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Initial Measurements of Site Boundary Neutron Dose and Comparison with Calculations*

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Introduction

For most accelerators adequate side shielding can be provided at minimal cost to meet the most aggressive radiation protection regulations and, further, the likely requirement to increase shielding thickness still more at a later date can be done usually by heaping more earth or applying local shielding at minimal expense and inconvenience. This moderately happy state of affairs does not unfortunately hold true with roof shielding. The cost of roof shielding is largely predicated on the roof span and the necessary structural engineering requirements for its support. These measures can be extremely expensive and where one is dealing with the rather extensive unsupported spans typical of experimental halls devoted to experiments with high energy electron beams; it is necessary to specify the roof thickness as carefully as possible with the constant concern that adding more earth later is not likely to be possible without rebuilding the hall. Because of the nature of roof skyshine, and for most high energy accelerator facilities neutron skyshine, the effect of the radiation is likely to extend to the facility fence-line where one is concerned about the exposure of the general population. Very properly the dose limit for the general population is set at a rather low value (1 mSv y^{-1}) and in order for the Jefferson Lab., (JLab) to ensure strict compliance with this limit we have a design goal for the fence line of 0.1 mSv y^{-1}. However, because natural neutron backgrounds are low (30 - 40 μSv y^{-1}) and the methods of detection and measurement permit rejection of background interference from photons, we can measure the JLab produced neutron radiation with good sensitivity and precision.

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† The Thomas Jefferson National Accelerator Facility (previously the Continuous Electron Beam Accelerator Facility - CEBAF) is informally called the Jefferson Laboratory (JLab). The existing accelerator facility at Jlab is still referred to as CEBAF.

Therefore, we are able effectively to track throughout the year any dose increments attributable to CEBAF operations to ensure that the overall increment to the annual dose equivalent at the fence post remains very low.

In an interesting analogy we can keep a set of radiation "account books" in which our annual (calendar year) "budget" is 0.1 mSv. We make "estimates of expenditure" by means of calculations which involve knowledge of the experiment conditions; beam energy, current, target material and thickness, any additional radiators or insertions such as windows and beam pipe filling gas and very importantly the angular acceptance of the beam dump channel. A computer code has been written by Stapleton (ELEC5 - Stapleton 1996) which permits radiation dose rates at all JLab boundary monitor positions for the specified experiment to be estimated (Degtyarenko and Stapleton 1995). These dose estimates, taking into account the time required for experiment set-up, permit us to manage our budget throughout the year, timing out or modifying rather costly experiments in good time to prevent serious budgetary "over-runs". Still more in line with the financial accounting analogy is the provision of "actual expenditure" figures by making measurement of neutron dose rates throughout the year. It is after all the actuals that tells us whether or not we have achieved our annual budgetary goal or whether we have to ask for a "supplemental" - always being very careful to keep well below the population limit.

The purpose of this paper therefore is to present our actuals for a portion of the first year when experimental activities gave rise to measurable dose rates, and to compare some of these data with actual experiment conditions and the estimates that were calculated. A further concern with this and subsequent studies is to verify that the shielding provided by the experiment end station roofs meets our design specification and that our monitoring instruments can perform adequately in keeping a good set of radiation account books.

Radiation Monitors

The location of the boundary monitors is shown in figure 1. The monitor detectors are based on the $He^3(n,p)H^3$ reaction. Because the spectrum of scattered neutrons arriving at the monitor extends to the fast neutron region it is necessary to provide a moderating sheath around the detector. The moderator is also designed to provide a response which matches approximately the dose equivalent. The design of Andersson and Braun is used and this is considered to function reasonably for a neutron spectrum extending from thermal energies to about 10 MeV (Andersson et al. 1964).

The primary source of data from the fence post monitors lies in "history files" which contain a running total of all counts recorded since an initial reset time. The history data files which are collected from each fence post monitor by the central radiation computer (CPU) system are organized into 1 minute, 10 minute, 1 hour and 1 day (24 hour) total increments. Each poll of the boundary monitor by the CPU results in an up-dated electronic record of total counts accumulated by the boundary monitor since it was last reset. Thus, the record stored in each of the history files is independent of CPU data manipulation. It is a direct reading of the data sent from the monitor itself.
Because the "count" is the smallest increment of dose detected, it is the count that can be used for statistical analysis and therefore all the results are treated as "counts" rather than converting to dose. On calibration the boundary monitors were all found to lie within specification after a year of continuous operation.

