Answers to "NuSAG Questions for Braidwood"

Submitted by the Braidwood Collaboration
June 30, 2005

Question 1

It seems that the ^9Li background is one of the most difficult ones. KamLAND experience suggests that the probability of ^9Li formation (as well as high multiplicity neutron production) is much larger for the relatively rare "showering muons" (more than 10^6 photo-electrons in KamLAND) than for the "standard muons." Thus, if one can separate the two classes of muon events, one can (as in KamLAND) veto the showering ones much longer, thus reducing the ^9Li background substantially. Can this be done in your detector?

The answer is yes; a method similar to that of KamLAND may be used to reduce the background from ^{9}Li at Braidwood. A study from KamLAND [1] shows that 85% of all muons which produce ^{9}Li deposit more energy than expected for a minimum ionizing particle crossing the detector diameter (3.7 GeV at KamLAND). The corresponding energy deposition for Braidwood is 1.5 GeV and 97% of all muons which enter the 5.2 m Braidwood inner vessel would leave less than this energy. Implementing this tag requires the dynamic range of the electronics extend beyond 1.5 GeV, perhaps 1.8 GeV for some margin of safety. We are pursuing this as part of the electronics design.

Based on studies of KamLAND data and simulations of muon showers in our detector we estimate that 72% of all ^{9}Li produced could be tagged by selecting events that occur within 500 ms of a muon that deposits more than 1.5 GeV in the detector volume. This simple approach would result in an effective loss of efficiency of only 7%, but it is likely that more complex tagging schemes would result in less signal inefficiency and better tagging. Based on our estimate of ^{9}Li production (see the answers to Questions 2 and 4), we expect 2.5/day neutrino-like decays from ^{9}Li of which 0.7/day would be untagged. This is an acceptable background. Clearly the use of tracking from the tagging and shield system leads to a more accurate prediction of the minimum ionizing energy expected from a muon entering the inner vessel. This would allow a lower energy deposition cut, which would exclude a larger fraction of the ^{9}Li background.

Currently, we assign a 100% uncertainty to the ^{9}Li production rate (see the answer to Question 2). Over the course of the experiment, a sample of 2,500 tagged ^{9}Li decays will accumulate and an analysis of the time interval between muon passage and ^{9}Li decay will allow the determination of the total production rate (tagged and untagged) with a precision of about 0.5/day and the estimation of the number of untagged neutrino-like ^{9}Li decays with a precision of 0.4/day.

Question 2

Expand on the background expected from ^9Li. KamLAND has a number but how does it extrapolate with depth (muon energy)?

Our estimate of the ^{9}Li production rate at 450 mwe (see Table 1) uses the cross sections for spallation isotopes measured using muon beams in Ref. [2]. The setup for this measurement is such that it effectively includes production by muon interactions in both the external shielding and in the detector. In that experiment, the cross section for ^{9}Li production was measured at E_μ=190 GeV and the energy scaling of the cross section of other isotopes (^{8}Li, ^{6}He) measured at E_μ=100 and 190 GeV is applied to the ^{9}Li cross section. This scaling contributes the primary uncertainty of 50%. The muon energy spectrum as a function of depth comes from Ref. [3], which gives a detailed comparison between simulation and data from underground experiments and agrees with our calculation [4] at the 10% level. Convolution of the muon energy spectrum with the scaled cross section for ^{9}Li production from muons gives the rates shown in Table 1. This calculation agrees with the observed rate at KamLAND [5] within a factor of two and we use this difference in assigning the uncertainty to our calculations.

Question 3

Some data are presented for the variation of absorbance vs. time for Gd-loaded scintillators. Are data available for possible deterioration of the scintillation light output of the scintillator vs. time?

