Calibration and Neutral-Current Detectors II

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1 Introduction

We revise and update SNO-STR-92-094 to identify and quantify sources of systematic uncertainty in determining the efficiency for detecting neutrons resulting from the neutral-current neutrino disintegration of deuterium. We conclude that allowing for two standardized neutron sources (one strong, one weak) that can be moved vertically within the cylinder defined by projecting the vessel neck downward through the vessel permits adequate calibration. Somewhat better results can be obtained with sources that can be moved in one or two vertical planes bisecting the vessel, but the precision is mainly limited by factors other than calibration.

2 Neutron Efficiency

It will be necessary to determine the neutron efficiency of the NC array. This is a fundamental experimental parameter that appears directly in the deductions about neutrino oscillations. The result also depends on the neutral-current neutrino cross section on deuterium, for which only theoretical input is available [1]. We consider here only the neutron efficiency determination.

2.1 Source Standardization

A precision of 2% or better is highly desirable. How accurately can a neutron source be measured? The source of choice is ^{252}Cf. With this isotope, there are 3 different methods of neutron efficiency calibration:

1. A source intensity can be determined absolutely by a standards laboratory. In the range 40 to 6 × 10^3 neutrons/second, calibration to an accuracy of about 1.5% is possible [2].
2. The mean number of neutrons emitted per fission (3.7676 ± 0.0047; [3]) is known to 0.2%, and so a comparison of the singles rate to coincidence rate (really all the "folds") in SNO can give the neutron efficiency without any need to standardize the source strength.
3. Because each neutron is preceded by fission, a tagged scintillation source can be used to produce an absolute neutron rate (dependent again on the multiplicity). An additional uncertainty is associated with backgrounds underlying the fission peak (from other isotopes and from alpha decay). These will be determined experimentally, and are probably at the percent level.

It may be concluded that source standardization effects contribute an uncertainty of 0.2%.

2.2 Monte Carlo Uncertainty

Unless it is possible to find a source that produces a completely uniform distribution of neutrons throughout the heavy water volume, and mimics exactly the energies of the primary unmoderated neutrons from NC events with a laboratory source, we must make the connection between measured neutron rates in detectors and NC neutron efficiency through Monte Carlos. (It is possible to dissolve short-lived radioactivity, e.g. ^{66}Ga, in the heavy water, which would address most of the concerns very well if the distribution of activity were sufficiently uniform [4]). Listed below are the presently identified sources of uncertainty in the Monte Carlo simulation, means for checking them, and estimates of their magnitude.

2.2.1 Calibration Source Location.

The efficiency for a point source depends on its location within the NC array. Closer to a detector string, the efficiency is higher. Wilhelmy has calculated this by Monte Carlo, as indicated in Table 1. A source that made 10,000 thermal neutrons was placed on the equatorial plane at various (x,y) grid points (in cm) from a counter string at the center of the vessel. The lattice constant was 100 cm. The quantity r_f is the Fermi Age thermalization length and w the acrylic wall thickness, both in cm. (These are the old-design acrylic counters.)

It is apparent that there is some sensitivity to source position, about 1% per cm close to a detector string, decreasing to zero at the center of a lattice cell. Positioning of a source to an accuracy of 20 cm near the center of a cell will provide an accuracy of about 2% to fix the normalization of the Monte Carlo efficiency.

Table 1: Detected counts (from 10,000 generated) in NC array for various source positions

(x,y)	r_f	w	He	Wall
0,25	0	0.3	5237	187
12.5,0	0	0.3	5988	208
25,25	0	0.3	4850	188
50,0	0	0.3	4887	173
50,50	0	0.3	4566	166
50,25	0	0	5429	-
50,25	27	0	5374	-
NC	27	0.3	3688	139
NC	27	0	4209	-

Table 2: Detected counts (from 10,000 generated at (50,50)) in NC array in detector strings. Detector string coordinates are in m.

	-5	-4	-3	-2	-1	0	1	2	3	4	5
5	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	2	0	0	0	0
3	0	0	1	1	0	2	3	1	1	0	0
2	0	0	0	2	5	14	16	9	3	0	0
1	0	0	1	10	40	116	118	43	6	4	0
0	0	1	3	11	124	830	826	111	13	1	1
-1	0	2	1	12	111	792	809	121	13	0	0
-2	0	0	2	9	32	121	119	32	13	1	0
-3	0	0	0	1	6	12	20	7	3	0	0
-4	0	0	0	1	1	3	1	1	0	0	0
-5	0	0	0	0	0	0	1	0	0	0	0

2.2.2 Neutron Transport

The spatial dependence of neutron capture from a point source is another testable prediction of the Monte Carlo. Table 2 shows the (x,y) projection for the source located at (50 cm, 50 cm).

2.2.3 Positions of Counters

There are additional uncertainties associated with the actual position of NC strings, which can be displaced from their nominal positions due to errors in locating the attachment points, circulation in the heavy water, and lateral forces from signal cables. The location of the lower part of the detector string is well determined by the position of the anchor.

Table 3: Detected rates in cylindrical-geometry NC array of detector strings, per string. Source strength 10 fissions per second. The last row is an extrapolation.

Radius m	Det. Prob. %	Events hr^{-1}	Sigma %
0.71	10.2	13790	1
1.58	1.4	1890	2
2.12	0.40	536	4
2.55	0.17	232	7
2.92	0.08	112	10
3.54	0.022	28	19
3.81	0.011	14	27
4.30	0.005	6	37
5.70	0.00013	0.18	-

However, without upper attachment points (the present plan) the string may be significantly out of vertical. The rate in each counter from a point neutron source near the axis of the vessel depends on the counter's distance from that source, and this provides a way of locating the counter. Table 3 shows the rates for a source located at the center of the vessel within the 1-m square lattice of detectors.

To ascertain that a counter is working correctly requires only 10 events. With a sufficiently "hot" source (about 100 - 1000 fissions per second), even the most remote counter strings can be checked in an hour from a source located in the central 0.7 - m radius of the vessel. The steep decrease of rate with distance places severe demands on the precision of the Monte Carlo if actual efficiencies are to be derived. By the same token, a satisfactory comparison of the measured slope with the Monte Carlo prediction assures the accuracy of the latter to much better accuracy than is needed for solar-neutrino work.

