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Feasibility of Whole-Body Radioassay of SNO Acrylic Panels

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Abstract

Because of apparent inhomogeneities in the distribution of Th and U in acrylic assayed by sampling techniques, the feasibility of directly counting the total gamma emission from Th in full-size, intact acrylic panels to be used in the construction of SNO has been reviewed. It appears to be technically feasible to reach a level of sensitivity of about 5 pg/g Th by this approach. However, no presently extant facility is known (with one possible exception) that would meet the requirements, and construction of one from scratch within the time frame of interest seems problematical. The cost of such an ab-initio facility is in the vicinity of $700,000.

1 Introduction

The heavy water containing vessel in SNO will consist of over 450 m^2 of 2- to 4-inch thick acrylic. The radiopurity of this material should be as low as possible especially with regard to U and Th ($<$ 5ppt). Relatively few techniques are available to assay Th and U in materials at the pg/g level. For acrylic, the methods used in SNO include inductively-coupled plasma mass spectrometry, thermal-ionization mass spectrometry, neutron activation analysis with or without radiochemistry, and alpha counting. These methods are all destructive and are "small-sample", that is, they can be applied to samples from a few grams to a few kilograms. Tests of acrylic to be used in SNO with these methods have revealed general levels of Th in the 5-20 pg/g range (close to the maximum considered acceptable), and occasional samples at >100 pg/g. If the Th and U activities are associated with randomly distributed particulate matter in the samples, then it will be very difficult to obtain adequate information on the overall distribution from the proposed sampling technique. There is a concern, then, that actual panels cannot be tested by any of these techniques, and, in view of the inhomogeneities, it is possible that certain panels might be very "hot".

The only approach to determining the Th content of a panel non-destructively is gamma-counting of a full-size panel in a well-shielded environment. The generic design of such a whole-body counting (WBC) facility is a large tank containing pure water and located far enough underground to avoid significant cosmic-ray backgrounds. Gamma-counting (for reasons of both size and background) would make use of solid or liquid organic scintillators. A slab geometry with layer(s) of scintillator next to the acrylic-under-test is appropriate.

2 Design Objectives

The SNO Radioassay Experiment (SNORE) should be capable of determining the activity of one or more acrylic panels:

1. Precision 5 pg/g (one sigma, one day).
2. Maximum panel size 4m x 2m.
3. Maximum panel thickness 10 cm.
4. Non-destructive, non contaminating.
5. Be able to perform analysis at a steady state rate which is commensurate with the delivery of product (i.e. certify a panel/day).

6. Ready to use by Nov. 1, 1992.

In addition to satisfying the primary objective of certifying the acrylic; a large, water shielded, low background detector could also be used by SNO for testing neutral current detectors, non destructive radioactivity measurements of other SNO components such as rope, and a test bed for electronic and data acquisition systems to be used in the main experiment.

3 Signal and Background

3.1 Signal

At the bottom of the Th chain is the ^{208}Tl decay that leads to the troublesome 2.614-MeV γ. Every 100 Th decays produce (in equilibrium) 36 of these gammas. The rate is 1.26x10^{-4} pg^{-1} d^{-1}. An infinite slab of material of thickness t_A g cm^{-2} and purity P_A pg/g emits gammas from one face at the rate

$$f_\gamma = 0.63 t_A P_A \ \mathrm{m}^{-2}\mathrm{d}^{-1} \tag{1}$$

The total 2.6-MeV gamma rate from a sheet of acrylic ($\rho = 1.18$) 4m x 2m x 0.05m is 345 per day at 5 pg/g Th.

3.2 Cosmic Ray Background

Table 1 gives cosmic-ray muon fluxes for the sites under consideration, taken from the SNO White Book.

A minimum-ionizing muon deposits about 1.5 MeV g^{-1} cm^2. If the scintillator thickness is at least 12 g cm^{-2}, the cosmic ray signal will peak at 18 MeV or more, and will not represent a background for the Th line at any site except possibly IMB. The main concern is "corner-clippers" that leave less than the full energy in the scintillator. Such events are a few percent of

Table 1: Cosmic ray muon fluxes for several underground sites.

Site	Depth (ft)	Rate $m^{-2}d^{-1}$
IMB	1800	548
WIPP	2200	192
Boulby	3300	27
Gran Sasso	4200	7
Sudbury	6800	0.2

the total for scintillators at least 1 m^2 in area. Another concern is spallation products that linger after passage of a muon. While these were present as much as 10% of the time in Kamiokande II, the much smaller sensitive volume of SNORE makes them unimportant. Finally, there may be some conversion and detection by the scintillator of Čerenkov light originating in the water, even when the muon does not pass through the scintillator. A veto may be required.

3.3 Gamma Flux from Rock

The flux F_0 of Th gammas from the walls of the cavity can be deduced from the known concentration of Th and the fact that the mass absorption coefficient μ at these energies is approximately independent of Z.

$$F_0 = 0.63P_r \int_0^\infty e^{-x/\mu}dx = 0.63P_r\mu \tag{2}$$

For Sudbury and Gran Sasso we take P_r = 3.3 ppm, and for IMB, WIPP, and Boulby, P_r = 100 ppb. The corresponding fluxes are then 4.9x10^7 and 1.5x10^6 $m^{-2}d^{-1}$, respectively.

EGS4 calculations give μ = 23.3 g cm^{-2}. The thickness of water shielding t_w required can then be determined, given a specified flux F at the test position.

$$t_w = \mu \ln(\frac{2F_0}{F}) \tag{3}$$

The factor 2 arises from the presumed symmetry of the detector, which recieves background equally from 2 walls. The other walls do not contribute in an infinite slab geometry, but do in a more realistic situation. If we specify an external background equal to the signal, then,

$$t_w = \mu \ln \frac{2F_0}{0.63 t_A P_A} = \mu[\ln \frac{2F_0}{0.63} - \ln t_A P_A] \quad (4)$$

Then,

$$t_w = [439 - \mu \ln t_A P_A] \text{ cm (Sudbury, Gran Sasso)}$$

$$t_w = [358 - \mu \ln t_A P_A] \text{ cm (WIPP, IMB, Boulby)}$$

For example, if we choose $t_A = 12$ g cm^{-2} and $P_A = 5$ pg/g, then t_w is 3.4 m (Sudbury, Gran Sasso), or 2.6 m (WIPP, IMB, Boulby).

3.4 Water Purity

The flux of Th gammas from the water can be calculated in a similar manner to give a value for F_0 for water,

$$2F_0 = 2(0.63\mu P_w) \quad (5)$$

which yields,

$$P_w = 0.02 t_A P_A \quad (6)$$

for equal contributions of water radioactivity and acrylic to the signal. This turns out to be a very modest specification, and water at 0.1 pg/g would make a negligible contribution.

3.5 Monte Carlo

We have used EGS4 calculations to determine the various backgrounds and the response of the detector. The geometry that we have used is meant to be realistic, but we have not had a chance to optimize the geometry. Our goal is to determine feasibility, rather than to establish various design parameters.

The geometry that we assumed is a tank, 7 meters high and 10 meters in diameter, filled with water. We assume two scintillator paddles, 2m by 2m. Each paddle is attached to a 2 m x 1.5 m flat light pipe, and then to a set of phototubes. The calculations are done assuming that there is a 4m x 2m x 0.50 m isolation box that allows one to isolate the acrylic samples from the water. For most of the calculations, we have used a box that is 5 cm thick and filled with air. The box has dimensions that are suitable to hold a curved sheet of acrylic from Rohm. However, we have only calculated the efficiencies for flat sheets.

Our Monte Carlo has been run to determine efficiencies and backgrounds for various configurations. The parameters we have tried to explore are scintillator thickness, sample position, effects of water in the box, and multisheet counting. The isolation box has a large impact on efficiency, and we have also investigated the scenario with a very thin (non-structural) container.

