AWE BONNER SPHERE MEASUREMENTS OF THE NEUTRON LEAKAGE SPECTRUM FROM THE GODIVA-IV CRICITAL ASSEMBLY AT NCERC

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ABSTRACT

The US National Criticality Experiments Research Centre (NCERC) is home to several critical assembly machines that were relocated from Los Alamos National Laboratory in the last decade. The centre is sponsored by the Department of Energy's Nuclear Criticality Safety Program (NCSP), which has the mission to ensure the safe handling of fissile materials from a criticality perspective.

Under the auspices of the NCSP, Lawrence Livermore National Laboratory (LLNL) is planning to host an international inter-comparison of nuclear accident dosimetry (NAD) using the Godiva-IV assembly at NCERC. The inter-comparison is motivated by a decline in the frequency of performance testing of NADs (both in the US, the UK and France) and the desire to modernize and harmonize dosimetry systems.

A pre-requisite for the inter-comparison is the characterisation of the neutron and gamma-ray leakage spectra associated with the Godiva-IV assembly at NCERC. AWE provided its Bonner-sphere spectrometry capability to LLNL for two experimental campaigns, in November 2013 and May 2014, to measure the neutron leakage spectrum of the assembly in both a sub-critical "steady-state" and a super-prompt-critical "burst". Nine points, at distances from 2 to 4 meters from the machine were measured with the Bonner-sphere spectrometer using both an active He-3 detector and a passive technique employing gold foils. This paper presents the spectra unfolded from the data and integral dose values, and compares these to previously published data. The limitations of the work and future plans are also discussed.

KEYWORDS
NAD, dosimetry, accident, neutron, spectrometry

1. INTRODUCTION

The system of Criticality Accident Dosimetry (CAD) used throughout the UK nuclear industry is based on a dosemeter developed by the UK Atomic Energy Authority, Harwell in the early 1960s [1]. In recent years the dosemeter has been maintained and developed by the Criticality Accident Dosimetry Users Group (CADUG), which has representatives from most of the UK nuclear licensed sites requiring accident dosimetry. On behalf of CADUG, the Atomic Weapons Establishment (AWE) is engaged in a programme of development of the dosimetry system to mitigate the effects of obsolescence and establish a more sustainable CAD system for the UK nuclear industry.

A pre-requisite for any development is the need for experimental facilities to test innovations and reassure the Health and Safety Executive (HSE) – who regulate dosimetry in the UK – that the system meets requirements [2]. With this purpose in mind AWE has been collaborating with Lawrence Livermore National Laboratory (LLNL) to establish the capability to perform dosimetry inter-comparisons utilizing experimental facilities funded by the US Department of Energy's Nuclear Criticality Safety Program (NCSP).

The NCSP's mission is to maintain and develop the technical infrastructure necessary to ensure safe, efficient operations from a criticality safety perspective. To this end, the NCSP has established the National Criticality Experiments Research Centre (NCERC) at the Nevada National Security Site. In the past decade, several of the critical assembly machines previously hosted at Technical Area 18 of the Los Alamos National Laboratory (LANL) have been relocated and refitted at NCERC. The NCSP is open to collaboration and has developed an administrative framework for the design and execution of critical and sub-critical experiments ($C_E$dt), and has built a web portal for the submission of Integral Experiment Requests (IERs) [3].

Heinrichs *et al.*, proposed an international inter-comparison for nuclear accident dosimetry using the Godiva-IV assembly at NCERC (IER-148) [4]; a pre-requisite for this was the characterisation of the leakage radiation field during a super-prompt-critical burst of the reactor, and this was submitted as a separate experiment (IER-147) [5]. AWE was invited to participate in IER-147 and offered to assist LLNL in the measurement of the neutron leakage spectrum from Godiva-IV. The experiment design is briefly described below. Full measurement results will be published elsewhere and are outside the scope of this paper, which will focus on the neutron spectrometry conducted with the Bonner sphere spectrometer fielded by AWE.

