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Low-Cost Neutron-Gamma Borehole Detectors for Hydrogen Content Prediction

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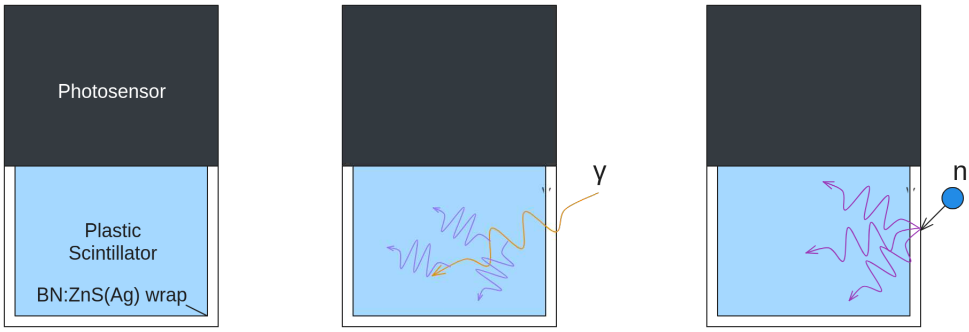
Abstract. In an oil well, high hydrogen content within the surrounding rocks is one indicator of the presence of hydrocarbons. Nuclear well-logging entails the deployment of a detector tool and neutron source downhole to characterise the strata properties as a function of depth. After neutron bombardment, the resulting distribution of radiation is sensitive to the hydrogen content. Current detectors favour use of radioisotopes, such as Am-Be or Cf-252 sources. Potential improvements in both safety and data collection capabilities are possible using Deuterium-Tritium Pulsed Neutron Generators (D-T PNGs) as an alternative neutron source when coupled with fast timing and position sensitive detectors. We propose a low-cost, modular detector system, that can measure the flux of thermal neutrons and gammas at various distances from a pulsed fast neutron source. The detector modules consist of in-house manufactured plastic scintillator coupled to BN:ZnS(Ag) thermal neutron converter foils. These mixed-field detectors show good figure of merit for neutron-gamma discrimination at low-cost, allowing us to construct positional and temporal distributions of detected neutrons and gammas. Based upon early simulations, these distributions are sensitive to the hydrogen content.

1 Introduction

Nuclear oil and gas-well logging involves the deployment of high activity neutron sources in a borehole to elicit a response from the surrounding rock formations. Within a rock formation, the pore space may contain hydrogenous fluids such as water or hydrocarbons. Interactions of neutrons with the hydrogen in these fluids affects the response of downhole neutron detectors. Variations in neutron counting rates inside a borehole can be related to the quantity of hydrogen present. When neutron rates are plotted as a function of depth, this forms a well log. For a review of neutron well-logging techniques see [1].

With the use of high activity neutron sources, there are inevitable safety and security concerns. Most commonly for neutron logging measurements, Americium-Beryllium (AmBe) sources are used, with activities in the GBq or TBq range, representing a major radiological risk in the event of mishandling or accidents. These sources have been known to become lodged downhole, as in [2], in which case the well must be sealed and capped to prevent future exploration and breaching of the source container. In other cases, such as in [3], sources have been lost during transfers between well sites, leading to exposure to members of the public. In January 2018, the nuclear security community met with members of the well-logging industry to discuss these issues, developing a roadmap to move to alternative technologies for radiation sources in well-logging [4]. In this workshop, it was determined that R&D into alternative detection systems using Deuterium Tritium Pulsed Neutron Generators (D-T PNGs) was necessary.



(a) Full Detector (b) Gamma detection (c) Thermal neutron capture

Figure 1: Foil wrapped plastic scintillator, coupled directly to a photosensor. Different particles yield different responses in the detector. Purple lines show optical photons generated in the detector.

PNG sources are already used in conjunction with spectroscopic scintillation detectors to measure induced gamma ray spectra [5]. These sources can be turned off when not in use, reducing unnecessary exposure to operators. In addition, these sources can be run in pulsed mode, which allows the propagation of a timing pulse corresponding to neutron emission, which can be used for time based measurements of the decaying neutron and gamma population. One issue is that these sources are expensive, and require the industry to also adopt alternative detector systems to leverage their full capabilities. Whilst Helium-3 based detectors are the current gold standard for thermal neutron sensing, they lack the sensitivity to also provide sufficient spectroscopic information on low energy gamma rays expected from neutron activation signals for well-logging applications. Their high cost can also be prohibitively expensive when considering the typical lifetime of a downhole tool.