The detected rate drops off approximately a factor 10 per m (25% per 10 cm) increase in distance from the source. (Towards the acrylic vessel wall, this rate can be expected to increase.) The radial positions of the tops of each counter string can thus be determined by measurement with a source placed near the top center of the vessel. In that location ($z = 5$ m), the rates are approximately 65% those indicated in the table [12], and a 3-hour measurement would determine the positions of the most remote counter tops to a precision of 10 cm.

The largest systematic effect is caused by a coherent displacement of the counter tops inwards or outwards. From the slopes of the efficiency curves given in the NC Proposal [5], the NC event efficiency varies 12% per 10-cm change in lattice constant, or 6% when the change is at the top and not the bottom (this is an overestimate, because the total mass of ^{3}He is conserved for displacement effects, but not in the calculation cited). Coherent displacements are determined more accurately in the calibration procedure by summing all events (essentially determining the total efficiency for a point source). Approximately, then, the efficiency for point-source detection near the top varies at the rate of 25% per 10-cm displacement, while the efficiency for solar-neutrino neutron detection varies at less than 1/4 of that rate. A 1% determination of the efficiency uncertainty contributed by displacement requires only a 4% measurement of the total source-induced rate (i.e. 1000 events). By the same token, displacements of the 112 counter tops by 10 cm in random directions induces a net NC neutron efficiency change less than 0.5%.

It has been estimated that the string position can be determined to ±10cm using the "global" view camera at the time of installation of the strings.

Being able to move the source off the central axis (by 75 cm, the neck radius) affords an opportunity to unravel the foregoing type of displacement error from errors that might be associated with defective counters. This is one reason why a source that can be suspended anywhere in the neck is preferable to one confined to a median plane.

2.2.4 Number of Target Deuterons

Uncertainty in the number of deuterons contributes directly to the uncertainty in the incident neutrino flux. To a first approximation one can assume that any deuteron within the spherical shell of the vessel is a potential target and from the dimensions of the vessel one can calculate the number of targets. The spherical shell deforms to a complicated shape when under load. However the volume contained within that shell can be determined by knowing the total amount of heavy water, the temperature, and the height of the water within the neck of the vessel (which does not deform). If the height of the heavy water in the neck can be determined to ±1 cm, this represents an uncertainty of 0.02 tonnes or ±1 part in 5×10^4.

There exists another source of uncertainty related to the number of target deuterons. With the expected purity of the heavy water the neck of the vessel can be considered as a "neutron pipe." Some fraction of the neutrons in the chimney of the vessel (which also sees a higher gamma flux) will random-walk into the vessel to be captured in the ^{3}He detectors. This excess of events in the region of the neck can be mapped using a movable source and the event-location capabilities of those detectors in the region of the neck. A worst-case estimate is to assume that it is unknown whether the 9.3 tonnes of D_2O in the chimney contributes or not, which leads to an uncertainty of ± 0.46%.

2.2.5 Efficiency Near Wall

The MC predictions for the way in which the neutron efficiency falls off near the wall are particularly relevant because there will be a strong (anti-)correlation between that and the behavior of acrylic-generated neutrons. Failure of the MC to get the radial dependence for NC-generated neutrons right would be a systematic error. To verify the Monte Carlo predictions near the wall of the vessel, it would be sufficient to be able to move the neutron source vertically. While the radial dependence will be different along the z-axis than in the x-y plane, confirmation of the dependence in one direction would be strong verification of the Monte Carlo in general (when taken with other verifications). We assume that calibration runs will be taken at various z-positions to statistical accuracies better than 1%.

2.2.6 Total Array Efficiency

The neutron capture efficiency for a point source of precisely known intensity is a quantity that can be measured. Converting that measurement to the more interesting efficiency for non-pointlike sources (e.g. NC events) requires a Monte Carlo calculation. The precision of the Monte Carlo can be determined in a number of ways, as mentioned above, but inevitably becomes worse the greater the separation between source and capture site. We cannot absolutely specify this distance, but if 2.23 ($=\sqrt{5}$) m is the largest distance over which the MC can be trusted to give 1% accuracy, then with source locations confined to the projection of the neck 32 strings, or 36% of the counters [6] (43% of the NC captures [13]) can be directly calibrated to "full precision." If, in addition, a source can be moved 4.5 m off axis along one plane, then 66% of the counters can be calibrated to "full precision." All but 6% of the counters can be so calibrated with a source movable in two orthogonal planes. The precision of the Monte Carlo itself can be tested and improved by measuring rates in detectors as a function of source-detector distance. Nevertheless, it may be observed that at the SSM NC rate, the flux can be determined to a statistical + systematic precision of 3 + 1% after one year with only the centrally-deployed source (neglecting other sources of uncertainty, such as photodisintegration background).

2.2.7 Physics of Primary Neutron Spectrum

The primary neutron spectrum from ^{252}Cf will differ substantially from that of NC events. This is manifested in a different "Fermi Age" and correspondingly different escape probabilities for neutrons from the vessel. The NC primary spectrum is expected to be quite soft. Ying, Haxton and Henley [7] show that for incident neutrinos of 40 MeV, the deuteron is excited by typically 1 MeV above breakup threshold, to produce neutrons of typically 500 keV. The corresponding spectrum for ^{8}B neutrinos can be expected to lie below 100 keV. By contrast, fission neutrons emerge with energies in the vicinity of 2 MeV. The Fermi Age for fission neutrons is 27 cm [8], while the mean distance to capture for thermal neutrons is 113 cm. The range of fission neutrons to capture is greater than neutrons born thermal (approximately NC neutrons). This has the effect of permitting the escape of fission neutrons from the vessel more readily than thermal neutrons. Roughly, the vessel volume is 9% smaller for fission neutrons started uniformly inside it. This is a major systematic, but one that can probably be calculated and measured to a precision of 10%.

