰B, multiplied by the intensity of each source (¹⁰B(n, α) reactions •Q).

Table 5 shows that the response of the RPM has three N 15 and three N 15 plus neutron detectors. For comparison, the ratio between the response of three N 15 plus detectors and the response of three N 15 detectors is shown. In all cases the system with three N 15 plus detectors has a better response. For ²³⁹Pu shielded, the N 15 plus response is 5% larger than the N 15 response. The mean energy of ²³⁹Pu neutrons is between 4 and 5 MeV. In the shield, neutrons are moderated and another moderation is experienced in the polyethylene in the detectors,

Fig. 9. Source hidden in the cargo scrap.

Fig. 10. Vehicle-based model with all RPMs in 3 different positions.

thus a large number of neutrons with the proper energy interact with ^{10}B . The lowest ratio is noticed in the cases of HEU shielded (94% ^{235}U enrichment). With the shielding, the mean energy of HEU neutrons is reduced, then these neutrons arrive at the polyethylene of N 15 and N 15 plus detectors having extra moderation, therefore the responses are almost the same.

In Table 6 the responses of the RPM are shown, with three N 15 and three N 48 plus detectors. Here, the N 48 plus to N 48 response ratios are also included varying from 4.3% to 9.1% for ^{252}Cf shielded and HEU bare (70% ^{235}U enrichment), respectively.

4. Discussion

Tables 5 and 6 show the calculated response of four neutron detection systems inside a RPM, the N 15, N 48, N 15 plus and N 48 plus, in counts per neutron multiplied by the intensity of each source. The neutron source was located at 200 cm from the detector and 143 cm with respect to the floor, with all responses occurring when the neutron

source is 200 cm from the detector frontal face.

The N 15 plus RPM shows the best efficiency with 2.5 c/s ng, fulfilling the PNNL (Kouzes et al., 2010) recommendation. This proposed detector has a better performance than the N 15. The N 48 plus is close to achieving this efficiency using only one detector.

In the model of the vehicle with SNM in customs, the charge scenery of the metal material isn't the most representative or sensitive for neutron detection. It could be better with a case where cargo materials act as a moderator, that is, materials are highly hydrogenous to reduce the neutron flux in the container. This is scenery when the SNM or source was mixed accidentally in the scrap cargo. If it were the intention to hide the SNM it would be better to model with highly hydrogenated materials. However the difference in the response of each detector when the SNM or the ^{252}Cf is either bare or shielded with lead and polyethylene (which is a hydrogenous material) can be seen in Tables 5 and 6. The detectors have a minor efficiency when the material is shielded. In this case, the detection can be done with the PVT detectors too, due the γ gamma ray produced during the neutron

(a) N-15 neutron detector

(a) N-48 neutron detector

Fig. 11. Measuring the N-15 and N-48 detectors responses at the LMN-UPM.

Fig. 12. Measuring the N-48 detector response in the RPM at the LIN-UPM.

interaction with the polyethylene, like 2.2 MeV induced during the neutron capture in hydrogen (Vega Carrillo et al., 2013).

The measurements and models with the manufactured detectors were made in different conditions, the “room return” effect in the measurements is due to the laboratory (floor, ceiling and walls) in the models only is contributed by the floor. The measurements and models were made with different source conditions, $^{252}\text{Cf}_{\text{UPM}}$ (measurements) and $^{252}\text{Cf}_{\text{PNNL}}$ (models). In this case it can't be directly compared.

Table 4

Detector efficiencies. For N-15 and N48 detectors were measured.

Measurements in the LMN with the $^{252}\text{Cf}_{\text{UPM}}$	
N-15	N-48
0.77 ± 0.17 c/s-ng to 200 cm (Guzman-Garcia et al., 2016a)	1.78 ± 0.19 c/s-ng to 200 cm (Guzmán-Garcia et al., 2016b)
Measurements in the LIN inside to the RPM with the $^{252}\text{Cf}_{\text{UPM}}$	
N-48	N-48
1.92 ± 0.15 c/s-ng to 220 cm (Guzmán-Garcia et al., 2016b)	Reported by the manufacturer BrigePort Instruments LLC
	1.77 ± 0.09 c/s-ng to 200 cm (BPI, 2013)

5. Conclusions

The increased probability of nuclear attack and the scarcity of the elemental material ^3He for the neutron detectors, forced us to seek interesting alternatives. In this paper, four neutron detectors have been studied (detectors constructed by BridgePort Instruments LLC (BPI, 2017)) in similar situations of operation, these models are based on previous studies (Guzman Garcia et al., 2016a, b).

The reactions in ^{10}B were calculated using Monte Carlo methods with MCNP6 code, each total response was adjusted with its own efficiency factor determined previously, to deduce the count rates in each case, N 15 and N 48 (Guzman Garcia et al., 2016a, b).

