Practical Considerations for Selecting Cylindrical ^{3}He-filled Proportional Detectors for Homeland Defense Applications

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Abstract

There is currently a tremendous effort underway to develop and deploy sophisticated neutron monitoring systems for homeland defense, placed strategically at ports and major transport arteries throughout the US. To meet the growing demands of Home Land Defense and traditional applications, the use of cylindrical ^{3}He filled proportional counters in neutron counting applications is set to rise. Gas-filled cylindrical proportional counters for the detection of thermal neutrons have been used successfully for many years but the expertise is concentrated in traditional areas and not readily accessible to this new and growing need.

Applications specialists are faced with the challenge of comparing and selecting detectors of contrasting types, anode material, anode diameter, tube dimensions, gas mixture, fill pressures and the like, in order to achieve a targeted performance. In this paper we offer guidance to designers and users so that they may have a better understanding of the factors which are important in the deployment of these detectors for homeland defense. Operational topics presented include: specifying the thermal neutron sensitivity, counter microphonics, RF pickup, export control, transportation and handling.

It is conventional for proportional counter manufacturers to quote in their product catalogs the neutron sensitivity in units of cps/nv. The definition and utility of this value is usually not explained adequately. It is frustrating to discover, upon examination of the product literature, that neutron sensitivity values for counters one would expect to have nominally similar performance characteristics can differ quite markedly. One is left wondering whether these differences are genuine or merely an artifact of how the term sensitivity has been applied. We set out from first principles the meaning of neutron sensitivity, explain with examples how it may be calculated, and discuss its value in practical situations.

Introduction

Recent initiatives around the world require fixed and mobile neutron detection capability for both overt and covert security operations. Neutrons are an important part of the detect-locate-identify objectives of the counter terrorist enforcement agencies involved in addressing radiological threats. Neutrons are penetrating particles thus sources of them are difficult to conceal. Strong neutron sources are not naturally occurring. These two features distinguish neutrons from gamma-rays and allow them to be used as an independent channel of information gathering and investigation.

The rapid growth in neutron counting applications for homeland defense purposes presents new challenges because the environmental and operational theatres of operations may be quite different from those of, for example, traditional Safeguards and waste assay. Furthermore, the need for neutron counting solutions to be integrated with a diverse set other kinds of security systems means that a new and broader range of instrument designers are engaged in such activities. Similarly a new and varied procurement specialist and user base must become familiar with neutron detection technologies.

Cylindrical ^{3}He-filled proportional counters are a mature neutron detection technology available immediately with minimal if any development effort, to meet a large subset of problems facing the security community. They offer high efficiency, low background, stable operation, excellent gamma-ray discrimination, geometrical flexibility and the advantages of a simple signal processing chain. If properly implemented ^{3}He-filled cylindrical proportional counters are effective and flexible tools. They are often the only practical and cost effective means of achieving a given target performance. The art of designing and deploying them however is cannot be learnt solely from textbooks and nor is it widely taught. The necessary experience lies within the vendor community and in expert user groups such as the nuclear waste measurement fraternity. The practical considerations and limitations that limit the selection of a given counter type must be weighed on a case by case basis. We wish to stress that early consultation with suppliers and experts in combination with fast prototyping studies performed under realistic test conditions could be vital to the overall success of a new instrument design.

The purpose of this paper is to broaden awareness of the many and often conflicting parameters that must be borne in mind when selecting a counter for a given task. The written text concentrates mostly on one aspect, namely the conventional specification of detection efficiency found in vendors' catalogs. The accompanying oral presentation treats a far wider range of topics. The authors' would be pleased to furnish a copy of the presentation materials to interested parties. In addition we draw attention to an up coming review [J Leake, S Croft and KP Lambert, A review of the design parameters of ^{3}He gas proportional counters used for neutron detection. Submitted to NIM in PR A.] that details those topics not included in depth here because of space limitations.

General considerations

If the ^{3}He content of an individual tube exceeds 1g then an export license is required. Tubes with a fill pressure exceeding 2 bar require hazardous material declaration for shipment and have special requirements for marking, placarding and training [49 CFR 173.115 (2.2)]. They cannot be carried in a personal vehicle. Below this fill pressure they are DOT and IATA excempt and can be transported without restriction. Staying below these thresholds is of major practical advantage in many situations.