2.2.8 Photodisintegration

Fission is accompanied by high-energy gammas that can break up the deuteron. A detailed calculation of this contribution has not been made, but qualitatively there are of order 4 gammas above 2.2 MeV per fission, and the photodisintegration probability is of order 0.002. Since 4 neutrons are produced per ^{252}Cf fission, the excess neutron rate in heavy water is approximately 0.2%.

2.2.9 ^{3}He Fill

The absolute pressure of ^{3}He in the detectors can be determined to an accuracy of 1%. The counters are almost black to neutrons: an increase in ^{3}He pressure from 2.5 to 3.5 atm increases the array efficiency 2.2% [14]. Hence a 1% uncertainty in the absolute ^{3}He pressure around 3 atm corresponds to an uncertainty in the array efficiency of 0.07%.

2.2.10 Counter construction

The main variable in counter construction is expected to be the wall thickness of the nickel tubing, which may vary from place to place. The capture cross section of nickel is 4.6 b. Monte Carlo calculations indicate that the nickel wall absorbs or reflects 3.6% of the neutrons *that would be detected in a wall-less counter* (1.5% of the total produced) [15]. The actual weight of each detector will be determined to a (systematic) precision of 1 gm (about 1%), which will limit the uncertainty in detector efficiency from this source to 0.04%.

2.2.11 Isotopic Enrichment

The neutron efficiency with ^{3}He counters is very sensitive to the isotopic purity of the heavy water. Increasing the enrichment from 99.85 to 99.92% increases the array efficiency from 40 to 45% [11]. If the enrichment can be measured to 0.01% [9], then the corresponding detection efficiency uncertainty is 1.7%. However, this uncertainty can be substantially reduced by direct measurement of the attenuation of neutron flux from a point source.

2.2.12 Residual Salt

Following runs with dissolved NaCl, there will remain a small proportion of dissolved salt. The neutron absorption by salt is equal to that by H_2O in 99.92% water at 23 ppm. The concentration can be measured to a precision of about 1 ppm [9], which corresponds to an efficiency uncertainty of 0.07%.

2.2.13 Cross Sections

The dominant loss mechanism for thermal neutrons in pure heavy water is the (n,γ) process with an evaluated cross-section of 0.519±0.007 mb [10]. With ^{3}He detectors in place and 99.92% enriched heavy water, radiative capture on deuterium consumes approximately 25% of the neutrons, and the cross-section uncertainty represents about 0.3% systematic error.

3 Proper Operation of Neutron Detectors

Neutral-current detectors will be assembled, filled with ^{3}He-CF$_4$, weighed, and tested for neutron response and gain before installation. An absolute measurement of neutron efficiency to the desired accuracy is probably impossible outside of the SNO environment, and not of great value considering that the neutron efficiency depends almost entirely on environment. Relative measurements are being considered as a part of the quality assurance program. Once installed, the continued integrity of the counters can be checked by taking a neutron spectrum with a calibration source. Because the gain is such a sensitive function of gas pressure and purity, leakage or contamination problems will show up long before capture efficiency is affected. As mentioned above, as few as 10 events are sufficient to locate the neutron peak centroid to 1%.

The proposed use of ^{147}Sm (2.23-MeV α) with a rate of about 1 event per hour as a calibration source has been shown to create some difficulties with the neutron signal. Even at that low rate, a few events will have degraded energy owing to wall collisions or backscatter, and will underlie the neutron peak at 0.76 MeV. Therefore, no internal source is planned for the NC detectors.

If a counter fails in operation, then the question arises what to do about it. Typical failure modes include:

1. Gas contamination. The presence of electronegative molecules (e.g. water) leads to a characteristic broadening of resolution and reduction of gain. In the limit, no signal can be obtained. Loss of a single counter 3 m in length will reduce the detected rate by an accurately known amount in the vicinity of 0.3%, depending on the location.

2. Leakage of ^{3}He. Loss of gas fill leads to increasing gain. Losses small enough to permit continued operation cause no perceptible change in efficiency. Large losses make it impossible to sustain high voltage on the entire string. Depending on the string length, known (calculable and calibratable) efficiency losses of up to 2% can result from switching off the string voltage, and unknown losses (uncertainties) of up to 0.5% from lack of knowledge of how much gas remains in the counter.

3. Wire breakage. Electrical measurements from outside can reveal this condition

(whether short or open). Depending on the nature of the break, a known fraction of the string's efficiency, up to 100%, is lost.

4. Insulator failure. Failure of a seal causes a 1% loss of gas pressure as the 3-atm fill expands into the interspace between detectors (initially at 1.3 atm). If no other problems accompany the seal leakage, then the discontinuous upward shift in peak centroid indicates this effect. The effect on array efficiency is negligible.
5. Permeation. A related, but more insidious, effect is permeation of the ^{3}He through the insulator into the interspace between detectors. Over time, the interspaces become efficient neutron traps that give no signal. When equilibrium has been reached, the entire array efficiency will have been reduced by approximately 1%.

Provided failures are few, there is no major consequence for the NC array's functionality. Some kinds of failure would go unnoticed between calibration and diagnostic checks, but it appears that such failures would not seriously compromise the data. The following diagnostic checks can be made:

1. Continuous monitoring of the spectra of natural α emitters and Compton backgrounds in the counters.
2. Periodic insertion of a neutron source for a single-point calibration of the entire array. Initially a 1-hr exposure to a 100-Hz source every 2 weeks might be appropriate until confidence was gained that the array was (or was not) stable.
3. Time-domain reflectometry (TDR) of the cables and counters. This activity could also take place every 2 weeks initially, and should be arranged so that only one string at a time needed to be disabled, while the remainder of the array continued to operate.
4. Measurement of the leakage currents in each string. A single HV supply (with one backup) and a single, cumulative current monitor is thought to be sufficient. In case a problem should be indicated, provision for disconnecting individual strings and measuring leakages by hand without interrupting operation should be provided.
5. It may be advisable to monitor the cover gas above the D_2O for the presence of ^{3}He, both as a trouble indicator and to protect the photomultipliers. (However, complete loss of the contents of one NC counter into the SNO cavity does not endanger the PMTs.)

