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SUDBURY NEUTRINO OBSERVATORY

UPDATE TO FEASIBILITY STUDY SNO-85-3

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UPDATE TO FEASIBILITY STUDY SNO-85-3
AND SUPPLEMENT TO GRANT REQUEST

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INTRODUCTION

A feasibility study for the construction of a deep underground neutrino observatory based on a 1000 tonne heavy water Čerenkov detector was completed in July 1985. The results indicated that the project is technically feasible, the proposed detector can measure the direction and energy of electron neutrinos above 7 MeV, and the scientific programs will make significant contributions to physics and astrophysics. The report of this feasibility study was submitted to the Natural Sciences and Engineering Research Council of Canada (NSERC), the National Research Council of Canada (NRC), and the National Science Foundation (NSF) and Department of Energy (DOE) in the United States. Copies have also been distributed to members of the physics community. This interim report is a supplement to our feasibility study.

Since our previous report (SNO-85-3) there have been exciting theoretical hypotheses about the fundamental properties of neutrinos which can only be examined experimentally by studying solar neutrinos with a detector such as the proposed heavy water Čerenkov detector. Our detector would enable a definitive solution of the solar neutrino problem and also would use the sun as a distant neutrino source to study fundamental neutrino properties. For example, the study of neutrino oscillations is of great importance since it can test theories of grand unification beyond the electroweak sector.

We only report here new information since our feasibility study. For reference, we show a conceptual design of the detector in Fig. 1. In the physics section we discuss the enhanced conversion of neutrinos in the sun and the new physics that could be learned using the heavy water detector. We do not include other topics such as neutrinos from stellar collapse which were covered previously. The other sections will discuss progress in the areas of practical importance in achieving our physics objectives. These include new techniques to measure, monitor and remove low levels of radioactivity in detector components; tests of electronics and phototubes with the possibility of improved timing from a new tube; the D_2O/H_2O system and preliminary design of an acrylic vessel; ideas on calibration of the detector and a small test detector; and the conventional construction of the laboratory. These areas are covered by working groups within the SNO collaboration. The membership of these groups is given in the section on Administration. The number of physicists involved has increased by nine.

PHYSICS

The only direct information on the reactions which power the sun is carried by neutrinos escaping from its dense interior. The pioneering experiment of R. Davis et al.$^{1)}$ did not observe the expected$^{2)}$ flux of neutrinos and the discrepancy, known as the solar neutrino problem (SNP), is widely considered a major problem in modern physics. Two categories of solutions to the problem have been extensively discussed. The first invokes some deficiency in the standard solar model (SSM) and many mechanisms have been suggested to lower the central temperature of the sun thus reducing ^{8}B production. The second suggests some lack of knowledge about neutrino propagation. Pontecorvo$^{3)}$ originally proposed that the reduction in ν_e flux at earth may be caused by large mixing angle oscillations of neutrinos between weak interaction eigenstates. More recently, Mikheyev and Smirnov$^{4)}$, following the theoretical framework of Wolfenstein$^{5)}$, have shown that a mechanism exists (matter enhancement) whereby, if this mixing of eigenstates is postulated, a large fraction of ν_e´s created in the solar interior could be converted into ν_μ´s (ν_τ´s), even for very small vacuum mixing angles. Weinberg$^{6)}$ suggested that the sun is a unique source offering a rare opportunity to search for neutrino oscillations in testing unification theories beyond the electroweak sector. He argued that such unification leads naturally to the heaviest neutrino mass of approximately 10^{-3} eV, a range for which solar experiments, with matter enhancement, are particularly sensitive. Other suggested solutions to the SNP include the possibility of neutrino decay$^{7)}$ or neutrino magnetic moment$^{8)}$.

Our proposed large heavy-water Čerenkov detector, would distinguish among the proposed solutions of the SNP by measuring the electron neutrino spectrum and direction, and the total neutrino flux. In particular, such measurements allow the sun to be used as a distant neutrino source for physics experiments free of complications from the standard solar model, and also allow a definitive test of the standard solar model free of complications from proposed new neutrino properties. Due to the use of high thresholds to suppress backgrounds, the detector would be sensitive only to ^{8}B neutrinos. However, its sensitivity would be 50 times greater than that of the Davis experiment[1]).

The detector would identify neutrinos through three complementary reactions: inverse-beta decay of the deuteron, neutrino electron scattering, and neutrino dissociation of the deuteron. The rates for these reactions under several scenarios are summarized in Table 1.

The ν_e flux, spectrum, and direction would be measured via the charged-current (CC) reaction:

$$\nu_e + d \rightarrow p + p + e \qquad (I)$$

Monoenergetic neutrinos produce electrons which are almost monoenergetic with kinetic energies approximately E_ν - 1.44 MeV[9]), and hence this reaction is well suited to spectroscopic studies. The electrons would have an angular distribution with respect to the neutrino direction given by:

$$W(\theta_e) = 1 - \frac{1}{3} \cos \theta_e$$

The second reaction to be used is neutrino electron scattering (ES):

$$\nu_x + e \rightarrow \nu_x + e \qquad (II)$$

In standard electroweak theory, while all neutrinos can scatter by the neutral-current process, only the ν_e's can interact through the charged current with the result that the cross section for ν_e 10) is six times larger than that of ν_μ or ν_τ 11). Thus, this reaction is mainly sensitive to the ν_e flux; but with an independent measurement of the ν_e flux and spectrum as described above, it can give a measure of the total neutrino flux. For ^{8}B neutrinos, the yield of this reaction is an order of magnitude smaller than that of reaction I, as can be seen in Table 1. The scattered electrons are kinematically constrained to a forward cone, thus providing excellent directional information on the flux and separating them from those of reaction I. A better measurement would come from a light water fill where events from reaction I would be absent. Since the electrons can take any fraction of the incident neutrino energy, with a distribution which is almost flat, and because of the lower yield, this reaction is less useful for spectroscopic studies than reaction I, as is clear from Fig. 2.

Finally, the total (left-handed) neutrino flux, independent of neutrino flavor, can be measured by the neutral-current (NC) reaction:

$$\nu_x + d \rightarrow \nu_x + p + n \qquad \text{(III)}$$

This reaction rate would be determined by counting the free neutrons produced. Chen 12) has pointed out that this reaction is particularly important for resolving the SNP because it gives a direct measurement of solar ^{8}B neutrino production independent of oscillations. While the rate for this reaction is comparatively high, but the detection efficiency for free neutrons depends sensitively on the choice of capture reaction. The simple choice (capture on deuterium) has a low efficiency since 80% of the neutrons will escape the D_2O vessel or be captured in the remaining 0.2% H_2O. Nevertheless, we have used it for the detection rates shown in Table 1.

An important recent development in physics is the realization that the conversion of one type of neutrino into another can be greatly enhanced in a high electron density environment[4,5]), such as in the core of the sun or the earth. In a simplified two neutrino mixing picture, the time development of neutrino oscillation can be described by the differential equation[13]):

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}A & B\\ B & D\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \qquad (1)$$

$$\text{where}\quad A = \frac{m_1^2\, c^4 \cos^2\theta + m_2^2\, c^4 \sin^2\theta}{2\hbar E} + \frac{\sqrt{2}\, G_F N_e}{\hbar},$$

$$B = \frac{(m_2^2 - m_1^2)\, c^4 \sin\theta \cos\theta}{2\hbar E},$$

$$D = \frac{m_1^2\, c^4 \sin^2\theta + m_2^2\, c^4 \cos^2\theta}{2\hbar E},$$

and where m_1 and m_2 are the rest masses of the neutrino mass eigenstates, $|\nu_1\rangle$ and $|\nu_2\rangle$, θ is the mixing angle defined by $|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$ and $|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$, G_F is the Fermi coupling constant, N_e is the electron number density, and E is the total energy of the neutrinos. The extra diagonal term in A, $\sqrt{2}\, G_F N_e/\hbar$, is due to the charged-current elastic scattering $\nu_e + e \rightarrow e + \nu_e$, an interaction not available to ν_μ.

