Water Conditioning for the Daya Bay Experiment

Jim Napolitano

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Abstract

This document outlines our understanding of the specifications and proposed technical design for the Daya Bay water conditioning system, as of June 2007.

In June 2007, the Daya Bay experiment has passed CD-0 and CD-1 reviews, and is preparing for technical reviews on the way to a CD-2 panel, which is expected to convene in Fall 2007. This document means to summarize the current status of the system. The overall experiment design is still in flux, however, and some of the changes are relevant to the water system. This includes the inclusion of a central water storage pool within the mountain.

1 Overview

A preliminary design for the water conditioning system is shown in Fig. 1. This system, or a modification of it, needs to meet specifications for water clarity, radioactivity, long term corrosiveness, and temperature stability. Our clarity specification is a requirement that the attenuation length for Cherenkov light be on the order of the pool dimensions or larger. A goal is to achieve at least 30 m for all relevant wavelengths. Most radioactive backgrounds will be carried on suspended particles and removed by filters, but radon presents a particular problem since it is dissolved in the water as a noble gas. Water can act as a corrosive agent, given certain characteristics related to its "purity" and to the materials that are submerged in the pool. Finally, the water pool will effectively serve as a temperature stabilization medium for the antineutrino detectors.

Bacterial growth in the water must also be minimized, at least for the sake of clarity. To first approximation, this is accomplished using an ultraviolet sterilization stage, followed by filtration to remove the dead organisms. Gas removal, aimed at radon, will also be used to remove dissolved oxygen, and we will aim for as low an operating temperature as possible, given other constraints.

Engineering specifications and constraints include the time to fill or drain any particular water pool, and the need to transfer the water over large distances while maintaining an appropriate level of purity. Of course, cost needs to be minimized as well.

Water systems used in other experiments, and the specifications they achieved, are summarized in Table 1. (For details, see the Appendix.) Note that the only two experiments

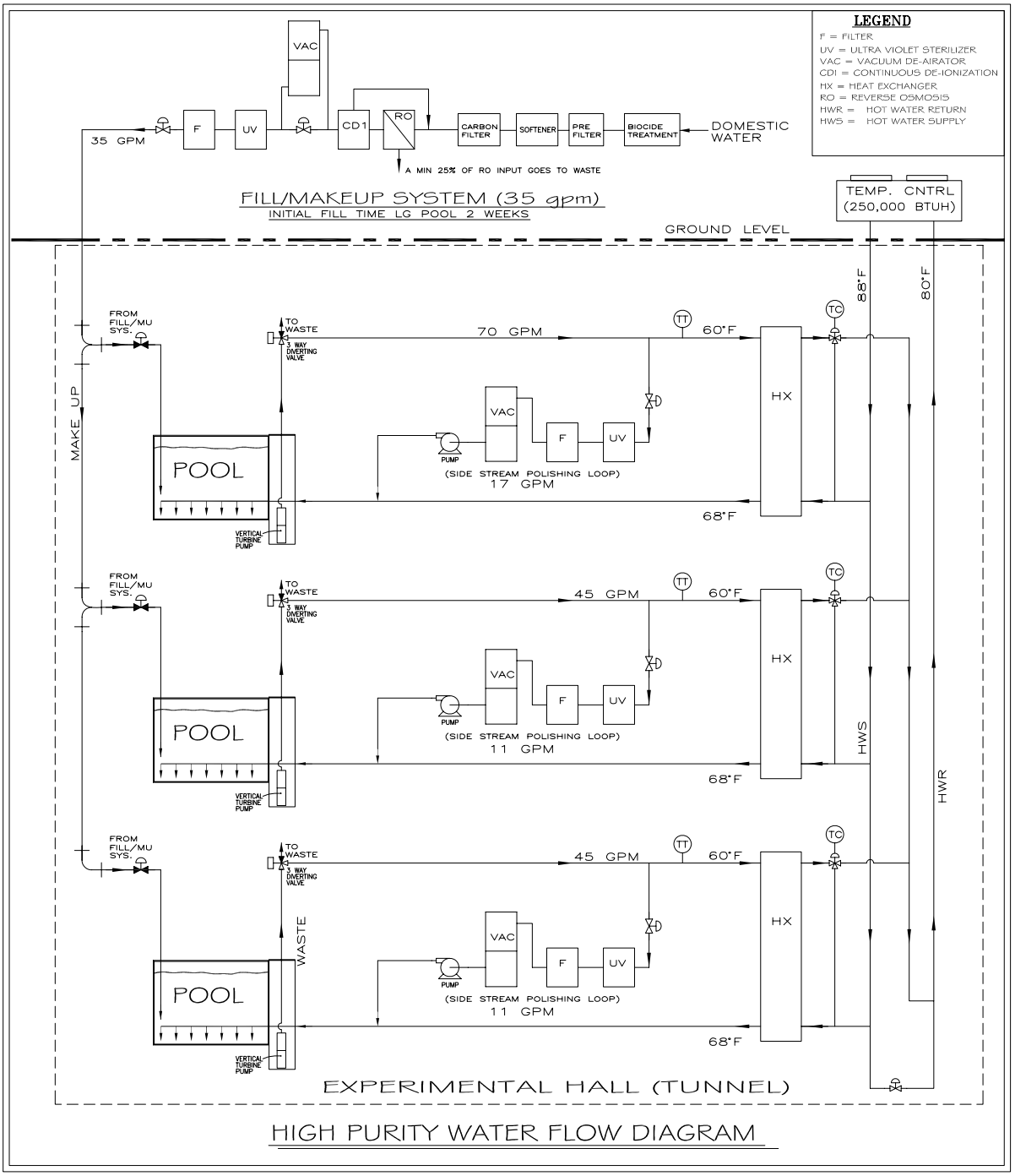

Figure 1: Schematic diagram of the water conditioning system as conceived for the Spring 2007 review panel. We now believe that some manner of ion removal needs to be included in the polishing loops.

Table 1: Water conditioning systems used in previous experiments. (See the Appendix.)

