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Wotan: a drill for ice cube

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Abstract: The Antarctic Muon and Neutrino Detection Array (AMANDA) project initially required placing 10-inch spheres in holes 1000 m deep at the South Pole. Drilling began during the '93-'94 field season using a hot-water drill because it was the best method capable of drilling holes that were plumb within 0.1 degrees. This type of drill is also modular allowing for expansion to provide more heat if necessary without constructing an entirely new drill. Discovery of bubbles in the ice at 1000 m required expansion of drilling capability to drill holes 2000 m deep to accommodate 13-inch spheres. We did this by adding more heating and pumping capacity and a larger hose.

The successful AMANDA drilling experiences and the analysis of the data returned from the AMANDA spheres has led to the IceCube project proposal. This project will require drilling 80～60-cm diameter holes to 2400 m. This paper describes the design of a production hot-water drill called Wotan that is capable of drilling 16 such holes per drilling season.

1. A brief history

We began AMANDA drilling in the '91-'92 field season using a drill assembled from parts left from other drilling projects. The drill had insufficient heat input to drill large diameter holes in $-50°C$ ice to 1000 m. As a result, drilling one hole to 800 m required nearly two weeks and 12000 gallons of fuel. Two years later ('93-'94), we returned with a new drill that doubled the heat input from 0.6 MW to 1.2 MW. With this new drill, we drilled four holes to a depth of 1000 m and successfully deploy four strings of Optical Module (OM) spheres. We reduced the drilling time to 70 hours and fuel consumption to 4500 gallons per hole.

No drilling was performed during the 94/95 season. In the '95-'96 season, we returned to South Pole and drilled four holes to depths ranging from 1900 to 2200 m and successfully deployed four strings of OMs. The greater depths were required due to the discovery of bubbles within the ice at depths less than about 1400 m. A depth of 2000 m allowed us to place the entire detector below 1400 m—a depth where we expected the ice to be clear and free of bubbles. At the same time, we went to larger 13-inch OMs, thus requiring larger diameter holes. To accommodate the greater depths and larger diameter holes, we had to nearly double the heat input to avoid unacceptable drilling rates. A $1^1/_2$-inch diameter hose was developed that would be capable of delivering adequate heat, more pumps and heaters were added, and new larger hose reels and winches were developed to handle additional hose and cable. We drilled four holes to depths ranging from 1900 to 2200 m and successfully deployed four strings of OMs. Drilling time varied from 90 to 110 hours per hole and fuel consumption varied from 8500 to 10000 gallons per hole. The time required to drill to 1000 m now required 30 hours and 2500 gallons of fuel, suggesting that a larger drill is more efficient.

The following season, we returned to drill six holes to 1950 m, further reducing drilling times to 75 hours and fuel consumption to about 6700 gallons per hole through procedural changes. In '97–'98, we returned to drill four holes to a depth of 2400 m. In addition, we had to increase the hole diameter to allow extra time needed to deploy 42 OMs between the depths of 1400 and 2400 m.

Predictions from the '95–'96 season proved correct as fuel consumption per hole increased markedly to 13000 gallons per hole while drilling times increased to 150 hours per hole. It became clear that we had started to reach the limit of this drill's depth capacity given the requirement for a 60-cm diameter hole. Figure 1 plots depth *versus* time for this drill, illustrating this fact. With hose lengths exceeding two km, flow was restricted to 60 gallons per minute (gpm) in the bottom 400 m keeping the heat input in that region limited to 1.4 MW, just over the heat loss through the hole wall, requiring extra reaming operations. As a reference, Table 1 lists and compares several parameters for all drills used to date with the addition of projections for an improved drill to be used this coming season and Wotan, the drill to be used for IceCube. Figure 2 demonstrates how drilling time increases with depth for the same set of drills.