The counts are integers so the summation of 60 minute totals results in exactly one hourly total and 24 one hour totals results in exactly a one day total etc. Thus we are able to sum up counts (and ultimately radiation dose) for any time interval or time "window" to the nearest minute to provide estimates of background or estimates of boundary dose to match any given machine or end station operational time window.

Results

The results for the first two quarters of the current year are given just for radiation boundary monitor (RBM) positions RBM-1, RBM-2 and RBM-3 because the other three detectors were not fully on-line and they are rather further away from the radiation sources.

The total neutron dose equivalent determined in the first quarter (Jan., Feb., Mar.,) are included in the following table for the three monitor positions:

monitor position	total dose (μSv)
RBM-1	0.26
RBM-2	0.70
RBM-3	4.32

and for the second quarter of calendar year 1996 (April, May, June):

monitor position	total dose (μSv)
RBM-1	0.66
RBM-2	1.89
RBM-3	7.55

These results have had background subtracted and it would appear that at the end of June 1996, we were well within our radiation budget, however, it must be remembered that the experimental program had only just started and there were significant gaps in the time schedule for beam physics and setting up conditions; this means that the results could be much lower than would be expected from a more aggressive experimental program. This could be seen by the peak measurements which if sustained would result in potential budget difficulties.

Comparisons of Measurements and Estimates for Different Experimental Conditions

The August 8 through August 24, 1996 run cycle at JLab provided us with a limited set of different experimental conditions that were used to show how the dose rate at the boundary depends on target material and thickness, and compare the results with calculated estimates.

Because the runs were all conducted at 4 GeV, this particular run cycle did not permit us to follow the important effect of changes in beam energy on boundary dose rate. At lower beam energies (with the same current) we would expect higher radiation levels at the fence due to increased beam scatter ($\propto E_0^{-1}$ on beam power). The experimental group at Hall C used cryogenic liquid hydrogen and deuterium targets, and the solid targets: carbon, iron, and gold all of different thicknesses, and beam currents 20 - 70 μA. Each target was exposed many times at different time intervals from 15 minutes to several hours.

To select and integrate the boundary dose information pertinent to each given set-up we used the databases from the experimental user group, accelerator operations software, and the one-minute CPU history files. The experimental group provided the information on the start, and stop time of each set-up. The accelerator database provided us with one-minute history files recording beam current and duty factor, such that we could integrate the beam current and normalize the dose measurements. There were several interruptions in accelerator operation which permitted us to measure the natural neutron background count rate throughout the run cycle. The background count rate was stable, and indicated no significant fluctuations. Figure 2 shows the neutron dose rate at the RBM-1 boundary monitor, measured during the seven accelerator down time periods. All five RBMs used in this work gave similar background dose rates between 3.5 and 4.0 nSv h^{-1}. The average background count rate, measured in this way, was subtracted from all dose measurements relevant to the accelerator operation. The dose rate measurements from the actual experiments also show good reproduceability. Figure 3 illustrates the dose rate at RBM-3, the boundary monitor closest to the experimental hall, during the experiments on a relatively thick (6% rad. length) gold target. The background was subtracted and the dose rate normalized to 50 μA beam current. The good reproduceability of the measurement allows us to use averages to compare different set-ups and different monitor positions. Figure 4 and figure 5 show the neutron dose rate at RBM-3 and RBM-2, for ten different targets used in the August run. The circles and the dashed line show the measurements made, the solid line and the dots show the result of

ELEC5 calculations. The dotted line indicates the level of natural neutron background. The spread in the skyshine dose values is quite significant, for example, for RBM-3: from 4.0 - 5.0 nSv h^{-1} at 50 μA for the thin iron target to 50 - 60 nSv h^{-1} at 50 μA for the thick targets such as 6% rad. length carbon, or 6% rad. length copper radiator followed by a cryogenic target. The dot-dashed line in the figures indicates the average dose rate that would give the "budget" value for a year (allowed annual average). For RBM-3 the dose rates measured on thick targets are above this level, so the experiments on thinner targets, and at smaller currents, should compensate the net dose and keep it within the "budget".