Experiment	Vol (m^3)	Flow (gpm)	Vol/Flow (days)	Att Len (m)	Resistivity (MΩ-cm)	Radon (Bq/m^3)
IMB [1, 2]	8000	80	18			
SuperK [3]	50,000	130	71	100	> 18	< 0.002
SNO [4, 5]	1700	40	7.8			≈ 0.001
KamLAND [6, 7]	3200	35	16.8		0.5	10^4
BaBar/DIRC [8]	6	4	0.28	≥ 50	$18 \rightarrow 10$	
Milagro [9]	≈ 4000	190	3.9	20		
DYB Far Pool	2560	17	28			
DYB Near Pools	1600	11	27			

which carefully measured their attenuation lengths (SuperK and BaBar/DIRC) made use of deionization stages in their water conditioning and achieved extremely clear water. Milagro did not make use of deionization, and observes a significantly lower optical attenuation length, albeit not determined with a particularly careful measurement.

2 Physics performance specifications

There are four specifications that directly affect the physical performance of the muon veto system. These are optical attenuation length, i.e. "water clarity"; radioactivity contamination levels, mainly from radon; thermal stability, as the water pool will be the heat bath which stabilizes the antineutrino detector volume; and corrosiveness of the water itself with regard to the various materials that must live in the pools.

2.1 Optical attenuation length

Current simulations indicate that the muon veto performance will be satisfactory if the attenuation length for Cherenkov light in the water exceeds 30 m, that is, an absorption coefficient less than 3×10^{-2}/m. Note that although the Cherenkov spectrum rises for small wavelenghts as $1/\lambda^2$, the glass envelope of the photomultipler tube will cut the spectrum off at wavelengths below 325 nm or so.

Particles at the micron size level, that is much larger than the wavelength of light, are one source of light attenuation. Assuming a volume density n, then we need $n \times \pi r^2 < 1/30$m. For $r = 1$ μm, $n < 10^{10}/\mathrm{m}^3$. This would be a volume fraction roughly equal to $\frac{4}{3}\pi r^3 n \approx 4 \times 10^{-8}$, or about 0.1ppm by weight. The IMB water conditioning system [1], for example, achieved 0.3ppm for *all* dissolved solids, using a series of filters followed by reverse osmosis. We consequently are confident that particulate contaminants will not limit the attenuation length, given our preliminary design for the conditioning system.

Dissolved salts present a larger problem, since the scattering and/or absorption cross section for ions is generally much larger than for water molecules, for visible wavelengths.

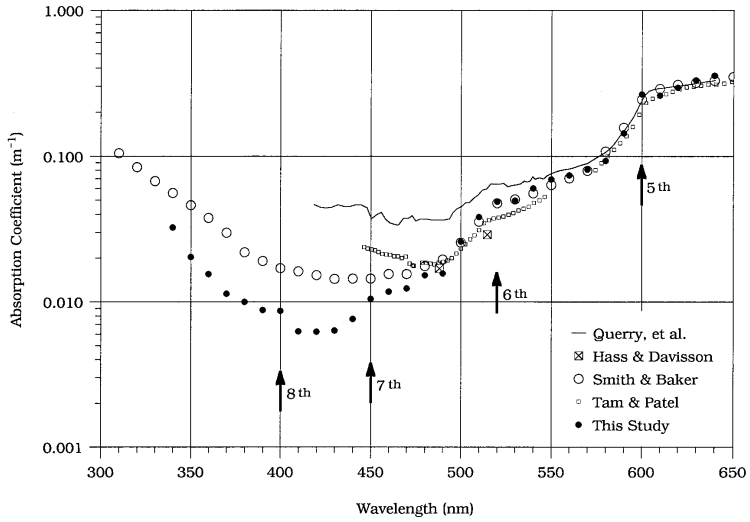

Figure 2: Optical absorption spectra of "pure" water from various measurements, taken from [10]. The vertical arrows mark the positions of shoulders expected from the $O-H$ stretch mode in the water molecule.

For example, pure water has an absorption coefficient $\sigma n \approx 7 \times 10^{-5}$/cm at 425 nm[10]. With $n = 6.02 \times 10^{23}/18$, this gives $\sigma \approx 2 \times 10^{-27}$ cm^2. However, the Thomson scattering cross section from a free electron is [11] 7×10^{-25} cm^2, some 350 times larger than for water. Although little data seems to be available for cross sections of specific ions dissolved in water, it is clear that at least some ion removal needs to be included in the conditioning system.

Recent studies [10, 12] indicate the ultimately achievable attenuation length for water, easily meets our specification over the desired range. However, these investigators also observe large discrepancies with earlier observations, which may be correlated with "unknown sample purity." Figure 2, taken from [10], shows the results of the recent measurements, along with previous work. We note that the Super Kamiokande experiment [3] (see also Sec. A.2) achieved attenuation lengths in excess of 100 m (absorption less than 10^{-2}/m). This would seem to about the achievable limit, based on these measurements. See Secs. 2.4 and 3.1.

2.2 Radioactivity

Radioactivity in the water is mainly due to long lived isotopes which are not uncommon in rocky environments such as that near Daya Bay. These isotopes can be part of the dust which finds its way into the ground water, and most of these dust particles are easily filtered out. However, radon is a typical daughter in these decay chains and, since it is an inert gas, will escape from the dust and become dissolved in the water.

There are several known isotopes [13] of radon, but most are very short lived. The most stable is ^{222}Rn with a half life of 3.8 days, and which occurs in relatively high concentrations as part of the ^{238}U decay chain. Other common isotopes are ^{220}Rn and ^{219}Rn which have half lives of 55.6 sec and 3.96 sec, respectively, which are too short to be of concern to our experiment.

The ^{238}U decay chain is shown in Table 2 [14]. The daughter ^{214}Bi is particularly important because more than 80% of its β decays go to excited states in ^{214}Po, and most (95%) of these go to the second excited state ($E = 1.28$ MeV) or higher [15]. Gamma rays of this

Table 2: The radioactive decay chain of ^{238}U, which is a source of ^{222}Rn. Taken from [14]. The daughter ^{214}Bi is produces particularly difficult backgrounds.

