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Evaluation of a 14 MeV Neutron Lead Probe Detector

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SUMMARY & CONCLUSIONS

We present an evaluation of a lead probe detector used within the Nuclear Security Enterprise (NSE) to estimate the total number of 14 MeV neutrons produced by a laboratory neutron source. A brief discussion of the instrumentation and the traceability chain for this measurement is given. The measurement test plan and results of an uncertainty analysis are also presented, based upon techniques outlined in the JCGM 100 *Guide to the Expression of Uncertainty in Measurement.*

Key results from this analysis were that the measurement uncertainty could be reduced by reducing the uncertainty in an attenuation factor or by increasing the net scalar counts per source neutron. Results from this study will be used in ongoing discussions regarding how this critical measurement may be improved.

1 INTRODUCTION

Critical measurements of 14 MeV neutrons are made within the Nuclear Security Enterprise (NSE) in support of product qualification, acceptance testing, and ongoing surveillance testing. All of the detectors used for these measurements are calibrated to a lead probe standard. It is therefore vital that the performance of the standard is well understood. This paper describes the evaluation of this standard in a laboratory “best case” setting. The instrumentation, traceability chain, test plan, and results of a measurement uncertainty analysis are presented.

2 INSTRUMENTATION AND TRACEABILITY

2.1 Instrumentation – Measurement of 14 MeV Neutrons

Neutrons do not produce electric fields, making them difficult to detect. Their presence can be detected only through interactions with surrounding materials such as silicon, certain gasses and lead. Detectors are thus built with materials that are known to interact with neutrons. Multiple measurement schemes for detecting low energy (“slow”) and high energy (“fast”) 14 MeV neutrons are described in reference [1]. The measurement techniques used for slow neutrons are often not viable for high energy neutrons, as higher energies decrease the probability of an interaction. The detector used within the NSE to measure high energy neutrons uses lead material and is known as a lead probe detector. This detector is used because of its traceability to an “exact” standard, and its relative portability. The lead probe neutron activation (scalar) detector counts the decay-product gamma-rays from the neutron activation of lead to measure total neutron fluence [2]. Figure 1 shows the basic design of a lead probe neutron detector. The lead surrounds a plastic scintillator in an approximately 1” thick sheath. Neutrons from the pulse hit the lead and create meta-stable, activated atoms that decay back to a stable state by emitting gamma-rays. The gamma-rays excite the plastic scintillator, creating light that is captured by a photocathode and amplified into a current signal by a photomultiplier tube (PMT). Counting the total number of PMT pulses in a time period equal to approximately 3 half-lives of the decaying lead atoms can, with proper calibration of the measurement setup, provide a count of the total number of neutrons produced in the pulse.

A second PMT is used to provide a real-time current representation of the neutron pulse (Figure 2). Neutrons from the pulse that directly interact with the atoms in the scintillator produce light. The light is converted to electrons by a photocathode that are amplified into a current signal by the PMT. The ratio of the area of the real-time PMT waveform to the total number of decay pulses counted from the scaler detector allows the experimenter to convert the real-time waveform from volts per unit time to neutron output per unit time. This neutron rate is the critical measurement used to assess the performance of neutron generators produced within the NSE.