In 2004, the Solar-Neutrino/Nuclear-Chemistry Group in BNL began to center its efforts on developing the gadolinium-loaded liquid scintillators for the newly proposed, high-precision θ_{13} experiments. This work was an expansion of our R&D of chemical techniques for synthesizing metal-loaded organic liquid scintillator for LENS-Sol (~10% of indium by weight in LS), which we had been studying since 2000. In late 2004, samples of 0.1%~0.2% of Gd by weight in LS with excellent optical transparencies (~15 meters of *1/e* attenuation length) and high light output (~95% of pure pseudocumene, PC) were successfully prepared in the form of gadolinium-methylvalerate (Gd-MVA) in PC or a mixture of PC and dodecane using solvent-extraction techniques under stringent chemical controls and extensive purifications that not only improve the optical properties, but also have impacts on the chemical stability of the final Gd-LS.

Similar chemical approaches to Gd-LS synthesis are also being studied by groups from MPI-Heidelberg and LNGS-Italy/INR-Russia (both groups were previous collaborators in LENS) for Double-CHOOZ. In addition to the solvent-extraction method, the Double-CHOOZ groups also synthesized solids of gadolinium acetyl acetonates or gadolinium carboxylates that will then be dissolved in PXE or PC, mixed with either dodecane or mineral oil. Our previous R&D indicated that the two-step, solid organo-Gd-loaded method had no decisive advantage over the solvent-extraction method, but required days more of lab preparation and might increase the chances of air exposure and introducing impurity to Gd-LS. It's not clear to us which type of Gd-loaded scintillator will be used for Double-CHOOZ. Note that there are significant differences in the chemical procedures used by the different groups in Double-CHOOZ, that lead to Gd-LS products with differing chemical and optical properties. A recent Double-CHOOZ presentation reported that some of their gadolinium carboxylates in either pure PC or a mixture of PC and dodecane have been stable for a period of ~12 months with attenuation length of ~10 m.

From the experience gained from recent reactor experiments (for example, CHOOZ had to be shut down because its detector deteriorated at a rate of 0.4% per day or >100% per year [6]), it is clear that the most critical ingredients for a long-term (>3 years) anti-neutrino detector are the