Nuclide	Decay	Half life	MeV	Daughter
U 238	α	4.468×10^9 a	4.270	Th 234
Th 234	β^-	24.10 d	0.273	Pa 234
Pa 234	β^-	6.70 h	2.197	U 234
U 234	α	245500 a	4.859	Th 230
Th 230	α	75380 a	4.770	Ra 226
Ra 226	α	1602 a	4.871	Rn 222
Rn 222	α	3.8235 d	5.590	Po 218
Po 218	α	3.10 m	6.115	Pb 214
Pb 214	β^-	26.8 m	1.024	Bi 214
Bi 214	β^-	19.9 m	3.272	Po 214
Po 214	α	0.1643 ms	7.883	Pb 210
Pb 210	β^-	22.3 a	0.064	Bi 210
Bi 210	β^-	5.013 d	1.426	Po 210
Po 210	α	138.376 d	5.407	Pb 206
Pb 206		stable		

energy can penetrate the steel outer shell of the antineutrino detectors, and would contribute to the background rate.

Since the half life of ^{214}Bi is much less than that for ^{222}Rn, it would build up over time and come to equilibrium after something like one week, assuming a steady input of the much longer lived isotopes of uranium, thorium, and radium. (See Table 2). The longer lived daughters further down the decay chain do not present significant backgrounds to the antineutrino detectors, nor, for that matter, to the muon detectors in the water pool.

We can estimate from this information, a specification on the concentration of ^{222}Rn in the water. Let R_0 be the radon decay rate per unit volume of water. Then, the rate of photons (above one MeV) is $0.8R_0$ per unit volume. The relevant volume is given by the absorption length in water of 1 MeV photons (about 30 cm) times the surface area of the antineutrino detector ($5 \times \pi 5 + 2 \times \pi 2.5^2 = 120$ m^2) or 36 m^3. The solid angle of the antineutrino detector active region, viewed from the water pool, is about 25% of 4π, and the 45 cm thick buffer oil layer will do its job to shield the liquid scintillator from photons by a factor of about $\exp(-45 \cdot 0.9/30) = 0.26$. (Oil is about 90% as dense as water.) Therefore

$$\text{Rate of photons in AD} = 0.8R_0 \times 36 \times 0.25 \times 0.26 \approx 2R_0$$

where R_0 is measured in Bq/m^3.

A target goal for the rate in the antineutrino detector is 10 Hz, so we need $R_0 < 5$ Bq/m^3. For a half life of 3.8 days, the rate constant is 2×10^{-6}/sec, so 5 Bq/m^3 is equivalent to 3×10^6 atoms/m^3. Indications from SuperK and SNO are that the degassification stage in our preliminary design should easily meet this specification.

2.3 Thermal stability

Bob McKeown has considered the thermal properties of the water pool [16].

The temperature of the water pool will be determined by the heating/cooling capacity of the recirculating purification system and by the heat exchanged with the surrounding rock. Rock has a specific heat of 750 J/kg-°K (within about 100 J/kg-°K [17]) and a thermal conductivity of about ≈ 3 W/m-°K [18]. If we approximate the pool as an 8 m radius sphere, the temperature in the rock will vary as $1/r$ until it reaches the ambient rock temperature. This will involve about 40kTon of rock, and the heat exchange with the water (per degree of temperature difference) is about 400W/K. So 1.6kW of heating/cooling can maintain a temperature difference of 4K, which is very reasonable from the point of view of operating cost.

Heating the rock will require roughly 30 GJ/°K (compared to about 10 GJ/°K for the water itself), or about 1 year if we use only 1.6 kW. So we may need to have a capacity of 100 kW to reach equilibrium in a time scale of weeks. The heat exchanger in Fig. 1 specifies 250,000 BTU per hour, or 73 kW. The total energy requirement is about 104 kW-hr/°K which should cost less than about US$1000/°K, so this is quite reasonable from the point of view of cost.

Note that if we are running in a stable situation with about 1 kW of energy transferred to maintain the pool temperature at 4°K temperature difference with the rock, this will be a very stable situation. If the 1.6 kW or recirculation system fails, the temperature will adjust with a very long time constant of about 3 years. That is, the temperature will take about 1 year to change by 1°K. (Recall that the time constant for the detector modules to respond to a change in water temperature is hours or days so the detectors will follow these very slow changes in water temperature accurately.)

Of course, these considerations are for putting the water pool into thermal equilibrium with the rock walls. If the ambient rock temperature at the near and far sites is different, then the detectors will be at different temperatures. For now, we tacitly assume that the detector liquid scintillator temperatures will be monitored closely and the yields corrected for any difference.

2.4 Corrosiveness

Materials in contact with the water for long periods of time include (phototube) glass, stainless steel, and cabling materials. Anecdotal evidence is plentiful for the effect of "ultrapure" water, especially water, but technical references are limited. There is a published statement [12] that "pure water is a hungry substance that leaches impurities out of nearly everything it contacts," but the justification for this statement is anecdotal.

Regardless of the effect on instrumentation in contact with the water, it seems that dissolved ions may seriously impact the attenuation length of the water. One piece of evidence [19] for this comes from Fig.10 of [12]. (See also Fig. 2 of this document.) The absorption coefficients measured by Tam and Patel veer off sharply from other measurements at wavelengths below ~ 500 nm. Unlike all the other experimenters, who use glass

or quartz containers, the cell used by Tam and Patel was stainless steel. This degradation of a factor of two or more in the attenuation length is attributed dissolved ions in the steel, although no detailed tests of this are available.

Some detailed tests have been carried out on the effect of high purity water on photomultiplier tube glass [20, 21] in the context of the DIRC [8] apparatus for BaBar. Of the 11,000 photomultiplier tubes submerged in water for ten years, only ≈ 50 were affected by rapid corrosion. There is empirical proof that corrosion in this particular borosilicate glass occurs at high rate when the glass has no Zn content.

3 Engineering considerations

3.1 Water volume and flow rate

The far site pool is $10 \times 16 \times 16 = 2560$ m^3 (680,000 gallons) and the two near pools are $10 \times 10 \times 16 = 1600$ m^3 (423,000 gallons) each. We specify that the large pool must be fillable in two weeks, giving a flow rate from the central fill/makeup system of 33.5 gallons per minute (gpm).