Figure 6 illustrates the dependence of the measured dose on the distance from the experimental hall to the monitor, for one of the targets. The dose falls almost exponentially as the distance increases, corresponding to the known neutron skyshine behavior. The results of ELEC5 dose rate calculations, shown in figs. 4-6, compared very well with the measurements. The parameters used for the calculations were chosen with a certain degree of caution so as not to underestimate the resulting dose. When the measurements are verified, the model parameters could be adjusted to reproduce and predict the dose rates with 20-30% degree of accuracy. The parameters could be optimized using the set of measurements at different targets and initial energies, and then used for future estimates.

Conclusions

We established a system of radiation budget accounting which is very well understood by the JLab user community and provides a method of calculating the radiation levels to be expected at the fence post boundary which takes into account the full complexity of the experimental set-up. We have also established a system of monitors at the fence line that permits us to measure continuously dose increments at levels at and just above neutron natural background. During our first year of operation we have been able to make limited comparisons of the calculation with actual measurements and to determine the effectiveness of the roof shielding which was designed during the early civil construction stage of the CEBAF/TJNAF project. We can now conclude that the calculational method performs satisfactorily and that the roof shielding is adequate to meet our present and forseeable experimental program and that the fence post monitor system meets our requirements.

Acknowledgements

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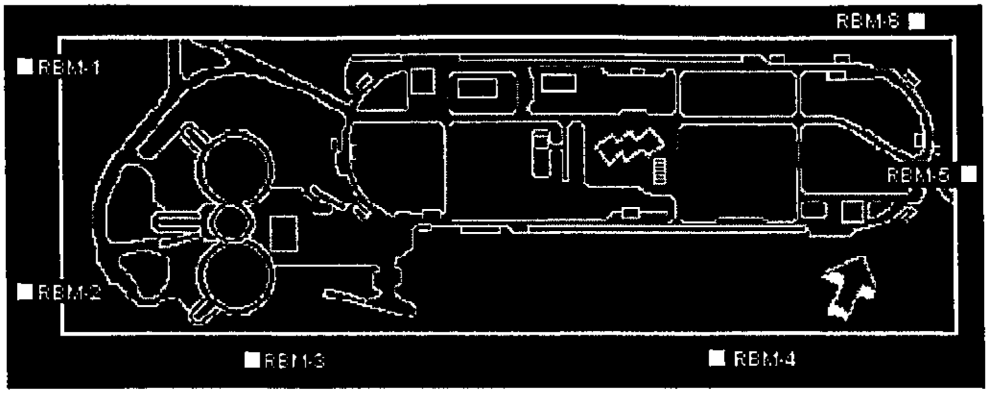