2. THE EXPERIMENT DESIGN

The performance criteria for nuclear accident dosemeters (NADs) is specified in ANSI-HPS-13.3 [6]; the standard mandates that for a performance test the dosemeter should be capable of measuring the total absorbed dose with an accuracy of +/- 25 %. Consequently the reference values in the Godiva-IV field need to be determined with an uncertainty less than +/- 10 %.

To obtain a complete picture of the radiation field measurements were made along 3 contours; at 2, 3 and 4 m from the centre of the Godiva-IV assembly. Along each contour 3 reference locations were established so that any anisotropy in the field could be mapped. The locations were enumerated from the innermost to the outermost points, as shown in Figure 1. Location 6 was originally intended to be at 3 m but, due to physical constraints in the irradiation cell, it was moved inwards to 2.5 m. In addition to the measurement of the spectra at various distances, it was also considered necessary to measure the linearity of the total fluence as a function of the number of core fissions – or some other core parameter – and also to measure the anisotropy in the field as a function of height.

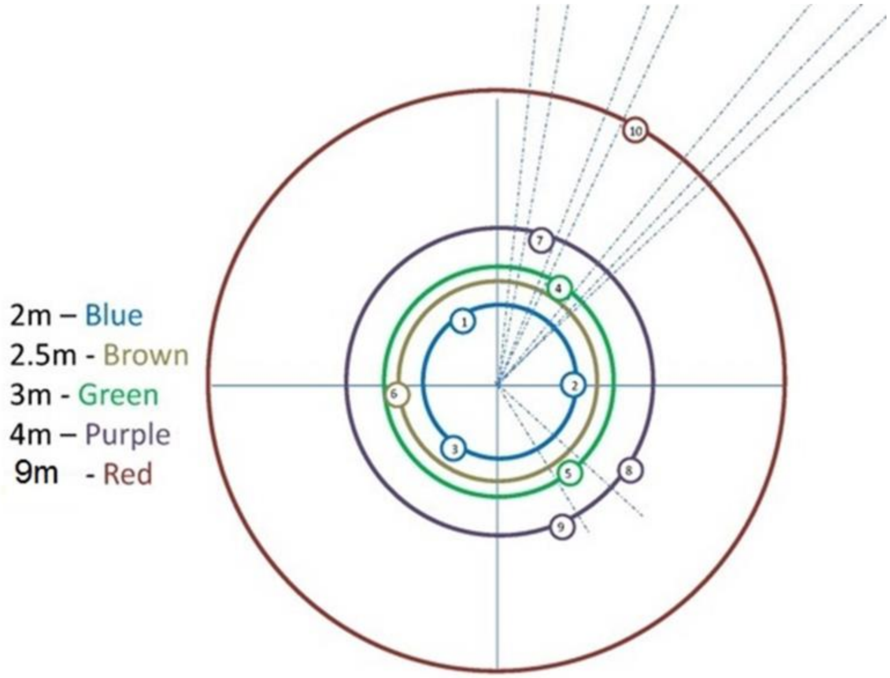

Figure 1: A stylized schematic of the layout of the reference locations

At the time of the proposal LLNL did not have the capability to deploy accurate neutron spectrometers in a high-dose pulsed radiation field therefore the characterisation campaign was divided into two experiments; in the first, Godiva-IV was operated in a sub-critical configuration with a Cf-252 source as a driver, to allow the deployment of active neutron spectrometers; in the second, the assembly was operated in the super-prompt-critical burst configuration and UK and US NADs were deployed, as well as a passive neutron spectrometer that was validated for this purpose by AWE.

2.1. Sub-Critical Measurement Methods

For the sub-critical experiment the principal detector system was the RoSpec neutron spectrometer [7], two of which were used; AWE deployed one unit, and LLNL deployed another. The two units were manufactured several years apart but were physically very similar and contained the same number and type of detectors, therefore it was anticipated that data measured with the two devices should be comparable. The RoSpecs were rotated through the 9 reference locations, such that repeat measurements were taken for each point in the field.