We can estimate a necessary recirculation rate, assuming that the main contaminant is stainless steel which contaminates the otherwise pure water by contributing dissolved ions which absorb in the blue [10, 12, 19]. (See Sec. 2.4.) The idea is to compare flow rates based on the surface-to-volume ratio (SVR) of water vessels [19].[1]

First consider Super-K [3] (see also Sec. A.2) which achieved very large attenuation lengths despite having a water volume contained by stainless steel. The tank is 39 m in diameter and 42 m high, so SVR=0.17/m. (This is very large compared to the cell used by Tam and Patel [19] which showed significant contamination, with SVR=350/m.) The water volume in Super-K was recirculated once every 71 days. (See Table 1.)

Now consider the large pool in the far hall. The water volume is 2560 m^3. Let the (four) antineutrino detectors (AD's) be 5 m diameter cylinders, 5 m high. Then, their own volume is $4 \times 98 \approx 400$ m^3 and their surface area is $4 \times 118 \approx 500$ m^2. This gives SVR$\approx$ 0.2/m, about the same as Super-K, although Laur estimates an additional surface area of about the same amount from 5 cm wide stainless steel bars every 2 m in both directions on both the inner and outer liners. So, we take SVR=0.4/m for the large pool. Our current design (Fig. 1) for the water system circulates 17 gpm through the (side stream) polishing loop, thus turning over the entire water volume once every 24 days. Thus, with twice the SVR of Super-K, we recirculate more than twice as often.

Of course, it is worth checking to see if the affect contamination on the attenuation length correctly scales up from test cells to SuperK, but fortunately Ed Fry [19] has done this for us. The change in absorption coefficient should be proportional to the change in impurity concentration. If C is the density of impurities, and ρ is the rate at which impurities are supplied to the water per unit surface area, then $\Delta C = \rho \Delta t \times \text{SVR}$. Pope and Fry [12] used a *quartz* cell with SVR=50/m, and observed a change in absorption coefficient of 6×10^{-6}/cm·day.

[1] Thanks to L. Littenberg for first considering this approach.

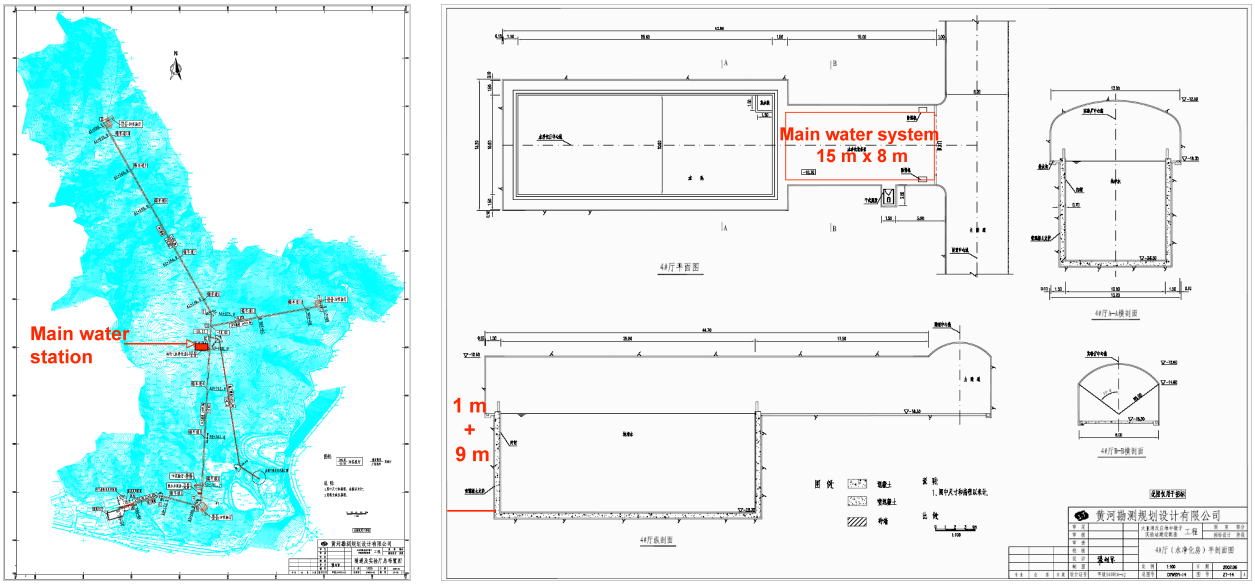

Figure 3: Location and dimensions of the centralized underground water station.

Scaling by SVR imples a change of $6 \times 10^{-6} \times 0.17/50 = 2 \times 10^{-8}$/cm·day for Super-K, or a change by 1.4×10^{-6}/cm over one turnover period. This would be imperceptible, given a 100 m attenuation length, i.e. an absorption coefficient of 10^{-4}/cm, i.e. a $\sim$1% effect.

However, stainless steel is much worse than quartz. If it were 100 times as bad, then there would be a factor of two change for Super-K. On the other hand, the water is being continuously cleaned, in fact de-ionized, so this would all appear to hang together.

Our conclusion is, therefore, that the flow rate in the straw man design (Fig. 1) will meet our specification for attenuation length, even in the face of corrosion of the stainless steel, although we likely need to include de-ionization stages in the polishing loop.

3.2 Site wide system layout

The most recent scheme for the water distribution system layout [22], which is now part of the civil construction bid package, is shown in Fig. 3. This includes a centrally located pool, aka "Pool Four", which would contain a volume of water somewhat larger than what is needed for the far hall. The hall in which it sits would also house a water polishing loop. This leads us to consider three different scenarios for supplying water to the experimental halls, and for emptying them:

A **Original.** The system in Fig. 1 was designed with no "Pool Four" in mind. It supplies water from some generic source at 35 gpm, which would fill the large pool in about two weeks. Drawbacks are that much of the cost is borne by this pumping speed, water needs to be pumped to the surface for dumping the pools, and every fill will require purchasing (and purifying) more water.

B **Pool Four as temporary storage.** This is the scenario in mind when this pool was included in the civil design bid package. The idea is to use it as a place to dump water from the experimental halls when we need access to the Antineutrino Detectors. Fast pumping can make dumping and re-filling relatively quick, albeit at the expense of purchasing the pumps. No water needs to be repurchased or (heavily) purified, and a simple, slow polishing loop can keep this water in good shape while it is in Pool Four. Presumably, an external Fill/Make-Up system such as is in Fig. 1 could be used for the initial supply of water.