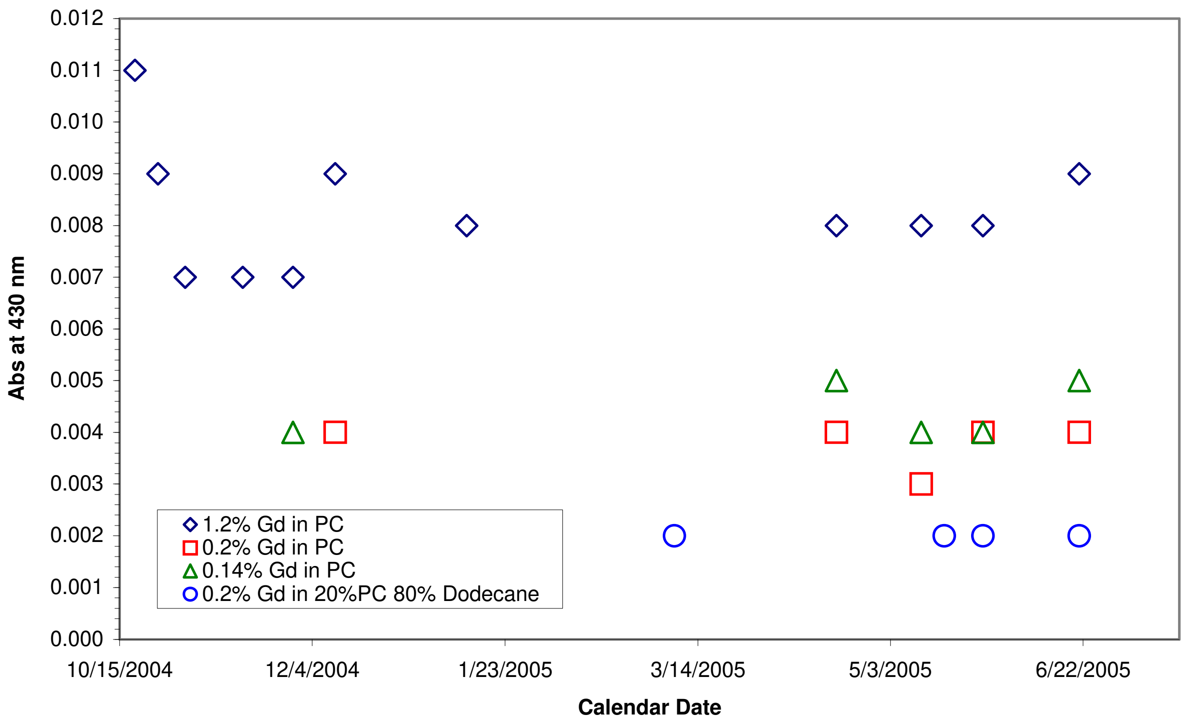

Figure 1: Variation of absorbance vs. time to date for BNL samples.

stability of its key characteristics: optical transparency and light output. To examine the long-term stability of the BNL Gd-LS, a quality control program (QC) has been implemented to monitor periodically the changes of attenuation length and light output of selected Gd-LS samples since their synthesis. Analogous to the previously presented BNL data of the variation of optical absorbance vs. time (see Figure 1, which shows up-to-date absorbance values), the light yields for selected Gd-LS samples are shown in the Figure 2 as a function of time. It should be noted that any trends of observed degradation of the optical transparency do not necessarily translate into degradation of the light yield. For example, the Palo Verde experiment reported a slow deterioration rate of its scintillator transparency of 0.03% per day or ∼10% per year, while no significant degradation of the corresponding light yield and the Gd loading was observed [7].

To date, BNL samples with 1.2% and 0.2% of gadolinium in PC have been stable over a period of ∼220 days. We know that the stability of the Gd-LS will also depend on any chemical interactions that it may have with the material of the detector vessel in which it is stored, e.g., in acrylic. Palo Verde reported that the dilution of its PC solvent with other inert organic solvents, such as mineral oil, could slow down the chemical attack of the vessel. To evaluate this possibility of preventing chemical degradation of the Gd-LS and the detector vessel, a sample of the BNL 1.2% gadolinium solution, which was originally synthesized in PC, was diluted with pure dodecane. The final formulation of this Gd-LS is ∼0.2% of gadolinium by weight in a mixture of 20% PC and 80% dodecane. To date, its light yield has shown no variation since its preparation, a period of ∼50