For the RoSpec measurements, the machine was configured to provide the maximum dose rate that could be tolerated without dead-time losses, which was around 4 mSv / hr, corresponding to a machine current of $8.5\text{x}10^{-11}$ Amps. At this dose rate, the machine had to be operated remotely and this increased the time taken for each measurement due to the safety procedures associated with entry and exit of the irradiation cell. The RoSpecs require a large number of counts ($10^5 – 10^6$) in each detector to minimize uncertainties in the unfolding process [8] therefore each run was between 1 and 2 hours in duration.

AWE also deployed a Bonner Sphere Spectrometer (BSS) using a ^{3}He proportional counter as the detector element. The sensitivity of the BSS is much greater than the RoSpec therefore it only requires short counting times (less than 1 minute in this case) but frequent user interaction. Consequently, the

BSS could not be deployed concurrently with the RoSpecs and BSS measurements were constrained to a few hours on the final day of the experiment. The machine was operated locally in a low-current mode 2.58×10^{-12} Amps) that allowed easy access to the spectrometer to change the spheres. However, even in the short time available 5 reference points were measured.

The analysis of the RoSPEC data will be omitted here but examples of the results are shown where comparison with the BSS data is illustrative of the accuracy of the systems.

2.2. Super-Prompt-Critical Measurement Methods

During the initial period of experiment design it was recognized that the AWE BSS could be modified to create a passive BSS (pBSS) by using a gold foil as the detector element. AWE completed a programme of modification and validation of the pBSS [9] and deployed it for the second phase of the characterisation campaign.

The pBSS has 9 spheres therefore it was possible to deploy all spheres simultaneously – one at each reference point – for a single burst of the Godiva-IV assembly. After each burst, the spheres were rotated through the points until each location had a complete set of measurements.

The number of machine cycles required to get a full set of pBSS data limited the measurements to a single burst magnitude and height, therefore the AWE and LLNL NADs were used to determine the linearity of the dose and the anisotropy of the field as a function of height. The results of the dosemeters will be reported elsewhere.

3. RESULTS

3.1. Sub-critical Measurements

All of the sub-critical measurement data was normalized to an arbitrary machine current of 8.5×10^{-11} A because this was the initial machine condition for the RoSpec measurements. The BSS data was initially unfolded using the parameterized unfolding code developed by AWE [10] and a comparison of the spectra at locations 2, 2.5 and 4 m from Godiva is shown in Figure 2. The spectra show the relative decline in the fast region as the distance from the reactor increases. In Figure 3 the three spectra obtained at locations 2 m from the assembly are shown; there is little observable difference, which demonstrates both the isotropy of the field and the accuracy of the measurement. Finally, in Figure 4 a comparison is made between the RoSpec spectrum and the BSS spectrum, re-formatted into the RoSpec bin structure. The spectra from the two devices are similar but the RoSpec measures a wider fission peak than the BSS.

The spectra were folded with dose-conversion coefficients for ambient dose equivalent, $H^*(10)$ from Ref. [11] and integrated across the full energy range to give a dose rate. The average dose measured with the BSS for locations at 2 m was 4.34 mSv / hr with a relative standard uncertainty of 1.2 %. For the same locations the RoSpec gave measured an average of 4.20 mSv / hr with a relative standard deviation of 1.3 %.

