Some of the PMTs are dead by short circuit or some other unknown response. The time variation in the number of dead PMTs is shown figure 3.14. The fraction of the dead PMTs is about 1.4%.

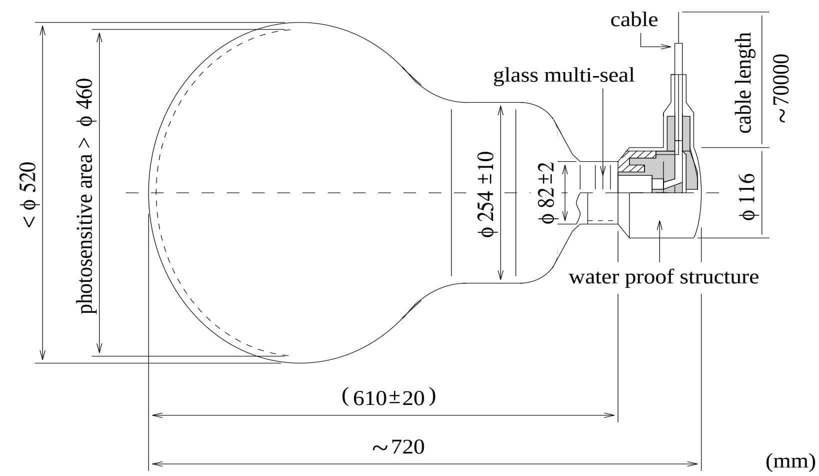

Figure 3.10: Schematic view of a 50 cm photomultipiler tube (HAMAMATSU R3600-05).

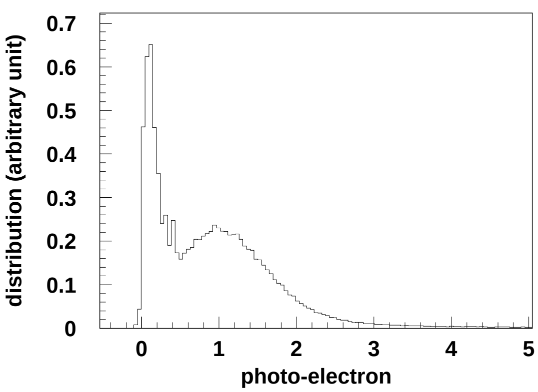

Figure 3.11: The single p.e. distribution from 50 m PMTs. There is a clear peak around 1 p.e.. A spike near the lowest region is caused by photo-electron that miss the first dynode.

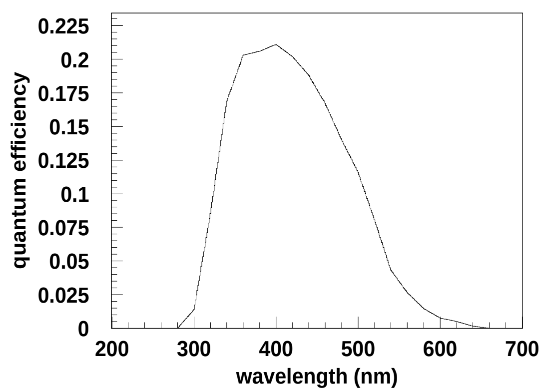

Figure 3.12: The quantum efficiency of the PMTs and the relative Čerenkov spectrum as a function of light wavelength.

Figure 3.15 shows the time variation of high and low energy trigger rate from the beginning of SK-I in ID detector. The right plot is high energy trigger rate and the left plot is low energy trigger rate.

3.4 The water purification system

In purities in the SK water can cause strong attenuation and scattering of Čerenkov light. Moreover, if they are radioactive, like ^{222}Rn and ^{220}Rn, they could become a possible source of background to the solar neutrino events, because the β-decay of their daughter nucleus causes a

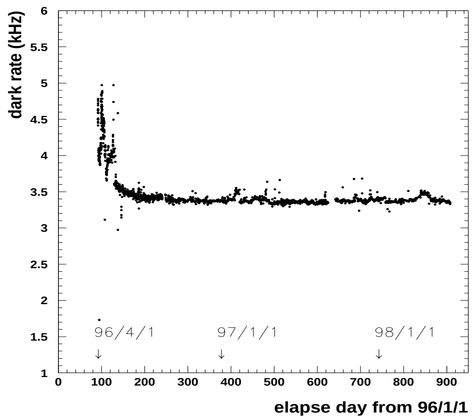

Figure 3.13: The time variation of dark rate from the beginning of SK.

