Chapter 6

Surface Detector Array Design

Water Čerenkov detectors have been selected as the primary detector technology for the Auger ground array. A suitably designed water tank array can adequately address the physics requirements discussed in the previous chapters while proving cost effective and having demonstrated reliability. The reference design presented here calls for an array of 10 m^2 cylindrical detector units in a 1.5 km spaced triangular grid. In the sections which follow several aspects of the design and performance of the basic surface array units are discussed.

For 20 years a 12 km^2 array employing more than 200 water Čerenkov units was operated at Haverah Park in the UK[7] to study extensive air showers. The experience gained during that experiment provides much useful information for the Auger project and, in particular, demonstrates that an array based on this technique can operate for a long period with both high stability and low maintenance.

Alternatives to the water Čerenkov technique were considered for the surface detector array. Sandwich detectors, which consist of two thin particle detecting layers separated by a layer of electromagnetic converter such as lead, steel, or even concrete, have been investigated in detail. Both scintillation counters [173][174][175][176] and resistive plate counters (RPC's)[177] were studied. Although the sandwich detectors were found to have suitable performance for this application, water Čerenkov detectors were selected as the preferred design because of their inherent simplicity, the confidence inspired by their previous experimental success, and because the response of the detector to shower components provides advantages lacking in the sandwich detectors.

The altitude of the selected sites for the Auger Observatory, approximately 1400 m above sea level, puts the surface detector array beneath 880 g/cm^2 of atmosphere, which is near the shower maximum for vertical tracks in the energy range of interest. Because the amount of atmosphere that a shower passes through before reaching the ground increases with zenith angle, most of the showers will be beyond the shower maximum. In this regime the shower particle population can be approximated by an exponential decay in which the electromagnetic component attenuates much more rapidly than the muonic component. As a result, different types of detector produce different effective shower attenuation lengths depending on their relative sensitivities to these two shower components. For the Haverah Park water Čerenkov array the attenuation coefficient for signal density at 600 m from the shower core was found to be 760±40 g/cm^2 while for the Yakutsk scintillator array a value of 500±40 g/cm^2 was derived[7]. (Both sites are very close to sea level.) These results suggest that the water Čerenkov array is less sensitive to atmospheric depth and hence to zenith angle than the scintillator array.

A detector with a large depth to lateral size ratio such as the water Čerenkov detector has another advantage: the projected area in the plane perpendicular to the shower axis falls much more slowly with increasing zenith angle than for a thinner detector. This geometrical effect, combined with the reduction in zenith angle sensitivity discussed in the proceeding paragraph, results in a greater collecting power per detector unit and a more uniform sky view in terms of declination angle. The experimental declination distributions from the Haverah Park and Volcano Ranch arrays which illustrate this point were shown in Figure 3.5.

6.1 The reference design

In its simplest form a water Čerenkov detector can be described as a volume of clear water acting as a Čerenkov radiator viewed by one or more sensitive light detectors. In this application the fact that the water also acts as a massive absorber and converter of the numerous shower gamma rays is very important.

Conceptually, the reference design proposed for the Auger ground array detector unit is a cylindrical volume of water viewed from above by three large (200 mm diameter) PMTs. The interior walls of the tank have a high diffuse reflectivity in the wavelengths of combined maximum Čerenkov light production, water transmissivity, and photocathode sensitivity. The water volume is 1.2 m deep and 3.6 m in diameter for a top surface area of 10 m^2. A conceptual drawing of the complete ground array detector station is shown in Figure 6.1.

6.2 Detector geometry and array spacing

The required detector area is a function of the array grid spacing and shower threshold energy desired. Since each station entails many fixed costs independent of the detector area (electronics, deployment, etc.), and for given array coverage the number of stations required is inversely proportional to the square of the array spacing, it is important that this spacing should be as large as possible. It is a requirement of the experiment that the array should be fully efficient for showers of energy 1×10^{19} eV and above. For a 1.5 km spacing a detector area of 10 m^2 will give adequate performance (see Chapter 5). With a spacing of 1.5 km the number of triggered stations will be large enough (15 to 20 units) at the very highest energies ($\geq 10^{20}$ eV) to allow high quality and unambiguous event reconstruction.

