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THE AMANDA PROJECT: DRILLING PRECISE, LARGE-DIAMETER HOLES USING HOT WATER

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Abstract: The Antarctic Muon and Neutrino Detector Array (AMANDA) requires drilling of multiple hot-water holes 50 cm in diameter to depths exceeding 1 km. Strings of photo multiplier tubes 200 m long are then lowered into these holes and allowed to freeze in.

Since these holes must be vertical and parallel, drilling techniques and instrumentation to provide these conditions are discussed. Freeze-back rates in –50°C ice and pressure developed during the freezing process are also considered. Additionally, adaptation of solar concentrators to minimize the use of large quantities of fuel is evaluated.

Finally, the use of mechanical drilling to generate chips that are melted down hole is investigated as a means to speed up the drilling process and make uniform holes.

1. Introduction

The Antarctic Muon and Neutrino Detector Array (AMANDA) is an experiment intended to look for neutrinos using clear glacial ice as the detecting medium. Light-sensitive photo multiplier tubes (PMTs) are lowered in strings 200-m long to a depth of 1100 m at the South Pole. Each PMT has an effective diameter of 30 cm when encased in the bathysphere that protects it from the high pressure of the freezing process. Holes of 40-cm diameter must be drilled to allow for freeze-back that occurs as the detector string is lowered.

Neutrinos are produced by high energy sources in the universe such as supernovas, black holes, and pulsars. Despite their copious numbers, they rarely interact with matter. As a result, large detector arrays are required to see the occasional interaction of a neutrino with a nucleus. SUTTON (1992) discusses neutrinos and their properties. Further discussions can be found in STEINBERGER (1993). The AMANDA detectors will face down to see these ghost-like particles that pass through the earth from the Northern Hemisphere.

Initial tests in a 220-m hole at GISP in 1990 and in 850-m holes at the South Pole Station have proven the concept and survivability of the detectors during freezing in. Since large volumes of detector material are required, the next stage of the project will be to drill nine 1100-m deep holes for the 190-m long strings of 20 PMTs. Eventually a detector of 1 km^3 may be required.

Photomultiplier tubes immersed in clear ice avoid problems of phosphorescing plankton and other light sources that result from biological activity on water. Additionally entanglement resulting from currents is not a problem in ice.

On the negative side, problems associated with drilling large-diameter holes in ice that is –50°C are potentially overwhelming. The holes are requested to be within 1 m of plumb so the timing and direction of events can be determined accurately.

2. Background

Hot-water drilling of access holes in glaciers to depths exceeding 1 km is now common. Freezing rates can now be predicted using finite element computer models (IKEN *et al.*, 1989). Most hot-water drills are used to drill minimum-diameter holes quickly so small instrument packages can be inserted to monitor glacier progress. Drilling holes in excess of 45-cm diameter in ice that is –50°C to the hole bottom requires more heat and a slower drilling rate. The principles remain essentially the same.

In 1987, a drilling hose equipped with wires for instrumentation, a strength member, and insulation was used to drill, instrument, and successfully recover bottom samples from the Crary Ice Rise in Antarctica. Capability for drilling 1-km holes in warm ice was demonstrated (KOCI, 1989; BINDSCHANDLER *et al.*, 1989).

During the 1991 season at South Pole, we resurrected the old Crary Ice Rise drill to prove the concept of drilling large-diameter holes to 1-km depth without requiring a large capital investment. Use of old equipment and hoses subjected to many seasons of ultraviolet radiation caused many problems but accomplished the task. Heat input was limited to 0.5 mW which matched heat losses in the hole. Figure 1 illustrates the results of such a close match. Drilling rate decreases with depth until all the available heat is used in reaming operations. Drilling of the second hole was faster illustrating the benefits of the learning curve. However, drilling ceased at the same level because total heat input once again matched hole losses. The next stage of the drilling project is nine holes to 1100-m depth potentially followed by many more holes.

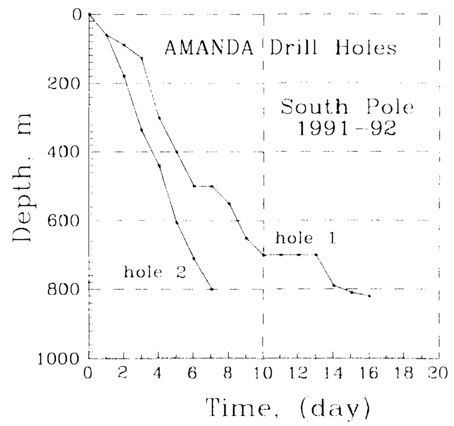

Fig. 1. Drill depth vs. time.