We have learned several lessons as a result of our drilling activities:

- We can drill holes plumb within one meter in 2400 m using a hot-water drill that relies only on gravity to keep it going straight.
- Larger drills have higher efficiency because they spend less time in the hole, dissipating heat into the surrounding ice. Additional heat disturbs the surrounding ice more by warming it up, allowing clathrates to come out of solution, forming bubbles.
- We cannot change hose reels when the drill head is near the location of an OM since

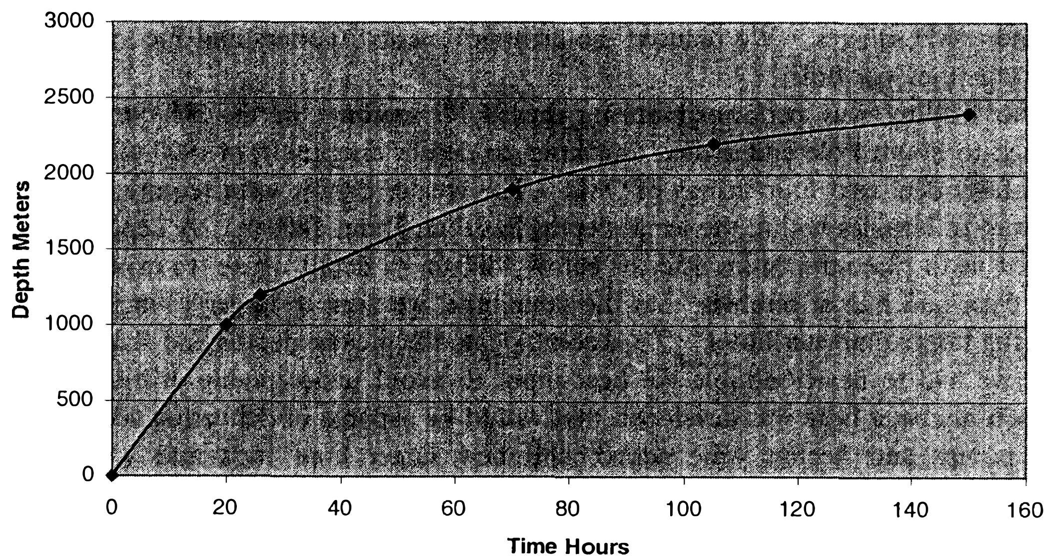

Fig. 1. Drilling time versus depth for drilling 60-cm holes during the '95–'96 season.

Table 1. A comparison of several parameters for all drills used to date, projections for an improved drill to be used this coming season and projections for Wotan.

	91-92	93-94	95-96	96-97	97-98	99-00 Estimates	Woton
Q	0.8 Mw	1.2 Mw	2.0 Mw upper 1000 m	2.2 Mw to 1000 m	2.0 Mw to 1200 m	2.5 Mw to 1400 m	5-6 Mw to 2500 m
			1.6 Mw 1000-1600 m	1.7 Mw to 1500 m	1.6 Mw to 2000 m	1.8 Mw to 2100 m	
			1.4 Mw 1600-1900 m	1.5 Mw to 1900 m	1.4 Mw to 2400 m	1.7 Mw to 2400 m	
			1.3 Mw 1900-2200 m				
Flow	30 gpm	45 gpm	85 gpm to 1000 m	87 gpm to 1000 m	82 gpm to 1200 m	96 gpm to 1400 m	175-200 gpm to 2500 m
			75 gpm 1000-1600 m	77 gpm to 1500 m	70 gpm to 2000 m	80 gpm to 2100 m	
			70 gpm 1600-1900 m	70 gpm to 1900 m	60 gpm to 2400 m	75 gpm to 2400 m	
			64 gpm 1900-2200 m				
Hose	1 in ID	1 1/4 in ID	1 1/2 in ID	1 1/2 in ID	1 1/2 in ID	2 in ID deepest 700 m	2 1/2 in diameter
						1 1/2 in remainder	
Time to depth	10 days to 800 m	70 hours to 1000 m	30 hours to 1000 m	24 hours to 1000 m	30 hours to 1200 m	30 hours to 1400 m	<12 hours to 1000 m
			80 hours to 1900 m	50 hours to 1500 m	80 hours to 2000 m	70 hours to 2100 m	30 hours plus 6 hour retrieval time to 2400 m
			105 hours to 1100 m	67 hours to 1900 m	150 hours to 2400 m	100 hours to 2400 m	
Fuel	4500 gallons	4500 gallons	3000 gallons to 1000 m	2500 gallons to 1000 m	3000 gallons to 1200 m	3000 gallons to 1400 m	7000 gallons to 2400 m
			8000 gallons to 1900 m	6500 gallons to 1900 m	8000 gallons to 2000 m	7000 gallons to 2100 m	
			10000 gallons to 2200 m		13000 gallons to 2400 m	<10000 gallons to 2400 m	
Heaters	6 Whitco model 75	6 Whitco model 75	12 Whitco model 75	12 Whitco model 75	12 Whitco model 75	16 Whitco model 75	24 Whitco model 75 with lager jets
	4 Stinger equivalents	4 Stinger equivalents	Up to 11 Stingers	Up to 11 Stingers	Up to 11 Stingers	Up to 13 Stinger equivalents	Up to 20 Stinger equivalents
Return pump	7.5 hp	7.5 hp	25 hp	25 hp	25 hp	24hp using 2 in hose (300 m)	50hp
							Note: Woton will include heat scavenging and efficient generators
Generator	28 Kw	28 Kw	150 Kw	150 Kw	150 Kw	150 Kw	300 Kw
Hp Pumps	Engine Driven (Gas)	Diesel (2)	Diesel (3)	Diesel (3)	Diesel (3)	Diesel (3)	Electric (3)