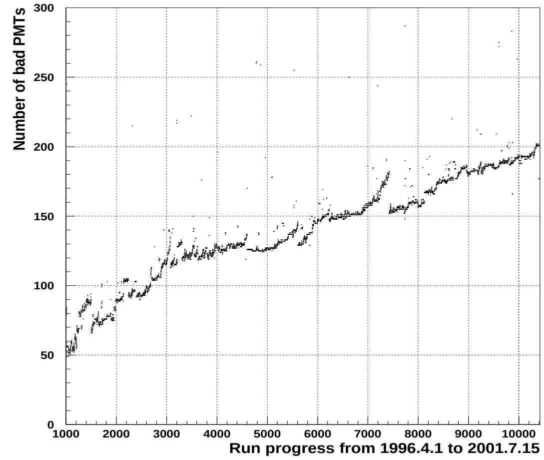

Figure 3.14: The time variation of the number of dead PMTs from the beginning of SK.

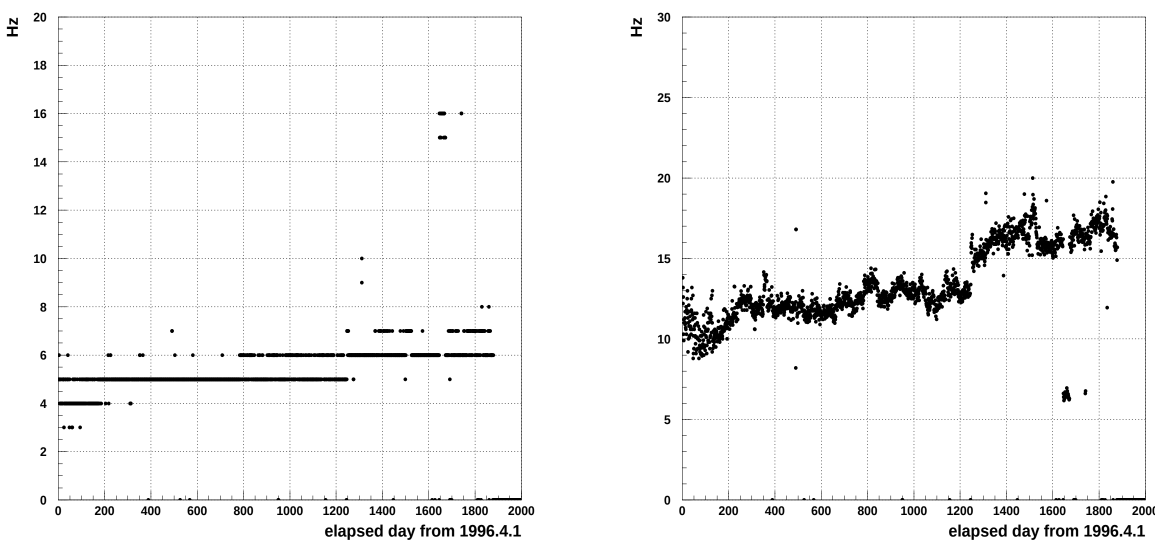

Figure 3.15: The time variation of high and low energy trigger rate from the beginning of SK.

similar event as solar neutrino event which means $\nu_e - e$ elastic scattering. The decay chain of ^{222}Rn is shown in figure 3.20. None of the electrons or γ rays from the decay chain have energy above threshold for this analysis 4.5 MeV. However, because of finite energy resolution of SK, such low energy electrons are sometimes observed as electrons with energy above 4.5 MeV. So, the purity of the water is essential for solar neutrino observation in SK.

The SK water purification system has been modified and upgraded with Organo Corporation. In this section, the basic components of the system is explained. The details of the modification and upgrading of the water system is explained in chapter 7 in detail.