4 Backgrounds

4.1 Alpha Background

Some of the neutron events in ^{3}He counters are not distinguishable from alpha decays originating in the wall of the detectors. Those events are subject to a background correction, while the remainder are not. The resulting effect on statistical precision is discussed in a separate paper [17]. However, the accuracy with which neutrons and alphas can be distinguished has not yet been assessed in sufficient detail to draw conclusions.

4.2 Acrylic Background

The acrylic background may have to be treated somewhat empirically because its radial dependence will be a (very weak) function of the relative amounts of U (2.44 MeV) and Th (2.62 MeV), and a (stronger) function of the intensity of external high-energy gamma backgrounds (up to 9 MeV). The U and Th function can be calibrated, but there will be a residuum of uncertainty from external backgrounds in the range 3-5 MeV. Above 5 MeV, external backgrounds will be obvious in Čerenkov light.

Calibration of the U and Th neutron radial function can most easily be achieved by lowering a source through the 6 light-water access ports on the deck. The source should be at the center of a Teflon sphere 6 cm in diameter and attached to a line. The required source strength is (for Th):

$$N_{Th} = 4\pi n(\eta_n \eta_{photo} b\omega A)^{-1},$$

where n is the desired neutron rate, η_n the neutron detection efficiency near the wall, η_{photo} the neutron production efficiency for 2.6-MeV photons, b the branch to 2.6-MeV photons, ω the solid angle subtended at the source by the D_2O, and A the γ transmission through the acrylic and Teflon. A detected neutron rate of 1 s^{-1} is satisfactory (10 years data at a point would take an hour), which implies a source strength of about 6×10^4 Bq, or 2 μCi. The corresponding U source would be 30 μCi.

4.3 Photodisintegration Background

In order to determine the photodisintegration background from U and Th in the heavy water and in construction materials of the NC detectors, the PMT "wall" will be used. Response in this region needs to be calibrated. Although it will not likely be possible to unfold the U and Th contributions individually, it will be necessary to establish the PMT response for each separately in order to set upper and lower bounds on this background. The Th and U sources needed for this application can be lowered down the neck, because only the central region of the detector is likely to be useful for this determination in any case.

The required source strengths are weak. A detected rate of 100 s^{-1} would imply a Th source of 300 Bq (10 nCi), and a U source of 3000 Bq (100 nCi).

5 Čerenkov Calibration

With the detectors in place, time and energy calibrations of the PMT array and the water transmission become more difficult. A separate document [16] describes calculations that show that all PMTs can be illuminated by a point source placed in a minimum of 4 locations under the neck. These positions are the midpoints of the square defined by the innermost 4 counter strings. Reaching them requires motion 0.5 m off axis in two orthogonal planes.

Energy calibrations with high-energy gamma sources may also need off-axis access, because events originating on one side of the vessel and heading across it to the other side encounter many detectors. Monte Carlo calculations are needed to tell us how serious a problem this might be. It is essential that good charged-current data-taking be possible while the NC detectors are deployed.

6 Calibration Procedure

The basic approach to calibration is to make an *a priori* prediction of the response of the system to neutrons from standardized ^{252}Cf sources placed at certain locations and to take data for comparison with those predictions. The data consist of the number of neutrons detected in each of 112 strings, further tagged by z-position subject to z-position resolution. The z information is integrated over in the analysis of the calibration data for all variables except z-resolution itself.

The objective is to characterize the predicted detector response in terms of a limited number of variables whose possible ranges of values are externally constrained by other information, and then to test the validity of the calculation in a least-squares sense by permitting those variables and counting statistics to have their known variances. A satisfactory χ^2 or other goodness-of-fit parameter then yields a confidence level for the agreement between prediction and data. Given a satisfactory confidence level in the calibration, the variables are allowed to have their known or determined variance while the Monte Carlo is performed for NC neutrons, from which the uncertainty in the neutron efficiency is obtained.

For each location of the source s and for each detector string i Monte Carlo calculations are performed to determine the differential rate coefficients

$$C_{nis} = \frac{\alpha_{nis}}{N_{is}} \frac{\delta N_{is}}{\delta \alpha_{nis}}.$$

Table 4: Physics and apparatus parameters to be fixed or tested during calibration.

Parameter	Description	Determined by
α_{1s}	3 source coordinates	rates in diametrically opposite counters
α_2	neutron absorption (many sources)	rate dependence on distance
α_3	number of deuterons	summed rates at 3 vertical source locations
α_{4i}	positions of counter tops	rates w/source at top *vs* bottom
α_{5i}	counter efficiencies	rates w/source at various (x,y,z) coordinates

The variable α_{nis} is a physics or apparatus parameter that can, in general, depend on the particular string i and the particular source location s, but usually does not. Table 4 describes the alpha parameters.

7 Error Budget

In this section the uncertainties in the NC rate are gathered together (see Table 5). The uncertainty in the source position is shown as a $2/\sqrt{N}\%$ effect, where N is the number of measurements made. However, systematic errors in source position are unlikely to be completely random, and there will actually be two error components, one correlated and one random. The uncertainty in the photodisintegration background correction is calculated under the assumption that the (γ,n) rate in D_2O is determined with good statistical accuracy from the PMT 'wall' in the Čerenkov spectrum, but that there is no information about whether the gammas come from U or Th. The quoted theoretical uncertainty in the neutrino NC rate on deuterium applies to the absolute cross-section; the uncertainty in the NC/CC ratio is below 1% [1]. Under these assumptions, the total flux of active neutrinos can be determined to 10%, and the NC/CC ratio to 8% in one year. It is clear from the above table where efforts to reduce uncertainties would be best focussed.

8 Source Deployment

Being able to suspend a source anywhere within the volume defined by projecting the neck downward into the vessel together with access to the 6 light-water ports is apparently sufficient to determine the neutron response. The ability to move the source laterally the 70 cm off axis allowed by this is needed in order to decouple position uncertainties and efficiency uncertainties. Motion in two intersecting planes would slightly improve the precision of the detector calibration. For the calibration of the Čerenkov response with NCDs in place, sources placed at the wall of the vessel together with sources in the cylindrical volume at the center appear to provide a good tests of the Monte Carlo calculations of transmission of photons in various directions through the NCD array.