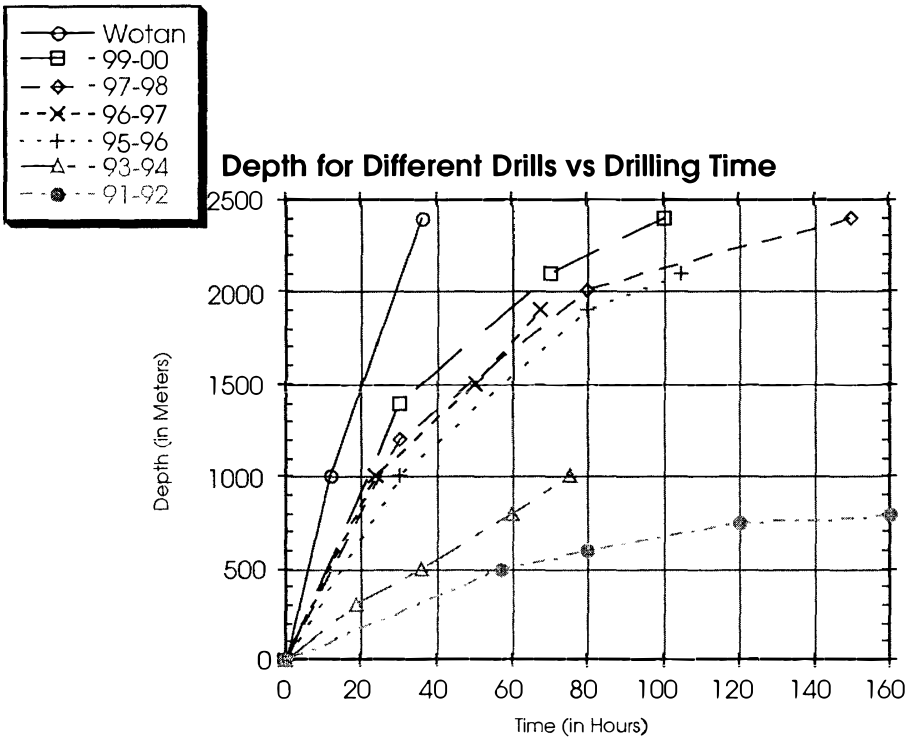

Fig. 2. *Drilling time versus depth for all drills used to date; the rates for Wotan are predictions.*

it causes a significant diameter change that increases the likelihood of an OM failure during freezing in.

- We know that drilling must continue at least 50 m beyond the bottom OM so the hole diameter at the bottom OM can enlarge to its final size. Hole taper in the vicinity of an OM causes uneven stresses during freezing in, which causes OM failures.
- We have to drill the region between 1400 and 2400 m nonstop.

2. Some thermodynamics

We have determined heat loss from the hole by measuring diameter decrease as a function of time. This gives us the volume of ice created, which we can be converted to heat loss by multiplying the volume and the density of the ice times latent heat. Heat loss falls off as depth increases because the ice becomes warmer with increasing depth. Figure 3 is a plot of total heat loss in the hole versus depth (3.6×10^6 BTU per hour is about 1.2 MW).