The source of water in SK is an underground aquifer in the Kamiokande mine. The water purification system makes highly purified water from the mine water. Figure 3.16 is a basic schematic view of the water purification system. The water passes through the following components:

- 1 μm normal filter :
  Remove relatively large particles. Some of Rn also rejected with dust.

- Heat exchanger(HEX) :
  Water pumps increase the water temperature. The heat exchanger decrease the temperature down to about 12$\sim$13°C to inhibit bacterial growth and to suppress the water convection in the SK tank.

- Ion exchanger(IEX) :
  Removes metal ion ($Fe^{2+}, Ni^{2+}, Co^{2+}$) impurities in the water. It can also remove ^{218}Po which is a daughter nucleus as a result of the decay of ^{222}Rn and easily ionize. The water resistance is best indication of the concentration of the ion in the water. If no ion is in the water, the water resistance will be expected 18.2 MΩ. In the SK water, the water resistance is 17.9$\sim$18.2 MΩ.

- UV sterizer(UV) :
  To kill bacteria. The documentation states the number of bacteria can be reduced to less than $10^3 \sim 10^4$/100ml.

- Rn-less-air dissolving system :
  Dissolve Rn less air in water to improve the Rn removal efficiency of the vacuum de-gasifier.

- Reverse Osmosis filters (RO) :
  Reverse osmosis by a high performance membrane which removes even organisms on the other of 100 modular weight. The output water is put back into the mine stream. The dissolving oxygen in the out put water is 10.8 μg/L after VD.

- Vacuum De-gasifier (VD) :
  Removes gases (Rn, Oxygen, etc) dissolved in water; about 96% of the dissolved radon gas is removed at this stage.

- Cartridge Polisher (CP) :
  High performance ion exchangers using high quality ion exchanger material.

- Ultra Filter (UF) :
  Removes sub-μm contamination. After the Ultra filter, the water is returned to the detector. The UF removes 10% of the water passed through. That water is recirculated through the water purification system again via the following equipment, which is shown by the dashed line in the figure.

- Membrane Degasifier (MD) :
  A membrane degasifier (MD) also removes radon dissolved in water. It is made of 30 hollow fiber membrane modules and a vacuum pump. A flow rate of 30 L/min of Rn-less

air from the air purification system is supplied to the MD system as purge gas. The typical pressure in the MD system is 2.6 kPa. The typical concentration of dissolved oxygen after the MD is 0.3 mg/L. The measured removal efficiency for radon is about 83%.

Usually, the water purification system supplies the purified water from the bottom of the tank and removes it from the top of the tank. The maximum capacity of the flow rate is 70 ton/hour. usually, the flow rate is 35 ton/hour. A summary of the quality of the purified water is given in table 3.3.

Impurities	Reduction efficiency
^{222}Rn	∼99%
O_2	∼96%
Dust > 0.1μm	∼99.7%
Bacteria	∼100%
Ion	∼99%

Table 3.3: The summary of the quality of the purified water.