Table 5: Contributions to final uncertainty in NC rate.

Origin	Assumptions	Sigma
Source Standardization		0.2%
Source (γ,n)	0.20(5)%	0.05%
Source Position	10 cm	$2/\sqrt{N}\%$
Counter Positions	$\sigma = 10$ cm	0.5%
Number of deuterons		negl.
Isotopic Enrichment	0.01%	1.7%
Cross Sections	$\Delta\sigma/\sigma = 0.013$	0.3%
Residual Salt	±1 ppm	0.07%
Neck Effects	± 5 tonnes	0.5%
Primary n spectrum		1.0%
^{3}He Fill	$\Delta P/P = 0.01$	0.07%
Gas Permeation		0.5%
Calibration Statistics		1.0%
(γ,n) background		7%
α background		?
(ν,n) statistics	SSM, 1 yr	3%
Theory		6%

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Unless it is possible to find a source that produces a completely uniform distribution of neutrons throughout the heavy water volume, and mimics exactly the energies of the primary unmoderated neutrons from NC events with a laboratory source, we must make the connection between measured neutron rates in detectors and NC neutron efficiency through Monte Carlos. (It is possible to dissolve short-lived radioactivity, e.g. ^{66}Ga, in the heavy water, which would address most of the concerns very well if the distribution of activity were sufficiently uniform [4]). Listed below are the presently identified sources of uncertainty in the Monte Carlo simulation, means for checking them, and estimates of their magnitude.

2.2.1 Calibration Source Location.

The efficiency for a point source depends on its location within the NC array. Closer to a detector string, the efficiency is higher. Wilhelmy has calculated this by Monte Carlo, as indicated in Table 1. A source that made 10,000 thermal neutrons was placed on the equatorial plane at various (x,y) grid points (in cm) from a counter string at the center of the vessel. The lattice constant was 100 cm. The quantity r_f is the Fermi Age thermalization length and w the acrylic wall thickness, both in cm. (These are the old-design acrylic counters.)

It is apparent that there is some sensitivity to source position, about 1% per cm close to a detector string, decreasing to zero at the center of a lattice cell. Positioning of a source to an accuracy of 20 cm near the center of a cell will provide an accuracy of about 2% to fix the normalization of the Monte Carlo efficiency.

Table 1: Detected counts (from 10,000 generated) in NC array for various source positions

(x,y)	r_f	w	He	Wall
0,25	0	0.3	5237	187
12.5,0	0	0.3	5988	208
25,25	0	0.3	4850	188
50,0	0	0.3	4887	173
50,50	0	0.3	4566	166
50,25	0	0	5429	-
50,25	27	0	5374	-
NC	27	0.3	3688	139
NC	27	0	4209	-

Table 2: Detected counts (from 10,000 generated at (50,50)) in NC array in detector strings. Detector string coordinates are in m.

	-5	-4	-3	-2	-1	0	1	2	3	4	5
5	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	2	0	0	0	0
3	0	0	1	1	0	2	3	1	1	0	0
2	0	0	0	2	5	14	16	9	3	0	0
1	0	0	1	10	40	116	118	43	6	4	0
0	0	1	3	11	124	830	826	111	13	1	1
-1	0	2	1	12	111	792	809	121	13	0	0
-2	0	0	2	9	32	121	119	32	13	1	0
-3	0	0	0	1	6	12	20	7	3	0	0
-4	0	0	0	1	1	3	1	1	0	0	0
-5	0	0	0	0	0	0	1	0	0	0	0

2.2.2 Neutron Transport

The spatial dependence of neutron capture from a point source is another testable prediction of the Monte Carlo. Table 2 shows the (x,y) projection for the source located at (50 cm, 50 cm).

2.2.3 Positions of Counters

There are additional uncertainties associated with the actual position of NC strings, which can be displaced from their nominal positions due to errors in locating the attachment points, circulation in the heavy water, and lateral forces from signal cables. The location of the lower part of the detector string is well determined by the position of the anchor.

Table 3: Detected rates in cylindrical-geometry NC array of detector strings, per string. Source strength 10 fissions per second. The last row is an extrapolation.

Radius m	Det. Prob. %	Events hr^{-1}	Sigma %
0.71	10.2	13790	1
1.58	1.4	1890	2
2.12	0.40	536	4
2.55	0.17	232	7
2.92	0.08	112	10
3.54	0.022	28	19
3.81	0.011	14	27
4.30	0.005	6	37
5.70	0.00013	0.18	-

However, without upper attachment points (the present plan) the string may be significantly out of vertical. The rate in each counter from a point neutron source near the axis of the vessel depends on the counter's distance from that source, and this provides a way of locating the counter. Table 3 shows the rates for a source located at the center of the vessel within the 1-m square lattice of detectors.

To ascertain that a counter is working correctly requires only 10 events. With a sufficiently "hot" source (about 100 - 1000 fissions per second), even the most remote counter strings can be checked in an hour from a source located in the central 0.7 - m radius of the vessel. The steep decrease of rate with distance places severe demands on the precision of the Monte Carlo if actual efficiencies are to be derived. By the same token, a satisfactory comparison of the measured slope with the Monte Carlo prediction assures the accuracy of the latter to much better accuracy than is needed for solar-neutrino work.

The detected rate drops off approximately a factor 10 per m (25% per 10 cm) increase in distance from the source. (Towards the acrylic vessel wall, this rate can be expected to increase.) The radial positions of the tops of each counter string can thus be determined by measurement with a source placed near the top center of the vessel. In that location (z = 5 m), the rates are approximately 65% those indicated in the table [12], and a 3-hour measurement would determine the positions of the most remote counter tops to a precision of 10 cm.