C **Pool Four as the water supply.** The water system construction cost tracks strongly with pumping speed. (See Sec. 3.3.) In principle, we could use Pool Four as our source, with a slow but high quality purification system to condition the water. This saves money on the construction side, but would still require purchasing new water after a refill, and also the ability to pump water to the surface for dumping.

These three scenarios need to be examined further, in order to optimize costs for the civil construction, for the construction of the water conditioning system, and for the operating costs throughout the life of the experiment.

3.3 Cost

The construction cost for the water conditioning system needs to be no more than about \$500K. Operating costs also need to be kept to a minimum.

Finalizing the construction cost will require a decision on the level of deionization needed in the polishing loops, and on the pump speed needed in both the filling and recirculation systems. We have access to a (confidential) report [23] prepared for Argonne National Laboratory in 1999, analyzing different water quality scenarios for the Auger project. They find an operating cost of about \$7 per 1000 gallons of product, or about \$2000 per 1000 m^3. This estimate assumes, among other things, 17¢/kWh in electrical costs, \$200 for 3 ft^3 of deionizing resin, and no cost for water. Another conclusion of this report is that pumping speed has a much higher impact on the system cost than does water purity specification.

Various other parameters need to be settled before, for example, analyzing the various options described in Sec. 3.2. The cost of "city" water in China is, currently 10 yuan/ton, or \$1300 per 1000 m^3, although this price is likely to increase. It may be possible, however, to use ground water seepage for a good portion of the water source.

4 Next steps

This section summarizes the questions that need to be settled, at least prior to a full technical review. Comments are welcome.

1. **Configuration of water supply, storage, and transfer.** This is the biggest job, and includes an estimate of time and costs for the construction of the system, as well

as operating costs. What is the best way to use "Pool Four", assuming that it is in fact constructed? (See Sec. 3.2.) What is the best material to use for the transfer piping? (One possibility is to use Polyvinylidene Difluoride (PVDF), a highly non-reactive polymer, also known as KYNAR or HYLAR, although the costs and availability are not yet known.)

2. **Resistivity and attenuation length.** It is becoming clear (i.e., see Table. 1 and Sec. 2.1) that the water needs to be deionized to at least some level in order to achieve our specification for attenuation length. Test to establish this correspondence are going on now at BNL and at IHEP. After this is established, suitable deionization stages need to be built into the polishing loops in Fig. 1.
3. **Temperature specification between halls.** We should establish some specification for the difference in detector temperatures between the near and far halls. There seems to be plenty of capacity for bringing the water pools into equilibrium with the surrounding rock in a reasonable time period. (See Sec. 2.3.) However, there is likely a difference in the ambient rock temperature between the near and far halls, and we should be confident that we can live with this difference, or prepare to otherwise heat or cool one or more of the pools accordingly.

A Systems from other experiments

A.1 The IMB Experiment

The IMB proton decay experiment [1, 2] consisted of 8000 m^3 of water. Figure 4 shows the water purification system. The primary system takes municipal water an filters it down to about 10 μm, followed by carbon filters for organics and chlorine, and then water softeners to remove magnesium and calcium salts. This is then taken through a reverse osmosis (RO) system where particles larger than 0.001 μm are removed. Next is a degassification stage, followed by a UV sterilizer, and finally a 1 μm filter. The system runs at 5 liters per second, i.e. 80 gpm, or 20 days to recirculate one complete volume. The result after recirculation is less than 0.3 ppm of dissolved solids. A parallel circulation system using only 5 μm filters, runs at 13 liters per second.

A.2 Super-Kamiokande

Super-Kamiokande [3], aka "SuperK", is a 50,000 m^3 water Cherenkov detector used for, among other things, few-MeV electron detection from solar neutrino events. This apparatus places extremely stringent limits on virtually all physical parameters.

Figure 5 shows the system devised by SuperK. This apparatus circulates 30 tons of water per hour (132 gpm). Raw water passes through the "first step" (particulate filters and Reverse Osmosis stages) before going on to a closed loop with more aggressive removal stages, which apparently have expendable but expensive components. It is the clear from their paper