The relationship between the effective mixing angle in matter, θ_m, and the mixing angle θ is:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\frac{L}{L_0} - \cos 2\theta\right)^2} , \tag{2}$$

where $L = 4\pi E\hbar/(m_2^2 - m_1^2)\, c^3$, is the vacuum oscillation length

and $L_0 = 2\pi\hbar c/(\sqrt{2}\, G_F N_e)$

For ν_e of energy E in a medium of electron density given by

$$N_e = \frac{(m_2^2 - m_1^2)\, c^4}{2\sqrt{2}\, E\, G_F} \cos 2\theta$$

the effective matter oscillation mixing angle is $\frac{\pi}{2}$ and ν_e can be completely converted into ν_μ independent of the value of θ, with a matter oscillation length given by

$$L_m = \frac{4\pi E\hbar}{(m_2^2 - m_1^2)\, c^3 \sin 2\theta} .$$

A number of calculations[13-19]) have been carried out to study the effects of matter oscillation on solar neutrino fluxes and how it might resolve the solar neutrino problem. The results of one of our calculations[19]) is shown in Fig. 3 in which the fraction of electron neutrinos emitted in the core of the sun that reach the earth is plotted against the parameter $\chi = E/(m_2^2 - m_1^2)\, c^4$ for a given mixing angle. Effects from neutrino propagation through the earth are included[20]) causing the day/night effect.

The essential feature of all oscillation hypotheses for solving the SNP is that there be a substantial ν_μ (ν_τ) flux with a corresponding reduction in the ν_e flux from the SSM prediction. Thus, the charged-current rate is decreased as required to explain the SNP, (ν_x,e) scattering has a rate roughly 30% higher than expected on the basis of reaction I as shown in Table 1, and the neutral-current rate remains fixed by the SSM, unchanged by any oscillation solution as already emphasized[12]). In addition, for some cases, gross distortions of the ^8B ν_e spectrum are predicted as shown in Fig. 2.

Typical cases that could occur are:

A) Vacuum oscillations of three neutrino flavors with large mixing angles and with mass-squared differences greater than 10^{-10} eV^2. This is basically the Pontecorvo oscillation solution without a change in the ν_e spectral shape. The key features are the rates for reaction II and III relative to reaction I as shown in Table 1.

B) $m_2^2 - m_1^2$ is about 10^{-4} eV^2. The high energy ν_e's from ^8B are converted to ν_μ's or ν_τ's[4,13,14]) leading to a gross change in the ν_e spectrum and thus the spectral shape of reaction I as shown in Fig. 2. In addition, many more (ν_x,e) scattering events would be observed above 9 MeV than expected from the observed ν_e events of reaction I.

C) The non-adiabatic limit is reached in the ^8B spectrum[4,13,15]). In this case low energy ν_e's are converted more than high energy ν_e's. Changes in the ν_e spectrum are gradual and therefore not easy to measure as shown in Fig. 2. However, the counting rates for reactions II and III can also be used to identify this case.

D) The resonant condition may be satisfied in the sun at terrestrial densities between 5 and 12 g cm^{-3}. Thus a ν_e can be converted to ν_μ (ν_τ) in the sun and reconverted back to ν_e in traversing the earth, provided that the mixing angle is large enough as shown in Fig. 3. In this case, the detector would observe ν_e's only at night while the measured total neutrino flux would be constant[20]).

E) Standard Solar Model wrong. In this case, the observed spectrum in reaction I would be that deduced from ^{8}B decay. In particular, reactions II and III would have rates determined by the lower observed ν_e rate of reaction I, as shown in Table 1, rather than the predicted rates of SSM. Furthermore, all reaction rates would be measured to be independent of time.

Other possible cases include:

F) Neutrino magnetic moment[8]). In this case, one would observe a correlation of the neutrino flux with the solar cycle, as well as a semi-annual correlation with the intercept of the solar equatorial plane and the ecliptic plane.

G) Neutrino decay[7]). In this case, relativistic time dilation affects the disappearance of low energy neutrinos the most. The ν_e spectrum is changed in a well-defined manner which would be tested by reaction I. If ν_e is the lightest neutrino, then ν_μ (ν_τ) cannot be produced in ν_e decay, so reaction II and III rates would be determined from measurements of reaction I. Otherwise, reaction II and III rates would be greater than expected from reaction I, depending on decay mode.

To study neutrino physics independent of the SSM, one needs to confirm that the sun is a source of ^{8}B neutrinos. Bahcall has examined the ^{8}B flux predicted by non-SSMs and noted2) that unless the ^{8}B flux is postulated to be zero, the minimum predicted flux is 5.4 x 10^5 cm^{-2} s^{-1}. This can be compared with our minimum observable flux of 5 x 10^4 and 5 x 10^5 cm^{-2} s^{-1} by reactions I and II, respectively (3σ measurement in a kt-yr, allowing for the expected backgrounds and fiducial cuts). Our minimum observable ^{8}B flux via reaction III depends critically on both backgrounds and detection technique, and an ultimate sensitivity within the above range is our goal.

To test the standard solar model free of complications from the new neutrino properties discussed, corrections may have to be made to the three observed neutrino reaction rates to determine the solar ^{8}B neutrino flux. However, all (left-handed) neutrino oscillation solutions, whether matter enhanced or not, leave the rate for reaction III an invariant measure of the primary flux.

RADIOACTIVITY

One of the important requirements for the direct counting of neutrinos from the sun is the elimination of background events below approximately 14 MeV. In the proposed design, solar neutrino detection will be at the rate of nine per day. Consequently, the background events associated with radioactivity in components of the detector or from the surrounding rock should be such that they give a total event rate of less than one per day. This requires low background construction and shielding materials which are unprecedented for a detector of this size. However, considerable progress has been made in determining the radioactive contributions from various components in the proposed detector and these will be described here. The detector will be placed at a depth of 6800′ (6200 MWE) to reduce background from the cosmic-rays to a negligible level.

Solar neutrinos, interacting via reactions I and II, will produce electrons with energies up to approximately 13 MeV, so high energy photons, from (n,γ) or fission, are the important sources of background. Any neutron produced by fission, (α,n) or (γ,n) reactions is a problem for the detection of reaction III. In particular, photons of energy greater than 2.23 MeV can produce neutrons by the photo-disintegration of deuterons in the D_2O. The main source of such photons is $^{208}T\ell$ (2.615 MeV), a daughter of the primordial radioisotope ^{232}Th, and to a lesser extent, ^{214}Bi (2.447 MeV), a daughter of ^{238}U.

The main feature of the design is an acrylic vessel holding the D_2O supported in a large volume of H_2O within a concrete-lined cavern. The phototubes are mounted in the H_2O with the photocathodes 2.5 m from the acrylic surface. In this detector, event rates from reactions I and II were estimated to be 8 and 0.6 per day respectively. The high-energy gamma-ray induced event rate was estimated to be one per day. Consequently, the background counting rate is not a problem for reaction I. When combined with the angular information, one per day is not a problem for reaction II either. However, the background counting rate for reaction III is uncertain and most of the effort within the radioactivity group is being directed to solving this problem.

Monte Carlo calculations have been carried out to determine the background event rates associated with terrestrial radioactivity. The number of neutrons produced by a 2.6 MeV gamma-ray source such as ^{232}Th distributed throughout the D_2O or in the acrylic have been calculated. The model detector is a spherical D_2O volume of 1000 tonnes. The number of neutrons captured on deuterium producing a 6.25 MeV gamma-ray have also been calculated, with allowance for neutron leakage from the D_2O. From these calculations, the background event rates due to Th and U impurities in the D_2O and acrylic vessel have been determined. Full Monte Carlo calculations and reconstruction of events produced by a planar high energy gamma-ray source at a distance of 2.5 m from the acrylic vessel have been performed. These detailed calculations show that less than 0.2% of the events in the light water region will be mapped into the D_2O fiducial volume, a large reduction from earlier estimates. This may allow some freedom in increasing the radius of the acrylic vessel to accommodate new designs. However, the levels of radioactivities in different components of the photomultiplier, photomultiplier support structure and concrete-liner will have to be kept low. The feasibility of using sulphur concrete21) and resin concrete[22]) as well as the possibility of mixing boron with the concrete to reduce (n,γ) reaction rates are being investigated. The gamma-ray attenuation, neutron transport and (n,γ) reaction rates in the concrete shielding and water shielding have been estimated. As more definite design criteria are established, more detailed Monte Carlo calculations will be carried out.

It is critical that the D_2O has the lowest possible concentration of radioisotopes. Measurements of the thorium and uranium concentrations in AECL and Ontario Hydro samples of D_2O have been made by Inductively-Coupled Plasma Mass Spectrometry (ICPMS) at NRC, Ottawa[23]). The method involves a 1000-fold preconcentration of Th and U on a resin bed of silica-immobilized 8-hydroxyquinoline. The ICPMS is then performed on the eluted concentrate. The concentration by mass of Th in two different samples of D_2O was determined to be $(0.04\pm0.01)\times10^{-12}$ and $(0.15\pm0.05)\times10^{-12}$ respectively. A concentration of 0.3×10^{-12} of U was found in one D_2O sample. After passing the D_2O sample with initial Th concentration of $(0.15\pm0.05)\times10^{-12}$ through the resin a second time, the concentration was found to be reduced by approximately a factor of 10, a limit imposed by the sensitivity of the method. Filtering with the resin is therefore a very effective way of removing Th. At the level of 0.01×10^{-12} of Th, the background event rate from Th impurities in D_2O would be less than half of the NC event rate. More measurements with higher sensitivities will be carried out in the near future. In addition, techniques are being developed to determine the radium concentration of D_2O by extracting radium using manganese-impregnated acrylic filters and counting the radon escaping from the filters. This is important because radium can be in disequilibrium with the parent U or Th in different materials and the high energy gamma rays which can cause the photo-disintegration follow radium in the decay chain.

