LIQUID SCINTILLATOR SPECIFICATION DOCUMENT

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Authors: Lothar Oberauer, Patrick Pfahler, Michael Wurm

L1 LIQUID-SCINTILLATOR DETECTOR TECHNOLOGY

Liquid scintillators are a widely used detection medium for low energetic radiation from nuclear decays. Given sufficient radiopurity, this technique can also be used to detect the charged particles originating from the interactions of neutrinos with electrons or atomic nuclei in a liquid-scintillator volume. Today, detectors based on large-scale tanks containing tons to kilotons of liquid scintillator are used to detect low-energy neutrinos from various sources, the most prominent examples being Borexino experiment for the detection of solar neutrinos and the KamLAND detector for reactor neutrinos. The low interaction probability of a neutrino dictates the target volumes to be large to collect reasonable statistics on the time-scale of years. Moreover, special purification techniques and shielding from external radiation are a prerequisite for a sufficiently low background level that allows extraction of the neutrino events from the data.

The detection chain for neutrinos is the following: Neutrinos interact for instance with one of the electrons of the target liquid scintillator, which is ripped from its atomic nucleus and travels a short way through the detector medium, thereby exciting or ionizing other scintillating molecules while loosing kinetic energy. The excited molecules loose their energy by emitting light. As the excitation energy of the organic solvent that makes up the bulk of the scintillator is in the order of a few eV, the emitted photons would lie in the UV range of the electromagnetic spectrum. As the organic solvent is not transparent to these wavelengths, a secondary component, a fluor or dye is needed, to shift the photons to longer wavelengths at which they can travel almost unimpeded through the liquid. Upon reaching the verge of the detection volume given by the tank walls, these photons are detected by photomultiplier tubes (PMT), light sensors able to perform single-photon counting. The amount of light collected in a single scintillation event is proportional to the energy of the initial charged particle and therefore the energy deposited by the neutrino in the target. The arrival time differences of the photons at individual PMTs can be used to determine the position of the scintillation event inside the volume. The last feature is used to separate neutrino events in the bulk of the detector from the background of external gamma rays expected close to the detector tank walls.

The nominal design of the next-generation experiment LENA aims at a target mass of about 50 ktons for neutrino detection. Figure L2-1 shows a schematic view of the detector. The tank (inner) volume is 100 meter in height and 32 meter in diameter (L2). The dimensions are dictated by the attenuation of the scintillation light in the target medium. The liquid scintillator envisaged consists of three components: the bulk is made up by an organic solvent, linear alkylbenzene (LAB), while small concentrations of two wavelength shifters are added, diphenyloxazole (PPO) as primary fluor and bismethylstyrylbenzene (Bis-MSB) as secondary fluor (L5). In order to ensure the chemical compatibility of the organic solvent and to reach the required radiopurity, special requirements are set for the tank materials (L3): Based on the study performed by Rockplan Ltd. in 2010, the tank bulk material is concrete, while the tank surfaces are covered by stainless steel sheets to fulfill the above demands. The scintillation light is collected by an array of 29,600 PMTs, mounted to a support structure (a stainless steel scaffolding) whose inner face is located at 14 m radius from the tank axis. Different to prior designs, this structure is directly immerged in the scintillating liquid filling the complete tank volume. In this configuration, the central detection volume is to be shielded from background light due to external radioactivity. For this, an optical separation is introduced at the inner face of the PMT support structure (PSS), reducing the rate of external background events to an acceptable level. The PMTs itself are enclosed on composite steel and acrylic housings, the optical modules (OMs) filled with inactive mineral oil to provide some shielding against the intrinsic radiation of the PMT glass and dynode chains. The design of the OMs and the necessary cabling running in the interspace of PSS and tank wall are presented in sec. L4. Finally, the infrastructure needed for filling and operation of the detector as well as the procedures envisaged for the filling process are described in L6 and L7. This includes the treatment and infrastructure needed for water (surrounding the detector tank and used in its initial cleaning) and nitrogen (for initial scintillator cleaning and buffering during operation). Other surface and underground installations are listed in L8.

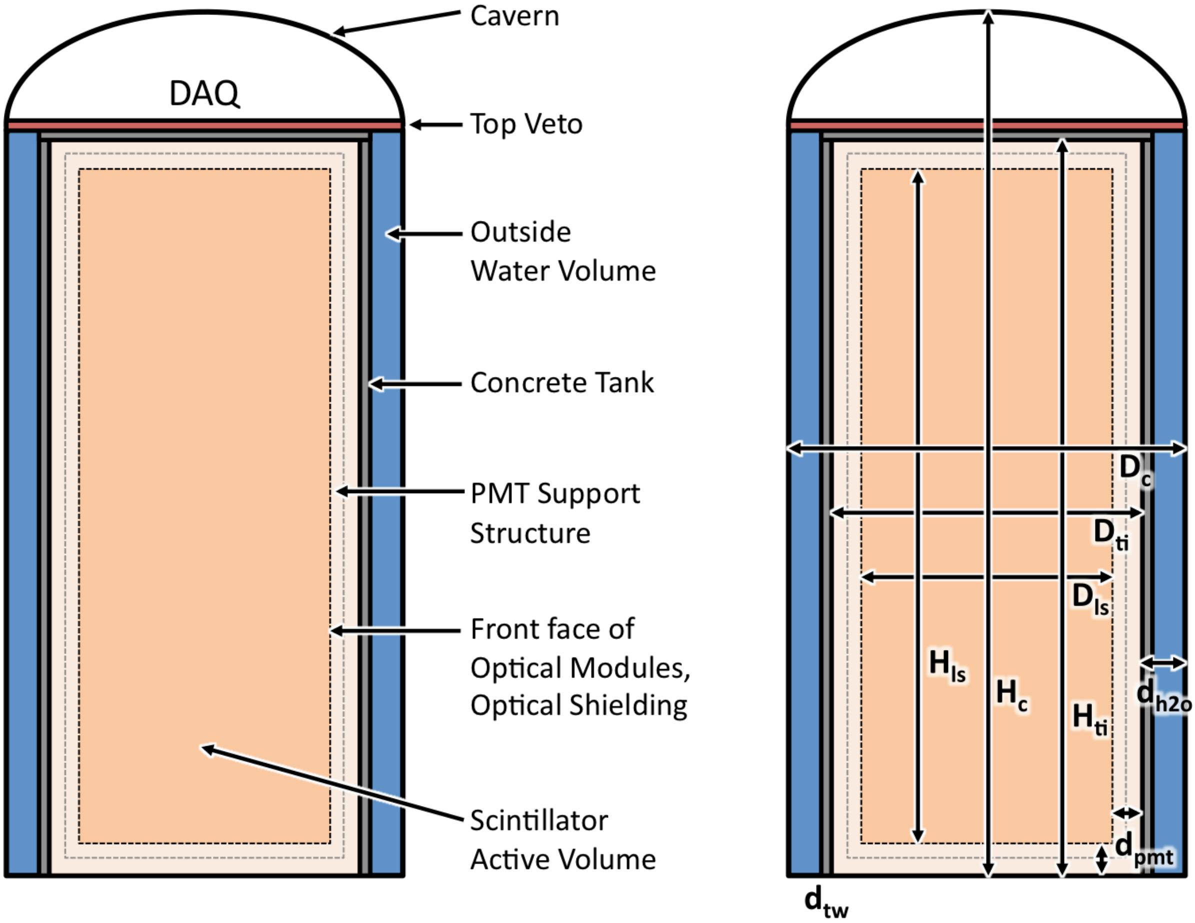

Figure L2-1 *Schematic drawing and dimensions of the LENA tank and cavern.*

L2 DETECTOR DIMENSIONS AND VOLUME

Figure L2-1 gives an overview of the dimensions of the experimental cavern and the detector itself. In the following, the main components, their dimensions, volumes and masses are described. Table L2-1 lists the corresponding values for both a 25-kt and 50-kt tank option. The latter is to be considered as default option.