Since we have a temperature limitation of about 90°C, the boiling point at South Pole, we can only increase the heat output of this drill by increasing the now. Fortunately, as the Manning equation suggests, for a constant pressure, flow increases as the diameter increases raised to the 8/3 power, which is clearly shown in Fig. 4.

We need about 3000 gallons of fuel just to convert the ice in a hole 2400 m deep and 60 cm in diameter to water. All additional heat produced by the drill is lost, which are primarily conductive losses to the hole wall ice. Therefore, losses are directly propor-

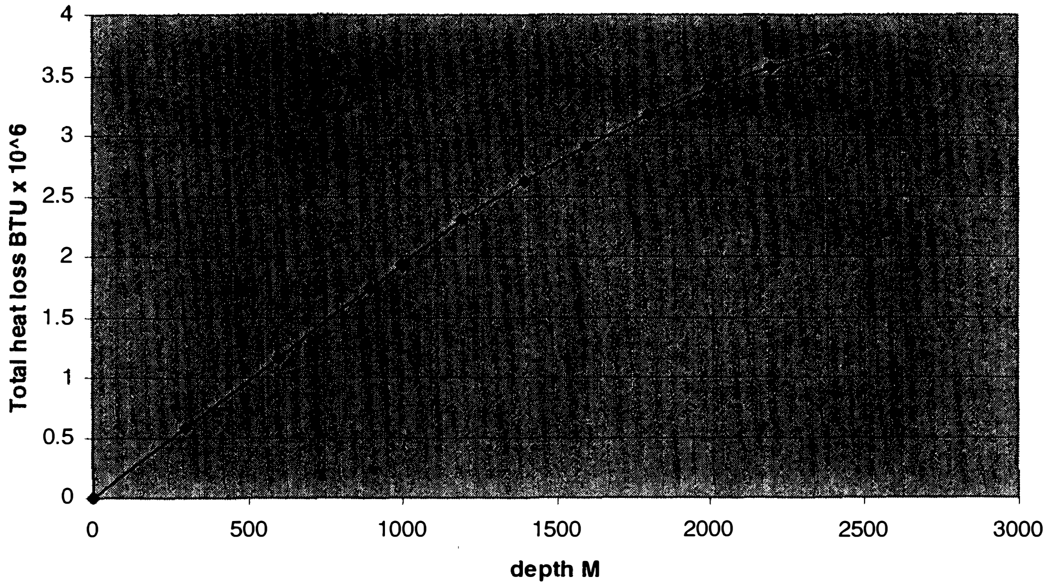

Fig. 3. *Total heat loss in hole versus depth.*

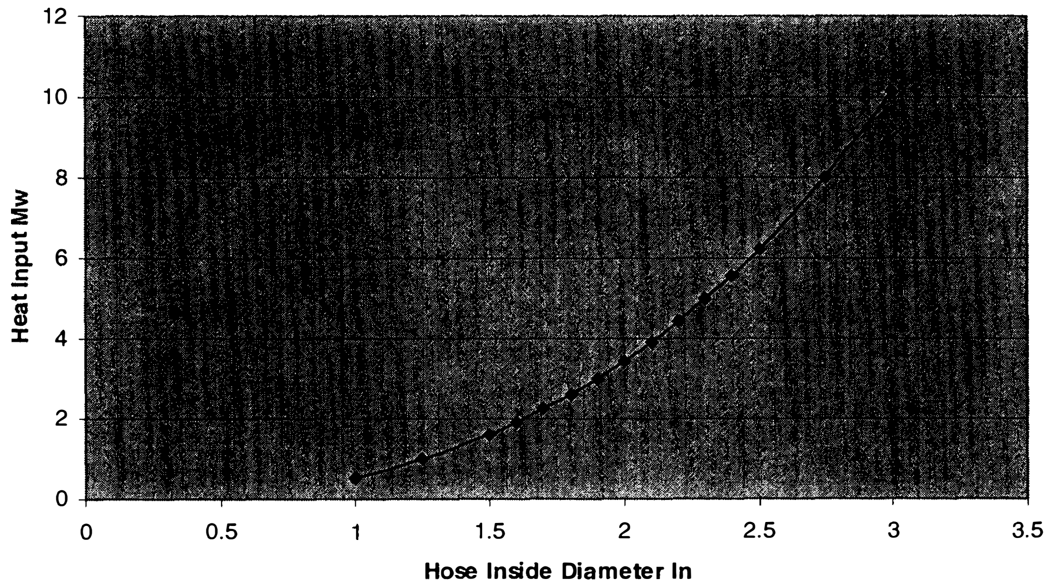

Fig. 4. *Heat input versus hose diameter.*

