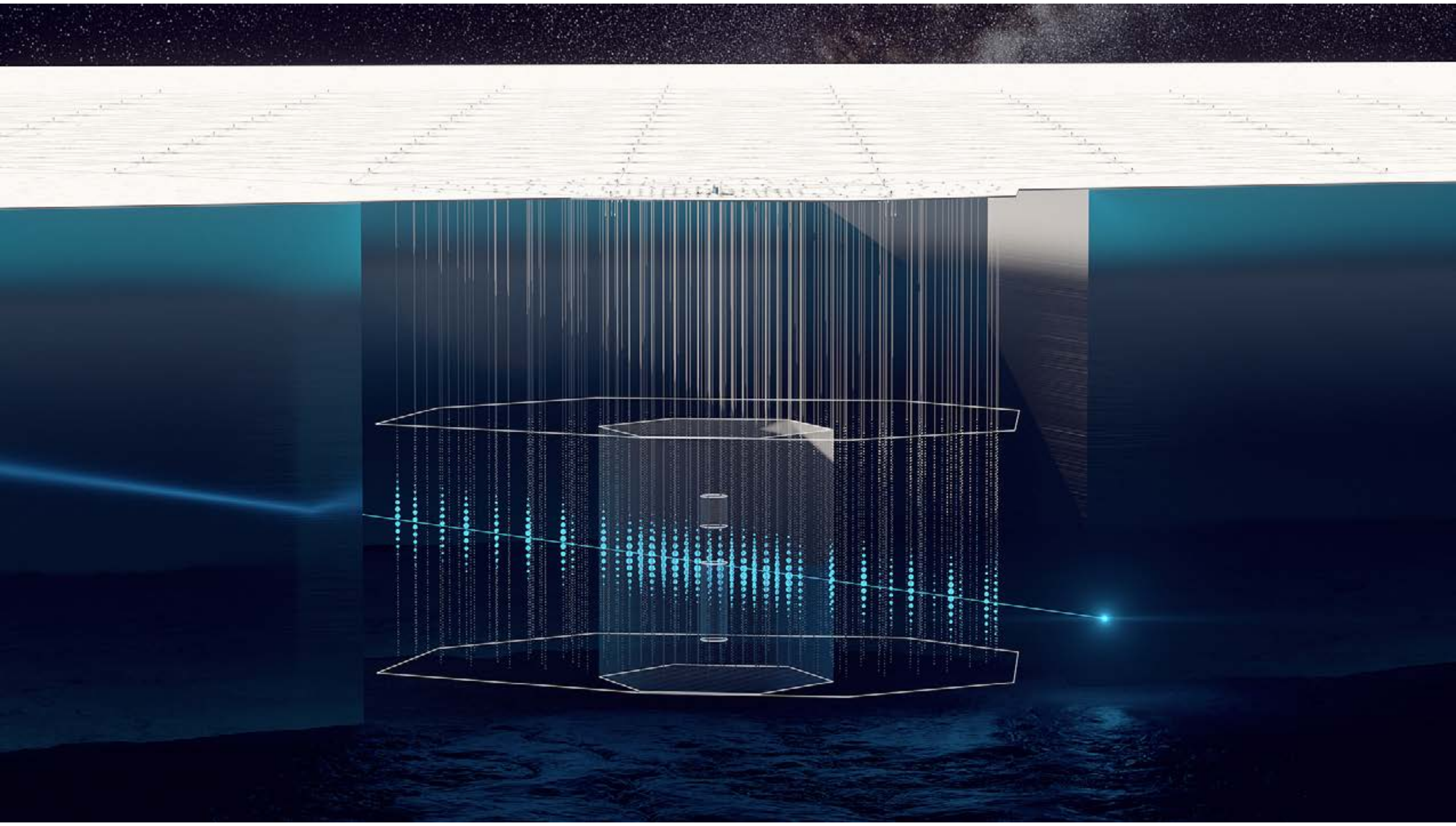
ICECUBE-GEN2 TECHNICAL DESIGN



The IceCube-Gen2 Neutrino Observatory

Part III: Detector Construction and Logistical Support Requirements

Version: May 25, 2024

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The authors gratefully acknowledge the support from the following agencies and institutions: USA – U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, U.S. National Science Foundation-EPSCoR, U.S. National Science Foundation-Office of Advanced Cyberinfrastructure, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin–Madison, Open Science Grid (OSG), Partnership to Advance Throughput Computing (PATh), Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS), Frontera computing project at the Texas Advanced Computing Center, U.S. Department of Energy-National Energy Research Scientific Computing Center, Particle astrophysics research computing center at the University of Maryland, Institute for Cyber-Enabled Research at Michigan State University, Astroparticle physics computational facility at Marquette University, NVIDIA Corporation, and Google Cloud Platform; Belgium – Funds for Scientific Research (FRS-FNRS and FWO), FWO Odysseus and Big Science programmes, and Belgian Federal Science Policy Office (Belspo); Germany – Bundesministerium für Bildung und Forschung (BMBF), Deutsche Forschungsgemeinschaft (DFG), Helmholtz Alliance for Astroparticle Physics (HAP), Initiative and Networking Fund of the Helmholtz Association, Deutsches Elektronen Synchrotron (DESY), and High Performance Computing cluster of the RWTH Aachen; Sweden – Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation; European Union – EGI Advanced Computing for research; Australia – Australian Research Council; Canada – Natural Sciences and Engineering Research Council of Canada, Calcul Québec, Compute Ontario, Canada Foundation for Innovation, WestGrid, and Digital Research Alliance of Canada; Denmark – Villum Fonden, Carlsberg Foundation, and European Commission; New Zealand – Marsden Fund; Japan – Japan Society for Promotion of Science (JSPS) and Institute for Global Prominent Research (IGPR) of Chiba University; Korea – National Research Foundation of Korea (NRF); Switzerland – Swiss National Science Foundation (SNSF).

Preamble

The vision of IceCube-Gen2 emerged soon after the IceCube Neutrino Observatory reported the discovery of a cosmic neutrino flux at high energies in 2013. The first conceptual design was presented as early as 2014 at a meeting in Arlington, VA. In the meantime, we optimized the design and made significant technical improvements. However, the overall science goals and the conceptual design have been remarkably stable. This document presents a preliminary design of IceCube-Gen2. Its purpose is threefold, to define a) the science case, b) the technical design to meet the science goals, and c) the approach to the construction at the South Pole. These three goals are laid out in three parts.

Part I, *Science and Conceptual Design*, presents the scientific goals, and the performance and sensitivity parameters. It is based on the IceCube-Gen2 Science white paper [1].

In Part II, *Detector and Performance*, readers will find the technical design and performance benchmarks. We present how the technical designs derive from the science requirements for the various detectors used in the IceCube-Gen2 optical, radio, and surface arrays. We also offer solutions for data transfer and processing, as well as calibration strategies.

The readers interested in *Detector Construction and Logistical Support Requirements* will find that information in Part III. We provide a detailed explanation of the challenges of constructing this next-generation observatory with an instrumented volume almost an order of magnitude larger than IceCube. The logistics of transporting 10,000 sensors to the South Pole, drilling 120 holes to 2600 m depth into the most transparent ice, and deploying the surface and a 500 km^2 radio array are laid out. They include cargo and population requirements, as well as high-level information about cost estimation.

The document intends to serve a broad audience for different purposes. The community and collaboration will find here the authoritative reference. Decision-makers and representatives of funding agencies will find a complete definition of IceCube-Gen2. Experimentalists working on other projects may find useful technical approaches in this document.

Part III

Detector Construction and Logistical Support Requirements

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11 Drilling and Installation

The scope of drilling and installation starts with complete instruments delivered to the South Pole and includes the planning and effort to drill holes, install instruments in the holes, install instruments on the surface, and install cables from the instruments to the IceCube Lab (ICL). The design, fabrication, assembly, testing, and use of the equipment required for this work is included in this scope. Two primary pieces of equipment are the deep hot water drill to make holes for optical modules and the mechanical radio drills to make holes for the radio antennas. Installation of the optical instruments is highly coupled to drilling with shared equipment and is time-constrained by freeze-back of the hole. There is some specific equipment for optical installation and testing. Radio installation is also done in sync with drilling, with the crews working in close proximity at a common work site. There is work on the surface for signal and power cable installation as well as surface detector installation.

11.1 Deep drill

11.1.1 Introduction and requirements

The hot water drill needs to make deep water-filled holes in the ice that are large enough in diameter to provide a comfortable time window in which to install the optical instruments before freeze-back of the hole. The rate of drilling should be optimized to minimize fuel usage and to allow completion of holes at a rate consistent with the project schedule. The drill for IceCube-Gen2 builds on experience gained from the Enhanced Hot Water Drill (Gen1) used for IceCube-Gen1. The Gen1 drill was based on knowledge derived from drilling holes for the Antarctic Muon and Neutrino Detector Array (AMANDA). Faster drilling is more fuel-efficient because there is less time to lose heat to the surrounding ice, therefore more of the heat energy goes to melting the ice locally in the vicinity of the drill nozzle. Faster drilling also allows more holes per season which reduces project schedule and cost. Increasing drill speed means delivering more power through the drill hose. Practical limits on hose strength and availability limit the diameter and pressure, which in turn limit flow to 200 Gallons Per Minute (GPM) in the required hose length. For safety reasons the temperature is limited to 88°C, which is two degrees below the boiling point of water at the South Pole. The flow and temperature set the thermal power for the drill to approximately 5 MW. Heat transfer into the ice directly in front of the drill nozzle limits the rate of penetration, and hence drill speed, to about 2.2 m/min for the nozzle velocity that can be achieved within the pressure limits of the hose. These parameters allowed drilling an IceCube-Gen1 hole with an initial diameter of about 60 cm that remained over 45 cm in diameter for a 37-hour time window. "Hole lifetime" is defined as the time window when every part of the hole is above the minimum hole diameter. The minimum diameter of an IceCube-Gen2 hole is slightly smaller than that of an IceCube-Gen1 hole because the instruments and the cable are smaller. There are more instruments to install in each hole (80 vs. 60) so the lifetime needs to be longer, resulting in an initial hole of nearly the same size. The goal is to be able to drill holes at a pace of one hole every two working days. The IceCube-Gen2 holes are deeper (2600 m vs. 2450 m) and farther apart (240 m vs. 120 m), and will therefore require improved efficiency in drilling each hole as well as in moving equipment between holes. Drill parameters for different generations of IceCube are shown in Table 1.

The IceCube Upgrade (ICU) will refurbish the Gen1 drill, restoring it to a usable deep hot water drill referred to as the ICU drill. The main difference between the Gen1 drill and the ICU drill will be a new control system based on Programmable Logic Controllers (PLCs) and Allen-Bradley

	IceCube-Gen1	**IceCube Upgrade**	**IceCube-Gen2**
Hole depth	2450 m	2600 m	2600 m
Hole size	45 cm diameter for 37-hour lifetime	52 cm diameter for 45 to 55-hour lifetime	45 cm diameter for 36-hour lifetime
Array	125 m hole spacing	22 m hole spacing, in the center of IceCube	240 m hole spacing
Holes	86 holes in 7 seasons	7 holes in 1 season	120 holes in 10 seasons
Drill Team	30	28	29
Logistics	LC130 (primarily)	Vessel and traverse (primarily)	COMSUR, Vessel, and traverse (primarily)
Instruments per Hole	60	112-115	80
Flow	200 GPM	200 GPM	200 GPM
Temperature	88°C	88°C	88°C
Max. speed	2.2 m/min.	2.2 m/min.	2.2 m/min.
Straightness	±1 m from vertical	±1 m from vertical	±1 m from vertical

Table 1: Drilling parameters for all generations of IceCube.

motor drives. The ICU drill is appropriate for a single season of drilling seven holes close together, to accomplish the ICU plan. However, improvements are needed for the system to endure 120 holes and to drill 21 or more holes in a season with a larger hole spacing to meet the IceCube-Gen2 plan.

The Whitco Model 75 heaters, used in the Gen1 drill system, that provide most of the water heating have steel coils that are slowly losing wall thickness. For reliability and safety, the drill architecture is being changed to heat the water before pressurizing it. The existing Meyers pumps can be used to pump hot water by modifying seal and valve materials.

This change also allows the addition of hot water storage on the surface so the pumps can continue to pressurize at 200 GPM even if the heating plant is not always heating the water. The IceCube-Gen2 drill will no longer be sensitive to a single heater failure disrupting smooth drilling. The hot water storage will also act as a settling chamber that allows gas to escape from the water and thereby improve the quality of water delivered to the hole. The water entering the pumps cannot be at the boiling point, so electrical heaters will be added to increase the water temperature by 3 to 5°C after pressurization.

The ICU drill has three 150 kW Caterpillar diesel generators. Two of these are run simultaneously to provide power for drill operations. These generators do not have enough capacity to provide electricity for heating the water after pumping. They will be replaced by a MicroTurbine (MT) array, which consists of five 160 kW MTs housed in a single International Organization for Standardization (ISO) container. The MT has significantly more electrical capacity than the existing generators. This change will improve the reliability of electrical power production while reducing manpower and cost for maintenance.

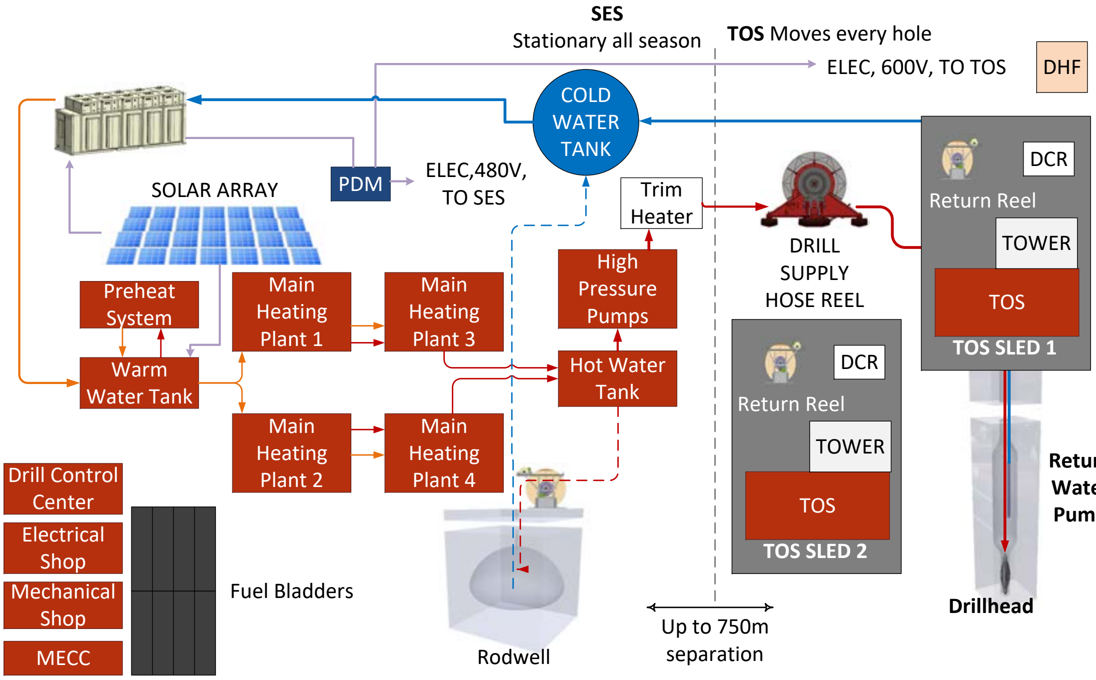


Figure 1: System diagram of IceCube-Gen2 drill system. Red lines indicate hot water circulation, and blue indicates cold water. The vertical dashed line separates the Seasonal Equipment Site and the Tower Operations Site. Water-flow from left to right starts at the preheat building and is directed through the Main Heating Plants to the hot water tank. The water is then pressurized in the High-Pressure Pump building. From there, the water is pumped from the Seasonal Equipment Site through the Main Supply Hose Reel and finally downhole through the drill head. Cold water from the borehole is pumped upward and recirculated back to the preheat system to begin the loop again.

The increased distance between holes drives the change to fiber optic communications, and longer water lines (750 m) connecting the Seasonal Equipment Site (SES) to the Tower Operation Site (TOS). The inner diameter (ID) of these water lines will increase from 2.5 in to 3 in to maintain acceptable pressure losses over the increased distance.

The equipment at each TOS will be mounted on a large Air Ride Cargo Sled (ARCS) to allow easier transportation between holes without groomed roads and reduced setup time at each hole. The TOS design reduces setup time between holes by integrating all of the equipment onto the ARCS. This eliminates the need to move and place equipment individually between holes.

Electrical power generation will be augmented by a solar PhotoVoltaic (PV) array that will be used to heat water in the tanks, thereby reducing the use of the Model 75 heaters and saving a significant amount of fuel.

These changes can be done incrementally, in the order described. At the end of ICU the system will be reconfigured to heat water before it is pumped. Next, the electrical power generation system will be upgraded with the MT array, and will include the solar PV array. Finally, the SES-to-TOS connection will be modified, and the TOS ARCSs will be constructed.

Figure 2: Aerial view of the Seasonal Operations Site and Tower Operations Site from IceCube Gen1. The top oval shows the Tower Operations Site (TOS), and the bottom oval circles the Seasonal Equipment Site (SES).

11.1.2 System overview

The hot water drill is implemented across two separate sites: The Seasonal Equipment Site (SES), and the Tower Operation Site (TOS). Figure 1 shows a schematic of the overall layout. Figure 2 is a aerial view of the SES and TOS site setup at the South Pole. The SES is stationary for the duration of a field season. It provides electricity, makeup water from a well, and a stable supply of hot pressurized water. The TOS is mobile and relocates to the location where the hole is drilled and instruments are installed into the ice. The two sites are connected by an umbilical of cables and insulated water lines that are 750 m long to allow the drilling of 21 holes at 240 m spacing in a season without moving the SES. There are two sets of TOS equipment, so drilling can occur at one TOS, while the other TOS is used to install instruments and then moved and set up to drill the next hole.

Seasonal Equipment Site (SES) The SES is composed of two insulated water tanks (WTs), one PreHeat System (PHS), four Main Heating Plants (MHPs), one High Pressure Pump building (HPP), a Drill Control Center (DCC), a mechanical shop (SHOP), and a Seasonal Electrical Workshop (SEW). Each of these existing subsystems are housed in a Mobile Drilling Structure (MDS) that is constructed by modifying an ISO container to allow transport in an LC130. The MDSs are insulated and heated with both a fuel-fired furnace and/or electric heaters. They are mounted on rigid aluminum skis that allow towing over groomed roads.

The existing Gen1 electrical power generation system consists of three diesel generators and a Power Distribution Module (PDM) housed on rigid skis in 20 ft ISO containers. A 1 MW MT array in an ISO container will replace the existing generators after the first season of drilling (3 holes). This increased power production will allow electrical heating of the pressurized water by a few degrees. A 160 kW solar array and the MT array will provide AC power. An 800 kW solar array will provide DC power to heaters in the warm and hot WTs.

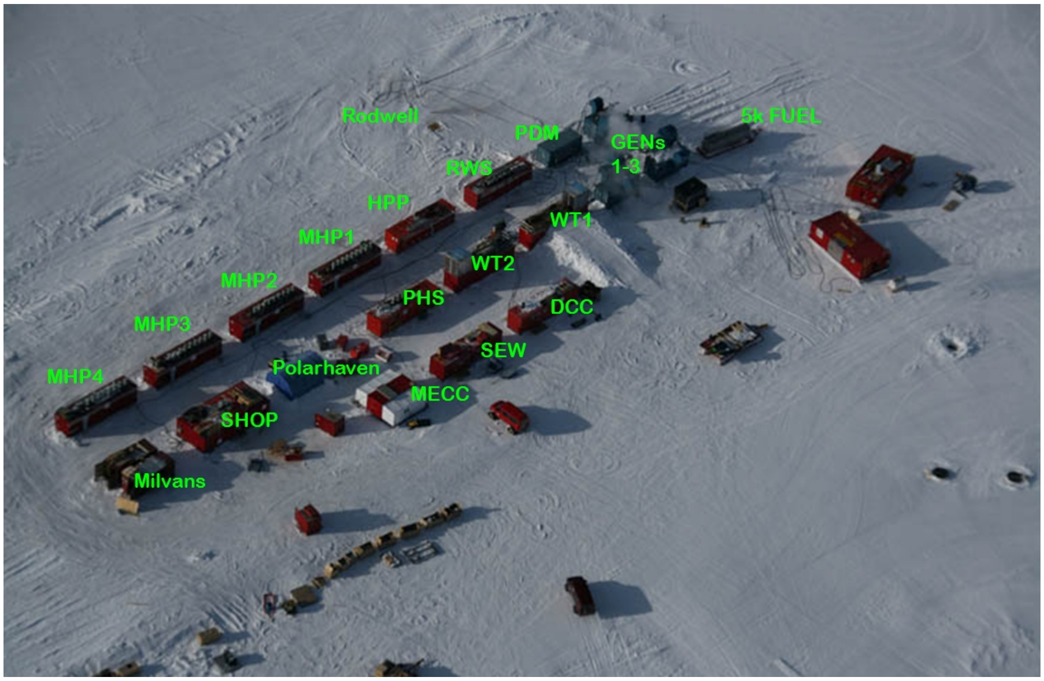


Figure 3: Gen1 Seasonal Equipment Site. Acronym definitions: Main Heating Plant (MHP), High Pressure Pumps (HPP), Rodwell System (RWS), Power Distribution Module (PDM), Generators (GENs), Water Tank (WT), Pre Heat System (PHS), Mechanical Workshop (MECC), Drill Control Center (DCC), Seasonal Electrical Workshop (SEW), 5k gallon fuel tanks (5k fuel), Polarhaven and Milvans.

The SES has a well to produce makeup water needed for drilling operations. This Rodwell System (RWS) sends hot water into a hole in the ice and returns even more cold water to the system, storing it in a cold WT. Snow can also be added to the cold WT and melted to create water.

A bathroom (outhouse), a driller meeting and break room container (MECC), and fuel storage tanks (10,000+ gallons total) are also located at the SES. An aerial view of the Gen1 SES is shown in Figure 3.

Tower Operation Site Each of the two TOSs will have a twin-walled polycarbonate-enclosed aluminum drill tower joined to a double-wide MDS. They will also each have a Main Drill Cable Reel (MDCR), and a return water combination (power and signal cable, and hose) reel mounted onto an ARCS. These sleds are designed to allow transport of large heavy cargo over ungroomed terrain. The larger size of the ARCS allows more integration of equipment than was achieved with Gen1, resulting in less time needed for set up at each hole.

The drill towers, double-wide MDSs, and one existing Main Drill Cable Reel (MDCR) will be reused. A second MDCR and two combined (power cable and hose) reels for the return water system will be constructed and added to the system. There will continue to be only one Drill Supply Hose Reel (DSHR) which will be used at the TOS that is actively drilling. Existing TU-20 cable reels will be used at the TOS during instrument installation. Each TOS has a drill head that mounts on the drill hose and a return water pump that connects to the return hose. The plan is to upgrade the drill head electronics, and to reuse the pressure housing and mechanical structure. The layout for the IceCube-Gen2 TOS is shown in Figure 4. The Gen1 TOS configuration is shown in Figure 5 for comparison.

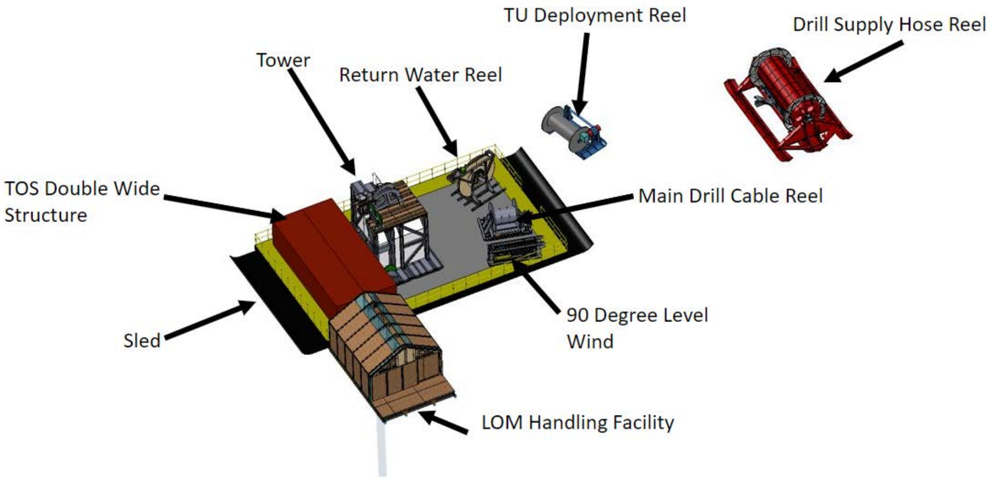


Figure 4: IceCube-Gen2 TOS site design.

SES-to-TOS Connection Hot pressurized water can travel from the SES to the TOS in sections of insulated drill hose for short distances, but beyond 800ft the additional pressure drop imposes a limitation. The IceCube-Gen2 hot water supply line will be replaced by a 3 in Schedule 40 stainless steel pipe with a 3 in ID from the previous 2.5 in ID hose. This will allow a separation of 750 m between the SES and the TOS. The cold water return line could be of the same construction, or a medium-pressure hose with a larger diameter could be used for reduced cost.

Electrical power distribution may require larger cables or additional transformers to compensate for the voltage drop in the long cable. The communications cable will transition from the existing Ethernet via copper wire to Ethernet via fiber optics cable.

Primary water loop During deep drilling water is returned to the SES from the TOS at a rate of 192 GPM and enters the 10,000-gallon cold WT. Water is pumped out of the cold WT and through the exhaust-heat exchanger on the MT array, where it is heated to 17°C, then enters the 10,000-gallon warm WT.

Water is circulated back and forth from the warm WT to the PHS, where it goes through three (of four) 125 kW Model 75 heaters to keep the warm WT at a steady temperature of 5°C. Electric heaters powered by a portion of the PV array will also be used to increase the water temperature, allowing some fuel-fired heaters to be turned off.

Water from the warm WT is pumped through 28 (of 34) 125 kW Model 75 heaters in the MHPs and enters the 84°C 10,000-gallon hot WT. The hot WT acts as energy storage and allows drilling to continue for up to 50 minutes without heat production in the SES.

Water in the hot WT is sent to the HPP where it is pumped up to 1,000 psi. When the 200 GPM from the cold WT is heated the thermal expansions causes an increase in the flow rate to 206 GPM. The hot water then flows through an inline electric water heater to trim the temperature up to 88°C.

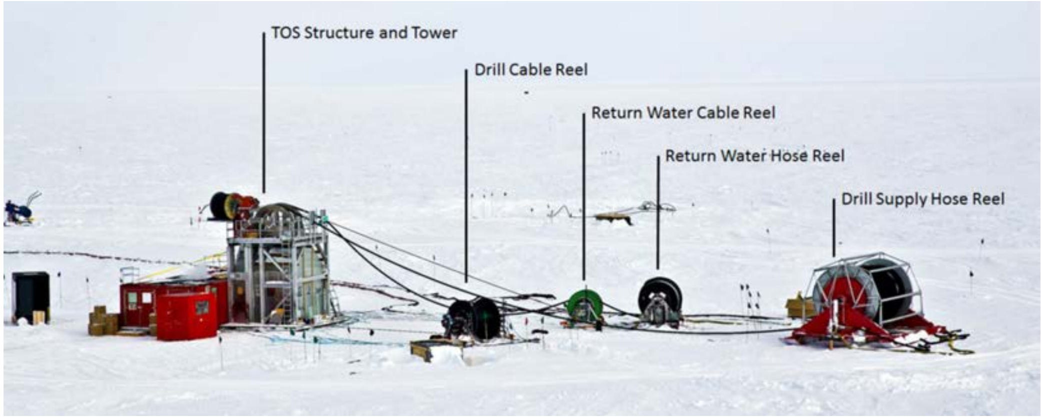


Figure 5: IceCube-Gen1 TOS site.

Hot water leaves the SES through an insulated surface line to the TOS. The hot water supply line connects to the Drill Supply Hose Reel that delivers the water to the drill head. Water exits the drill through a 0.75 in diameter hole in the bottom of the drill head weight stack, and impacts on the ice at a speed of 45 m/s.

The hole in the ice is the first part of the water return path. The return water pump is located near the top of the hole, just below the water level. It pressurizes the water to lift it out of the hole and returns it to the SES through the cold water return line. It is important to maintain a sufficient head of water on top of the return water pump. The water level is constantly changing due to the decrease in volume when a mass of ice melts to water. Therefore, the water level in the hole is monitored by a pressure gauge that provides feedback to control the pump flow and maintain the head of water. The return cold water flow is approximately 192 GPM.

When the drill is in idle mode, water flows through the same path except that the drill head, hole ice, and return water pump are not part of the system. In order to facilitate this, the return water line is connected to the output end of the hose on the DSHR (Drill Supply Hose Reel). An idle flow rate of 15 GPM is sufficient to keep all parts of the system from freezing with minimal pressure drops around the water loop. Solar power can be used during the idle period to melt ice in the RWS to refill the tanks, and to heat the water up to appropriate temperatures. This allows productive continuous use of the solar panels.

Electrical power generation The drill uses 300 kW of electric power during deep drilling primarily to run the heaters and pumps. This power can be provided by two of the three 160 kW piston generators at South Pole that were used on the Gen1 drill and in ICU. The third generator acts as redundant backup and allows downtime of individual generators for maintenance. Additional power will be used to control the final water temperature through electrical heating during deep drilling.

The MT array will eventually replace the Gen1 generators, thereby increasing electrical power generation to 640 kW. The heat recovery system in the MT array would provide up to 6°C of heat to the water. This energy recovery improves the net fuel efficiency for the MTs to about 75%.

Solar power generation will augment the fuel-based power production. The MT array generates a sufficient amount of electrical power to operate the drill on a cloudy day, but typically there is an abundance of solar insolation at the South Pole, and one MT could be shut down entirely.

When the drill is idle it uses less than 150 kW of electricity, therefore one piston generator, one MT, or the solar PV array could provide this power. A portion of the electricity produced by the solar PV array will be used to heat water in the WTs, allowing reduced fuel use and operating hours on the Model 75 heaters.

Rodwell When the drill system is idle the Rodwell at the SES is used to produce the 20,000 gallons of makeup water required for each hole. Producing makeup water during idle keeps water flowing in the system and allows productive use of energy from the solar panels. Makeup water is needed to keep the water level in the drill hole constant such that there is an adequate column of water above the return water pump. The water tank levels can be lowered to provide makeup water as well. The return water pump delivers cold water from the drill hole to the cold water tank.

Hot water is pumped from the hot WT to the single-spiral Rodwell reel and down into the Rodwell to melt enough ice to keep liquid water available in the well. The heat input does not have to be synchronous with the water usage. At the end of IceCube-Gen2 there will be a large, air-filled cavern at a safe depth under SES.

During drilling, 206 GPM of hot water enters the top of the hole and, as it cools, reduces to 200 GPM of cold water at the drill; the difference in the flow rate is due to thermal contraction. The heat from the drill melts ice at a rate of 91 GPM. The resultant water has a smaller volume that requires a lower flow rate of 83 GPM to maintain constant head above the water pump. Since water takes up less space than ice, the amount of water pumped out of the hole should be less than the amount of water that is put into the hole. The return water flow is set to 192 GPM to account for the 8 GPM volume change.