Item			25 kt	50 kt
cavern: minimum diameter	D_c	mm	40000	36000
cavern: estimated height	H_c	mm	50000	115000
concrete tank: inner diameter	D_{ti}	mm	36000	32000
concrete tank: inner height	H_{ti}	mm	40000	100000
concrete tank: wall thickness	d_{tw}	mm	600	600
scintillator: total volume		$10^3\,m^3$	40.7	80.3
scintillator: total mass		kt	35.0	69.1
active volume: diameter	D_{ls}	mm	32000	28000
active volume: height	H_{ls}	mm	36000	96000
scintillator: active volume		$10^3\,m^3$	28.9	59.1
scintillator: active mass		kt	24.9	50.8
ratio: active/total			71%	74%
outer water volume: width	d_{h2o}	mm	2000	2000

Table 2-1: *Dimensions of the LENA tank.*

The main dimensions of the **concrete tank** are its inner radius of 16 m and its height of 100 m, a total volume of 80,300 m^3. The complete tank is filled with liquid scintillator, corresponding to 69.1 kt for the density of LAB. Circular shape and radius are chosen due to the experimental advantages of a radial-symmetric detector and the transparency of the organic liquid to the scintillation light.
According to the Rockplan study, the baseline design of the tank itself is envisaged as a Hollow-Core Concrete Tank: It features a sandwich structure of a 600 mm wide concrete layer covered on both sides by thin steel sheets. Cylindrical cavities of 300 mm diameter and 500 mm interspacing are kept open to reduce the needed amount of material, at the same time leaving space for installations (e.g. cooling or active leak proving). A schematic view of the tank wall is shown in Figure L2-2.

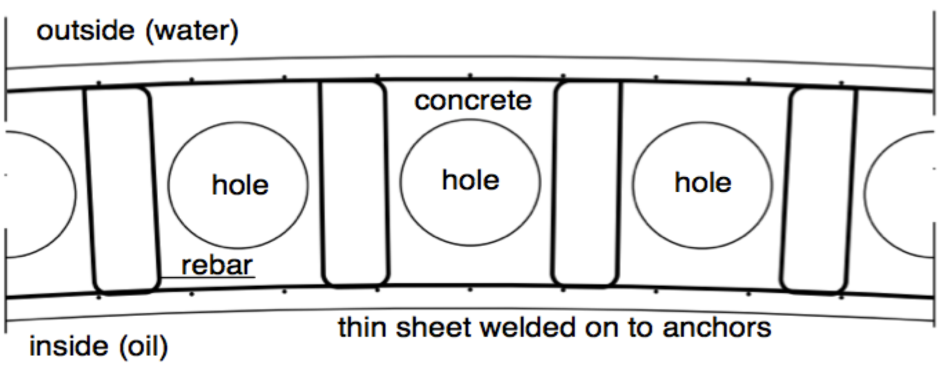

Figure 2-2: *Cross-section of the tank wall structure from the Rockplan study.*

Removed by about 1 m from the tank wall, the **PMT support structure** (PSS) carries the Optical Modules (OM). The stainless steel scaffolding has a width of about 1 m (wider than the length of the OMs), the front face ending at 14 m from the detector axis or 2 m from the tank walls. A similar structure is to be installed on the tank lid and bottom. In total, 29,600 OMs for 12'' PMTs will be mounted to this scaffolding with regular spacing (see L4 for more details on the corresponding dimensions).

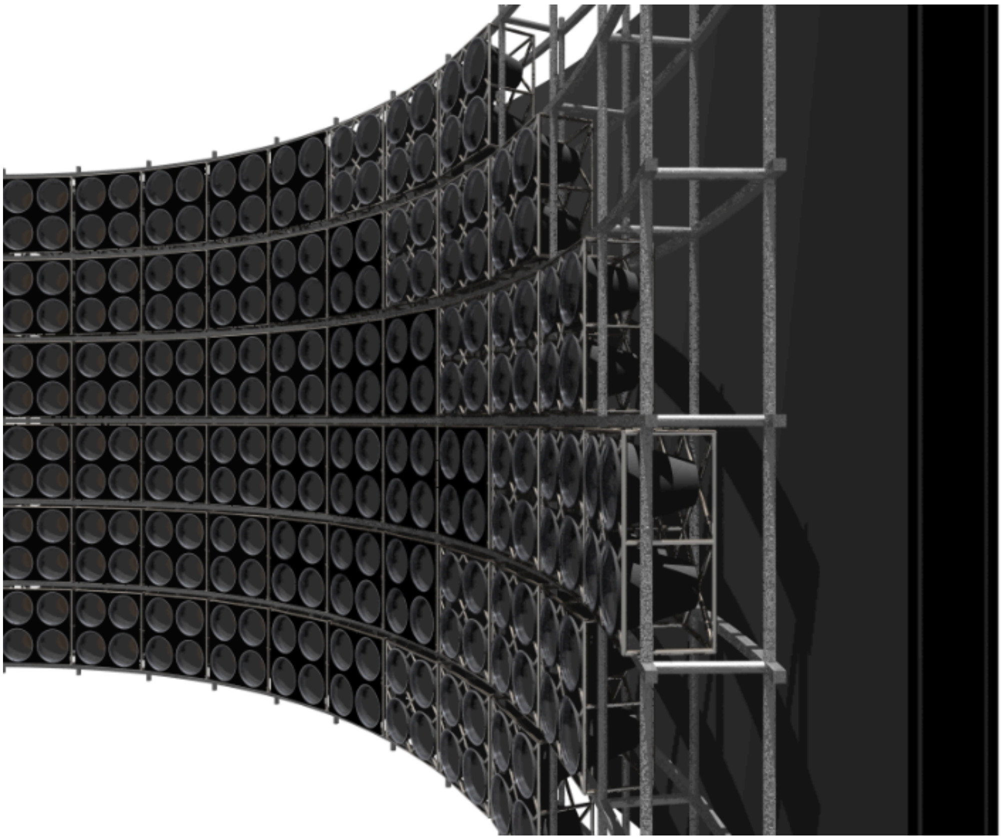

Figure 2-3: *PMT support structure with mounted array of optical modules.*

Enclosed by the PSS is the **active volume** used for neutrino detection. With a radius of 14 m and height of 96 m the total volume is about 59,082 m^3, corresponding to 50.8 kt of LAB. For low energy neutrinos, only part of this volume will be available for detection because of the external radioactive background that concentrates at the outer verges. Based on the the MC studies in the appendix of the Rockplan tank study, we expect a total rate of 13 kHz due to external gamma rays inside the active volume (8.5 kHz originate from the PMTs, 4.5 kHz from the tank). To avoid the background light from the much higher event rates expected in the radial region between 14-16 m (behind the PMTs), a shield of optically opaque foils mounted to the inner face of the PSS has been introduced in the design (see L4).