tional to drilling time. In Fig. 5, we plotted heat input versus time to achieve multiple given total heat inputs. This same graph also represents capital costs versus fuel costs. In both graphs, we clearly want to be close to the origin. We show the helpful graphs of the theoretical drilling and reaming rates in -50°C ice with no allowance for heat dissipation versus increasing hose diameter for increasing heat inputs in Figs. 6 and 7.

3. Transition to Wotan

We plan to begin making the transition to Wotan in the '99–'00 drilling season by replacing about 700 m of $1^1/_2$-inch hose with 2-inch hose to increase flow in the bottom

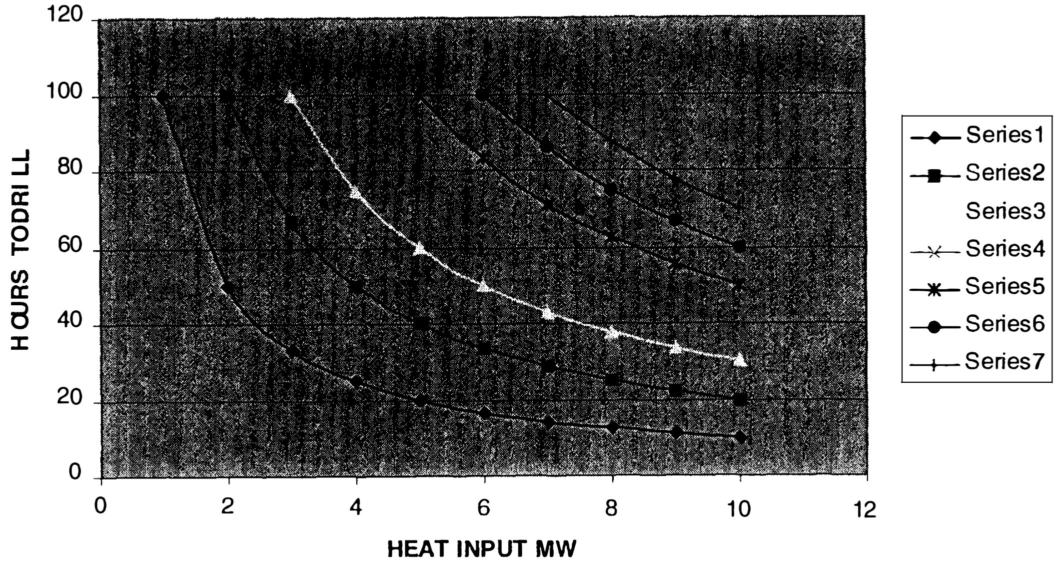

Fig. 5. *Time versus heat input for different heating requirements (100–700 MWh).*