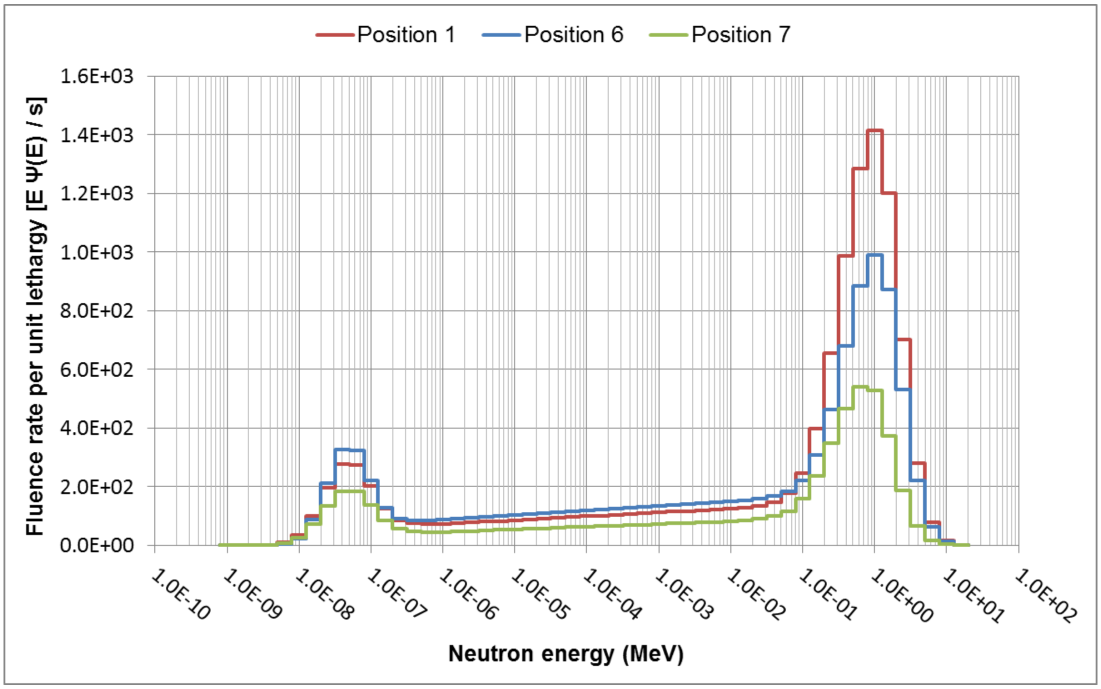

Figure 2: Spectra for locations 2, 2. 5 and 4 m from the Godiva-IV assembly

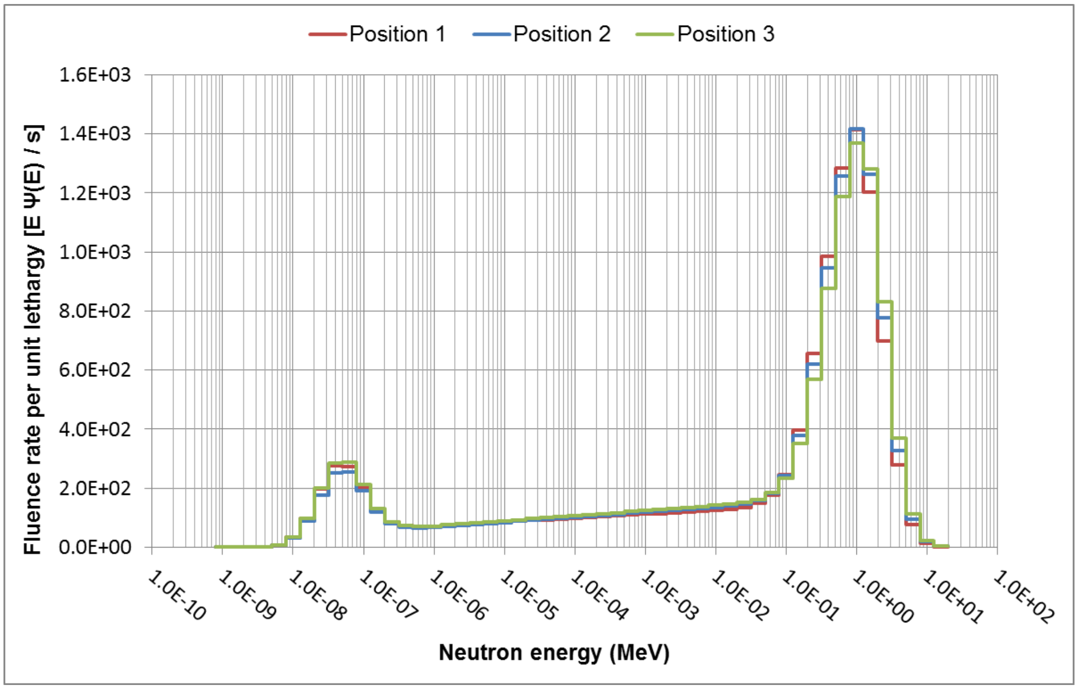

Figure 3: Spectra measured for locations along a contour 2 m from the Godiva-IV assembly