The detailed implementation of neutron counters is vital, especially if the environment is harsh (condensing atmospheres, vehicle or wind vibration, high electromagnetic levels, etc.). A partial list of things to consider includes: microphonic control measures; RF pickup protection; quench gas specification and associated implications for the electronics chain that result from the gas dynamics; gamma sensitivity; detector lifetime and maintenance issues and constructional details (such as cathode wall and anode material and diameter) which directly impact performance [we again refer the interested reader to the forthcoming review by Leake et al for a further information]. The supplier should have a track record of responsiveness and service and be able to deliver the quality and documentation needed for the time horizon envisioned.

Advanced features

The real time remote monitoring of the health of a system in-situ without the need for of a controlled neutron source to be periodically brought up to the monitor and without loss of Signal-to-Noise ratio would be of operational benefit in certain situations. To achieve this we propose the use of an alpha seeded cathode wall containing an excempt quantity (only a few 100Bq say) of alpha emitter. The resulting peak (4-5MeV) is well above the thermal neutron peak (0.76MeV) used for neutron counting and can be monitored separately (for mean rate, gain, energy resolution and so forth) without degrading the background signal to noise ratio to any significant extent. Furthermore, each detector can be monitored independently of its neighbors (an external ^{252}Cf neutron source would flood all detectors).

Specifying ^{3}He tube efficiencies

In this section we consider the role of cps/nv values quoted by some manufacturers. Consider an isotropic, uniform sea of thermal neutrons in free space (that is a large volume of neutrons behaving like an ideal gas and distributed in energy according to the Maxwell-Boltzmann profile). The scaler neutron flux (fluence rate) impinging on a detector placed in the field does not therefore depend on the local regeneration or the return of passing neutrons. This because in this idealized scenario the neutron field has been created not by scattering of the neutron flux by materials local to the detector but by physical material far from the region of interest. The sensitivity, S, expressed in cps/nv in such an ideal unperturbed flux is a characteristic of the ^{3}He proportional counter rather than a property of a specific measurement geometry. The value of S may be estimated from the physical characteristics of the detector as follows:

$$S = C / \phi$$

where

C is the counting rate, $cnt.s^{-1}$
and
ϕ is the true thermal neutron flux, $n.cm^{-2}.s^{-1}$. By convention ϕ also goes by the notation 'nv' as shall be made clear later. We note in passing that the true flux is a factor of $2/\sqrt{\pi}$ times larger than the conventional or Westcott flux which is the product of the neutron number density, n, and the modal speed ("$2200m.s^{-1}$") of a Maxwell-Boltzmann thermal distribution of 20 °C (293.15K).

Now:

$C = \phi\cdot A\cdot \varepsilon\cdot f_w$

where

A is the total surface area, in cm^2, of the gas volume present in the detector that is exposed to the neutron flux

ε is the probability of detecting a neutron, $cnt.n^{-1}$, that strikes the cylinder of ^3He. It can be thought of as the "blackness" of the tube. Evaluating ε is closely related to the calculation of the self-shielding factor in activation foils [1,2] as will be shown below.

and

f_w is the integrated over angle thermal neutron attenuation factor of the proportional counter wall. To a good approximation, since the attenuation is generally light, we can approximate f_w by approximating the wall as a plane sheet. The ends of the ^3He tube usually represent only a small fraction of the exposed area and on the grand scale can be ignored in most cases. Flux hardening through the wall (but not the gas) will also be ignored in this work.

For cylindrical ^3He filled proportional counters which have an aspect ratio (length-to-diameter) much greater than unity we can write the intrinsic efficiency as a universal function of the ^3He fill-pressure and internal diameter product. That is:

$\varepsilon = \varepsilon(P\cdot D)$

The product $P\cdot D$ represents the characteristic absorption parameter. Only the partial pressure of ^3He matters since the quench gases commonly used (e.g. P-10 counter gas, CO_2, CF_4 etc. are not strong neutron absorbers). The ε-factor accounts for the self-shielding of the ^3He, the inner regions of the tube have less worth than the outer region.