Figure 1 Outline of CEBAF with location of boundary monitors

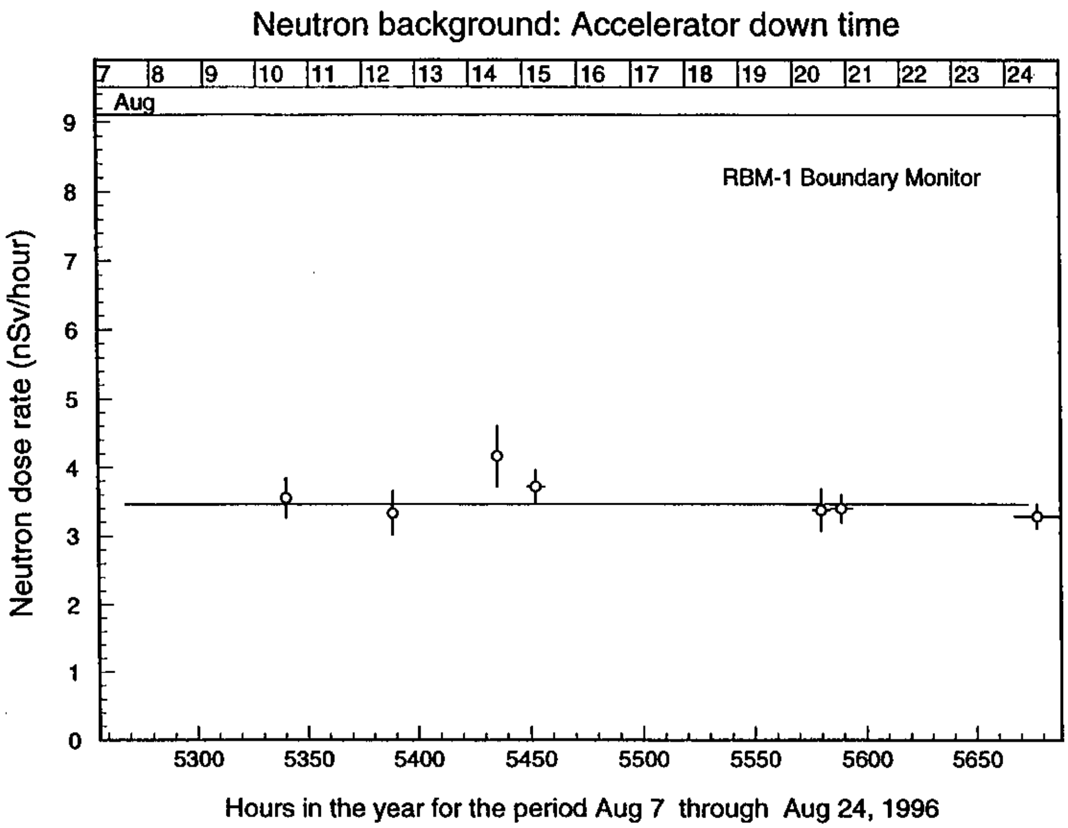

Figure 2 Measurement of neutron background

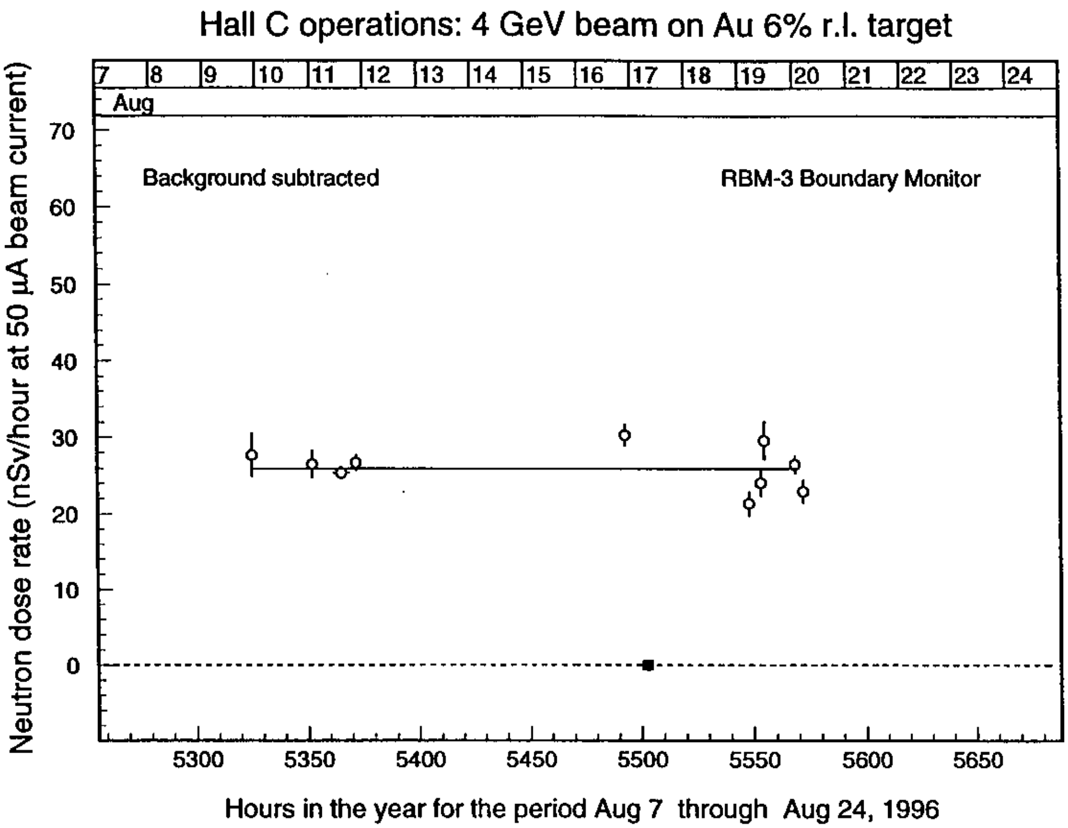