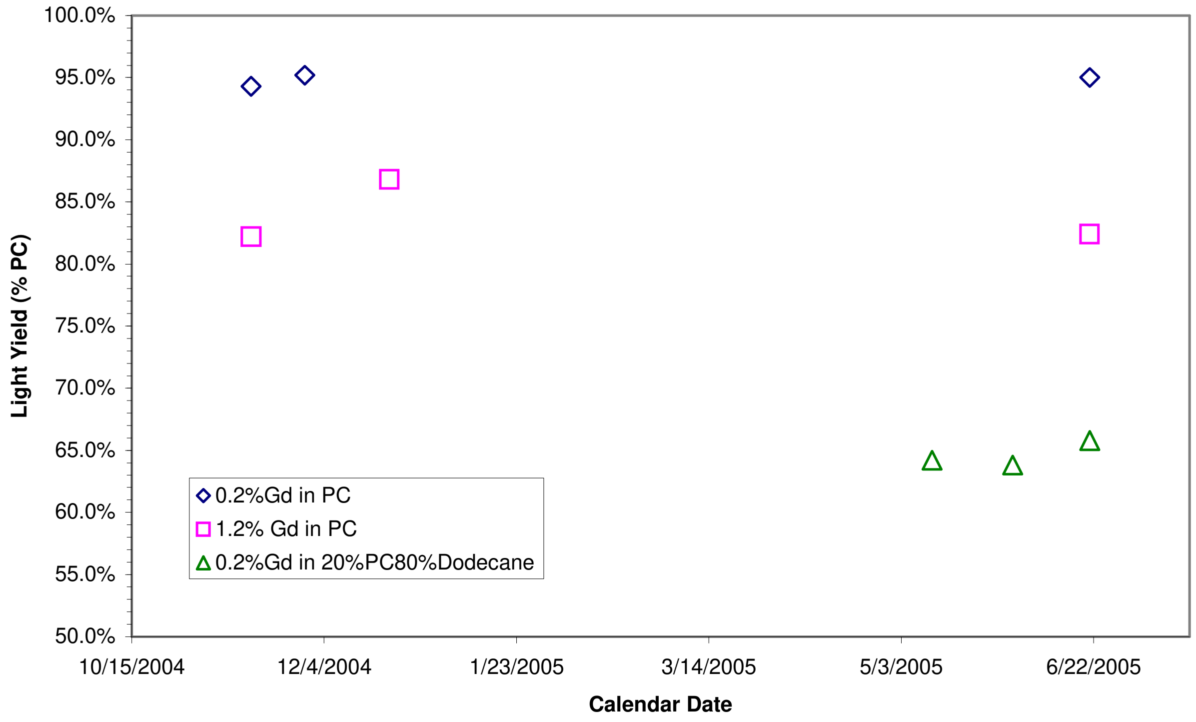

Figure 2: Variation of light yield vs. time to date for BNL samples.

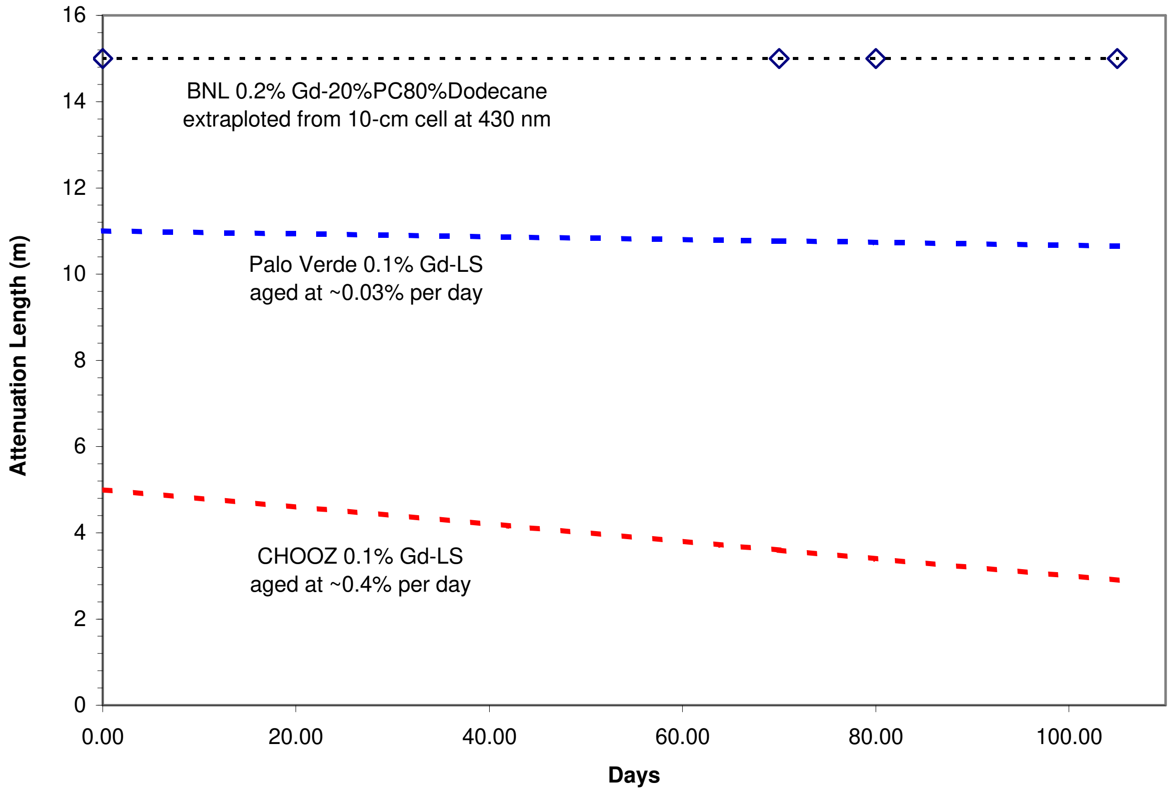

Figure 3: Comparison of the variation with time of the BNL scintillator mixture compared to the scintillator used in CHOOZ [6] and Palo Verde [7].