The total surface area for an active length, L, of the ^3He tube can be expressed as:

$A = \pi\cdot D\cdot L$

Combining all of the concepts discussed so far we see immediately that we have:

$(C/\phi)/(D\cdot L) = (S/D\cdot L) = f_w\cdot\pi\cdot\varepsilon(P\cdot D)$

Inspection of this expression immediately shows that within a family of similarly walled proportional counters the value of $(S/D\cdot L)$ should be equal for all detectors of the same $(P\cdot D)$ product. That is a plot of $(S/D\cdot L)$ vs $P\cdot D$ is a expected to be a universal curve. In other words S, P, D and L are not independent variables that can be specified independently: once D, P and L are specified S is defined by the underlying physics. Thus, in ordering counters D, P and L should be the primary factors specified with S being used only in a qualitative and supportive role rather than as an independent parameter to be demonstrated or certified. To the extent that f_w and $\cdot\pi\cdot\varepsilon(P\cdot D)$ can be treated as independent the evaluation of the latter collapses to a very good approximation in the case of L>>D to a pure physics problem for an infinite cylinder and a perfect 1/v absorber.

By convention it have become customary for ^{3}He proportional counter manufacturers to quote S/L values without regard to end effects – that is even short tubes are treated as if they are long in relation to their diameter. Furthermore the true active length is somewhat less than the nominal active length defined by the physical distance between the guard tubes shrouding the ends of the anode wire. Guard tubes (resembling hypodermic needles) are part of the support at the end of the anode wire and electrically connected to it, are used to define the active length of the anode wire, but the gas gain will only reach its full value approximately one counter radius from the end of the tube (so that the active length is approximately equal to the distance between the guard tubes minus one counter internal diameter). By convention however the active length of a counter is taken to be the distance between the ends of the guard tubes. This is a manufacturing dimension that can be controlled.

Of course in a given application the optimum parameter set to achieve a particular performance may require other factors to be considered in some detail. Remember that S is an idealized concept; merely a short hand for specifying a characteristic property of the detector. In reality the flux sampled by the detector in a given application may be perturbed by the presence of the detector and it is unlikely to be constant over the entire surface of the ^{3}He tube. S, like ε, is an intrinsic property of the detector. For a given application, such as the direct measurement of a point-like neutron source, the configuration of the moderator around the detector to achieve a given count-rate (or, if you will, effective flux) may be quite different for (a collection) of different tubes that happen to be of equal S. For example, the analysis presented above suggests that (all other factors being equal) a proportional counter of 25mm internal diameter containing 4 atmospheres of ^{3}He will have the same sensitivity (S-value) as a counter of half the active length but with an internal diameter of 50mm and a ^{3}He fill pressure of 2 atm. But, the physical arrangement necessary to create an optimized moderator for these two cases would necessarily be different.

For illustrative purposes we shall take the ^{3}He-detector specification of Canberra-Harwell Ltd. as being reasonably representative. We treat two common tube types explicitly both with type 347/D stainless steel walls. The smaller of the two tubes considered has an outer diameter of 25.4mm (1") and a wall thickness of 0.46mm (0.018"). The larger of the two has an outer diameter of 50.8mm (2") and a wall thickness of 0.71mm (0.028"). Using the Monte Carlo N-Particle code MCNP™ 4B with the ENDF/B-6 nuclear cross section library the attenuation factor for the stainless walls has been estimated. These values agree within experimental uncertainties with values measured by adding sleeves of stainless steel around the tubes. The MCNP™ results suggest there is a weak spectral dependence that depends on the moderator configuration but this proved difficult to establish experimentally. Therefore we adopt a scaling rule based on the experimental results. In a given application efficiency loss due to wall attenuation scales in direct proportion to wall thickness over the range of wall thicknesses of practical interest. The scaling rule as expressed as follows in the case of stainless steel walls.

$$f_w = (0.928 \pm 0.017)^t$$

where t is the wall thickness in mm. For t = 0.46 and 0.71mm this relationship yields wall attenuation factors of (0.9666 ±0.0082) and (0.949 ±0.012) respectively.

We note, in passing, that Al walled proportional counters suffer practically no wall loss. This is a consequence of the fact that the macroscopic absorption cross-section for Al is only about 5.4% of that for stainless steel [the corresponding scaling factor is $f_w = (0.9960 \pm 0.0010)^t$]. However, Al is a soft metal and a wall thickness of the order of 0.5mm may be too thin for some applications, particularly those involving longer tubes. Experience shows that bowing of the tubes can take place following annealing. Thus thicker Al walls (circa 1mm) are typically used for counters longer than about 1m. In this case the reduction in gas volume for a given external diameter offsets the benefit of the lower wall loss (e.g. for the 25.4mm counters the relative efficiency difference is about 1% rather than about 3.5%).

