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On the optimisation of the use of ^{3}He in radiation portal monitors

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ABSTRACT

Radiation Portal Monitors (RPMs) are used to detect illicit trafficking of nuclear or other radioactive material concealed in vehicles, cargo containers or people at strategic check points, such as borders, seaports and airports. Most of them include neutron detectors for the interception of potential plutonium smuggling.

The most common technology used for neutron detection in RPMs is based on ^{3}He proportional counters. The recent severe shortage of this rare and expensive gas has created a problem of capacity for manufacturers to provide enough detectors to satisfy the market demand.

In this paper we analyse the design of typical commercial RPMs and try to optimise the detector parameters in order either to maximise the efficiency using the same amount of ^{3}He or minimise the amount of gas needed to reach the same detection performance: by reducing the volume or gas pressure in an optimised design.

1. ^{3}He detectors used in radiation portal monitors

Radiation Portal Monitors (RPMs) are used to detect illicit trafficking of nuclear or other radioactive material concealed in vehicles, cargo containers or people at strategic check points, such as borders, seaports and airports. Three levels of combating illicit nuclear trafficking were indicated by the IAEA [1]:

1. Preventive level with physical protection.
2. Detective level with border control, and
3. Response level with nuclear forensics.

It is the second level of detection that has to ensure global nuclear security. From the different ways of detection, transport monitoring (e.g. by equipping containers with passive sensors) or cross-border checking, border control with RPMs is essential and so far not satisfied by another technical solution [2]. Most RPMs include passive neutron detectors for the interception of potentially illegal cross-border shipment of plutonium or other trans-uranium elements with neutron signature.

The most common technology used for neutron detection in RPMs is based on ^{3}He proportional counters. These detectors are gas-filled tubes where neutrons are absorbed due to the high thermal cross-section of ^{3}He. The reaction products (energetic proton and triton) induce ionisation into the gas and the charge collected at the electrodes produces a current peak that is processed by the acquisition electronics. In order to increase the neutron detection efficiency, the fast neutrons generated by fission and (α,n) reactions in the measured objects need to be slow down to thermal energies; this is achieved by embedding the proportional tubes into a suitable hydrogenated moderator. Most of the ^{3}He neutron counters use polyethylene as moderator, because of its high hydrogen content and density, but in some RPMs the plastic scintillator is also exploited.

The world market of ^{3}He based neutron detectors is suffering of a severe shortage of this rare and expensive gas. Being the daughter of the beta decay of tritium, currently ^{3}He is mostly produced by purification of the tritium stockpiles in nuclear arsenals. This limits both the geographic production capacity (practically today restricted to USA and Russia [1]) and the maximum amount produced. Current US production capability is of the order of 8000 l per year [1]; an equivalent amount can be expected from Russia. On the contrary the demand has risen from few thousand litres per year before 2001 to several ten thousand litres per year (80,000 in 2008 [1]). This disproportion has rapidly exhausted the stocks and outstrips the current production capacity. Alternative production ways are under investigation, such as purification of tritium from activated heavy water in CANDU reactors [3], and Research and Development projects investigate alternative detection technologies for neutron detection [4,5].

In this paper we do not look for alternative materials replacing ^{3}He as tested, for example, by PNNL [4] and JRC [5], but we try to optimise the use of ^{3}He in commercial RPMs and try to modify the detector design in order either to maximise the efficiency using

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the same amount of gas or minimise the amount of ^{3}He needed to reach the same detection performance. We will play on the dimensions of the tubes, on their number, on the gas pressure, on the geometrical disposition and on the moderator geometry. Current designs are far from optimal, emphasising simplicity and cost of manufacture when ^{3}He availability and price were not an issue.

2. The reference case

The reference ^{3}He-based RPM selected for the analysis is a two-pillar vehicle RPM manufactured by TSA Systems, model VM-250AGN, providing both neutron and gamma detection capabilities. This module is characteristic of those commonly used in RPMs, and a similar design was previously analysed in [6]. A complete description of the detector system can be found in [7].

The portal is composed by two vertical pillars, each equipped with two modules (upper and lower) containing both a plastic scintillator photon detector and a neutron module. Each neutron module contains two neutron detector tubes with 2" diameter × 36 in. length (5 × 91 cm), filled with 2 atm partial pressure of ^{3}He (1 atm = 101.3 Pa), enclosed in a moderating polyethylene box of dimensions 27.9 × 98 × 12.7 cm, as shown in Fig. 1.