Figure 3 Normalised dose rate for experiments using the 6% gold target

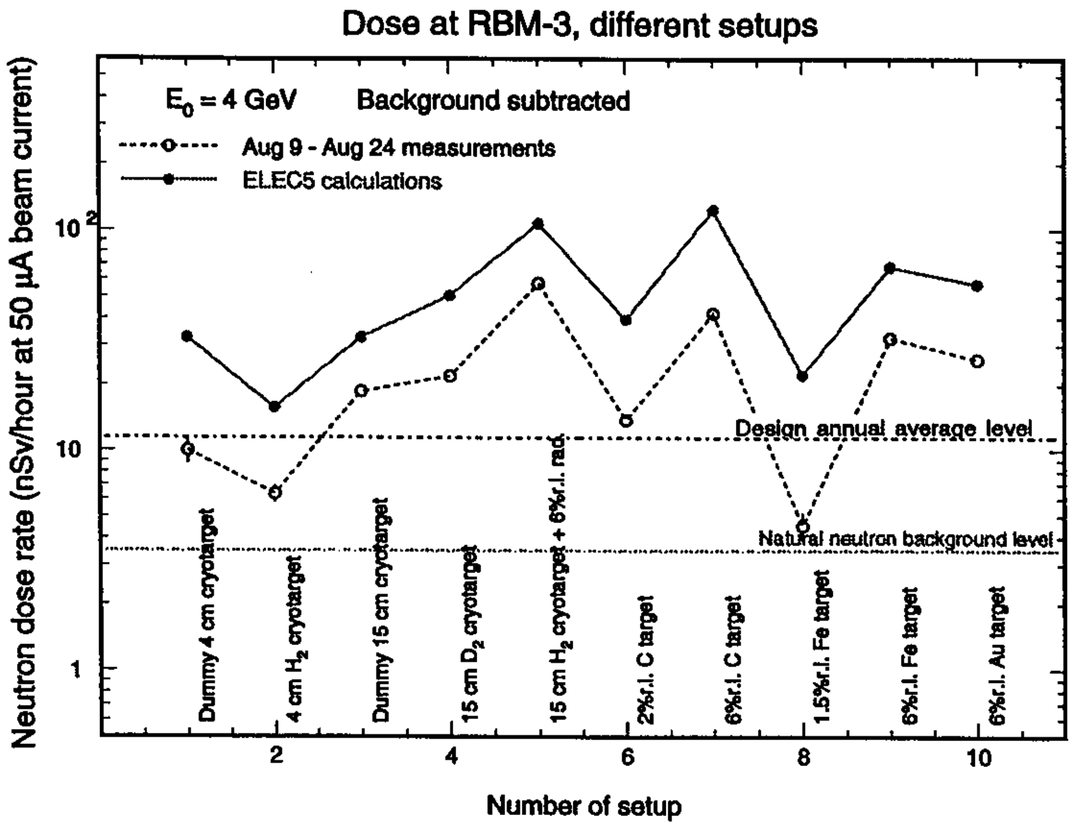

Figure 4 Normalised dose rate for selected experimental set-ups

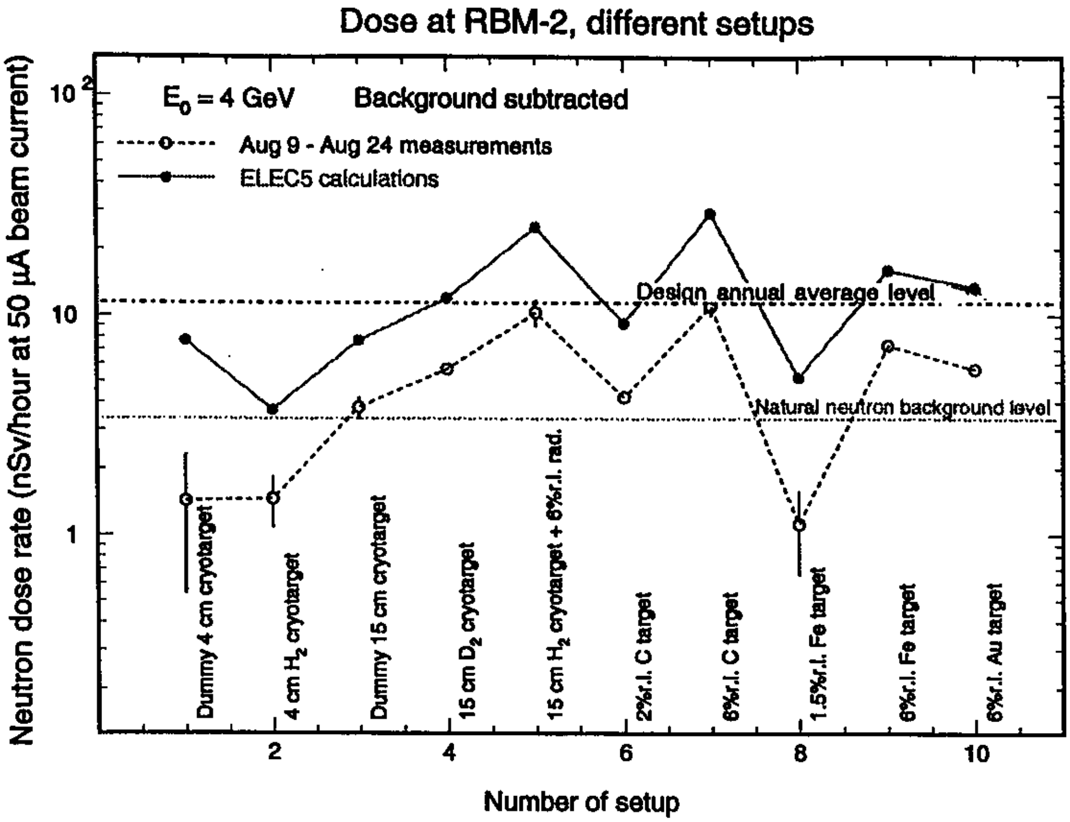