11.1.3 Reference design

11.1.3.1 Existing equipment The original drill system used for IceCube will have been refurbished and upgraded to meet the needs of ICU. Many of the subsystems from the ICU drill will be repurposed for use on the IceCube-Gen2 drill system. This scope of work is shown in Figure 6. Some of these subsystems are not applicable or appropriate for the new architecture and they may be retired. A summary of this equipment is provided below.

Control System The control system is the most extensive system upgrade being made for the ICU drill and will be leveraged and expanded for the IceCube-Gen2 drill. The obsolete Gen1 control system was based on serial communications, Unico motor drives, and custom C and Python programming. ICU replaces this with modern industrial PLC-based controls and Allen-Bradley motor drives, along with an Ignition Supervisory Control and Data Acquisition (SCADA) user-interface platform. While the ICU system maintains a serial interface with most legacy sensors and actuators to reduce rewiring effort, the IceCube-Gen2 configuration aims to eliminate this layer and replace it with direct PLC I/O connections. This change will reduce points of failure and improve robustness and reliability. There will be additional subsystems to incorporate into the upgraded control system, such as the MT and PV arrays, and trim heating.

For both the Gen1 and ICU drill control system configurations the primary functions are to provide monitoring, safety interlocks, and data logging. There is not much in terms of process automation. Instead human operators make most of the decisions and tune the system. Once a reliable hardware and software architecture has been established for the ICU drill, those modernized industrial controls will be built upon for the IceCube-Gen2 system, and there will be a search for opportunities to add layers of automation if they can potentially yield improvements

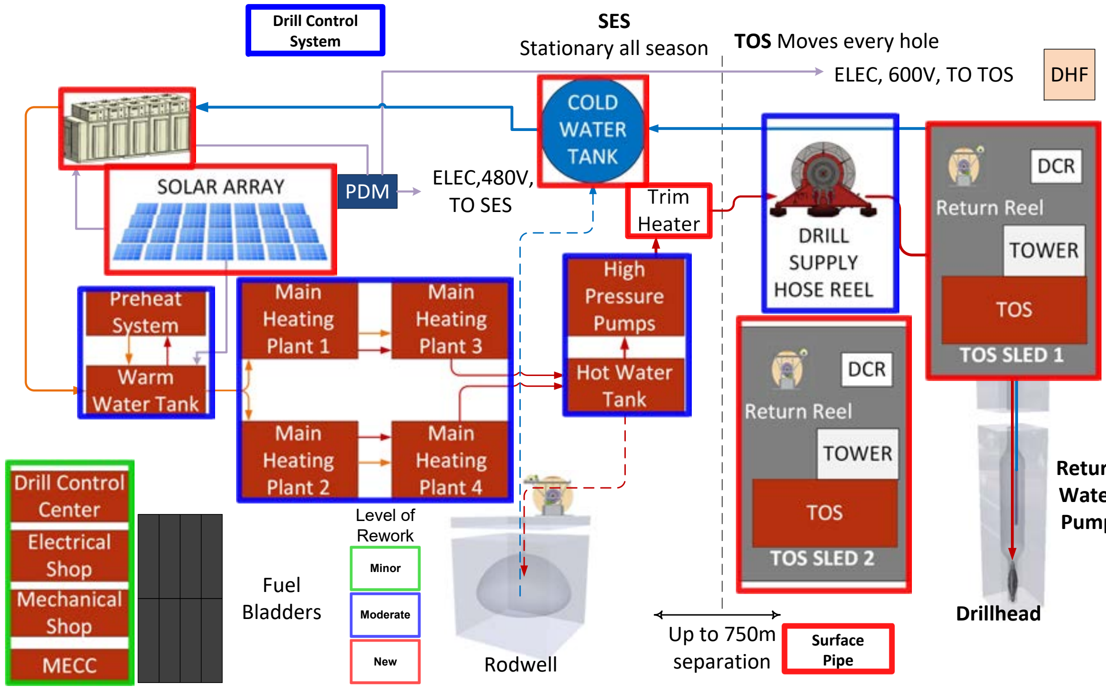


Figure 6: Scope of work to change the ICU drill system to the IceCube-Gen2 drill system.

to system performance, efficiency, and safety. An example of a system that has automation potential is an automated hose-taping system, pending a trade study and feasibility investigation.

Water Tanks (WTs) The two 10,000 gallon water tanks (WT1 and WT2) will be reused and converted to warm and hot water storage tanks. A third water tank will be added to the system for cold water storage. The tanks are customized ISO containers lined with thermal foam and an inner welded stainless steel liner. The liner will be inspected after use with the ICU drill and additional lower ports will be added to the tanks to allow new inducer pumps to bottom feed water to the tanks.

Additional insulation may be added to the exterior of the WTs to reduce heat loss, however initial heat transfer calculations have determined that this is likely unnecessary.

A potential improvement to the water tanks is to add a conveyor and hopper system to dump snow into the cold WT to replace water lost at the hole and drilling site. This is an alternative to the current method of using a loader and operator to manually add snow to the cold WT.

High-Pressure Pump MDS (HPP) The HPP will be reused and converted such that it is capable of pumping hot water. This will involve replacing the seals, check valves, and accumulator internals with high-temperature components, and reconfiguring the main pressure-relief valves. The existing motor drives for the submersible charge pump will need to be replaced with motor drives for the new inducer charge pumps. Insulation and/or protective covers will be added to some of the systems to reduce potential for burns from contacting hot metal. The building may need to be cooled due to the heat load from the water combined with heat from the pump motors.

Main Heating Plants (MHPs) The MHPs will still provide most of the thermal heating of the water, but the new drill system configuration will be permanently converted from high-pressure to low-pressure operation. This will extend the lifetime of the heaters. Heater lifetime is dictated by the wall thickness of the coils and the resulting working pressure margin. The main coils are steel, which corrodes and leads to reduction in wall thickness and decreased pressure margin. However, significantly lowering the operating pressure gains back sufficient working pressure margin based on investigation into the coil condition and lifetime estimates. The coil condition will be monitored throughout the IceCube-Gen2 project, and some number of heater replacements or possibly replacement of entire MHP modules is possible. The heater controls will be streamlined and improved.

PreHeat System (PHS) The PHS will mostly be reused in its current configuration. This building will provide temperature and level control of the warm WT, just as it does for WT2 in the ICU drill system. It also contains the bag filtration bank and the centralized condensate management for the system. Condensate processing, neutralization, and re-injection will be revisited for IceCube-Gen2.

Caterpillar generators The three reciprocating diesel generators from Gen1 and ICU will be maintained as a backup power source. They could also be used to replace the aging Cold Regions Research and Engineering Laboratory (CRREL) generator in support of firn drilling operations. If it turns out that these generators are not needed for IceCube-Gen2, they could be repurposed to support USAP operations.

ARA system For the ICU drill the ARA drill system is being used for the RWS. This is a good short-term solution, but this subsystem is slightly undersized for the job and does not have the long-term reliability required for the IceCube-Gen2 drilling effort. It will be maintained on-site as a stand-alone system for backup firn drilling, exploratory drilling, and general wet or dry hole and subterranean bulb drilling and development. A new RWS will be required.

Reels: Drill Supply Hose Reel (DSHR), Main Drill Cable Reel (MDCR), Return Water Hose Reel (RWHR), Return Water Cable Reel (RWCR), TU-20s, TU-15 The DSHR will remain a standalone piece of equipment but would need to be put on a sled to decrease ground pressure for more agile movement and lower pad and road preparation requirements. The MDCR will be reworked with the addition of a 90° level wind and packaged onto a large sled with the TOS and Tower to eliminate the need for set up at each hole. A second MDCR with the same configuration will be built to be paired with the second TOS/Tower. The existing return water reel will not be used. Instead, a new system will be developed that uses a combination (electrical cable and water hose) deployed from a single spiral reel. The two TU-20 instrument installation reels will be reused in their current configuration. With the significant reduction in the instrument cable diameter and mass, a smaller, easier to manage TU-20 axle will likely be possible.

TOS and Tower The TOS equipment and Towers will be reused to all extents possible. Modifications include packaging these structures onto a sled to eliminate the need for setup at each hole and other functional enhancements as described below in the Tower Operations section.

Drill Control Center (DCC) The DCC will be expanded to about twice the current size to provide more space for control system hardware, SES operations, and communications headquarters. This could be accomplished by combining it with another MDS to form a building twice the original width. A more likely option is to purchase or build a new structure on skis. In this case, the current DCC MDS would be available to convert to another purpose such as housing the water trim heaters, solar power support electronics, or pump motor drives.

Support Buildings (SHOP, SEW, MECC, storage milvans) Significant modifications or additions to these support buildings are not required.

Independent Firn Drill (IFD) A study will be conducted for an upgraded power source to replace the aging CRREL generator that has supported the IFD during the IceCube-Gen1 and the ICU drilling efforts. One option is to re-purpose the original diesel reciprocating generators as they are phased out and replaced with the MT array. Another option is to specify and purchase a smaller MT system with integrated heat recovery.

11.1.3.2 Combined systems: Electrical power generation and water heating

The existing Gen1 electrical power generation system consists of three 160 kW Caterpillar diesel generators (Gen1, Gen2, Gen3) and the PDM. Each of these is housed in a separate 20' ISO container that has rigid skis. The three generators are kept on a rotating schedule so that two of them are run simultaneously during deep drilling, while the third generator goes offline for maintenance. Due to their age and long service in a harsh environment they are not as reliable or efficient as modern equipment, therefore new electrical power solutions will be implemented.

The diesel generators will be used to power the drill during the first season of IceCube-Gen2. During subsequent seasons two separate systems will be brought online to replace them for electrical power generation: a MT array and a solar PV array. Each system will also supply energy to heaters in the water tanks.

Microturbine array Most of the electrical power will be provided by a 1 MW Capstone CS1000S MT array, which consists of five 200 kW MT generators in a packaged set which is mounted inside a standard ISO container. The MTs are designed to synchronize their 480 Vac outputs; additional equipment is not required for this purpose. The MTs are derated for South Pole altitude (10,000 feet) to 160 kW each, for a total of 800 kW. It is anticipated that four of these will be in operation at any one time, allowing one spare. This will supply up to 640 kW for drilling operations. The MTs require minimal maintenance, have fast start times, good efficiency, and are fuel-flexible; including AN8 jet fuel which will be used to power them at South Pole. They can also run on diesel fuel, if necessary.

Each MT has an exhaust-heat recovery system which will provide heat to the water tanks. The UW-Madison Physical Sciences Laboratory (PSL) conducted tests on a single MT. The test results showed that the heat exchanger was able to capture 1.3 times the output of the engine in thermal energy. Therefore, when the MT array is operated at full capacity using four MTs, it could provide up to 832 kW of thermal energy.

A custom-built enclosure will allow the engine to intake the cold ambient air, while protecting the MT from blowing snow. Cold air is denser than warm air, which allows the MT to produce more power. This will help compensate for the derating due to altitude.

The change from diesel Caterpillar generators to the MT array is not expected to introduce major engineering design challenges. The MTs have better uptime and power quality, require less maintenance, and have integral heat recovery, and therefore should be a better solution. Figure 7 shows the MT generator array at PSL.

Solar PV array Power generation is augmented by a solar array with a capacity of up to 960 kW. This will supply 800 kW to resistive heaters in the water tanks. The remaining 160 kW is equal to the generation capacity of one MT. It will be integrated into the overall electrical power generation system.

Figure 7: A Capstone CS1000S microturbine has been purchased by PSL and is currently being used for research and development and testing in support of IceCube-Gen2. The microturbine is currently installed in the PSL testbed.

The solar array will consist of bifacial PhotoVoltaic (PV) panels mounted to sleds that are anchored to the snow. Panels are located on each face of the array such that solar insolation will be incident on approximately half the panels as sunlight moves around the array. The panels are expected to generate a greater amount of power than their nameplate capacity. This is due to the effect of low ambient temperatures, which increase the efficiency of PV panels, and the additional reflected light from the snow.

The group of panels on each face will be wired together and connected to the Maximum Power Point Tracking (MPPT) electronics. The MPPT system adjusts the operating voltage to a level that produces the most power for the current conditions. The output voltage will also control the amount of heat produced by the immersion heaters in the water tank. Design details such as the number of panels, necessary electronics, and a facility to house the auxiliary equipment is still under consideration.

The integration of electricity from the solar array is not yet specified. Traditionally, the DC power produced by a solar array would be converted to AC power by an inverter, which introduces some inefficiency into the system. An inverter can also condition and synchronize the power prior to adding it to the AC grid. Rather than using an inverter, it may be possible to feed this DC power directly into the MT battery bank, thereby eliminating the costs and electrical ineffi-

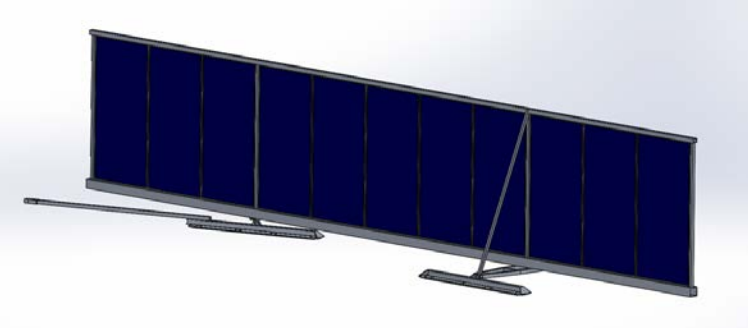


Figure 8: Concept of sled to hold solar panels.

ciencies associated with conversion to AC power. This possibility is currently under discussion with the MT representatives.

The sleds to hold the panels are in the conceptual design phase. The design criteria include an overall length restriction of 40', such that the sled will fit into an ISO container. The weight of each sled will be less than twice the weight of the panels. Each sled will have skis that can pivot to allow them to be towed over ungroomed snow using a snowmobile. Both ends of each ski will have an anchor point. The overall solar PV array and sled system will be designed to withstand winds exceeding the maximum recorded wind speed at the South Pole, which is 55 mph. The sled shown in Figure 8 has three skis, 11 panels with dimensions of 1 meter x 2 meters each, and a total weight of approximately 1,000 lbs.

11.1.3.3 Electrical power distribution

The electrical power distribution architecture designed for IceCube-Gen1 proved to be simple and robust. The design for IceCube-Gen2 will be similar. The electrical power generation system sends electricity to the PDM. This MDS contains circuit breakers, switchgear, and other equipment to distribute and monitor the electricity, as shown in Figure 9.

The PDM also distributes power to loads in the SES and the two TOSs. The distribution cables will be connectorized at each end. All cables and connectors will be rated for the expected loads and environment. Power connectors are ubiquitous in the drill system. The Appleton power connectors used on the IceCube-Gen1 drill proved to be unsuitable for the application and the environment. Over time, they deteriorated and became difficult to mate properly. A connector trade study will be conducted to determine a more robust type of power connector.

Figure 9: The Power Distribution Module distributes all of the electrical loads to the Seasonal Equipment Site and Tower Operations Site.

Figure 10: Arctic Ultraflex Blue® power distribution cable rated at 64 amps with five stranded 2 AWG conductors and a nominal outside diameter of 35 mm.

Each MDS contains an electrical panel to distribute power locally to the various loads inside the building and in the vicinity. Polar Wire developed Arctic Ultraflex Blue® cable specifically for the IceCube-Gen1 power distribution system. It is extremely durable and is rated for -70°C. This cable has a tough, flexible Thermoplastic Elastomer (TPE) jacket with finely stranded copper conductors that remain flexible at low temperatures. It is likely this cable will be used for IceCube-Gen2. A sample is shown in Figure 10.

The 750-m-long cable from the PDM to the TOS that powers a 50 hp return water pump is a concern for the power distribution system. This cable is used to deliver 55 kW of power to the pump. The cable run is shown in Figure 11. The lengthly cable will experience a voltage drop that may be large enough to disrupt the motor drive or impact the efficiency of the pump. The plan is to test this part of the system at PSL to determine if the motor drive and the pump will operate well, thus eliminating the need to upgrade this line. If the equipment does experience problems, there are several alternatives to address this issue:

- Transformers could be used to allow for cables that have a larger wire gauge, which would experience lower voltage drops. These are two options:
  - A transformer could connect to the output of the PDM to step up the voltage to 600 V. A cable would then run with this larger voltage rating from the PDM to the TOS that is actively drilling. At this TOS, a second transformer would be installed to step the voltage back down to 480 V
  - A transformer could connect to the output of the PDM to step up the voltage to transmission-line level of greater than 1,000 V. A second transformer would then be installed at this TOS to reduce the voltage back to 480 V. The high-voltage level of this option opens up a new realm of cost, support equipment, PPE, and personnel training, which may not be feasible.
- Each TOS could have a second 480 V cable to provide approximately 25 kW of power to ancillary loads such as computers, heaters, and reels. These two parallel lines would divide the current, and therefore each cable would experience less voltage drop.
- One feasible solution involves relocating one MT from the MT array to the TOS area. This would allow the TOSs to operate in an "island" mode, meaning they would be electrically disconnected from the main system, thus removing the need for a 750 m power cable.

Studies will need to be conducted to determine the best of these four options; considering cost, feasibility, risk, and safety.

The equipment will be designed to be durable and reliable, while also protecting personnel from hazards. To that effect, the following studies will be conducted:

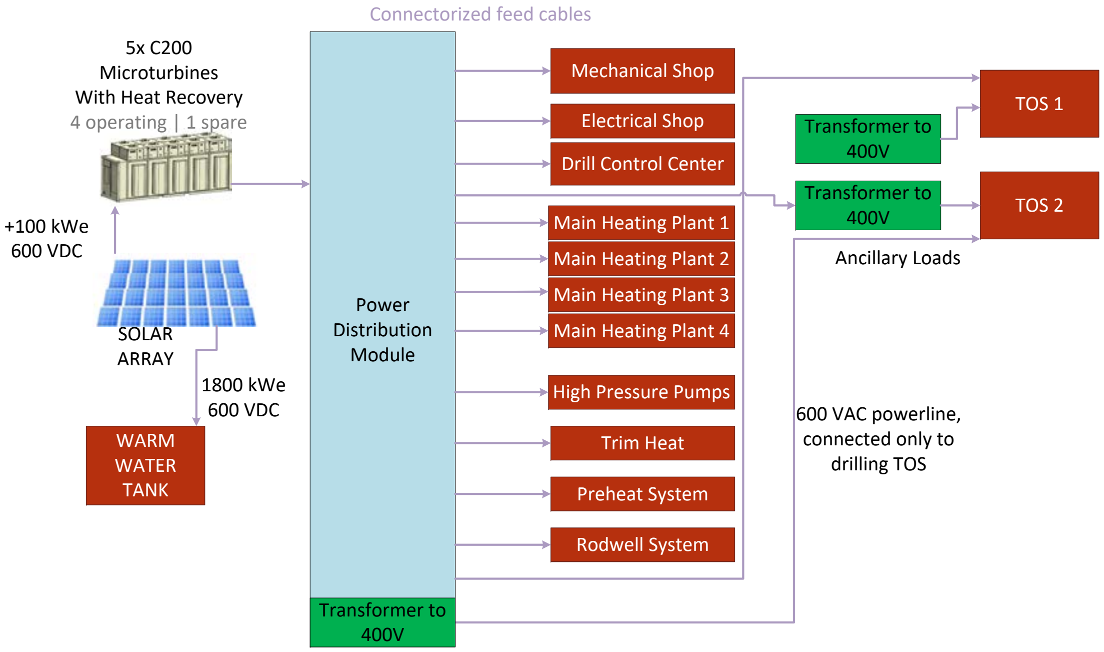


Figure 11: IceCube-Gen2 power distribution diagram.

System	**Rated power (in kW)**	**Used power (in kW)**
High Pressure Pump	191	115
Main Heating Plant 1	14.9	5.6
Main Heating Plant 2	14.9	5.6
Main Heating Plant 3	14.9	5.6
Main Heating Plant 4	14.9	5.6
Pre Heat System	30.4	12
Rodwell System	39.5	28.1
Drill Control Center	17.5	1.8
Tower Operations Site 1	148.3	64.1
Tower Operations Site 2	148.3	64.1
Seasonal Equipment Workshop	12.9	1.3
Total	**647.5**	**308.8**

Table 2: Breakdown of IceCube-Gen1 power consumption by major subsystem.

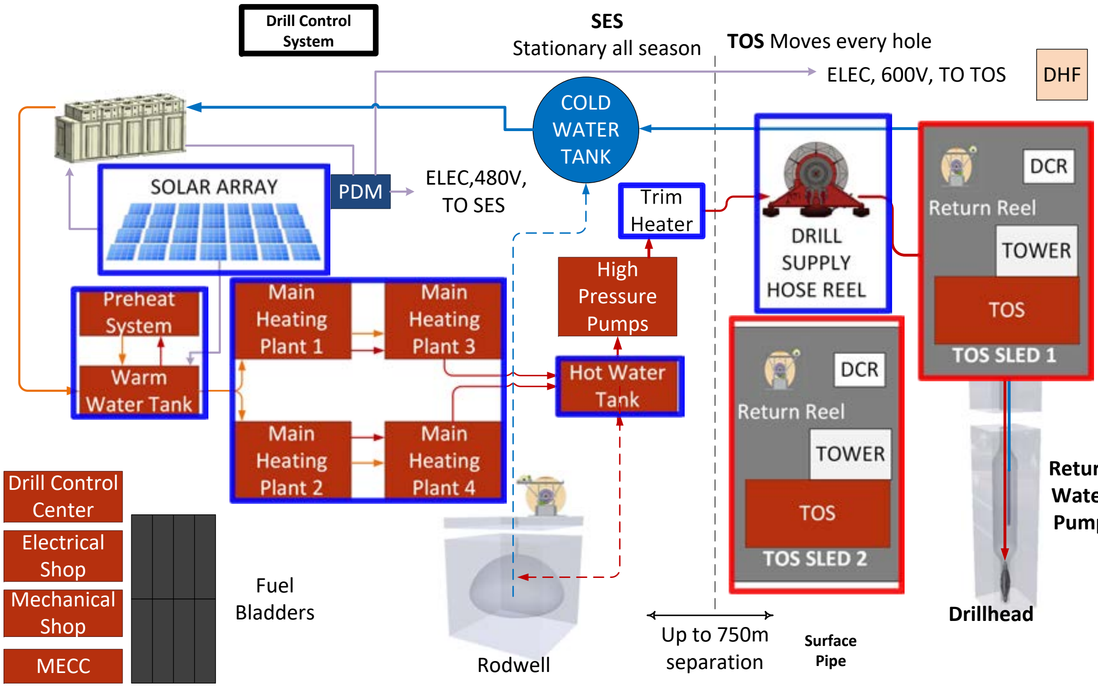


Figure 12: Water flow diagram of direct heating systems are highlighted in blue boxes.

- A load analysis will ensure that the PDM circuit breakers and switchgear are sized, rated, and certified for the loads and the environment. Over the years this type of equipment has experienced tremendous technical advances and cost changes, with manufacturers such as Schneider, SquareD, and Allen-Bradley providing different architectures.
- A coordination study for the circuit breakers will ensure that they will operate with minimal load interruption should they be tripped.
- An arc-flash study will determine the amount of energy that would be released during an event. This information will be utilized to minimize risk to personnel.

Power consumption for the entire system has not yet been determined; however, historic loads from many MDSs were documented. The loads for IceCube-Gen2 are expected to be similar to those of the Gen1, and for initial planning purposes this provides a good estimate. Table 2 shows power data for the Gen1. This will be updated as systems are refined, and equipment is specified.

Optimized power distribution is essential to the drill system and must be safe, reliable, and cost-effective. The components of this system are large, technical, and require considerable engineering effort to integrate. As such, power generation and distribution will be one of the main cost drivers for this project.

11.1.3.4 Direct water heating: Whitco Model 75 and DC immersion heaters

There are four heating systems that the water moves through. These systems are shown in a water flow diagram in Figure 12. First, submersible pumps in the cold WT move the water to the MT array to recover waste heat. This is accomplished by having the water flow through a Heat Recovery

Module (HRM) on top of the MT array where there is a heat exchanger located between the water (0 to 2°C) and the exhaust gas (500°C) from the MTs. Most of this water then goes from the HRM to the warm WT, but some can be returned to the cold WT to keep it from freezing (not shown on the flow diagram).

A set of vertical turbine pumps in the warm WT circulate the water through the PHS, where up to four Model 75 heaters raise the temperature of the water. A filtration system in the PHS cleans the water before it is returned to the warm WT. The temperature of the warm WT is kept at 24°C. The warm WT also holds a set of immersion heaters powered by the DC solar PV array that can be used to maintain the temperature of the warm WT, thus allowing some or all of the Model 75 heaters to be turned off.

Model 75 heaters A second set of vertical turbine pumps in the warm WT sends water to the four MHPs. Two parallel lines carry water, each to a set of two MHPs, which are connected in series. Warm water enters the MHPs at a rate of 200 GPM where it gains the majority of the temperature rise to 84°C. Hot water exits the MHPs and flows through a pre-filter and into the hot WT. In the four MHPs there are a total of 34 Model 75 heaters, although only 28 are in operation at any one time. Each Model 75 heater consumes 3.25 GPH of fuel to provide 125 kW of energy to approximately 7 GPM of water passing through it. All heaters are plumbed in parallel and the thermostats are set to heat the output water to 84°C. The MHP heaters are pictured in Figure 13.

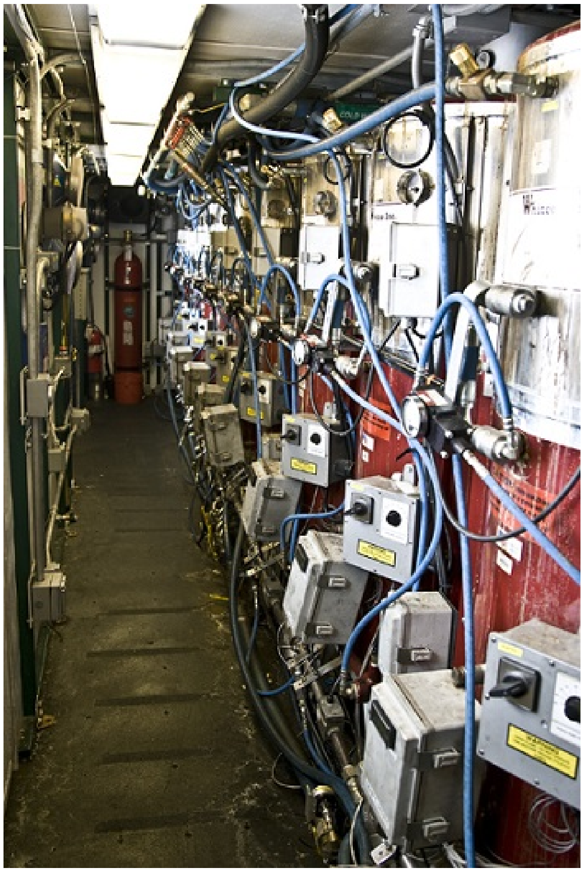


Figure 13: Model 75 heaters shown inside the Main Heating Plant

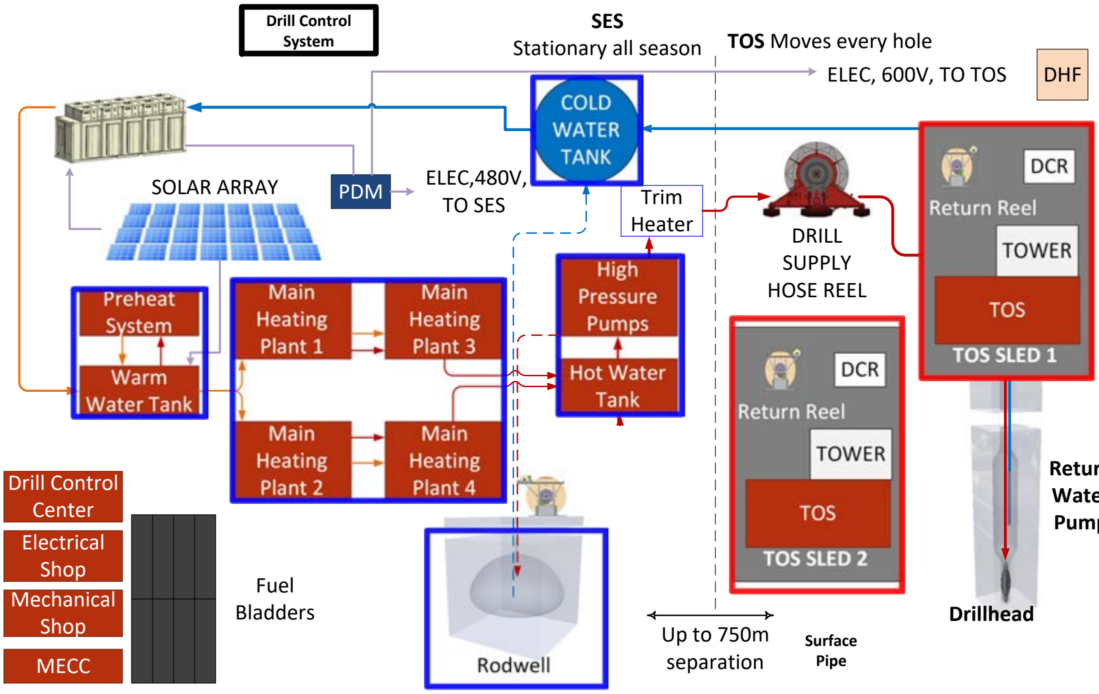


Figure 14: System diagram with water-handling system components highlighted in blue boxes.

Immersion heaters Water passes through the MHPs then flows into the hot WT where it will be stored for drilling. The hot WT currently has no electrical heating, but a system of immersion heaters powered by a DC solar PV array is planned for IceCube-Gen2. A set of electric immersion heaters will also be installed in the warm WT.

These DC heaters will add up to 800 kW of heat to the water, which would reduce the total amount of heat required from the Model 75s. Water will still flow through the Model 75s, but some of the burners could be turned off, thereby reducing fuel consumption and heater maintenance, and extending heater lifetimes. During idle mode, if there is sufficient solar insolation, all Model 75 heaters could be turned off and no personnel would be required to be on site to monitor the heating plants.

The sizing of the DC solar PV array and the immersion heater system is designed to provide sufficient heat to melt enough ice to provide the makeup water for one hole and heat it to 84°C during the expected idle period. During early season operations the immersion heaters can be used to melt snow to make water in the WTs.

Trim heaters After the water is heated by the MHPs it flows through a pre-filter and into the hot WT. Water output temperature from the MHPs is limited to 84°C for safety of personnel and to keep a margin underneath the boiling point. This margin keeps the heaters from tripping their safety limits.

Upon exiting the hot WT the water flows through a post-filter and then moves to the HPP. This MDS contains a series of high-pressure pumps that move the water to the trim heaters, which are a bank of circulation heaters that provide heat after pumping. They will be powered by the AC electrical power generation system. These trim heaters would heat approximately 200 GPM

Component	Specification
System pressure	1050 psi
System flow	200 GPM
High-pressure pumps	4
Supply pumps	2
Water tanks	3
Total water tank volume	30,000 gallons

Table 3: Specifications of the water-handling system in IceCube-Gen2.

of 932 psi water at 84°C and raise it to a temperature of 88°C. The temperature limit of 88°C was chosen because pure water at the South Pole (3658 m elevation) boils at 90°C.