This work proposes a low-cost detector for hydrogen content prediction using alternatives to Helium-3 focusing on the use of (BN)-based converter foils coupled to plastic scintillators for a detector. Whilst typical scintillating foil neutron detectors considered Li^6F enriched scintillator mixtures, this work considered BN/ZnS:Ag as it is possible to produce detectors at significantly lower cost using this compound using only natural un-enriched materials. Given the high natural abundance of B^{10} in BN, this has a comparable cross-section to LiF based systems. The reduced Q value of B^{10} capture however results in lower overall light yield, necessitating studies into the performance of optical readout systems. These lower cost systems are expected to offset a portion of the cost of new PNG systems, and demonstrate the potential for using neutron/gamma timing information in hydrogen content prediction.

2 Detector Development

2.1 Mixed-field Detection

Usually neutron well logging is performed by measuring the ratio of thermal neutron counts in a near and a far detector (spacings are tool dependent). This ratio can be related to the hydrogen content of a rock formation using geology-specific calibrations. In this work, the goal was to use low-cost detectors for this purpose, and therefore a plastic scintillator wrapped in boron-based (as opposed to more expensive lithium-based) thermal neutron converter foils (BN:ZnS(Ag)) was selected for investigation. A single detector module is shown in Figure 1a, and the different detection methods within this detector shown for gammas (Figure 1b) and neutrons (Figure 1c).

Given the difference in characteristic decay time between fast plastic scintillator and slow ZnS(Ag) inorganic scintillator, each of these different particle interactions yield different pulse shapes within the detector. Using pulse shape discrimination (PSD) algorithms, it is possible to separate the neutron and gamma counts in each module. It is expected that in both plastic scintillator, and ZnS are both sensitive to fast neutrons, primarily through inelastic scattering of neutrons producing proton tracks in the scintillator. In ZnS this looks like a scintillation pulse with overall less light yield than a neutron capture, and in plastic scintillator this looks like a prompt scintillation pulse, which is difficult to distinguish from gammas. Fast neutron shielding is typically used to remove this sensitivity to fast direct signals.

2.2 Multi-detector system

In order to image the neutron distribution within a borehole, it is necessary to use many detectors. This work explored the potential for highly segmented detector designs using a stack of the proposed scintillator modules coupled to arrays of wavelength shifting fibres for optical readout. This design is shown in Figure 2. Each fibre sits in a different groove and reads out a separate scintillator module.

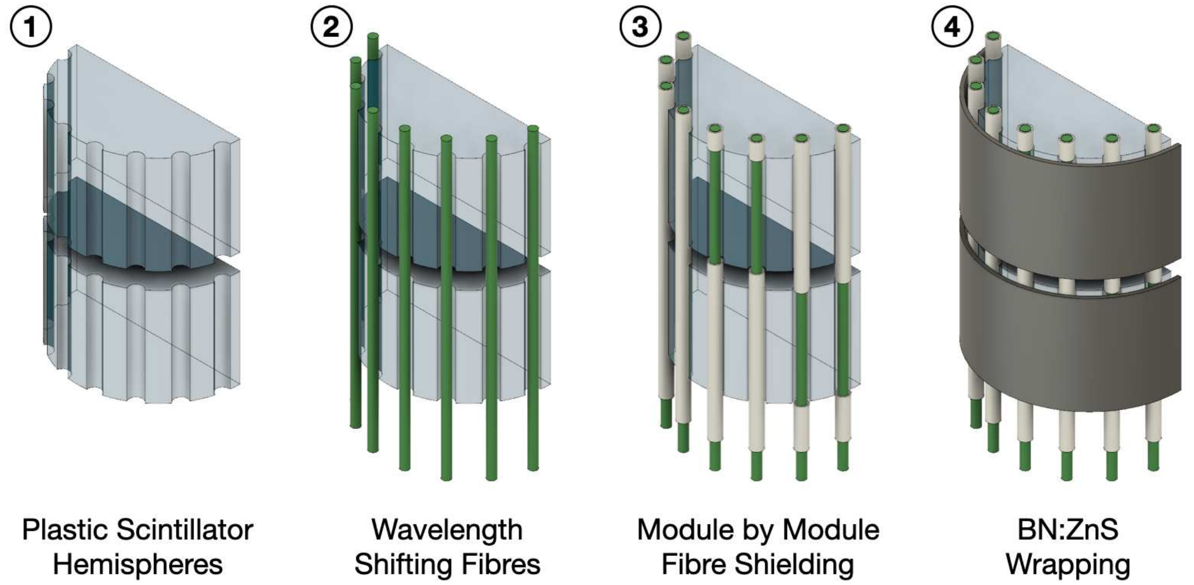


Figure 2: Fibre-readout based design for gapless segmented detector. Green shows an exposed fibre, white shows masked fibre. The multi-anode Photomultiplier (PMT) would be used to readout fibres at the bottom of the diagram. This is an example assembly geometry for the case of two-fibres inlaid in a scintillator block module with exaggerated fibre sizes to highlight masking differences across modules when considering a two fibre readout geometry