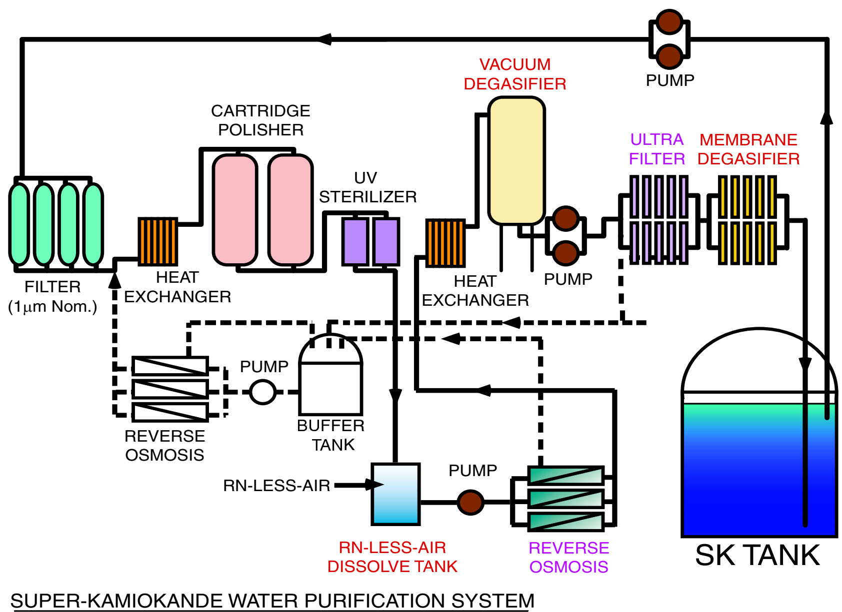

Figure 3.16: A schematic view of the water purification system.

3.5 The air purification system

SK is situated in mine, and the ^{222}Rn concentration in the mine air is 50∼2000 mBq/m^3. Therefore the detector is literally surrounded by the source of Rn gas. The rock dome above the water tank and the hallway are covered with Mineguard polyurethane material, which prevents Rn gas emanation from rocks. Double doors at all entrances also limit the amount of mine air that entries the detector area.

To keep radon levels in the dome area and water purification system below 100 Bq/m^3, fresh air is continuously pumped at approximately 10 m^3/min from outside the mine through an air duct along 1.8 km Atotsu tunnel to the experimental area. This flow rate generates a slight

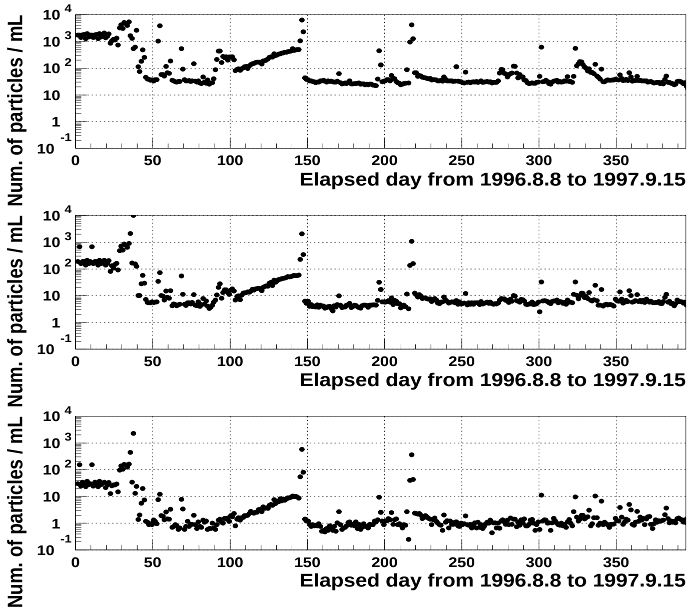

Figure 3.17: The time variation of the number of particles in the purified water. Each figure shows the number of particles of 0.1,0.2, and 0.3 μ size respectively from the top figure.

over-pressure in the SK experimental area, minimizing the entry of ambient mine air. A "Radon hut" in figure 3.7 was constructed near the Atotsu tunnel entrance to house equipment for the dome air system : a 40 hp air pump with 10 m^3/min/15 PSI pump capacity, air dehumidifier, carbon filter tanks, and control electronics. Fresh air from an intake (initially located at the Radon hut) is fed in to the air pump, and is then pumped through a dehumidifier, a carbon filter tank, and finally through a 1.8 km air duct from the Atotsu entrance to the experimental area. An extended intake pipe was installed at a location approximately 25 m above Atotsu tunnel entrance, where radon level concentration was found to remain at 10$\sim$30 Bq/m^3 all year long. Thus the 10 m^3/min fresh air flow from the Radon hut keeps the radon levels in the experimental area at approximately 30$\sim$50 Bq/m^3 throughout the year.