The concrete tank is not in contact with the cavern walls. The interspace will be filled with water, the fill level not exceeding the upper tank lid. This **outside water volume** will serve both as shielding from external radiation as well as an active Cherenkov veto against muons entering the detector from the sides. The light will be collected by 4000 encapsulated 8''-PMTs mounted to the outside of the tank in regular spacing. The minimum width required is 2 m. Therefore, the total diameter of the cavern should not be lower than 37.2 m (however, small zones at the bottom of the detector of smaller water shielding could in principle compensated by zones of higher width at intermediate heights).

The vertical orientation of the tank is favorable as it mitigates the effects of the density difference between the inside scintillator (0.86 kg/l for LAB) and the outside water. In particular, buoyancy plays no role in this configuration, while there is of course a net inward pressure at the bottom of the detector tank. For neutrino physics, the missing water coverage at the upper detector lid is replaced by the flat **top muon veto** that should cover the complete cross section of the cavern right above the detector. There are several options for the veto detectors, ranging from plastic scintillator panels to limited streamer tubes or resistive plate chambers. They all have in common that one layer of these detectors are relatively flat (order of 100 mm), but several layers would be needed to obtain the required veto efficiency or spatial resolution, respectively. The platform carrying the DAQ system will be installed above this veto. The total height of the cavern is close to 115 m.

In the following, the volume and instrumentation inside the concrete tank will be referred to as **Inner Detector** (ID), while the outer water tank and PMTs will be called **Outer Detector** (OD).

A requirement for the presented approach without a separating membrane inside the ID is the minimization of liquid exchange between the volumes inside and behind the PSS. The OS impedes such an exchange, but for sure not completely as it most be permeable for liquids to avoid problems during filling. In addition, a **temperature control system** is required to compensate the natural temperature gradient of 1 °C in the rock surrounding the cavern. This could be achieved by cooling the OD water by introducing fresh (cold) lake water at different heights and quantities. It also needs a system to cool the tank fundament to prevent heat absorption of the scintillator at the ID bottom.

L3 TANK MATERIALS AND PURITY

This section summarizes the demands on the tank materials and the PMT support structure. Optical modules and cabling are treated in L4.

L3.1 Tank materials, life time

As described in L2, the 60 cm wide bulk of the tank wall is made of concrete. On both inside and outside, thin stainless steel sheets are welded, as well as on the inside top and bottom ends of the tank. The inside steel liner will be in contact with both water (during pre-cleaning) and scintillator (during operation). Outside, only contact with water is foreseen.

The detector lifetime is foreseen to be 30 years. No collapse of the cavern or tank under any circumstance is allowed. The basic safety of the people should be assured under any circumstance (along the whole underground facility). One output of the feasibility study should be the expected power spectrum for the maximum probable seismic activity in the area. The stability requirements should be fulfilled for earthquakes with the according power spectrum.

L3.2 Purity demands

Purity comprises two aspects: The first is the chemical purity and compatibility with the water and the organic liquids. This is assured by choosing stainless steel for the tank surface and the PSS, and by the precleaning of the tank with ultrapure water.

The welding joints of both tank and PSS steel must be passivated after welding in order to reestablish their chemical inertness.

The second aspect is radioactive purity to fulfill the background requirements of the experiment. The dimensions quoted in L2 rely on radiopurity levels for building materials used at the Gran Sasso National Laboratory (LNGS) and the Borexino tank in central Italy. In both cases, concrete (for the laboratory walls) and steel were preselected, investigating products from a variety of providers in Germanium-spectrometers and selecting the optimum material. Similar measurements can be performed in the underground laboratory at TUM (Garching, Germany). Beyond this selection, no further (material) purification has to be applied.
The required radiopurity levels listed in table 3-1 correspond to the formerly used materials at LNGS. They are expressed in terms of Bq per kg of material and represent upper limits that should not be exceeded. These limits are set for the concentrations of natural uranium and thorium (and their respective decay daughters), potassium and cobalt (which only applies for steel). There are no special requirements stated for the steel surface of the tank – steel is generally less radioactive than concrete, and the mass of the sheets will be negligible compared to the concrete bulk. However, no radioactivity must be introduced by the welding of the steel, i.e. either laser-welding or thorium-free tips for conventional welding must be used.
If these limits are followed, a background rate of 4.5 kHz due to external gamma rays emitted by the tank material is expected in the active volume. The main contribution is made up by the concrete, while the radioactivity of the steel surface and PSS are negligible.

Isotope	Concrete	PSS Steel	OM-PMTs	OS Sheets	Scintillator
^{232}Th	14 Bq/kg	0.2 Bq/kg	0.3 Bq/OM	150 Bq/kg	10^{-8} Bq/kg
^{238}U	62 Bq/kg	0.5 Bq/kg	3.2 Bq/OM	600 Bq/kg	10^{-8} Bq/kg
^{40}K	17 Bq/kg	0.03 Bq/kg	0.2 Bq/OM	200 Bq/kg	10^{-8} Bq/kg
^{60}Co	--	0.03 Bq/kg	--	--	--

Table 3-1: *Radiopurity requirements of the LENA tank, PMT support structure, optical modules (assuming 12''-PMTs), optical shielding and scintillator.*

L4 TANK INSTRUMENTATION

L4.1 Optical modules

The design value for the effective optical coverage (i.e. the fraction of the detector walls covered by active photosensitive area) is 30%. This value can be achieved by employing either 29,600 photomultiplier tubes (PMTs) of 12'' diameter (considered as the default option) or 66,500 8''-PMTs. Both solutions correspond to an optical coverage of roughly 20% (this value already includes an inactive margin of 0.5 cm width on the PMT circumference). The 20% can be further enhanced if light-concentrating mirrors (so-called Winston cones) are added in front of the circular PMT photocathodes. Due to the geometry of the cylindrical, cones increasing the aperture by a factor x1.85 are necessary to gain an effective increase in light collection of 50% to meet the required 30%. (Only regarding the integral area of cone apertures, the coverage would be 56%.) Alternatively, the required number of PMTs could be reduced if high-quantum-efficiency PMTs were used. The baseline value used here are a conservative 20% efficiency for single photon detection.

For several reasons, these PMTs must be mounted in individual encapsulations: As the inner tank is pre-cleaned with water, the electronics at the base of the PMT must be protected from the conducting medium. Further on, the pressure at the bottom of the tank is around 10 bar. While the most recent 12'' PMTs of Hamamatsu meet these specifications (if encapsulated only at the PMT base), an extra margin in pressure resistance seems advisable. Finally, each PMT will bear its individual buffer to its own gamma rays right in front of the photocathode: an oil volume of about 30 cm thickness enclosed by the light concentrator will shield gammas from the PMT glass and the dynode chain.