Considerable progress has been achieved in improving the sensitivity of measuring Th and U concentrations in acrylics. We have developed a neutron activation scheme which can now be routinely used to test Th levels down to about 10×10^{-12} and U to about 30×10^{-12}. We have found that one sample of acrylic supplied by Reynolds and Taylor Inc., (manufacturer of acrylic tanks) has Th $< 15\times10^{-12}$ and U $< 28\times10^{-12}$. For the acrylic vessel specified in Fig. 1, a concentration of 5×10^{-12} of Th and 40×10^{-12} of U will each contribute a background event rate of one per day to reaction III. A large quantity of monomer (47% of acrylic by weight) and cross linker (~1% of acrylic by weight) has been reduced by distillation and the alpha activities of the residues measured. The ^{232}Th, ^{228}Th (radium daughter) and ^{238}U concentrations in acrylic due to this monomer are $< 3.5\times10^{-12}$, $<1.5\times10^{-21}$ and $< 1.2\times10^{-12}$, respectively; and due to crosslinker are $< 6.5\times10^{-12}$, $< 1.7\times10^{-21}$ and $< 3.6\times10^{-12}$, respectively[24]). The polymer component will be investigated. Assuming similar results from the polymer, the limits on the background event rates would be < 0.2/day from U and < 2.5/day from Th. Higher sensitivity equipment for measuring Th concentration in acrylic has been installed at CRNL.

We have also tested distilled light water for ^{232}Th by neutron activation analysis. The concentration is below the level of 2×10^{-12}. The ICPMS technique can be used to measure and monitor the Th concentration in the light water with much higher sensitivity. Filtration through resins, similar to those used for D_2O, will undoubtedly reduce the Th concentration in the light water to an acceptable level.

The glass and most of the other components in 50 cm photomultiplier tubes manufactured by Hamamatsu Photonics K.K., Japan, have also been tested by direct counting techniques as reported in our earlier report. We have since examined a variety of other glasses and ceramics for Hamamatsu Photonics K.K. to try to find lower activity components. Unfortunately, all low activity glasses we identified so far are unsuitable for long term use in water.

PHOTOMULTIPLIER TUBES AND ELECTRONICS

The photomultiplier tubes (PMTs) and electronics are designed to provide maximum detection sensitivity, good timing and energy resolution and high count rate capacity. In our detector, Monte Carlo simulations show that, for low energy neutrino induced events ($E_\nu<14$ MeV), approximately 1.2 photoelectrons (p.e.) will be produced per hit PMT (50 cm diameter photocathode). It is therefore advantageous to use large area PMTs with high single p.e. detection efficiency. At present only two companies are developing such PMTs.

The Philips company in the Netherlands has developed a "smart" 35 cm PMT with a hemispherical photocathode which can readily be modified to suit any detector design. The calculated full surface illumination transit time spread (TTS) is ~4 ns. The estimated cost of this tube is around $10,000 (U.S.) in small quantities, and is unlikely to be less than $5,000 (U.S.) in large quantities. Hamamatsu Photonics K.K., Japan, has produced 50 cm and 38 cm PMTs. Three of each have been on loan from Hamamatsu Photonics K.K. for evaluation, and subsequently two of the three 50 cm PMTs have been purchased.

A fast pulsed red LED light source (width < 2.1 ns) has been built to measure the single p.e. response of the Hamamatsu PMTs. The intensity of the LED is adjusted so that only 15% of LED flashes produce anode pulses. Fig. 4 shows the single p.e. pulse height spectrum from a 50 cm PMT. The pulse height resolution is not adequate for identifying one or two p.e. peaks. Similar pulse height spectra were obtained from the 38 cm PMTs.

The TTS of these Hamamatsu PMTs were measured using a leading edge constant fraction discriminator (CFD). Of the three 50 cm PMTs, one (serial number ZW4730) has low gain and poor TTS (FWHM>12 ns). The other two, (serial numbers ZW4706 and ZW4763) are better, with TTS of ~10 ns and ~8 ns respectively. Fig. 5 summarizes the results from PMT ZW4706.

The TTS of ZW4706 has also been measured using a Tektronix 466 Storage Scope. For spot illumination at the centre of the photocathode, the TTS is 7 ns, substantially less than the value of 9.1 ns obtained using a CFD. The degradation of the timing resolution may be due to the small amplitude (~mV) and large dynamic range of the single p.e. pulses. Measurement using a leading edge (LE) discriminator with amplitude correction gives a timing resolution of 9.6 ns (FWHM) with a time slewing of 16 ns.

Similar measurements were carried out for a 38 cm PMT. The spot illumination TTS is in the range 5 to 7 ns at FWHM. However, the transit time difference from different points on the photocathode is 20 ns, indicating a geometrical deficiency in the curvature of the photocathode. These 38 cm PMTs are not suitable for our experiment.

Recently Hamamatsu has redesigned the dynode structure of the 50 cm PMTs, and measured a full surface illumination TTS of 4.4 ns (FWHM) for a prototype. A factor of two improvement in the timing resolution will reduce the noise trigger rate, increase the spatial reconstruction accuracy and reduce reconstruction uncertainties. The cost of these improved PMTs moreover remains unchanged.

Analog and timing signals from the PMTs are digitized in a front end circuit board, and passed onto microprocessors which perform preliminary sorting of the data. First-in first-out (FIFO) units are used to accommodate high data burst rates. To achieve low energy threshold (low number of tubes triggered) and to reduce the amount of data to be stored for later analysis, it is desirable to have fast on-line reconstruction capability.

The design of the front end analog and timing board is in progress. Different timing concepts will be tested. The design of an M68010 based crate controller board is near completion. The hardware and software for fast on-line reconstruction is being developed. The system is based on M68020 multi-processor arrays, similar to those used at Fermilab.

D_2O/H_2O/ACRYLIC VESSEL

Properties of H_2O and D_2O have been investigated. Measurements of the purity of H_2O and D_2O with respect to U and Th contaminations are described above in the Radioactivity Section. Studies on the attenuation of light in H_2O and D_2O have now been completed and have been published25).

A 1.5 L/min water purification system with reverse osmosis and ionic and inorganic filters (MILLI-Q components) has been installed at Oxford University. A clean laboratory with appropriate working surfaces, equipment and electronics has been set up to provide large volumes of purified water necessary for tests of filters (such as permanganate) as a means of removing trace amounts of Ra. Techniques to count the radioactive Ra daughters will be investigated. These techniques, if sufficiently sensitive, will be used to verify that water of the desired purity can be obtained with appropriate filters.

Stringent requirements are placed on the acrylic vessel containing the heavy water. Physics requirements demand that absorption and scattering of the ultra violet (UV) photons be minimal, and that the radioactivity of the material be as low as possible. The high cost of the heavy water requires that the integrity of the vessel under foreseeable operating conditions be unquestionable for at least 10 years.

To determine the integrity of such a vessel, an engineering design has been carried out by Reynolds and Taylor Inc., at Santa Anna, California26). The study included finite element stress analysis for both empty and filled conditions (with D_2O inside the vessel and H_2O outside). The D_2O level was adjusted so that the vessel was everywhere under positive internal pressure. The model vessel consists of a 11.5 m diameter cylinder, 5.35 m high with crown and base spherical domes which have a 2.75 m rise. The wall thickness is 5.1 cm everywhere. Two 107 cm diameter openings at the apex and base are included to model access hatches. The vessel is supported by twenty-four 20 cm thick slabs. Such a vessel was found to be able to withstand the loading anticipated with a safety factor of 46 for at least 10 years. The acrylic support structure will reduce the transmission of Cerenkov photons to the photomultipliers mounted at the bottom of the acrylic vessel. Alternate methods of supporting the vessel which would reduce this effect will be considered by the engineers.

The engineering design report of the acrylic vessel has been submitted to AECL for their consideration. If the design criteria satisfy the requirements of CANDU Operations (a branch of AECL which handles D_2O), the manufacturer is confident that the basic design may be refined and optimized.