The 88°C water then travels out of the SES through the surface pipe to the Drill Supply Hose Reel at the TOS to be used for drilling.

11.1.3.5 Water-handling system The IceCube-Gen2 water handling system will be modeled after the ICU water handling system. Hot water will be supplied to a water tank, where it will be pumped into a system of high-pressure pumps before being sent through the surface hose system to the DSHR. Some components will be different from the ICU system, such as the supply pumps, the surface pipe system, and some of the motor drives. Other components such as the high-pressure pumps and water tanks will be repurposed from the Gen1 system. The IceCube-Gen2 water handling system will also include filters, a Rodwell system, return water pumps, and general plumbing equipment. Figure 14 highlights the components of the water-handling system on the overall system diagram. Table 3 shows specifications of the water handling system.

High-Pressure Pump MDS The HPP system from ICU will be repurposed for IceCube-Gen2. The interior of the HPP building is shown in Figure 15. The ICU system consists of four Myers Triplex positive-displacement pumps operating in parallel. Each provides 50 GPM to pressurize the water system flow to 200 GPM and 900 psi. In the event of a pump going offline, three pumps are able to provide 65 GPM at 900 psi to maintain drilling requirements.

Each of these high-pressure pumps are driven by a 50 HP Baldor motor. Each pump is coupled to its motor with a toothed belt drive. For ICU the motor drives will be updated from 50 HP Unico vector motor drives to 50 HP Allen-Bradley variable frequency motor drives. For IceCube-Gen2 the Baldor motors and their Allen-Bradley motor drives will remain in the system. There is a spare Baldor motor in storage at the South Pole.

Due to the configuration and operating specifications of IceCube-Gen2 some changes will need to be implemented. The Myers pumps will require internal components such as seals, valves, and seats to be replaced with parts rated for the higher water temperature. This work can be performed on site. There are two spare Myers pumps in storage at the South Pole.

Each pump has a one-gallon 3000 psi accumulator to dampen pressure spikes caused by the pump. These accumulators will require new bladders, as the current material (buna-nitrile) is not rated for the higher temperature of the IceCube-Gen2 water. They will need to be replaced with an ethylene propylene bladder.

Figure 15: Four Myers pumps (green) and Baldor motors (gold) inside the High Pressure Pump building.

Each pump has a pressure-relief valve (PRV) that is set to open at 1200 psi. These PRVs protect the system against overpressure. They are not rated for the high temperature fluid that will be used in IceCube-Gen2, therefore will need to be replaced.

Supply pump A pump will transfer water from the hot water tank to the HPP. Four Grundfos submersible pumps are planned to be used for ICU, but they are not rated for high temperature and so cannot be used in IceCube-Gen2. The HPP requires 75 PSI at the suction end for high-temperature fluid. A replacement for the Grundfos pump could be a centrifugal pump with an inducer that allows the high-pressure pump to operate with a low Net Positive Suction Head (NPSH). The proposed pump is shown in Figure 16.

The body of the pump is made of stainless steel. The supply pumps will supply between 65 to 80 GPM and 115 to 140 psi to each HPP to reduce the risk of cavitation. The preferred pump candidate is the SPX Flow model number SPX W+ 70/40. This pump can operate with a low suction pressure due to the inducer at the inlet of the pump. Also, this pump is streamlined so there are not many components; this simplifies the system and makes servicing the pumps easier for the field team.

The plan for IceCube-Gen2 is for two centrifugal supply pumps to operate in parallel. They will pump water through a manifold that evenly delivers water to all four HPPs. Two pumps in the system will provide redundancy in the event of one pump going offline. Each pump could

Figure 16: An SPX Flow centrifugal pump will transfer water up to 80 GPM and 115 to 140 PSI from the hot water tank to the HPP. The pump is shown attached to a 50 horsepower Baldor motor.

supply the necessary flow and pressure required by the HPP suction. The centrifugal supply pumps operate via a 40 hp motor that requires 3-phase 60A 460V power. Each pump motor will be operated with an Allen-Bradley motor drive. The centrifugal pumps use mechanical seals, therefore do not require extensive servicing before or after the drilling season.

The pumps will be located near the HPP MDS and the water tanks. There are two options for the location of the pumps in relation to the water tanks.

- The pumps could be positioned next to the WT where a port feeds water from the base of the tank into the pump. This option requires minimal changes to the WT and minimal effort to position both the WT and the pumps.
- The pumps could be positioned in a small hole dug out underneath the WT prior to positioning the WT. In this case, a port would feed water down to the pump from above. This option would require additional effort to dig a hole and make the connection to the pump, however it provides increased Net Positive Suction Head (NPSH) for the centrifugal pump.

A new building will be required to house these supply pumps, their motor drives, support equipment for an additional water tank, and the trim heating system.

Surface pipe ICU will employ an ethylene propylene diene monomer (EPDM) rubber surface hose with a pressure rating of 1000 PSI and polyethylene foam insulation. The ICU surface hose has a 2.5 in ID and delivers water from the SES to the TOS. The ICU hose will not be used in ICU-Gen2 for several reasons:

- IceCube-Gen2 requires higher pressures than the ICU surface hose is rated for.
- A larger hose ID is necessary in order to minimize pressure losses and improve thermal efficiency.
- Custom ordering a 3" ID hose similar to the ICU hose is not an option because the vendor for that hose is not able to produce a product with the required pressure rating.

IceCube-Gen2 may use a multi-layer insulated pipe rated for 1300 PSI with an ID of 3". IceCube-Gen2 hose will be procured through one of two possible vendors: Rovanco or Tricon. The hoses between these vendors are nearly identical, only differing in insulation thickness. Figure 17 shows a cross-sectional view of all dimensions and materials along with a hose sample from Tricon.

Figure 17: Left: Cross section of insulated Rovanco pipe. Differences in Tricon dimensions are shown in blue. Right: Sample of a cross section of insulated pipe. This sample features the polyisocyanurate insulation and a layer of pyrogel (cryogel/aerogel), which is another form of insulation.

Insulated stainless steel pipe is appealing because it has a higher pressure rating and it offers custom options for lengths, joints/unions, and jacket material. The jacket needs to be made of a material that will allow the assembly to slide easily over the surface, without the risk of melting the snow underneath it and sinking. It also needs to be durable enough to withstand the ambient conditions. The preferred jacket material is high-density polyethylene (HDPE) for its smooth finish and low-temperature rating. The plan is to have a majority of the surface line consist of insulated pipe with occasional joints and both ends (the SES and TOS DSHR connections) made up of a short section of braided metal hose. Using hose sections at the SES and TOS DSHR allows for easier connection by the drillers.

A surface hose heat loss analysis was conducted to compare the two IceCube-Gen2 hose options to ICU hose. Given known parameters of temperature, pressure and flow rate at the SES in conjunction with the calculated heat loss, the water state entering the TOS can be predicted. Heat loss calculations were conducted using a 1D-cylindrical, steady state, convection model representation and assume that most of the heat loss is through convection out to the ambient air. Table 4 shows a comparison of results between Rovanco, Tricon, and the IVG hose from ICU.

While these results are theoretical they provide an estimate of what can be expected in the field. The water temperature drop is anticipated to be slightly higher than what the results indicate. However, this analysis does show that the IceCube-Gen2 insulated pipe has greater thermal efficiency than that of the ICU hose.

	Tricon	**Rovanco**	**IVG Hose**
Temperature drop (℃)	0.4	0.4	0.7
Pressure drop (psi)	71	71	168
Heat loss (kW)	18.6	18.7	37.8
Surface temperature (℃)	-28	-28	-23

Table 4: Comparison between IceCube-Gen2 pipe candidates and IVG hose from ICU.

Figure 18: Left: Water Tank 2 at South Pole is shown in service during IceCube Gen1. Two of the existing water tanks will be repurposed for Gen2, and a third will be purchased to accommodate more water capacity than Gen1. Right: The “doghouse” structure on top of the water tank that shelters (from left to right) a vertical turbine pump, a bag filter, a vertical turbine pump, and a centrifugal pump.

For drilling, IceCube-Gen2 will have to be more strategic than IceCube-Gen1 and ICU regarding moving the pipe between holes. The current plan is to move the surface pipe in a manner similar to a windshield wiper, where the pipe swings in an arc which reaches all of the holes to be drilled during that season. This process is simplified by including quick connections and sections of flexible metal hose between larger sections of the rigid, stainless steel pipe.

For the first three drilling seasons no SES moves are required in order to hit all holes, and the path can be optimized by grouping holes in arced paths. Using this method, the flexible hose would allow the rigid pipe to swing across the arc.

Water tanks IceCube-Gen2 will feature three water tanks: A cold water tank, a warm water tank, and a hot water tank. The cold WT will store water that is pumped out of the Rodwell, and water that is returned from the hole. The warm WT will store the water that is heated by the exhaust-heat exchanger in the MT array, and water that is circulated through the Model 75s in the PHS. The hot WT will store the water that is heated by the MHPs. Two of these water tanks will be repurposed from the ICU drill system.

One tank will need to be purchased. The existing water tanks each have a capacity of 10,000 gallons. They have insulated walls with a stainless-steel panel liner. It has not yet been determined which of the three tanks (cold, warm, or hot) will be the new tank and which will be a repurposed ICU tank. A preliminary analysis was conducted to verify that the ICU tanks have sufficient insulation to meet the IceCube-Gen2 system requirements. The results show the ICU tanks will stabilize at 88°C.

Additional iterations of this analysis will be run to ensure the validity of the results, however the initial results are promising and provide evidence that the ICU water tanks have sufficient insulation in their current state.

Filters Two types of water filters were used in the ICU drill system: Centrifugal filters and bag filters. Due to the nature of snow at the South Pole and the multitude of components that the water comes into contact with, debris is expected to infiltrate the water system. Filters prevent this debris from damaging sensitive equipment throughout the system as well as preventing backups or blockages. IceCube-Gen2 will use filters that are similar to those used in ICU. Centrifugal filters are used to filter out larger debris while bag filters are used to filter out particulates as small as 25 microns. These specifications are carried over from ICU.

There will be filters before the hot water tank (pre-filters) and filters after the hot water tank (post-filters). There will also be a combination of a centrifugal filter and a bag filter in the PHS. The plan is to reuse the ICU filters. However, a thorough inspection and evaluation of the filters has not yet been conducted. Should any filters be determined to be unsuitable for continued use after ICU then stainless steel filters will be purchased. Using the ICU filters would reduce project cost and implementation. If new filters are needed, purchasing stainless steel filters would prevent future corrosion within the filter housing and ensure reliability for the duration of the project.

RodWell System (RWS) For the Gen1, surface pumps move water from the cold WT to heaters in the RWS. The heated water is sent through the RWS hose reel and delivered to the Rodwell. A submersible pump in the Rodwell then closes the loop by circulating cold melt water from the Rodwell back to the cold water tank. The RWS design for IceCube-Gen2 is not yet finalized. ICU intends to use the ARA hot water drill system for the RWS, however the ARA system is undersized for IceCube-Gen2.

Return water pumps The return water system includes two pumps: a downhole pump and a boost pump. The downhole pump is lowered into the drill hole to deliver melt water to the surface. The boost pump assists the downhole pump in delivering the water on the surface into the cold WT. ICU is reusing the downhole pumps from IceCube-Gen1. IceCube-Gen2 may also reuse these downhole pumps, depending on their smooth operation during ICU drilling. If the downhole pumps do not meet the requirements then new ones will be purchased. This same plan will be applied to the boost pumps.

11.1.3.6 Tower Operations Site (TOS) The TOS is where the deep drilling and deployment operations occur. Design objectives for the two TOS sites are to minimize labor and time required to transition from drilling to deployment and during hole moves. Also, the TOS will be packaged on a sled to allow for improved mobility over ungroomed terrain.

The tower, TOS double-wide building, MDCR, and return water reel system will be consolidated onto one sled. This is an improvement from the ICU design which required each component to be individually positioned on the snow. A layout of the TOS design for IceCube-Gen2 is shown in Figure 4. The old layout for IceCube-Gen1 and IceCube Upgrade is shown in Figure 5 for comparison.

Operational improvements A significant amount of labor involved with TOS relocation, setup, and teardown is eliminated by permanently fixing the positions of these systems with respect to the drill tower on the TOS sled. Mating of the TOS/Tower, positioning, alignment of reels, cable setup, and pulling cables and hoses into the towers are all steps that would be eliminated by this design. Trenching and anchoring is not required for the MDCR and Return Water Reel (RWR), which is advantageous for holes located in areas of densely buried cable. The operational efficiency resulting from these improvements will be taken advantage of 120 times. This will contribute to reductions in seasonal labor costs.

The positions of the MDCR and RWR were chosen such that the TU-20 deployment reel can be staged and setup during drilling long before deployment activities are started. This is an improvement over Gen1 because placement of the TU-20 reel for deployment could not begin until

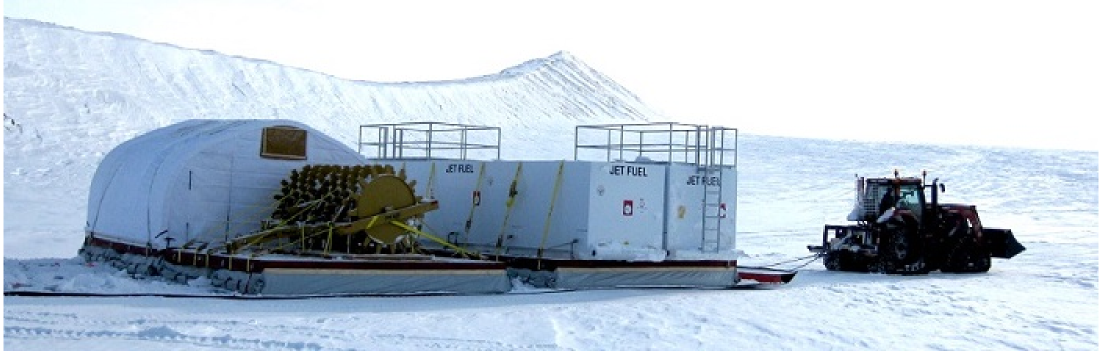


Figure 19: ARCS carrying two 25,000-lb steel fuel tanks and a 14,000-lb roller-packer for an outbound trip from Thule to Summit Station.

all other reels were relocated after drilling. This would eliminate 4 to 6 hours of time between the end of drilling and the start of deployment, thereby increasing operational efficiency.

A trade study will be conducted to investigate the feasibility of using an automated hose-taping system. This system is currently outside the scope of the design but may be implemented depending on the cost and likelihood of developing a robust system. The Gen1 system required a driller to tape the drill supply hose to the main drill cable every few feet as they traveled down the hole together. This ensured that the vertical load from the downhole equipment was distributed between the hose and cable. This is a repetitive, labor-intensive process that could potentially be automated. If an appropriate system could be developed, this improvement to the tower design would likely reduce labor requirements, and therefore seasonal costs.

TOS ARCS The IceCube-Gen2 TOS is packaged onto a large ARCS. The decks of ARCS are supported by air-filled pontoons over HMW-PE sheets. These types of sleds have been used in the past for high-payload polar traverses, as depicted in Figure 19. They have superior performance to ski-based cargo sleds, especially when moving on a fresh snow surface. Experiments performed by the U.S. Antarctic Program show they have a coefficient of friction (COF) of about 0.11.

Baseline design The full 40 ft x 60 ft sled is made from 8 ft x 30 ft basic units. These are shown in Figure 20. The design target is a 200,000-lb payload weight. Each basic unit has three pontoons, each filled to 1 psi, and a poly sheet underneath. All units are connected together using steel straps to ensure sufficient structural integrity. Safety handrails 42 inches tall are attached to the wooden decks. Depending on the layout of the TOS equipment, one of the basic units that supports the tower structure would have a cutout so that the drill could be lowered through it.

The intent is to make these 8 ft x 30 ft basic units so that they can be easily shipped on an ISO flat rack container to McMurdo Station where they will be assembled into the full size sled to be traversed to South Pole.

Alternatives The following are possible modifications to the ARCS pontoons:

- **Foam-based sled** Rectangles of polyethylene (PE) foam could be used to replace the air-filled pontoons on the ARCS. This foam type is known as closed-cell with a firmness level of extra firm, and has a COF of 0.11 on snow. It is rated for temperatures as low as -110°F. The

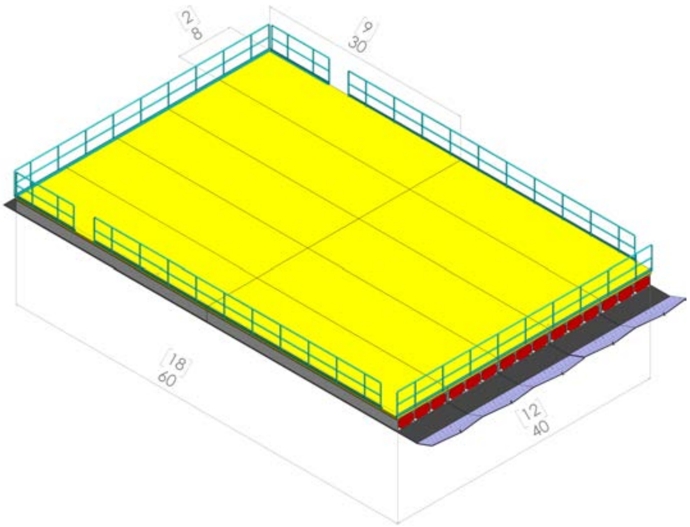


Figure 20: Base structure of an ARCS. Railings are required in the design to protect personell from falling when working on the Tower Operations Site. The length of the sled is 60 feet, and the width is 40 feet, made up of 10 individual panels that are 30 feet long and 8 feet wide. Bracketed numbers in the figure are meters.

foam density is 2 pounds per cubic foot (PCF) and the indentation-load deflection (ILD) is 90. It is not water absorbent and is difficult to tear due to its excellent tensile strength.

- **Tire-based sled** From a force-of-friction standpoint, rolling is generally better than dragging. The air pontoons and PE sheet could be replaced with tires that have low surface pressure, and therefore the sled would have a lower net COF. A comparison of the different options for the sled base is summarized in Table 5. Further development is required to compare the ARCS and foam based sled options. The tire based sled concept was too expensive and difficult to repair and was eliminated from consideration.

Towers Each drill tower contains hardware and equipment required to direct the Drill Supply Hose (DSH), Main Drill Cable (MDC), drill head, and return water cable, hose, and pump through the drill hole. There are also instruments that provide feedback to the control system to coordinate drilling and instrument deployment. The towers from Gen1 will be re-used, after some slight modifications.

The original crescent design was driven by requirements that no longer apply. The design was driven by a maximum height constraint for the tower related to flight regulations at the airfield. This requirement is not a factor for IceCube-Gen2.

Tower improvements will include replacing the crescents with a simple, more robust design using large-sheaved wheels. The existing crescent design uses a belt that has carriages attached along its outside surface that travel in a D shape around the crescent as the hose passes over it. This design requires belts that can be worn and bearings that need to be serviced and occasionally replaced. Using sheave wheels will reduce the preventive maintenance requirements associated with the current crescent design.

The sheave wheel also offers control system improvements. The existing crescent requires higher inertia and friction between the hose and belt to rotate, which can result in slippage and the potential for gaps in feedback from the encoder to the control system. The sheave wheel

Criteria	ARCS	Foam-Based Sled	Tire-Based Sled
Target weight of load (lbs.)	200,000	200,000	200,000
Tare weight (lbs.)	~37,500	~38,500	76,000
COF	0.11	0.11	?
Ground pressure (psi)	~0.68 With each pontoon filled to 1 psi	~0.69	~5.0 With tires filled to 1.5 psi
Cost estimate ($)	62,000	83,970	176,000
Pros	• Low tare weight • Prior use in Antarctica	• No potential for leaks	• Expect to have a lower COF
Cons	• Potential problem of small leaks	• 1000 lbs. more tare weight • Expensive • Design is untested	• Very expensive • High tare weight • Repairs are difficult

Table 5: Comparison of IceCube-Gen2 sled-base options.

design requires less inertia and friction to rotate, therefore the encoder will provide a more reliable output signal. The Gen1 TOS towers are shown in Figure 21.

Main Drill Cable Reel (MDCR) The MDCR and level wind system will be located on the deck of the TOS sled. This would require a solution for compact cable management. For this reason, the design includes a right-angle level wind. Two identical MDCRs and two identical level wind systems are required for IceCube-Gen2. This will require a combination of refurbishing, modification, and fabrication of existing equipment. The plan for this is outlined below:

- Main Drill Cable Reel 1: Refurbish and modify ICU Main Drill Cable Reel to work with a 90° level wind.
- Main Cable Reel 2: Refurbish and modify an existing reel owned by PSL that is similar to the ICU MDCR. If this is not feasible or cost-efficient a new reel will need to be fabricated. A trade study will be conducted to understand the best option.
- Level Wind Systems 1 and 2: New design and fabrication based on the 90° level wind system used by Ice Drilling Design and Operations (IDDO) of UW-Madison. See Fig. 22.

The level wind system for IceCube-Gen2 includes an improved control system and mechanical design to allow automated cable winding. The ICU system uses an electronic gear ratio, limit switches, and pre-programmed dwell times to wind the cable onto the drum. The current strategy requires frequent observation and manual intervention to smoothly transition between layers. The IceCube-Gen2 system will incorporate a closed-loop feedback system that monitors the fleet angle between the drum and level wind sheave. The system involves a higher level of automation. This decreases the risk of creating instabilities in the load sharing controls due to imperfections in cable winding and reduces manual intervention during cable winding. This

Figure 21: Towers 1 and 2 are shown from Gen1 operations. For Gen2, the towers will be on top of an Air Ride Cargo Sled and no longer on the snow.

technology has been proven in the IDDO Disc Drill over several seasons at WAIS Divide. It is illustrated in Figure 23.

Another option is being investigated that would eliminate the requirement for the 90° level wind system. This design would use the existing level wind (as used in Gen1) but with a modified roller design so that the cable could never exceed its maximum bend radius even at extreme fleet angles. If it can be proven, this simplification would offer large cost savings and reduce the complexity of the design. .

Return Water Cable/Hose Reel The ARA Hot Water Drill cable/hose reel is shown in Figure 24. This system uses a bundle comprised of a combination power/signal cable (similar to the combo cable used on the Gen1 and the ICU drill), and a hose. Instead of using two reels at each TOS to carry the combo (power and signal) cable, and the hose separately (as done on the Gen1 and the ICU drill), all utilities are bundled together into one system. Since this approach proved to be challenging to build and manage for the ARA system, the design will be improved for IceCube-Gen2.

There will be one return water reel on each TOS sled. This approach reduces the number of reels required from four (used on Gen1 and the ICU drill) to just two for IceCube-Gen2. It will use a single cable/hose, known as an umbilical, that carries power, signals, and water all in one unit. The umbilical also contains an integrated strength member.

The umbilical is an improvement over a cable/hose bundle design. Combining all utilities into a single cable makes the system more robust and eliminates the need to manage separate

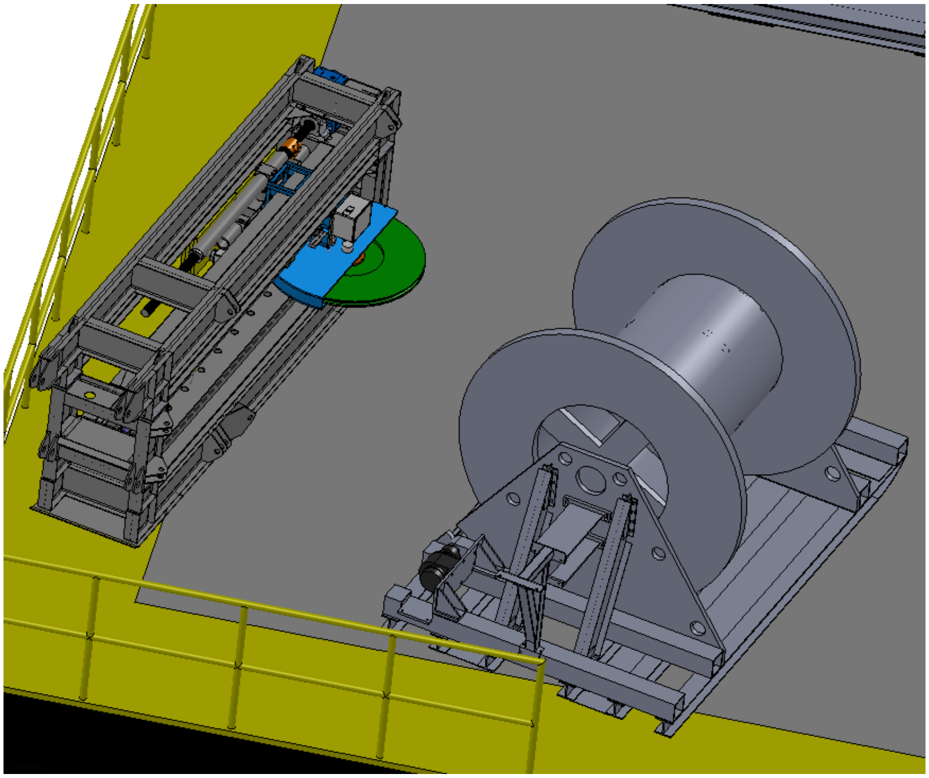


Figure 22: Left: 90° level wind system and the Main Drill Cable Reel is shown on the right. This arrangement is necessary to protect the main cable from exceeding its maximum bend radius and because the arrangement of equipment on the Tower Operations Site is compact.

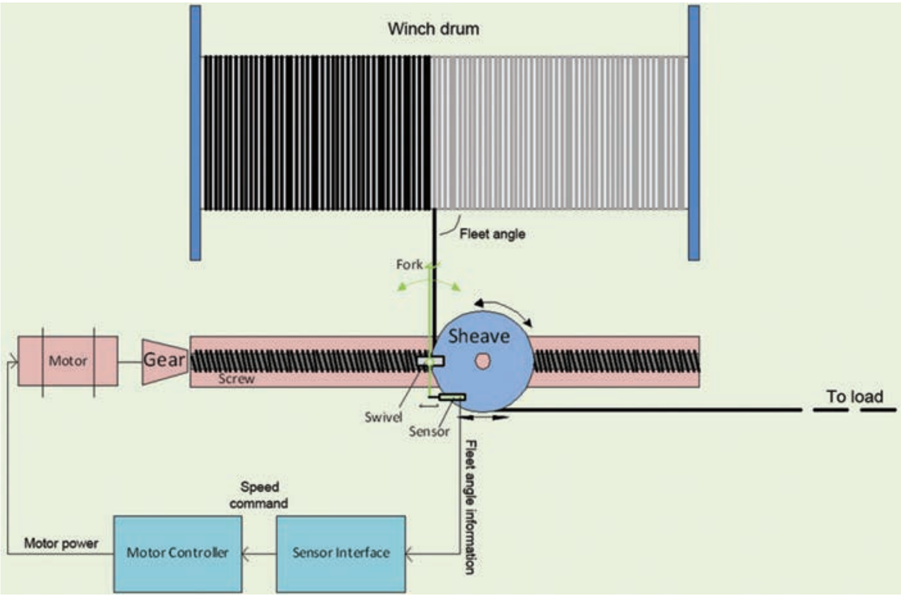


Figure 23: A closed-loop feedback level wind system diagram is shown. Wrapping the cable back onto the drum uniformly without automation is time-consuming. By maintaining a 90-degree angle of the cable relative to the winch drum the cable is wrapped uniformly. This automation reduces time-consuming labor required for manual winding and improves the quality of wraps. [2].

Figure 24: Antarctic Rodwell Apparatus Return Water Cable/Hose Reel. This design accommodates the usage of a bundled cable that carries power and signal. This allows the design to be compact enough to integrate onto the Tower Operations Site Air Ride Cargo Sled.

cables. A spare umbilical is an affordable risk-mitigation plan due to the short length required (200 m).

Each return water reel will be a dual-drive, single-width, spiral reel. It would need to fit onto the space available on each TOS sled, which means that a critical step is to determine the diameter of the reel. This spatial modeling has not yet been completed.

Drill Supply Hose Reel (DSHR) The Gen1 and ICU drill DSHR will be reused, with some operational improvements. The current design of the DSHR includes metal skis that the reel is moved on. The skis often dig into the snow and made it difficult to move the reel between holes. The DSHR used for Gen1 and continued to be used for the ICU drill is shown in Figure 25.

The design objectives for IceCube-Gen2 are to reduce friction and decrease ground pressure by modifying the weight distribution of the reel and putting a polyethylene sheet under the skis to act as a sled.

TOS building The TOS building is a double-wide ISO container mounted on the deck of the TOS sled. This building will be reused from Gen1 and the ICU drill. Its purpose is to provide shelter and a working area for the instrument installation process.

The DOM Handling Facility (DHF) is a building added to the system for the IceCube Upgrade and fitted with a telescopic knuckle boom truck crane converted to be used with generator power. The optical sensors are stored in cardboard boxes organized in pallets. The pallets are delivered to the active TOS site on a ultra high molecular weight polyethylene (UHMW) sled, then lifted into the DHF using the crane. Once unpalletized, the sensors are slid into the TOS

Figure 25: The Drill Supply Hose Reel from Gen1 and the IceCube Upgrade will be repurposed for IceCube Gen2.

building via a roller conveyor spanning the two buildings. The DHF was designed so that no changes to the TOS buildings would be required.

Drill supply hose The drill supply hose will utilize a well-proven design that was implemented for the Gen1 and the ICU drill. The specifications are shown in Table 6. The hose is designed to withstand up to 1500 lbs. of tension using high-strength Aramid fibers. These fibers are also known informally as boot straps.

The design and construction of this hose is the result of several iterations over the course of the Gen1 effort, resulting in a reduction in fillers in the EPDM for a low specific gravity and optimized boot strap materials and geometry. Extensive cyclical bend-testing at operating load and pressure was completed before it was used on the Gen1. The design worked well throughout the Gen1 project, and this same design will be implemented for IceCube-Gen2.

Material	**Heat-resistant EPDM rubber**
Temperature range	0°C to 90°C
ID/OD	63.5 mm / 95 mm 63.5 mm / 95 mm
Working pressure	1000 psi
Specific gravity	1.04
Rated tension	1500 lbs.

Table 6: Drill supply hose specifications.