Selection of drilling procedure is governed by many factors. The economics must be weighed against number of holes and how long it takes to drill each hole. While mechanical drilling with reverse air circulation is fast, equipment weight and expense is not justified for a few holes. This may change if the entire 1-km^3 array is desired.

For the present, it appears that hot-water or hot-water/mechanical drilling is the most effective way to drill. Later addition of solar power may prove feasible to provide heat or mechanical energy to drill a large number of holes.

3. Design Requirements

Since the anticipated freeze-back rate was expected to be, and is, 15 cm per day on the diameter, at a hole depth of 1 km the heat loss is 0.5 mW. To preserve a reasonable drilling rate to the hole bottom, heat input of 1 mW was selected to determine system size. From this, hose size, pump size, and heat input become readily apparent. Figure 2 illustrates the system layout.

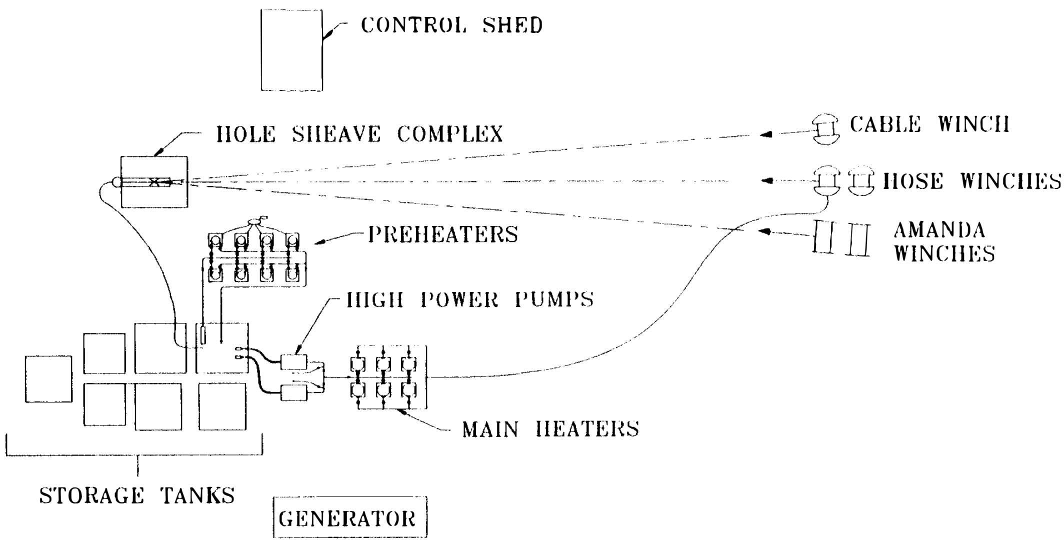

Fig. 2. AMANDA site layout.

This drill system remains like any other drill system designed to work where the firn ice transition is below the surface. At South Pole, the depth of pooling is 40 m which is much shallower than the 115-m ice transition depth. A deep well pump (Grundfos 40S75-25) delivers up to 220 l min^{-1} from the hole to a tank where the water is preheated and water added to make up for phase change (Fig. 3). At this stage the water is also degassed which helps keep the ice clear as it re-freezes. Twin triplex pumps powered by Lister 4 cd diesel engines take water from the tank and pump it through the heaters and 1200 m of hose. Operating pressure is expected to be 50 bars at a flow of 200 l min^{-1}. Water is heated to 90°C by six Whitco Model 75 oil-fired heaters each rated at 150 kW at sea level. Because of altitude the heaters are de-rated to approximately 100 kW each. Preheat is supplied by up to twelve 80 kW (50 kW at altitude) oil-fired heaters bringing total heat input to over 1 mW. Hot water is supplied to the drill through a 3-cm inside diameter thermoplastic hose. Tension and drill rate are controlled using a kevlar reinforced electromechanical cable which also transmits information from the instrument package.