Monte Carlo simulations of the detector's performance, using commercially available data on acrylic, indicate that 20-40% of the photons will be lost due to attenuation the acrylic vessel. Acrylic transmission measurements have been made at NRC27) and are summarized in Fig. 6. These data agree with the manufacturer's specifications. We are presently investigating alternate sources of UV transmitting acrylic with a view to reducing the transmission losses. The manufacturer of another type of acrylic (POLYCAST) claim that their product is at least a factor of two better in the UV and a sample has been sent to NRC for verification of this claim.

Calculations of the permeation of D_2O through the acrylic tank due to a

D_2O/H_2O hydrostatic difference and due to diffusion through the walls were performed at CRNL[28]). The diffusion component is negligible and the permeation, if the H_2O and D_2O water levels are the same, was only 45 kg per year.

CALIBRATION

A detailed understanding of the procedures needed to maintain long term calibration of water Cerenkov detectors located deep underground is required in order to optimize and to maximize the full physics potential of our project. For high energy processes in detectors located at relatively shallow depths (IMB and Kamiokande proton decay detectors), cosmic-ray muons traversing the detector can provide a useful calibration since the muon event rates are reasonable and the energy ranges overlap. However, for processes with energies below 14 MeV, no convenient process with adequate event rate exists for calibration purposes. Cosmic-ray muons traversing the detector deposit several orders of magnitude more energy than typical solar neutrino events. Stopped muon decay events have an energy about a factor of four too high, and their rate is too low at the 6800′ level. Hence it is essential to establish a reliable procedure to check the stability and calibration of the detector with light sources and electron sources.

The requirements for an electron source are portability, variable energy (5-15 MeV) and low intensity (1-200 Hz). Two possibilities are under investigation. The first consists of a ^{252}Cf neutron source with a ^{7}Li target producing ^{8}Li. The electrons (maximum usable energy of 13 MeV) from the beta decay of ^{8}Li would subsequently be energy analysed and transported to the detector. This approach has the disadvantage of requiring a strong neutron source and much shielding. A portable D-T accelerator may be an alternative to the Cf neutron source.

The second possibility is to use a variable energy electron linac similar to the commercially available AECL "Therac 25" units used for treatment of various cancers. Enquiries have established that energy resolution is not a problem but achieving a low beam intensity requires some development work. The development, costing and licensing of this approach will be pursued with the CRNL Accelerator Physics Branch.

To check Monte Carlo simulations of 5-11 MeV electrons in water, a small test detector (STD) has recently been assembled at the NRC electron linac. It consists of forty-four 5" photomultipliers (on loan from the IMB collaboration) arranged around the surface of a 50 cm diameter, 60 cm high cylinder to provide approximately 40% coverage of the surface. Mono-energetic electrons in the 3 to 12 MeV range are introduced through a tube to the centre of the cylinder. The response of the detector is being measured using 5, 8 and 11 MeV electrons. A preliminary effort demonstrated the presence of a number of problems - for example, the calibration of the photomultipliers. New calibration procedures using a flash lamp and an alpha source-scintillator combination are being implemented.

For more detailed tests of detector performance a large test detector (LTD) is desirable. We are actively considering an LTD that would be a 5.5 m diameter, 5.5 m high cylinder with 200 20" Hamamatsu photomultiplier tubes (40% coverage). This would be used to optimize the detection of reaction III and to prototype the SNO detector.

CONVENTIONAL CONSTRUCTION

The site of the neutrino laboratory in the norite host rock at the 6800′ level of the Creighton mine offers the advantages of excellent shielding from cosmic-rays, a stable and homogeneous rock formation, a manageable level of terrestial radioactivity background, and proximity to an active mining area which will be maintained for the lifetime of the laboratory. The presence of a shear zone in the norite has led INCO to suggest that the laboratory be moved to a site near that indicated as alternative #2 in Fig. 7. The shear zone dips to the north and should not affect the stability of the cavern. Cutting of the access drift has started and INCO′s schedule calls for its completion in 7-8 months. INCO plans to excavate the drift to the 70° bend and then select the final location of the cavity on the basis of data from test holes drilled into the norite. A geotechnical survey involving in-situ stress measurements will be done and INCO will then prepare the design of the laboratory in consultation with the SNO group.

Following the drawing up of a contract with INCO, measurements of stress release cracking in the rock were made at the 7000′ level crusher station, the largest cavity at comparable depth in the Creighton Mine. As outlined in their report[29]), modelling based on these measurements provides encouragement that a 20 m diameter cavity can be safely excavated at this depth.

A schematic drawing of the detector is shown in Fig. 1. Preliminary designs for various systems associated with the detector have been prepared; these include mounting arrangements for the photomultiplier tubes, a gas tight seal to maintain an inert gas blanket above the H_2O and feedthroughs for cables and calibration equipment. Consideration of the constraints on construction at the 6800′ level and the systems required for the laboratory have resulted in the preliminary layout shown in Fig. 8. It is envisaged that filtered air will be supplied to the utility area and that a second stage of filtering and chilling will be provided for the air supplied to clean the work area and the vault above the detector. Heat introduced into the laboratory from the surrounding rock and from electrical power used will be rejected to the air circulated through the mine. The investigation and specification of systems to filter and chill air, circulate, purify and chill H_2O, circulate and purify D_2O, and to provide electrical power free from surges are in progress. Assurances have been given by INCO that adequate services for the laboratory will be available namely, 300 kVA of electrical power, 25000 cfm air flow at 20°C and 100 gal/min of potable water.

ADMINISTRATION

The membership of the collaboration has expanded to include an additional six physicists from Queen's, three from NRC and one from Oxford. One research associate from Guelph has finished his appointment. H. H. Chen and G. T. Ewan are the spokesmen and E. D. Earle is the technical coordinator. Responsibilities for important areas of the project have been assigned to working groups with the following membership:

Radioactivity	J. J. Simpson (Chairman) R. C. Allen, W. F. Davidson, E. D. Earle, P. Jagam, H. W. Lee, J. D. MacArthur, A. B. McDonald, B. C. Robertson, D. Sinclair.
Electronics	H.-B. Mak (Chairman) R. C. Allen, H. H. Chen, C. K. Hargrove, P. Skensved, R. L. Stevenson, D. Sinclair.
D_2O/H_2O/Acrylic	E. D. Earle (Chairman) H. H. Chen, W. F. Davidson, P. J. Doe, G. T. Ewan, L. Howie, H. W. Lee, W. McLatchie, R. S. Storey
Calibration	H. H. Chen (Chairman) R. C. Allen, J. D. Anglin, M. Bercovitch, A. L. Carter, W. F. Davidson, C. K. Hargrove, D. Kessler, J. R. Leslie, D. Sinclair, P. Skensved, R. S. Storey.
Conventional Construction	H. C. Evans (Chairman) P. J. Doe, E. D. Earle, E. D. Hallman, H. W. Lee.

Administration	G. T. Ewan (Chairman) H. H. Chen, W. F. Davidson, P. J. Doe, E. D. Earle, H. C. Evans, C. K. Hargrove, J. R. Leslie, H.-B. Mak, W. McLatchie, J. J. Simpson.

There is considerable overlap in membership to ensure good communication.

The contract for the access drift is being signed by Queen's University representing the collaboration. Funding for the SNO project was provided by the participating institutions as follows:

Queen's University	- $130K
University of California, Irvine	- $100K US (~$140K CAN.)
NRC, Canada	- $100K
University of Guelph	- $ 20K
Carleton University	- $ 15K
Laurentian University	- Request pending

In addition to these direct grants CRNL has made a major contribution from its budget to cover their engineering and services.

After completion of the access drift a geotechnical evaluation of the site will be done to establish that a 20 m diameter cavity can indeed be excavated and that it will remain stable for 15-20 years.

We plan to complete the detailed design study by September 1987 and request capital funding at that time.

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TABLE 1

Response of the detector to ^{8}B solar neutrinos. The rates are given in events per kilotonne-year for various solutions to the SNP and a SSM ^{8}B flux[19]) of 4 x 10^6 cm^{-2} s^{-1}, except as indicated in the last row. The number of ν_μ,ν_τ + e scattering events is given in parentheses to highlight the increase over the value expected from a ν_e measurement using reaction I.

	[a]	[b]	[a]	[b]	[a,c]
Reaction	I	I	II	II	III
Standard Solar Model	6487	1533	730 (0)	119 (0)	712
A Vacuum Oscillations	2162	511	322 (78)	52 (12)	712
B Matter Osc. E_c = 9 MeV	1028	67	273 (84)	25 (16)	712
C Matter Osc. Non-adiabatic	2269	623	312 (79)	57 (11)	712
E Solar Model Wrong (^{8}B flux: 1.3 x 10^6 cm^{-2} s^{-1})	2162	511	244 (0)	40 (0)	237

Notes: [a] Threshold at 5 MeV.