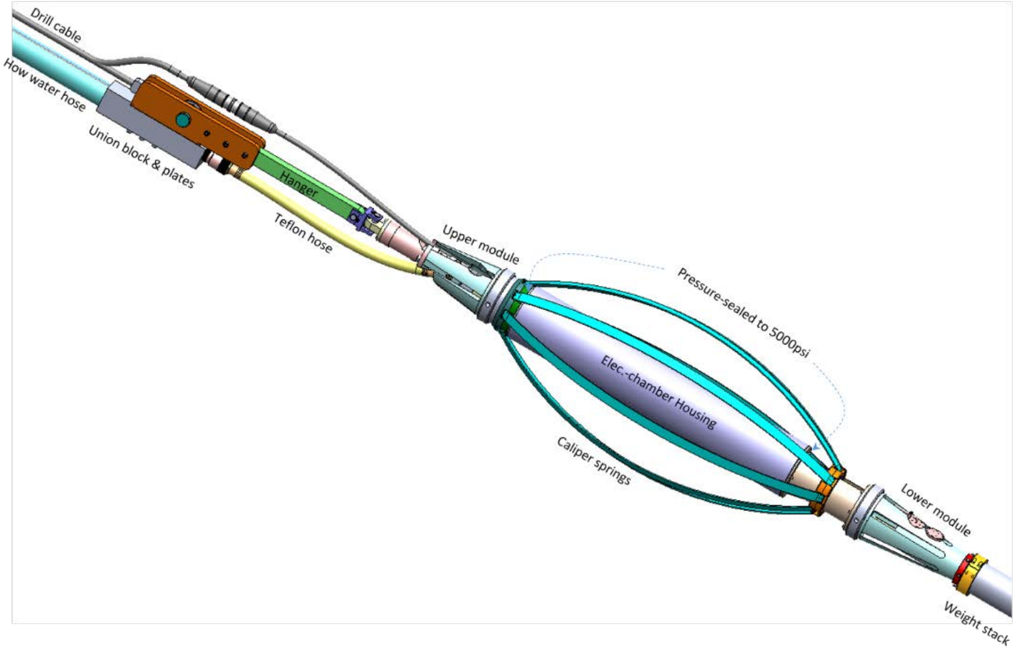


Figure 26: Drill head mechanical components.

Drill heads The progress of the drilling operation is monitored through numerous sensors, located in both the drill head and the uphole instruments. There will be one drill head at each TOS. The following sections describe the hardware configuration of the drill head, and its related subsystems.

Drill heads: Mechanical In the middle of the drill head, a cylindrical shell houses an internal column with mounting surfaces for the instrument package and electrical connectors, as shown in Figure 26. This section is pressure-sealed with end caps using T-seals and backup rings at each end of the column which could withstand 4500 psi of external pressure at 3000 m. The column also provides a thermal break between the electronics hardware and the hot water pipe.

A caliper assembly with eight spring leaves is attached to the drill body to measure the average hole diameter. The operating range is a 12 in diameter to a 30 in diameter. This is done by using the deformation of the springs to move a magnet sleeve along a Magnetostrictive Linear Displacement Transducer (MLDT). In addition, the caliper springs serve to keep the drill body centered in the hole and provide a pivot for the weight stack to hang from, keeping the hole straight during drilling. The caliper assembly is designed to rotate freely about the drill axis.

Drill heads: Electronics In the drill, a variety of sensors are employed to observe the physical quantities of interest. This includes a load cell to measure weight on the main drill cable, a pressure transducer to measure the depth of the hole, a number of temperature sensors to record hose water temperature, hole ambient temperature, instrument compartment ambient temperature, and heat sink temperature, a cavity air pressure sensor, two T-seal pressure sensors, regulator input and output voltage sensors, and two MLDTs to record hole diameter as registered by the drill calipers. The drill also contains a navigation package that gives the tilt of the entire drill assembly in both the X and Y-axis (where the Z-axis is the vertical) and the compass heading of a fixed reference point on the drill.

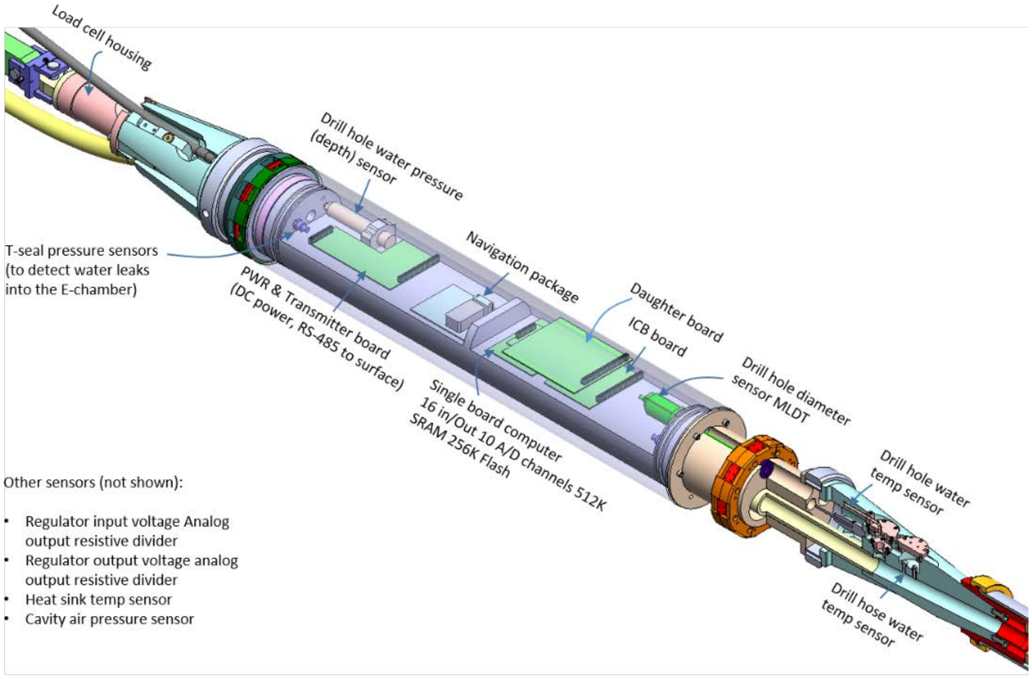


Figure 27: Drill head electronic components.

Drill heads: Power and data transmission The main 24 VDC drill head power supply is fed by a 0 VDC to 100 VDC power supply (Kepco ATE 100-1DM) located on the surface. Electrical current is carried by the 3200 m drill cable to a local DC/DC converter on the drill head. There are a total of 15 cables inside this cable assembly: Three 20 AWG twisted pairs with drain wires, and six 18 AWG power cables (three carry source power, and three are used as ground wires). The DC voltage at the surface is set to a fixed voltage with sufficient headroom to account for resistive losses in the conductors.

Data is carried over an individually-shielded, 3200 m twisted pair, through the slip ring at the cable reel shaft, and over an additional length of twisted pair to the drill power supply and communications interface box located in the TOS. All data values are formatted into fields of a single ASCII string. This single string is transmitted by the onboard controller to the surface at 9600 baud. In terms of bandwidth, the transmitter sends up to five 123-byte data strings per second from the drill head to the surface, which is sufficient for the drilling effort.

The hole diameter requirement for IceCube-Gen2 remains nearly the same as for the first generation of IceCube (40 cm IceCube-Gen2 vs. 45 cm IceCube-Gen1) despite the increase in depth requirement from 2450 m to 2600 m.

The existing IceCube-Gen1 drill heads (X-drill, Y-drill, and R-drill) were all mechanically designed to work at a depth of over 3000 m. For IceCube-Gen2, the design will use the same mechanical assembly but replace the electronics package and reduce its size to potentially allow inclusion of additional instruments or batteries. The communication protocol will be changed from serial RS-485 to a higher frequency band, and greater noise tolerance for data such as Digital Subscriber Line (DSL) to improve the reliability of the drill head operation.

Main drill cable The plan for the IceCube-Gen2 main drill cable is to reuse the same cable design as the ICU drill. The cable length is 3200 m with a 13.4 kN maximum safe working load.

IceCube-Gen1 (Gen1)	**ICU drill**	**IceCube-Gen2 drill**
Unico motor drives	Allen-Bradley motor drives	Allen-Bradley motor drives
Custom-programmed controls	Industrial standard Allen-Bradley PLC	Industrial standard Allen-Bradley PLC
Python user interface	Industrial SCADA (Ignition)	Industrial SCADA (Ignition)
Serial Network	Ethernet	Ethernet
DGH Sensor I/O	DGH Sensor I/O with Remote PLC I/O	Local: PLC backplane-based Remote: Ethernet-based

Table 7: Summary of control system evolution over three generations of IceCube drill systems.

This is a dual-purpose cable that is designed to carry power and signal to the drill head and to carry the load downhole to protect the hose from being overloaded. This design has been proven to be mechanically and electrically robust.

11.1.3.7 Control system

Building on control strategies utilized during Gen1 and the planned ICU drilling efforts, the IceCube-Gen2 hot water drill control, communication, and monitoring system will be upgraded based on standard automation models used across industrial, production, and public utility infrastructures. The core of the system will employ a distributed control system using commercial off-the-shelf hardware controllers (PLCs), which will be custom-configured and programmed for the IceCube-Gen2 drilling effort. Table 7 shows how the control system has changed over the generations of IceCube. The primary goals of the control system are to design a low-maintenance framework, meet or exceed performance requirements, and exceed standard safety protocols.

SES Control operations will be centralized within the DCC. The core control and monitoring of all SES functions will be executed from the DCC. Each MDS in the SES will be connected to the DCC over standard Ethernet connections. Network-enabled instruments within each MDS will interface the data monitoring system to physical sensors located in the MDS. These instruments will include analog/discrete I/O blocks, high-speed counting hardware, and Ethernet connected motor drives with I/O modules installed. A section of relevant monitoring and control information will be displayed via dedicated touchscreens to allow local operators transparency into MDS-based metrics.

TOS Each TOS will utilize a local PLC infrastructure to add a distributed control element to the system. For example, all drilling operations will be handled within each TOS independent of the state of centralized DCC control operations. Each TOS can be linked uniquely to the DCC over standard Ethernet connections depending on which one is being used. Although drilling could be executed from the DCC, the local nature of the TOS control provides redundancy to the system in the event of a communications failure.

Control network layout All inter-MDS communications will be carried over standard Ethernet connections. Base network speeds will start at 100 M Bits Per Second (bps) and could scale to 1000 Mbps (1 Gbps) depending upon the device. A hub and spoke topology will ensure optimal, collision-free throughput between the system core in the DCC and other MDS instruments. Industrial-class network devices (switches) will be placed within each MDS to support the communications backbone. The Common Industrial Protocol (CIP) will be the standard data transport. A configurable, enterprise-grade security appliance to block unwanted network traffic (e.g., firewall) will be placed in front of the network to harden access to the system.

Software Custom application software will be required to optimize performance of the IceCube-Gen2 control hardware for the drill. Software will be written within hardware-compatible development environments to allow for the most seamless integration between controllers, sensors, and actuating devices. A top-down design strategy using industry-accepted SCADA frameworks and software will allow system developers to adopt a modular approach to mapping individual subsystem functions. Revision control will be provided using a mixture of vendor and standard solutions. Data archiving will be achieved using commercially available solutions.

11.1.3.8 Fuel system

The fuel system will consist of main supply tanks provided by ASC and hoses with quick couplers that connect from the main supply tanks to day tanks located on the drill sleds. There will also be a pump system that supplies fuel from the supply tanks to the day tanks, and a pumping loop that supplies fuel to the individual drill structures that require fuel.

Main supply tanks Tanks used to bring fuel from the station storage system to the drill site will likely be the same 5000-gallon cylindrical tanks used in IceCube-Gen1. Another option would be to use fuel bladders on a sled.

Day tank supply lines The day tanks will be supplied via hose that is rated for cold weather and fuel. It will be sized to allow flow of approx 58 GPM. There will be dry, quick-disconnect connectors on each end of the hose.

Day tank: Four tanks are required to provide the fuel for heating water and for the MDS furnaces. The day tanks will meet all National Fire Protection Agency (NFPA) codes for safety.

Two vane pumps, each with a 480V, 3-phase motor, will send fuel to the day tanks. This dual-pump system provides redundancy. The vane pumps are Blackmer TX1.5, 2.0 hp, each with a capacity of 40 GPM. They will be mounted on a stand, as shown in Figure 28.

Each day tank will have dual switches (for redundancy) to prevent the tank from over-filling or running empty. The day tanks will have an overflow basin with a capacity of 100 percent. This basin is used to mitigate any spills, should they occur. Figure 29 shows a 500-gallon day tank on a sled. Table 8 shows information about each day tank.

Day Tank Distribution System A pump loop and distribution system is located on the day tank frame. The pump loop consists of a pump that will supply a constant pressure that is optimal for supplying fuel to oil burners located in containers on individual sleds, and a distribution system made up of fuel manifolds that feed hoses to each container. The hose will be rated for fuel and sized such that it could supply the drill container with the largest fuel demand. The hose ends will use JIC connections between containers and the day tank manifold.

11.1.3.9 Ancillary Equipment

Drilling requires several pieces of heavy equipment to support operations and logistics. This ancillary equipment is shown in Table 9. The criteria for determining which equipment is owned by the project or supplied by ASC are the frequency and duration of use as well as the importance

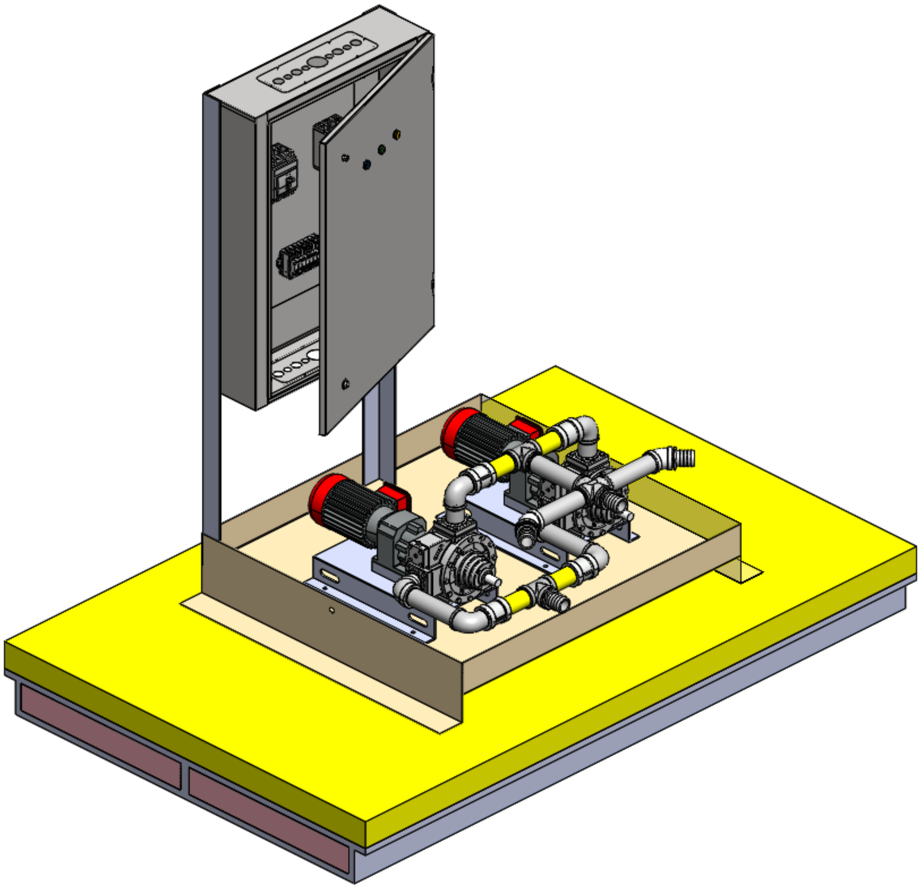


Figure 28: Dual-pump day tank stand. Two vane pumps will send fuel to the day tanks. This dual-pump system provides redundancy. The vane pumps are Blackmer TX1.5, 2.0 hp, each with a capacity of 40 GPM

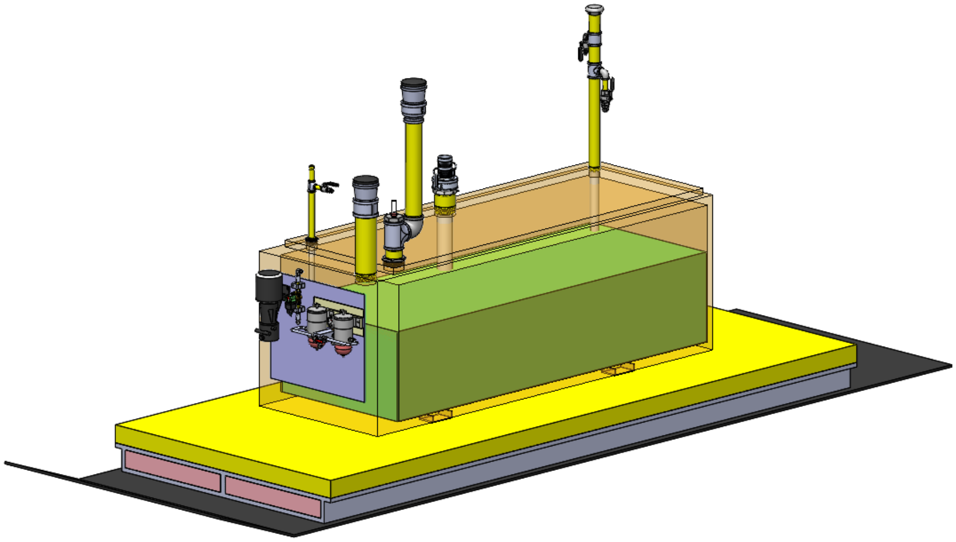


Figure 29: A 500-gallon day tank sits on a foam-based sled. Overall size of the sled is 66" x 160".The mobile tank will provide the fuel for heating water and to run the furnaces. The design includes shut off switches to prevent over filling.

Tanks	**Day Tank 1**	**Day Tank 2**	**Day Tank 3**	**Day Tank 4**
Gallons	500	500	500	300
Supply for fuel	MT generator array	MHP1, MHP2	MHP3, MHP4	TOS, firn drill, etc.
Fuel consumption (gph)	TBD	58.5	58.5	TBD
Transfer pump flow from main supply tank or fuel bladder to day tank (GPM)	40	40	40	N/A
Booster pump for pushing fuel from day tank to designated module(s)	Flow rate (min.): 90 gph Pressure range: 10 to 20 psi	Flow rate (min.): 90 gph Pressure range: 10 to 20 psi	Flow rate (min.): 90 gph Pressure range: 10 to 20 psi	Flow rate (min.): 25 gph DC-powered fuel pump

Table 8: Summary of day tanks.

of the task it is used to accomplish. Past experience from Gen1 and ICU provides confidence in selecting specific equipment required for IceCube-Gen2.

Fuel-fired heaters Early-season startup of the drill system will require portable stand-alone fuel-fired heaters. They are primarily used to heat up large pieces of equipment, such as pre-warming the DSHR. The heaters will be the same type that are typically used to warm aircraft engines in cold environments. Polartherm, ESI 700B, or HDU-43 model heaters will be purchased by the project. Figure 30 shows an example of this type of heater.

Figure 30: Polartherm ES700 portable stand-alone heater.

Equipment type	Owner	Manufacturer	Model number	Quantity
Fuel-fired heater	Project	ESI	ES700B	1
Agricultural crawler tractor	Project	Caterpillar	Challenger MT865	1
Bulldozer	Project	Caterpillar	D7	1
Track loader	Project	Caterpillar	953	1
Compact tracked loader	Project	Caterpillar	289D3	1
Snowmobile	Project	Alpina	Sherpa 1.6 liter, TI-VCT, 16V	6
Personnel van with Mattracks	Project	Ford	C-350 with 175 series tracks	1
Flat rack with ISO skis	Project	Used	40-foot	1
Independent firn drill	Project	N/A	N/A	1

Table 9: Ancillary equipment requirements.

Agricultural crawler tractor Challenger MT865 agricultural crawler tractors have been proven to be robust in Antarctica and are helpful to have available for drilling operations. Fassi loading cranes mounted to the back offer a safe method to lift heavy objects with multi-directional control. The tractor is critical for the initial setup of the SES. Other applications for the tractor include overhead lifting, cargo movement, and moving the TOSs and their reels.

Caterpillar D7 bulldozer Snow removal equipment includes heavy equipment such as the Caterpillar D7 bulldozer.

This piece of equipment will be owned by the project. It is especially useful for completing major snow removal early in the season, leveling roads and drill pads, building snow ramps, and piling snow into berms that will be used to fill the cold WT. The dozer also provides redundancy for pulling heavy drill components.

Caterpillar 953 track loader The tracked loader is a mid-sized machine that is able to perform heavy fork support, moderate snow removal, and pulling of mid-size loads such as deployment reels. It can also be used to move crates and cargo. The Caterpillar 953 has the ability to use many different attachments. The required attachments are a bucket, forks, and a stinger.

This is an essential piece of heavy equipment that is used frequently. For this reason, the project will purchase it, rather than rely on coordinating use of this equipment with the needs of the South Pole station.

Cat 289D3 compact skid loader The compact skid loader is used for light fork support, snow cleanup around drill structures, dragging hose and cables, cargo movement, adding snow to the cold WT, and light grooming. The skid loader is another essential piece of equipment that will be purchased by the project. Attachments that are required include a blade, bucket, forks, and a stinger.

Snowmobiles Snow machines are required for moving personnel from the South Pole station to the drill site, as well as between the SES and the TOS. Sleds with seats will be considered for this purpose. Snowmobiles are also useful for pulling small cargo sleds that are hand-loaded with light cargo.

Electric snowmobiles are an emerging technology that will be considered. A trade study will be conducted to determine the number of snowmobiles and sleds that would be needed based on operational requirements. A preliminary study shows that electric snow machines just started coming into the market during the fall of 2022. Therefore, more time is needed to evaluate their capabilities.

Standard snowmobiles (electric or gas) are undersized and only useful for hauling light loads and limited personnel. Mid-sized snowmobiles need to be investigated to determine if they are capable of towing larger loads and if they can be used to move power cables and surface hoses.

Vans with Mattracks Four-wheel drive vans with Mattracks have proven to be effective at the South Pole as personnel transport vehicles. It is used several times a day to transport personnel between the drill camp and the station at shift changes and at mealtimes. The van is required to be owned by the project due to its frequent use.

Flat racks Flat racks with ISO Skis are an economical way to move heavy pieces of equipment that can be connected into a subsystem but would otherwise be very difficult to put on skis. The project will purchase used 40-foot flat racks for this purpose.

Firn drill The first 40 m below the surface is a mixture of hard snow and ice called the firn layer. The firn layer is softer than the deeper solid ice layers, therefore it cannot be efficiently drilled in the same manner. When hot water from a nozzle contacts the firn it spreads out and creates an area of slush, instead of drilling a clean hole downward. IceCube-Gen1 and ICU use the Independent Firn Drill (IFD) to penetrate the firn layer and start each deep ice hole. The IFD is a system with its own water, pump, heaters, and hose reel. The IFD was refurbished at PSL so it could be used for ICU. Figure 31 shows the IFD at the South Pole.

The IFD functions by heating water and circulating it through a closed-loop conical drill head made up of stacked, wrapped copper tubes. This drill head is referred to as the carrot, and is shown in Figure 32. The copper tubes heat up as hot water circulates through them, then the carrot is gradually lowered into a small hole that was pre-drilled using an auger. The carrot slowly melts the firn, creating a relatively clean hole through this entire layer. The melted snow and ice is absorbed into the surrounding firn, therefore melt water does not need to be removed from the hole.

The IFD is completely separate from the rest of the drill system. This makes it easier to maneuver from hole to hole. The IFD will be used to create firn holes for IceCube-Gen2. Firn holes can be drilled during preceding seasons since they do not require hot water and produce an empty hole. Once a firn hole is created, it will remain open provided it is covered to prevent blowing snow from entering. Coverings are also required for the safety of personnel.

11.1.4 Integrated verification and testing (IVT) program

Procedures will be established to test critical components and systems of the drill. The procedures will be written on an as-needed basis and will include all relevant test objectives and acceptance criteria. Test requirements will be written by the subsystem owners and/or subject matter experts. Standard IVT templates were created for the Gen1 and ICU drill and can be easily modified for testing repurposed or new systems used in IceCube-Gen2. The templates for IceCube-Gen2 will be located in SharePoint to enable easy collaboration and formatting flexibility.

Figure 31: The Independent Firn Drill (IFD) shown in service at the South Pole.

Figure 32: The Independent Firn Drill head also known as the "carrot" in service at the South Pole.

The extent of IVT for IceCube-Gen2 will be determined at the end of the ICU drill project. Equipment that is intended to be reused for IceCube-Gen2 will be evaluated and retrograded for testing in the north, depending on the complexity of the test and logistical considerations. Subsystems that are new to IceCube-Gen2 will also need thorough testing, which can mostly be completed in the north prior to shipping to South Pole. Some system tests will still need to be completed in the field.

The IceCube-Gen2 drill tests in the north will be supported by the PSL test bed. This facility is used to simulate drilling scenarios and perform IVT on critical components and subsystems. The test bed consists of four main subsystems; a water loop, electrical, fuel, and the test tower and hole. The test bed will require significant updating between ICU and IceCube-Gen2, including electrical grid updates (for the MT array), refurbished buildings, electrical closet expansion, and improvements to the water supply system. Another design requirement is to replace high voltage power feeds and elevate high voltage cables above the ground by installing overhead cable trays.

In addition to the test bed, PSL has a load-rated aluminum drill tower similar to the drill towers at each TOS in the ICU drill system. The tower is an important piece of equipment used for various IVT projects in the north and will be used extensively for testing and developing new and repurposed equipment such as reels and level wind systems, as well as control system development such as reel motor synchronization, and load sharing algorithms.

11.1.5 Seasonal operations

Drilling and installation activities will take place at the South Pole station in Antarctica over the course of 10 field seasons. In total, 120 deep holes will be drilled and instrumented, along with 144 deep radio and 168 shallow radio holes. Field work is scheduled to begin the season immediately following completion of ICU, with a transition season that addresses equipment upgrades, subsystem tests, and cargo movement. Drilling activities begin in field season 2 in parallel with continued upgrades. Drilling activities will ramp up each season to a peak output during seasons 6, 7, and 8 before completion in field season 9. Field season 10 will be focused on retrograde, the removal of equipment from the South Pole.

Each season at the South Pole will run 10 to 12 weeks depending on annual station opening and closing dates, weather, and contractor support considerations. Those weeks fall between the middle of November and the beginning of February each austral summer.

The drill team population will be similar to the planned ICU team: three shifts of nine drillers each, plus a drill manager and a safety manager for a total of 29 persons. Each shift will run for nine hours with an hour of overlap on either end for turnover with other shifts. Drillers work six days a week for a 54-hour work week.

Seasonal hole plan The hole plan for IceCube-Gen2 is based on a plan of drilling 120 holes across eight drilling seasons (“drilling seasons” are distinguished from normal “on-ice” seasons). These holes must be drilled so that the new holes are adjacent to old holes and located such that the SES movements are as simple as possible.

Constraints The primary constraint on the hole plan is the total allowable length from the SES to the hole. For the first two drilling seasons the total reach will be 365 m. For season 3 and beyond, there will be up to 750 m of reach.

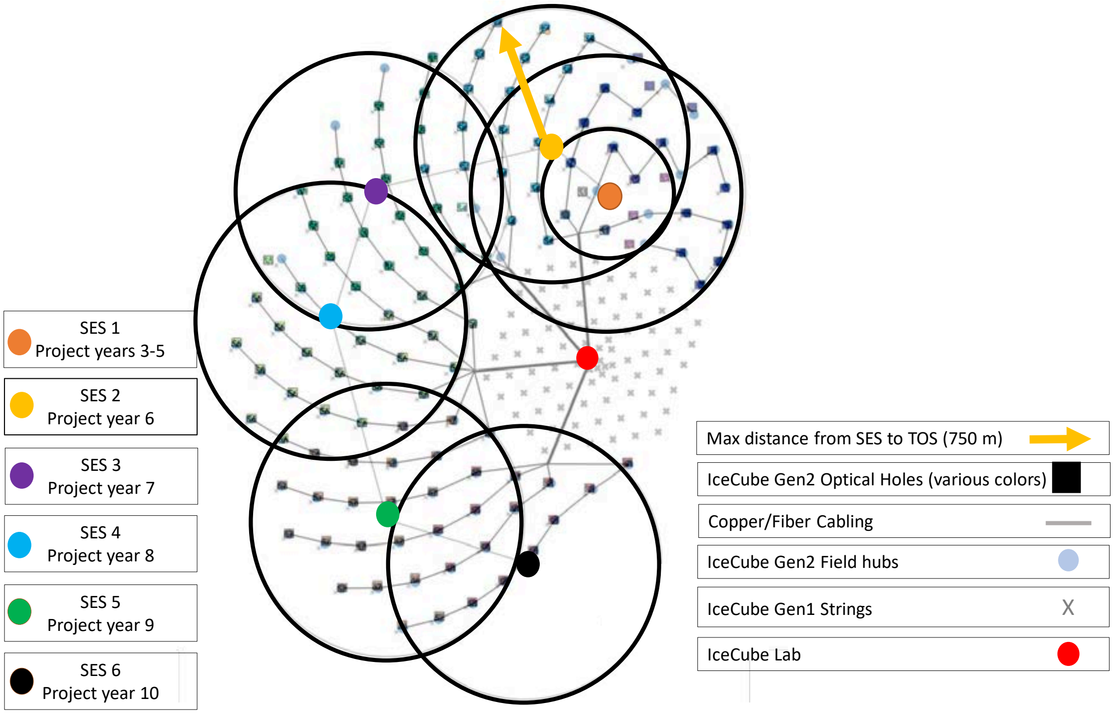


Figure 33: Map of the hole plan and SES movements.

Another requirement is that each new hole must be adjacent to an operational, instrumented hole. This is a physics requirement so that the new sensors can be immediately connected and brought online.

Hole map A map of the hole plan (Figure 33) shows each SES (Seasonal Equipment Site) throughout the duration of the project. Optical hole locations are indicated by square boxes. The large black circles show the maximum distance between the Tower Operations Site and the SES (750 m). Table 10 is included to show the Project Year (PY), SES site location and number of holes per season.

11.1.6 Drilling Schedule

The schedule is driven primarily by risk mitigation associated with getting critical components of the drill system to the South Pole by PY2 (project year 2). This equipment must be on the ice to support conversion and upgrade work that has to be completed before any drilling can start. It is critical to get experience in drilling for the drill and installation crews as much as possible and as early in the project as possible. Other upgrade work to the drill that does not need to be done to make the drill operational for practice will be done during PY3 and PY4. During PY3 and PY4 the balance of the drill upgrades will be completed after drilling is finished. By PY5 the drill system and crew need to be fully operational and ready for full scale production to ramp up to 16 holes.