In calculations, we have concentrated on the 2.6-MeV gamma ray in thorium. Higher energy gamma rays can be generated by neutron capture, but their intensity is significantly reduced from the primary decay. Lower energy gamma rays can be discriminated against by energy resolution.

3.6 Plastic Scintillators and Expected Response.

3.6.1 Light Collection and Resolution

Normal plastic scintillator produces about 1 photon/100 eV of energy deposited in the detector. This light has to be transported through the scintillator and lightpipe to photomultiplier tubes. The number of photoelectrons one produces should be equal to

$$N_e = \frac{E_\gamma}{100eV} e^{-\lambda x} \Delta\Omega f_{PMT} Q \tag{7}$$

where E_γ is the gamma energy, λ is the attenuation coefficient, x is some mean distance travelled in the scintillator and the light pipe, $\Delta\Omega$ is the fraction of phase space for which light in the light pipes undergoes total internal reflection, f_{PMT} is the fraction of coverage of the ends of the light pipe with photocathode, and Q is the quantum efficiency. For our case, E_γ = 2.6 MeV, $\lambda = 1/3$ m^{-1} (this corresponds to a typical measured attenuation of 0.016 in SNO acrylic and a similar number for scintillator from the Particle Data Handbook), x = 4 m, f_{PMT} = 0.50, and Q = 0.20. $\Delta\Omega$ can be calculated from the relative indices of refraction of acrylic (1.5) and water (1.33). Hence,

$$\theta_{crit} = sin^{-1}(1.33/1.5) = 62.5^\circ$$

$$\Delta\Omega = (1 - 2\theta_{crit}/\pi)\cos(\theta_{crit}) = 14\%$$

$$N_e = 96pe$$

This is probably somewhat conservative; it is quite possible to find acrylic lightguides with a somewhat longer attenuation length, and we could use somewhat shorter lightguides as well. In any event, we can expect an energy resolution of about 10% one-sigma, or 23% FWHM. To cover each end of a 2 m wide scintillator paddle with phototubes, at 50% coverage would use 5 phototubes; for two scintillator paddles we use 20 phototubes.

We do not expect to wrap the scintillators or light guides. The tank will be kept dark to prevent light from reaching the PMTs. This means that we don't have to worry about contamination in the wrapping materials.

We can also build an apparatus in which there are no light guides – we would just use phototubes to view the scintillator through the water. The relative economy of these two methods is dependent on the size of the scintillator – for small-area scintillators, the light guide allows one to collect a significant amount of light with few phototubes. As the area of the edge grows in size, light pipes become less advantageous. The size of our scintillators is right at the break-even point.

In this case,

$$N_e = \frac{E_\gamma}{100}\frac{\Omega}{4\pi}Q \tag{8}$$

assuming that there is essentially no attenuation in the water. This would require covering 2% of the area with photocathode; if we put 8-inch tubes on a 1.5-m radius, we can get approximately the same amount of light with 18 phototubes. We have not worked out the optics to demonstrate whether one could use the same phototubes for both scintillators, and if the isolation tank or sample interfere with the light leaving the scintillators and arriving at the phototubes. For more than 2 scintillators, or scintillators thicker than 20 cm, this is certainly the preferred option.

3.6.2 Solid vs. Liquid Scintillators

We have not presupposed a particular form of the plastic scintillator. The geometry that we modelled supposes scintillators that are 10, 20, or 40 cm thick and 2 x 2 m. This could be either a tank, made of thin acrylic and filled with liquid scintillator, or a solid plastic scintillator.

The advantages of solid scintillator are that it is easy to work with, has a typically higher light output, and is stable. The disadvantage is that they have not been demonstrated to have low radioactivity. The one measurement, from Bicron, was -0.5 ± 1.3 ppb Th and 1.6 ± 1.3 ppb U. We view these numbers as upper limits, and not evidence for U at this level. In principle, the scintillator should not necessarily have higher backgrounds than the acrylic. That remains to be determined.

The advantage of liquid scintillator is that it has been demonstrated that it can be made with thorium and uranium levels below 0.01 ppt. The difficulties, as quoted from the MACRO proposal, are "poor and/or unstable transparency, leaky containers, toxicity and flammability, etc... Many plastics are attacked by the aromatic solvent in the scintillator causing the containers to weaken and develop leaks... Proper handling of the scintillator is very important. Tank wagons, drums, mixing tanks, pumps, hoses and all other objects with which the scintillator comes into contact must be examined with the same care as the detector components themselves.... The areas where significant problems were encountered and overcome were in the transparency of the mineral oil and aromatic components, the purity and stability of the scintillation phosphors, the proper materials handling, the inhibition of oxidative degradation of the scintillator, the control of water content and the elimination of suspended particles". Clearly if we are to pursue the liquid scintillator option, we will need to devote significant effort into learning the necessary techniques.

3.6.3 Čerenkov Detection

We have made a cursory investigation of the possibility of using Čerenkov radiation for the measurement of the radioactivity background in the acrylic panels. In this scenario the WBC would be configured in a manner similar to SNO. An array of phototubes would be placed around the internal periphery of the WBC vessel in order to view the acrylic panel placed in the center of the vessel. An estimate of the relevant parameters:

WBC Parameters

Th in 6.5'x12.5'x2.25" panel (5ppt)	2.55 μgm
2.6 MeV ^{208}Tl γ-rays	322/day
Estimated Čerenkov (300-650 nm) production from:	
Compton scattering of 2.6 MeV γ's	168/γ
^{208}Tl β decay particles	79/β
	—
Total	247/^{208}Tl decay
Radioactivity backgrounds	
Th in 600 tons H_2O (@ 10^{-13}g/g)	60 μgm
Th per photomultiplier assembly	120 μgm

With a 15% quantum efficiency and 50% coverage (3500 PMTs!), we would get 18 PM hits per ^{208}Tl decay. With so few events it would be difficult to perform very accurate position extraction (we have not performed any detailed Monte Carlo calculations on this system). This means we would not be able to discriminate against the background events from spatial considerations. The assumed H_2O concentration of 10^{-13} g/g of Th would be over a factor of 20 greater in total Th content than that in 5ppt acrylic. Even more serious would be the contribution from the photomultipliers. The current estimate is that each PMT will have 120 μgm of Th. Since 3500 are required for 50% coverage this would mean 0.42 g of Th. This level of Th is 160,000 times as great as that present in the acrylic. Some spatial discrimination would certainly be possible but this still seems to be a background level that would overwhelm any direct signal.

3.7 Backgrounds

3.7.1 Thorium 2.6 MeV γ

The calculated backgrounds are shown in Table 2, for 10, 20 and 40 cm thick scintillators. Each entry represents 25000-100000 generated events. External events were generated uniformly over the exterior of the cylinder, with a direction so that they would uniformly illuminate a 3 meter diameter sphere in the center of the tank. EGS4 was modified so that the initial interaction always occurs after an attenuation by a factor of 10^{-6}. This allows reasonable statistics without generating an unreasonable number of events.

Events inside the water, lightpipes, scintillators, isolation box, and sample were generated with a uniform distribution in position and direction. Events in the photomultiplier tubes were generated, but did not interact before attenuation by a factor of 50.

The column "ppt-days" in the table shows the product of radioactivity and running time represented by the number of events thrown. "Counts" are the detected number of gammas with energies between 1.7 and 3.0 MeV in the scintillator, "Normalized Counts" is column 3 divided by column 2. No instrumental resolution has been included, but is not expected to be important inasmuch as the lineshape is dominated by statistics and showering. To calculate the expected counts, we multiply by the expected level of radioactivity; we use 115 ppb for exterior events, and 0.1 ppt for water, and 10 ppt for lightpipes, scintillators, and isolation box. The acrylic sample is at 5 ppt. For the PMTs, activity is given per tube, rather than per ppt. For the expected activity we assume that there are 20 PMTs each with 100 μg of thorium.

It is clear from this table that there is little advantage in going to thicker scintillators. Although the signal improves, so does the background. This may not be true for liquid scintillators, where the background would essentially come completely from the container.