Each PMT is part of an optical module (OM). The layout is shown in figure 4-1. Each OM consists of the PMT, an electronics socket at the PMT base, a liquid-tight connector on the back for high voltage and signal cables (or one cable carrying both), the pressure encapsulation, the light-collecting Winston cone in front of the PMT photocathode, a curved acrylic window closing the cone aperture, a mineral oil buffer enclosed inside the Winston cone, as well as a mu-metal shielding at the inner surface of the encapsulation shielding the PMT from external electromagnetic fields.
For 12'' PMTs, the OM will have at its front a diameter of 560 mm, and a length of about 700 mm. (For the 8'' solution, diameter is 370 mm, length about 500 mm). This means that the OMs can be arranged on a rectangular grid without overlap, and that they will be fully contained in a PSS of 1 m width. The front windows of the OMs will be aligned with the inner face of the PSS at 14 m distance from the detector axis.

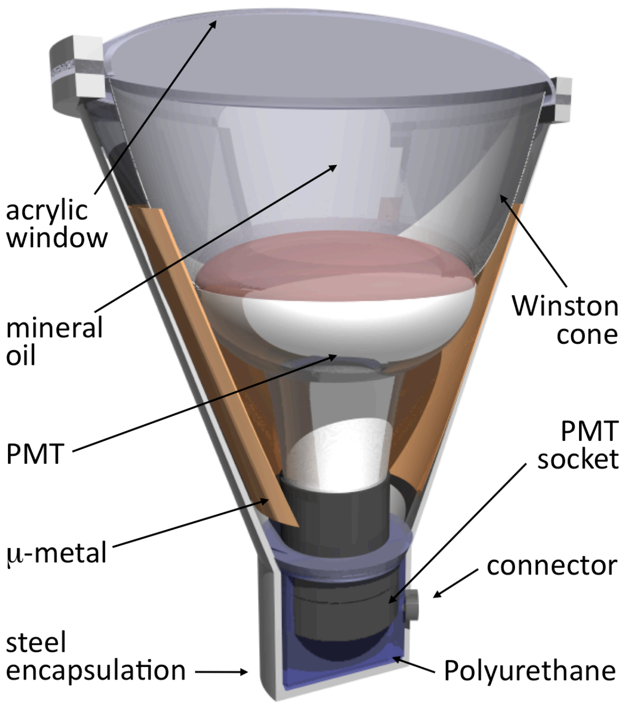

Figure 4-1: *Layout of the optical module (OM).*

The materials to be used for the encapsulation are stainless steel for the roughly conical back part and acrylic for the front window. The encapsulation must be able to bear an external pressure of about 13 bar. This is currently studied in finite-element

simulations at TUM. A transparent mineral oil will be used to fill the interspace of PMT and encapsulation. As the volume of the Winston cone is quite large (and the PMTs themselves are evacuated), the weight of the OM is mainly determined by this mineral oil. We expect about 30 kg for the total OM (10 kg for 8'' version), which corresponds to about 900 tons for all modules.
Each OM requires a high-voltage supply. The HV can either be brought down from external modules located above the detector in the DAQ area, or generated at the base of each individual PMT using low or middle voltage (which must be also provided by a cable from top). Based on the maximum allowed current I=0.125 mA and the mean HV level of 2 kV needed per PMT, the estimated power needed per PMT is 0.25 W. This corresponds to about 7.5 kW for the total number of OMs (12.5 kW assuming the same values for 8'' PMTs).
The radiopurity requirements of the OMs mostly apply to the PMTs: Their radioactivity is in turn mainly determined by the PMT glass and the materials of the dynode chain. In Borexino, each PMT produces around 0.2 Bq of ^{40}K, 3.3 Bq of ^{238}U and 0.3 Bq of ^{232}Th (cf. table 3-1). For LENA, this would correspond to a total background rate of 120 kHz. However, the introduction of the 30 cm wide OM buffer volumes should reduce this rate by about an order of magnitude to manageable 8.5 kHz. Therefore, this already achieved level or radiopurity is set as default for LENA.

Mining activity close to the detector could have a negative impact on the PMT electronic performance. The allowed noise and vibration levels are still to be investigated.
Table 4-1 summarizes the most important parameters for the OMs.

Properties	12'' PMT	8'' PMT
OM front diameter	560 mm	370 mm
OM length	700 mm	500 mm
PMT length	330 mm	220 mm
Light cone length	320 mm	210 mm
Weight	30 kg	10 kg
Maximum current	0.125 mA	0.125 mA
HV requirement	2.0 kV	1.5 kV
Power per OM	2.5 W	1.8 W

Table 4-1: *Parameters of the optical modules for 12'' (default) and 8'' PMTs.*

L4.2 Optical shielding (OS)

The OS shields the active volume inside the PSS against the light produced by external gamma rays between PSS and tank walls. The basic idea is to mount thin plastic sheets to the front (inner) face of the PSS at 14 m radius. Of course, the sheets should not cover the OM front windows but should be fastened to the verges of the optical modules. The sheets should be less than 1 mm thick, optically opaque to the external light and black on the inner face to reduce the amount of backscattered scintillation light. While being light-tight, the OS should not be completely tight to liquids to ease the filling process. However, such a shield is expected to reduce the diffusion of radon emanated by the tank walls, PPS and cables into the active volume. As all other components of the inner detector, the OS must be chemically compatible to water and LAB.

The expected weight for foils of 1 mm thickness is around 5 tons (density of 1 t/m^3), as about half of the surface at 14 m radius must be covered. As there will be no buffer volume in front of the sheets, the required radiopurity per area is higher than for the OM. However, due to the thin sheets, the requirements per kg listed in table 2 are by comparison less restrictive.

L4.3 Cabling

There are two classes of cables. First, all OMs must be supplied with an electrical connection to the external power supply and DAQ on top of the detector. Moreover, optical fibers will be used for detector calibration. The design for this is not yet completed. The descriptions given here are extrapolating the situation in Borexino.

The **electrical connections** to the OMs serve two purposes: The high voltage for the PMTs must be brought down from the HV supplies, and the PMT signals must be transmitted to the DAQ, both located on top of the detector. It is possible to do both in one coaxial cable, the signal travelling as AC pulse on top of the DC high voltage. However, different scenarios are possible in which the HV generation, the decoupling and preampflication of the signal pulses or even their digitization are done directly in the OM. Following the PMm2 approach, arrays of OMs could be bunched together for both HV and signal transmission.
The cables themselves must be chemically compatible to water and LAB and liquid- (especially water-) tight at 10 bar. The former could be achieved by a Teflon-coating of the cables which will also prevent radon-emanation from the cables.