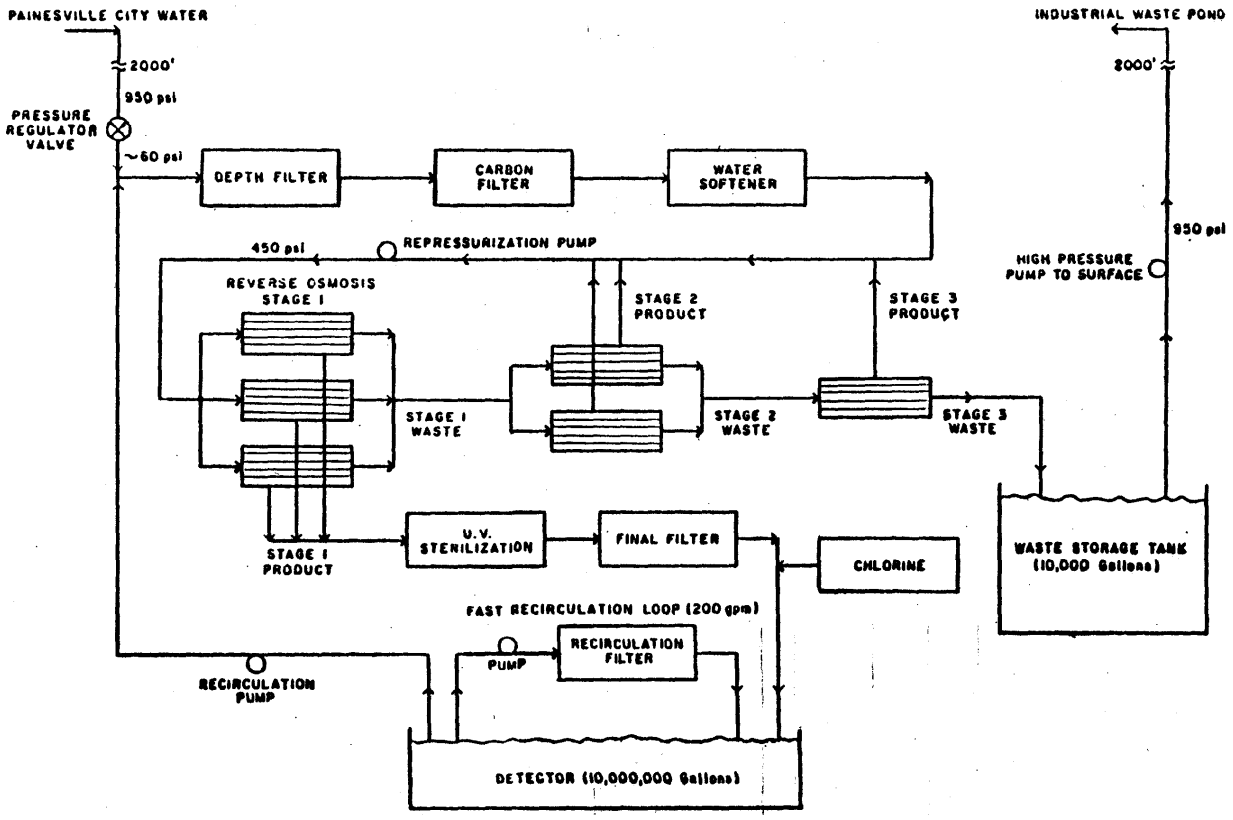

Figure 4: The water purification system used by IMB.

that the system was augmented and upgraded over time, by adding and exchanging various components in the loop.

Water from an external supply is first passed through the 1μm filter to remove dust and particulates. Heat exchangers reduce the water temperature to about 13°C to suppress bacteria growth and phototube noise. A UV sterilizer between the heat exchangers kills surviving bacteria.

Ions are removed by a cartridge polisher. This replaced an ion exchanger which turned out to be a source of radon. The water resistivity went from 11MΩ-cm before the polisher, to 18.24MΩ-cm afterwards. Wikipedia tells me that the theoretical maximum resistivity at 25°C is 18.2MΩ-cm.

A series of aggressive degasification steps follow, including the introduction of radon-reduced air (from a separate air purification system) to assist in further radon removal. Radon removal efficiency is about 83%. Residual radioactivity from radon is a few$\times 10^{-3}$ decays/m^3 or less. The "dissolved solids" fraction appears to be extremely small, namely six ≤ 2 μm particles per cubic centimeter, or 25×10^{-9}ppm.

SuperK paid careful attention to the light attenuation in the water tank. At 420 nm, they demonstrate an attenuation length of 97.9 ± 3.5 m. For different wavelengths, they observe a dependence consistent with that shown in Fig. 2. Over years of running, steady

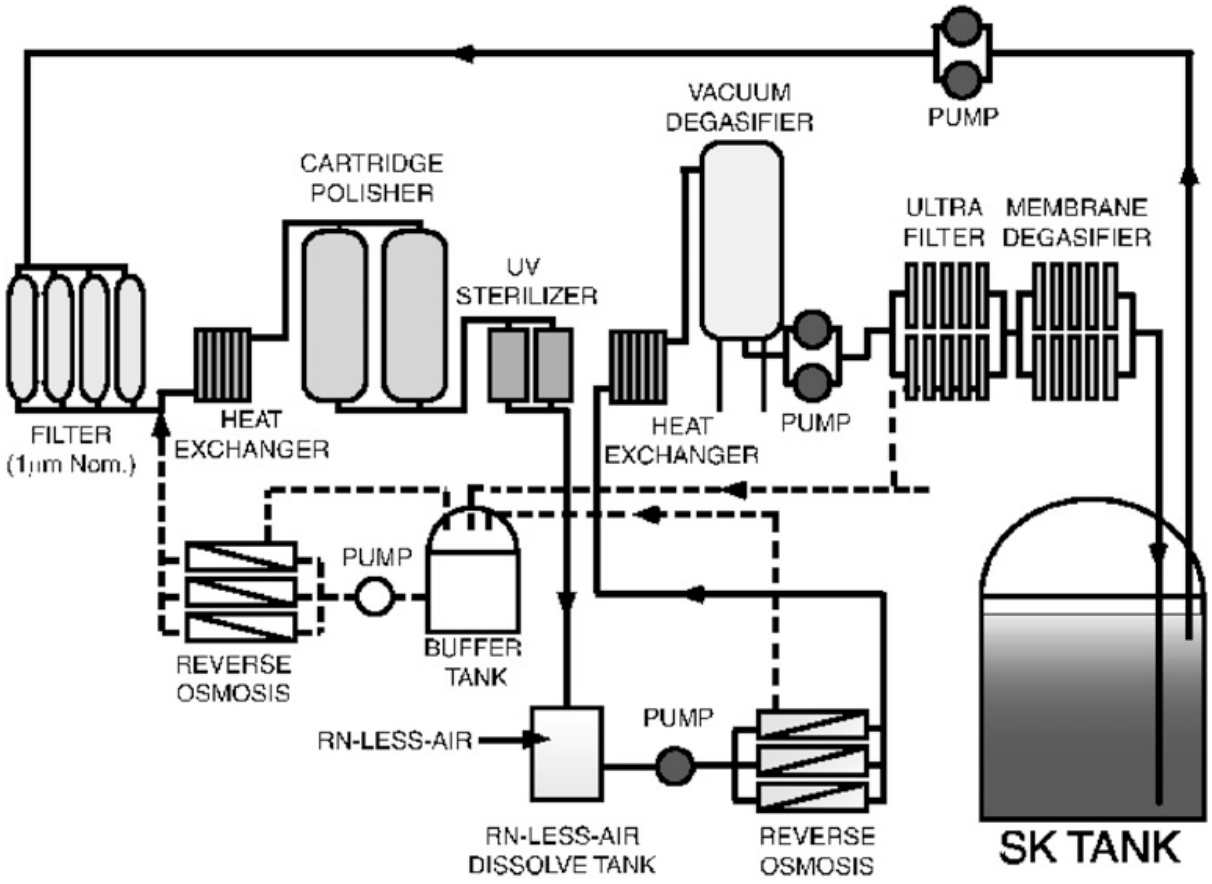

Figure 5: The water purification system used by Super-Kamiokande.

variations of the attenuation length occur between ~ 90 m and ~ 130 m.