The drilling implementation schedule is shown in Figure 34 and Figure 35 for PY1 through PY10 for optical, radio drilling and installation. Off ice activities are focused on large procurements

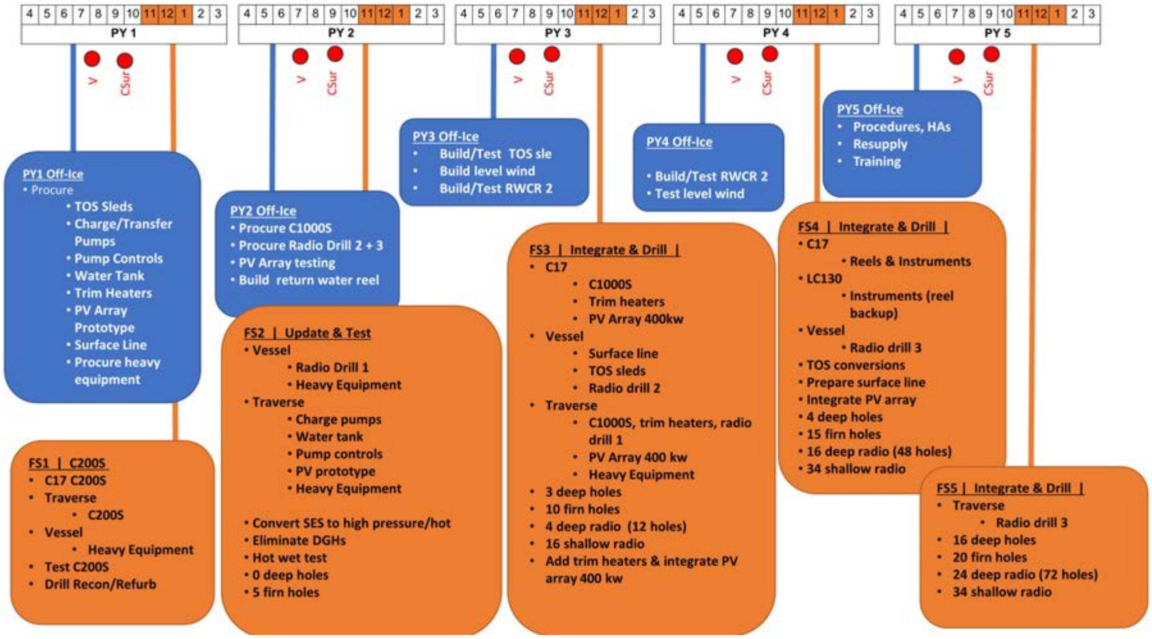


Figure 34: Drilling implementation schedule PY1-PY5. The red dots show the cadence of Vessel shipments (V) and Commercial Surface shipments (Csur).

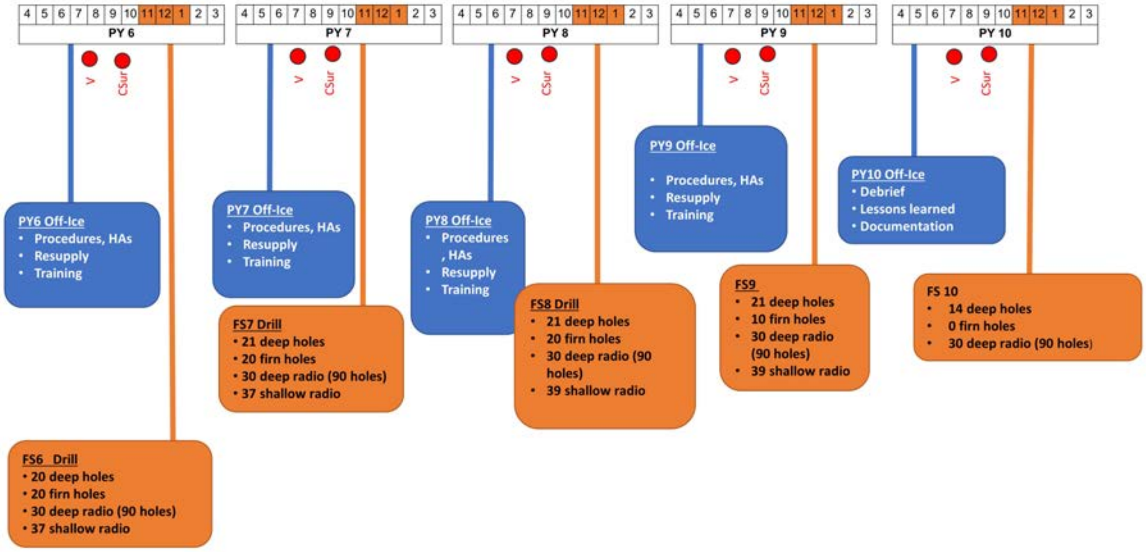


Figure 35: Drilling implementation schedule PY6-PY10. The red dots show the cadence of Vessel shipments (V) and Commercial Surface shipments (Csur).

Project Year	**Reach** (in m)	**Holes**	**SES Site**
PY3	750	3	SES 1
PY4	750	4	SES 1
PY5	750	16	SES 1
PY6	750	20	SES 2
PY7	750	21	SES 3
PY8	750	21	SES 4
PY9	750	21	SES 5
PY10	750	14	SES 6
Total	N/A	120	N/A

Table 10: Holes for each IceCube-Gen2 drill season.

and completing the drill design in PY1. Completion of the drill design is dependent on the outcome of the C200 Microturbine testing at the South Pole. If C200 testing is unsuccessful, the contingency plan for drill power will be to use traditional piston generators as used in Gen1 and ICU. This approach would require refurbishment or replacement of the existing three 225 kW Caterpillar generators and converting the PDM to automatic synchronization. As part of this contingency plan, the three Caterpillar generators and PDM will be retrograded at the end of ICU in case they are needed for Gen2. Replacement or refurbishment will occur off ice in PY2 in time to be traversed in FS3 instead of the C1000S. PY2 work off ice is focused on procurement of Radio drills 2 and 3 as well as testing the PV array and construction of the new return water reel and design completion of the 90-degree level wind system. On ice activities include controls upgrades, mechanical upgrades (SES) followed by a hot wet test of the drill system. The off-ice milestones in PPY3 are to complete builds and testing of the TOS sleds, 90-degree level wind systems and new return water cable reels. The first half of the field season will be dedicated to integrating and testing a 200 kW portion of the PV array, adding trim heaters and integrating the power generation system (Microturbine or piston generators). The latter half of the season will be used to drill 3 deep holes and train personnel. The major off-ice activities in PY4 include construction and testing of the new main drill cable reel and integration with the 90-degree level wind systems. On-ice upgrades continue to include TOS conversions and integration with the upgraded return water reels. A surface pipeline will be installed and tested, and the PV array integration will conclude. In the second half of the season, 4 deep holes will be drilled to test and commission the Gen2 system in its completed state. In PY5, the pace of drilling is increased to 16 deep holes.

Drilling increases to 21 deep holes by PY7 and continues through PY9. During the last field season, 14 deep holes will be drilled and the system will then be winterized for retrograde and decommissioning the following year.

11.1.7 Fuel Requirements

The seasonal fuel required to support deep drilling, firn drilling (direct fuels), and indirect fuel is summarized in Table 11. Indirect fuel consumption before and after deep drilling is estimated to be 20,000 gallons per season. The total estimated fuel required for deep drilling is estimated to be approximately 940,000 gallons.

Field Season	Deep Holes	Firn Holes	Fuel for DH (in gal)	Fuel for FH (in gal)	Base Fuel (in gal)	Total Fuel (in gal)
FS1	0	5	0	1,750	0	1,750
FS2	0	10	0	3,500	20,000	23,500
FS3	3	15	17,400	5,250	20,000	42,650
FS4	4	20	23,200	7,000	20,000	50,200
FS5	16	20	92,800	7,000	20,000	119,800
FS6	20	20	116,000	7,000	20,000	143,000
FS7	21	20	121,800	7,000	20,000	148,800
FS8	21	10	121,800	3,500	20,000	145,300
FS9	21	0	121,800	0	20,000	141,800
FS10	14	0	81,200	0	20,000	101,200
Total	120	120	696,000	42,000	180,000	918,000

Table 11: Total fuel usage per field season. The fuel consumptions for the drill of Deep Holes (DH) and Firn Holes (FH) are estimated as 5800 gal and 350 gal per hole, respectively. The item “Base Fuel” is an estimate of indirect fuel consumed before and after deep drilling.

11.2 Drilling and Installation Personnel

Projected crew sizes for drilling, installation and sensor testing are shown in Table 12. There are no requirements for installation personnel for PY1-2. The deep drill crew starts with 9 members PY1 and increases to 18 in PY2 to support drilling upgrade and system testing work as well as building experience in the crew early in the project before drilling begins. A full crew of 28 is planned for PY3 and PY4 to support integration activities and to further build expertise and train the drill crew before drilling frequency increases in PY5. Further consideration and analysis needs to be done to determine if the drill crew size can be reduced in PY3 and PY4. PY5 through PY10 require a full crew of 28 to support required hole production rates. During high production years the operations will be 24/7 with 3 shifts and 9 drillers per shift. Skillsets in the crew need to cover all areas of expertise as shown in Table 13 . Cross shift expertise (backup) is required in the areas of drill engineer, software expert, generator/microturbine technician and electrician. Two shifts of 5 dedicated crew members are needed for the installation of sensors, with the tasks illustrated in Table 14.

11.3 Drilling and Installation Cost

Estimated cost percentanges are shown below in Figure 36. Labor accounts for the highest cost. It is separated into direct (wages) and support (housing, PQ, meals, etc.) for employing the optical drill and installation crew for the duration of the project. Factors that contribute to the expense of deploying personnel to the South Pole include travel, Physical Qualification (PQ), per diem, and weight. Once at the South Pole the daily cost per person is driven by food, fuel costs, and wages.

The total labor costs make up 42% of the total detector construction and logistics support cost, the largest fraction of this budget.

Projected Crew Sizes										
Optical Drill	9	18	28	28	28	28	28	28	28	28
Optical Installation (sensor testing)	0	2	2	2	2	2	2	2	2	2
Optical Installation	0	0	10	10	10	10	10	10	10	10

Table 12: Personnel numbers for deep drilling and installation of the Optical strings.

Optical Drill Crew Skillsets		
Shift Lead	TOS Operator	Mechanical Expert
Deputy Shift Lead/Safety Officer	Heater Expert	Installation Expert
DCC Operator	Electrical/Controls Expert	Equipment Operator

Table 13: Drill crew expertise requirements per shift.

Optical Installation Crew Task	
Shift Lead/Safety Officer (1)	Logbook keeper
DOM suppliers (2)(1 driller)	DOM Installers (2)
Main cable reel operator (driller)	Hoist operator (driller)

Table 14: Installation-dedicated crew tasks per shift. Five dedicated crew members and three drillers are needed per shift, thus a total of ten dedicated installers are needed to cover the two shifts per day.

Capital investment in the drill design to attempt to reduce manpower could have the most impact on reducing total project cost, although it is a difficult goal to achieve. A major design objective is to attempt to increase the number of holes with the same manpower.

Fuel costs are almost as large as the cost of on-ice labor. Fuel costs are separated into two categories: Base and direct. Base cost refers to the fuel consumed before and after drilling. Direct cost involves the fuel used for firn drilling and deep drilling. It does not include the fuel required for deployment of personnel; this is included in the labor section.

The total cost of fuel is driven by consumption, price per gallon, and cost per pound to be transported on the vessel and the traverse. Base fuel cost was estimated using the assumption of 20,000 gallons per season and direct fuel usage was based on 5,757 gallons per hole. Methods to reduce fuel consumption are critical in the design of the drill system. There is not much potential to increase the fuel efficiency of the drill system, however a solar PV array has been integrated into the design to reduce dependency on fossil fuels. Solar power will reduce the total energy cost as well as fuel delivery costs.

Capital spent to reduce fuel costs and increase hole efficiency will have a large impact on the total cost of the project. Reliability is also an important design consideration to reduce base fuel costs during drilling downtime or idling. Drill crew efficiency and experience is imperative to reduce downtime and maximize the number of holes completed in a season.

The design, acquisition, and construction of the drill system represents about 21 percent of the total project cost. Reliability, redundancy, and efficiency are the three most important design criteria. In order to mitigate risk of an extra season it is critical that the system operates reliably

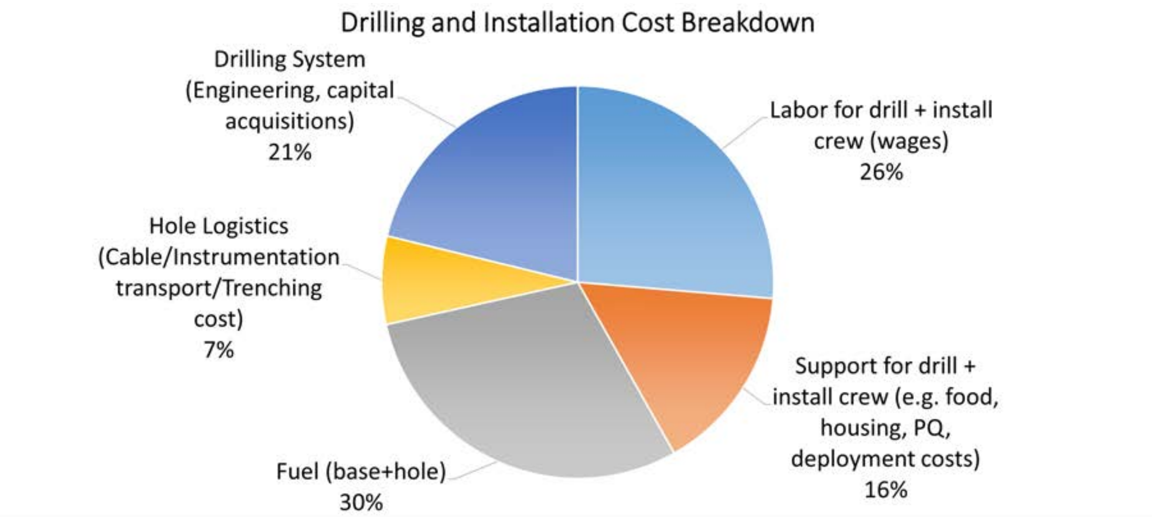


Figure 36: Estimated Detector Construction and Logistics Support cost allocations.

throughout the drilling effort. For this reason, the design approach is to deploy and perfect methods and technologies that are well understood from experience gained from the Gen1 and ICU drill. Testing at the South Pole and PSL Test Bed is also an important investment, as it reduces the risk of on-ice failures or other unexpected issues that would need troubleshooting and repairs during a season.

11.4 Optical installation

The installation of optical sensors will follow the IceCube-Gen1 model very closely. Sensors reach the South Pole in custom-designed cardboard boxes, each equipped with perforated handles and a larger hole to access the penetrator cable assembly. It is foreseen that sensors will be palletized in groups of 8 on 40x40 inch or 12 on 40x60 inch pallets, keeping the penetrator hole accessible.

The pallets of sensors to be installed in one hole are loaded onto a 40-foot High Molecular Weight (HMW) sled equipped with plastic modular Associate Intermodal Platform (AIP) pallets. The sled is pulled into a dedicated, unheated, testing tent that is connected to a heated shack. The external connector of the Penetrator Cable Assembly (PCA) is extracted and connected to a mini-field hub via a cable bundle. Testing will be a quicker operation than in IceCube-Gen1 and similar to what is being developed for ICU. It will aim at spotting quickly any sensor that may have been damaged during the transport from the point of origin to the South Pole.

Using three HMW sleds allows for a contingency buffer between testing and installation, with a string being under test, a string already tested ready to be installed, and a string loaded on the third sled, ready to be tested.

Tested sensors are then staged at the tower site, while drilling is ongoing. The sensor staging will follow more closely what is planned for ICU rather than what was done for IceCube-Gen1. In IceCube-Gen1 the sensors were unboxed and staged on the shelves inside the TOS. For ICU the sensors will be moved into a custom-designed mobile building (the DOM Handling Facility, or DHF) via a deck-mounted knuckle boom telescopic crane. The boxes will be staged and sorted, and passed on to the TOS via a roller bridge as installation proceeds. Keeping the

	IceCube-Gen2	**IceCube-Gen1**
Number of sensors per string	80	60
Spacing between sensors	17 m	17 m
Dry weight of each sensor	22 to 26 kg	15.37 kg with harness
Wet weight of each sensor	-3.5 to -7 kg	-3.826 kg with harness
Max diameter of sensors	12” (30.5 cm)	13” (33 cm)
Max tension on cable during deployment	< 8 kN	8 kN
Minimum breaking strength of cable	25 kN	40 kN
Cable diameter	25 to 28 mm	50 mm
Cable dry weight (wet)	0.5 to 0.8 kg/m	2 kg/m
Cable minimum static bend radius	15 to 20 cm	40 cm

Table 15: Installation parameters.

sensors in their boxes as long as possible will reduce risk related to touch points and human lifting.

During drilling operations, the TU-20 (loaded with the main cable) is placed in position about 25 m from the tower. After drilling operations are complete, the drill team hands over TOS operations to the installation team.

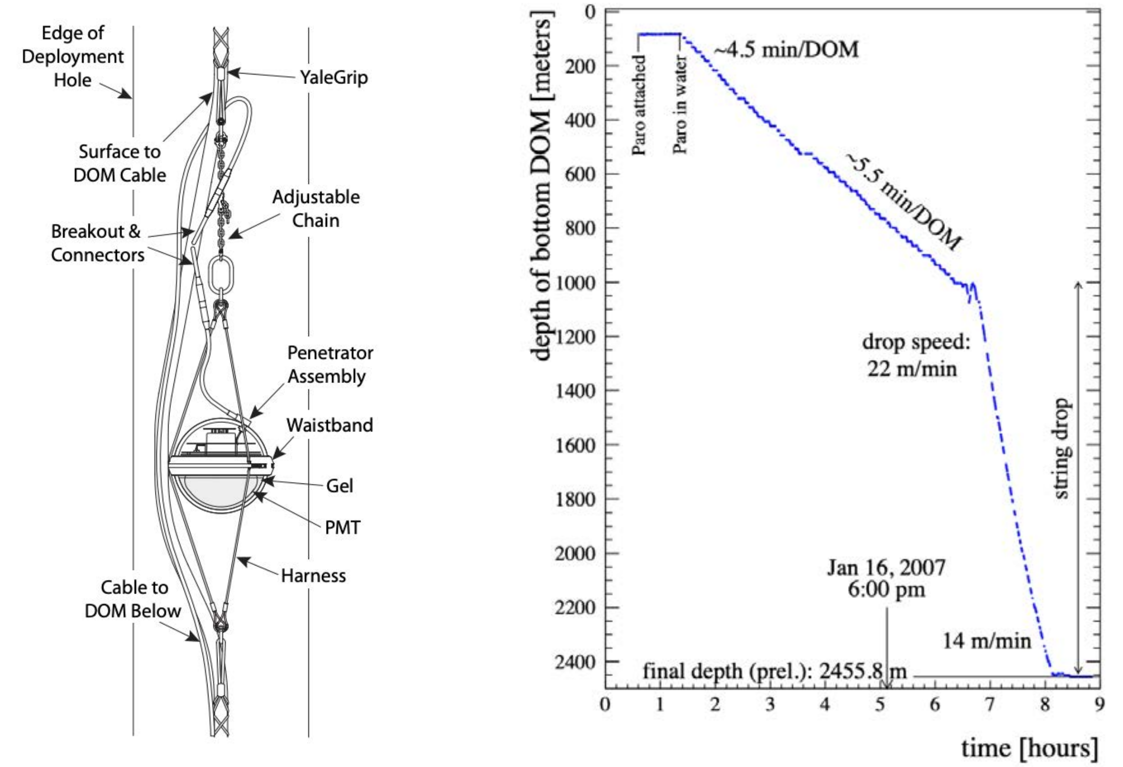
The size of the installation team is similar to IceCube-Gen1 and ICU with the following roles: shift lead, logbook keeper, winch operator, hoist operator and one DOM supplier on the TOS side. Typically, two or three drillers cover some of these roles and are part of the installation team.

Installation operations start with the main cable end being pulled onto the crescent and into the tower. Bottom weights are attached to the cable to ensure that a positive weight is maintained in water throughout installation. A pressure sensor will be connected at the bottom of the string to determine depth through installation. The cable is then lowered, and the sensors are attached to the cable according to the string geometry.

Table 15 compares IceCube-Gen1 and IceCube-Gen2 parameters that are relevant to installation.

The installation procedure will be very similar to the one adopted for IceCube-Gen1. The main cable holds the load of the string, and the load shifts from the cable to the sensor at each sensor. As illustrated in Figure 37a, this installation method ensures that the sensors will be at the center of the hole with the main cable, as both are load-bearing elements. However, this method increases the requirements on the minimum breaking strength of the sensor harness, which in this configuration needs to hold the maximum working load of the whole string (up to the topmost sensor). Alternative methods are being explored for IceCube-Gen2, such as a side-load harness.

The plan is for the installation to take no longer than 12 hours per string. This is consistent with what was routinely achieved with IceCube-Gen1: A rate of 6 minutes per sensor, a drop speed



(a) IceCube-Gen1 DOM and main downhole cable. This shows how the load transfers from the main cable to the sensor (the main cable is slacked around the sensor). The IceCube-Gen2 assembly will be very similar.

(b) Example of depth vs. time in the installation for IceCube-Gen1 String 48, deployed in 2006-2007 season. The depth shown is measured by a pressure sensor installed at the bottom of the string in the proximity of the lowermost DOM.

Figure 37: The IceCube-Gen1 DOM assembly (left) and an example of the installation progress of String 48 (right).

of 9 to 11 m/minute, and a setup time of 60 minutes (see Figure 37b). After the last (topmost) sensor is hooked up to the main cable, the main cable is lowered until the bottom sensor depth hits the target depth of 2680 m, as determined by the pressure measured by the bottom sensor. This pressure reading is corrected for the temperature-dependent compressibility of water, and well depth. It will be possible to record data from selected devices during the string drop.

Once the bottom pressure sensor has reached the target depth, the string is anchored to the snow. The remaining cable (about 45 to 50 m) is then unspooled off the TU-20 reel, and the TOS sled is moved away from the hole. Next, the main cable is connected to the Junction Box located near the Field Hub.

It is foreseen that dust logging will happen in several holes, prior to installation of the instruments. Hole lifetime will be adjusted accordingly.

11.5 Radio drill

Radio drilling will be accomplished using the British Antarctic Survey (BAS) BigRAID drill system. The first generation BigRAID system is already being used to support the Radio Neutrino Observatory in Greenland (RNO-G) project (https://radio.uchicago.edu) [3].

Figure 38: BigRaid Drill as used at RNO-G in field-season 2022. Left: during operations, the drill rig is covered by a tent to prevent ice forming on the barrel and protect the drill crew from the environment. Right: The drilling barrel raised on the tower.

The BigRAID drill (see Figure 38) is an electromechanical drill that works in a similar manner to a conventional ice-coring drill, however, instead of producing an ice-core, the entire ice from the borehole is chopped into chips. A drill sonde (the part of the drill that travels up and down the hole), approximately 6.1 m long, is suspended on a cable. On each drill run, ice chips equivalent to approximately 1 to 2 m of solid snow and ice are drilled and collected within the drill sonde. The drill sonde is returned to the surface and the chippings are discharged from the drill, leaving behind a dry empty hole. Chips are discharged into a snowblower which spreads them over a large area to minimize snow accumulation at the drill site.

The drill assembly features a barrel that is 4.1 m long, with a diameter of 273 mm. The barrel is equipped with two cutters at its bottom end, which are very similar to ice augers used for ice fishing. These cutters are manufactured from hardened A2 tool steel which allows for field sharpening and they stay sharp for approximately 100 m of drilling. The top of the barrel is directly coupled to a brushless motor (Kollmorgen KBM-79H05-A) with no gearing, that provides up to 222 Nm of continuous torque. A static auger inside the barrel transports the chips up the barrel during drilling. The drill motor is driven by a digital servo (Elmo Gold Tiger) with communication with the surface drill controller using CANBus. The drill servo receives a nominal 560 V DC power from the surface. Motor rotation direction and speed can be changed during operations and an encoder allows the cutter position to be accurately set when stopped. During drilling, the drill is normally spun at 80 Revolutions Per Minute (RPM), clockwise. When the drill is at surface, the barrel is emptied by spinning the motor counterclockwise, at a lower speed of 20 to 40 RPM. Feedback current from the motor and rotational speed are streamed back to the surface and displayed in the drill controller display.

The top section of the drill sonde assembly, the anti-torque section, provides the torque required for drilling the ice and prevents the cable from twisting when the drill is operated. This section only has pass-through electrical connections and its operation is purely mechanical. Two versions of the anti-torque mechanism have been implemented so far. Both of them have three vertical blades, 80 cm long, nested into three sets of skates, 120°C apart. These blades are also manufactured from hardened A2 tool steel to allow field sharpening. The position of the blades within the skates (and therefore their protrusion into the ice) can be adjusted depending on the ice hardness (and therefore drilling depth). Once the drill is at the bottom of the hole and the load comes off the cable, the top part of the skates is pushed outward into the borehole wall. In one version the movement of the top of the skate is actuated by a vertical steel die spring, and in the second version three pneumatic pistons and an air reservoir are used to create an adjustable air spring. The bottom of the skates are actuated using a cam. This cam is connected by a shaft to the motor section directly below the anti-torque section. When the drill motor is engaged and starts rotating, the shaft and cam rotate, pushing out the bottom part of the skates and fully engaging the anti-torque blades in the borehole wall. This cam mechanism is able to provide as much torque as the drilling requires. Skates and blades are then fully retracted automatically once drilling terminates and the drill is lifted.

The winch system includes a MacArtney MERMAC winch and custom-designed controls. The winch features a frequency converter, a 5.5 kW AC motor, and a gearbox able to provide controlled cable speeds from 0.05 m/minute up to 50 m/minute and a pull force of 500 kg. Low and high speed settings are required for the low-speed drilling and high-speed traversing of the borehole. This fine control is provided by dual encoders, one on the motor and a second one on the cable drum. The Safe Working Load (SWL) for the winch is 5 kN.

The winch cable is 250 m long (max capacity is 260 m). It is an armored, four-conductor, 22 AWG, wireline cable with a diameter of 6.35 mm (4-H-250 by Pittsburg Wire). It delivers 560 V DC power and communication signals to the drill sonde. The minimum breaking strength for the cable is 25.8 kN while the SWL is 10 kN. Mechanical termination to the drill sonde is provided by a MacArtney Trusslink connection.

The winch controller is relatively smart and provides automatic functions to control the winch during different phases of a drill run. The “auto-up” and “auto-down” functions are used to quickly move the drill between the surface and bottom of the hole at a preset speed. The “auto-drill” mode will payout cable for a pre-set cut length, and is used during drilling. The payout speed can be set independently for lowering and raising the drill, and for drilling. It can also be adjusted as necessary with knobs. Typical speeds are 50 m/minute for going up and down, and 0.4 to 0.8 m/minute for drilling. Tension on the cable is monitored via a load cell and displayed on the winch controller, together with the cable payout. Cable payout can be zeroed as necessary, for example, at the beginning of a new hole. A depth above surface, suitable for the drill barrel to be emptied, can be memorized as “auto-up stop depth.” The last depth drilled, minus an offset (which can also be tuned) to collect lost chips, can be memorized as “lock depth.”

The drill system is powered by a fuel-injected Honda 16 kW (nominal power) generator running on unleaded gasoline. The average fuel consumption for a single 100 m hole is approximately 12 gallons. Alternative power systems, such as solar PV panels, are being considered to reduce fuel consumption.

The complete drill system sits on a sled made out of a 0.5 inch thick, 96 inches wide, 45 feet long, black UV resistant High Molecular Weight Polyethylene (HMW-PE) sheet. Slots along the side of the sled allow for the drill frame to be securely strapped. A 29.5’ modular aluminum mast with sheave wheels at the top is used to support the drill sonde above the surface. This mast system is able to be erected in 5 minutes using a truck winch. The mast is guyed out from the top to four snow anchors. A white tent was added after the first drilling season to reduce insulation and heating of the drill. The system is self contained and once assembled it can be easily moved as a single piece. Extra parts and fuel (besides a few days' supply) are usually stored elsewhere. The total weight of the rig is estimated to be about 3000 lbs.

So far, the system has delivered up to twelve 100 m deep, 11.25 in diameter holes during an Arctic season. Note than an Arctic season is typically 8 to 10 weeks long, and includes setup and pack up time and a typical weather-related downtime of 20 percent. It is therefore shorter than a typical Antarctic season.

Lessons learned are being and will continue to be applied, including system upgrades and operational modifications. At least two additional seasons of drilling are planned for RNO-G using this drill.

For IceCube-Gen2 construction the plan is to increase the number of drills operating simultaneously from one (in the first drilling season) to three (from the third drilling season onward). By the third drilling season three complete drill systems will be operated simultaneously by a team of three drillers (one at each drill) at one station, and will be capable of completing three 150 m deep holes over three shifts. Two teams working day and swing shifts will allow for the completion of drilling within seven years.

11.6 Radio installation

Drilling and installation for the radio detector is simpler than for the optical detector, due to the holes being dry and shallow, and the instruments being much lighter.

Radio installation will follow the procedure developed by the RNO-G team in Greenland during the 2021 and 2022 summer seasons.

The deployment of an RNO-G station involves lowering antennas down boreholes, digging trenches and installing the shallow LPDA antennas (Log-Periodic Dipole Antennas), and installing the main instrument electronics. Since RNO-G stations are autonomous, the installation includes also raising the solar panels and wind turbines and wiring up the battery bank. The positions of the strings, LPDAs, and other station instruments are measured using a post-processed kinematic Global Navigation Satellite System (GNSS) survey.

A custom-designed, easy to tow, hard-sided structure is used for the borehole-antenna installation. The structure features a floor with a hole and a gantry system rated to support the maximum weight of a string. The building takes advantage of passive solar heat and doubles as a warm-up module for personnel at the station.

The building is aligned so that the hole on the floor matches the dry hole previously drilled. The string is assembled at the hole, using 3/8 inch polyester diamond braid as the load-bearing member. Each antenna is attached to the rope via butterfly knots and carabiners. The load is shifted to the antenna at the bottom attachment point of the antenna, and shifted back to the rope above the antenna, to ensure the instrument is centered in the hole. In the densely instrumented section of power strings, modules are directly attached to the modules below via knots and carabiners. Figure 39 shows the shack and the rigging required for the installation of the antennas into the hole.

The order of installation of strings within a station can be adjusted based on the team effort on other tasks, but it is foreseen that one of the two helper strings be installed last. This would

Figure 39: Deployment shack being positioned on top of a finished hole, while the next station hole is being drilled (left); antenna being lowered inside the shack (right).

allow for calibration data to be taken while the string is lowered, with the previously installed antennas simultaneously taking data.

A team of three to four people is currently needed for the deployment of the deep component of a hybrid station. The shallow component of hybrid stations and shallow-only stations requires trenching of three slots, 5 m long, around 2 m deep, perpendicular to the center-to-string direction (6 to 7 m from the station center). Thus far, the slots have been dug manually during RNO-G construction. It takes a single person two hours to dig all three slots. Dedicated melters can also be employed for slot construction for the LPDAs, reducing shallow installation times further.

All channels are connected to the central data acquisition system that sits at the center of the station.

A shallow-only station is also equipped with 20 m holes, which will be created using automatic melters as employed in the ARIANNA installation. The installation for both the shallow component and shallow-only stations will be identical. Once hole and trenches are in place, the installation of the central DAQ box and antennas is straightforward, and they are connected by coaxial cables. After installation the trenches are filled by hand with surface snow to ensure that no air pockets are being formed from drifting snow. Making slots and melting the hole dominate the time requirement.

The overall expectation is that a team of five will be able to install a hybrid station in two shifts and be able to install two shallow stations in one shift. The cabling effort will proceed ahead of the station installation.

The first drilling year will be the first South Pole field test of the BigRAID drill. It is expected that the drill will need to be tuned, as factors such as ice density and temperature, and the environment will be different than those encountered in Greenland where the drill is being developed.