days. A comparison of the optical stability for this mixed-solvent 0.2% Gd-LS with values reported by Palo Verde and CHOOZ is presented in Figure 3.

Question 4

As an exercise and to understand the importance of various overburden patterns, please provide a calculation of the background for twice as much overburden over the far detector as was assumed so far. (This is NOT a suggestion to go deeper!).

The answer is given in Table 1. All the rates come from the calculation described in the answer to Question 2 except for the line labeled "KamLAND, measured" which is the observed value from Ref. [5]. We have categorized the topography as "flat" for a a flat overburden (as at Braidwood) and "hemispherical" for a mountainous region approximated by a hemisphere. Mountains are generally more sharply peaked than hemispheres, so for a given depth, a hemispherical approximation will under estimate the background rate. For a given overburden, a flat topography gives a factor of 2-3 lower background rates than a hemispherical topography.

Depth (mwe) and topography	Muon flux (m^{-2}-s^{-1})	Avenge muon energy (GeV)	Neutron production rate (ton^{-1}-d^{-1})	^{9}Li production rate (ton^{-1}-d^{-1})
450, flat (Braidwood)	0.21	84	178	0.078
450, hemispherical	0.56	68	404	0.18
900, flat (2 × Braidwood)	0.029	134	35	0.015
900, hemispherical	0.090	114	97	0.042
2700, hemispherical (KamLAND, this calculation)	0.0021	214	3.6	0.0015
2700, hemispherical (KamLAND, measured)	0.0026 [8]			0.003 [5]

Table 1: Muon, neutron and ^{9}Li rates for various depths and topographies. "Flat" refers to a flat overburden, "hemispherical" refers to the approximation of a mountainous overburden with a hemisphere. All values come from the calculation described in the answer to Question 2 except the last line, which is the measured value from KamLAND.

As is apparent from Table 2 of the Project Description [9], we expect the dominant uncertainties in our measurement of $\sin^2\theta_{13}$ will come from relative normalization between the near and far detectors (0.3%) which will contribute twice as much to the overall systematic error than the background (0.15%). Therefore, there is little gain in moving to depths greater than 450 mwe.

Question 5

What are the safety considerations related to moving a detector full of scintillator on the surface?

5.1 Trailer Overturning

The detectors will be constructed and filled within the Braidwood site. They are too large for overland shipping, even with special permits. The detectors will be moved, slowly, on special rigging trailers. These trailers have independently controlled hydraulic arms for each set of wheels, to keep the load level independent of the grade surface. Figure 4 is a picture of such a trailer, carrying an 800,000 pound transformer.

5.2 Catastrophic Rupture in a Traffic Accident

Even though this move has much lower risk than, say, that of a gasoline filled tank trailer traveling over a public highway at high speed, we can, to put things in perspective, examine if our detector would qualify as a "cargo tank" under OSHA 49 CFR-Part 178. The code can be found at URL:

http : //www.setonresourcecenter.com/49CFR/Docs/wcd0000b/wcd00b3c.asp

Figure 4: Goldhofer hydraulic platform trailer.

The comparison shows that 49CFR requires a minimum wall thickness of 0.187 inch (4.75 mm). The Braidwood tank has a 6 mm wall thickness. The code allows stresses in the tank up to 25% of tensile strength of the tank material.