Optical fibers will be used to calibrate the OM PMTs. The light of a defined light source (most probably a laser) is transmitted to the PMTs in order to determine their timing, single photoelectron charge for low energy physics and charge linearity for high-energy applications. In Borexino, each individual PMT features its own fiber. They are fed by a common laser light source outside the detector. This possibility might be to costly for the large number of PMTs in LENA. Therefore, groups of PMTs could be calibrated by a common fiber across the active volume.
In addition, light beams across the volume could be exploited to regularly check the optical transparency of the liquid. The diffuser balls mounted to the PSS will be fed by additional optical fibers.
Technically, the fibers are required to transmit the calibration pulses without a divergence of the pulses by more than 1 ns over 100 m length. The fibers should be coated to avoid stray light escaping the fibers during transmission. This coating must be compatible with water and scintillator.

L5 SCINTILLATOR PROPERTIES

Liquid scintillators are compounds of at least two organic materials. In case of LENA, the bulk material of choice is the organic solvent linear alkylbenzene, LAB. Moreover, two solutes will be added in small concentrations, diphenyloxazole (PPO) at 3 gram per liter (g/l) of the solvent and bismethylstyrylbenzene (Bis-MSB) at 20 mg/l. Therefore, the chemical properties of the liquid will be mainly determined by LAB. The material data sheets for all substances are attached.

LAB molecules are compounds of an aromatic ring and a carbon chain of variable length (around 12). It has a density of 0.86 kg/l, somewhat lower than the water surrounding the tank. Therefore, the vertical orientation of the tank was chosen in order to prevent buoyancy forces (L2). Compared to water, it is rather viscous, 4.2 cps. Unlike other organic solvents, it is in all respects a relatively save material. It features HMIS ratings of 1 for both health and flammability and none for reactivity.
From the point of view of scintillation counting, the light yield is comparable to other solvents as PXE or PC, while the emission time profile is somewhat slower. For the large diameter of LENA, transparency to the scintillation light plays an important role to allow the light to travel from a bulk event to the OMs on the verge of the active volume. The minimum attenuation length required is about 10 m. Laboratory samples of LAB have shown 10-20 m. Attenuating processes are absorption (which can be followed by re-emission of the light) and scattering. In laboratory studies, these quantities have been determined separately at a wavelength of 430 nm which is most relevant for the light transport. The parameters are listed in table 5-1.
While the default design is to use only LAB as a solvent, it is possible to adjust the transparency of the liquid by diluting the solvent with mineral oils like dodecane or tetradecane, a measure taken in both KamLAND and Double-Chooz. Moreover, the solvent used in DC, phenylxylylethane (PXE) is a possible backup option to replace LAB entirely.

Like LAB, **PPO** and **bisMSB** are aromatic compounds. Both arrive in form of a powder that has to be dissolved into LAB. This can happen at much larger concentrations than envisaged for the final experiment. Due to its fabrication and large surface, the solute powders will feature a much lower radiopurity than the solvent itself. Therefore, a dedicated purification chain will be necessary (L6 and L7).

Properties of LAB	
Chemical data	
Chemical formula	$C_{18}H_{30}$
Molecular weight	241
Density	0.863 kg/l
Viscosity	4.2 cps
Flash Point	140 °C
HMIS ratings	
Health	1
Flammability	1
Reactivity	0
Optical parameters	
Index of refraction	1.49
Attenuation length	~15 m
Absorption length	40 m
Abs.-reemission length	60 m
Rayleigh scattering length	40 m

Table 5-1: *Properties of linear aklylbenzene (LAB).*

To allow for solar neutrino detection (especially ^{7}Be neutrinos), the radioactive contamination of the scintillator must not exceed a level of 10^{-8} Bq/kg or 1 count per day and ton, respectively. While this is technically demanding to achieve, such

conditions have been achieved in the Borexino experiment. Potent techniques for the removal of low-level contaminations with radioactive isotopes are distillation, water extraction and nitrogen purging (L6 and L7). It should be noted that the LAB is very likely to fulfill this requirement when leaving the distillation plant at the production site. If clean transport vessels and air-tight sealing are provided, a new distillation at the experimental site might not even be necessary. However, the baseline design presented in the following sections also includes purification plants for pure LAB.
Contact of the scintillator to the ambient air must be prevented. Even if exposed to relatively moderate amounts of oxygen, both scintillation light yield and pulse shaping capabilities are considerably reduced. Longer exposures lead to a reduction in optical transparency and visible discoloration. Moreover, radioactive krypton and radon contained in the air will dissolve in the scintillator and constitute a dangerous background for solar neutrino detection.

L6 LIQUID AND GAS HANDLING SYSTEMS

The liquid handling systems will be used both for filling and during the operation of the detector. The liquids in question are scintillator and water. The scintillator is a compound of solvent (LAB) and wavelength shifters (PPO, Bis-MSB) and is described in L5. In addition, an inert gas will be needed for purging and buffering of the scintillator, which must not be exposed to air (L5). The default option for the gas is nitrogen. In this case, the gas supply is provided by liquid nitrogen (LN) to reduce the volume required for transport and storage. Moreover, there are efficient techniques for the cleaning of LN from radioactive noble gases. As an alternative to N, we study the use of argon. Besides technical aspects, the impact of radioactive isotopes (Ar-37, Ar-39) on the background levels has to be assessed.

L6.1 Surface systems: Liquid Scintillator

The surface installations for liquid scintillator have to fulfill the following tasks:

- Unloading of the scintillator raw materials
- Fabrication of a Master Solution (MS) using part of the LAB and dissolving a high concentration of PPO (~60 g/l) and Bis-MSB (~0.4 g/l)
- Purification of the remaining pure LAB and the MS
- Dilution of the MS in pure LAB to reach the target solute concentrations
- Feeding into the trunk line system connecting surface and detector cavern
- Storage of raw materials, MS, and final scintillator in order to mitigate the effects of irregularities in delivery, purification or filling

The overall system dimensions are designed to allow for the (scintillator) filling of the detector within 1 year. The delivery chain preceding the on-site infrastructure assumes that the 80,000 m^3 (69 kt) of LAB are transported from the producer's distillation plant in relatively large containers to a nearby port. From there, batches of about 800 m^3 are transported twice per week to the mine by railway, corresponding to trains of at least 25 wagons. 240 tons of PPO and 1.6 tons of Bis-MSB are foreseen for a delivery in a single or relatively few batches.