The largest systematic effect is caused by a coherent displacement of the counter tops inwards or outwards. From the slopes of the efficiency curves given in the NC Proposal [5], the NC event efficiency varies 12% per 10-cm change in lattice constant, or 6% when the change is at the top and not the bottom (this is an overestimate, because the total mass of ^{3}He is conserved for displacement effects, but not in the calculation cited). Coherent displacements are determined more accurately in the calibration procedure by summing all events (essentially determining the total efficiency for a point source). Approximately, then, the efficiency for point-source detection near the top varies at the rate of 25% per 10-cm displacement, while the efficiency for solar-neutrino neutron detection varies at less than 1/4 of that rate. A 1% determination of the efficiency uncertainty contributed by displacement requires only a 4% measurement of the total source-induced rate (i.e. 1000 events). By the same token, displacements of the 112 counter tops by 10 cm in random directions induces a net NC neutron efficiency change less than 0.5%.

It has been estimated that the string position can be determined to ±10cm using the "global" view camera at the time of installation of the strings.

Being able to move the source off the central axis (by 75 cm, the neck radius) affords an opportunity to unravel the foregoing type of displacement error from errors that might be associated with defective counters. This is one reason why a source that can be suspended anywhere in the neck is preferable to one confined to a median plane.

2.2.4 Number of Target Deuterons

Uncertainty in the number of deuterons contributes directly to the uncertainty in the incident neutrino flux. To a first approximation one can assume that any deuteron within the spherical shell of the vessel is a potential target and from the dimensions of the vessel one can calculate the number of targets. The spherical shell deforms to a complicated shape when under load. However the volume contained within that shell can be determined by knowing the total amount of heavy water, the temperature, and the height of the water within the neck of the vessel (which does not deform). If the height of the heavy water in the neck can be determined to ±1 cm, this represents an uncertainty of 0.02 tonnes or ±1 part in 5×10^4.

There exists another source of uncertainty related to the number of target deuterons. With the expected purity of the heavy water the neck of the vessel can be considered as a "neutron pipe." Some fraction of the neutrons in the chimney of the vessel (which also sees a higher gamma flux) will random-walk into the vessel to be captured in the ^{3}He detectors. This excess of events in the region of the neck can be mapped using a movable source and the event-location capabilities of those detectors in the region of the neck. A worst-case estimate is to assume that it is unknown whether the 9.3 tonnes of D_2O in the chimney contributes or not, which leads to an uncertainty of ± 0.46%.

2.2.5 Efficiency Near Wall

The MC predictions for the way in which the neutron efficiency falls off near the wall are particularly relevant because there will be a strong (anti-)correlation between that and the behavior of acrylic-generated neutrons.

Failure of the MC to get the radial dependence for NC-generated neutrons right would be a systematic error. To verify the Monte Carlo predictions near the wall of the vessel, it would be sufficient to be able to move the neutron source vertically. While the radial dependence will be different along the z-axis than in the x-y plane, confirmation of the dependence in one direction would be strong verification of the Monte Carlo in general (when taken with other verifications). We assume that calibration runs will be taken at various z-positions to statistical accuracies better than 1%.

2.2.6 Total Array Efficiency

The neutron capture efficiency for a point source of precisely known intensity is a quantity that can be measured. Converting that measurement to the more interesting efficiency for non-pointlike sources (e.g. NC events) requires a Monte Carlo calculation. The precision of the Monte Carlo can be determined in a number of ways, as mentioned above, but inevitably becomes worse the greater the separation between source and capture site. We cannot absolutely specify this distance, but if 2.23 ($=\sqrt{5}$) m is the largest distance over which the MC can be trusted to give 1% accuracy, then with source locations confined to the projection of the neck 32 strings, or 36% of the counters [6] (43% of the NC captures [13]) can be directly calibrated to "full precision." If, in addition, a source can be moved 4.5 m off axis along one plane, then 66% of the counters can be calibrated to "full precision." All but 6% of the counters can be so calibrated with a source movable in two orthogonal planes. The precision of the Monte Carlo itself can be tested and improved by measuring rates in detectors as a function of source-detector distance. Nevertheless, it may be observed that at the SSM NC rate, the flux can be determined to a statistical + systematic precision of 3 + 1% after one year with only the centrally-deployed source (neglecting other sources of uncertainty, such as photodisintegration background).

2.2.7 Physics of Primary Neutron Spectrum

The primary neutron spectrum from ^{252}Cf will differ substantially from that of NC events. This is manifested in a different "Fermi Age" and correspondingly different escape probabilities for neutrons from the vessel. The NC primary spectrum is expected to be quite soft. Ying, Haxton and Henley [7] show that for incident neutrinos of 40 MeV, the deuteron is excited by typically 1 MeV above breakup threshold, to produce neutrons of typically 500 keV. The corresponding spectrum for ^{8}B neutrinos can be expected to lie below 100 keV. By contrast, fission neutrons emerge with energies in the vicinity of 2 MeV. The Fermi Age for fission neutrons is 27 cm [8], while the mean distance to capture for thermal neutrons is 113 cm. The range of fission neutrons to capture is greater than neutrons born thermal (approximately NC neutrons). This has the effect of permitting the escape of fission neutrons from the vessel more readily than thermal neutrons. Roughly, the vessel volume is 9% smaller for fission neutrons started uniformly inside it. This is a major systematic, but one that can probably be calculated and measured to a precision of 10%.

2.2.8 Photodisintegration

Fission is accompanied by high-energy gammas that can break up the deuteron. A detailed calculation of this contribution has not been made, but qualitatively there are of order 4 gammas above 2.2 MeV per fission, and the photodisintegration probability is of order 0.002. Since 4 neutrons are produced per ^{252}Cf fission, the excess neutron rate in heavy water is approximately 0.2%.

2.2.9 ^{3}He Fill

The absolute pressure of ^{3}He in the detectors can be determined to an accuracy of 1%. The counters are almost black to neutrons: an increase in ^{3}He pressure from 2.5 to 3.5 atm increases the array efficiency 2.2% [14]. Hence a 1% uncertainty in the absolute ^{3}He pressure around 3 atm corresponds to an uncertainty in the array efficiency of 0.07%.

2.2.10 Counter construction

The main variable in counter construction is expected to be the wall thickness of the nickel tubing, which may vary from place to place. The capture cross section of nickel is 4.6 b. Monte Carlo calculations indicate that the nickel wall absorbs or reflects 3.6% of the neutrons *that would be detected in a wall-less counter* (1.5% of the total produced) [15]. The actual weight of each detector will be determined to a (systematic) precision of 1 gm (about 1%), which will limit the uncertainty in detector efficiency from this source to 0.04%.