3.7.2 Other Thorium and Uranium Induced Backgrounds

We have two worries in this area. One is neutrons from α-n reactions and the other is alphas and betas from thorium inside the scintillator.

Neutron capture in the water produces a 2.2 MeV γ; neutron capture in the salt surrounding the tank can produce 8 MeV photons. The neutron yield from NaCl, due to the alpha decay of imbedded thorium has been calculated to be 3.5 n/y/g/ppm, and for Uranium is 7.3 n/y/g/ppm. From this, one can show that the external high energy gamma rays are down by a factor of more than 6500 as compared to the 2.6-MeV line (for thorium). Neutrons that reach the water will thermalize quickly and be captured around the

Table 2: Calculated backgrounds.

Source	ppt-days	Counts	Normalized Counts/ppt-d	Expected Counts/d
10-cm scintillator				
Exterior	3.9×10^8	600	1.5×10^{-6}	0.18
Water	1.5	45	10	1
Lightpipes	561	712	1.3	13
Scintillator	841	24035	29	286
Sample	1681	5885	3.5	17
Isolation Box	662	5838	9	88
PMTS	396	10	0.025	0.5
Total Background				389
Signal				17 ($= 0.9\sigma$)
20-cm scintillator				
Exterior	9.7×10^7	347	3.6×10^{-6}	0.4
Water	1.5	73	49	5
Lightpipes	70	311	4.4	44
Scintillator	105	9252	88	880
Sample	420	2428	6	29
Isolation Box	166	2260	14	140
PMT	99	3	0.03	0.6
Total Background				1070
Signal				29 ($= 0.9\sigma$)
40-cm scintillator				
Exterior	9.7×10^7	732	7.5×10^{-6}	0.9
Water	1.5	123	82	8.2
Lightpipes	35	487	14	140
Scintillator	52.5	12743	243	2430
Sample	420	3291	8	39
Isolation Box	166	2982	18	180
PMT	99	3	.03	0.6
Total Background				2760
Signal				39 ($= 0.8\sigma$)

edge of the tank; they will essentially be attenuated by the same factor as the external neutrons. Neutrons produced by thorium and uranium inside the other components of the detector are also suppressed when compared to direct gammas.

Inside the scintillator, one has to worry about the entire thorium-uranium chain. The scintillator will detect all the charged particles in the decay chain with high efficiency. The high energy alpha decays have lower light output by about a factor of 10, so they will not contribute to background in the scintillator. There are, however, high energy betas also produced, which may provide an additional background. We need to investigate this further.

3.7.3 Cosmic-Ray Neutrons

Bozrukov et. al. (S.J. Nuclear Physics, 1973) measured and calculated, that at 316 m water equivalent, the number of neutrons produced by cosmics was $1.21 \pm 0.12 \times 10^{-4}$ n/muon/ (gm/cm^2) For our tank, about 8.5% of all muons will produce a neutron; every neutron will be captured in the water and produce a 2.2 MeV gamma. At 2000 feet underground, there are 300 muons/m^2/day, so we find 2000 neutron/day in the tank. These are totally equivalent, as far as the response of the detector is concerned, to having an additional 2000 thorium decays/day, or an additional 16 μg of Th in the water. This is the same as an increase of concentration of 0.03 ppt. From the table above, the water contributes 10 counts/day/ppt; so we get 0.3 counts/day from cosmic neutrons. We might be able to afford a hundred-fold increase in cosmic ray flux, but certainly not much more. It is not absolutely necessary to have an incredibly deep mine to do this experiment.

3.7.4 Multiple Sheet Counting

Since the attenuation length of plastic is about 20 cm at these energies, adding a second sheet allows one to count both at the same time. The efficiency is somewhat decreased, because there is some self absorption, and the geometry is somewhat worse. Table 3 summarizes the efficiency for multi-sheet counting.

Counts represent the number of γs detected with energies between 1.7

Table 3: Calculated signal and uncertainties.

	Counts Detected	Ppt-Days thrown	Normalized Counts	Expected per Day	Background per Day	σ
10-cm scintillator						
1 sheet	5885	1682	3.5	17	389	0.9
2 sheets	1227	210	5.84	29	389	1.5
3 sheets	1064	140	7.60	38	389	2.0
4 sheets	963	105	9.2	46	389	2.4
5 sheets	869	84	10.3	52	389	2.7
20-cm scintillator						
1 sheet	2428	420	5.78	29	1070	0.9
2 sheets	2058	210	9.8	49	1070	1.5
3 sheets	1726	140	12.3	62	1070	1.9
4 sheets	1514	105	14.4	72	1070	2.2
5 sheets	1396	84	16.6	83	1070	2.6
40-cm scintillator						
1 sheet	3291	420	7.8	39	2760	0.8
2 sheets	2814	210	13.4	67	2760	1.3
3 sheets	2491	140	17.8	89	2760	1.7
4 sheets	2234	105	21.3	107	2760	2.0
5 sheets	2041	84	24.3	122	2760	2.3

and 3.0 MeV. The ppt-days column indicates the integrated activity to which the Monte Carlo run corresponds. The Normalized column is column 2 divided by column 3. We assume 5 ppt to calculate the expected number of counts per day, and for the backgrounds. The σ column indicates how well the total rate has been determined, assuming 5 ppt.

It is clear that we gain considerably by counting more than one sheet at once. The negative feature is that it is not as straightforward to assign a definite radioactivity to each sheet.

Table 4: Efficiency variation with distance.

Position	0 cm	5 cm	10 cm	15 cm	20 cm
Air	1470	1006	707	569	535
Water	1058	732	566	494	422

3.8 Isolation Box Configurations

3.8.1 Efficiency Variation with Position

We have studied the efficiency as a function of position for a single flat sheet within the box, oriented horizontally. The reason for doing this was to see how well a rectangular box would work for counting a curved sheet of acrylic – essentially the vertical position then varies as a function of where you are on the sheet. This was done with both an empty box, and the box full of water. The results are given in Table 4.

The position corresponding to 0 cm is with the sample lying on the bottom of the box; the position at 20 cm has the top of the sample in the center of the isolation box. Symmetry dictates the results for positions between 20 and 40 cm. As is evident, there is a considerable variation in efficiency between the bottom and the middle of the box. This is due to the fact that the detection probability is greatest for photons with steep angles; as one moves away from the detector, not only does the solid angle decrease, but the incident angle becomes more normal. There is, moreover, a substantial absorption effect that exacerbates this problem – when many sheets are stacked, the outer sheets shield the center ones.

From this we conclude that a structural isolation box operating at atmospheric pressure is not an attractive option. Bagging the acrylic in polyethylene, suspending it in the tank, and then moving the scintillators as close as possible gives much better signal-to-background. Simpler handling and more detailed information about each sheet would result if we confined ourselves to single-sheet counting. While the statistical accuracy is less, it is still within our target objective.

3.8.2 Thin isolation box

The isolation box has a quite dramatic effect on the efficiency of the system. It forces the detectors to be moved back a considerable distance from the sample. In addition, in order to resist the water pressure, it requires very thick walls (the walls that we have used in the calculations are probably far too thin). Since there is no physics reason why the tank has to be there, we have investigated the scenario where the tank is made very thin. Then there cannot be any pressure differential across it. One can envisage the acrylic sheets laid on an acrylic "saw - horse" type structure immersed in the water. Table 5 summarizes the data. The column "Counts" is the number of detected photons, with energies between 1.7 and 3.0 MeV, for the number of events shown in the column "ppt-days". The "Expected" column is the number of counts for a 5 ppt activity level in the acrylic. "Background" is the number of counts, with the radioactivity levels assumed for the table in section 3. A 5 ppt sample results in a measurement after one day at the level shown in the column labelled "σ".

3.8.3 Systematic Concerns

While the main focus has been statistical, there are important systematic effects that need to be considered. The variation of sensitivity with position both from solid-angle and absorption effects means that there are fundamental limits to the precision of the result, which may be as large as a factor 4, and will almost certainly exceed 1.5, depending on design and operation. This is a consequence of lack of knowledge of the distribution of Th in the sample. The evidence that it is highly inhomogeneous is what has forced us to this method in the first place.