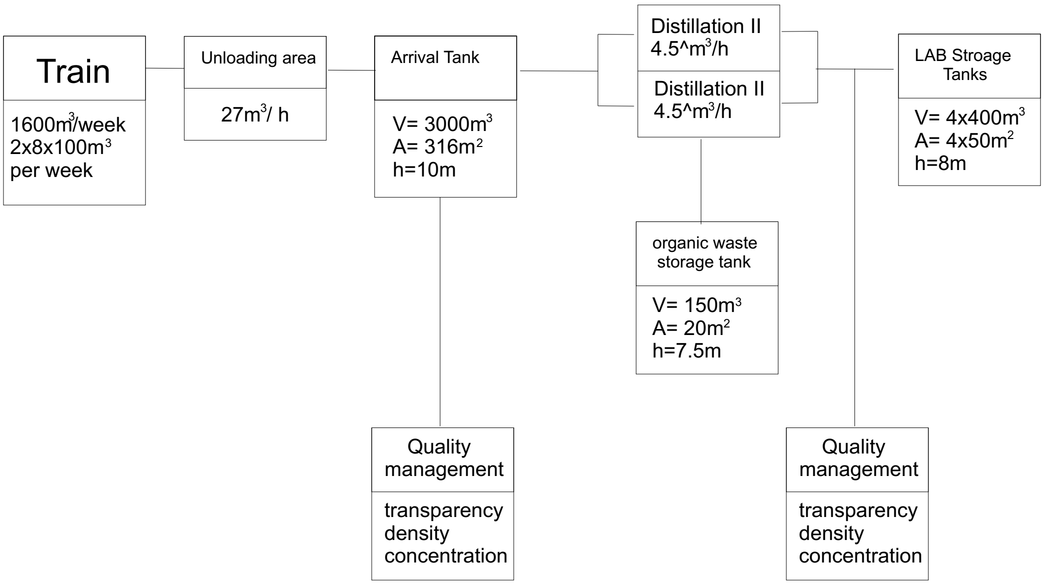

***Figure 6-1:** Layout of the LAB processing line.*

The **LAB processing line** is depicted in figure 6-1: The unloading area contains transfer system from the train wagons to an arrival tank of sufficiently large dimension to buffer the deliveries of two whole weeks (3000 m^3). Relying on a single pipeline of 3'' diameter, unloading of a train could be achieved in 30 h. From the arrival tank, the LAB is forwarded to two distillation plants, each able to purify 5 m^3 per hour in a one-stage distillation column. (This is about five times the size of the Borexino distillation plant.). The approach based on more than one plant was chosen to allow for a continuation of the liquid processing in case of a failure in one of the plants. From there, the purified liquid goes on to an array of several small storage tanks (at least), each holding 400 m^3 which corresponds to the output of one distillation plant during half a week. In this way it is assured that a batch polluted due to failure of one distillation plant does not contaminate the others batches. The purity of the LAB before and after distillation will be determined by measuring its optical transparency, most likely in an online system. In addition, a relatively large tank of about 150 m^3 is necessary to hold the liquid wasted during distillation.

The **master solution production line** is shown in figure 6-2. Its purpose is to mix a small amount of LAB (about 5% of the total liquid) with the solutes PPO and Bis-MSB to generate a highly concentrated master solution (MS), featuring 75 g/l PPO and 1g/l Bis-MSB. The experience of Borexino suggests that the solutes are carrying most of the radioactive contaminants. Therefore, special care will be given to the MS purification.
The mixing unit, capable to process 40m^3 of LAB per semi-weekly delivery, takes the LAB directly from the arrival tank of the LAB line. In addition, a storage volume for PPO and Bis-MSB is needed which are both in powdery form prior to dissolution. Typically, such a unit consists of a tank containing the LAB with a rotor, the powder is added from above. Next in the line a storage tank for the MS large enough to hold the production of two weeks (150 m^3). The MS is than purified by nitrogen purging and either water extraction (mixing of water and scintillator removes polar impurities) or three-step distillation (LAB, PPO and Bis-MSB are extracted at different temperatures), or a combination of both. As the whole line, the purification plant must be large enough to process 80 m^3 a week. At the end of the line, an array of storage

tanks large enough to hold the line output of about 4 weeks is required. Quality controls are necessary after the mixing and after distillation. In addition to transparency, the density of the liquid and thereby the concentrations of PPO and Bis-MSB have to be determined to assure to allow for uniformity of the MS and the later scintillator and to assure that none of the purification steps is removing one of the materials disproportionally.

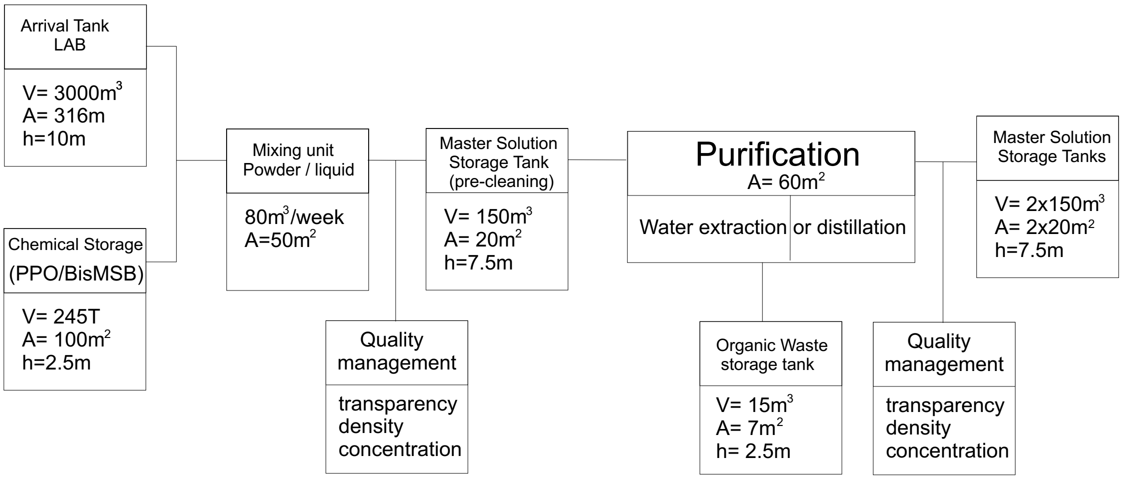

Figure 6-2: *Layout of the master solution production line.*

Last to both lines is the **scintillator mixing unit** in which pure LAB and MS are mixed at a ratio of 24:1. Its capacity must be at least 160 m^3 per week. The unit is followed by another stage of quality management. After this, the ready-made scintillator is fed into the trunk line system (TLS, figure 6-4 and L6.3).

L6.2 Surface systems: Water and gas

The water necessary for the pre-filling of the ID, the filling of the OD volume and (if necessary) for water extraction for MS purification will be taken from the Pyhäjärvi lake. The aim is to pre-fill the detector within half a year. Assuming the concrete tank is a stand-alone, this needs a system capacity of about 320 m^3 per week. If both inner and outer volume have to be filled at the same time, the capacity has to be adjusted.

The **water processing line** is depicted in figure 6-3: Starting from a pumping station that takes the water in from the lake, the water is under-going four types of purification: Filtering (in the line to the pumps), reverse osmosis to remove large molecules and ions, deionization, and an anti-biological treatment (e.g. by UV irradiation). At the end of the line, a relatively large storage tank is needed. From there, water is fed into the trunk line and to the other surface systems for purposes of cleaning and purification.

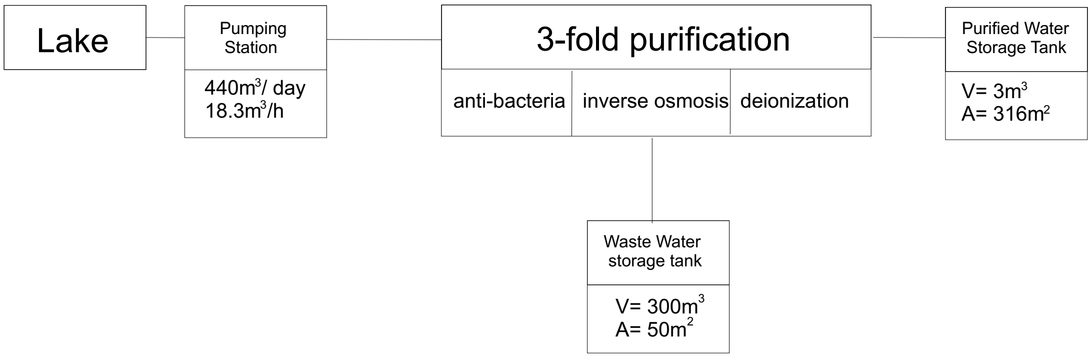

Figure 6-3: Layout of the water processing line.