We shall now consider the quantitative evaluation of S from basic nuclear data. To proceed we cast the expression for the reaction rate, RR, as follows:

$RR = S\cdot\phi = V\cdot\Sigma\cdot\phi\cdot SSF$

where
V is the volume of ^{3}He in cm^3. Algebraically, $V = \pi\cdot(D/2)^2\cdot L$.
Σ is the macroscopic (n, p) cross-section in cm^{-1}. Treating ^{3}He as an ideal gas such that 1 mole has a mass of 3.016029301g and occupies a volume of 22,414.1 cm^3 at STP (0°C, 760 torr = 1 atm.) and taking the microscopic-cross section averaged over a a Maxwellian flux at 293.15K to be 4777.9b [scaled from ENDF/B-V value evaluated at 300K] we can write:
$\Sigma = 0.1196\cdot P$, where P is the ^{3}He pressure in atm. (1 atm. ≡ 760mm Hg ≡ 760 torr).

and

SSF is the self-shielding factor defined as the ratio of the average flux over the volume to the incident flux.

A closed form expression for the SSF can be derived for the case of an infinite cylinder bathed by a uniform isotropic flux of mono-energetic neutrons. Case et al [3] describe the approach elegantly although there is a mistake in the formula they give. The correction expression is available from [1] and is reproduced below:

$SSF(x) \equiv f(x) = (2\cdot x/3)\cdot\{\, 2\cdot x\cdot[K_1\cdot I_1 + K_0\cdot I_0] - 2 + K_1\cdot I_1/x - K_0\cdot I_1 + K_1\cdot I_0 \,\}$

where K_n and I_n are the modified Bessel functions, defined by Abramowitz and Stegun [4], and evaluated at the argument x.

and

$x = (D/2)\cdot\Sigma$, Σ being the macroscopic cross-section at the incident energy.

In the present case however we have a spectrum of incident particles. ^{3}He exhibits near perfect "1/v" absorption cross-section behavior and for a thermal flux this results in a hardening of the spectrum as it penetrates into the tube of gas. A simple empirical weighting scheme has been shown to account for this effect rather effectively [2]. Thus for the present purposes we use the following expression:

$$SSF = \frac{\left[\dfrac{1}{\frac{4\cdot\tau}{\pi}}\cdot f\left(\dfrac{4}{\pi}\cdot\tau\right) + \tau\cdot f(\tau)\right]}{\left[\dfrac{1}{\frac{4\cdot\tau}{\pi}} + \tau\right]}$$

where f(x) is the analytical expression for the SSF of the infinite cylinder to a mono-energetic flux and $\tau = (D/2)\cdot\Sigma$ is the radius of the cylinder expressed in units of the Maxwell-Boltzmann flux averaged mean free path. All of the elements to calculate sensitivity values (such as S and S/L) are now in place. We have taken pains to explain the assumptions made by in these calculations and hence the limitations that the resultant values presented by manufacturers are likely to have for practical applications.

Results

Of particular interest is the ability to estimate the relative efficiency of different tube configurations in order to perform preliminary cost trade-off analyses quickly and simply. In cases where the ^{3}He tubes are in competition for the neutron flux, the free field approximation is expected to over estimate the benefits. To illustrate realistic benefits of changing the fill pressure we consider two cases. The first case is that of Canberra-Harwell Ltd.(CHL) tubes of 25.4mm outer diameter embedded in the walls of an N95 thermal well neutron chamber [5,6]. The second case is for CHL tubes of 50.8mm outer diameter tubes embedded in the albedo cavity walls of an N94 waste drum counter [7,8]. The results, which are based on a combination of MCNP™ simulation and direct experiment, are summarized in the Table-1 and Table-2 for the two tube types respectively. Also listed are the calculated results based on the analytical model presented above. For completeness note that (S/L) values for the two cases predicted by the model for the two reference cases (i.e. 1", 4atm. and 2", 2atm.) are 1.107 and 2.200 cnt.s^{-1}.cm^{-1}.(n.cm^{-2}.s^{-1})$^{-1}$.