Another effect is that insertion of the sample will change the background quite significantly, by increasing absorption. This problem is most severe with an isolation box (several standard deviations), but occurs even in the absence of such a box owing to the difference in density of water and acrylic. However, it is probably calculable and measurable to the necessary level.

Table 5: Several sheets, no isolation box.

	Counts	ppt-days	Expected	Background	σ
10 cm thick Scintillator					
1 Sheet	2764	420	33	300	1.9
2 Sheets	2276	210	54	300	3.1
3 Sheets	1892	140	68	300	3.9
4 Sheets	1621	105	77	300	4.5
5 Sheets	1461	84	87	300	5.0
6 Sheets	1276	70	91	300	5.3
20 cm thick Scintillator					
1 Sheet	4457	420	53	930	1.8
2 Sheets	3572	210	85	930	2.8
3 Sheets	3120	140	112	930	3.7
4 Sheets	2668	105	127	930	4.2
5 Sheets	2284	84	136	930	4.5
6 Sheets	2105	70	155	930	5.0
40 cm thick Scintillator					
1 Sheet	5977	420	71	2580	1.4
2 Sheets	5050	210	120	2580	2.4
3 Sheets	4281	140	153	2580	3.0
4 Sheets	3713	105	177	2580	3.5
5 Sheets	3373	84	201	2580	4.0
6 Sheets	2978	70	213	2580	4.2

4 Required Resources

The whole body counter is in many aspects a mini version of SNO. It, therefore, requires many of the same generic components. In order to minimize the time and cost associated with the WBC it is desirable to use as much of the SNO resources as practical.

4.1 Design for WIPP

In order to have a definite model, we have focussed on an installation at WIPP. Figures 1-3 sketch the general idea. Acrylic panels are introduced through the side of the water tank via an interlock.

4.2 Electronics

If we pursue the approach of externally counting scintillation light using photomultiplier arrays located at or near the walls of the WBC then we can directly use the SNO experience and expertise. An array of 200-300 Hamamatsu R1408 PMs would be utilized from the SNO inventory. Rick van Berg was consulted regarding the availability of the ancillary components required to field an array of detectors by the summer of 1992. Under the current SNO scenario there would be no production bases and circuit boards available on this time scale. The master plan calls for production to commence in the fall of 1992. With a rearrangement of priorities within SNO, there are no fundamental reasons the schedule could not be moved up to meet the WBC requirement. There are, however, two major concerns with speeding up the process. The first is the implicit belief, born out by past experience, that electronic components get better and less expensive as a function of time and we should, therefore, wait to commit our production till the last minute. The second is associated with funding. There would be a crunch associated with the U.S. DOE funds if we tried to go in to production on a shorter time scale. In large volumes, Rick estimates the channel cost at $\sim$ \$30 for bases and IC boards plus another \$40 for cables and wet end connectors. The start up costs for doing the artwork and prototyping the electronics is in the \$100k range. If we make 200 - 300 channels then the cost per channel should go from about \$70 to around \$100. We assume the initial start up costs will have to be born by SNO and would not be charged against the WBC project. Similarly the produced channels should be directly convertible to SNO applications. The only explicit cost for the WBC would be associated with the shipping and clean up of the boards, cables and connectors. A reasonable estimate for this would be $10-15/channel ($2000 -$5000 total).

4.3 Data Acquisition

John Wilkerson was consulted with regard to the data acquisition system needed for the WBC. His feeling was that the easiest thing to do would be to use commercial (FERA/CAMAC) modular data acquisition electronics. These could be readily coupled to a PC based analysis/storage system. Though this might be the easiest approach, it would not be of benefit to the SNO effort. If SNO prototype boards could be obtained by the end of 1991 then it would probably be best to try to develop the WBC data acquisition system around these. This would serve as a debugging effort for SNO and speed up our total efforts. John has some other severe time constraints over the next several months, but he feels if the prototype boards were available by the end of 1991 he would have sufficient time to implement a SNO test data acquisition system for use in an operational WBC system by the summer of 1992. If we do not use a system which could be costed to SNO, John guesstimates a minimal stand alone system (electronics, crate controller and computer) to be around $25-30k.

4.4 Photomultiplier Support Structure/Reflectors

If we proceed with a WBC project which utilizes photomultipliers mounted in the external periphery of the counter (as opposed to using scintillator paddles with PMs attached via light pipes) then it would be desirable to use the SNO photomultiplier support structure to mount the detectors. Kevin Lesko was consulted about the availability of the support structure for use in the WBC. As with the other components, the current SNO schedule would not have production support structure cells available in time to meet the WBC requirements. However, there are prototypes being worked on now and there should be available up to 160 cells which could be configured into an acceptable configuration for the WBC. Again if sufficient encouragement was provided by SNO the production schedule could be accelerated and adequate number of cells provided.

The cells under development are designed to accept the 198 mm diameter composite system containing the photomutipier and the reflector. According to Kevin, the mechanical attachment of the PM and reflector system into the cell is being developed at Oxford. We were not able to obtain a response from Oxford regarding the availability of the reflectors and mechanical couplings and if it would be compatible with the WBC schedule.

4.5 Water Purification

Since the WBC will rely on detection of scintillation (as opposed to Čerenkov) light and does not have to cope with the SNO complications associated with neutral current measurements, there is much less stringent requirement on the water purity. Table 2 shows that water purities on the order of 10^{-13} (and possibly as poor as 10^{-12}) with respect to U and Th would be acceptable. David Sinclair was consulted on the availability of a SNO water purification system for use by the WBC. He informed us that the testing and development required to meet the SNO schedule would preclude our borrowing and using one of the systems. However, he felt with our much more modest purity requirements that a commercial system could be obtained at a reasonable cost. Though we are proposing a large water volume for WBC (up to 600 tonnes) we can save substantially on the costs by going to a system which has a lower flow rate (10 l/min as compared with the 50 l/min SNO system). With this lower flow rate it would take on the order of a month to fill the WBC. The recirculation rate would also be lower than SNO, but, again because of the relaxed purity requirements this should not be a serious impediment.

A commercial vendor was consulted and we were informed that we could obtain a turnkey system for $30-50k. It would consist of a pre treatment stage (sand filter + C filter + 5 μm mesh filter), a reverse-osmosis system, and a post-treatment deionization phase (cation + anion + mixed bed). The total floor area required for such a system would be about 6 m^2 and the system would use about 5 kW of power supplied at 220 volts. The reverse-osmosis process generates a waste stream of about the same magnitude as the product stream. This may create a problem in a mine where all water has to be brought in and then lifted out. If this becomes an important concern then the first two stages of treatment could be performed on the surface and the RO output water brought to the WBC site for the final post treatment deionization and recirculation phase. The vendor contacted has a similar operating system which could be made available to test potential feed water streams to verify that adequate U/Th purity is obtained.

4.6 Schedule

Figure 4 shows a PERT chart for the WIPP case. While the tasks identified on it are probably broadly representative of the actual situation, the times must be considered completely undetermined as yet. In particular, the item "DOE/WIPP review" contains many steps (EPA review, NMEID review, etc.), and could easily take a year instead of the indicated 30 days.

4.7 Cost Estimates

The costs of this project are very stringently tied to the site location, the availability and possibility of using SNO components, and the detection method employed in the WBC. The costs listed below were based on estimates of installing the WBC at WIPP. Because of the very stringent inspection and certification requirements for operating at WIPP, the engineering and installation charges will be high. These will be mitigated to some extent by the ready availability of technical resources within the WIPP complex (mechanical and electrical shops, extensive utilities, experience with other ongoing scientific projects).