In the following we have assumed the dimensions of the reference design described in

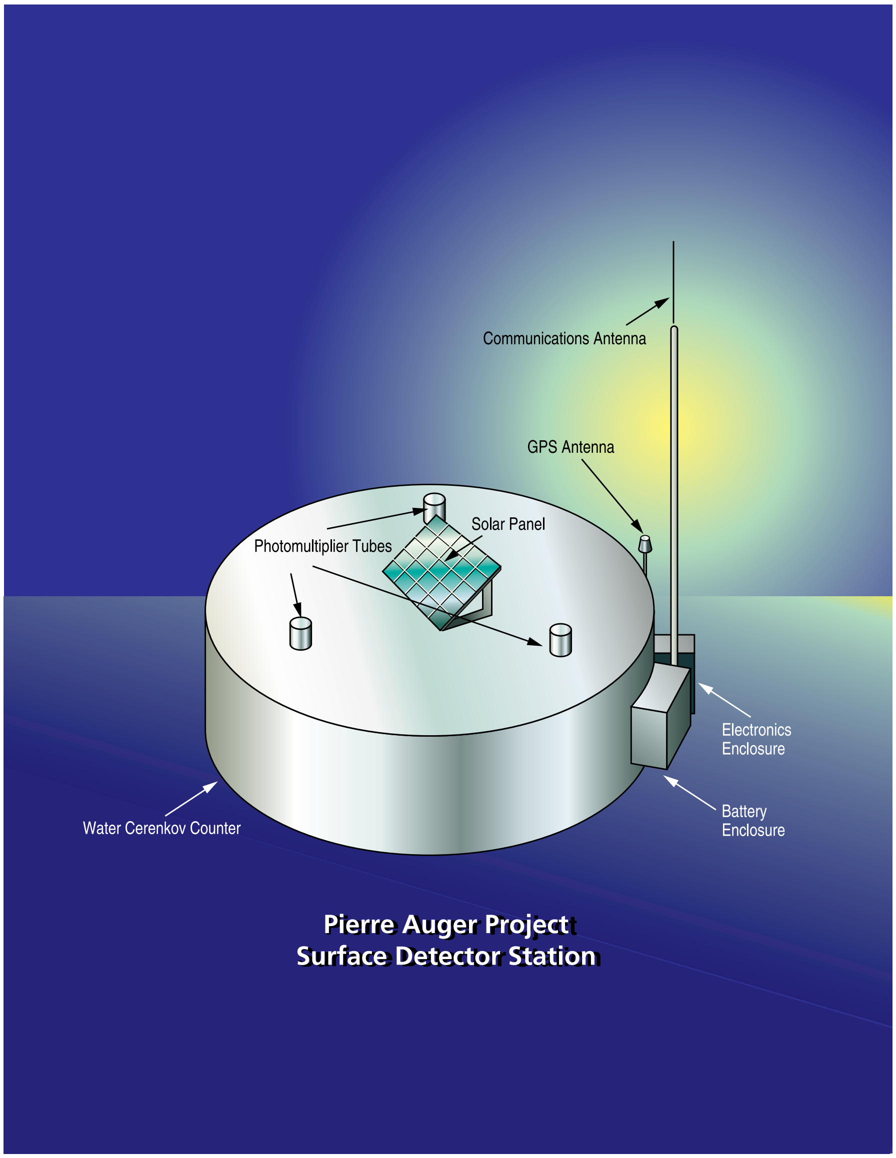

Figure 6.1: Concept for the Auger Project surface detector station.

the previous section. As discussed in Chapter 5, 3.5 radiation lengths of water is sufficient to absorb $\geq 90\%$ of the incident electromagnetic shower particles. A depth of 1.2 m was found to be optimum in some simulation studies[178], although other simulations[179] assuming different tank material properties suggest a slightly greater depth may be preferred to enhance the muonic content information which can be extracted from the differential time/amplitude signal profile.