[b] Threshold at 9 MeV.

[c] Assumes 20% probability neutron capture on deuteron.

FIGURE CAPTIONS

Fig. 1. A conceptual design of a detector for ^{8}B solar neutrinos. Neutrinos interacting in the heavy water can produce relativistic electrons which emit Cerenkov light. This light is detected in an array of phototubes covering 40% of the surface. The detector would be located at a depth of 6800′ in the Creighton Mine near Sudbury.

Fig. 2. Calculated spectra for reactions I and II for some possible solutions of the SNP. Curve A and a are for vacuum oscillations (case A in text); B and b are for conversion of high energy ν_e′s (case B); C and c are for non-adiabatic conversion (case C). It is clear that reaction I (capitals) is significantly better than reaction II (lower case) for measuring the neutrino spectrum.

Fig. 3. The calculated fraction of neutrinos reaching the detector as ν_e is shown for a given value of mixing angle to illustrate the effects of matter enhanced oscillations. ν_e regeneration in the earth causes the day/night difference.

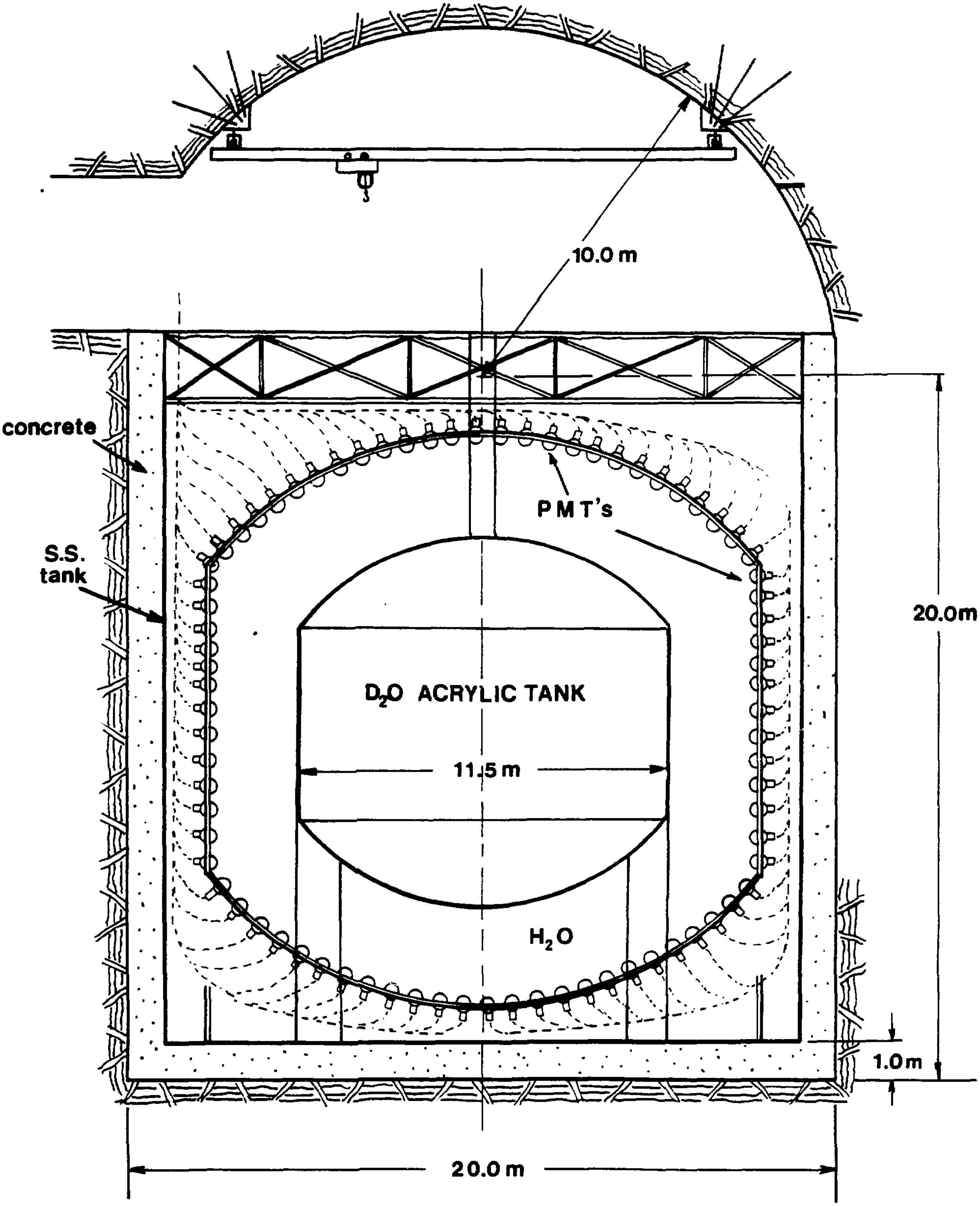
Fig. 4. One photoelectron pulse height spectrum for a Hamamatsu 50 cm PMT. The light source was at the centre of the photocathode.

Fig. 5. Anode uniformity (a), transit time difference (b) and spot timing resolution (c) of a Hamamatsu 50 cm PMT (ZW4706) across the photocathode surface. The cut-off channel for the pulse height spectrum is at channel 46. The crosses and dots are for scans perpendicular and parallel to the vanes in the first dynode.

Fig. 6. Spectral transmittance of a 45 mm thick acrylic sample, as measured in the Photometry Laboratory, NRC. Note that reflections at the air-acrylic interfaces cause a 8% reduction in light transmission. These reflections are negligible at water-acrylic interfaces.

Fig. 7. The location of the access drift and the detector cavity at the 6800′ level in the Creighton mine.

Fig. 8. Possible layout of the Sudbury Neutrino Observatory in the 700' long access drift in the Creighton Mine. The detector cavity, working space and utility areas are indicated.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S.S.
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D_2O ACRYLIC TANK
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H_2O
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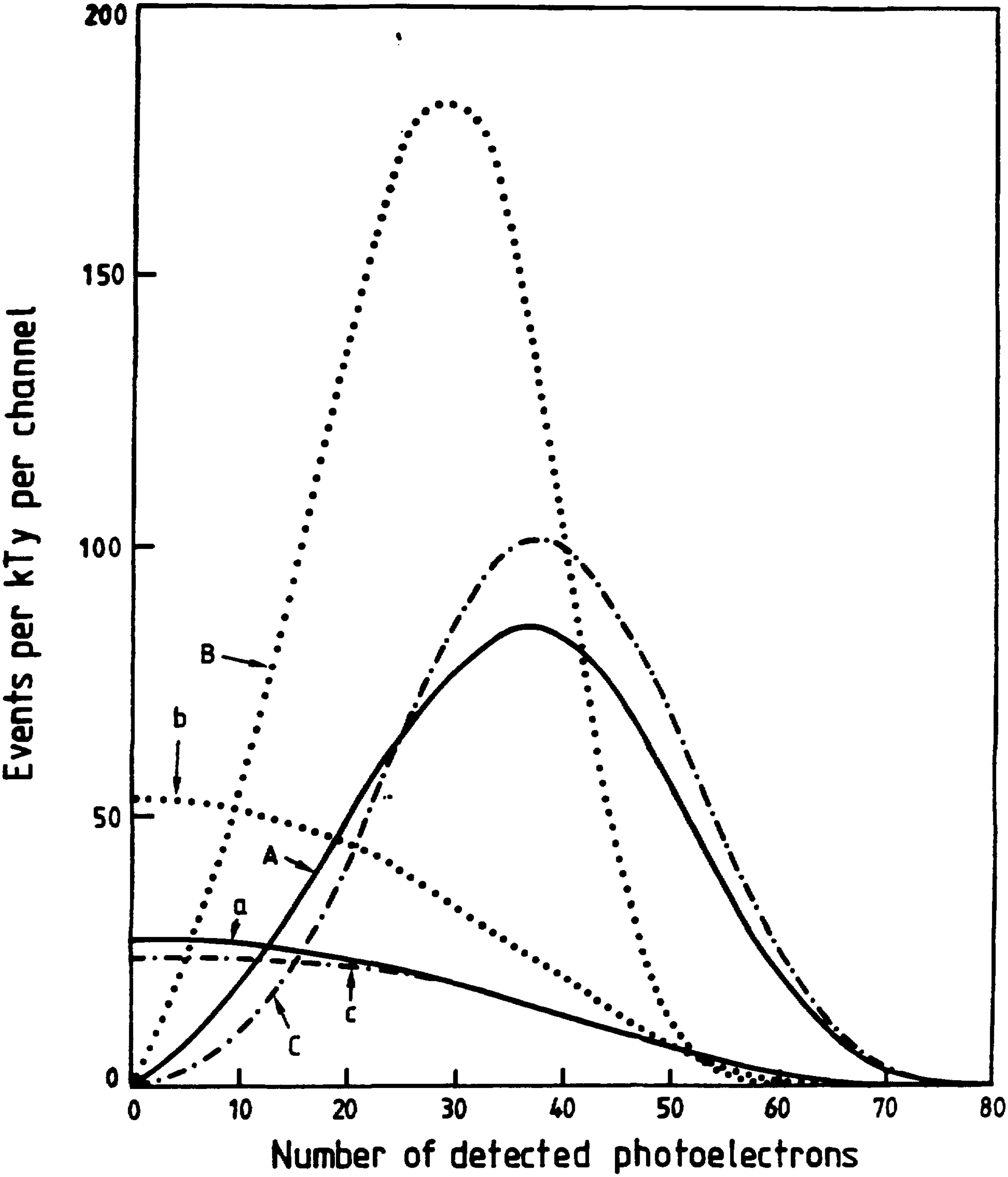
20.0 m