These detectors have the capability to detect the pass of the ^{252}Cf and ^{239}Pu because neutrons are emitted above the background. However, HEU is harder to detect by measuring the neutrons emitted in spontaneous fission. In the RPM, the PVT detectors could detect HEU by measuring the characteristics of the emitted γ rays.

The response increases significantly in efficiency for both detectors when calculation is based on the PNNL neutron source $^{252}\text{Cf}_{\text{PNNL}}$ configuration. This is probably due to the larger moderation of the source that increases the thermal neutron flux, thus obtaining a better efficiency than reported from the sources used in the UPM (Guzman Garcia et al., 2017).

The $^{10}\text{B} + \text{ZnS}(\text{Ag})$ detectors are an alternative to replace ^3He detectors in RPMs. The N 15 detectors are considered suitable for portable backpack detectors. The N 48 detector is considered a replacement for ^3He detectors. An improvement in the geometry of the detector, in creasing the amount of ^{10}B , could increase the detector efficiency with the aim to reach 2.5 cps/ng ^{252}Cf , defined as a goal for using this type of detector as an alternative in RPMs (Kouzes et al., 2010). But using the N 15 plus as an improvement in the geometry of the detector, and raising the amount of ^{10}B and the PMMA thickness increases the detector efficiency with the aim to reach 2.5 c/s ng ^{252}Cf , defined in the PNNL (Kouzes et al., 2010). Combined with the requirements of the ANSI standards, a goal is to use this type of detector as an alternative in RPMs (ANSI, 2006). These systems are required to meet all aspects of the ANSI N42.35 standard.

In all cases the plus detectors are much more efficient than the manufactured detectors N 15 and N 48. The position of the detector with respect to the ground is an important feature due to the detector response to scattered neutrons (Vega Carrillo et al., 2007).

Acknowledgments

The first author, K.A. Guzmán García, thanks the scholarship granted by the CONACYT and the COZCYT, Mexico. The helpful comments received from M. Momayezi (BridgePort Instruments LLC) are appreciated.

Table 5
Comparison of RPM, with three N-15 and N-15 plus detectors, responses.

SNM/Source		RPM with three N-15 detectors [¹⁰ B(n, α) reactions/s]	RPM with three N-15plus detectors [¹⁰ B(n, α) reactions/s]	N-15plus -to- N-15 response ratio
²⁵² Cf		2.557 ± 0.090	2.627 ± 0.093	1.027 ± 4.99%
²⁵² Cf _{sh}		1.609 ± 0.071	1.643 ± 0.073	1.021 ± 6.26%
70%	HEU	2.53E-03 ± 8.48E-05	2.60E-03 ± 8.79E-05	1.028 ± 4.77%
	HEU _{sh}	1.50E-03 ± 6.42E-05	1.54E-03 ± 6.69E-05	1.027 ± 6.10%
94%	HEU	3.31E-04 ± 1.10E-05	3.42E-02 ± 1.14E-05	1.033 ± 4.72%
	HEU _{sh}	2.00E-04 ± 8.00E-06	2.10E-04 ± 8.88E-06	1.050 ± 6.05%
²³⁹ Pu-WGP		134.611 ± 4.246	138.420 ± 4.409	1.028 ± 4.48%
²³⁹ Pu _{sh} -WGP		84.985 ± 4.516	89.264 ± 3.308	1.050 ± 6.48%

Table 6
Comparison of RPM, with three N-48 and N-48 plus detectors, responses.

source or SNM		RPM with three N-48 detectors [¹⁰ B(n, α) reactions/s]	RPM with three N-48plus detectors [¹⁰ B(n, α) reactions/s]	N-48plus -to- N-48 response ratio
²⁵² Cf		1.806 ± 0.038	1.919 ± 0.025	1.063 ± 2.475%
²⁵² Cf _{sh}		1.134 ± 0.036	1.183 ± 0.038	1.043 ± 4.516%
70%	HEU	1.76E-03 ± 2.22E-05	1.92E-03 ± 2.40E-05	1.091 ± 1.776%
	HEU _{sh}	1.06E-03 ± 1.70E-05	1.14E-03 ± 1.84E-05	1.075 ± 2.275%
94%	HEU	2.32E-04 ± 4.16E-05	2.48E-04 ± 2.38E-05	1.069 ± 3.181%
	HEU _{sh}	1.40E-04 ± 1.93E-05	1.50E-04 ± 1.84E-05	1.069 ± 2.394%
²³⁹ Pu-WGP		94.030 ± 1.160	101.695 ± 1.201	1.082 ± 1.708%
²³⁹ Pu _{sh} -WGP		59.562 ± 1.281	63.767 ± 1.260	1.071 ± 2.921%

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