A single unsegmented tank is also most efficient in terms of the photocathode area required for a given photoelectron yield, i.e., the ratio of photocathode to tank wall area must be maximized because the reflectivity of the tank wall is less than fully efficient. In addition, the cylindrical shape is favored as it is simple and has inherently uniform response to showers of given zenith angle incident from different azimuthal angles.

6.3 PMT positioning and detector uniformity

When reasonable values for the properties of the tank wall reflectivity, water clarity, and PMT performance are inserted in simulations the results indicate that three 200 mm PMTs will be sufficient for the 10 $\mathrm{m}^2 \times 1.2$ m deep reference design detector. When the three PMTs are arranged looking downward from the top surface of the tank a mean photoelectron yield of 50 in response to a vertical through-going muon is easily obtained, which results in acceptable Poisson fluctuations. (When deionized water was used in a prototype tank at Fermilab with a Tyvek lining, yields exceeding 150 photoelectrons per vertical through-going muon were observed.) Very good proportionality between Čerenkov light produced and photoelectron yield is obtained when the PMTs are placed at 120° intervals on a circle of radius 1.2 m (2/3 of the detector radius.) The uniformity of response is shown in the upper part of Figure 6.2, representing a simulation of the reference design detector, and in Figure 6.3, which displays the results of measurements made with a 6.6 $\mathrm{m}^2 \times 1.2$ m deep test tank operated at Fermilab. (The test tank differs from the reference design in that it had a slightly smaller area and had four 200 mm diameter PMTs arranged in a circle with a diameter 2/3 that of the detector.) Measurements with the test tank[180] also demonstrated that the response was proportional to the track length through the detector for inclined tracks.

The uniformity of response would be seriously degraded if Čerenkov radiation were to impinge directly on the photocathode of any of the PMTs as would occur, for example, if the PMTs were mounted at the bottom of the water tank looking up. This is illustrated by the simulation results in Figure 6.2.

There are other ways in which the photocathodes can be directly illuminated with Čerenkov radiation and hence produce an anomalously large signal. The angle of Čerenkov emission in water does not exceed 42° but when a particle passes through the tank with a zenith angle greater than 48° direct illumination is possible. Use of plane-faced PMTs would completely suppress direct illumination up to the maximum 48° angle between particle trajectory and the zenith, and hence would be preferable to the more usual hemispherical design, although the manufacture of plane-faced PMTs may not prove to be cost effective in this large size. Particles with large angles relative to the zenith (our proposed accep-