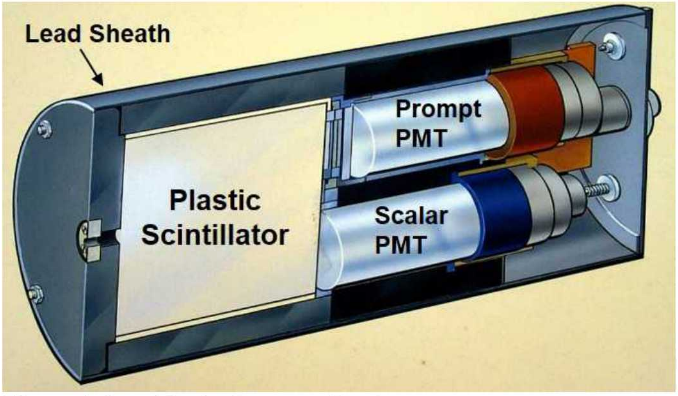

Figure 1. Lead Probe Detector Design

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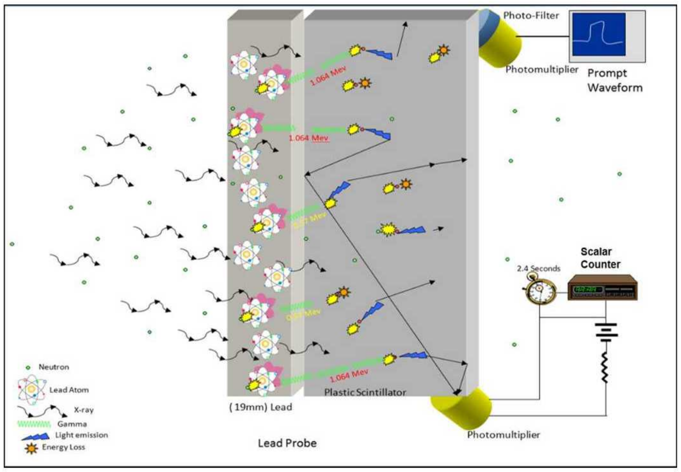

Figure 2. Lead Probe Function

2.2 *Traceability Chain – Measurement of 14 MeV Neutrons*

The calibration of lead probe neutron detectors begins at an ion beam laboratory. The ion beam uses the associated particle technique for neutron measurement. This measurement technique detects the recoil product of a fast neutron transferring a portion of its kinetic energy to a nucleus coincidence with detecting the neutron itself. The time interval between the detection of a neutron and the detection of its recoil is measured, and from this time interval the neutron energy is calculated. This allows a neutron flux rate to be established as a standard.

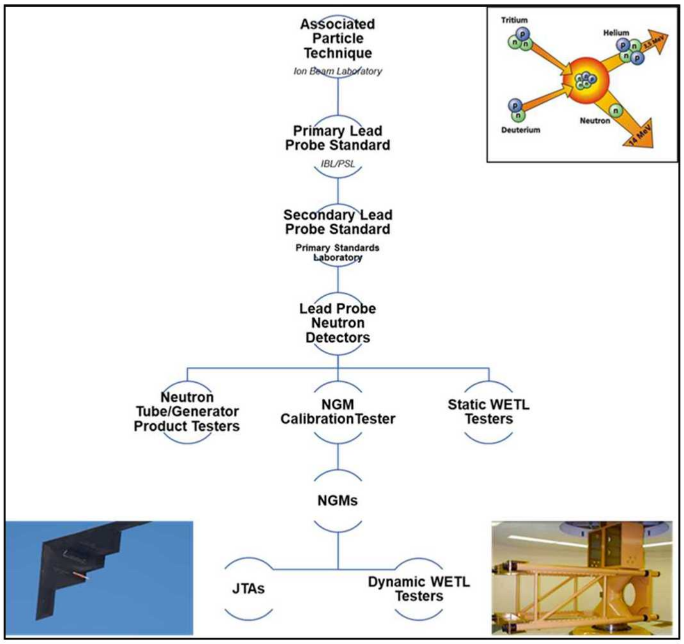

Figure 3. Traceability Chain for 14 MeV Neutron Flux Measurements

The primary lead probe standard is calibrated using a neutron source measured via the ion beam standard. The primary lead probe standard is in turn used to calibrate the secondary lead probe standard. The secondary lead probe is then used to calibrate all the tertiary lead probe neutron detectors used in product acceptance and surveillance testing. This traceability chain is illustrated in Figure 3. It is the uncertainty of the secondary lead probe that is of interest in the study below.