Fig. 1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Events per kTy per channel
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C
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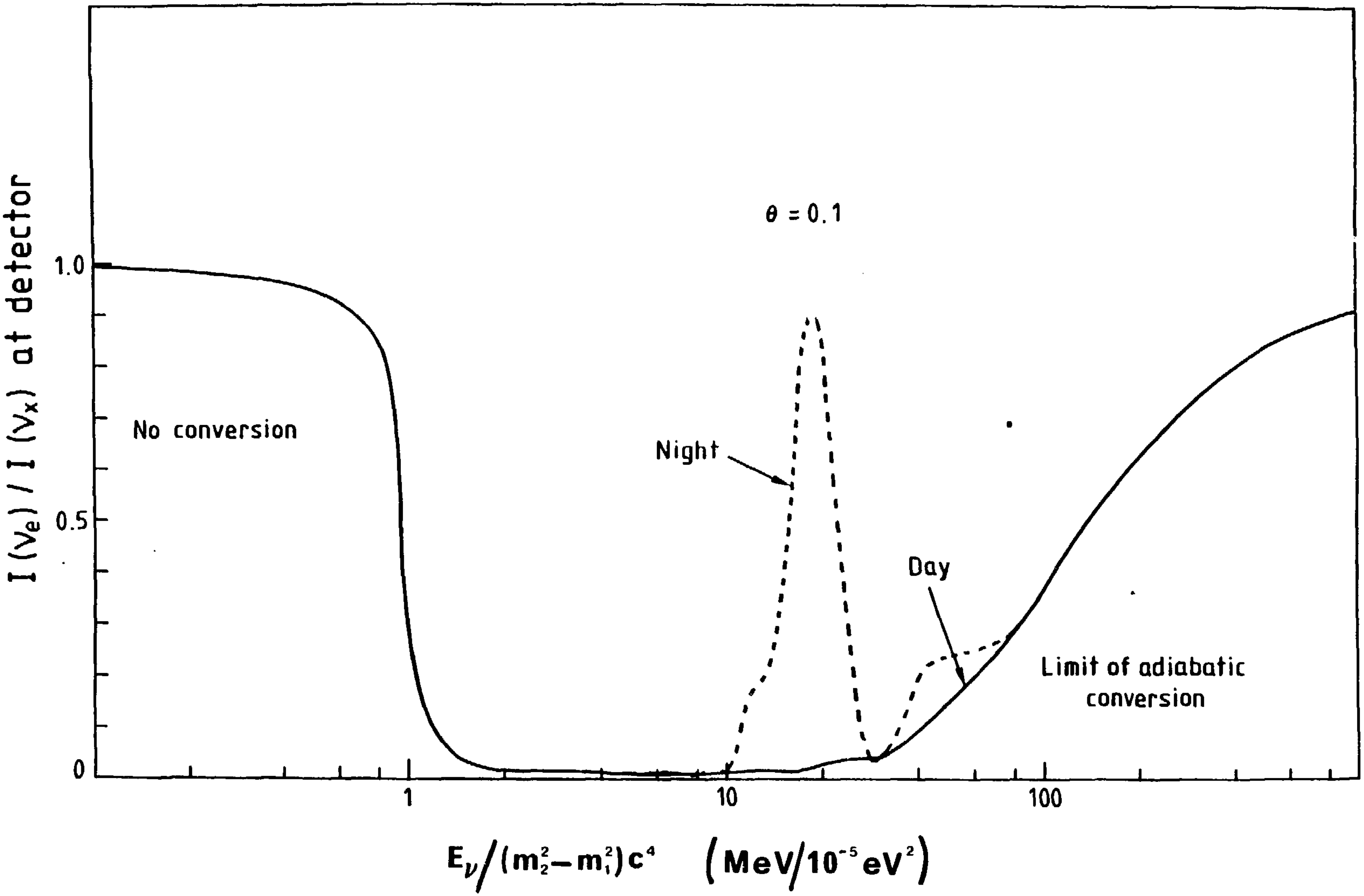
80
Number of detected photoelectrons

Fig. 2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Night
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Fig. 3