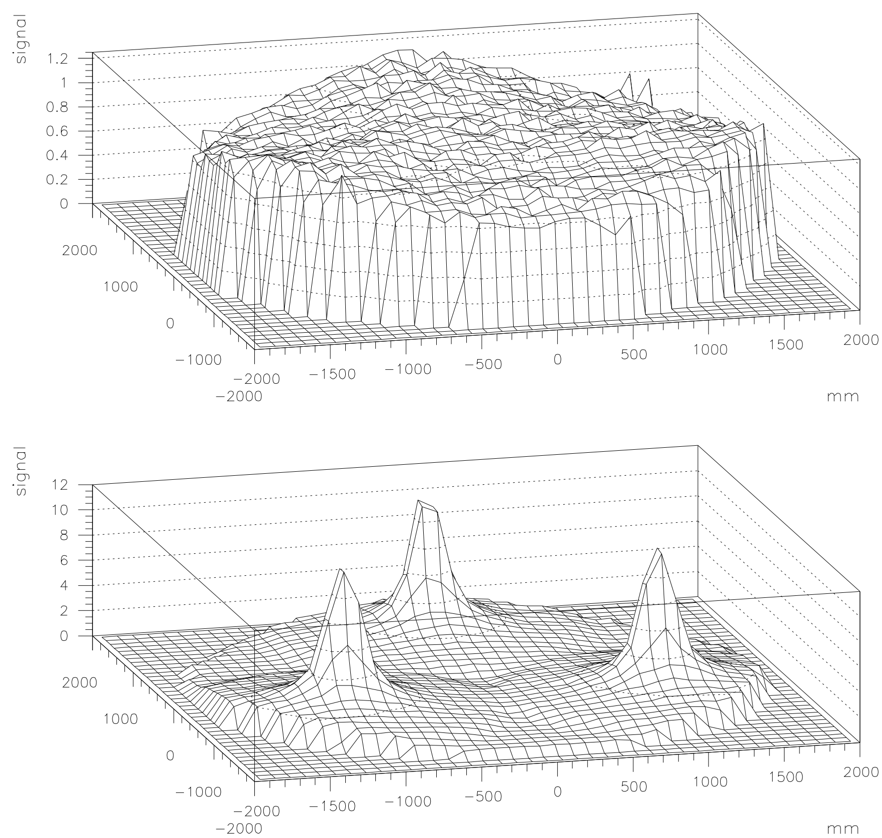

Figure 6.2: Simulated non-proportionality plot for the reference design water Čerenkov detector unit. The upper plot shows response with PMTs placed at the top looking down, and the lower plot is identical with the PMTs at the bottom looking up. Many 1 GeV muons were injected vertically at random positions over the detector top surface, and the resulting photoelectron yields averaged in 10 cm square bins. The vertical axis scales are relative to the overall mean signal in the down looking case.