2.2.11 Isotopic Enrichment

The neutron efficiency with ^{3}He counters is very sensitive to the isotopic purity of the heavy water. Increasing the enrichment from 99.85 to 99.92% increases the array efficiency from 40 to 45% [11]. If the enrichment can be measured to 0.01% [9], then the corresponding detection efficiency uncertainty is 1.7%. However, this uncertainty can be substantially reduced by direct measurement of the attenuation of neutron flux from a point source.

2.2.12 Residual Salt

Following runs with dissolved NaCl, there will remain a small proportion of dissolved salt. The neutron absorption by salt is equal to that by H_2O in 99.92% water at 23 ppm. The concentration can be measured to a precision of about 1 ppm [9], which corresponds to an efficiency uncertainty of 0.07%.

2.2.13 Cross Sections

The dominant loss mechanism for thermal neutrons in pure heavy water is the (n,γ) process with an evaluated cross-section of 0.519±0.007 mb [10]. With ^{3}He detectors in place and 99.92% enriched heavy water, radiative capture on deuterium consumes approximately 25% of the neutrons, and the cross-section uncertainty represents about 0.3% systematic error.

3 Proper Operation of Neutron Detectors

Neutral-current detectors will be assembled, filled with ^{3}He-CF$_4$, weighed, and tested for neutron response and gain before installation. An absolute measurement of neutron efficiency to the desired accuracy is probably impossible outside of the SNO environment, and not of great value considering that the neutron efficiency depends almost entirely on environment. Relative measurements are being considered as a part of the quality assurance program. Once installed, the continued integrity of the counters can be checked by taking a neutron spectrum with a calibration source. Because the gain is such a sensitive function of gas pressure and purity, leakage or contamination problems will show up long before capture efficiency is affected. As mentioned above, as few as 10 events are sufficient to locate the neutron peak centroid to 1%.

The proposed use of ^{147}Sm (2.23-MeV α) with a rate of about 1 event per hour as a calibration source has been shown to create some difficulties with the neutron signal. Even at that low rate, a few events will have degraded energy owing to wall collisions or backscatter, and will underlie the neutron peak at 0.76 MeV. Therefore, no internal source is planned for the NC detectors.

If a counter fails in operation, then the question arises what to do about it. Typical failure modes include:

1. Gas contamination. The presence of electronegative molecules (e.g. water) leads to a characteristic broadening of resolution and reduction of gain. In the limit, no signal can be obtained. Loss of a single counter 3 m in length will reduce the detected rate by an accurately known amount in the vicinity of 0.3%, depending on the location.

2. Leakage of ^{3}He. Loss of gas fill leads to increasing gain. Losses small enough to permit continued operation cause no perceptible change in efficiency. Large losses make it impossible to sustain high voltage on the entire string. Depending on the string length, known (calculable and calibratable) efficiency losses of up to 2% can result from switching off the string voltage, and unknown losses (uncertainties) of up to 0.5% from lack of knowledge of how much gas remains in the counter.

3. Wire breakage. Electrical measurements from outside can reveal this condition

(whether short or open). Depending on the nature of the break, a known fraction of the string's efficiency, up to 100%, is lost.

4. Insulator failure. Failure of a seal causes a 1% loss of gas pressure as the 3-atm fill expands into the interspace between detectors (initially at 1.3 atm). If no other problems accompany the seal leakage, then the discontinuous upward shift in peak centroid indicates this effect. The effect on array efficiency is negligible.

5. Permeation. A related, but more insidious, effect is permeation of the ^{3}He through the insulator into the interspace between detectors. Over time, the interspaces become efficient neutron traps that give no signal. When equilibrium has been reached, the entire array efficiency will have been reduced by approximately 1%.

Provided failures are few, there is no major consequence for the NC array's functionality. Some kinds of failure would go unnoticed between calibration and diagnostic checks, but it appears that such failures would not seriously compromise the data. The following diagnostic checks can be made:

1. Continuous monitoring of the spectra of natural α emitters and Compton backgrounds in the counters.

2. Periodic insertion of a neutron source for a single-point calibration of the entire array. Initially a 1-hr exposure to a 100-Hz source every 2 weeks might be appropriate until confidence was gained that the array was (or was not) stable.

3. Time-domain reflectometry (TDR) of the cables and counters. This activity could also take place every 2 weeks initially, and should be arranged so that only one string at a time needed to be disabled, while the remainder of the array continued to operate.

4. Measurement of the leakage currents in each string. A single HV supply (with one backup) and a single, cumulative current monitor is thought to be sufficient. In case a problem should be indicated, provision for disconnecting individual strings and measuring leakages by hand without interrupting operation should be provided.

5. It may be advisable to monitor the cover gas above the D_2O for the presence of ^{3}He, both as a trouble indicator and to protect the photomultipliers. (However, complete loss of the contents of one NC counter into the SNO cavity does not endanger the PMTs.)

4 Backgrounds

4.1 Alpha Background

Some of the neutron events in ^{3}He counters are not distinguishable from alpha decays originating in the wall of the detectors. Those events are subject to a background correction, while the remainder are not. The resulting effect on statistical precision is discussed in a separate paper [17]. However, the accuracy with which neutrons and alphas can be distinguished has not yet been assessed in sufficient detail to draw conclusions.

4.2 Acrylic Background

The acrylic background may have to be treated somewhat empirically because its radial dependence will be a (very weak) function of the relative amounts of U (2.44 MeV) and Th (2.62 MeV), and a (stronger) function of the intensity of external high-energy gamma backgrounds (up to 9 MeV). The U and Th function can be calibrated, but there will be a residuum of uncertainty from external backgrounds in the range 3-5 MeV. Above 5 MeV, external backgrounds will be obvious in Čerenkov light.