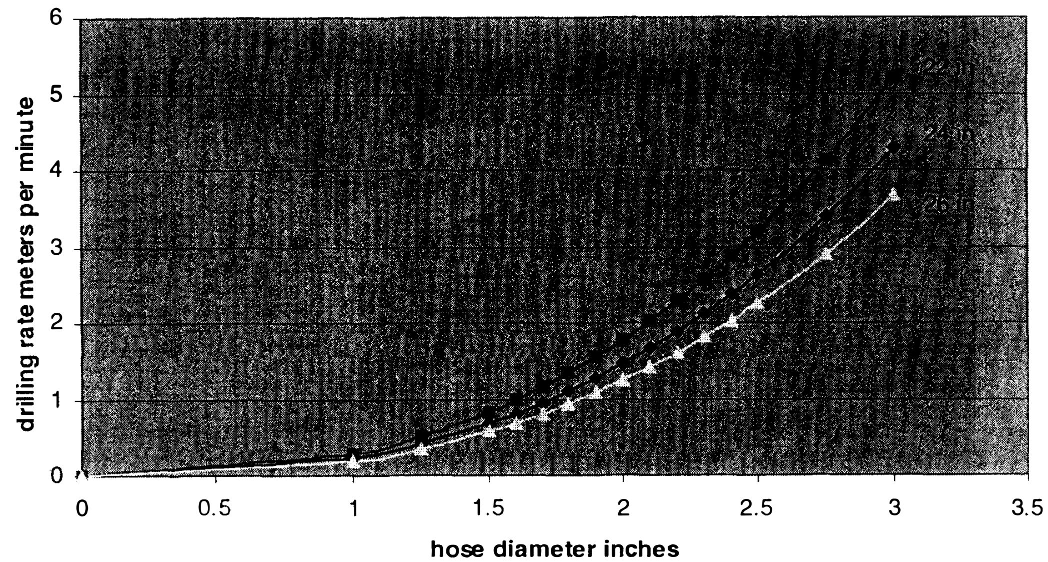

Fig. 6. *Drilling rates versus hose diameters for 22, 24 and 26 in holes, 2400 m of hose.*

portion of the hole. Flow in the upper 1400-m portion of the hole will also increase from the current 80 gpm to over 90 gpm. We will add enough additional heaters to the heating system to allow drilling to proceed at a rate of over 1 m per min compared with the current 80 cm per min using 1 1/2-inch hose. While still smaller than the 2 1/2-in diameter hose proposed for Wotan, the 700 m of 2-in hose will give us a better idea of how the drill performs with higher flows. We expect to reduce drilling time from the current 100 hours to drill 2100-m holes to the 70-hour range, reducing fuel consumption from 10000 gallons per hole to the 7000 gallon per hole range.

A 2 1/2-inch hose with a single large hose reel designed to hold 2500 to 3000 m of hose forms the heart of Wotan. By using one reel, we will save about 8 hours normally

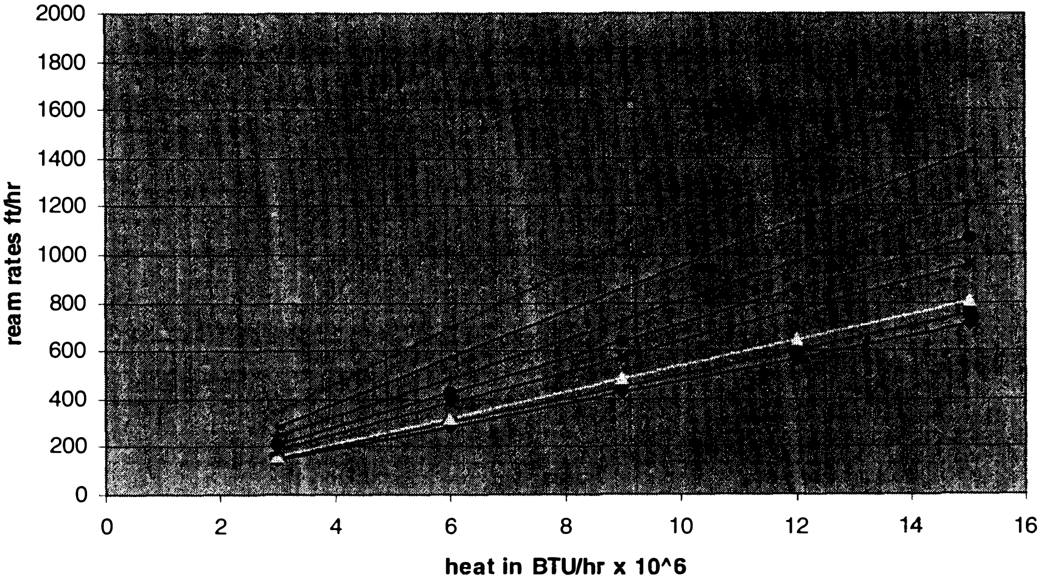

Fig. 7. *Reaming rates versus heat input for 4-in through 12-in diameter increases to a final diameter of 60 cm.*

used for making and breaking connections as we add or take off lengths of hose. We will also add a large wheel for the hose that will measure tension and pay out. In addition, a single generator will replace several smaller generators, providing power for all pumps; allowing control of pumping rates from a central location. Part of the transition to a production drill clearly must involve making the system easier to run with more critical information displayed at the drill console (Fig. 8, Table 2).