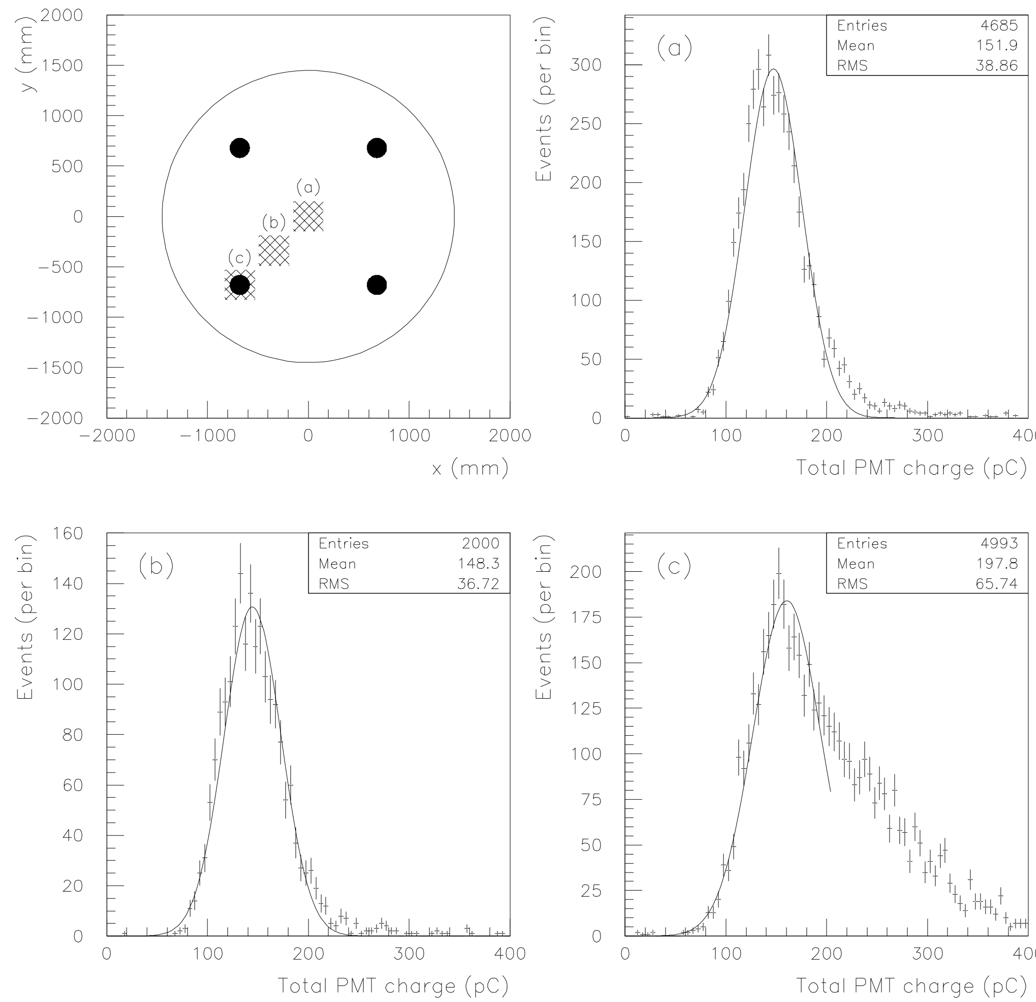

Figure 6.3: Test results from the cylindrical 6.6 $m^2 \times 1.2$ m test water Čerenkov tank. The top left plot is a diagram of the detector top surface showing the positions of the 4 PMTs. Also indicated are the positions of scintillator paddles placed above and below the tank to trigger on through-going muons for the three calibration runs labelled (a), (b), and (c). The charge distributions shown are the analog sum of the signals from all 4 tubes. The high side tail of plot (c) is due to muons which pass through the tube itself.

tance extends to primaries with zenith angles up to 60°) will inevitably produce some direct Čerenkov illumination and hence some nonuniformity will necessarily be tolerated in these cases. In addition, decays of muons which stop in the detector tank volume will produce an unavoidable source of direct photocathode illumination.

Shower particles arrive with a large spread of angles relative to the shower axis although the high energy particles which produce significant Čerenkov radiant track lengths have a much smaller spread of angles. (Shower simulations indicate that particles with energy >10 MeV have median space angle deviation of <20° relative to the shower axis.) Particles do not scatter significantly away from their incident trajectory while passing through the water until the last few centimeters of the track, where little or no Čerenkov radiation is produced.

An increase in the number of photoelectrons would be possible if a water-soluble waveshifter such as 4-methyl umbelliferone[181][182] were added to the water. However, since the emission from a dissolved waveshifting material is isotropic, the "pseudo-direct" photocathode illumination due to a particle whose trajectory passes very close to a PMT would produce an anomalously large number of photoelectrons, leading to a degradation of the proportionality between total radiated Čerenkov light and detected signal.

Čerenkov radiation produced in the glass of the PMT face has not yet been simulated. The effect is minimized by positioning the PMTs looking downward and in direct contact with the water. The effect of muons passing through the PMT is evident in Figure 6.3c.

6.4 Mechanical realization and prototypes

The Haverah Park detectors were made from galvanized iron tanks of rectangular cross section (1.85 m×1.24 m×1.29 m high) filled to a depth of 1.2 m. The walls (sides, top and bottom) were lined with a white diffusing PVC material supplied by ICI under the commercial name "Darvic." The tanks were air tight and were opened only to replace defective photomultiplier tubes (on average once every five years). A single 100 mm diameter plane-faced PMT was positioned in the center of the top surface with the face dipped into the water. Only two tanks were refilled during the entire 20 year run of the experiment, and the loss of performance over this time was less than 10%. There were 225 tank units deployed in clusters of up to 34 m^2 total top surface area. Each cluster was housed in a heated, concrete floored wooden hut.

The Auger Project will require detector units which will withstand a harsh outdoor desert environment for 20 years with very little maintenance. They must withstand high winds, hail, temperature extremes, and casual vandalism. An important step in the Project is to develop a detector which meets these durability requirements as well as the performance requirements discussed earlier at a minimum cost. To this end, several prototype detectors have been built and operated and more are under construction. All of the prototype tanks have performed well as cosmic ray detectors and each one has been used to investigate different practical aspects of hardware.