Fill Pressure, P/atm.	**N95**	**Model**
2	0.83	0.66
4	1.00	1.00
6	1.046	1.21
8	1.078	1.35
10	1.124	1.44
12	1.153	1.50

Table 1 Relative efficiency of 25.4mm O.D. ^{3}He proportional counters

Fill Pressure, P/atm.	**N94**	**Model**
1	0.78	0.66
2	1.00	1.00
3	1.11	1.21
4	1.16	1.34
5	1.20	1.44
6	1.20	1.50

Table 2 Relative efficiency of 50.8mm O.D. ^{3}He proportional counters

The model exhibits the expected scaling between these two tube sizes which differ in wall thickness only slightly and in diameter by almost exactly a factor of two. However the performance in real systems is significantly different than predicted. This demonstrates that although S-values are widely used as a figure of merit to compare tube they should be treated as accurate predictors of performance in real-life situation. In under-moderated assemblies high-pressure ^{3}He counters can respond to epi-thermal neutrons. In densely packed situations they compete with each other to scavenge the neutron field.

Discussion

Extension of the model calculations to BF_3 counters is trivial by noting that the atom worth of ^{10}B is in proportion to the ^{10}B(n, α) to the ^{3}He(n, p) thermal microscopic cross-sections. Based on ENDF/B-V cross-sections this ratio is equal to (3840/5327). Thus 1atm of BF_3 containing boron enriched to 90% by atom in ^{10}B is equivalent to $(0.90 \cdot 3840/5327 =)$ 0.649 atm. of ^{3}He. BF_3-filled proportional counters are often manufactured using copper tubes. The absorption of neutrons in the wall can be scaled from that in stainless steel using macroscopic absorption cross section, although for most practical purposes the difference is inconsequential. The macroscopic absorption cross-section for Cu is approximately 25% greater than for stainless steel. Thus for a tube wall of a given thickness the absorption in the copper will be approximately 25% greater in the case of copper [the corresponding scaling factor is $f_w = (0.911 \pm 0.021)^t$].

Conclusion

In this note we have considered the specification of ^{3}He filled cylindrical proportional counters according to either the (cps/nv) sensitivity, S, or the (D, P, L) designation. The two approaches are equivalent and redundant ways of specifying the counting rate of high aspect ratio detectors (L/D>>1) in an unperturbed free field thermal flux. In a manufacturing environment it is more pertinent to set production values and tolerances on (D, P, L) than it is to target a particular S-value. In practice, S-values are difficult to determine experimentally and so we have seen, do not uniquely relate to the counting efficiency per source neutron in a particular moderator configuration.

All commercially available ^{3}He counters are made using highly pure helium enriched to greater than 99.9% in the ^{3}He isotope. Therefore variation in the enrichment from one production batch to another is utterly negligible.

Internal cathode tube diameters, D, are usually known to within a small fraction of a millimeter, the relative standard deviation (σ_D/D) therefore being less than a fraction of 1%. Active lengths (defined by the distance between the guard rings at each end of the anode wire and which are designed to control the region of high gas gain) have a nominal standard deviation of less than 0.7mm due to manufacturing tolerance for the detector types taken as illustration here. The pressure can be controlled to a fraction of 1% provided a suitable quality control program is in place for routine calibration of the transducers and the values are temperature-compensated at the time of filling. Given these manufacturing controls the relative sensitivity within a typical production batch of ^{3}He tubes (e.g. 25.5mm OD, 4atm. ^{3}He, 300 active length or 50.8mm OD, 2atm., 1000mm active length) or between batches will be insignificant for most Safeguards, waste assay and homeland security applications. That is the ^{3}He counters may be treated as interchangeable components with respect to counting efficiency. We have used the MCNP™ Monte Carlo transport code to generate values for the wall attenuation in the cases of Al and stainless steel. These are consistent with sleeve experiments. The universal curve $(S/D{\cdot}L.f_w) = \pi{\cdot}\varepsilon(P{\cdot}D)$ may also be generated by Monte Carlo simulation. For convenience, a simple interpolation scheme based on a self-shielding factor formulation was constructed. Calculations were presented over a range P·D values. The formalism will allow the sensitivity, S, to be estimated for a wide variety of ^{3}He specifications. This is useful information when first-order system-design cost-benefit trade-off decisions are being considered.

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