In order for this design to be effective, it must be possible to collect enough light to properly perform PSD to determine whether a neutron or gamma event occurred. GEANT4 [6] simulations were performed to examine the PSD performance of scintillator-foil modules coupled to optical fibres. This work also explored doped epoxy resin scintillators, which are prone to exotherm above a limited pour depth. As the plan in this work was to explore the use of this scintillator in this same geometry, a hemi-cylindrical detector module of 5 cm diameter was used with inlaid fibres at 22.5 degree intervals that could be masked to consider scintillator modules coupled to varying numbers of fibres.

The QGSP_BERT_HP physics list was used, with extensions for scintillation, Cerenkov, absorption, and Rayleigh Scattering processes, alongside full optical boundary tracking (see Geant4 documentation for further information [6]). Optical simulation in Geant4 can be complicated to set up, but has been found to be accurate, albeit slow, for the propagation of optical fibre readout systems when high resolution interpolation of optical data from material datasheets are used. For a recent review see [7]. Optical data of all detector components was taken from a combination of material data sheets and spectrophotometer measurements to support these simulations. EJ-200 and ZnS(Ag) optical data was obtained from Eljen Technologies. Fibre wavelength shifting response was obtained from Saint-Gobain data sheets. Hamamatsu were able to provide data on the wavelength dependent quantum efficiency of the PMT used in these simulations. G4Scintillation allows for the use of long and short decay components, for example those present in ZnS scintillators.

2.3 Optical Simulation of PSD in segmented detector

An Eljen EJ-200 plastic scintillator wrapped in BN:ZnS(Ag) thermal neutron converter foils was simulated. Thermal neutrons with energies of 0.025 eV were used to bombard the full area of the detector in simulation. Neutrons were either captured on the foil, or produced a gamma within the scintillator itself when captured by hydrogen. This provided an ideal distribution of both neutron and gamma events to test the quality of PSD in this detector. In either case, scintillation light was produced (either by the plastic scintillator or ZnS(Ag)) with characteristically different decay times.

Photon hits from the detector simulation were then recorded on the Photo-Multiplier Tube (PMT) in position, time, and energy. These hits were processed offline into realistic PMT pulses for PSD. A rejection sampling approach was applied to incident photons based on the full quantum efficiency spectrum of the candidate PMT, the H8711A from Hamamatsu. Hits were assigned a randomised transit-time based on PMT data (12 ns transit time with a 0.33 ns spread), convolved with a single photoelectron response from laboratory tests, and amplified assuming a front end with gain of 10. Baseline noise jitter was added based on typical experimental noise (Gaussian noise with $\mu = 0$ and $\sigma = 0.5\,\text{mV}$)). A long-short integral (see Equation 1) was calculated for all pulses to determine a PSD ratio to be used for discrimination. L and S denote the times of the long and short gates respectively (selected as 1000 ns and 15 ns, based on a typical gamma pulse ending at 15 ns obtained in early plastic scintillator studies).

$$PSD = \frac{\int_0^L V(t)dt}{\int_0^S V(t)dt} = \frac{Q_L}{Q_S} \tag{1}$$

2.4 Results of Optical Simulations

Simulations were performed exploring the possibility of bundles of 2, 4, 6, or 8 wavelength shifting fibres (each 1.5 mm diameter) coupled to a single detector module. In each case, photon hits were converted into realistic pulses, and PSD was performed on the predicted oscilloscope trace. PSD histograms are shown in Figure 3, along with a test case (purple) that shows a setup in which a PMT was coupled directly to the face of the detector module, rather than via optical fibre. This test case represents the maximum yield possible as there is no loss due to coupling to the fibre readout.