A carbon steel tank was fabricated, fitted with three Hamamatsu R1408 200 mm PMTs (the type used on all of the prototype tanks discussed here) and operated at Fermilab[183]. The perceived advantages of carbon steel are low cost and ease of fabrication by commercial processes as well as great durability and strength. The greatest challenge is seen as the need to provide a durable protection of the water from contamination by rust, so that the steel of the tank should will not come into contact with the water of the detector. A wave shifting epoxy paint was developed[184] for Fermilab which used the same paint technology normally used for water tanks in domestic and industrial water supplies, a technology which results in a paint lifetime of at least ten years in water tank service (and perhaps much longer life in the service planned here because the paint lasts longest when fully submerged, not when partially exposed to air as in more ordinary water tanks.) This paint increased the photoelectron yield by 70% over ordinary white epoxy paint in tests performed in a small (55 gallon drum) test water Čerenkov detector. (A careful quantitative extrapolation of the results to a tank the size of our reference design has not been performed.) Initial tests in the Fermilab prototype tank were made with the waveshifting paint on the inner surfaces. The photoelectron yield for a through-going muon was approximately 36 when the tank was filled with domestic water treated only by filtration through a one micron absolute filter.

An even more effective reflector of light in the important 300-400 nm wavelength range is Tyvek, a fibrous polyolefin manufactured by Dupont for various industrial and commercial purposes. The diffuse reflectivity was shown in Figure 5.8. When the Fermilab prototype tank was lined with Tyvek the number of photoelectrons per vertical through-going muon increased to about 56. Later tests in which the water was deionized by passing through ion exchange resins produced photoelectron yields exceeding 150. Tyvek is promising as a reflective inner surface on the tank wall or as the inner lining of a bag which would contain the water. A bag might be fabricated from a lamination of Tyvek and polyethylene. In the case of a bag system, the tank structure need only support and protect the bag and other detector components and this may lower the overall cost of the detector because the structure would not be required to be corrosion-free or even to be completely water tight. Perhaps a tank structure based on corrugated, galvanized steel would be cost effective. Test laminations of Tyvek and polyethylene have been made with encouraging results.

A prototype tank has been operating at AGASA[185] which has the same geometry as the reference design described herein and also uses a Tyvek lining. The tank structure in this case consists of a relatively light, nonrigid plastic structure supported by a steel frame, a technology commonly used for water storage systems in Japan. When AGASA triggers on a giant air shower, the signals from the three tank photomultipliers are recorded by a FADC system. Shower reconstructions are available from AGASA for each event so it is possible to compare the prototype tank's data with simulations. A sample event is shown in Figure 6.4. The time dispersed signature of the giant air shower far from the core is clearly visible with correlated late pulses seen in all three PMTs. It is clear that individual particles are being recorded. The data are in good agreement with the predictions of the simulations described in earlier chapters. Studies with this unique prototype arrangement are continuing.

A prototype detector has been fabricated and operated at the Tandar Laboratory in Buenos Aires[186]. The tank for this detector is 0.68 mm thick type 304 stainless steel welded by an automated fusion welding process. The very thin wall was selected to minimize material