Calibration of the U and Th neutron radial function can most easily be achieved by lowering a source through the 6 light-water access ports on the deck. The source should be at the center of a Teflon sphere 6 cm in diameter and attached to a line. The required source strength is (for Th):

$$N_{Th} = 4\pi n(\eta_n \eta_{photo} b\omega A)^{-1},$$

where n is the desired neutron rate, η_n the neutron detection efficiency near the wall, η_{photo} the neutron production efficiency for 2.6-MeV photons, b the branch to 2.6-MeV photons, ω the solid angle subtended at the source by the D_2O, and A the γ transmission through the acrylic and Teflon. A detected neutron rate of 1 s^{-1} is satisfactory (10 years data at a point would take an hour), which implies a source strength of about 6×10^4 Bq, or 2 μCi. The corresponding U source would be 30 μCi.

4.3 Photodisintegration Background

In order to determine the photodisintegration background from U and Th in the heavy water and in construction materials of the NC detectors, the PMT "wall" will be used. Response in this region needs to be calibrated. Although it will not likely be possible to unfold the U and Th contributions individually, it will be necessary to establish the PMT response for each separately in order to set upper and lower bounds on this background. The Th and U sources needed for this application can be lowered down the neck, because only the central region of the detector is likely to be useful for this determination in any case.

The required source strengths are weak. A detected rate of 100 s^{-1} would imply a Th source of 300 Bq (10 nCi), and a U source of 3000 Bq (100 nCi).

5 Čerenkov Calibration

With the detectors in place, time and energy calibrations of the PMT array and the water transmission become more difficult. A separate document [16] describes calculations that show that all PMTs can be illuminated by a point source placed in a minimum of 4 locations under the neck. These positions are the midpoints of the square defined by the innermost 4 counter strings. Reaching them requires motion 0.5 m off axis in two orthogonal planes.

Energy calibrations with high-energy gamma sources may also need off-axis access, because events originating on one side of the vessel and heading across it to the other side encounter many detectors. Monte Carlo calculations are needed to tell us how serious a problem this might be. It is essential that good charged-current data-taking be possible while the NC detectors are deployed.

6 Calibration Procedure

The basic approach to calibration is to make an *a priori* prediction of the response of the system to neutrons from standardized ^{252}Cf sources placed at certain locations and to take data for comparison with those predictions. The data consist of the number of neutrons detected in each of 112 strings, further tagged by z-position subject to z-position resolution. The z information is integrated over in the analysis of the calibration data for all variables except z-resolution itself.

The objective is to characterize the predicted detector response in terms of a limited number of variables whose possible ranges of values are externally constrained by other information, and then to test the validity of the calculation in a least-squares sense by permitting those variables and counting statistics to have their known variances. A satisfactory χ^2 or other goodness-of-fit parameter then yields a confidence level for the agreement between prediction and data. Given a satisfactory confidence level in the calibration, the variables are allowed to have their known or determined variance while the Monte Carlo is performed for NC neutrons, from which the uncertainty in the neutron efficiency is obtained.

For each location of the source s and for each detector string i Monte Carlo calculations are performed to determine the differential rate coefficients

$$C_{nis} = \frac{\alpha_{nis}}{N_{is}} \frac{\delta N_{is}}{\delta \alpha_{nis}}.$$

Table 4: Physics and apparatus parameters to be fixed or tested during calibration.

Parameter	Description	Determined by
α_{1s}	3 source coordinates	rates in diametrically opposite counters
α_2	neutron absorption (many sources)	rate dependence on distance
α_3	number of deuterons	summed rates at 3 vertical source locations
α_{4i}	positions of counter tops	rates w/source at top *vs* bottom
α_{5i}	counter efficiencies	rates w/source at various (x,y,z) coordinates

The variable α_{nis} is a physics or apparatus parameter that can, in general, depend on the particular string i and the particular source location s, but usually does not. Table 4 describes the alpha parameters.

7 Error Budget

In this section the uncertainties in the NC rate are gathered together (see Table 5). The uncertainty in the source position is shown as a $2/\sqrt{N}\%$ effect, where N is the number of measurements made. However, systematic errors in source position are unlikely to be completely random, and there will actually be two error components, one correlated and one random. The uncertainty in the photodisintegration background correction is calculated under the assumption that the (γ,n) rate in D_2O is determined with good statistical accuracy from the PMT 'wall' in the Čerenkov spectrum, but that there is no information about whether the gammas come from U or Th. The quoted theoretical uncertainty in the neutrino NC rate on deuterium applies to the absolute cross-section; the uncertainty in the NC/CC ratio is below 1% [1]. Under these assumptions, the total flux of active neutrinos can be determined to 10%, and the NC/CC ratio to 8% in one year. It is clear from the above table where efforts to reduce uncertainties would be best focussed.

8 Source Deployment

Being able to suspend a source anywhere within the volume defined by projecting the neck downward into the vessel together with access to the 6 light-water ports is apparently sufficient to determine the neutron response. The ability to move the source laterally the 70 cm off axis allowed by this is needed in order to decouple position uncertainties and efficiency uncertainties. Motion in two intersecting planes would slightly improve the precision of the detector calibration. For the calibration of the Čerenkov response with NCDs in place, sources placed at the wall of the vessel together with sources in the cylindrical volume at the center appear to provide a good tests of the Monte Carlo calculations of transmission of photons in various directions through the NCD array.

Table 5: Contributions to final uncertainty in NC rate.

Origin	Assumptions	Sigma
Source Standardization		0.2%
Source (γ,n)	0.20(5)%	0.05%
Source Position	10 cm	$2/\sqrt{N}$%
Counter Positions	$\sigma = 10$ cm	0.5%
Number of deuterons		negl.
Isotopic Enrichment	0.01%	1.7%
Cross Sections	$\Delta\sigma/\sigma = 0.013$	0.3%
Residual Salt	±1 ppm	0.07%
Neck Effects	± 5 tonnes	0.5%
Primary n spectrum		1.0%
^{3}He Fill	$\Delta P/P = 0.01$	0.07%
Gas Permeation		0.5%
Calibration Statistics		1.0%
(γ,n) background		7%
α background		?
(ν,n) statistics	SSM, 1 yr	3%
Theory		6%

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