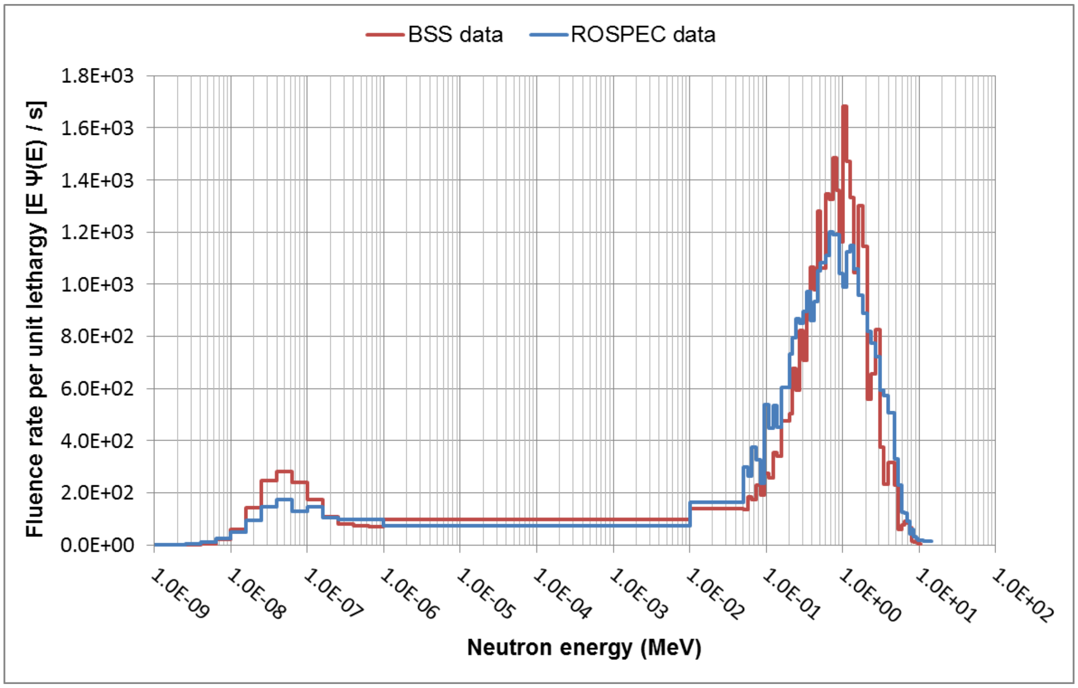

Figure 4: Comparison of spectra measured for position 1 using the BSS and the AWE RoSpec

3.2. Super-prompt-critical Measurements

All locations were measured with the pBSS during the second phase of the characterisation. The 9 critical excursions required to obtain the complete data set had a mean temperature rise of 69.1^{o}C with a standard deviation of 2.2^{o}C so the data from the detector in each sphere was normalized to a nominal 70^{o}C. The data for individual detectors were combined and de-convolved using the MAXED code [12]. Figure 5 shows the spectra measured at each distance from the reactor; 2, 2.5, 3 and 4 m. Figure 6 displays the spectrum for positions along the 4 m contour and demonstrates the isotropy of the neutron field, as observed in the sub-critical data for the 2 m contour. Similar data for positions 4 and 5 – at 3 m – provide further confirmation of the isotropy of the field.

The spectra were folded with fluence-to-dose conversion coefficients for tissue kerma from Ref. [13] and integrated. The average dose for locations at 2 m was 1.54 Gy with a relative standard deviation of 2.2 %. This reduces to 0.89 Gy (+/- 1.2 %) at 3 m and 0.64 Gy (+/- 1.6 %) at 4 m.