A.3 Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNO [4, 5]) uses two separate systems, one for the D_2O detector, and another for the H_2O jacket. This note summarizes the latter, shown in Fig. 6. Water input to this system comes from a surface purification plant that produces potable water for use in the mine. A nitrogen "regassing" step is included in the recirculation loop because "ultrapure water leaches out soluble components when in contact with solid surfaces."

The light water volume is separated into two sections, 1700 m^3 of "clean" water between the heavy water containment vessel and the photomultiplier tube array, and 5700 m^3 of "dirtier" water outside of this, through which all the cabling and other utility connections pass. The circulation rate is 150 l/min=40 gpm.

After descending into the mine, the water passes through a series of passive filters (10μm, charcoal, 3μm), a water softener, and then through a reverse osmosis stage before entering a

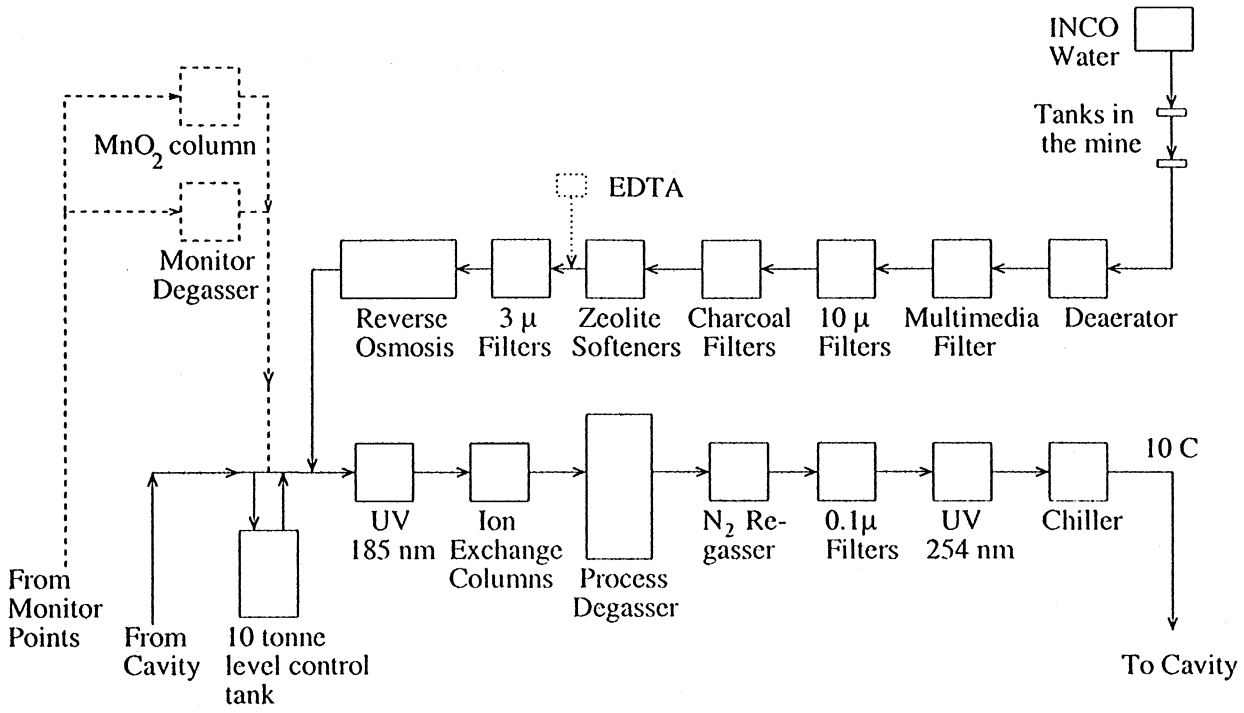

Figure 6: The light water purification system used by the Sudbury Neutrino Observatory.

closed recirculation loop. The charcoal and water softener appear to be mainly preparation stages before entering the reverse osmosis stage, which is the "workhorse of the purification system." This stage reduces inorganic salt levels by a factor of 20 and removes large organic molecules with $> 99\%$ efficiency.

Past this point, the water remains in a closed loop which focusses on degassing. Oxygen and radon are removed with a custom designed stage, the Process Degasser [5]. This system reduces the radon concentration to 2.07×10^{-19} mol/m^3, or about 10^{-3} Bq/m^3.

The NIM paper [4] alludes to the problem summarized last summer by Chris Jillings, where degassed water leads to problems inside the PMT high voltage connectors. This appears to be a second reason for including the nitrogen regassing stage in the closed loop.

A.4 KamLAND

The Kamioka liquid scintillator antineutrino detector (KamLAND) [6, 7] is a reactor neutrino experiment not dissimilar from Daya Bay. In particular, it also utilizes an outer water shield for radioactivity abatement and active muon detection through Cherenkov radiation. Unfortunately, there is no published information on the details of the water conditioning system. Kam-Biu Luk has therefore provided an internal note [7] which provides some of this information.

The liquid scintillator in KamLAND is surrounded by 3200 tons of purified water, fed

by ground water which passes through a conditioning system. The radon concentration in the native water is 10^4Bq/m^3, and is not removed. (The size of the active region makes it possible to live with a rather high level of radon activity.) The circulation rate is 8000 tons per hour, or 35 gpm.

The conditioning system consists of two filtering stages, one at 10μm and the second at 1μm, followed by two reverse osmosis membranes, and then by an ultraviolet sterilizer. The electrical conductivity of the water is 0.5 MΩcm. A cartridge polisher with ion-exchange resins was located downstream of the reverse osmosis stage, but was not used for shield water purification.

A.5 The BaBar DIRC

The DIRC [8] particle identification system for BaBar makes use of 6 m^3 of purified water. Water is the medium used to transmit Cherenkov light from the ends of the quartz bars to the photomultiplier tubes used to detect it. Good transparency at short wavelengths is important, and the approach is to use ultra pure water with resistivity close to the theoretical maximum of 18 MΩ-cm.