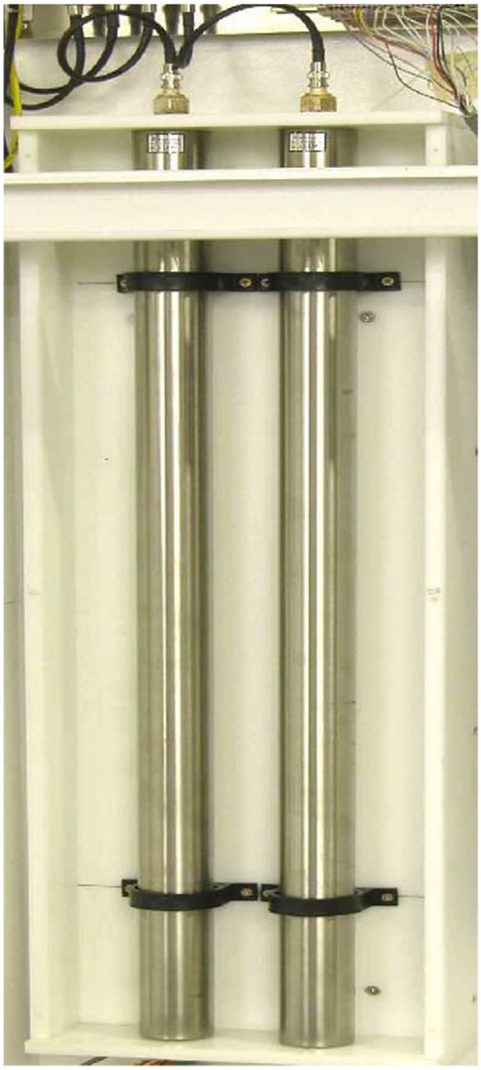

Fig. 1. Internal view of the polyethylene box (open) and the internal He-3 tubes of the TSA-RPM [7].

The polyethylene slabs are 1.1 cm wide in all the sides of the box, with the exception of the back side, which is 5.1 cm thick to prevent the escape of neutrons and scatter them back into the "albedo cavity" to increase the detection efficiency. The two tubes are placed 4.7 cm apart from each other and 6.5 cm from the polyethylene lateral slab faces, whereas an air gap of 1 cm is left between the front face of the polyethylene assembly and the tubes.

Each tube has a volume of 1.85 l, so it contains 3.7 l of ^{3}He at 2 atm (at room temperature), for a grand total of approximately 30 l in the entire RPM.

The intrinsic efficiency of a module has been computed with the Monte Carlo code MCNP [8] to be 5.2% for a bare ^{252}Cf source. We define intrinsic efficiency to be the ideal ratio between neutron detections and the number of un-collided neutrons entering the front surface of the module's polyethylene box, and it does not include the contribution of neutrons scattered in the surrounding environment. The model has been validated versus direct measurements done with the RPM installed at the JRC training centre with a ^{252}Cf point source located at 2 m from the central point of the front face of the module [5].

This intrinsic efficiency will be used as a reference target in this study. We will also introduce a Figure-of-Merit (FoM) to evaluate the different design options defined as the ratio between the intrinsic efficiency and the litres of ^{3}He used to obtain that efficiency: in the reference case the FoM is 0.007.

It should be noted that this efficiency meets the performance requirements for RMPs stated in the major international standards [9,10], which is to detect the passage of a ^{252}Cf neutron source with an intensity of 20,000 n/s between the two pillars of the RPM at a speed of 8 km/h. This dynamic condition is difficult to translate into terms of required detection efficiency. PNNL has proposed an alternative condition for a static test: a detector should read a count rate of 2.5 cps when a ^{252}Cf source of 1 ng is placed at a distance of 2 m from the detector surface [4]. Considering that 1 ng of ^{252}Cf generates 2300 neutrons per second, this source will generate a flux at the detector surface of about 0.0046 n/cm^2/s; therefore an intrinsic efficiency of about 5.0% is necessary to achieve the 2.5 cps in a portal having the same surface of the TSA RPM.

3. Effect of the diameter of the proportional counters

The detection efficiency increases when increasing the amount of neutron absorber, but it increases in a less-than-proportional way due to the self-shielding effect. Generally speaking, the efficiency tends to improve when the absorber is homogeneously distributed within the moderator. For obvious reasons in moderated ^{3}He proportional counters the gas is contained in tubes. It is reasonable to expect that, when replacing a few large tubes with a larger number of smaller tubes, the better spatial distribution of ^{3}He can bring some advantages from the efficiency point of view.

The traditional choice in RPMs is to use 2" external diameter tubes. We investigated whether there could be some gain to replacing these with smaller 1"-diameter tubes. It is obvious that, for the same gas pressure, a 1" tube contains 1/4 of the amount of gas than a 2" tube. Self-shielding effects will be reduced.

Table 1 shows the intrinsic detection efficiency (and corresponding FoM) of a neutron module of a RPM, when replacing the ordinary 2" tubes by a variable number of 1" tubes (at constant gas pressure). The FoM of the 1 in. tubes is always larger than the reference case confirming that these 1" tubes perform better than the 2" ones. Moreover a similar intrinsic efficiency of 5% as with the reference module is reached in the design with only 7 tubes, instead of 8, leading to a reduction of