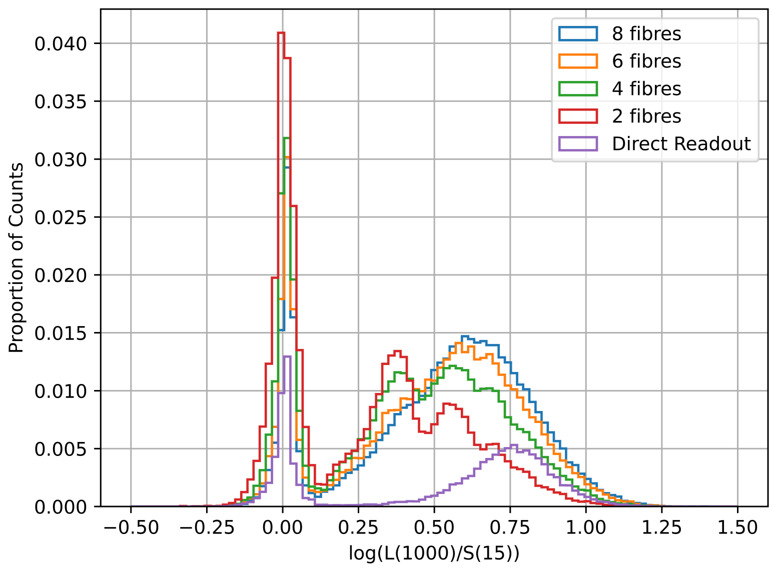


Figure 3: PSD histograms are shown for 8, 6, 4, and 2 fibre combinations. The x-axis shows the logarithm of the long-short ratio from the 1000 ns and 15 ns time windows. Also shown (in purple) are the noticeably better separated, more clearly Gaussian peaks yielded from direct PMT readout.

Figure 3 shows gradually worsening PSD separation as more fibres are removed, eventually resulting in discrete features appearing. A more complete picture of pulse degradation is obtained when considering the misclassification of particles based on an optimal PSD cut to classify particles. Misclassification error is quantified as the proportion of particles classified incorrectly (i.e a neutron falsely classed as a gamma and vice-versa). Selecting all particles below an optimised PSD cut as gammas, and above this cut as neutrons, the total misclassification error was calculated for each setup in simulation. These results are presented in Table 1.

Detector Configuration	Optimal PSD Cut	Total Misclassification
Direct Readout	0.162	0.018
8 Fibres	0.094	0.27
6 Fibres	0.077	0.36
4 Fibres	0.094	0.53
2 Fibres	0.128	0.72

Table 1: Detector PSD performance for different detector configurations

Based on these simulation results, it was found that using fibre combinations to readout light for PSD resulted in unacceptable levels of misclassification. Even using 8 fibres, the total misclassification is at 27%, compared with just 1.8% for direct readout. It is possible that alternative designs or larger fibres could improve the misclassification error, but for the purposes of this work it was decided to instead explore low cost modular detectors at the expense of coarser detector segmentation.

Further simulations were performed to examine the ideal size of these directly PMT-coupled detectors, of the same design as Figure 1a, finding the ideal detector size to be cylinders with length and diameter 5 cm, when coupling to 5 cm PMTs.

3 Mock Rock Formation for Detector Testing

3.1 Mock Rock Formation Simulations

In order to test prototype detectors to investigate sensitivity to hydrogen content, a detector testbench was required of well known material composition, with access to a DT PNG. The University of Sheffield Neutron Facility was used to carry out detector prototyping and characterisation. GEANT4 simulations were performed to examine the potential detector response for a container of sand placed in line with the DT PNG in the Neutron Facility.

A monolithic detector consisting of EJ200 plastic scintillator wrapped in BN:ZnS(Ag) thermal neutron converter foils was simulated atop a container with 135×80cm length and width, and a container height which was varied across simulations. Simulations were performed filling several heights of test container with sands of varying water contents, and examining the detector responses. When referring to heights of test formation, this is the z-height of a filled box of simulated material placed adjacent to the pulsed neutron generator.

3.2 Simulation Results

The near-far ratio in the simulated monolithic detector is plotted against hydrogen index in Figure 4. The near-far ratio is the relative proportion of counts in a section of detector close to, and far from, the source. This demonstrates the potential response for a detector tested with mock formations of varying heights within the neutron facility. With increasing hydrogen content, the near-far ratio increases, as neutrons are less likely to reach the far end of the detector monolith due to scattering and eventual capture on hydrogen. A 90 cm test formation will be constructed on account of its measurable near-far ratio response to hydrogen content, and this also permits the detector to be placed directly in line with the DT PNG, analogous to a more realistic borehole setup.

In addition to near-far ratios, the time of neutron detections relative to the initial neutron pulse was also related to hydrogen index. Exponential fits were performed to the decay of neutron counts between pulses in the detector across the range of hydrogen indices. These results are shown in Figure 5.