Estimated Whole Body Counter Costs

Excavation of Site	\$80k	(2500 tonnes @ \$32/ton)
Engineering	120	(4 man months @ \$30k/month)
Main WBC Vessel	50	(10 m Φ x 7 m high mild steel cylinder)
Acrylic Chan. in Ves.	30	(40 m^2 x 1 inch thick @ \$750/m^2)
Plastic Scintillator	40	(8 m^2 x 4 inch thick @ \$5000/m^2)
Containment Vessel	20	(10 m x 15 m x 2.5 m plast. lined tank)
Tank Support Struct.	30	(I beams and air flotation)
X-ray Insp. of Welds	50	(WIPP quality assurance requirement)
Water Purification	50	(10^{-13} Th with recirculation)
Inert Cover Gas Syst.	10	(Cryogenic LN boil off for Rn protect.)
In Vessel Electronics	25	(250 PM channels @ \$100/channel)
External Elect., Comp.	30	(FERA/CAMAC, controller, PC based)
Utility Connections	30	(WIPP support to supply utilities at WBC)
Monitoring Systems	20	(Leak sensors, air quality, etc.)
Halon Fire Prot. Syst.	10	(WIPP required system)
On Site Buildings	20	(Electronics/computer room, storage, etc)
Total Listed	\$615k	
Contingency (15%)	\$95k	
Project Total	\$710k	

4.8 Manpower

This is the fundamental issue relating to the practicality of the project (technical issues aside), and the task force members have been unable to agree on manpower requirements (by factors of 10). Further efforts will be made to define these needs.

5 Site

5.1 WIPP

The Waste Isolation Pilot Plant in Carlsbad, NM, is located at the 659-m level of the Salgado formation, consisting of halite and a small amount of clay. Neutron activation analysis at LANL gave 100 ppb Th and 30 ppb U for samples. It is a technically advanced operation, with a large scientific contingent operated by Sandia National Lab. Support operations are provided by Westinghouse as a subcontractor. A fairly detailed report on the site visit made in Dec. 1990 by M. Fowler and H. Robertson is available.

The advantages are, in addition to the good scientific environment, the presence of extensive underground shop facilities, heavy equipment, easy excavation, electrical and HVAC services, high-speed data links from the mine, ready access, a large 45-tonne hoist, 2200 mwe of overburden, relatively low levels of radon (assumed), and proximity to a SNO Institution (LANL). Although no direct contact has been made with DOE Albuquerque (the owner), we have indirectly heard that they are favorably disposed to the general idea.

The disadvantages are a political fishbowl environment with half a dozen federal and state agencies exercising or claiming jurisdiction, recent approval to begin storing low-level waste (9000 barrels), a crash program to study gas production in waste, extra costs required to meet tough standards (e.g. full weld X-rays, halon fire protection, oxygen monitoring, secondary containment for water), and coupling to an extensive scientific program (which takes the SNO schedule out of SNO's hands to some extent).

5.2 HPW

The Harvard-Purdue-Wisconsin experiment was an early proton-decay experiment located in a silver mine in Utah. The experiment was literally blown up in 1984 and trucked away in pieces, but there were some facts of interest that Jim Gaidos at Purdue passed on to us. The 850-tonne water container was a redwood barrel assembled by coopers from National Tank Company in Oregon at a cost (1980) less than $100k. The barrel was lined with Hypalon, a fiber-reinforced plastic sheet. The mine environment was cold, and no biological growth occurred. Only UV sterilization of the recirculated water was used. Gaidos and Peter Doe both provided us with graphic descriptions of the access to the (abandoned) mine sufficient to convince us that one would never wish to reenter it.

5.3 IMB

The Irvine-Michigan-Brookhaven experiment in the Morton Salt Mine near Cleveland is a well-known 10-kT water Čerenkov detector. Recently the plastic liner sprang a leak and the water is escaping. The company is entertaining a request for construction of a new cavity, and apparently would be willing to excavate other rooms, too. Not much is known about this possibility yet, but it is being pursued through Peter Doe, Bill Kropp and Hank Sobel (the latter two at Irvine).

The advantages are an existing scientific infrastructure, very clean food-grade salt walls, proximity to SNO Institutions (Penn, Queen's, Guelph, Sudbury, and others), a more relaxed approach to construction standards (cf. WIPP). Enormous cavities can be, and have been, excavated, so one could, if desired, have a top-loading tank.

The disadvantages are a start from scratch, marginal overburden (cosmic veto would likely be required), and possible difficulties with coordination in an active mine.

5.4 Boulby

The following is an abstract provided by John Barton.

"The U.K. Dark Matter group [led by Peter Smith at Rutherford Accelerator Lab] has prepared a site in the Boulby (North Yorkshire) potash mine at a depth of about 3000 mwe. This site is in an underlying layer of rocksalt [halite] with a potassium content of about 0.1%. A full analysis of the rock has not been made – it varies with position. A water tank of 6-m diameter and 6-m height has been installed in the reserved area, which includes an air filtering system to provide some control over radon. Recently, the tank has been filled and the water is now being recirculated through an ion-exchange purifier. Its conductivity on Oct. 9 was 11μS and is expected to reach 1μS by [Oct. 18]. They will then ask Oxford to do an MS analysis as soon as possible. The total rate of a 2"x2" NaI scintillator from 10 keV to 3MeV outside the tank is 20 /s. This falls to 0.13 /s at 1 m below the water surface and is then limited by the crystal background. Extrapolation suggests a central rate of 10 /day. The neutron rate has not been measured but should be sufficiently low. The tank is made of steel and lined with a poly butyl material. Underneath there is a 10-cm layer of lead and there is space for a similar amount around the periphery and on most of the top. The space at the sides is not sufficient for a thicker layer. The top of the tank is not sealed (the argon layer over the water relies on gravity) and the covering steel panels are not arranged to be light-tight, though this could be done. However, all apparatus is lowered into the water from above with a hoist and it might be awkward to make the support light-tight. The hoist can handle individual items up to 500 kg. The cage down to the level can be used for pieces up to 6m x 2m.

"The total cost to RAL of the Boulby facility has been 80$\pm$20 k pounds. The RAL engineer has established very good relations with the mine management; he believes that they could find a neighbouring site for a rather larger tank.

"I explained the requirements of SNO to the dark matter committee under the separate headings of initial scintillator testing and subsequent production testing. The main problem is the amount of time required."

"Several potential dark matter detectors are being prepared and all will need testing during their final development. Most of the projects are behind schedule, so that delays caused by other work at Boulby will not be popular. My own *guess* is that they will only need a week or two before they return to the laboratory for further work and that the total use of Boulby will be less than 50%. It will be hard to get a program of several months work agreed even though that amount of time may well become available. The idea of using perchloroethylene was thought to raise too many questions of safety but the provision of additional lead would of course be welcomed.

"My overall impression is that some initial testing of scintillators could be acceptable, especially if the work was regarded as the development of a rather larger dark matter detector. Any approach should be through Peter Smith as he and the RAL administration can see the advantages of cooperation provided other experiments are fully financed."

A figure showing the Boulby lab is attached.

The advantages of Boulby are, it already exists, it has ample overburden, and it is fairly close to a SNO Institution (Oxford). The salt contains 100 pb of U and Th (whether total or separately is not clear).

The disadvantages are, the shielding is marginal, it may not be physically large enough to handle 4m x 2m sheets, and it may not be available to SNO. We have examined the shielding question by scaling calculations done for a cylinder with a slightly different aspect ratio. The external background (refer to line 1 of Table 2) would increase from 0.18/d to between 100 and 1200/d. Addition of about 150 tonnes of Pb would reduce this background, but only if the lead were much cleaner than 100 ppb Th. Nevertheless, acrylic at 10 ppt would give a one-sigma signal in one day, with other things being as assumed for Table 2. There may also be logistical concerns: If the sheets are to be assayed after thermoforming, they must be shipped from Germany to Orange County, Orange County to Boulby, and then Boulby to Sudbury. SNO use of Boulby would almost certainly require some "quid" pro quo.