3 ESTIMATING LEAD PROBE UNCERTAINTY BY THE PROPAGATION OF ERRORS

3.1 Measurement Equation and Propagation of Errors

In this section we provide an overview of the uncertainty analysis of the secondary lead probe standard. For additional details, see [3]. The analysis follows the methodology outlined in the JCGM 100 *Guide to the Expression of Uncertainty in Measurement* (a.k.a., the GUM) [4].

The equation that is used to convert lead probe counts into neutrons is:

$$n = AfF(S - B). \qquad (1)$$

In equation (1),

n = Total number of 14 MeV neutrons produced at the target

A = Factor to account for differences in the neutron attenuation between source and detector in different measurement geometries ≅ 1.0

f = Nominal conversion value (≅ 3300 neutrons per output count)

F = Calibrated modifier of the nominal lead probe conversion factor for a specific measurement geometry ≅ 1.15

S = Total scalar counts from the lead probe

B = Background counts from lead probe.

A general form for the total (expanded) uncertainty (U_n) in a neutron measurement is based upon the root-sum-of-squares of both Type A and Type B uncertainties associated with the measurement as given by the following expression:

$$U_n = t_{97.5}(\nu) \cdot \sqrt{u_A^2(n) + u_B^2(n)}. \qquad (2)$$

In this expression,

U_n = Total neutron measurement uncertainty (95% confidence)

$t_{97.5}(\nu)$ = 97.5th percentile of the central t-distribution with ν degrees of freedom

$u_A(n)$ = Type A standard uncertainty

$u_B(n)$ = Type B standard uncertainty.

The terms that appear in equation (2) are determined by "propagating" the errors (both Type A and Type B uncertainties) associated with each variable in measurement equation (1) above. The propagation of errors approach is basically an analysis of how measurement errors in each of the variables $A, f, F, S,$ and B in equation (1) contribute to the uncertainty in the calculated neutron measurement.

Standard GUM techniques are applied to measurement equation (1) to generate estimates of both Type A and Type B uncertainties. Type A uncertainties are those based on the statistical analysis of the present experimental data, and the Type B uncertainties are all other uncertainties. These (Type B) uncertainties are typically derived from sources such as previous experience with similar instruments, previous measurement data, manufacturer's specifications, calibration certificates, and reference data from handbooks.

3.2 Experimental Test Plan and Results

The test plan consisted of forty scalar measurements taken at each of twenty-five different levels of neutrons between roughly 0.4 million and 19 million neutrons (see Table 1 below). The neutron source was set at the desired level of neutrons for each shot. Ten background radiation measurements were taken using the lead probe immediately before the forty scalar measurements. The forty shots were made within an hour or two on the same day, and the entire experiment was completed within a few days. The photo below (Figure 4) shows the laboratory test setup.

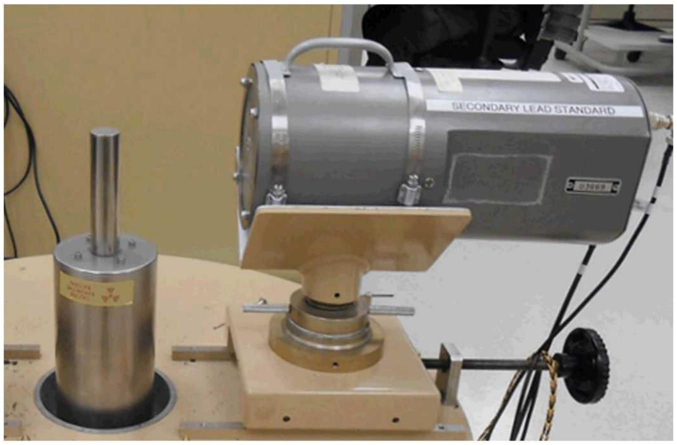

Figure 4. Test setup with neutron source and lead probe. The neutron source is pointed vertically up, with the lead probe set at a 90-degree angle approximately six inches from the source.