We have carried out a finite element analysis of the Braidwood tank and its supports by Fermilab engineer Ang Lee. This FEA analysis shows a maximum stress of less than 4200 psi in the walls of the sphere, with an allowable stress of 21,000 psi. This is only 20% versus 25% allowable. The 49 CFR code also uses a "longitudinal deceleration of 2 g" The concern is pressure buildup at the front end of the tank at impact. This acceleration must not create stresses larger than 75% of the ultimate strength. The Braidwood tank creates stresses of only 45% of the allowable stress.

We will determine definite maximum acceleration levels from a detector moving study that is an urgent component of our R&D proposal. Verbally we have been told that dynamic accelerations can be held routinely below 1 g. The stresses in the steel pads have a safety factor of 3, hence are good to 2 g dynamic. The stresses in the column legs have a safety factor of 2.25 and are good to 1.25 g dynamic. The last two items can be beefed up inexpensively to whatever safety factor is desired.

5.3 Risk of a Small Oil Spill

The detector is in a spherical tank. The tank has a large flange just above the equator. This flange will have an O-ring seal and will be bolted very strongly to resist shifting between the lower and upper hemisphere during handling. This seal is extremely unlikely to leak.

All penetrations are at the top, above the oil level which guards against leaks there. The oil volume is sealed with O-ring seals there, except for a small vent pipe to allow pressure equalization with the atmosphere and to admit inert shield gas to protect the scintillating oil from oxygen. The vent pipe reaches well above the oil level and will have a small phase separator canister for additional protection against small spills.

5.4 Rigging the Detectors Up and Down the Shafts

We will use a professional and insured rigging company with documented experience in such moves. We expect to use a jacking system (subject to the moving study we hope to commission soon). The jack clamps are self-locking and require hydraulic pressure to open. The system is always in a safe state even when all power is lost during rigging. Redundant steel cables will be used to protect against cable failure. No personnel will be allowed below the load at any time.

Question 6

What are the safety considerations related to (lack of) escape routes in the shafts?

The initial design includes a safety refuge at the far end of the excavation, two independent routes from the detector halls to the shaft, and two elevators in each shaft which are accessible from each of the independent paths.

The cost estimate was prepared by independent consultant, Don Hilton, who has extensive experience in the U.S. underground industry. The estimate was reviewed by a second independent consultant, W.D. Whightman, with similar industry experience, most notably as a manager of the contractor construction work at the DOE's Yucca Mountain facility.

There is no appropriate code for a project as unique as this. We intend to conduct a site specific code/safety review and have allocated funds from our September 2004 R&D grant proposal for this task.

Question 7

Does the cost quoted for civil engineering of shafts include all safety precautions for personnel working underground? A similar exercise for a shallower shaft at CERN was estimated at around $30M for a single shaft.

In our cost estimate study we have included all standard safety provisions consistent with U.S. normal practice and OSHA regulations. U.S. safety practices generally allow for a higher safety level than in most European and Asian countries.

Our geotechnical engineer, Chris Laughton, Ph.D., P.E., CENG., was the site engineer for the construction of 20 LEP shafts ranging in diameter from 5 to 20 meters. He considers our excavation methods and means, and shaft design, including safety provisions, to be sufficient. Nevertheless, the code/safety review mentioned in the answer to Question 6 is essential.

While we are not familiar with the CERN exercise referenced, we would welcome any further information on this case study so that we can determine if it has any relevance to our situation.

Question 8

Please provide some information that will indicate the ruggedness of the engineering to make it possible to move the detectors between sites. How big are the expected dynamic loads encountered during movement compared to the static loads that enter for the normal engineering design?

We will determine definite maximum acceleration levels from a detector moving study that is an urgent component of our R&D proposal. Verbally we have been told that dynamic accelerations can be held routinely below 1 g.

8.1 Detector Tank and Supports

Please see answers to question 5.