The water purification system is shown in Fig. 7. The input line constans five mechanical filters (three 10 μm, one 5 μm, and one 1 μm), a charcoal filter, and a reverse osmosis (RO) unit with a 5 μm prefilter. This line supplies a holding tank, parallel pumps, and a deionization bed with 1 μm exit filters. A single UV (250 nm) lamp irradiates the water to prevent growth of bacteria. The irradiated water then goes to parallel 0.2 μm filters. The parallelism allows serviceable items to be replaced without interrupting operation.

The normal running mode bypasses the RO system. There are 2 modes of RO "running," One to fill (after a dump or to top off the system) and one to back flush the membrane. The total time is recorded on an hour meter. Our total time is now 532.64 hours, after eight years. The fill cycle is turned on and off by level sensors in a tank. The back flush cycle is on a timer.

The water resistivity in the supply line is typically 18 MΩ-cm, and 8 MΩ-cm to 10 MΩ-cm in the return line. The operating temperature is 23-26°C, and the pH is typically close to 6.5. Sodium, which is easy to detect and which leaches out of the photomultiplier tube glass, is used to monitor this effect by comparing the difference between input and output lines, typically 0.2-0.3 ppb. This would correspond to a 2-4 μm/year reduction in the thickness of the front glass surface of the PMT.

Light transmission is monitored with a laser system operating at three different wavelengths. At 325 nm and 442 nm, they find transparency varying between $\sim$ 98%/m and $\sim$ 99%/m (attenuation lengths between 50 m and 100 m) over a one year period. The transmission is $\approx$ 92%/m (12.5 m attenuation length) at 266 nm.

The flow rate is about 4 gpm which circulates the entire volume about three times each day. Because this is a closed system and the RO is on primary input circuit - under normal conditions the duration is about 5 min. Our water loss is limited to evaporation in what we call the bird house above the standoff box and the small amount of water that is pulled

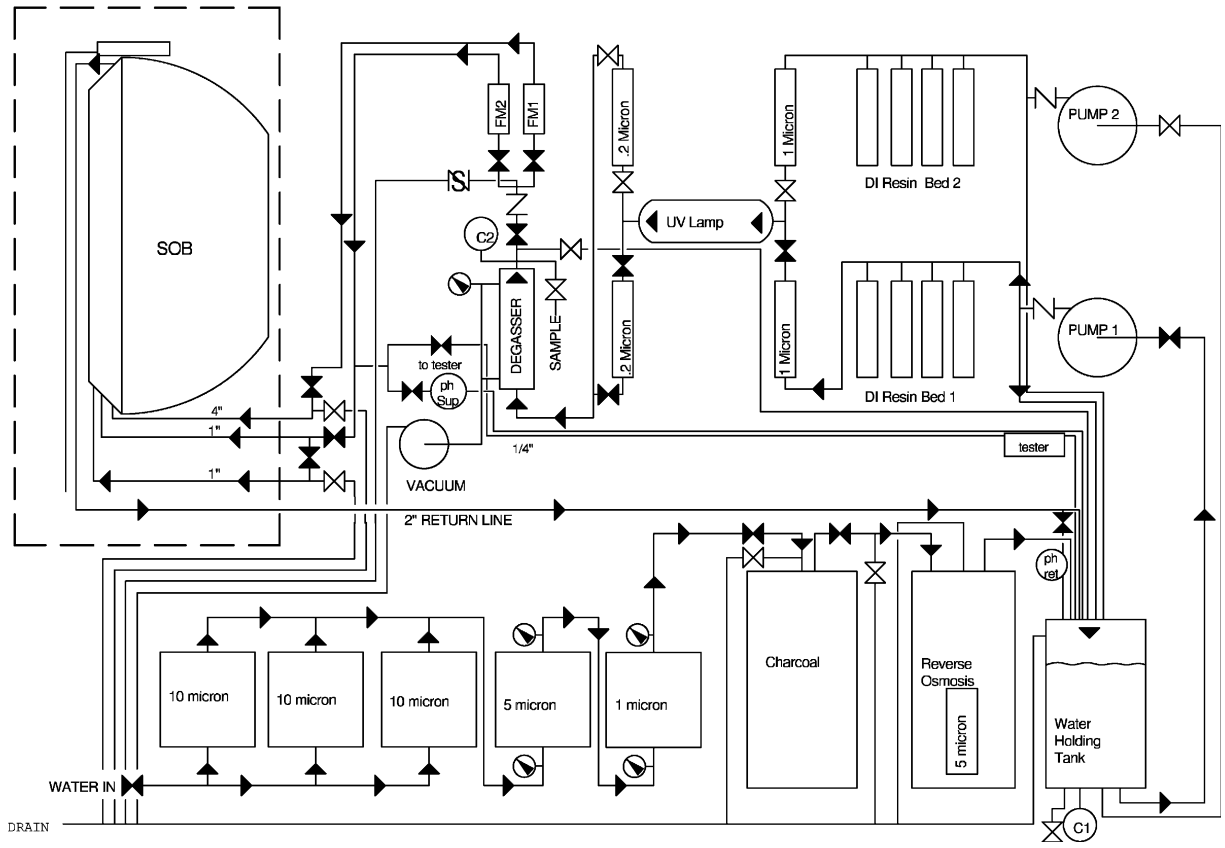

Figure 7: The water conditioning system for the DIRC apparatus of the BaBar experiment.

through the de-gassing membrane and the larger amounts necessary to purge the system at time of taking water samples for analysis. Depending on these factors frequency is about four to eight times per year.

A.6 Milagro

Milagro [9] is a large area water Cherenkov detector used to study extended air shower cosmic ray events.

Water was drawn from the fresh water well located on the site. The conditioning system consisted of a media filter, a water softener, a carbon filter, a 1 μm filter, a UV lamp, and a 0.2 μm filter. The fill rate was 300 liters per minute (80 gpm). During operations the total amount of water in the pond was between 3000 m^3 and 4400 m^3 liters depending upon the depth. A pump located at the bottom of the pond was used to continuously recirculate the water at 725 liters per minute (190 gpm) during normal operations. The media filter and softener were bypassed during recirculation.

The attenuation length of the water at a wavelength of 350 nm was around 4 m at the start of the experiment, and rose to about 20 m in the final configuration. It should be noted

that the measured attenuation length includes both absorption and scattering of the light.

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