Hole accuracy and mapping, as required to assure scientific data return from every hole, require a complex instrumentation package. A navigation package consists of three axis flux gate magnetometers, inclinometers and rate sensors. Position of the drill relative to the hole wall is monitored using ultrasonic devices (Fig. 4; Zagorodnov *et al.*, 1992). These devices also provide information on hole diameter at two locations different from the hole caliper. Because of this, the melting process can be monitored. It is known that the heat transfer within the hole for large systems is slow. We see water temperatures of

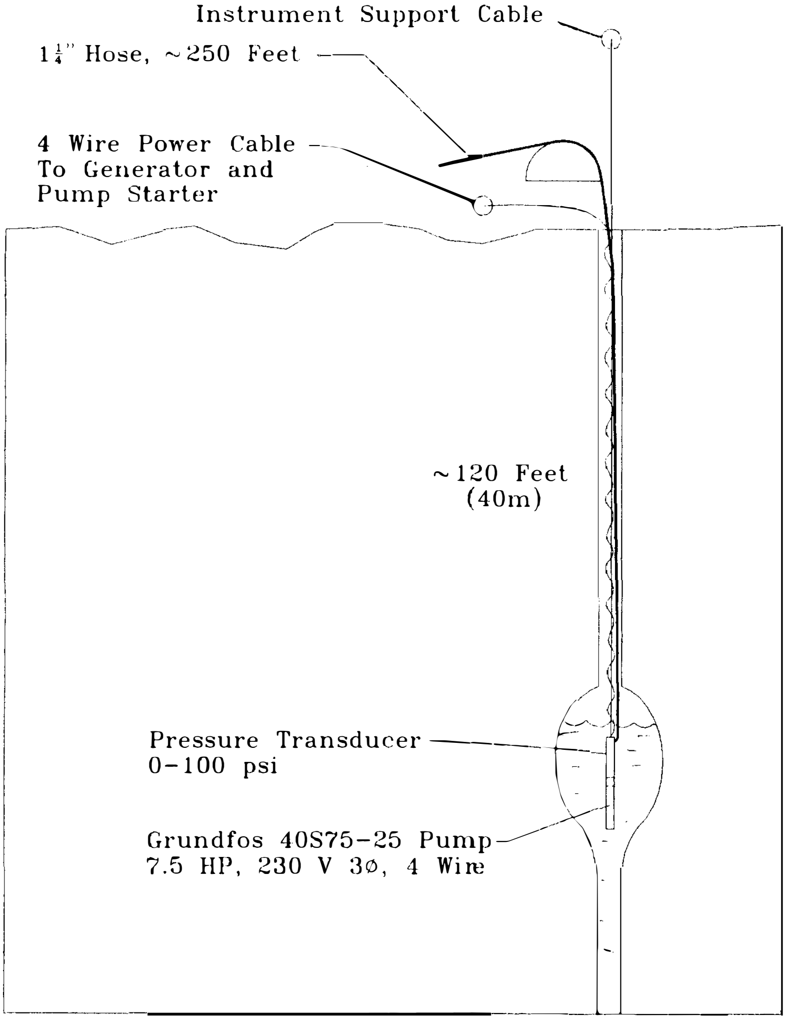

Fig. 3. AMANDA well detail.

10°C 50 m behind the drill nozzle (Fig. 5). Careful monitoring of the melting shape will supply information essential to performing freezing-rate calculations, since we have determined that ideal cylinders do not exist in this process. Information from the drill is combined with process information from the surface in the drill monitoring. Prior to instrument emplacement and reaming, a complete map of the hole can be reviewed to locate problem areas.

We currently expect drilling time to vary between 30 and 50 hours. Drilling can proceed at 0.5 m/min with available heat to provide a hole 40–50 cm in diameter (Fig. 6; Li and Koci, 1993). We did not consider the change in specific heat or conductivity of ice with temperature in making these calculations. Since the heat transfer coefficients are abysmal, melting will continue to a level approximately 50 m behind the drill nozzle. This number is based on well temperatures measured as the drilling proceeded during the 1991–92 season. Because of this, the drill will free itself if flow is maintained through upward circulation of the heated water.

Since the freeze-back rate has been measured at 15 cm day^{-1} on the diameter, 45-cm