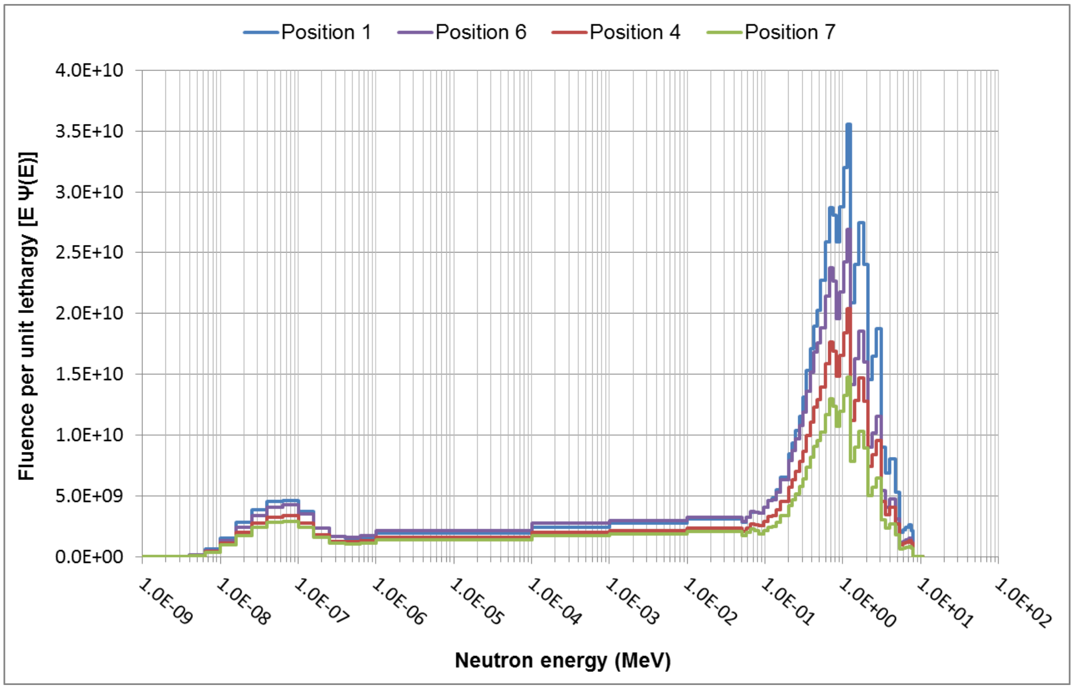

Figure 5: Spectra measured at 2, 2.5, 3 and 4 m from the Godiva-IV assembly during a super-prompt critical burst