5.5 Gran Sasso

The Borex collaboration has come to the same conclusions that SNO has, and is now building their own WBC in Gran Sasso with Italian resources. The tank is 9m in diameter and 7.25m high, and detection will be with 4 tonnes of liquid scintillator. Raju Raghavan has kindly provided SNO with a draft proposal (not for circulation outside SNO). Construction will be finished in Fall 1992. Borex have expressed willingness to discuss collaboration with SNO on almost any level, but clearly they need to have access to their own facility at a time when SNO would also need it.

The advantages are, the facility is already under construction and does not require SNO resources, it is located in a purely scientific laboratory, and it would meet or exceed all SNO technical requirements.

The disadvantages are, probable conflict with Borex use of the facility, logistical problems, remoteness from SNO Institutions, and lack of SNO control over the schedule. SNO use, if possible at all, would probably require some quid pro quo.

5.6 Sudbury

No room at Sudbury exists that is large enough to accommodate SNORE, and diverting INCO effort to prepare a room would delay excavation for SNO itself. As this is already on the critical path, that possibility has been rejected.

6 Summary

The task force concludes that it is technically feasible to measure the Th content of 8-m^2 sheets of acrylic to a level close to 5pg/g counting 4 m^2 per day. To reach this level at one standard deviation, counting a single sheet 6 cm thick 4 m^2 at a time, requires scintillator (whether solid or liquid) of purity below 8 pg/g of Th. The 2-σ level is almost reached with scintillator containing no Th. There is little dependence on scintillator thickness for 10 ppt material; however, the spectroscopic quality of the data improves significantly with thickness. If 1 ppt material is possible, then further gains in signal-to-background can be made with thicker scintillator.

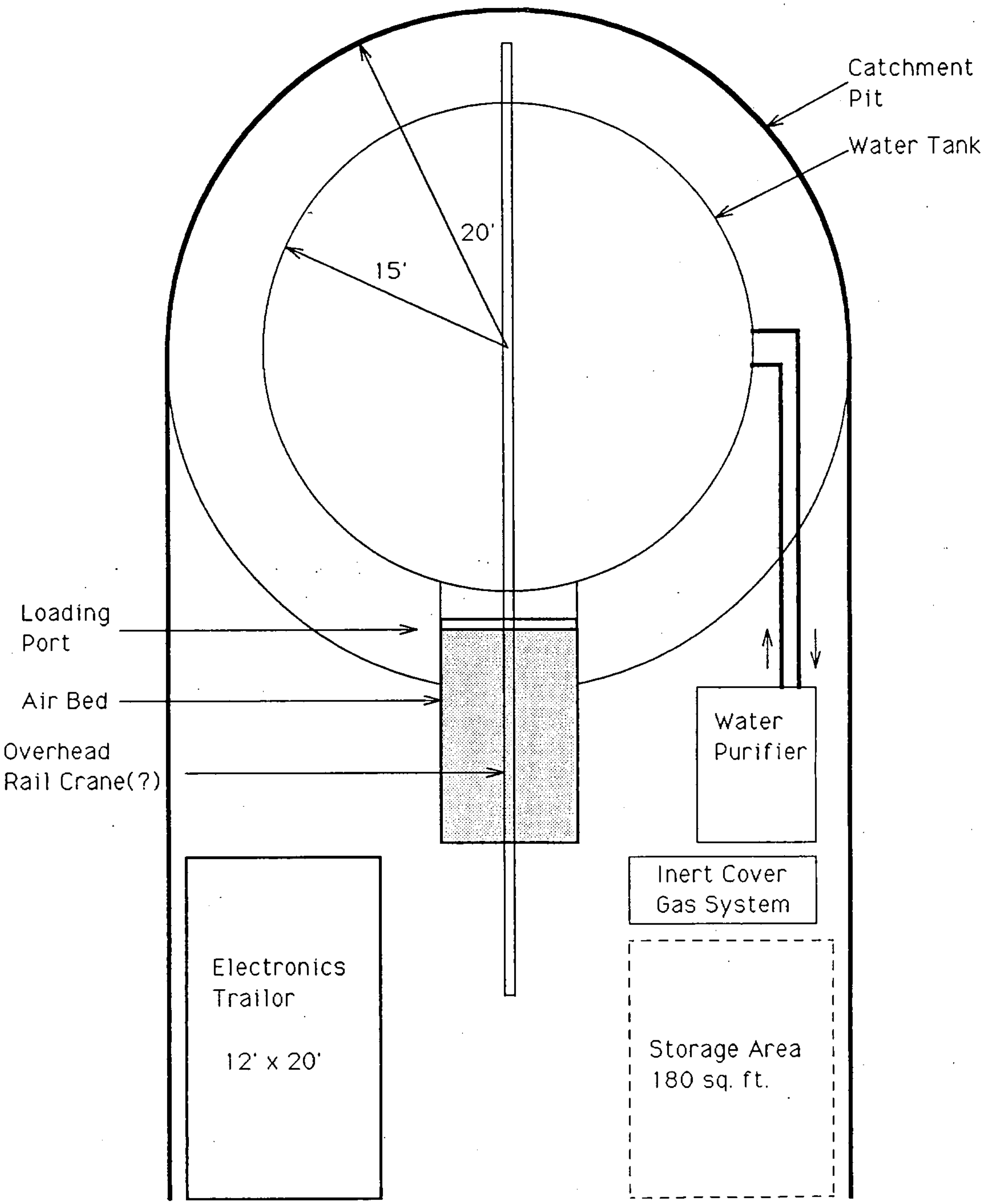
A completely satisfactory scheme for deploying the scintillator has not yet been achieved, but there are advantages in handling if an isolation box can be used. This results in roughly a factor of 2 penalty in signal (which was included in the figures given above).

The most hopeful site at present appears to be the Morton Salt Mine in Ohio, mainly because the least is known about it.

Manpower and resource needs have proven very difficult to assess. Construction costs of $U 700k for a new facility are thought to be conservative, especially if the IMB site can be used. A full-time project manager and a second physicist for a year, and several (about half a man-year each?) engineers, draftsmen, and technicians would be needed during construction, and then two technicians full time for a year assaying panels. Completing the project in the 9 months available would require luck.