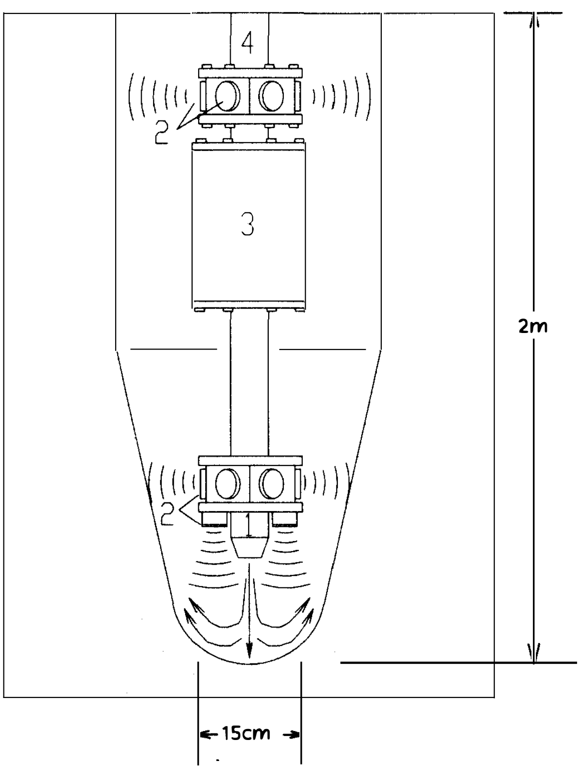

Fig. 4. Hot-water drill with acoustic sensors: 1) Nozzle; 2) Acoustic sensors; 3) Instrumentation package; 4) Hose and cable line.

holes will allow a 24-hour period to lower each instrument package. Later, as more experience is acquired, hole size can be reduced to 40 cm, which will reduce drilling time by 20%.

4. Future Developments

Since the current AMANDA project requires nine or ten holes, a basic hot-water system appears to be the most cost-effective approach.

If more holes are required, a down-hole mud motor driven by the water may be beneficial during reaming operations, since it provides assurance of a minimum hole diameter without shelves. Use of standard under-reaming techniques will be used to minimize drill diameter and chances of sticking the drill. Since the cost of this attachment approaches $50K, it is wise to establish need before proceeding.

A similar adaptation can be used to drive coring drills for warm basal ice, till, or rock (Fig. 7). This problem is addressed by Das and Koci (1993). We have demonstrated the ability of using warm water as a chip transport/melting medium in the University of Alaska test well. A 15-cm core over 1 m in length was retrieved successfully despite the presence of rocks, sand, leaves, cracks in the ice, butyl acetate, and old drill parts. Since then, the well has been cleaned and will be refilled with clean ice.

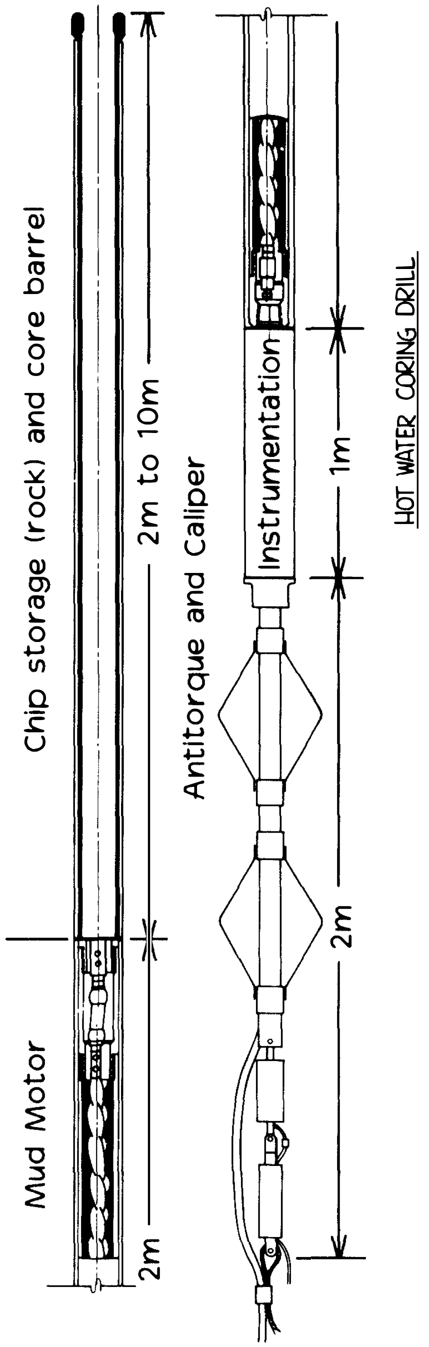

Fig. 5. Cross-section of hot-water coring drill.

5. The Solar Alternative

Since the cost of fuel delivered to South Pole can be estimated to be at least \$4 l^{-1} based on a cost of \$6000 hr^{-1} for C130 time, softer technology must be considered. It makes little sense to use a 1500°C flame to heat water to less than 100°C. Twenty-four-hour sun, clean dry air, and nearly cloudless skies suggest the solar alternative. Direct-beam solar radiation has been measured and is shown by Wills (1988).