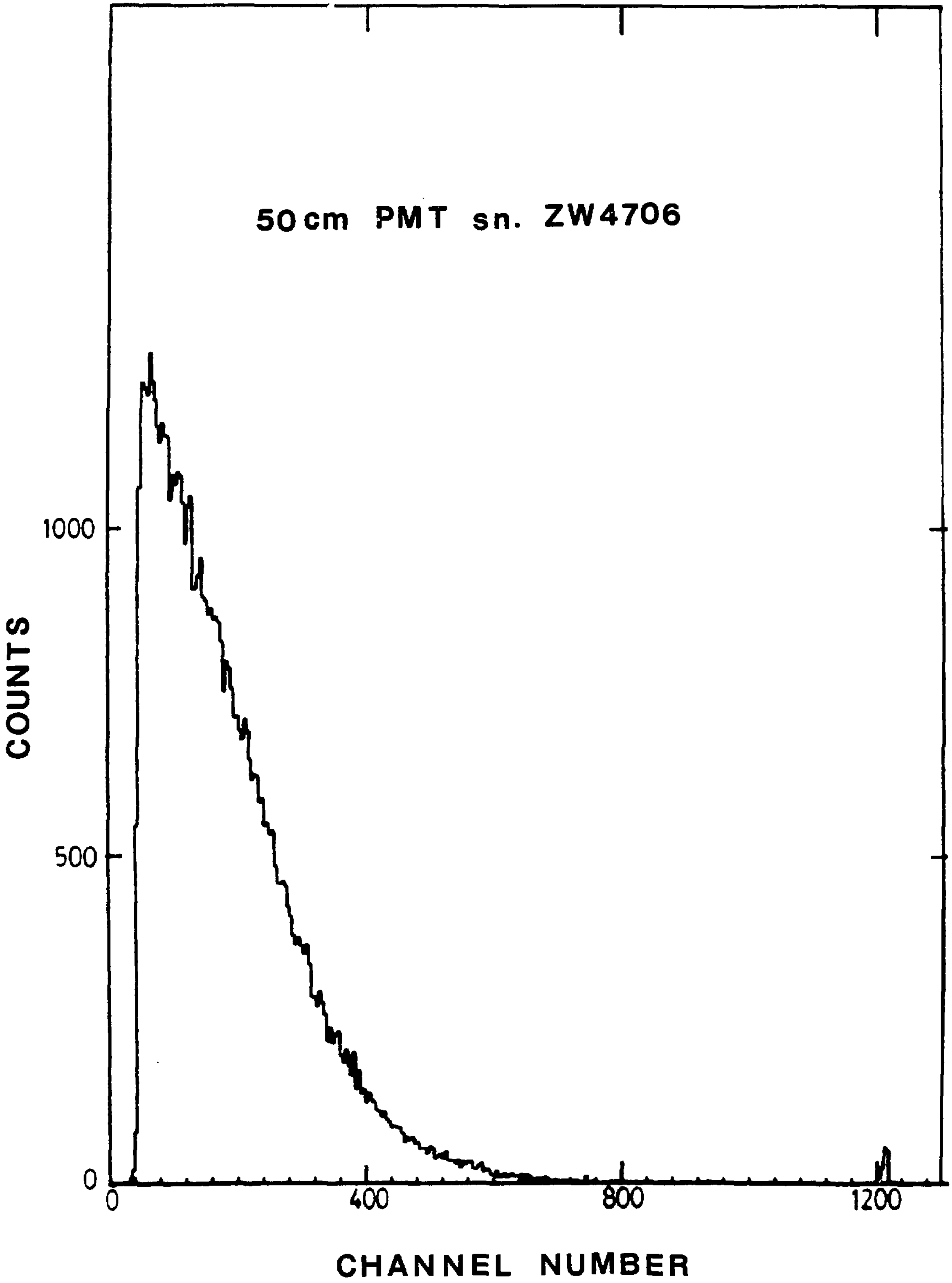
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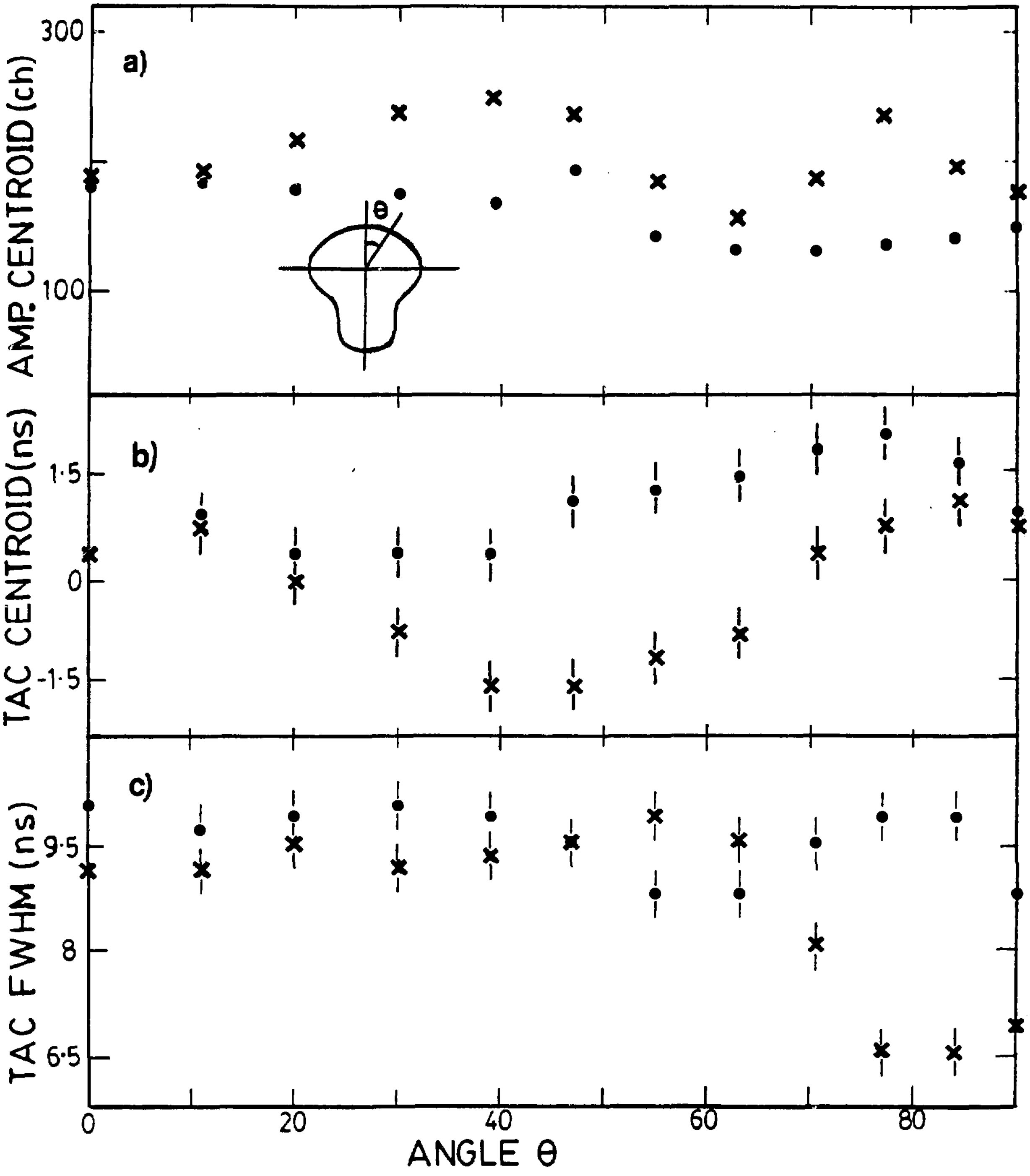
Fig. 4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a)
AMP. CENTROID (ch)
100
θ
b)
TAC CENTROID (ns)
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0
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c)
TAC FWHM (ns)
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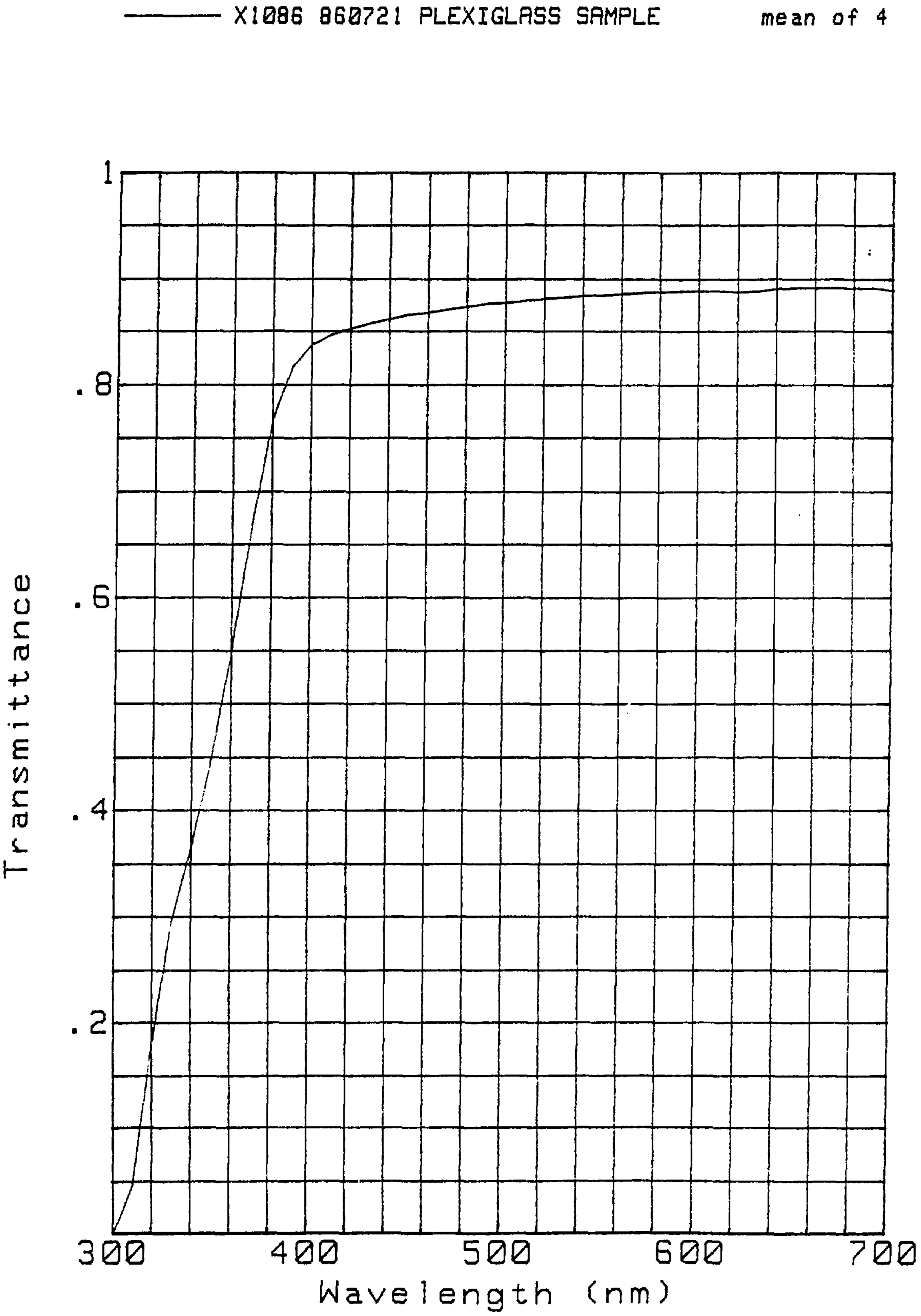
8
6·5
0
20
40
60
80
ANGLE θ