In year one, a single drill is planned to be operated by a team of three people. The drill schedule is similar to what has been achieved in Greenland. The schedule is scaled by a larger hole depth and a longer season (twelve 100 m holes in 6 weeks vs. twelve 150 m holes in 8 weeks). Two

Radio Installation plan	PY3	PY4	PY5	PY6	PY7	PY8	PY9
Hybrid stations	4	16	24	30	30	30	30
Shallow stations	16	34	34	37	37	39	0
Peak total population	12	16	16	16	16	16	11
Percent of season at max population	41%	45%	49%	49%	49%	49%	99%
Average population per season	7.3	12.4	11.7	13.3	13.3	13.3	10.8

Table 16: Schedule for installation of radio stations.

more drills will be added; one in year two and the other in year three. Staffing will increase to allow for two shifts per day, with three people per shift.

Since the time to commision a hybrid station does not align with the drill time, doubling drilling shifts allows for drilling to finish earlier. The efforts will be focused with more personnel performing installation in order to end the season with all the stations in place.

To compensate for the relatively soft ramp up effort in the installation of hybrid stations, shallow stations are installed with a more aggressive schedule from the beginning of the project. This will also allow for modifications to the total number of stations, should the drilling encounter unexpected issues.

With these assumptions and reasonable expectations regarding duration of the seasons, the installation of the radio component of IceCube-Gen2 can be accomplished over seven radio drilling and installation seasons. The total population dedicated to radio installation will peak at 16 people, and scales with the number of stations, as outlined in Table 16. Occupancy has been calculated by taking into account not only installation times, but also a buffer to setup and take down equipment.

The effort presented above does not include the cable infrastructure installation effort which is detailed in the following section.

Due to the distance between South Pole Station and the radio installation sites, most personnel moves will require enclosed vehicles. These vehicles will be on site from the beginning of the first shift to the end of the last shift of the day. Snowmobiles will be used as means of local transport or for shift change. Since drilling and installation can proceed asynchronously, it is foreseen that two crews will operate independently.

Vehicle requirements will include the following types:

Tracked vehicle A tracked vehicle such as a PistenBully 300 Polar (or similar), equipped with cabin and blade, will be used for the radio drilling crew, and more specifically for cargo hauling and snow removal. It will also serve as warm-up shack, and emergency response capability.

Snowmobiles Snow machines are required for moving personnel from the South Pole station to the radio drill and installation sites. Sleds with seats will be considered for this purpose. Snowmobiles are also useful for pulling small cargo sleds that are hand-loaded with light cargo. The use of electric snowmobiles will be considered, similar to those foreseen for the hot water drilling fleet.

Arctic truck A four-wheel Arctic truck will be used for installation teams (both hybrid and shallow) to reach the hybrid installation site. The van is shown in Figure 40.

11.7 Surface infrastructure and surface detector installation

Surface installation covers the deployment of:

- the surface cable infrastructure that connects optical strings, surface stations and radio stations to the power and communication centers
- the surface array stations detectors, including elevated scintillator panels and antennas
- the interface components for the optical/surface detector, such as the FieldHubs and Surface Junction Boxes (SJB)
- the interface components for the radio detector, such as the Radio FieldHubs (each serving a section of the radio detector) and Radio Surface Junction Boxes (one for each station).

The surface components for each in-ice string are shown in Figure 41. Surface deployment at a particular string location is scheduled for the field season before deep drilling at that particular site and will coincide with firn drilling. There is not a tight coupling between surface installation and firn drilling, but in general, conducting the activities in the same area during a particular field season will mean that mutual support is possible as well as potential sharing of, for example, heavy equipment operators.

The first step in the surface installation for the project is the installation of surface cable "backbones" running from the counting house to the edges of the current IceCube-Gen1 array. This consists of trenched optical fiber and power cables sufficient to connect the entire cabled detector (optical and radio) back to the counting house. The backbones terminate in passive junction boxes that remain accessible throughout the construction of the array, in order to allow surface cable connections and maintenance in later seasons.

Trenching for each surface installation consists of trenching from: 1) the previous FieldHub location to the current site (240 m); 2) the FieldHub to two nearby antennas and surface detector sites (144 m total); 3) the FieldHub to the in-ice SJB (~5 m). One of the surface array arms is already aligned with the string-to-string trench. Shallow pits are excavated at the FieldHub and SJB sites in order to allow cable consolidation at the FieldHub and to install the SJB below

Figure 40: Four-wheel drive arctic truck with Mattracks.

the snow surface. All other components are elevated above the surface in order to facilitate long-term maintenance.

Similarly to the optical array, the radio array will also be installed in sections. Power cables and fibers for each section will be first installed along a main run (backbone), and will be terminated into a Radio FieldHub containing DC/DC converters and fiber switches. The Radio FieldHubs will serve as connection points between consecutive backbone sections and between a backbone and branches. Each branch will connect up to 6 radio stations (either hybrid or shallow-only). Branches and radio installation will proceed based on the schedule shown in Figure 42 and Table 17.

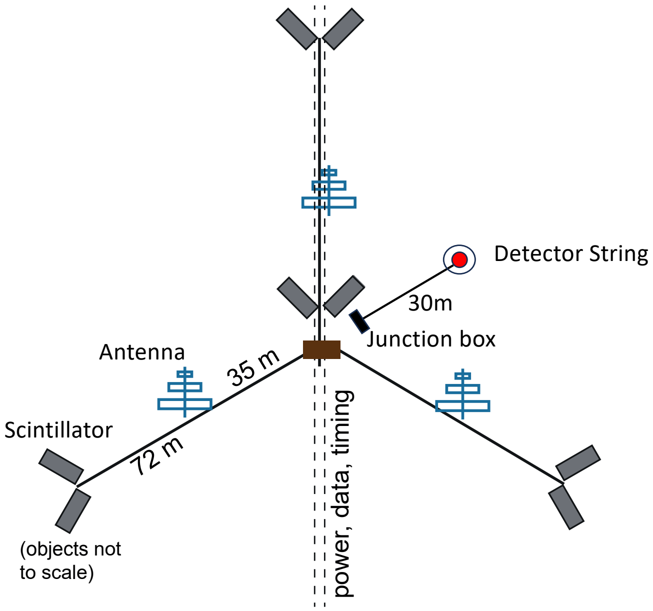


Figure 41: Detector and infrastructure components for surface installation (per in-ice string).

Surface Infrastructure	PY2	PY3	PY4	PY5	PY6	PY7	PY8	PY9	PY10
Opt./Surf. Backbones ([km])	4 (1)	4 (1)	6 (1.4)	4 (1)					
Opt./Surf. FieldHubs	5	6	16	22	23	21	23	14	
Surface Stations	5	6	16	22	23	21	23	14	
Radio Junction Boxes	30	60	60	71	79	61			
Radio FieldHubs	1	1	2	2	1	1			
Radio Backbone [km]	8	10	20	14	13	6			
Radio Branches [km]	43	86	85	107	121	86			

Table 17: Installation plan for the components of the surface infrastructure serving the optical, surface and radio detectors part of IceCube-Gen2 from Project Year 2 to Project Year 10.

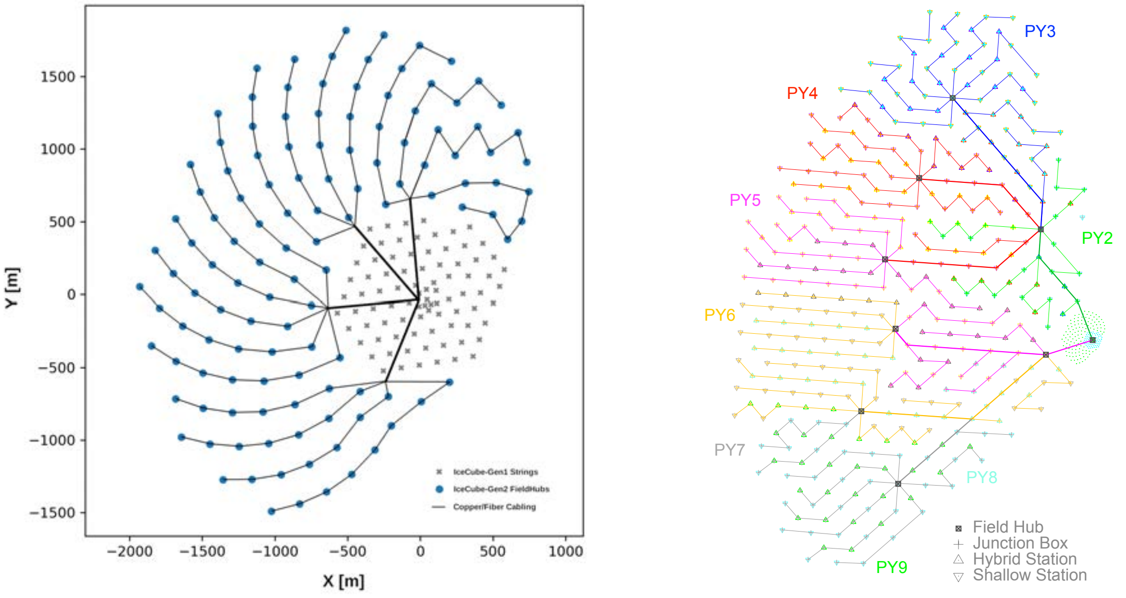


Figure 42: Optical (left) and radio (right) cabling and infrastructure installation plan.

All surface cables are required to be trenched into the snow. Trenching for IceCube-Gen2 will use new equipment and an optimized procedure that significantly reduces trenching time and required personnel compared to past operations.

Since cables are the first element to be installed, a pre-deployment survey is necessary to locate and flag the sites for the surface components and the cable trench runs. The accuracy requirement for the pre-deployment survey is lower than for the post-deployment survey and may be performed by the surface deployment team using standard differential GPS / RTK survey equipment.

A dedicated **Challenger MT865** equipped with a surface leveling blade is used to groom the terrain before trenching.

The spools of surface cables to be installed are loaded on a dedicated UHMW sled using the crane fitted on the MT865 and then hauled out to the site with the MT865.

Other components required for the installation (such as detectors, FieldHubs, and junction boxes) are transported to the flagged sites using Siglin sleds.

At the time of trenching, the cable spool is loaded onto a self propelled, quad-track chain-type trencher equipped with reel carrier (**Vermeer rtx1250i2** or similar, see Figure 43). Sufficient slack is measured at the starting location and anchored to prevent slippage of the cable along the run. The trencher proceeds to trench the routes and lay the cable along the main runs.

Surface cables from all trenches is consolidated at the FieldHub, where the slack is managed for future raises.

A **Utility Tracked Vehicle** (such as rtvx1100 or similar) follows behind and deploys the fiber and inspects the layout.

A 289 skid steer equipped with a trencher unit is used to trench smaller runs (such as the short runs within a radio station or those within a surface station).

Figure 43: Self propelled trencher with cab and reel attachment.

Once all the cables are installed the MT865 with the land plane back fills the trenching routes.

The general approach to cable installation is the same for both the optical/surface component and the radio component, and it is expected that a dedicated crew of three people will be sufficient for trenching operations.

The tasks that follow are specific to the detector component.

For the radio detector, Radio FieldHubs and radio junction boxes are installed along or at the end of each trench and cables are connected. Basic commissioning is executed to verify continuity. Hybrid or shallow radio stations are connected to the junction boxes as they are installed.

For the optical detector, string patch cables are installed from the FieldHub to the SJB, where they are connected to the internal patch panel in the SJB from the FieldHub side. The SJB and the opposite string are covered with a temporary plywood cover so that during the deep drilling season the SJB can be accessed to connect the downhole cable to the SJB patch panel, and thus to the string electronics in the FieldHub. After the downhole cable connection is made, the SJB is buried.

For the surface detector, the scintillator panels are installed using four steel poles at each of the panel corners, each inserted into the snow. Movable hangers are attached to the poles, and the panels are in turn hung from the poles at a height of 1 to 1.5 m above the snow surface. The panel is leveled by adjusting the pole hangers. The assembled radio antennas are installed on a lightweight, non-conductive frame that can also be extended during the lifetime of the experiment. The antennas are leveled, however the azimuthal orientation is not critical but needs to be measured after deployment.

After deployment of all elements and connection of all cables, a post-deployment survey is performed in order to determine the final location of all components. For the elevated scintillators and antennas, all four corners will be surveyed to provide the azimuthal orientation of the detectors, which has been shown from experience with the prototype station to be sufficiently accurate.

11.8 Risk and risk mitigation

Logistics for executing large scale projects in Antarctica is one of the largest risk factors that can impact the success of the project because logistical risks are not predictable or easily controllable. Successful logistics planning and execution are one of the highest priorities to minimize schedule risk for the project. An integrated approach to project planning, where the support contractor (ASC) is an integral part of the project, will be developed to minimize risks in the logistics sector. Primavera P6 project management software will be used to prioritize, plan, manage, and execute all project tasks as already demonstrated in the ICU rebaseline schedule. The key risk mitigation strategy for logistics is to both procure long-lead-time items early in the project and perform integration work in the North for prioritizing shipments early in the project. A risk register will be created to identify areas of the plan where there is potential for assumptions to break and create backup plans or implement risk mitigation plans proactively. Cargo shipment will be designed to rely heavily on the vessel and the traverse, based on the prediction that early season C17 support will be limited or reduced as compared to IceCube-Gen1. An evaluation of deep drilling risks is shown in Table 18.

Equipment failure and technical performance is another major risk category. Experience from previous drilling projects (IceCube-Gen1 and ICU) has established confidence in procedures and drill design and utilizes equipment that has been proven to be robust. New methods, technology, and equipment introduced to the system will be tested rigorously before integration. The drill is fault tolerant because it has redundancy built in for heat, power and and energy storage on the surface. Unlike logistics, design can be controlled and therefore is less susceptible to failures due to unmitigated risks.

An evaluation of surface installation risks is presented in Table 19. As with other instrumentation, the surface installation schedule depends on timely delivery of cargo. In case of issues in a particular season, the schedule can be adapted, including shifting deployment of certain stations to the following season. It should be noted that the ability to delay the schedule is eventually limited by the fact that the surface installation hardware is required for commissioning of the deep instrumentation at the same string location. The speed of trenching and surface cable deployment also may be slower than expected, which would require a rework of the schedule. This risk should be well-understood after the first season of surface cable deployment. Finally, severing the optical fibers (e.g., with heavy equipment) also poses some risk as repair is more difficult and time-consuming than for copper cables. This is mitigated by having repair equipment (e.g., a fusion splicer) on site and personnel on the installation team trained to use it.

Tables 20, 21 and 22 summarize risk evaluations for Radio Drilling, Optical Installation and Radio Installation respectively.

Risk Evaluation: Deep Drilling			
Risk description	**Risk type**	**Level**	**Mitigation**
Fuel delivery delayed	Logistics	Moderate	Early and clear communication with ASC and NSF
Driller acquisition	Personnel	Moderate	Initiate staffing planning and recruitment early. Network with and engage experienced drillers in the search. Develop training plans. Engage collaboration early on for contributed drillers. Allow for flexibility with deployments.
Solar performance	Technical	Moderate	Staged rollout of major technical updates. Backup piston generators. Robust IV&T
Microturbine performance	Technical	Moderate	Staged rollout of major technical updates. Backup piston generators. Robust IV&T
ARC sled performance	Technical	Moderate	Staged rollout of major technical updates. Reconstruct TOS sites on snow. Robust IV&T
Emergency Response	Safety	Moderate	Include enhanced safety and emergency response measures in project plan. Dedicated medical vehicles and sleds
Surface Pipe relocation	Technical	Moderate	Staged rollout of major technical updates. Backup surface hose lines. Robust IV&T

Table 18: IceCube-Gen2 deep drilling risk descriptions and mitigation

Risk Evaluation: Surface Installation			
Risk description	**Risk type**	**Level**	**Mitigation**
Trenching speed slower than expected	Schedule	Moderate	Adapt trenching/installation schedule
Optical fiber broken or severed	Schedule	Moderate	Have repair equipment and expertise on site
Delay in delivery of equipment or instrumentation	Schedule	Moderate	Re-evaluate or shift the schedule

Table 19: IceCube-Gen2 surface installation risk descriptions and mitigation

Risk Evaluation: Radio Drilling			
Risk description	**Risk type**	**Level**	**Mitigation**
Drilling is slower than expected	Schedule	Moderate	Re-evaluate geometry, schedule and stations configuration
Delay in delivery of equipment or instrumentation	Schedule	Moderate	Re-evaluate schedule and stations configuration
Equipment breaks	Schedule	Moderate	Robust spare parts plan

Table 20: IceCube-Gen2 radio drilling risk descriptions and mitigation

Risk Evaluation: Optical Installation			
Risk description	**Risk type**	**Level**	**Mitigation**
Instrumentation delivery delays	Schedule, Technical	Moderate	Adapt drilling/installation schedule, install fewer modules per string
Cable delivery delays	Schedule, Technical	Moderate	Adapt drilling/installation schedule
Sensors are damaged during installation	Technical	Moderate	Spares, ESD protection

Table 21: IceCube-Gen2 in-ice installation risk descriptions and mitigation

Post-mitigated Risk Evaluation: Radio Installation			
Risk description	**Risk type**	**Level**	**Mitigation**
Delay in delivery of equipment or instrumentation	Schedule	Moderate	Re-evaluate schedule and station configuration
Equipment breaks	Schedule	Moderate	Robust spare parts plan

Table 22: IceCube-Gen2 radio installation risk descriptions and mitigation

12 Logistical Support Requirements

12.1 South Pole Facilities

The extremely clear deep glacial ice and existing United States Antarctic Program (USAP) infrastructure, operated by the National Science Foundation (NSF), make for the best large-scale optical neutrino observatory site on Earth. The optical and radio clarity of the South Pole ice is critically important for a detector whose active volume is a natural material.

The IceCube Neutrino Observatory is located in the South Pole "Dark Sector", a defined region near the geographic South Pole with controls on emitted electromagnetic radiation, especially in the radio spectrum, to avoid conflicts with radio telescopes.

IceCube-Gen2 will build out on the existing IceCube infrastructure in the Dark Sector. The IceCube Laboratory (ICL), at the center of the existing installation, hosts surface electronics, workshop and storage areas, and the on-site computing resources for the IceCube detector's array. IceCube Upgrade and IceCube-Gen2 plans both house surface electronics and computing equipment within the existing ICL structure.

The South Pole, the Antarctic Specially Managed Area No. 5, is managed by the NSF's Office of Polar Programs (OPP) under the mandate of the United Nations Antarctic Treaty which reserves the coldest, highest, driest continent for scientific purposes. Near the geographical South Pole is the NSF's Amundsen-Scott South Pole station which sits at an elevation of 2835 m. The core of the station consists of an elevated facility with berthing for about 150, food services, medical clinic, bath and laundry facilities, and recreation spaces. It also contains the Jack F. Paulus Aerodrome, a 12,000-foot skiway to support aircraft operations, a 1 MW diesel reciprocating engine-based power plant, and a 450,000-gallon fuel storage facility. In the past, such as during the simultaneous construction of IceCube-Gen1, the South Pole Telescope, and the South Pole Station Modernization project, additional people were housed in temporary summer housing.

Figure 44: Aerial view of the Amundsen-Scott South Pole Station.

The normal work week at the station is six days per week, nine-hour daily shifts. The normal working Austral summer season extends from early November until the middle of February with the best weather conditions in December and January.

The station supports a number of scientific laboratories, including the IceCube Lab (ICL), the Martin A. Pomerantz Observatory (MAPO), the Atmospheric Research Observatory (ARO), and the Dark Sector Lab. Support facilities include a cryogenics lab, a vehicle maintenance facility, extensive storage, and shops for electrical work, carpentry, tool fabrication, and plumbing. The NSF provides flights, meals, housing, cargo, and data transmission for all South Pole projects.

Personnel travel commercially to Christchurch, New Zealand, and then take U.S. military logistics flights south. Flights are typically on U.S. Air Force C-17 cargo planes or New York Air National Guard LC-130 (ski-equipped) cargo planes down to the U.S. Antarctic coastal base of McMurdo Station.

From McMurdo to South Pole, the LC-130s provide the primary personnel route, with some additional contracted flights on Ken Borek Air Baslers (significantly overhauled Douglas DC-3s). In recent years, fuel has been transported to the South Pole via an overland traverse consisting of large tractors pulling flexible fuel bladders on large plastic (High Density Polyethylene) sheet sleds. Construction work primarily takes place during the summer season.

During the winter the staff is reduced to about 50 “winterovers” who operate the detectors and keep the station functioning. (IceCube employs two winterovers who are tasked with monitoring of the detector operations and providing primarily computer hardware and software repairs.) During major construction projects this population has been larger, over 250 persons. The ICL is about 1.5 km from the Amundsen-Scott South Pole Station and people typically travel by foot, or by motorized vehicle during the summer.

12.2 Logistics management

IceCube-Gen2 will work with the NSF and their service contractors (Antarctic Service Contractors, where ASC is the primary contractor) on all aspects of the logistics tasking, including the shipping of all cargo, personnel, and support equipment to South Pole. The detailed logistics path, along with schedule and costs, will be developed in coordination with the ASC and with the Antarctic Infrastructure and Logistics (AIL) branch of the National Science Foundation’s Office of Polar Programs. AIL manages the vessel and airlift cargo to the continent and on the continent, including contracting for military flights, while ASC manages the on-ice personnel and equipment support including housing, meals, vehicle operations & maintenance, and the use of station support personnel for project purposes. All of this work is costed and included in the project costs, and the scheduling will be verified between the three organizations (project, AIL, and ASC). The project WBS 1.7 category captures the activities from the support contractor directly supporting the IceCube-Gen2 activities along with indirect level of effort activities at the contractor.

The project and the Support Contractor work closely on all construction procedures and facility work to be conducted at the South Pole. The IceCube project employs a safety engineer who coordinates with ASC safety personnel and South Pole firefighters, and ensures the compliance of all operations with the relevant safety requirements. All work activities are documented, safety assessments are publicly available, and all safety incidents are reported through university, ASC, and NSF channels. Construction on the South Pole glacial plateau is subject to a number of unique conditions, including the absence of a sensible electrical ground, extreme

Figure 45: Ski-equipped LC-130 “Hercules" of the New York Air National Guard in McMurdo. Image: Albrecht Karle, IceCube/NSF

Figure 46: South Pole Traverse (SPoT) delivering fuel and materials to the South Pole. The nearer tractor is towing sleds with fuel bladders.

cold, highly abrasive ice crystals, and wind-borne snow drifting. The IceCube group has had nearly three decades of experience with this site.

During IceCube-Gen2 construction, approximately 90 people will deploy to the South Pole, with a maximum population at South Pole of about 60 at any given time. This is similar to the IceCube construction population which was supported in 2003 to 2010 in parallel with South Pole Telescope and the South Pole Station Modernization project. During IceCube, about 9.5 million pounds of cargo and fuel were delivered to South Pole. All of this was delivered by LC-130s and all of the logistics support was paid for out of the Major Research Equipment and Facilities Construction (MREFC) funding so that it did not affect Antarctic science support funding from the NSF directorates or other Antarctic projects. We expect all of the fuel to be traversed overland for IceCube-Gen2, and following the example of the IceCube Upgrade, some significant cargo will be traversed as well.

12.3 Cargo requirements

The cargo requirements have been looked at from a bottom-up perspective, summing up the materials and supplies needed for all of the subsystems described in this TDR. This is the start of our IceCube-Gen2 master cargo spreadsheet which will ultimately include every item shipped, or to be shipped, to South Pole for the project, along with weight, volume, customs information, handling instructions, packing details, and preferred shipping routes and South Pole "required on station" dates. This spreadsheet is similar to what is currently used in the IceCube Upgrade and will gradually increase in fidelity as the items to be shipped are purchased or produced.

Tables 23 and 24 show the overall logistics need in total and by year compared to IceCube. Figure 47 and Figure 48 shows the breakdown of the overall weight and volume by subsystem and by Field Season respectively.

The optical array of the IceCube-Gen2 accounts for about half of the weight and volume to be shipped to the South Pole. This includes 120 downhole cables and about 10,000 optical modules. Design work over the last few years, in coordination with our cable vendor and our digital communications team, has reduced the required cabling significantly, saving several tons of weight per string. The optical modules have fairly large volume packing boxes, explicitly tested for surface and air shipment of the relatively delicate glass pressure vessel-housed instrumen-

	IceCube-Gen2		**IceCube**
	Total Cargo	**Average/Yea**	**Average/Year**
Cargo Weight [1000 lb]	3540	354	Similar
LC130 Flights	69	7 or less	45
40’ ISO Sleds	139	14	0
Population [beds at Pole]		60	50
Fuel [1000 gallons]	918	92	82

Table 23: The overall logistical footprint of the IceCube-Gen2 Project, compared to IceCube original construction. Note the far fewer flights to South Pole, with the South Pole Overland Traverse (SPoT) carrying most of the cargo on sleds.

South Pole Field Season	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
Cargo Weight [1000 lbs]	164	440	610	151	360	408	411	393	362	238	**3540**
40' ISO sleds = 2x TEUs	12	18	27	8	14	16	15	13	11	6	**139**
LC130 Cargo Flights	0	0	4	3	9	11	12	12	12	8	**69**
Population [beds]	12	40	64	64	64	64	64	56	45	43	
Operations Power [kW]	75	79	82	91	105	125	142	163	179	189	**189**
Fuel [1000 gallons]	20	21.7	41	48	120	143	149	149	145	81	**918**

Table 24: Total logistical support requirements by South Pole season.

tation. This size can be seen to the relatively larger fraction of the shipping volume versus shipping weight for this subsystem. Module weight, when possible, will be minimized, and such minimization would be encouraged by all of the other metrics for the in-ice optical modules. There has been some weight (and cost) savings in these modules in the exploration of the gel pad optical coupling of the PMTs to the glass rather than the gel pour used in the Upgrade mDOMs. In total, the cargo for the IceCube-Gen2 optical instrumentation will be less than for IceCube (Gen1), yet the total photo detection coverage will be about eight times larger.

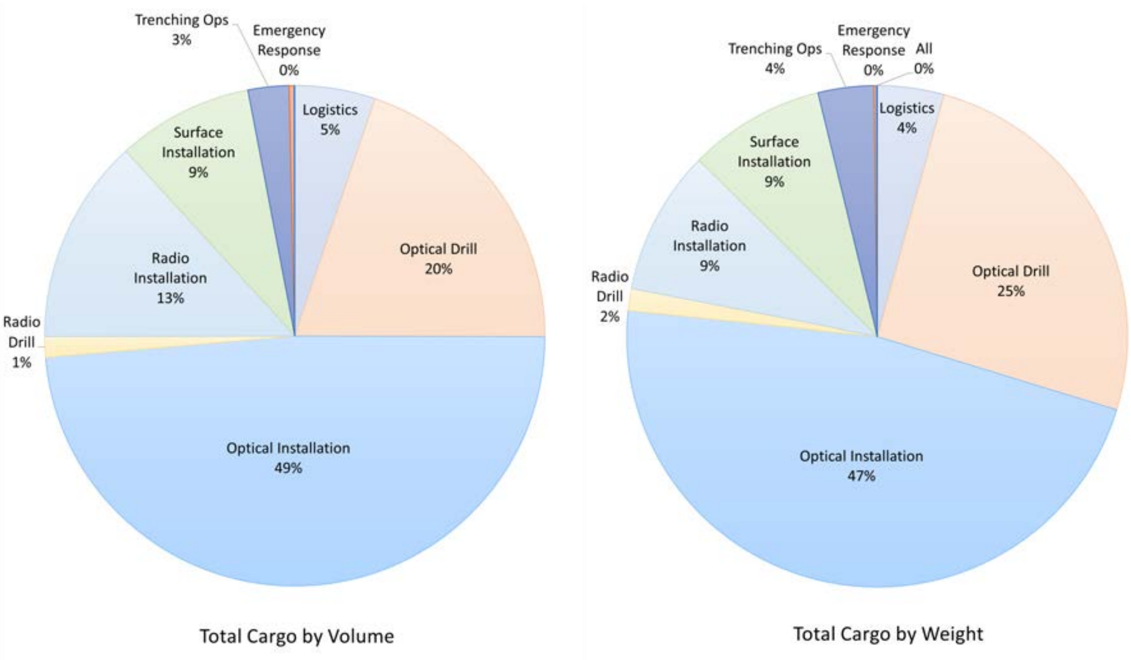
The surface and radio installed hardware each take up about 10% of the total weight and volume to be shipped to South Pole.

The radio stations have been optimized with easy-to-assemble antennas to reduce the shipping volume associated with the light, but relatively large antennas. Weight savings in both of these detector systems will be primarily in smarter packaging which still needs to be explored.

The remaining approximate 25% of the shipping volume and weight are the drill systems and some smaller logistics elements. The drill cargo impact is being reduced through the reuse of as much of the existing Upgrade drill system as possible, although there are significant cargo needs for the new power systems for the IceCube-Gen2 drill and the sleds required for the mobility of the drill camp.

Since IceCube construction the logistics landscape at the South Pole has changed considerably, and it is likely that there will be additional changes before the IceCube-Gen2 installation is completed. IceCube originally was highly dependent on LC-130 flights between McMurdo and Pole, with most of these flights now replaced with the South Pole overland traverse (SPoT) for both fuel and many of the sturdier IceCube required elements. Total cargo weights per year are similar between IceCube-Gen2 and original IceCube shipping plans. In order to further reduce our reliance on LC-130 aircraft, we are investigating if a significant fraction of cargo could be transported using SPoT. Investigations on shock and packaging requirements are ongoing for the IceCube requirements at the time of this writing, and an initial assessment suggests that more than 80% of all instrumentation can be transported overland. This would reduce the number of LC-130 flights for cargo to as few as two to four per year.

Personnel needs at South Pole will be somewhat higher than during IceCube construction, due to radio, deep ice, and surface installations happening simultaneously. Personnel reduction is carefully considered for all tasks, ultimately with ensuring safety in the Antarctic field environment pushing the numbers higher.



(a) Total cargo by volume, broken out by subsystem.

(b) Total cargo by weight, broken out by subsystem.

Figure 47: Total cargo by subsystem.

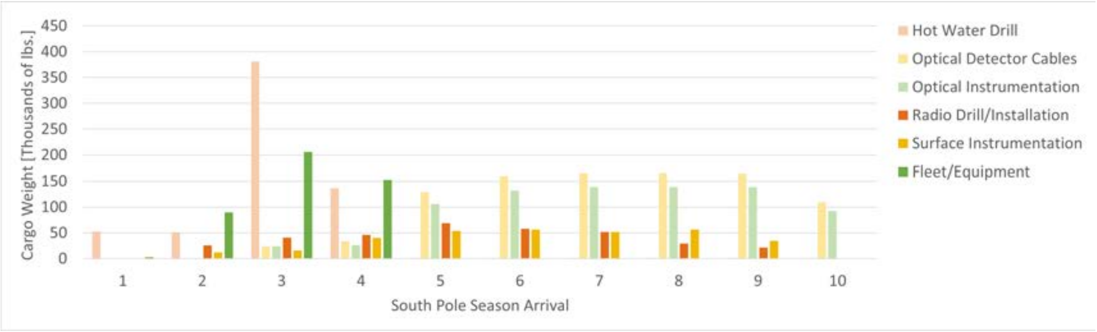


Figure 48: Weight of Cargo needed at South Pole by Field Season and subsystem.