We are transitioning to a smart drill that will set drilling and reaming speeds as a function of the desired hole diameter and heat available at the nozzle. The drill will basically drill the type of hole we want and provide uniform hole diameter over the entire length. We expect this drill enhancement to save fuel and provide higher quality holes.

The current drill makes no attempt at saving fuel. We use old generators that produce about 8 kWh per gallon of fuel when they should be producing at least 12. We

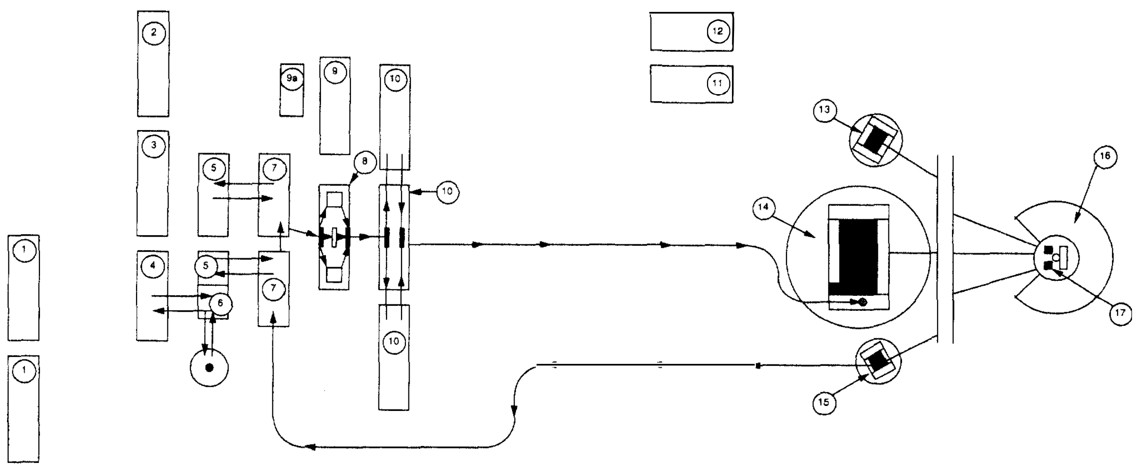

Fig. 8. *System sketch.*

Table 2. Wotan components shown in the Fig. 8 sketch.

Key	Component	Configuration	Weights
1	Parts and Workshop	2 sleds	12,000 Ibs. ea.
2	Auxiliary generators, 2 x 50kW	1 sled	12,000 Ibs.
3	Main generator 275 kW	1 sled	20,000 Ibs. ea.
4	Main generator		
5	Preheat	1 sled	12,000 Ibs.
6	Preheat, water well	1 sled	12,000 Ibs.
7	Water tanks 2 ea.	2 sleds	10,000 Ibs. empty, 90,000 Ibs. full
8	HP pumps	1 sled	20,000 Ibs.
9	Fuel tank 10,000 gal	1 sled	20,000 Ibs. empty, 80,000 Ibs. full
9a	Auxiliary tank	1 sled	20,000 Ibs.
10	**Main heating plant**		
	8 heaters/sled	3 sleds	15,000 Ibs. ea.
11	Drill control room	1 sled	6,000 Ibs.
12	Electronics	1 sled	6,000 Ibs.
13	Cable winch	1 sled	13,000 Ibs.
14	Hose reel	1 sled	75,000 Ibs.
15	Pump return winch	1 sled	6,000 Ibs.
16	Tower shelter		
17	Tower platform, tower		

have made no attempt at heat scavenging because of diffuse power sources. By using electric motors on all the pumps, a single prime mover can be used to power the entire drill, making it easy to use waste heat to operate the water well. These changes will save about 8 gallons of fuel per hour.

Finally, we expect to use solar heat to assist in heating the water. The direct beam radiation at South Pole has been measured at slightly greater than 1 kW per square meter, a very high number. The weather is generally clear—an important consideration since we will have to use solar concentrators to get reasonable efficiency. We have found solar collectors that have over 80% efficiency at 90°C. The back radiation from flat plate collectors renders them nearly useless for our application. While it is doubtful that we would try to supply the entire 6 MW of heat, we can use modular solar heating on any scale. We would try to make solar modules useful for remote field camps after we finish with them. Each module would produce about 100 kW of heat and 10 kW of electricity, enough heat and power to supply water and operate a small camp.

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