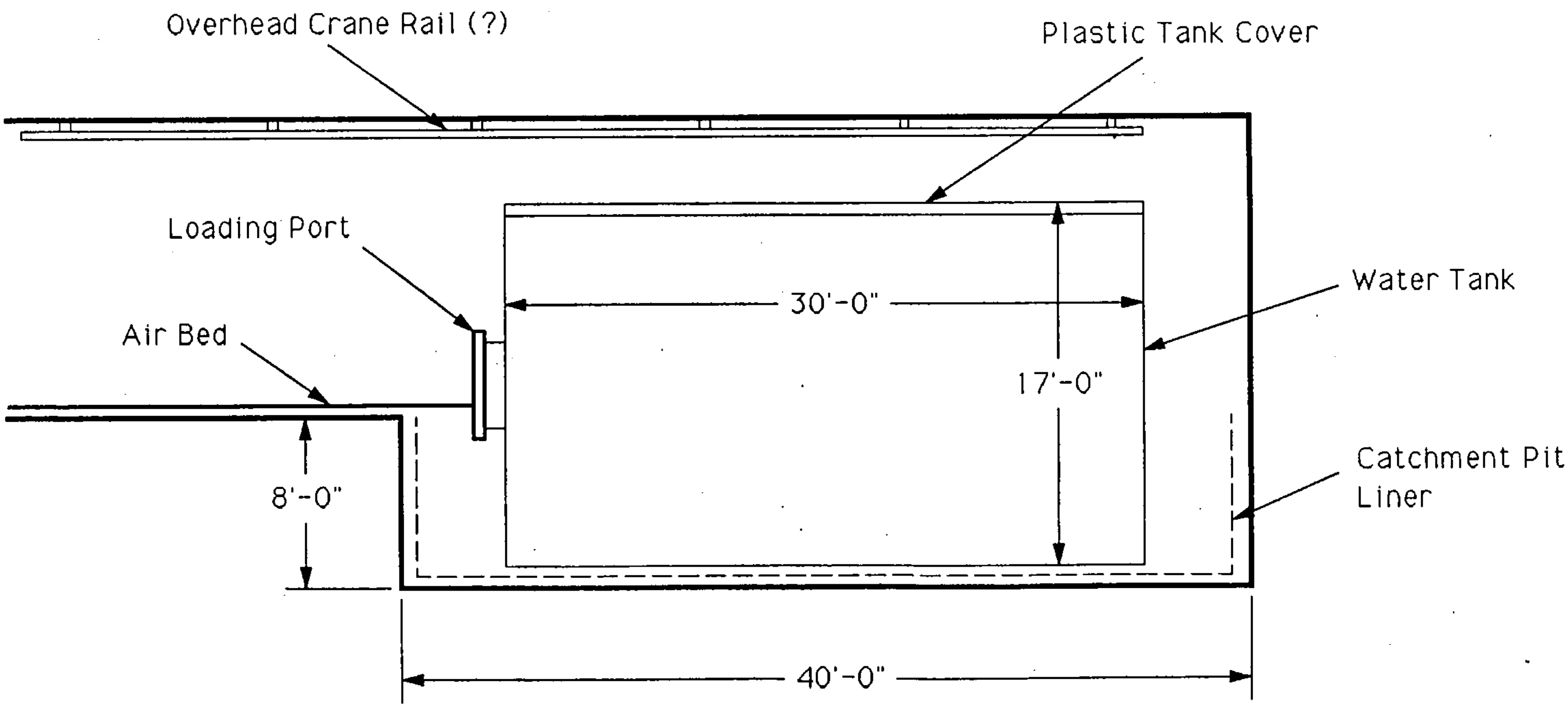
EXPERIMENTAL CAVITY

Plan View

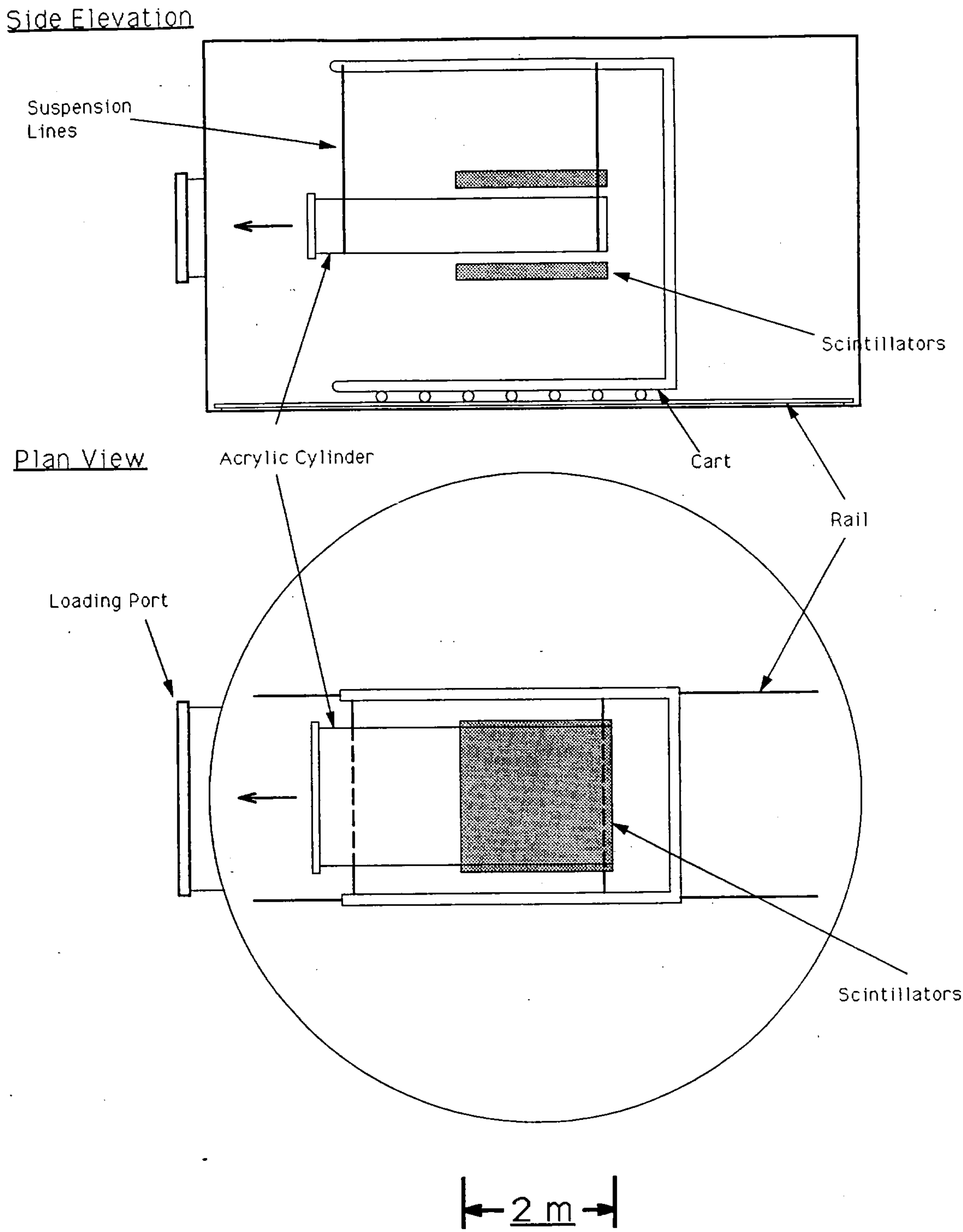


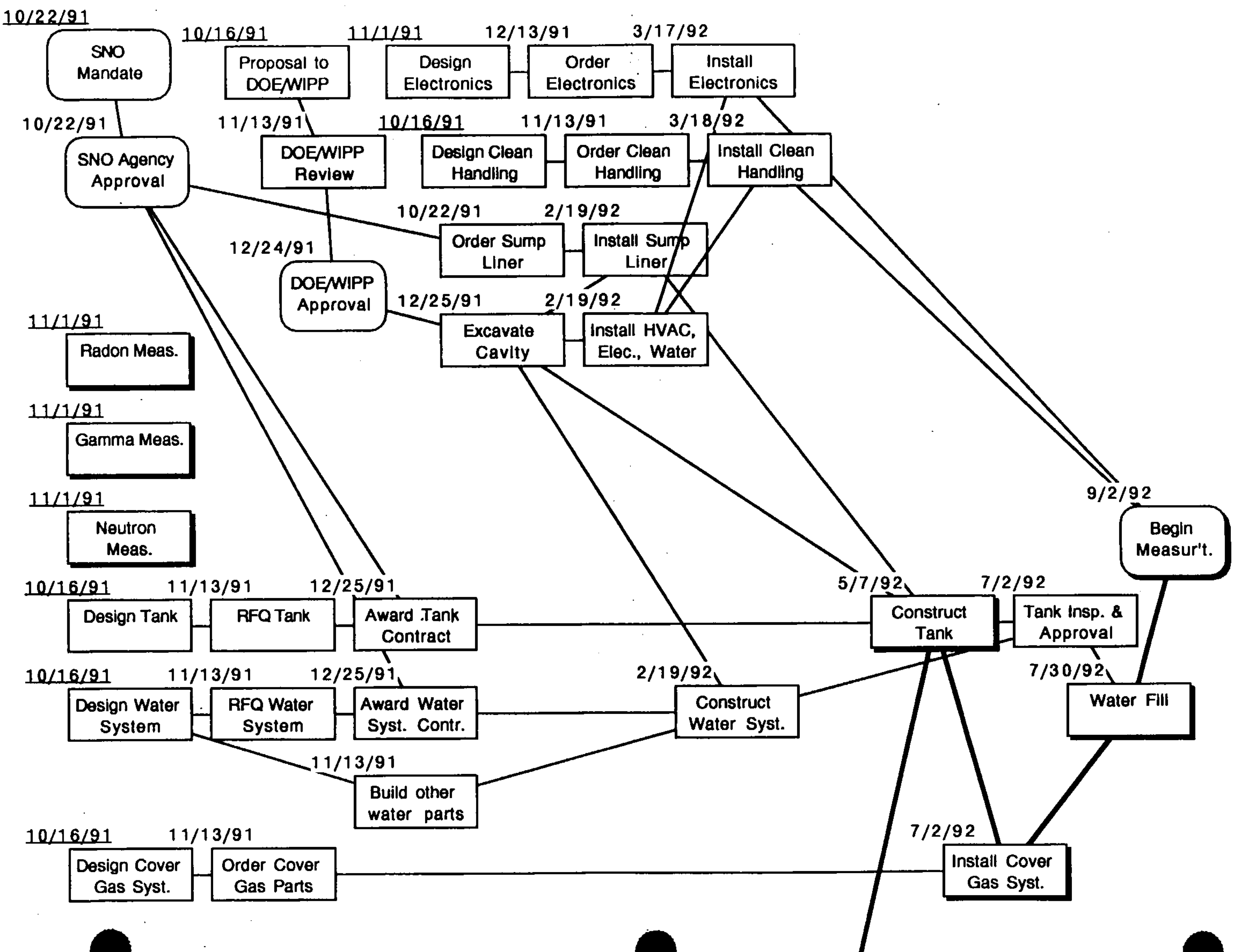
EXPERIMENTAL CAVITY

Side Elevation



LOW BACKGROUND DETECTOR

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10/22/91
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10/16/91
Proposal to DOE/WIPP
11/13/91
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DOE/WIPP Approval
11/1/91
Design Electronics
12/13/91
Order Electronics
3/17/92
Install Electronics
10/16/91
Design Clean Handling
11/13/91
Order Clean Handling
3/18/92
Install Clean Handling
10/22/91
Order Sump Liner
2/19/92
Install Sump Liner
12/25/91
Excavate Cavity
2/19/92
Install HVAC, Elec., Water
11/1/91
Radon Meas.
11/1/91