A part of the fresh air from the Radon hut is purified to Rn-less air with the air purification system. Figure 3.18 is a schematic view of the air purification system. It consists of three compressors, a buffer tank, driers, filters, and activated charcoal filters. The components of the air purification system as follows:

- Compressor : Takes in air from outside the mine and pressurizes it 7$\sim$8.5 atom.
- 0.3,0.1,0.01 μm filter : Removes dust in air.
- Air drier : Absorbs moisture since the radon reduction efficiency of the carbon column dependents on the humidity air.
- Carbon column (8 m^3): CO (Activated charcoal) absorbs Rn.
- Active charcoal (50 L) : Active charcoal cooled to -41°C traps the Rn.

Finally, after the air purification system, Rn reduction efficiency is $\sim$99.98% [1]. Figure 3.21 and figure 3.22 are the time variations of the radon concentration in various air.

Rn-less air is mainly supplied to $\sim$60 cm gap between the water surface and the top of the Super-Kamiokande tank. The Rn-less air is kept at a slight overpressure to help prevent ambient radon-laden air from entering the detector. Typical flow rates, dew point, and residual radon concentration are 18 m^3/hour, $\sim$-80(+1 kg/cm^2)°C, and a few mBq/m^3, respectively.

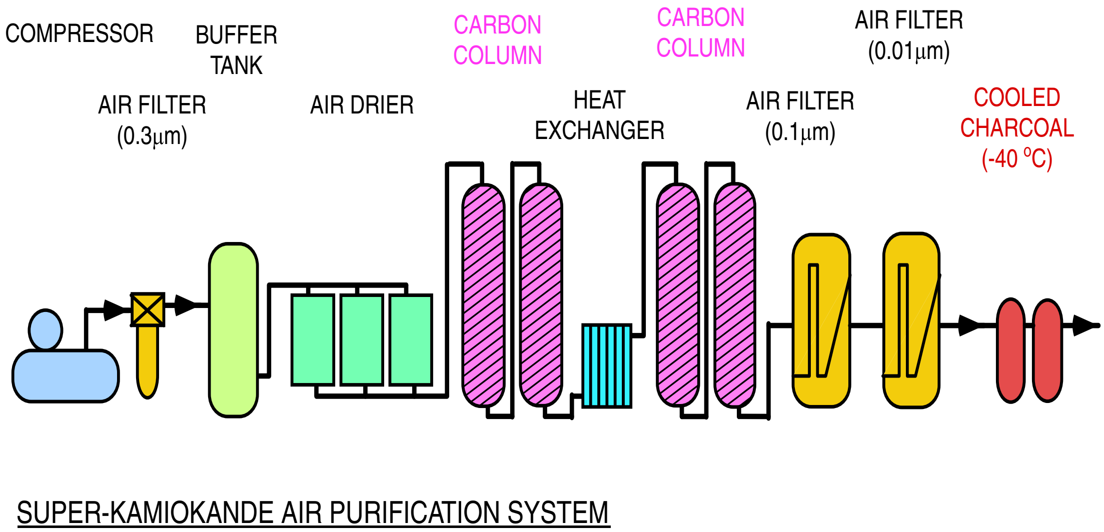

Figure 3.18: A schematic view of the air purification system.

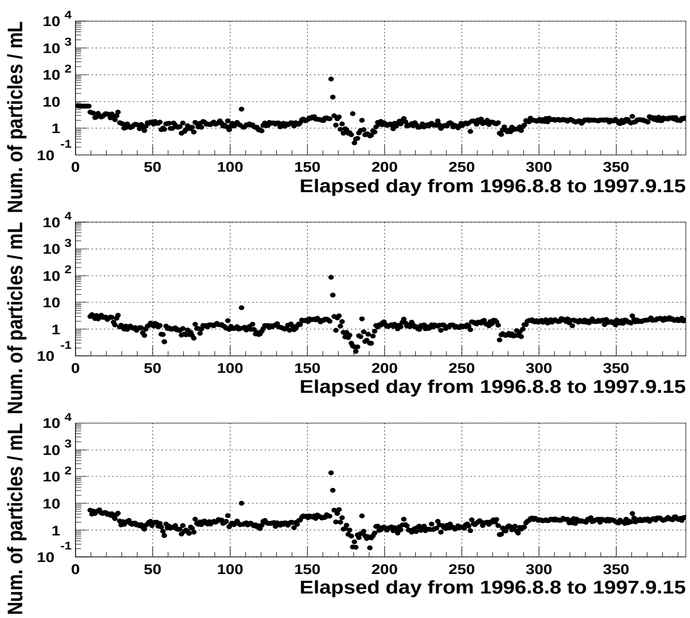

Figure 3.19: The time variation of the number of particles in the purified air. Each figure shows the number of particle of 0.1,0.2, and 0.3 μ size respectively from the top figure.