Nitrogen is used to shield the liquids from ambient air or to purify the liquids from oxygen or radioactive noble gases. It will be used to pre-fill tanks before the liquids arrive, to create gas blankets on top of filled tanks, and to purge liquids by introducing it at the tank bottom. Therefore, all tanks have to be connected to the nitrogen supply.

In order to meet the large demand using only a limited amount of space for the storage of the gas, liquid nitrogen (LN) storage tanks will be used. The supply will be located on the surface. It might be necessary to install a system for LN cleaning on-site in order to remove small traces of radioactive noble gases in the supply itself. Such techniques have been thoroughly tested in Borexino and work highly efficient. The nitrogen will be distributed to the liquid handling systems by a high-pressure (HPN) system at a pressure of 4 bar. A corresponding line is part of the TLS. Locally, low-pressure (LPN) systems will be needed.

L6.3 Trunk Line System (TLS)

The TLS connects the surface installations to the detector cavern below. It has to transport scintillator, water and HPN from the surface to and from the cavern.

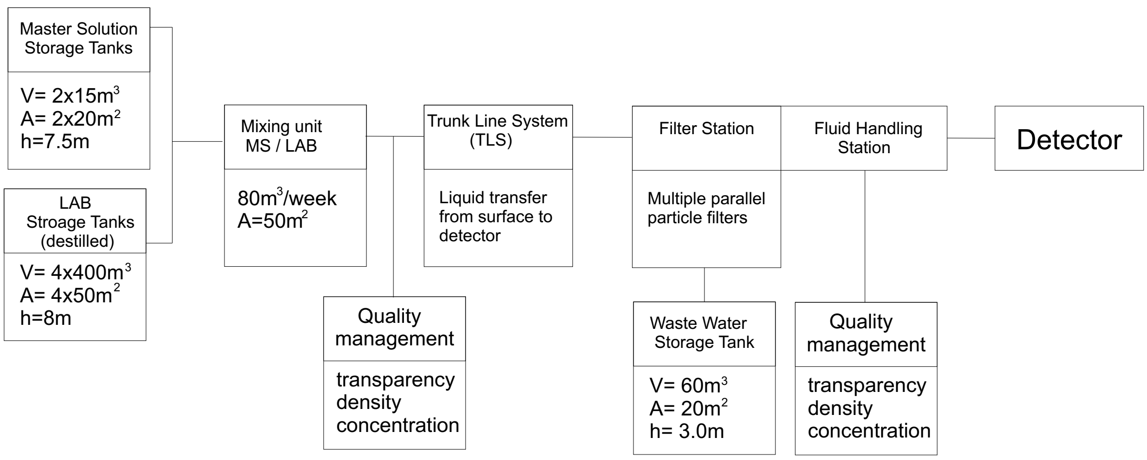

Figure 6-4: Scintillator prepration, Trunk line system and fluid handling.

The default design for the **scintillator lines** are stainless steel pipelines. The system must be able both to fill and empty the detector, the latter being a hard task due to

the large height difference that has to be covered. For the downward line, regular intermediate stations will be needed to reduce the drop height of liquid. Moreover, it must be possible to prevent leakage of the scintillator to the outside or (more likely) of air to the inside in all parts of the system even after installation, suggesting that the line should be accessible over its full length. The best solution might be to install the pipelines along the spiral road ramp of the mine.
A large advantage of a system featuring both a downward and an upward line is the possibility to circulate the liquid in order to clean the inner surfaces of the pipes at the beginning of the filling or also latter on if scintillator operations should become necessary, e.g. a re-purification of the scintillator as it has been done several times now in Borexino. There, the single-line system led to the need to pour contaminated scintillator into the detector as the lines could not be emptied otherwise.

Also the **water line** must be able to transport the water both downward and upward. In this case, it might be done in a single line, while two lines are clearly preferable. The material of choice is again stainless steel. However, even plastic hoses might be sufficient if the inner surfaces can be cleaned and there occurs no introduction of the hose material into the water. Again, prevention of leakage is an important issue.

For the **nitrogen line**, a single pressure-tight system will be sufficient. The default solution is stainless steel piping.

L6.4 Detector Filling and Operation System (DFOS)

The main system in the detector cavern will be the DFOS. Its task is the filling of both detector volumes. However, it should also have from the beginning the possibility to extract the liquids from the detector. This will be necessary primarily for the water pre-filling but might be also needed for the scintillator. While the DFOS has to be able to handle large amount of liquids streaming through it, it is expected to be less complex than the one of the Double-Chooz experiment as only two (and not four) volumes have to be filled separately, and differences in filling level will only play a minor role.

The liquids arriving from the TLS are considered to be clean. Nevertheless, filters will be installed and quality control will be necessary after the passage through the mine. Only minor liquid tanks are foreseen at this level, storage vessels are located at surface. It has been argued that underground storage would be favorable due to the production of cosmogenic nuclides (mostly ^{7}Be from the carbon of the scintillator) on surface. However, ^{7}Be is with a half-life of 53 days the most long-lived isotope playing a role for neutrino detection. This is still short against the overall operation time of LENA. Moreover, distillation has been found to remove ^{7}Be very efficiently in Borexino, were no contamination was observed.

Both for ID and OD, it should be possible to add liquids not only from the top but also from the bottom in order to control were liquid of different temperature, concentration and/or contaminations enters or leaves the detector. In case of the water, also intermediate stages might offer an advantage. By adding cold or warm water at different levels of the OD, convection inside the ID can be prevented or stimulated.

L7 DETECTOR INSTALLATION AND FILLING

After construction of the tank, the installation of the detector instrumentation and the filling with water and scintillator are the final steps before the start of detector operation. In the following, a first draft of a procedure involving both steps will be given. For sure, a lot more discussion is needed. For the moment, mounting of OD PMTs and of the top muon veto are neglected.

The envisaged time for these tasks is 2 years, the first year devoted to water filling and OM installation, the second to scintillator filling. The PSS is already constructed at the beginning of this period. Both tank steel liner and PSS have to be cleaned before, and all welding joints have been passivated (if necessary).