Gamma Meas.
11/1/91
Neutron Meas.
9/2/92
Begin Measur't.
10/16/91
Design Tank
11/13/91
RFQ Tank
12/25/91
Award Tank Contract
5/7/92
Construct Tank
7/2/92
Tank Insp. & Approval
10/16/91
Design Water System
11/13/91
RFQ Water System
12/25/91
Award Water Syst. Contr.
2/19/92
Construct Water Syst.
7/30/92
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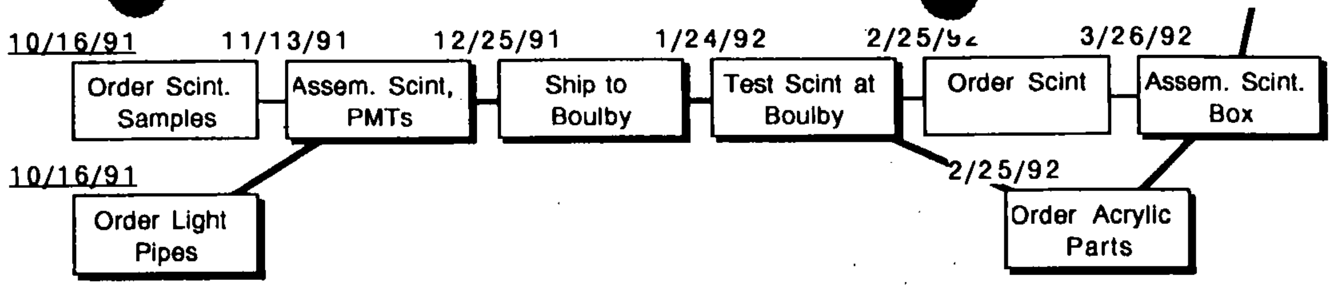
7/2/92
Install Cover Gas Syst.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1/24/92
Test Scint at Boulby
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Order Scint
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Order Acrylic Parts

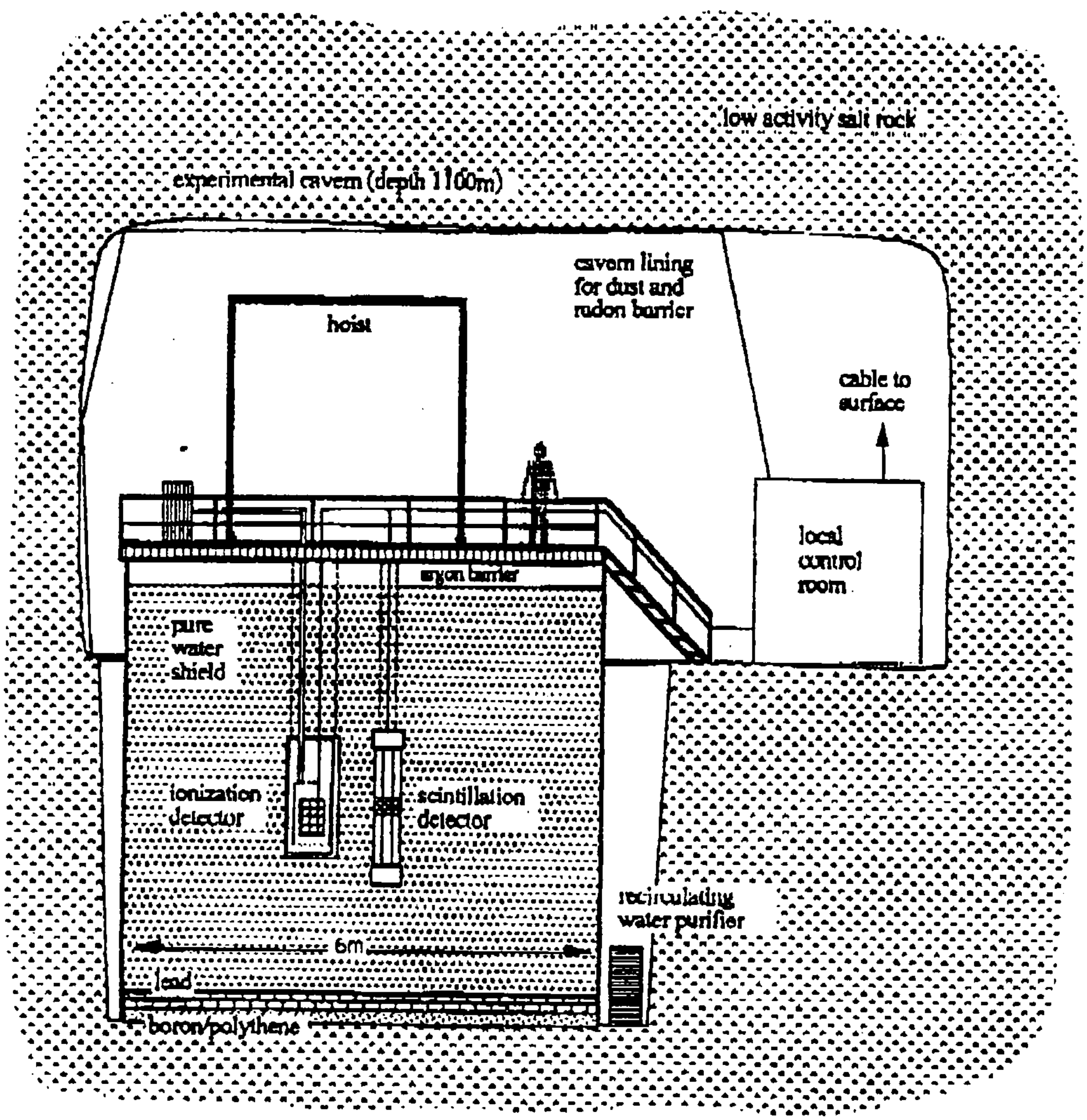

Fig 2.1.1 General layout of Boulby underground dark matter laboratory