12.4 Population requirements

The expected population requirement for each of the main installation seasons (seasons with deep drilling and installation of optical modules, radio drilling and installation of radio stations, and surface station installation) is about 60 individuals. This is higher than the IceCube total by 10 persons per year, mainly to support radio drilling and installation.

The deep drill requires about the same team size as the enhanced hot water drill during IceCube drilling and installation. In many cases, the population requirement is driven by needing two persons in various buildings and operating various drill subsystems. Every sensible, and safe, effort to minimize the population would be employed in the planning process.

There have been a number of proposed solutions for housing this flux of personnel at the South Pole. These range from building temporary housing similar to the IceCube construction era with the station supporting all on-site logistics except for beds to a more substantial “field camp" near

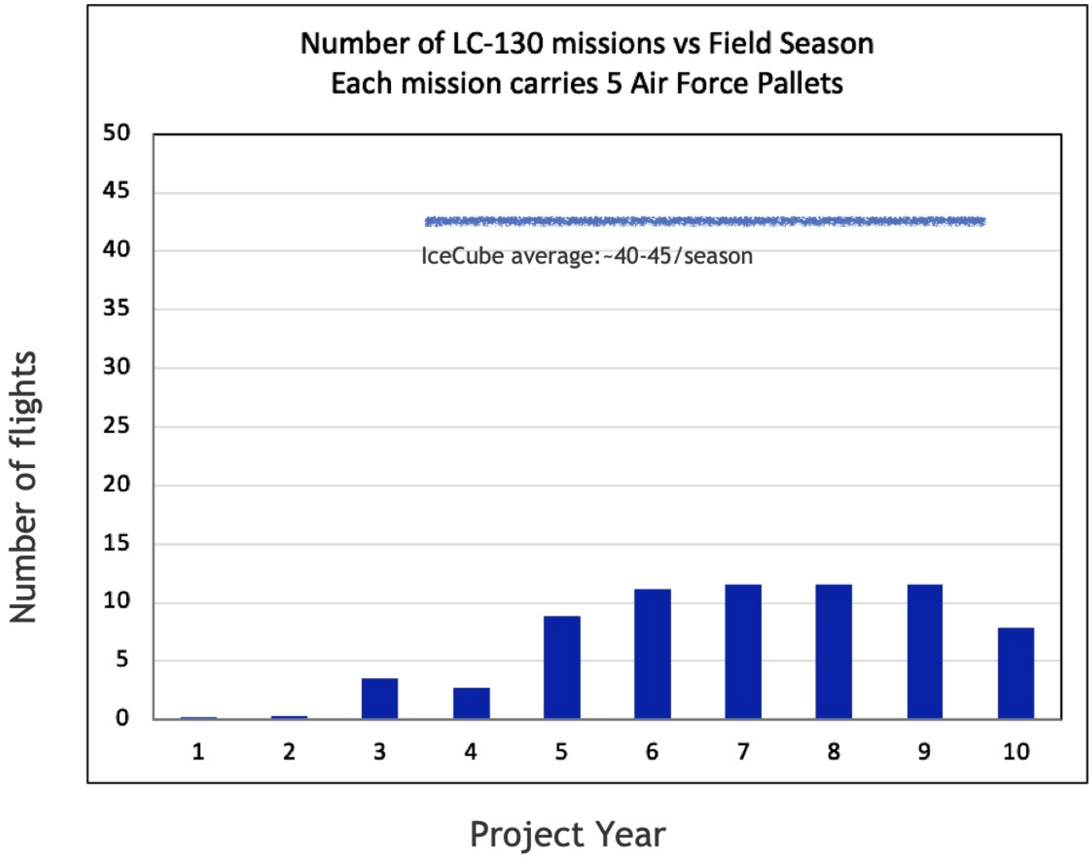
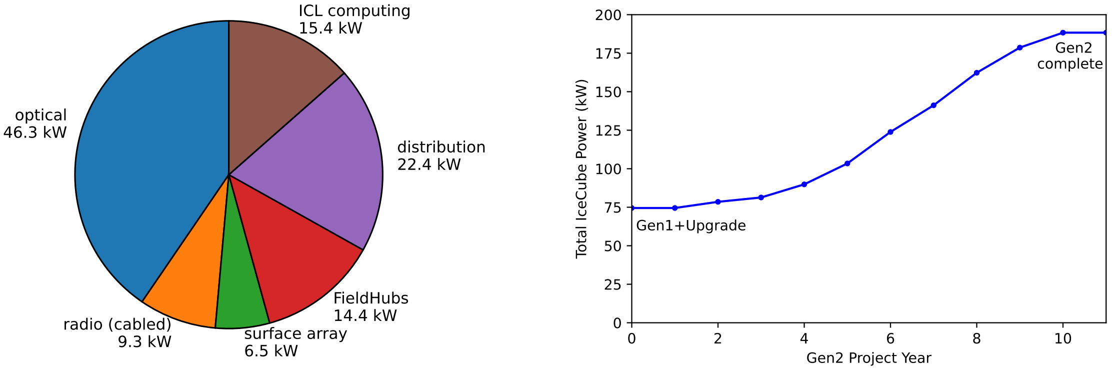


Figure 49: Comparison of IceCube versus IceCube-Gen2 use of LC-130 flight to the South Pole.

Area	PY1	PY2	PY3	PY4	PY5	PY6	PY7	PY8	PY9	PY10
Management/PI	2	2	2	2	2	2	2	2	2	2
Safety	1	1	1	1	1	1	1	1	1	1
Cabling/Field Hub	0	3	3	3	3	3	3	0	0	0
Radio	0	0	12	16	16	16	16	16	11	0
Surface	0	2	2	2	2	2	2	2	2	0
Optical - Drill	9	18	28	28	28	28	28	28	28	28
Optical - Sensor Testing	0	2	2	2	2	2	2	2	2	2
Optical - Installation	0	0	10	10	10	10	10	10	10	10
Total Peak Population	12	28	60	64	64	64	64	61	56	43

Table 25: South Pole Peak Population needs by Project Year and work areas.



(a) Breakdown of power usage for IceCube-Gen2 by subsystem.

(b) Total IceCube operational power vs. time during construction.

Figure 50: IceCube-Gen2 power consumption by subsystem and by year during construction.

the drill area with all of the on-site logistics handled there locally. IceCube-Gen2 will work with NSF and the Antarctic Services Contractor to select the best solution to support the needed personnel at the pole.

Table 25 summarizes the breakdown of population needs across all subsystems by Project Year.

12.5 Power

The total additional power consumption of the IceCube-Gen2 detector during operations is expected to be approximately 115 kW, including all detector components, ICL computing and other equipment, and power distribution and conversion losses. When including the current IceCube and planned ICU power consumption, this is a total of 190 kW. A breakdown of this power usage is shown in Fig. 50a. The largest single component is the power usage of the optical array, which in turn is driven by the power usage of the Gen2 DOMs. The baseline power of the Gen2 DOM has been reduced by 60% relative to the Upgrade mDOM, and there are opportunities for further power savings.

Because IceCube-Gen2 operation will start successively as construction progresses, the IceCube power profile will increase gradually, with the power profile ramping up as the number of strings and stations deployed increases. A preliminary profile of power during construction is shown in Fig. 50b. Because of this, any additional power generation needed for IceCube–Gen2 operation is not required immediately at the start of construction.

Later during construction though, the required power exceeds what is readily available from the station. There are a number of options ranging from the use of renewables in the Dark Sector, to the use of the drill microturbines for science operations power, to a possible combined power system of IceCube-Gen2 and other astrophysics experiments, to enhancements of the station generator installation. We expect to work closely with the NSF, the contractor, and potentially other projects at Pole with significant electrical power needs.

12.6 IceCube Laboratory

We will use the existing IceCube Laboratory for the counting house facilities of the IceCube-Gen2 additions to IceCube. Additionally, we will use temporary structures used by the IceCube and IceCube Upgrade drill programs for the components of the IceCube-Gen2 drill system.

The ICL is an existing elevated building near South Pole station. The elevated nature of the building is to minimize snow drifting on or near the building; the wind blows through/under the building. The building was originally a small, elevated, dorm facility at South Pole which was extensively modified for use as the counting house and electronics work space for the IceCube project.

The ICU and IceCube-Gen2 expansions of in-ice sensors have significantly lower surface electronics requirements, at least in volume of hardware, so no additional counting house structures or major additions to the ICL are anticipated. New cable entry systems and changes to the electrical power in the building will be required, and have preliminary budgeting within the project, to be confirmed with the contractor. The new cables would only be power and fiber optic communication cables, and the FieldHubs would be buried at the top of the drillholes. This cable entry is similar to what has previously been installed for the scintillator upgrades within the IceCube foot print and the Askaryan Radio Array (ARA) experiment.

A Dark Sector computing data center could centralize the computing for existing and future astrophysics experiments at South Pole. This combined operation is in the early discussion phase and is not currently in the cost or schedule baseline for the IceCube-Gen2.

12.7 Shipping and storage locations

The primary shipping path from the United States to the South Pole is via Port Hueneme (California, U.S.A.), Christchurch (New Zealand), and McMurdo Station on Ross Island near the Antarctic coast. Materials originating in the United States will follow this shipping path. International shipments have the option of shipping to Port Hueneme or directly to New Zealand (Christchurch air cargo or Lyttleton harbor) for on-shipment through the US Antarctic Program (USAP). All cargo, once delivered to USAP, will be delivered by a scheduled date for each package with handling and routing under USAP control.

At the South Pole, the Do Not Freeze (DNF) storage space is severely restricted, and additional warm storage buildings there would be logistically difficult. For the IceCube Upgrade, we have been able to store some materials indoors at the South Pole in the Cryo Building. In the longer term, for IceCube-Gen2, we would setup a storage facility at McMurdo as a buffer for materials headed to the South Pole, especially DNF cargo in coordination with the contractor and the NSF.

In general, materials are shipped as early as possible, to minimize short deadlines in shipping and enhance flexibility of shipping routes, but this is subject to the available storage at the intermediate locations such as McMurdo, Christchurch, and Port Hueneme.

12.8 Trenching

Cables at the South Pole are trenched into the snow to protect the cables and prevent vehicle-cable collisions. The trenchers used have been small skidsteer tractors (CAT 287) with a "chainsaw-like" trenching tool attachment. These work well for short trenches, and the equipment operators are able to trench between installed pieces of hardware in the field, such as in the radio stations, putting in perhaps a dozen or more 10-20m trenches in a half day of work. Long distance trenches, 1-2km long, have been put in at South Pole using this same equipment, but typically requiring much of a day for each such cable run with multiple people walking and helping the cable into the trench. In all of the trenching, the surface must be compacted first, typically as a snow road compacted with the heavy tractors over the course of a season.

The IceCube-Gen2 detector will require several hundred kilometers of trenching, mostly for the radio array, but also for the surface and optical arrays as well. This is best done with a dedicated piece of long distance trenching gear familiar to many in the northern hemisphere from fiber cable installations alongside their streets. A dedicated trenching tractor, carrying the cable to be deployed, can in one pass dig the trench, install the cable, and cover over the open trench. Trenching yields of several kilometers per hour can be achieved at Pole, limited by bringing out more cables to the field for installation rather than the actual trenching time. These tractors are available with full tracks and the snow compaction required for their use could be less than for the existing trenching options. It might be a single run of track compacting along the intended cable routes.

Discussion of the particulars of the equipment choice has taken place with the South Pole heavy shop supervisor with the contractor. Final selection of equipment specifications would be in coordination with the NSF and the contractor.

13 Maintenance and Operations

Unified data acquisition, data filtering, and data handling software systems will support the IceCube-Gen2 optical, surface, and radio arrays; the IceCube Upgrade; and the original IceCube-Gen1 array. The maintenance and operations of the full IceCube–Gen2 experiment is therefore a straightforward extension of procedures and plans developed and refined over more than a decade of IceCube operations. A smooth hand-off from the construction project to operations is ensured by a prompt, phased commissioning approach (Sect. 13.1).

The IceCube concept of operations is that the detector takes data continuously without intervention. The average uptime (efficiency) of the detector is greater than 99.7% (Sect. 13.3). Detector hardware or software failures that cannot be automatically corrected will alert both on-site winterover personnel as well as experts in the Northern hemisphere, via an always-on dedicated satellite link (over the Iridium satellite constellation). Redundancy is implemented wherever possible, in order to eliminate single points of failure. In the case that full-detector data-taking is not possible due to component failure, partial-detector data-taking is started automatically. IceCube-Gen2 operations will follow naturally from procedures laid out in the IceCube Management and Operations Plan. The existing experiment control, monitoring, and alert handling mechanisms will all be extended and enhanced to support additional IceCube-Gen2 instruments.

Year-round 24-hour IceCube operations are supported by two full-time winterovers stationed at the South Pole. Before their 13-month South Pole deployment, they are trained for approximately three months on detector operations, hardware, and computing infrastructure. The winterovers are supported from the Northern hemisphere by operations managers and subsystem experts, including the Detector Operations Manager, the Run Coordinator, the Winterover and South Pole Systems Manager, and the software developers responsible for the online systems. Detector maintenance requiring outdoor operations or significant cargo is scheduled for the South Pole austral summer seasons (Sect. 13.5, 13.2).

IceCube operations is also responsible for delivering both experimental and simulated data to the collaboration in the Northern Hemisphere (Sect. 13.7, 13.8). The data warehouse at the Wisconsin Particle Astrophysics Center (WIPAC) stores these data at various stages of processing, reconstruction, and selection, up to and including analysis levels. Computational processing resources, both CPUs and GPUs, are provided both in the form of a local computing cluster as well as tools to use grid computing and/or clusters at other institutions. Regular calibrations of the data are required in order to analyze sensor output (Sect. 13.6). IceCube operations also develops and maintains the core software (IceTray) that enables data analysis (Sect. 13.9).

A high-level summary of operational support levels required by IceCube-Gen2 is provided in Table 26. Winterover staffing remains the same as in current IceCube operations. The summer maintenance population will increase modestly in order to support maintenance and calibration of the additional array types (radio and surface arrays). Satellite bandwidth levels for data transmission will increase, especially with new data products from the radio array; however, this is scalable depending on availability by tuning the online filter algorithms run in the ICL. Operational costs are expected to increase 50-70% from IceCube levels, largely from inflation and adding new specialized software and computing support for the radio and surface arrays.

Category	IceCube	IceCube+Upgrade	IceCube-Gen2
Winterovers	2	2	2
Summer Population (beds)	7–9	7–9	8–13
Power (kW)	60	75	190
Satellite bandwidth (GB/day)	100	150	300

Table 26: Estimated high-level operational support requirements for IceCube-Gen2. IceCube-Gen2 support levels include ongoing operation of IceCube and the IceCube Upgrade.

13.1 Transition to operations

As in IceCube construction, the IceCube-Gen2 installation plan enables newly deployed instrumentation to be commissioned and to take engineering data each season, before an official transition to physics operations begins. Cabling infrastructure, field electronics, and ICL electronics are deployed ahead of drilling for the optical and radio arrays, generally by one season. This enables rapid feedback on the health of the instrumentation after deployment. Any issues with surface electronics can be corrected, and any issues with deployment procedures can be identified and corrected quickly. This procedure also facilitates new scientific results even before construction is finished and the formal hand-off to maintenance and operations.

This transition to operations proceeds in a phased manner as instrumentation is integrated into the existing IceCube online infrastructure. After low-level commissioning, instrumentation calibration procedures allow individual configuration of array sensor elements to optimal settings. These settings are combined into an expanded detector configuration that integrates new optical array strings, radio stations, and surface array stations. The triggering, filtering, and other online subsystems will have already been exercised in the South Pole Test System before deployment using simulated data to identify any software or hardware bottlenecks and address these before deployment.

After detector completion and the commissioning of the final season instrumentation, a formal hand-off to maintenance and operations occurs, and full-detector physics runs will commence.

13.2 Physics runs

IceCube science operations follow a yearly schedule, known as “physics runs." The physics run specifies the detector calibration and configuration, the trigger conditions of the array components, the event filtering streams that select physics-quality data samples for satellite transmission to the Northern hemisphere data warehouse, and the online alert criteria used to notify the multi-messenger scientific community after the detection of significant astrophysical neutrino events. In order to balance requests for limited South Pole computing and bandwidth resources, trigger and filter proposals are submitted by IceCube collaboration working groups in advance of each physics run start to the internal Trigger, Filter, and Transmission (TFT) Board. The proposal provides the scientific case for each trigger/filter configuration, in addition to providing estimates of resource usage. The TFT Board evaluates the proposals and determines a unified run plan.

The operations group performs yearly calibrations and implements the physics run plan, beginning with a 24-hour test run. The test run data are validated by the physics working groups prior to the physics run start. Special operations, such as calibration runs, new software release commissioning runs, and planned hardware upgrades are vetted and approved through the run coordinator and operations team. Data processing and reduction are performed in a series of steps (Level 1, Level 2, Level 3, etc.) of increasing complexity and specificity to a particular physics analysis. Level 1 processing is performed by the Processing and Filtering (PnF) system running at South Pole. Level 1 processing is performed on all triggered events and includes basic calibrations and fast event directional and energy reconstructions. In IceCube, the typical latency between the event trigger and Level 1 processing is 20 to 30 seconds, facilitating rapid detection of astrophysical neutrino candidates and enabling alerts to the wider scientific community. PnF also performs online data reduction as determined by the TFT filter selection process in order to satisfy satellite bandwidth constraints. Level 2 and higher-level processing occurs once the Level 1 data are transferred via satellite link to the IceCube data warehouse in the Northern hemisphere.

13.3 Detector uptime, monitoring, and data quality

IceCube total uptime, or efficiency, is defined as the fraction of time that some portion of the detector is taking data. For the existing IceCube detector, the average total uptime in the IC86-2011 to IC86-2021 physics runs has been 99.6%. The average “clean" uptime, defined as the fraction of full-detector, analysis-quality data, is 96.4%; this has improved in recent years to over 98%. For IceCube-Gen2, as in the original IceCube-Gen1 construction, strings will be added into data-taking after each drilling season. After an initial calibration and commissioning phase, we expect to achieve similar uptime metrics as with the current detector. In particular, our target uptime for IceCube-Gen2 is 99%, and our target full-detector clean uptime is 95%.

IceCube Live is the software system that integrates control and monitoring of all of the detector’s critical subsystems into a single, virtual command center. It provides an interface for monitoring the detector both via automated alerts and with interactive screens displaying current and historical states of the detector and associated subsystems. IceCube detector monitoring is the system within IceCube Live that provides a comprehensive set of tools for assessing and reporting data quality. IceCube collaborators participate in daily monitoring shift duties by reviewing information presented on the web pages and evaluating and reporting the data quality for each run. The shift takers, frequently graduate students, compile reports on detector performance during their shift. A summary of the monitoring shift is given at weekly teleconferences, where experts determine if the detector is operating as expected and take actions to correct malfunctions as needed. IceCube Live will be expanded for IceCube-Gen2 operations to include the expanded optical array, the surface array, and the radio array, providing an integrated experiment control and detector monitoring software system.

13.4 Electromagnetic interference (EMI)

The IceCube detector including the IceCube Upgrade, the IceCube Laboratory (ICL), the future IceCube-Gen2 site, and the South Pole Cosmic Microwave Background (CMB) experiments are all located in the specially managed South Pole “Dark Sector." This is an NSF-mandated area in which radio emissions are strictly controlled, especially during the Austral Winter astronomical observing season. The technical provisions of the EMI restrictions have been maintained by an informal experimenters’ user group which has met on an ad hoc basis to evaluate proposed Radio Frequency (RF) emissions in the South Pole area. With the small size and controlled makeup of the South Pole community housed at the Amundsen-Scott South Pole station, emission control has been reasonably straightforward. RFI monitoring campaigns have been conducted both by the IceCube and CMB communities. The CMB observations have stricter EMI requirements than IceCube has had historically, though one meteor radar system at South Pole did produce observable background noise in a single IceCube DOM as the radar's beam pattern changed (directing more energy downward) with snow accumulation. This radar was deactivated a number of years ago.

The in-ice radio array of IceCube-Gen2, as well as the radio antennas of the surface array, rely on the low EMI background of the South Pole "Dark Sector", as the data improves with lowered background. Many EMI backgrounds are self-induced, in particular through power systems (e.g. DC-DC converters). All hardware for IceCube-Gen2 installed at the surface will be tested for emission. It is desirable to lower the power of the emission to that of the thermal background. Experience with mitigation strategies have been gathered during operation of smaller-scale radio arrays such as RNO-G, ARA, and ARIANNA that IceCube-Gen2 draws from. Austral summer calibration activities that result in emissions, such as the use of surface radio calibration pulsers, will be coordinated with other Dark Sector experiments.

13.5 On-site Maintenance

IceCube's high uptime and expansion in scientific programs is facilitated by a robust summer maintenance and upgrade program. Failure rates of both custom and off-the-shelf components are tracked to detect issues. Hardware within the ICL is maintained and/or replaced at a regular cadence to ensure ongoing reliability and availability of spares (Table 27). Commercial equipment such as uninterruptible power supply (UPS) batteries and the ICL servers have the highest cadence, while specialized or custom components may only be replaced once during the operational period, or not at all. Data archival disks are shipped north to the data warehouse every season, but some fraction of the disks can be re-used each season.

As the DOMs are frozen in, maintenance or replacement is not possible. However, due to the engineering focus on reliability and a rigorous testing program, the existing IceCube DOMs have an exceptionally low failure rate after freeze-in — as of this writing, 4 sensors of 5484 have

Component	Replacement Cadence
Archival Disks	1–2 yrs
UPS Batteries	3–5 yrs
ICL Servers	5–7 yrs
ICL Networking	10 yrs
UPSes	10 yrs
ICL Power Supplies	as needed
Field Electronics	as needed
In-ice DOMs	n/a
Radio Antennas + DAQ	n/a

Table 27: Operational replacement cadence for various IceCube-Gen2 hardware components.

failed during the past 10 years of operation. By following similar procedures for IceCube-Gen2, we plan to achieve similarly low failure rates over decades of operation.

As described previously, the surface array detectors and key elements of the surface electronics are elevated above the snow surface in order to improve long-term maintainability. The average annual snow accumulation at the South Pole is 24 cm [4], so elements deployed at 1.2 m height above the snow must be raised every 5 years in order to avoid being buried. Cable slack is included at the time of installation to facilitate multiple raises. This maintenance can be achieved on a rolling basis by servicing 20% of the surface array and FieldHubs per season. Based on experience raising the existing surface array station in 2023–24, this can be achieved with approximately 4 person-weeks of effort in total per season.

Given the large geographic footprint and distance from South Pole Station, the radio array is designed to minimize austral summer maintenance. DAQ electronics at each station are buried in shallow vaults and are designed and tested to achieve low operational failure rates, similar to the in-ice DOM strategy. Since the radio array stations function largely independently, failure of a single station only affects the integrated exposure of the array, not the quality of physics result. Given this, an $O(1)$% annual station failure rate without replacement is tolerable. Radio array infrastructure such as the radio FieldHubs are also designed with redundant components, but these are also elevated to provide long-term access as failures would affect a larger number of stations. Only 1–2 of the 8 radio FieldHubs must be raised each season, achievable with less than 1 person-week of effort and with vehicle support enabled by equipment acquired during construction.

In addition to the maintenance described above, other on-site austral summer activities include operationally sensitive software deployments (such as operating system upgrades); calibration activities; on-site winterover training; and managing retrograde cargo.

The IceCube operations plan and winterover training emphasize operator safety above all other procedures. Safety risks during normal IceCube–Gen2 operation are minimal and involve mainly the environmental hazards at the South Pole. While standard DOM power is low voltage (±48VDC to ±75VDC), maintenance during the austral summer may require access to high-voltage power supplies in the ICL and/or high-voltage DC-DC converters in the FieldHubs. Proper training and lockout-tagout procedures will be used in accessing these components, which will be isolated from the low-voltage electronics.

13.6 Calibration

Calibration of all detector instrumentation is required for ongoing IceCube-Gen2 operations in order to translate raw measured quantities in the various sensors to physical units and to enable production of high-quality science products. These calibrations are repeated at various intervals in order to track any changes due to temperature effects or other time dependencies. Calibration of the detector geometry, which will be refined from surveys during construction and deployment logging instrumentation, is also required in order to reconstruct events. The detector geometry is typically stable over short time scales, as the arrays move with the ice sheet, but over longer time scales, differential movement of the ice may need to be measured and taken into account.

Measuring the optical properties of the ice is critical for accurate reconstructions of the energy and direction of neutrino events. The ice remains a major source of systematic uncertainty in IceCube science analyses. The collaboration will continue to improve the ice model with data from LED flasher calibration runs and other calibration devices. The ice properties, for example the tilt (vertical offset) of the dust layers, also vary across the array and require IceCube-Gen2-specific measurements.

Measuring the radio properties of the ice is also critical to analysis and reconstructions of signals received in the radio array antennas. Ongoing operational activities include radio calibration pulser runs and/or surface pulser activities during the austral summer.

13.7 Computing and Data Management

Experimental data from the South Pole are retrieved over bandwidth- and time-limited satellite links and/or by transferring physical storage media during the summer season. Significant computing infrastructure in the Northern Hemisphere supports data storage, common data processing for the collaboration, and computing resources used by physics working groups and data analyzers for specific scientific analyses. IceCube's data warehouse stores experimental and simulated data on a distributed file system, with archival copies stored on magnetic tape at NERSC and DESY-Zeuthen. Data integrity is ensured via a dedicated software system that manages data retrieval and transfer throughout the process, from South Pole to archival tape.

This model is generally scalable to IceCube-Gen2. Additional data processing capacity will be needed not only for increased data volumes but also to handle dedicated processing and reconstruction algorithms needed for the surface and radio arrays. We anticipate a continuous increase in IceCube's use of Machine Learning (ML) algorithms, requiring additional ML-specific computing hardware to accelerate model training and evaluation. For general data processing and simulation, IceCube-Gen2 will continue to expand IceCube's use of resources provided by opportunistic computing consortia (e.g. the Open Science Grid) and allocation-based high-performance computing (HPC).

13.8 Simulation Production

Monte Carlo simulations of IceCube-Gen2 data are required for developing analysis methods to identify signal from background, for testing the performance of reconstruction algorithms, and for determining the background contamination of data analysis samples. Ideally, one would generate an order of magnitude more statistics in Monte Carlo as data, requiring ongoing simulation production as the experiment runs. Optimizing the computational demands and improving the efficiency of simulation is required to keep resource requirements feasible. IceCube-Gen2 will leverage the existing Monte Carlo software designed for IceCube, IceTop, and RNO-G to provide simulated data for the optical, radio, and surface arrays, after modifications for IceCube-Gen2-specific detector hardware. As ongoing calibration activities refine the knowledge of the radio and optical properties of the ice, these improved models will be used to generate higher-fidelity simulations, reducing systematic errors and improving the quality and scientific reach of physics analyses.

13.9 Physics Software

IceCube's current physics software codebase (IceTray) is used directly by a majority of the collaboration and covers a wide range of applications, including online filtering, real-time systems, offline data reprocessing, and offline simulation generation. It currently consists of over 100 projects and 1M lines of code. Their functions range from the core IceTray framework to user-defined simulation and reconstruction modules. Nearly all of IceCube's data (both archived and active) are stored in an IceTray-custom serialization format. In the near term, IceTray's capabilities will be expanded for the IceCube Upgrade in order to support new sensor types and data products, and IceTray's support of the IceCube-Gen2 optical array will be a natural extension. Support for the radio and surface instrumentation will also be added to IceCube-Gen2's physics software framework. Continued maintenance and expansion of this software is required in order to add physics capabilities (e.g. new event reconstruction algorithms), compatibility for future hardware and operating system platforms, and to fix issues.

13.10 Open Data

The IceCube Collaboration provides public access to reconstructed neutrino event data on several levels and on various timescales. Data sets are provided in an open format to be usable by researchers outside of the collaboration. These include real-time neutrino alert events transmitted to the wider multi-messenger astrophysics community, collections/catalogs of high-quality neutrino candidates that can be used to test a variety of astrophysical source models, and targeted data releases associated with specific publications or analyses. IceCube-Gen2 will provide access to these various data products as specified in a future data management plan and in accordance with the collaboration's data-sharing policies.

14 Environmental Impacts and Decommissioning

14.1 Site selection

The IceCube detector and its extensions are located at the South Pole, due to the unique properties of the ice as described in Part 1 of this Technical Design Report. The IceCube-Gen2 detector will expand the existing envelope of the IceCube Neutrino Detector at the South Pole by a factor of ten for the optical detectors and a factor of one hundred for the radio detectors.

The IceCube collaboration has a successful track record of working closely with the Antarctic Services Contractor and the United States Antarctic Program to ensure a safe environment and mitigate potential impacts of the extreme cold and low humidity at the South Pole.

Instruments will be delivered and deployed during the construction period, with annual shipments leaving for Antarctica in August, and project staff working on site from mid-November until mid-February. As the construction spans multiple years, operations will begin with a partially deployed detector. This strategy was successfully employed during IceCube construction.

14.2 Environmental aspects

The Antarctic Treaty stipulates that Antarctica shall be used for peaceful purposes only and for free exchange of scientific investigation, plans, personnel, and results. Additionally, the Protocol on Environmental Protection to the Antarctic Treaty designates Antarctica as a natural reserve and protects the Antarctic environment and dependent and associated ecosystems. Appendix B of the Protocol defines the various sectors of the South Pole (Clean Air Sector, Quiet Sebctor, Downwind Sector, and Dark Sector). The IceCube detector and the IceCube Laboratory are located in the Dark Sector; IceCube-Gen2 will also be located in the Dark Sector. The IceCube-Gen2 collaboration is further dedicated to minimize the environmental impact of the experiment and engage in sustainable operations of the experiment.

14.2.1 Environmental Impact and Sustainability

The significance of environmental impact and sustainability is increasingly integral to scientific endeavors, particularly in the polar regions.There are many examples of successful utilizations of renewable energies in Antarctica and the Arctic. While the environment at the geographic South Pole holds additional challenges, utilization of renewable energies offers potentially substantial cost-savings and reductions in the logistics footprint for operations and construction. For instance, as described in Chapter 11, integrating solar panels for the deep ice drilling can lead to significant fuel savings. In terms of detector operations, energy concepts can be considered in the broader context of the South Pole power infrastructure and power requirements. The IceCube-Gen2 collaboration will continue to engage in the formulation of comprehensive strategies for sustainable operations at the South Pole to lessen the overall environmental impact. The collaboration continues to scrutinize the detector to minimize power needs, in particular those associated with cost-savings for operations or reductions in logistics needs at the experimental site.

14.3 Comprehensive Environmental Evaluation process

Proposed USAP actions in Antarctica are subject to the environmental impact assessment requirements of Annex I, Article 3 of the Protocol on Environmental Protection to the Antarctic

Treaty, Environmental Impact Assessment, and the implementing regulations in the United States, Environmental Assessment Procedures for National Science Foundation Actions in Antarctica (45 CFR §641). These requirements specify that, for actions expected to have a more than minor or transitory impact on the Antarctic environment, a Comprehensive Environmental Evaluation (CEE) must be prepared. A CEE was prepared and approved for the original IceCube project and finalized in August, 2004. The CEE was prepared by the NSF (more specifically, the Antarctic Science Section and the Office of Polar Programs) with expert input contracted from a well established professional environmental engineering firm. The draft CEE Notice of Availability was published in the *Federal Register* in September, 2003 to allow for public comments and concerns, as well as presented to the Antarctic Treaty Consultative Meeting / Council on Environmental Protection for comments. All comments were satisfactorally addressed before the CEE was finalized in August, 2004. The IceCube Upgrade project was also reviewed for environmental impact, and it was determined that the environmental impact would be minor and no CEE needed to be prepared. We anticipate that IceCube-Gen2, with its larger footprint at the South Pole, will have more than a minor or transitory impact and thus would need a CEE. Details on the CEEs that have been prepared for Antarctic, including for the IceCube Neutrino Observatory, can be found in [5].