Fig. 5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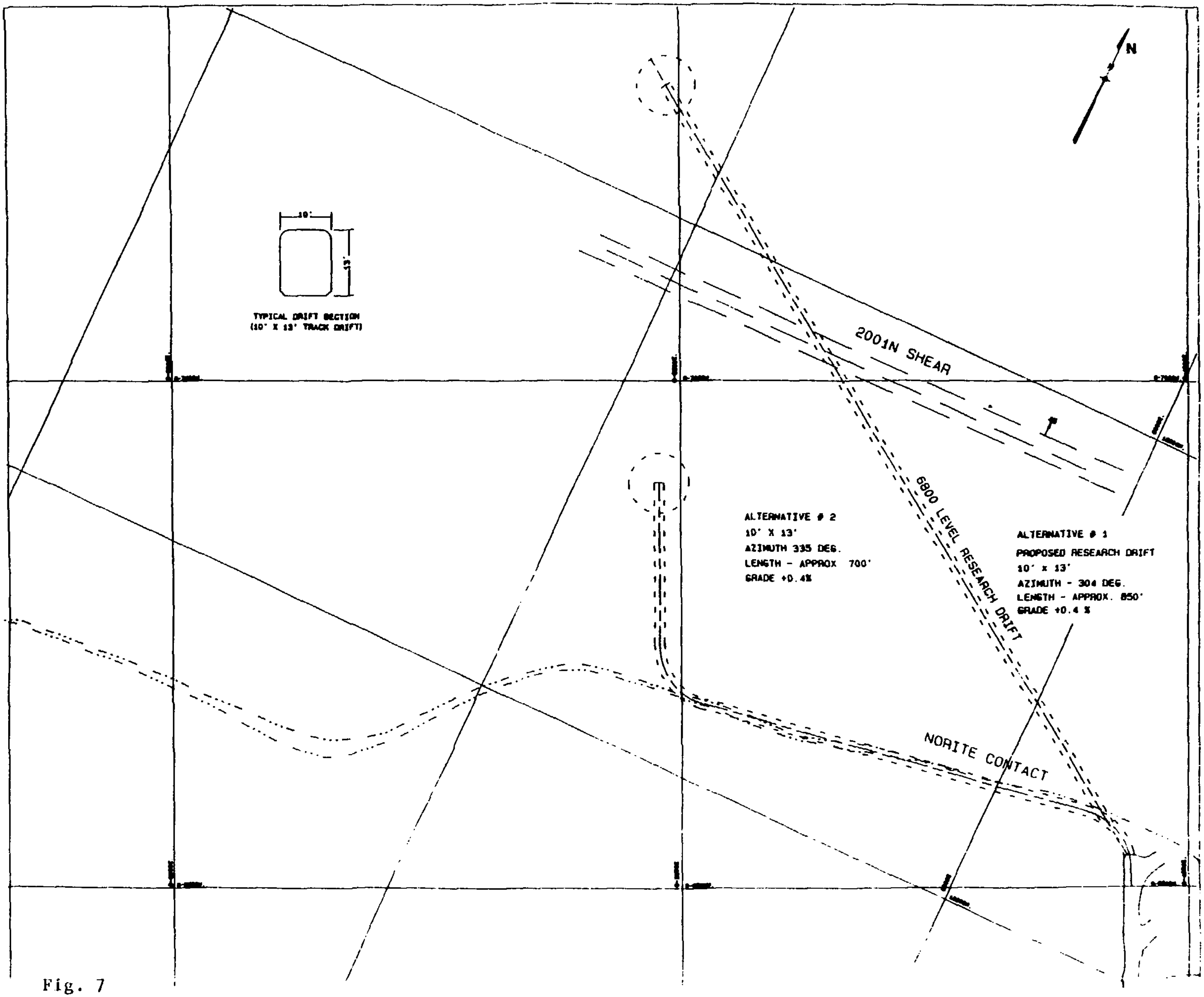
700
Wavelength (nm)

Fig. 6


N
10'
13'
TYPICAL DRIFT SECTION
(10' X 13' TRACK DRIFT)
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6800 LEVEL RESEARCH DRIFT
ALTERNATIVE # 2
10' X 13'
AZIMUTH 335 DEG.
LENGTH - APPROX 700'
GRADE +0.4%
ALTERNATIVE # 1
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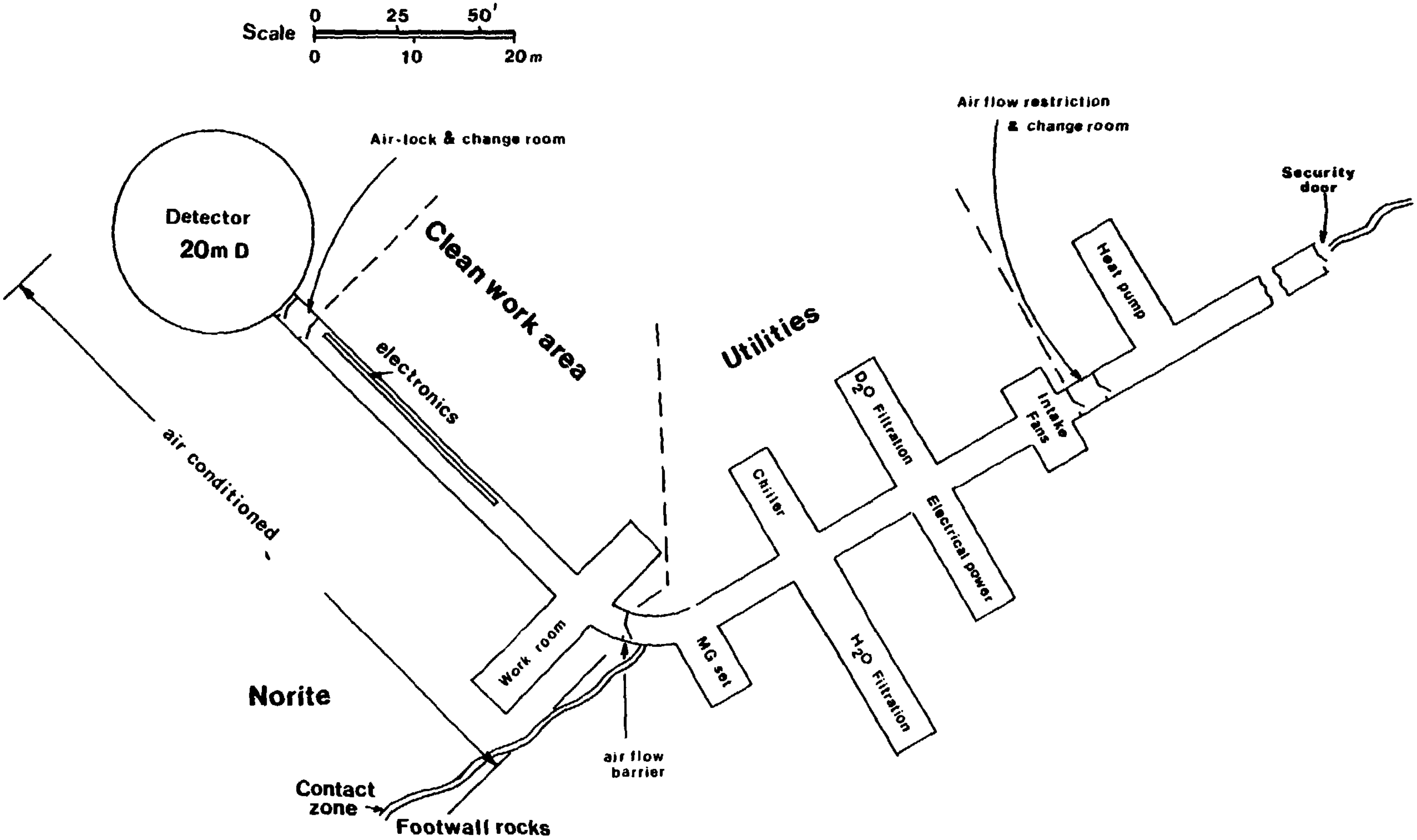
NORITE CONTACT

Fig. 7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Detector
20m D
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air conditioned
Utilities
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& change room
Security door
Heat pump
D_2O Filtration
Intake Fans
Chiller
Electrical power
Work room
MG set
H_2O Filtration
Norite
air flow barrier
Contact zone
Footwall rocks

Fig. 8

Errata to Feasibility Study for a Neutrino Observatory Based on a Large Heavy Water Detector Deep Underground

SNO-85-3

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Sudbury Neutrino Observatory

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J. D. Anglin, M. Bercovitch, W. F. Davidson, C. K. Hargrove,
R. S. Storey, G. Aardsma, P. Jagam, J. J. Simpson, E. D.
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