Table 1 below displays the total (U_n) and relative measurement (U_n/n) uncertainty of the lead probe over the range of total neutrons produced by the laboratory neutron source. Figure 5 shows the same data plotted as a function of lead probe scalar counts. These values represent the nominal best-case scenario for measuring neutrons with the lead probe detector. Use of the lead probe in other configurations will result in a different estimate of uncertainty due to geometry effects, neutron attenuation effects, etc.

(S-B)	n	U_n	U_n/n
100	3.83 E+05	1.85 E+05	48.2%
150	5.75 E+05	1.95 E+05	33.9%
200	7.67 E+05	2.05 E+05	26.8%
300	9.58 E+05	2.16 E+05	22.5%
350	1.15 E+06	2.27 E+05	19.7%
400	1.53 E+06	2.49 E+05	16.3%
500	1.92 E+06	2.73 E+05	14.2%
600	2.30 E+06	2.97 E+05	12.9%
800	3.07 E+06	3.46 E+05	11.3%
1000	3.83 E+06	3.96 E+05	10.3%
1200	4.60 E+06	4.47 E+05	9.7%
1400	5.37 E+06	4.98 E+05	9.3%
1600	6.13 E+06	5.50 E+05	9.0%
1800	6.90 E+06	6.02 E+05	8.7%
2100	8.05 E+06	6.80 E+05	8.5%
2400	9.20 E+06	7.59 E+05	8.3%
2600	9.97 E+06	8.12 E+05	8.1%
3000	1.15 E+07	9.17 E+05	8.0%
3400	1.30 E+07	1.02 E+06	7.9%
3800	1.46 E+07	1.13 E+06	7.8%
4000	1.53 E+07	1.18 E+06	7.7%
4200	1.61 E+07	1.24 E+06	7.7%
4600	1.76 E+07	1.34 E+06	7.6%
4400	1.69 E+07	1.29 E+06	7.6%
4800	1.84 E+07	1.39 E+06	7.6%

Table 1. Uncertainty in lead probe measurements with 95% confidence

Note that as the scalar count $(S - B)$ increases the *absolute* uncertainty also increases, but the *relative* uncertainty (U_n/n) decreases from roughly 50% to roughly 7.5%.

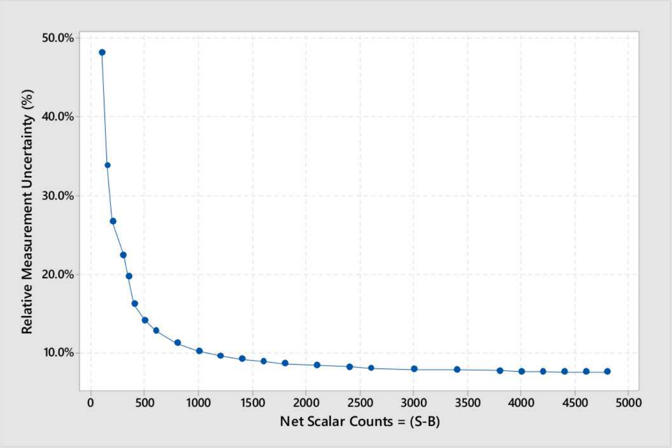

Figure 5. Relative Uncertainty (U_n/n) in Lead Probe Neutron Measurements (95% confidence).

A comparison of the Law of Propagation method and the Monte Carlo method (see the JCGM 101 GUM) showed that the two methods agree within 0.1% across the neutron count levels considered [5].

An important part of the uncertainty analysis is to identify which variables in the measurement equation (1) are responsible for most of the uncertainty in the measurement. Knowledge of the relative "components of variation" can suggest ways to improve the measurement. Key results from this analysis were that the measurement uncertainty could be reduced by reducing the uncertainty in the attenuation factor A or by increasing the net scalar counts per source neutron (i.e., reducing f).

ACKNOWLEDGMENT

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