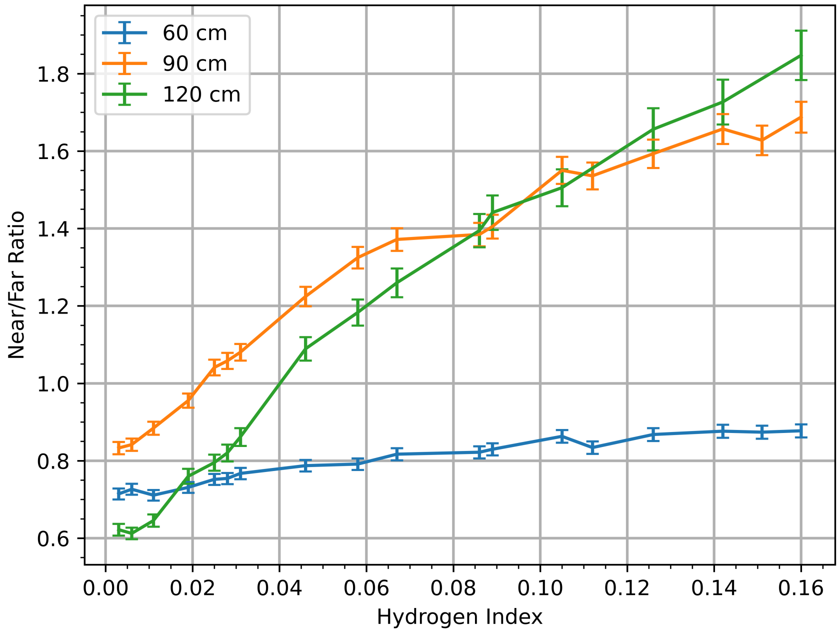


Figure 4: Simulated near-far ratios over the range of tested hydrogen indices for different heights of test formation for a DT source spectrum in GEANT4.

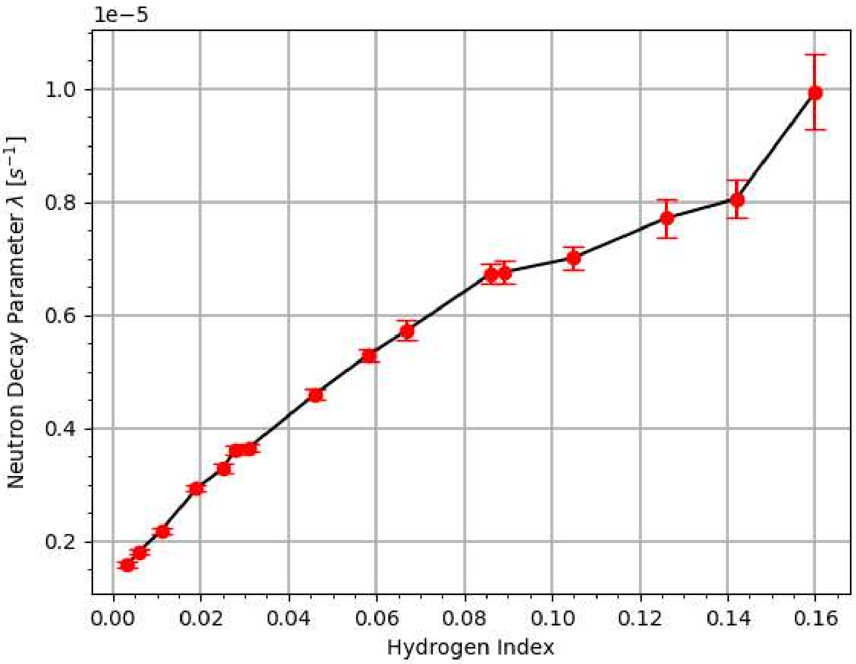


Figure 5: Exponential fit parameters for the detection time of neutrons relative to the initial DT PNG pulse vs hydrogen index from simulation.

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4 Conclusions

Alternative mixed-field detector designs for well-logging applications have been explored using plastic scintillator coupled to low-cost thermal neutron converter foils. Optical simulations found that PSD performance was poor for a proposed design with fibre readout, reaching 27% for 8 fibres. This is a result of poor light collection by optical fibres. This requires an alternative design in which light is read directly into PMTs, at the expense of active detector volume and segmentation. In addition, a detector testbench has been simulated which is compatible with the existing DT PNG setup at the University of Sheffield Neutron Facility. An ideal response in the near-far ratio was observed for increasing hydrogen content in formations of 90 and 120 cm height. A 90 cm height formation will be constructed to test prototype detector designs, and investigating the positional and time response to the DT PNG source.

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