8.2 Acrylic Sphere

It is important to note two design requirements for the Braidwood Detectors:

a. Both the inner scintillating oil volume and the outer buffer region will be filled to the neck area. The neck has relatively narrow fluid channels, connecting to overflow spaces above the tank. Hence, there is no room for oil sloshing even if some lateral accelerations should occur (the overflow space will have perforated anti-sloshing separators, as are commonly used in cargo tanks).

b. The density of the mineral oil in the buffer will be carefully and precisely matched to the density of the scintillating oil in the inner zone. This is necessary to limit hydraulic forces (weight and accelerations) on the acrylic sphere. The dry weight of the acrylic sphere is 1200 kg. This force must be supported, with a safety factor, before the oil filling. By matching the oil densities, this force will decrease to less than half, due to buoyancy. This makes the acrylic spheres and their supports capable of resisting accelerations in excess of 2 g total. Our preliminary design for the supports system of the acrylic sphere meets that 2 g requirement in all directions.

8.3 Photomultiplier Protection

Following the photomultiplier (PMT) implosion incident at Kamiokande, the MiniBooNE collaboration conducted a careful analysis of their PMTs, which was carried out by Len Bugel for presentation to the Fermilab Directorate.

The most credible event would be an acceleration of the detector tank during a move, creating a pressure wave. The pressure wave would, somehow, destroy a PMT. The shock wave from that PMT would destroy more PMTs. Note that the R5912 PMTs are rated to 7 atm pressure. A dynamic acceleration of (7atm)/(1.6atm) = 6.25 g would be required to reach that pressure.

The SNO experiment did a test with four 8-inch PMTs (same as Braidwood PMTs), mounted with 4 inch separation, and subjected to 6 atm water pressure. One tube was punctured mechanically. The remaining PMTs were not damaged. The energy released from the punctured tube was the tube volume times (6+1) atm. At the close test spacing (8 inches center to rim of next tube) versus the Braidwood spacing of 12 inches, the energy density is down a factor $(8/12)^3 = 0.3$. We can now derive a safety factor for Braidwood of $(7 \text{ atm})/(1.6 \text{ atm}) \times (1/0.3) = 14.6$.

Additionally, the Hamamatsu corporation states that the model R5912 PMTs, as proposed for the Braidwood detectors, are designed to survive an 80 cm drop of the shipping package. It is not easy to derive a maximum acceleration value from this, as it depends on the construction of the shipping package. If we make the conservative assumption of 5 cm compression of the shipping material on impact, then the acceleration at impact will be 20 g, in any direction. This represents a safety factor of 10 if dynamic accelerations during the detector move are held to under 1 g.

Question 9

What detector parameters (volume? PMT gain? energy calibration? other?) must remain constant, and to what level, when the detectors are moved for this cross-calibration to work?

"Cross-calibration" of the detectors by moving them is intended as a bottom-line test of Braidwood's entire data acquisition, calibration, and analysis chain. The requirements for constancy of detector parameters is minimal, however, because nearly all the parameters will be re-measured before and after any move. The most important part of the detector which must remain the same is therefore the calibration system itself, in particular its geometry and its positioning accuracy, as these can affect the calibration we will do at each position. As we hope to have a positioning accuracy of the calibration system better than 2 cm, we would not like this to change significantly more than that when we move. Even here, however, we will be able to check for changes in the system, for example by comparing the expected point at which a source just touches the inner vessel to the point when it actually does. We are not concerned with changes in the calibration sources themselves, as these can be moved from one detector to another at any time. We will also check our relative efficiencies to a precision of $\sim$0.5% using the β-decays from ^{12}B. The ^{12}B decays will be produced via muon spallation throughout the volume of each detector, and at a nearly identical rate near and far because of Braidwood's uniform overburden. We outline below some of the explicit detector parameters whose changes we have considered.

9.1 Handling of Explicit Parameter Changes

We describe here how we will deal with the changes in detector parameters that can be affected by moving.

9.1.1 Volume

A change in detector volume will result in a change in the effective number of hydrogen targets, which in turn will appear to be a loss of efficiency. We will measure the volume at both locations using the known expansion coefficients, temperature, and height of the scintillator in the neck region. Nevertheless, the analysis is simpler if the volume stays constant at a level small compared to 0.1% ($\sim$ 75kg).