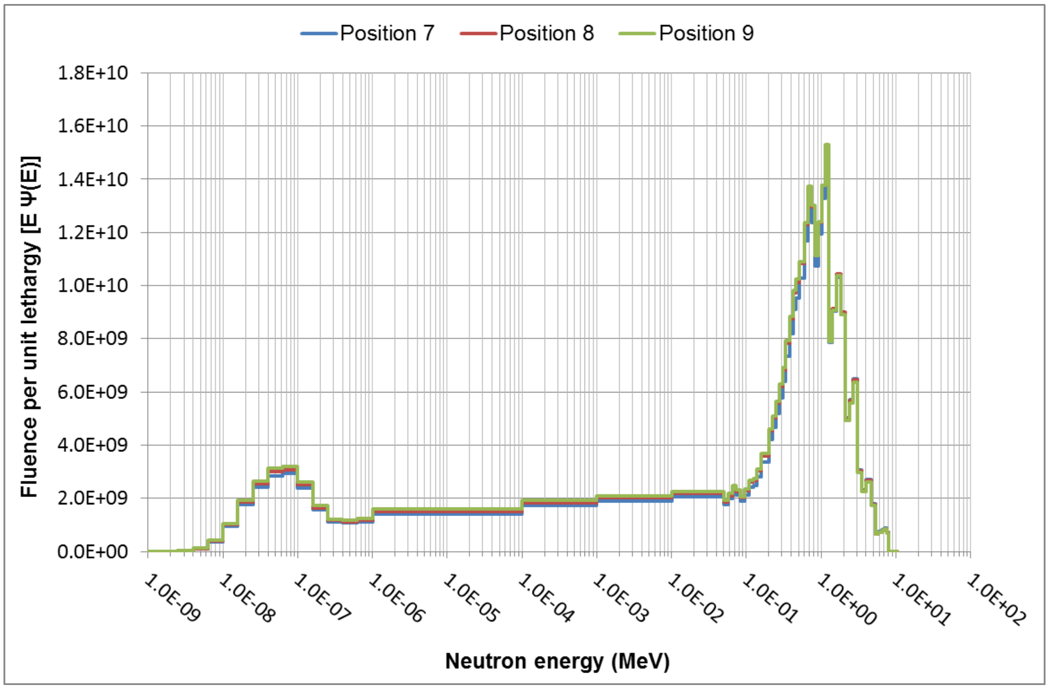

Figure 6: Spectra measured along the 4 m contour demonstrate the isotropy of the neutron field

4. DISCUSSION

The Bonner sphere measurements produced self-consistent results that were confirmed by other measurement techniques. In the case of the sub-critical measurements the BSS and RoSpec integrated dose data differed by only 3.3 %, although the shape of the fission peaks did not exactly match. This deviation could be due to the different unfolding techniques used by the devices and is an area where further exploration of the data could prove valuable.

The spectra for different locations along a common contour were found to be nearly identical, which suggests that the field was isotropic. If that was the case then the measurements of points along a contour can be considered as repeat measurements of the same quantity, from which the uncertainty in the measurement system can be assessed. In the case of the sub-critical data the standard deviation of the integrated ambient dose was 1.2 %, and for the pBSS data the standard deviation for measurements along a contour did not exceed 2.2 %. This suggests that the expanded relative uncertainty of the measurement technique is less than 5 %.

It was found that the integrated dose as a function of distance does not follow the inverse-square law but shows significant enhancement due to scattering. The magnitude of the enhancement is dependent on distance and at 4 m the observed dose is 75 % greater than the dose calculated using the value at 2 m scaled according to the inverse-square law. The data is shown in Table 1, below.

Table 1: The integrated dose as a function of distance from the reactor, compared with an inverse-square calculation

Distance	H*(10) (measured)		H*(10) (inverse square)		Relative enhancement	
m	BSS (msv / hr)	pBSS (Sv)	BSS (msv / hr)	pBSS (Sv)		
2	4.34	24.23	4.34	24.23	1.00	1.00
2.5	3.13	18.58	2.78	15.51	1.13	1.20
3		14.41	1.93	10.77	-	1.34
4	1.65	10.52	1.09	6.06	1.52	1.74

A comparison of the BSS and pBSS measurements shows small deviations in some energy bins (see Figure 7) but overall the structure is very similar. During the sub-critical measurements there was several tons of copper in the irradiation cell for another experiment and this may have increased scattering of fast neutrons, causing the observed broadening of the fast peak. This is another area where further investigation could be valuable.