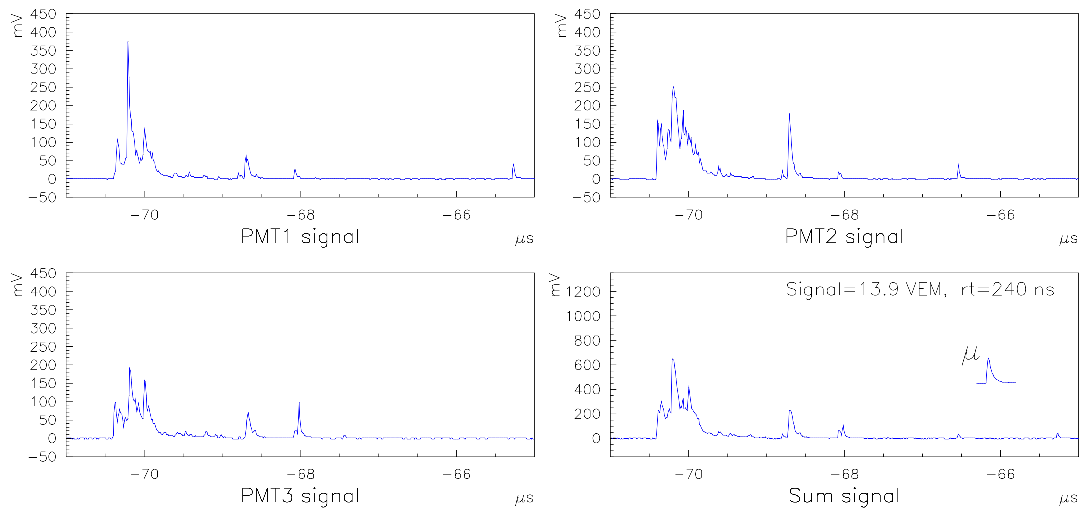

Figure 6.4: An extensive air shower event observed at a core distance of $\approx$ 1 km by the prototype Auger tank at the AGASA array in Japan. The signals from each of the three PMTs are shown, together with their sum. The shape of an average single muon is also shown on the same plot. The integrated shower signal is about 14 vertical equivalent muons.

costs, but otherwise this is a common technology for domestic water tank fabrication. The water depth and PMT positions may be varied to study the effect of these parameters on performance, and measurements have been made with the bare polished stainless interior and with a Tyvek lining. Although rusting was seen at the welds of the early Fermilab 6.6 m^2 stainless steel test tank due to chromium carbide precipitation in the weld zone, no rusting has been observed either on the inside or outside surfaces of the Tandar tank, suggesting the careful temperature control of the automated welding process has eliminated this potential problem. Because of the potential for chloride-induced stress corrosion cracking in the salty desert environment in which the detectors will be installed, further careful alloy selection or a protective finish may be required, or an installation which minimizes exposure to salt may be appropriate. This would not be important, however, if the Tyvek lined bag were to be selected as the water container with the stainless steel tank serving only as a protective support.

Additional prototype tank designs under consideration include two types of polyethylene tank: one type would be made by rotational molding and the other would be made by the extrusion welding process. These technologies are being considered because they are resistant to corrosion, have expected lifetimes without maintenance that are more than adequate for the Auger Project, are very robust (with wall thicknesses of 12-18 mm), and may prove to be cost effective. While either type of polyethylene tank construction could accommodate the Tyvek bag liner discussed above, the type made with the extrusion welding process could be formed of polyethylene plates which already had the Tyvek laminated to the inner surface, eliminating the need for the bag. Studies of these possibilities are continuing in the United States, Brazil, Mexico (especially tank technology) and China (especially Tyvek bag technology).

6.5 Water purification and stability

During the construction of the Auger surface detector arrays about 20000 tons of suitably pure water will be needed at each site. The Haverah Park tanks were filled with untreated water from a nearby borehole in magnesium limestone. That water proved to be adequate. Suitable sources of natural water are available near the Auger Observatory sites and, if required, the local water can be treated with standard industrial processes to suitable purity. (The water used in ordinary power plants is typically no less pure than that required for the Auger Project, and there exists a large industry which can supply that water.) The transport of water to each individual detector site represents a straightforward challenge, probably requiring substantial tanker trucks capable of carrying the 12 ton water load for each detector tank. For the Observatory locations selected in Argentina and the United States, truck access to most of the detector sites during most of the year should not be particularly difficult.

Some preliminary tests of water purification via filtration were conducted at Fermilab using a 55 gallon drum adapted for use as a small water Čerenkov tank. One Hamamatsu R1408 200 mm diameter hemispherical PMT was mounted in the center of the top surface. The tank interior was lined with Tyvek and the tank completely filled with water. A trigger on through-going muons was established with a scintillation counter telescope. The tank was successively filled with distilled water, unfiltered water from the Fermilab domestic water supply, domestic water filtered with a 3 μm absolute filter and domestic water filtered through a 1 μm absolute filter.

Figure 6.5 shows the average time versus amplitude profiles for sets of 100 muon tracks for each grade of water. Repeatability was checked for each fill of water and also for refills of the same type of water. The filtered water results were found to be fully reproducible but some drums of distilled water from the Fermilab stockroom gave better results than others, a result suggestive of contamination in some of the distilled water containers. Two examples are shown, one being little better than the 1 μm filtered water.