9.1.2 Vessel Shape

Our simulations have shown that a change in the sphericity of the acrylic vessel holding the scintillator is a small effect even if the result is that the major and minor axes differ by as much as 20%.

We will explicitly check this, however, by deploying sources near the edges of the active volume and comparing the response there to what we expect based on our calibrations of the optical, PMT, and electronics responses made before and after the move.

9.1.3 Neutron Capture Efficiency

The neutron capture efficiency depends primarily on the Gd fraction within the scintillator. We will measure this before and after the move both through Americium-Beryllium (AmBe) source deployments and by the capture time profile of the neutrons produced by anti-neutrino interactions. These measurements are independent of any other changes in the detector parameters, and therefore we can tolerate large variations, although we do not anticipate any changes at all to this mixture during the move.

9.1.4 PMT Gains and Efficiencies

The most likely change during the move will be to some fraction of the PMTs and associated electronics. The number of tubes (if any) which fail during the move will be easily determined through the measurements by the embedded LED sources, and can be accounted for in the detector model to allow us to predict the response after the move. Changes in gains will likewise be measured with the single photoelectron spectrum created by the light sources. Changes in the tube-by-tube (and related electronics) efficiencies will be measured using a normalized light source deployed at the center of the detector, and checked by the deployment of a radioactive source (probably AmBe). The local magnetic field differences between the two sites will also be known through explicit field measurements, and our knowledge of the PMT responses as a function of field strength and direction will have to be incorporated in the detector model. As a final comparison, the mean and width of the Gd capture peak from anti-neutrino reactions will be used to check for changes before and after the move.

We are very insensitive to changes in these efficiencies and the consequent change in the energy response because our analysis thresholds are low compared to the Gd capture peak and the positron annihilation edge. Only catastrophically large changes—perhaps 50% or more—leading to a substantial broadening of the energy response will make it difficult to accurately re-calibrate the energy response.

9.1.5 Optical Parameters

Extinction and scattering lengths at wavelengths spanning the scintillator response will be remeasured through the use of both the embedded sources and a diffuse optical source deployed inside the active volume. Our measurements and simulations currently show that we are very insensitive to these parameters, in part because the relevant lengths are large compared to the size of the detector itself, and in part because our energy thresholds are low. Again, we would not like to see a dramatic change in these lengths (change less than a factor of two) because then the requirements on the precision of the new measurements will be far higher. The same is true of the reflection coefficients of the vessel and the PMTs.

9.1.6 Scintillation Light Output

A change in the light output or quenching of the scintillator must be re-measured after the move through a combination of radioactive source deployments and the mean and width of the Gd capture peak. Our energy response depends directly on the number of photons/MeV produced in the scintillator, and therefore small changes can have a big effect. The fact that the Gd peak integrates over positions and that the radioactive sources can be deployed at many locations within the vessel will allow us to break the covariance between these changes and those associated with optical parameters and PMT efficiencies.

9.1.7 Temperature

Changes in temperature can lead to changes in PMT noise rates, electronics constants (e.g., pedestals), and of course detector volume. Anecdotal evidence from SNO shows that large temperature excursions may also alter PMT angular response, perhaps due to biological growth on the tubes (which would not be a problem in oil-based detectors like Braidwood). Although we will re-calibrate all of these characteristics before and after the move, and can therefore tolerate large (non-catastrophic) differences, we nevertheless have several mechanisms for ensuring that the temperature remains constant at the $\pm 1^{\circ}$ level during the move. The first of these will be to plan on moving the detectors during months where the outdoor temperatures are nearly those of cavities in which the detectors normally reside. In addition, the large volume of the detectors would require exposure to a temperature difference for much longer than the ~ 1 day moving time in order to produce a large change within the detector. Lastly, the cooling system for the detector (which will remove heat generated by the PMTs and associated electronics during normal running) will help ensure that once the move is completed the detector returns to its equilibrium state as quickly as possible.

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