Figure 5 Normalised dose rate for selected experimental set-ups

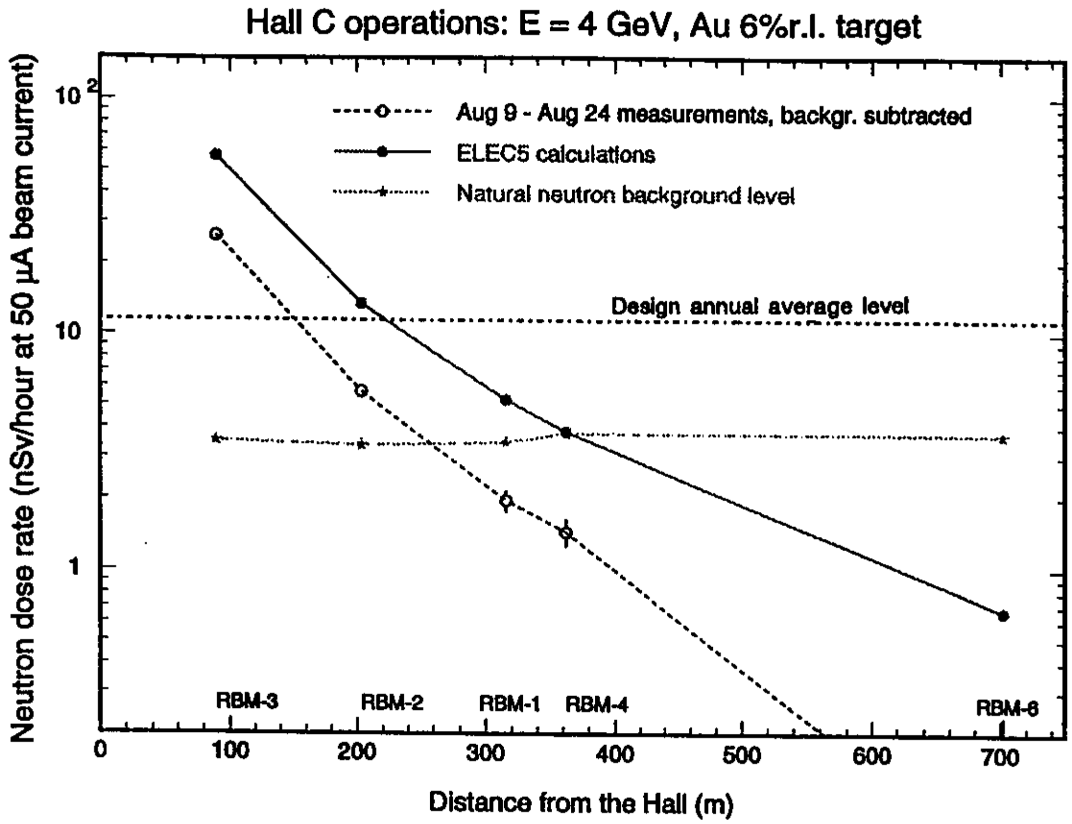

Figure 6 Normalised dose rate for 6% gold target as function of distance from hall