Solar collectors may be grouped into concentrating and flat-plate collectors for both

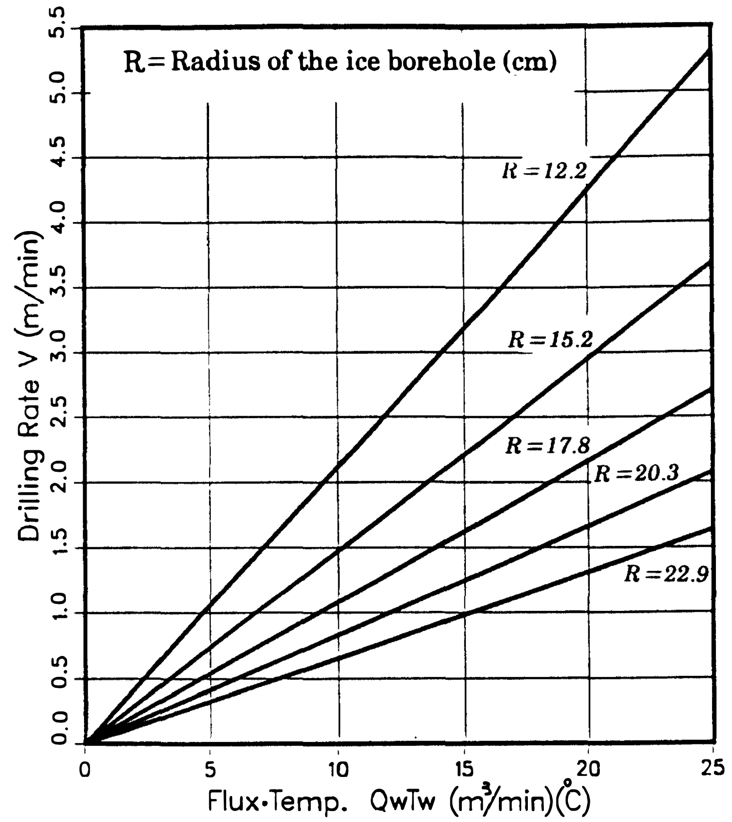

Fig. 6. Graph of flux temperature versus drilling rate.

electricity and heat. While flat-plate collectors work well for generating electricity at altitude, generation of heat is less appealing. Flat-plate heating collectors were developed for the southwest desert in North America or other warm, dry climates. Their efficiency drops as air temperature drops due to back radiation and convective losses. The information is available in any text on solar heating and will not be repeated here.

A more attractive alternative is the concentrating collector. This type of collector concentrates sunlight on a relatively small area, hence does not suffer from the same heat losses as flat-plate collectors despite lower optical transmission efficiencies. In this case, the large temperature differences between storage and operating conditions create thermal expansion and contraction problems that make the use of reflectors inadvisable. A notable exception is the compound parabolic reflector or Winston lens which serves as a light funnel.

Another promising collector is the Freznel lens developed by Entech and 3M Co. Pyron has yet another promising design. At this stage of investigation, other designs may be available that remain unknown to us. Each has advantages and problems that must be overcome. Cost is variable between \$1 watt^{-1} and \$3 watt^{-1} installed heating capacity. Most can supply electricity in addition to heat with efficiencies approaching 20%.

The 1.5 mW system envisioned here will occupy a little over 1 hectare. The problems associated with controlling and tracking such a large array are not trivial, but the potential savings in fuel and pollution as well as the ability to drill many holes once the system is installed cannot be ignored. The electricity available as a by-product amounts to 300 kW,

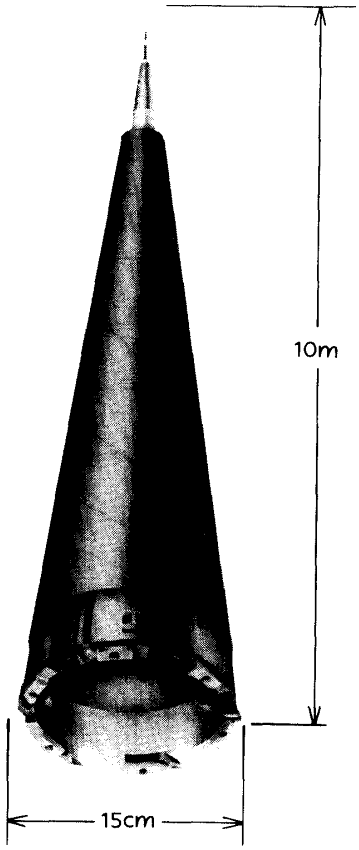

Fig. 7. Conceptual drawing of hot-water mechanical drill.

which is enough to power South Pole Station during the summer months.

Currently we estimate pay-back to be 20 holes or less given our fuel consumption and the cost of delivered fuel to the South Pole. Present plans call for drilling 20 to 50 or more holes, creating the largest neutrino detector array on this planet, possibly 1 km^{-3}.

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