The **OM installation** is performed from a floating platform. After mounting the OMs at the bottom of the tank to the PSS, water is filled into the tank until these OMs are covered. Then the platform is lowered to the water surface by the crane fastened to the cavern dome. Following this, arrays of OMs (either 2x2 or larger) are lowered with the same crane to the platform. These arrays have been mounted before, either in the laboratory or outside and brought down by truck or lift. As these modules will be rather heavy (4 OMs already account for 120 kg), smaller cranes or other load-carrying devices will be necessary to move the arrays around and to mount them to the PSS. One can imagine two or three groups working in unison at different places at the platform perimeter. Following the montage, the necessary cabling is lowered and connected to the OMs. After a full ring of OM arrays has been mounted, new water is poured inside the ID, elevating the platform to the next level of montage. Assuming arrays of 4 PMTs, a total of 7500 arrays has to be mounted, which amounts to about 30 per day if one assumes an overall installation time of 50 x 5 days. If three teams are working in parallel, each has to mount 10 modules per day. Larger modules (e.g. 4x4) would reduce this number considerably

The **scintillator filling** is done from the top, as the scintillator will be floating atop the water body below. During filling, it is of course necessary to drain the water from the bottom. Assuming a stand-alone tank, this water can be directly used to fill the OD. Otherwise, it must be brought back up to the surface or disposed directly underground. In any case, it has to be filtered by a charcoal filter that should effectively reduce the low amount of scintillator going into solution in the water (typically on the level of 10^{-6}).
The scintillator will be continuously prepared above ground. The capacities of all plants are chosen to fulfill this task in one year. They are about a factor 10 larger than the infrastructure currently used in Borexino. Moreover, tank dimensions are large enough to buffer delays in production or purification of about 2 weeks, in order to allow for a smooth running of the system. While normal liquid operation assume a 5-day working week, distillation plants will be run continuously. Cooling and reheating of the columns would consume a lot of time and energy. In full operation, one assumes a constant current of liquid running down the TLS (being slowed done by intermediate stages) and entering directly the detector. This continuous-flow mode has been successfully practiced in long periods of the Borexino and Double-Chooz filling campaigns. To a large extent, no special expertise will be needed for the filling crews. However, at least one experienced shifter will be needed to supervise the work at all times in order to react to unforeseen problems.

L8 DETECTOR OPERATION

L8.1 Surface installations for liquid handling

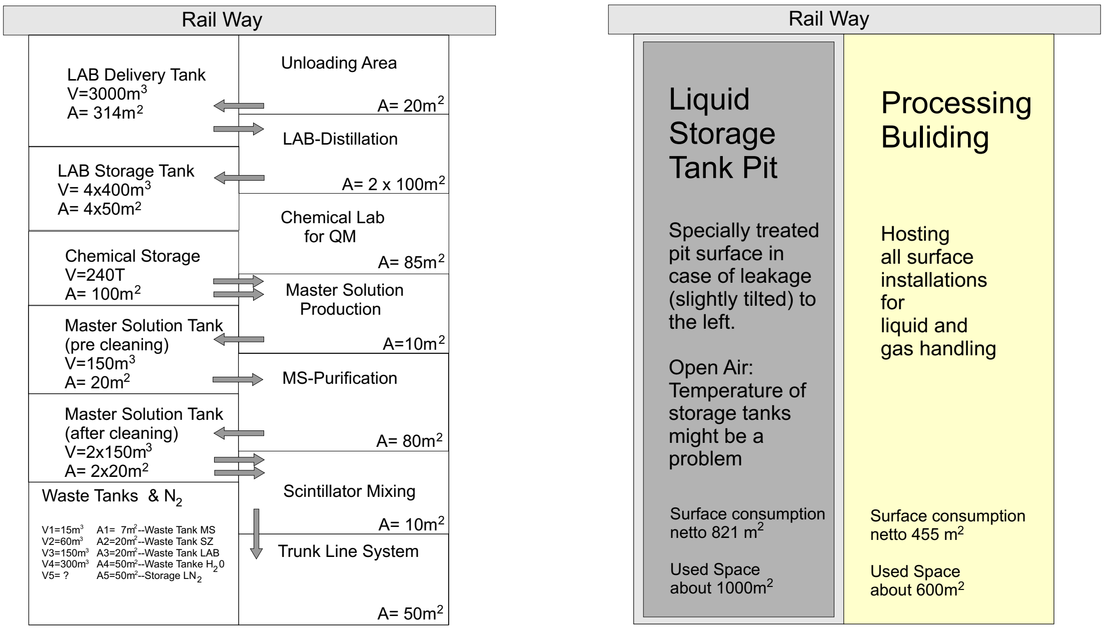

Figure 8-1: *Layout of the surface liquid handling systems and areas.*

The systems for liquid handling above ground should be directly adjacent to the existing railway on the mine area. Based on the capacity of the system and the necessary tank dimensions, we estimate that the needed area is about 1600 m^2. While storage tanks will be under free sky but on an inclined leak-tight platform to minimize the risk of spillage, most liquid processing facilities should be installed inside a building. A possible layout is shown in figure 8-1.

Storage of the liquids outside might cause a problem in winter when the temperatures drops for a longer time below 50 degree in the case of scintillator, or below 0 for the water plants. Therefore, some kind of heating must be included at least for the water processing line. Also, some temperature control might be needed before adding scintillator and water to the 23 °C environment of the detector cavern (probably along the TLS).

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L8.2 Operation room areas

Room types
- Control and electronic room
- Control room for liquid and gas handling
- Clean room, to be free of dust (class 1000) and to be used to assemble and clean all detector components and being equipped with an air flow system (top-down direction).
- Low background laboratory
- Offices, seminar rooms, laboratories, workshop and technical rooms

- Storage area
- Liquid nitrogen plant
- Water station

Room locations
- Control and electronic room: underground, as close as possible to the detector, preferably on top of the detector
- Control room for liquid and gas handling: underground, liquid but not more than approx. 50 m
- Clean room: underground, to be on top of the detector
- Low background laboratory: underground, could be farther away from the detector, but not more than approx. 100 m as the control room has to serve for the detector as well as the installations in this room.

- Offices, seminar rooms, laboratories, workshop and technical rooms: on surface
- Storage area: on surface
- Liquid nitrogen plant: on surface
- Water station: on surface

Size demands of the rooms
- Control and electronic room: 200 m^2 and 600 m^3
- Control room for liquid and gas handling: 200 m^2 and 600 m^3
- Clean room: 500 m^2 and 1 500 m^3, considered to be enough for any necessary HEVAC-equipment
- Low background laboratory: 100 m^2 and 1 000 m^3
-
- Offices, seminar rooms, laboratories, workshop and technical rooms: at
- least 1 000 m^2
- Storage area: 1 000 m^2 and 6 000 m^3
- Liquid nitrogen plant: 100 m^2 and 300 m^3
- Water station: 200 m^2 and 1 600 m^3

L8.3 Number of personnel working underground

Maximum 10 people working underground at the same time, usually 3-5 people

L8.4 Technical connections between tank and surface

Passenger lift
- for 3-5 people

Communication
- Telephone, GPS signal, internet and computer connection between data acquisition system (underground) and data analysis computing system (surface).

Electricity
- Own power generator. Power of 100 kW for the instrumentation and a second power line for pumping, ventilation, light, cooling and cleaning.

Pipes

- For Nitrogen: 1 x ½ inch. Liquid nitrogen plant would be placed on surface while just gas will be transported through the pipeline.
- For liquid organic scintillator filling: 4 x 3 inch
- For water: 4 x 3 inch

Filling speed / pumping capacity

- $20 m^3/h$