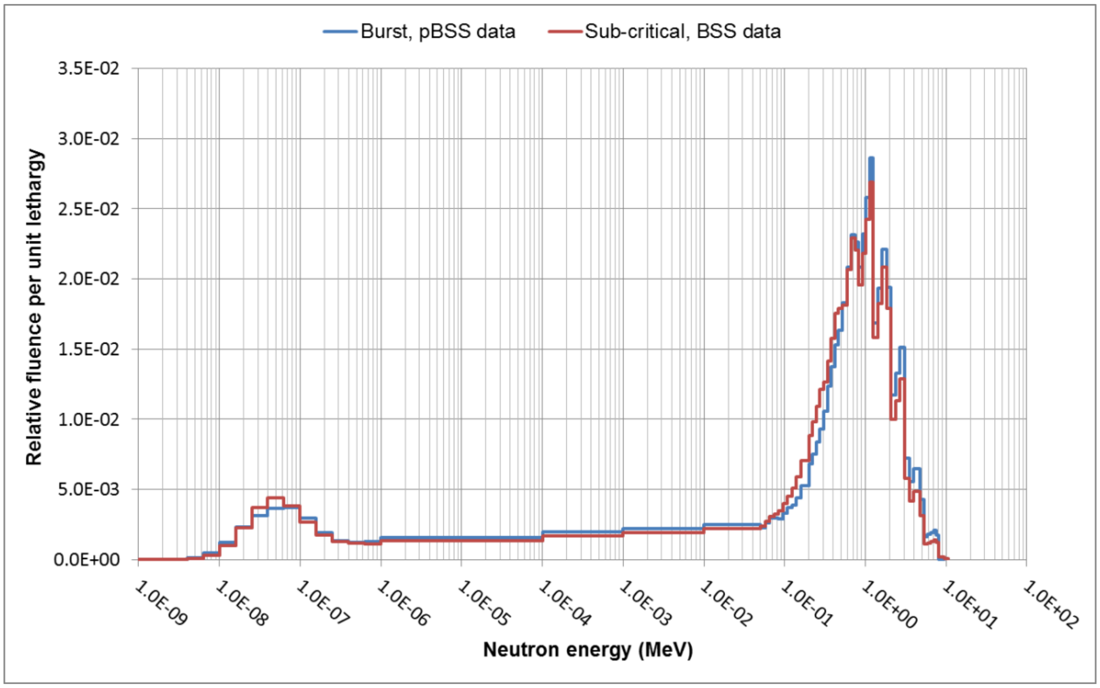

Figure 7: A comparison of the spectra measured in the sub-critical and super-prompt-critical configurations with the BSS and pBSS, respectively

The similarity of the spectra measured in the two configurations suggests that the fluence measurements can be used as a means of correlating the current measured in the sub-critical configuration with the number of fissions in the super-prompt-critical configuration. During the second phase of the campaign the number of fissions in the core was derived from measurements on a fission foil placed in Godiva's glory hole. For a nominal ΔT of 70°C the average number of fissions measured for 15 bursts was 1.45×10^{16} with an expanded relative uncertainty of 9 % (k = 2.13). Taking the average ambient dose equivalent per fission measured with the pBSS and comparing with the ambient dose equivalent rate per pA measured with the BSS gives a value of 2.9×10^{22} fissions / A hr. This implies that during the sub-critical measurements with a nominal current of 8.5×10^{-11} A, the fission rate was 2.4×10^{12} fissions / hr. The standard uncertainty on the ratio correlating the fission rate and with current is not known precisely but it is likely to be dominated by the uncertainty in the fission foil measurements, and is therefore approximately +/- 10 % for the 95 % confidence interval.

The fission foil data can also be used to compare the measured dose data with other sources. Trompier *et al.* [14] characterized the CALIBAN reactor for mixed-field dosimetry work; the results from that experiment are presented in Table 2 along with the data measured with the pBSS. The uncertainties for all of the data are given for one standard deviation and the Godiva-IV data is significantly less certain than the results from CALIBAN due to the uncertainty on the true number of fissions. The two assemblies are very similar in terms of the fuel used and the construction, although CALIBAN is around twice the overall mass of Godiva-IV, therefore some differences in the spectra were anticipated. The similarity of the two data sets illustrates the accuracy of the measurement techniques.

Table 2: A comparison of Godiva-IV data with CALIBAN

Assembly	Neutron tissue kerma (10^{-16} Gy fissions^{-1})		
	2 m	3 m	4 m
Godiva-IV	1.06 (0.04)	0.62 (0.04)	0.44 (0.04)
CALIBAN (measured)	1.15 (0.01)	0.54 (0.01)	0.39 (0.01)
CALIBAN (calculated)	1.09	0.59	0.41

5. CONCLUSION

The AWE Bonner sphere measurements of the Godiva-IV neutron leakage spectrum have successfully established reference dose values with an expanded relative uncertainty less than 5 %. The measurement of the spectrum at multiple points along a contour demonstrates that the field is isotropic; and the change in the field as a function of distance from the assembly has been quantified. A comparison with data from sub-critical and super-prompt-critical configurations has allowed a derivation of the fission rate per Amp of current measured in the core in the sub-critical configuration, which may prove useful in future studies of the assembly.

The reference values for the Godiva-IV critical assembly machine will be used to underpin nuclear (criticality) accident dosimetry systems in the US, UK and France through a programme of inter-comparisons. It is hoped that the data could also be incorporated into a benchmark criticality safety evaluation and used for future studies into criticality accident alarm systems (CAAS).

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