The tests conducted earlier with the Fermilab prototype tank showed the number of photoelectrons tripling when the 1 μm filtered water was deionized. This very large increase in performance is not necessarily inconsistent with the results shown in Figure 6.5 because the extrapolation to a full size tank would be expected to show a greater dependence on water clarity due to the increased path length for the average Čerenkov photon. The water in the Tandar Laboratory prototype tank was treated by reverse osmosis (less effective but less expensive than ion exchange resin treatment) and the water in the AGASA prototype tank was untreated domestic water. All prototypes had acceptable performance (defined as at least 50 photoelectrons per vertical through muon), suggesting water purity will not be a critical issue.

The stability of the water, however, is critical for the successful long term operation of the experiment. There are two sources of contaminant to be considered: chemical activity and biological activity. The former is typified by rust, known to have a strong adverse impact on light transmission in the water. This can be controlled by material selection,

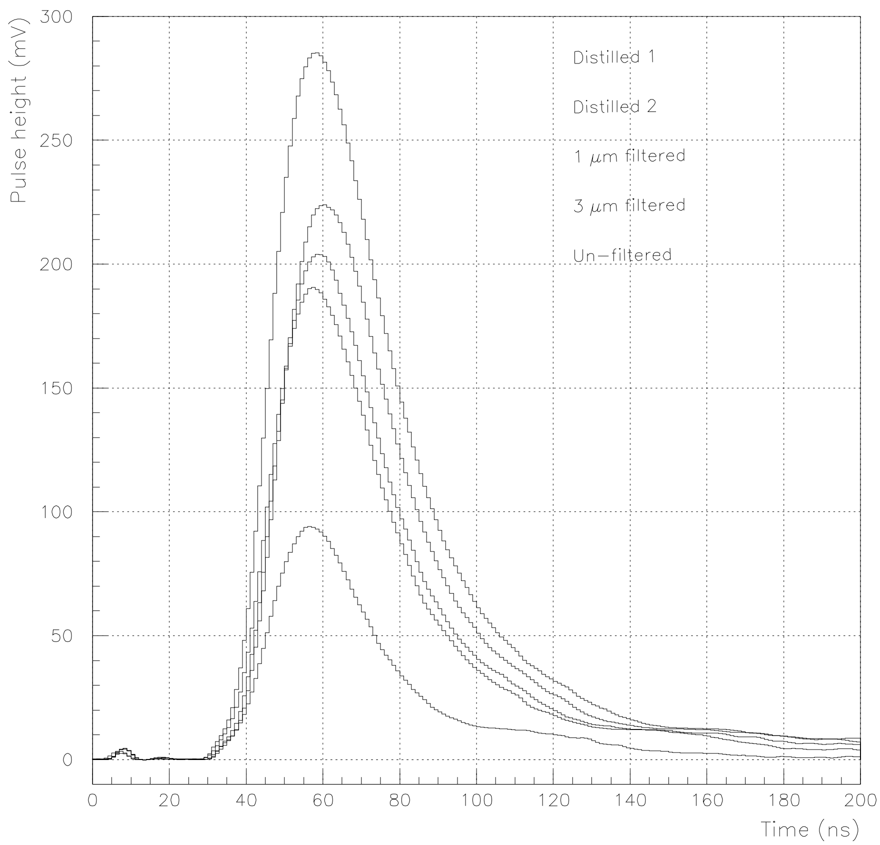

Figure 6.5: Water filtration test results. The time/amplitude profiles shown are each the average of 100 vertically penetrating muon events recorded on a 400 mega sample per second (MSPS) digital oscilloscope. (A cut has been made to remove multiple muon air shower events).

separating any rusting component from the water by using either a plastic barrier (e.g., a Tyvek-polyethylene bag) or a paint barrier (e.g., the epoxy-based paints.)

Biological activity in the water is being studied carefully [186][187], even though Haverah Park took no special precautions, and had no difficulties during the lifetime of that experiment. Bacterial activity can be suppressed by controlling the chemical impurities in the water (essentially depriving the bacteria of nutrients and a hospitable environment), by adding a biocide to the water, by sterilizing the water before installing it in the sealed detector tanks, or by a combination of these techniques. The choice of techniques will depend on the details of the water available at the selected sites and on the results of ongoing studies of bacterial growth in water.