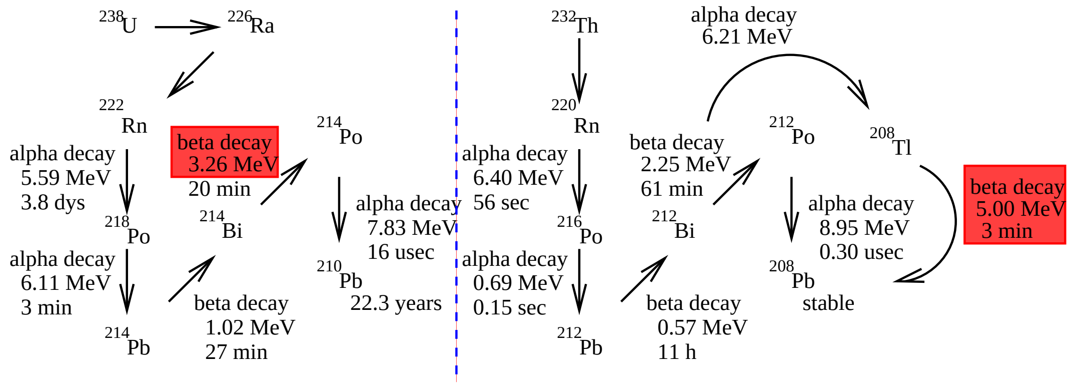

Figure 3.20: Rn decay series. The left side shows Uranium series of Rn. The right side shows Thorium series of Rn.

Table 3.4 is the summary of the radon concentration in the various samples. Table 3.5 is the list of the temperature condition at the various points.

Standard Samples	Rn concentration(Bq/m^3)
Fresh air	$0.5\sim1.0$
Air in the underground	$1.0\times10^3\sim4.0\times10^6$
Water in the underground	$3.0\times10^3\sim4.0\times10^7$
Kamioka Samples	**Rn concentration(Bq/m^3)**
Air in the mine	winter $8.0\times10^1\sim1.0\times10^2$
	summer $6.0\times10^3\sim1.0\times10^4$
Dome air on the tank	$5\times10^1\sim6.0\times10^1$
Purified air after the system	$3.0\times10^{-3}\sim4.0\times10^{-3}$
Purified air in the tank gap	$1.0\times10^{-2}\sim2.0\times10^{-2}$
Purified water after the system	$6.0\times10^{-3}\sim10.0\times10^{-3}$ (before upgrade)
	$<1.0\times10^{-3}$ (after upgrade)
Purified water in the SK tank	$\sim5.0\times10^{-3}$ (before upgrade)
	$1.0\times10^{-3}\sim2.0\times10^{-3}$ (after upgrade)
Return water from the SK tank	$1.0\times10^{-2}\sim1.5\times10^{-2}$ (before upgrade)
	$<2.0\times10^{-3}$ (after upgrade)

Table 3.4: The summary of the Rn concentration. Before and after mean before water system upgrading and after water system upgrading respectively.

3.6 The data acquisition system

3.6.1 The inner detector system

An overview of the data acquisition (DAQ) system is shown in figure 3.23. The signal cables which come from PMTs of ID and OD are extended on the top of the tank, where the electronics systems are located. The ID PMT signal cables (70m) are fed into ATM (Analog Timing Module) modules in a TKO (Tristan-KEK-Online) system. A TKO crate contains a GONG module (GO or NoGO, which distributes control signals as a master module to its slave modules), a SCH module (Super Controller Header, which is a bus-interface module between TKO and VME (Versa Module Europe)), and 20 ATM modules (which digitize analog signals from PMTs for