14.4 Decommissioning

Decommissioning the IceCube detector and all of its extensions would occur at the end of the useful lifetime of the facility. A decommissioning plan for the existing IceCube Neutrino Observatory (including the IceCube Upgrade extension) can be found in [6]. This plan outlines the steps that will be followed after a decision for divestment is made for the closeout of IceCube Neutrino Observatory (ICNO) operations and decommissioning in the scenario where the science return no longer warrants the continued operation of the ICNO, and will be updated to include the future IceCube-Gen2 extension as the project moves towards approval.

When the decision to decommission the ICNO is reached, the WIPAC management team that oversees IceCube management and operations will consult stakeholders and the NSF program office, and appoint a management team with personnel familiar with Antarctic operations that will be responsible for managing the decommissioning and divestment activities. The transition team will develop a final transition plan and will submit it to the NSF program office for approval. A full resource loaded schedule will be developed with input from the NSF and the Antarctic Services Contractor to capture the decommissioning process, including decommissioning the physical detector, computing, and infrastructure at the South Pole. Most of the detector infrastructure is deep under the ice and its final disposition, namely to leave it in place, for the current ICNO is covered by the CEE. This would be updated for the IceCube-Gen2 extension to the ICNO. All surface and accessible infrastructure equipment will be removed and retrograded. A full estimate of effort and retrograde cargo will be developed and associated costs estimated as the IceCube-Gen2 project moves foward. All northern hemisphere equipment will be decommissioned and surplussed according to applicable regulations.

The disposition of the IceCube drills (Hot Water Drill, ARA (Rodwell) drill, radio (BigRAID) drills will be considered separately, as these drills may prove of use to the South Pole station, for example constructing additional outfalls or supporting other infrastructure or scientific needs. This will be discussed in advance of any retrograde activity with all stakeholders to maximize the benefits of the NSF's investment in these tools.

15 Cost and Schedule

15.1 Introduction

In this chapter, we give a preliminary estimate of the cost and schedule for the IceCube-Gen2 Project. A bottom-up cost estimate was done in 2020 in preparation for the National Academies of Sciences, Engineering, and Medicine decadal survey in astronomy and astrophysics (Astro2020) [7]. An independent, external Technical, Risk, and Cost Evaluation (TRACE) review was done as part of the Astro2020 process, which found both the programmatic and schedule risks of IceCube-Gen2 to be medium-to-low. The independent cost estimate was about 20% higher than the project estimated costs, however this was not considered a concern, and the review noted that the MREFC review process will lead to more accurate accounting. As with the original IceCube project, the committee believes that IceCube-Gen2 can be successfully executed within a fixed budget.

The installation of additional strings of detectors for the current IceCube Upgrade is scheduled for the FY26 Field Season. Work is ongoing to refurbish and commission the drill systems needed for the installation, and a new cadre of experts are being trained in hot water drilling at the South Pole. Hot water drilling forms the critical path for the project; minimizing the gap between the end of the IceCube Upgrade Field Seasons and the start of the IceCube-Gen2 Field Seasons allows us to retain expertise, minimizing costs and risks to the Project.

15.2 Schedule

Below we present a generic schedule for construction. In terms of the MREFC gate reviews, we would be ready to begin moving through the process as early as 2024, with Final Design Review and Construction start in 2027, however this schedule is not compatible with the current Antarctic Program logistical assumptions.

The Project construction schedule estimate is based on both the IceCube-Gen1 experience for drilling and installing optical strings, and from the RNO-G experience in drilling and installing radio stations. Using this experience as a guide, we have estimated the time for building, shipping, drilling and installing the detectors. In this section we describe the high level schedule assuming realistic technical assumptions as described in previous sections.

15.2.1 Schedule Overview

Figure 52 shows a high level overview of the schedule for the project by project year. The construction schedule is generic without assuming a calendar year date for construction start. We continue working with the NSF to specify the actual start of funding and the start of IceCube-Gen2 on-ice seasons (Field Seasons), which will depend upon baseline approvals as well as the ability to support the effort at the South Pole. For the costing exercise, we assumed the start of the Project (PY1) in 2027, however, the start can be shifted out, impacting the start of on-ice seasons, the completion of the project, the project time-phased cost profile, and changing the at-year dollar profile (e.g., increasing the cost of the project by inflation and possibly additional effort needed in developing the project technical scope in light of parts availabilities).

The construction project spans over 10 years, paced by the speed and efficiency of deep ice drilling and installation of the optical detector strings. During the original IceCube installation of 86 strings, the maximum number of strings installed during an on-ice season was 20 [8].

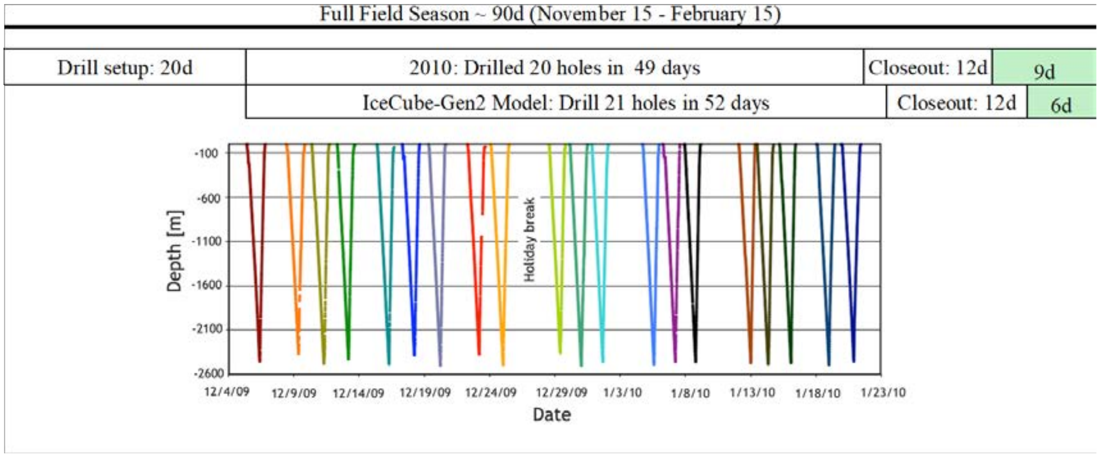


Figure 51: Depth versus date for the 20 holes drilled during the 2009/2010 Field Season.Drilling and deploying the 20 strings took 49 days; we anticipate ramping up to the same level of efficiency in IceCube-Gen2. Hot water deep drilling is the pacing item for the IceCube-Gen2 detector installation.

We anticipate being able to achieve a slightly higher level of efficiency during construction of IceCube-Gen2 due to the upgrades in the hot water drill as described in Chapter 11. The slow ramp up of the number of deep holes drilled in the IceCube-Gen2 schedule reflects the expected inefficiency as the team gains experience and makes improvements to the drill. Figure 51 shows the drilling profile as a function of date during IceCube's penultimate drilling season in 2009/2010. During this season, drilling started in early December and took 49 days; for IceCube-Gen2 we assume the same cadence, drilling 21 holes in 52 days. Also included in the figure is the estimate of the drill startup and close down, directly from IceCube-Gen1. The green denotes additional days (i.e. schedule contingency) left in the season.

For the Radio detector, drilling will start with one drill and expand to three drills, allowing the drilling to proceed at three holes (one station) every three shifts. This cadence will comfortably allow for drilling and installation of 70 stations during a field season. We anticipate having more detailed experience with drilling radio stations from the ongoing RNO-G project in Greenland. Note that installation of the radio portion of the project is independent of the in-ice optical installation in terms of equipment and personnel, and delaying the start of the radio installation by a year would not impact the overall timeline for completing the project.

15.3 Cost Estimate

The project cost was estimated using mature designs as described in this Technical Design Report, and building on the expertise acquired during IceCube construction and the ongoing IceCube Upgrade construction. The original cost estimates were developed for the Astro2020 Decadal Survey, and have been robust. The development of optical sensors is ongoing now and will be tested in-ice as part of the IceCube Upgrade project. Drilling and installation procedures are also very mature, and cost estimates have been derived from previous experience, or in some cases from actual costs. The radio detector is similar to one being deployed in Greenland (Summit Station) as part of the RNO-G project. Computing and power estimates are done using extrapolations from current operations of the IceCube detector. Surface detector costs are well-informed by the current surface detector.

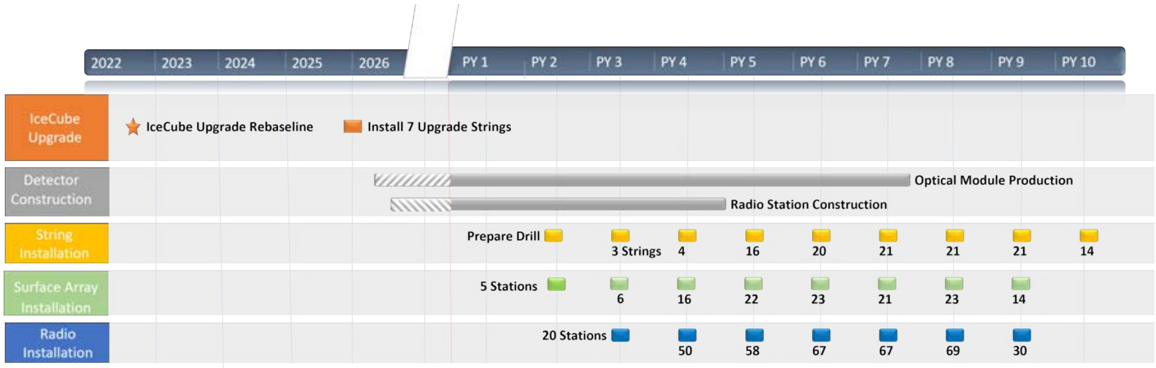


Figure 52: High-level schedule of the project. In orange is the current IceCube Upgrade; the final field season for the Upgrade will be the CY25-26 Field Season. The gray hashed areas preceding the NSF Final Design Review represents early in-kind contributions.

The project costs were estimated by first defining the Work Breakdown Structure (WBS) and ensuring that all project deliverables and necessary infrastructure were captured within the WBS. Each area was then further divided into work packages, and Subject Matter Experts costed each work package. Because of extensive experience with IceCube-Gen1 and IceCube Upgrade, most of the estimates were done parametrically, while taking into account changes in cost drivers for each work package. The estimates were done in year 2020 equivalent dollars, and escalated according to Table 28. This table represents an averaged Labor (specifically University Labor) and Capital Equipment escalation by year according to ongoing current large projects centered at Fermilab and Brookhaven National Laboratory. We used the average as the on-project labor and equipment cost ratio is equivalent, which was also our experience with the IceCube construction project.

Year	Escalation
2021	4.2%
2022	5.9%
2023	4.4%
2024	3.8%
2025	3.4%
2026	3.2%
2027 and onwards	3.1%

Table 28: Escalation assumptions from 2021 onward.These numbers are an average of escalation on labor and equipment costs as the overall labor and equipment costs on the project are equivalent.

Project Year 1 was assumed to be 2027, with the first on-ice season in 2028-2029 in order to begin upgrading the drill. Drilling and detector installation would start slowly in the 2029-2030 Field Season and ramp up over the following two years.

Table 29 shows the estimated costs of the project by Level 2 of the WBS. The WBS is defined below.

- **1.1 Project Office**

  Project management and finance, systems engineering, production and technical oversight, logistics planning and management

- **1.2 Implementation**

  Costs for drills design, production and maintenance, hole drilling, instrument installation, and detector integration at the South Pole

- **1.3 Instrumentation - Deep**

  Deep-ice detector modules, their integrated cabling, electronics. This includes detector sensors and calibration devices.

- **1.4 Instrumentation - Shallow**

  In ice Askaryan signal detector array at surface and shallow depths, as well as the surface scintillator array.

- **1.5 Data Systems**

  Hardware and software systems starting inside the IceCube Laboratory and including core software for data acquisition and filtering as well as offline software packages

- **1.6 Commissioning and Calibration**

  Calibration of the array and commissioning of newly deployed modules

- **1.7 Antarctic Service Contractor Coordination and Polar Support**

  Antarctic Support Contractor work specific to the IceCube Gen2 Project. This area holds the costs for logistics support; the actual logistics manager is in the Project Office.

  Contingency was calculated by WBS Level 2 area and came to a total of 31.3% (see Chapter 17 for more details).

15.3.1 In-kind Contributions

The in-kind contributions shown in Table 29 are an underestimate since they only capture expenditures on capital equipment, and not labor. In order to make a more direct comparison, the major pledges thus far, in percent of deliverables, is shown in Table 30

IceCube has a long history with international collaborators in North America, Europe, and Asia. For the current Upgrade detector, for example, in-kind contributions make up all of the in-ice optical modules and most of the cables from the in-ice detectors into the IceCube Laboratory. For IceCube-Gen2, international in-kind contributions represent half of the in-ice detectors and downhole cables, a third of the Radio detectors and about two thirds of the surface detector hardware. There are on-going discussions with collaborators which will likely lead to additional in-kind contributions.

L2 WBS	WBS Name	Total Cost ($M)	In-Kind ($M)	NSF ($M)
1.1	Project Office	38.4	-	38.4
1.2	Implementation	82.4	-	82.4
1.3	Instrumentation - Deep	182.6	64.0	118.6
1.4	Instrumentation - Radio and Surface	40.5	10.0	30.5
1.5	Data Systems	18.0	-	18.0
1.6	Commissioning and Calibration	16.8	-	16.8
1.7	ASC Coordination and Polar Support	72.7	-	72.7
	Total Without Contingency	451.4	74.0	**377.4**
	Contingency (31.3%)	118.2	-	118.2
	Total With Contingency	569.6	74.0	**495.6**

Table 29: Project Costs by WBS Level 2 Area. Estimates were done in year 2020 equivalent dollars, and then escalated to at year dollars as described in the text. The bolded numbers are the estimated NSF Total Project Cost. In this exercise, PY1 is assumed to be 2027. With the assumptions we have used, each year of delay of project start after 2027 adds an additional 3.1% ($15.4M) to the Total Project Cost due to escalation.

15.3.2 Cost Profile for the U.S. Project

The time phased costs for the proposed U.S. part of the project is shown in Table 31 and plotted in Figure 53. This cost profile assumes the schedule presented in section 15.2.1 Just as for the previous cost table, the estimates were made in year 2020 equivalent dollars and escalated by the factors in Table 28. Project Year 1 (PY1) was assumed to be 2027 for this exercise. Because of up front costs for major equipment for the hot water drill and the slower ramp up of optical module production in the U.S., the bottom line is that the project profile over the first seven years is approximately flat at about $60M per year.

While no new complete cost reassessment has been completed since Astro2020, additional Research and Development has been carried out to solidify the design of all of the cost drivers of the project, with some resulting cost savings and cost increases due to maturing interfaces,

Item	Country	In-Kind (%)
Optical Modules	Germany	41.7%
	Japan	7.5%
Downhole Cables	Sweden	20.7%
	Japan	30.6%
Radio Detector	Belgium	30.2%
Surface Detector	Germany	65%

Table 30: Current percent of in-kind contributions by items. Substantial in-kind contributions are being pledged for the detector instrumentation.

WBS	PY01	PY02	PY03	PY04	PY05	PY06	PY07	PY08	PY09	PY10	Total
1.1 Project Office	3.54	3.69	3.84	4.00	4.17	3.77	3.75	3.91	4.06	3.67	38.41
1.2 Implementation	27.14	6.50	5.54	5.77	6.19	6.37	6.02	6.26	6.51	6.08	82.37
1.3 Instrumentation - Deep	7.86	8.73	12.22	19.53	22.29	22.93	17.41	7.65	0.00	0.00	118.63
1.4 Instrumentation - Radio and Surface	1.89	2.71	3.73	3.82	4.46	4.02	4.24	3.33	1.22	1.02	30.45
1.5 Data Systems	1.59	1.32	1.38	1.82	1.95	1.77	1.90	1.96	2.10	2.26	18.04
1.6 Commissioning and Calibration	1.41	1.47	1.54	1.59	1.34	1.74	1.80	1.88	1.97	2.05	16.80
1.7 ASC Coordination and Polar Support	1.14	10.19	13.94	11.07	10.43	10.44	5.39	4.76	4.02	1.36	72.73
Total U.S. without Contingency	45.57	34,61	42.17	47.60	50.85	51.05	40.52	29.75	19.88	16.43	377.42
Contingency (31.3%)	13.96	10.84	13.20	14.90	15.92	15.98	12.69	9.31	6.22	5.14	118.16
Total U.S. with Contingency	58.53	45.44	55.38	62.50	66.77	67.03	53.20	39.06	26.10	21.57	495.59

Table 31: Time phased project costs showing the cost profile assuming the schedule shown in Fig. 52. Estimates were done in year 2020 equivalent dollars and escalated according to the text. In this exercise, PY01 was assumed to be 2027. With the assumptions we have used, each year of delay after 2027 adds an additional 3.1% ($15.4M) to the Total Project Cost due to escalation.

requirements, and processes. Continued development will be undertaken with the goal of lowering the costs for the same requirements (value engineering).

The cost of logistics (moving cargo and people to the South Pole) was estimated using the IceCube-Gen1 experience, where all logistics was paid on-project. IceCube Upgrade logistics is more difficult to extrapolate from, as these costs were born entirely by the NSF Office of Polar Programs and paid directly to the Antarctic Services Contractor (ASC). The model for IceCube-Gen2 will be similar to IceCube-Gen1; that is, all logistics costs will be paid on-project. The current cost estimate used the best information we had from ASC as of the end of 2019 (and escalated at the same rate as the rest of the Project).

15.3.3 Cost Drivers

Figure 54 shows the breakdown of costs by Work Breakdown Structure. Over half of the project cost is captured in WBS areas 1.2 and 1.3 which are discussed in more detail below. Another 20% of the total project cost is to support needed logistics and cargo movement at the South Pole (WBS 1.7). Figure 55 shows the breakdown of costs by technical area for the two main WBS cost drivers. These costs will be discussed in more detail below.

15.3.4 Cost Drivers in WBS 1.3 Instrumentation - Deep

Figure 55(a) shows the breakdown of costs by area for the in-ice instrumentation. Nearly three quarters of the costs come from the IceCube-Gen2 Optical Modules and another 20% from the downhole (in-ice) cable assemblies. The remaining costs for the surface cables, readout field hubs, and calibration and cosmic ray devices make up less than 10% of the costs.

The optical modules represent the majority of the on-project costs and in-kind contributions. The model for manufacturing the modules is similar to the current IceCube Upgrade module production: we will have several production sites across the U.S. and internationally. The U.S. module production is funded on-project and represents about 50% of the total module production. The rest of the modules will be built by our international colleagues in Europe and Japan.

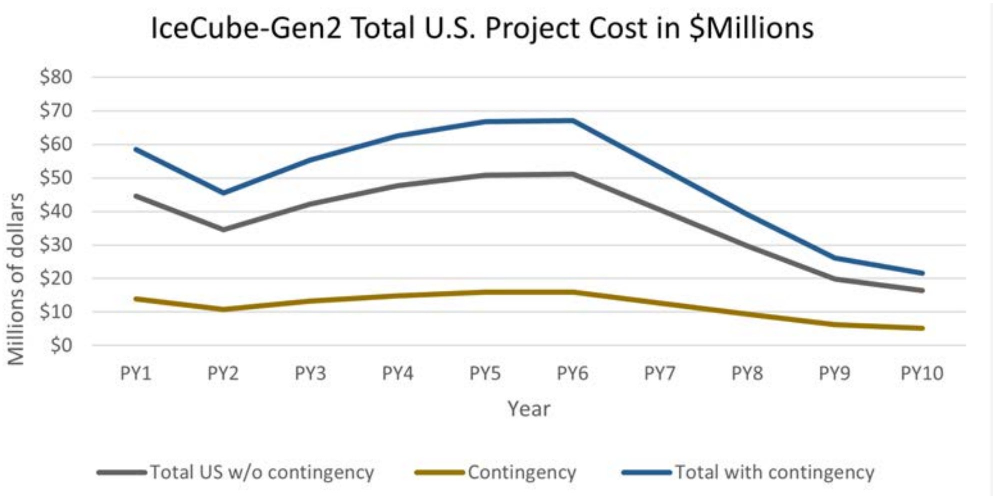


Figure 53: Cost Profile for the U.S. portion of the total project cost. The cost per year is relatively flat due to the investment in drilling equipment and slower ramp up of the U.S. part of the optical module production. The total project cost, including contingency, is roughly $ 60M / year, and begins ramping down in year seven of the project as all of the equipment is built and shipped to the South Pole.

The costing of the optical modules is informed by the current Upgrade optical modules and is robust. Figure 56 shows the contribution to costs by optical module element. The cost of the Photomultiplier Tubes (PMTs) makes up nearly half of the total cost of the module. We have developed module prototypes using PMTs from two different vendors, reducing both cost and risk. Additionally, the current optical modules are filled with gel, for the IceCube-Gen2 modules, a newer method forming an optical seal with a gelpad, which uses a fraction of the amount of gel has been developed, which also maps into a cost savings. We are also looking at simplifying the mainboard to reduce risk and costs. These potential cost savings have not yet been factored in to the overall costs.

The downhole cable assemblies also represent a significant cost driver. We have up to date costing of these cables from the Upgrade project – while they came in more expensive than estimated in our original cost estimate, recent technology advances allow us to reduce the amount of copper by 66%, representing an overall savings from our original estimate.

Overall, the deep instrumentation costs are well understood and stable due to a robust R&D campaign on the modules and current data and vendors for the cables. Several prototype IceCube-Gen2 modules will be deployed in-ice as part of the current Upgrade project, which will further solidify the robustness of the design and costing.

15.3.5 Cost Drivers in WBS 1.2 Implementation

Implementation includes designing, procuring, shipping, and commissioning the drill systems, as well as the Field Seasons required to drill and install the radio and deep ice sensors. Figure 55(b) shows the breakdown of the costs for this area. More than two thirds of the cost is captured in the design, purchase, testing, and commissioning of the hot water drill. Costs have been developed at a detailed level, and the estimates show that the overall costs are divided roughly evenly between management and engineering costs, and equipment costs. The Deep Hot Water Drill is a redesign of the current drill, allowing for more mobility in order to support drilling holes that are further apart. Expertise in hot water drilling at the South Pole is cen-

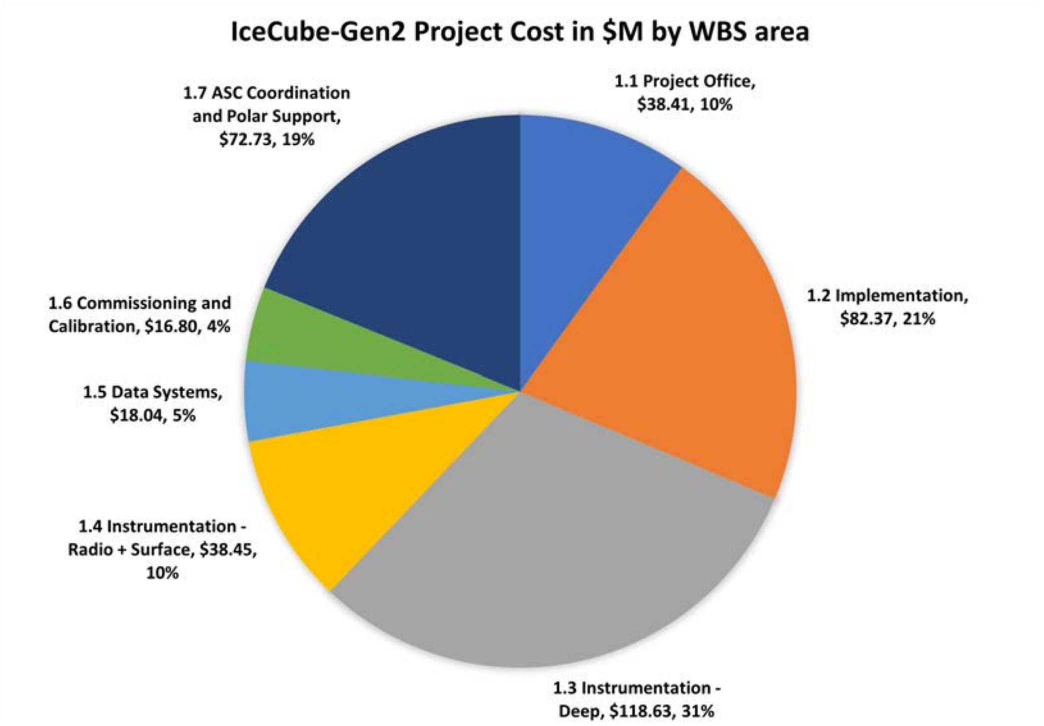


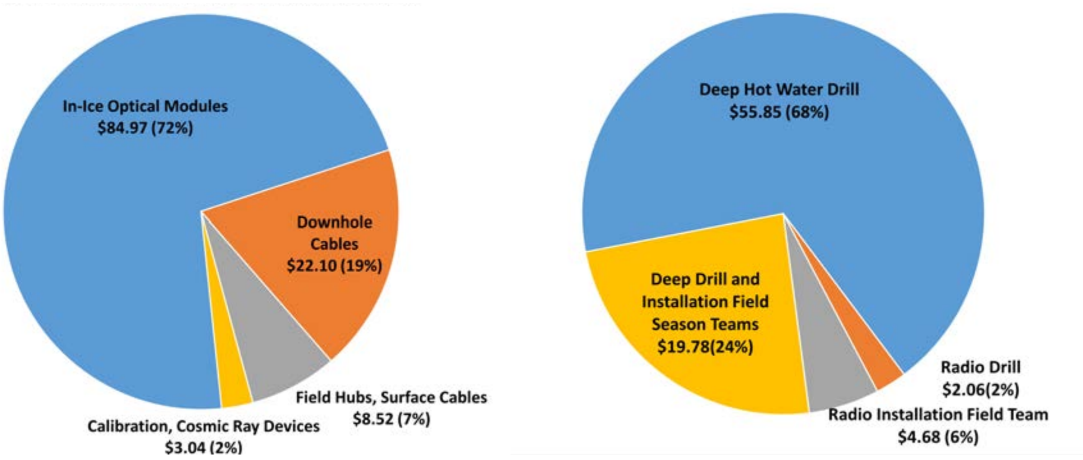
Figure 54: Pie chart of IceCube-Gen2 Total Project Cost showing contributions from the different WBS areas.

tered at the University of Wisconsin - Physical Sciences Laboratory (UW-PSL), and the current Upgrade is training a new generation of drilling experts. The IceCube-Gen2 drill design is advanced, and testing of some parts of the design has started in the test bed at the UW-PSL. A full bottom-up costing was done of the reference design, and additional design considerations may decrease the costs.

The cost of the Field Season and Installation teams is the second largest cost driver for the implementation area. This cost is also robust and is informed by drilling and installation experience from IceCube-Gen1. While the proposed module complexity and number of modules per string is larger in IceCube-Gen2, the considerations of hole size and hole lifetime is well modeled, allowing us to estimate the team size and drilling and installation times with confidence.

The radio drill is a smaller effort and will use drills currently being tested as part of the Radio Neutrino Observatory in Greenland (RNO-G). The costs and effort needed for deployment of the radio array is informed by the current RNO-G effort.

The third largest cost driver, as shown in Figure 54 is the effort needed for support at the South Pole (shown in the figure as WBS 1.7 - Antarctic Service Contractor Coordination and Polar Support). This area captures the cost for shipping equipment and personnel to the South Pole, fuel for drilling, temporary summer housing, and other logistics costs. These costs were informed by IceCube-Gen1 logistics costs, as well as expertise from former Antarctic Service Contractors. Unlike the current Upgrade, where logistics are paid directly from the NSF's Office of Polar Programs, the model for IceCube-Gen2 would be similar to the one from IceCube-Gen1, where a substantial amount of the logistics was paid for on-project. While we have had experience in costing these areas, logistics costs can be volatile, and it is important that we



(a) Deep Instrumentation Costs in $M by Area

(b) Implementation Costs in $M by Area

Figure 55: Project costs in millions of dollars showing the breakdown by WBS areas and the breakdown of costs in the technical areas for the two main WBS cost drivers.

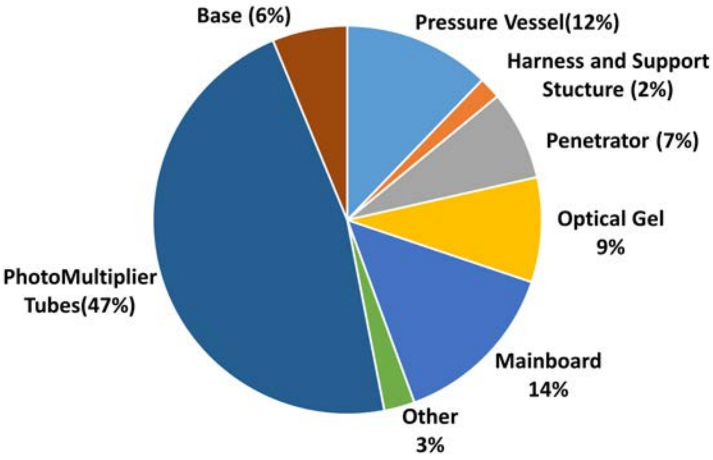


Figure 56: Contributions to the Optical Module Costs.

interface directly with the NSF and the Antarctic Service Contractor to review the costs, and do a full bottom up cost estimate with the most current assumptions.

15.3.6 Future Plans for Cost Estimates

We plan to initiate a full re-estimate of the total project cost once we secure funding to complete the preliminary designs and plans, and using additional experience gained during the current IceCube Upgrade Project. As discussed above, it is critical that we interface with the Antarctic Service Contractor and the NSF Antarctic Infrastructure and Logistics teams in order to update the costs and schedule for moving cargo, people, and effort to the South Pole to support the project.

15.4 Current Status

As described in this Technical Design Report, the design for the project is well advanced. IceCube-Gen2 prototype in-ice modules are being built now, and will be deployed as part of the current IceCube Upgrade Project during the FY26 Antarctic Field Season. Cable designs will be verified in the current Northern Test Stand. The deep hot water drill design is well advanced and parts of the design is being tested at the University of Wisconsin Physical Sciences Laboratory IceCube test area. The radio drill is built by the British Antarctic Survey and is being used currently to drill radio stations in the Arctic (Summit Station) as part of the Radio Neutrino Observatory - Greenland project (RNO-G). Additional drills for drilling the deep-ice pilot (Firn) holes and the "Rodriguez Wells" (RodWells) for supplying make up water for the hot water drill exist and are being exercised at the South Pole during the current (FY24) Field Season as part of the Upgrade Project.

Substantial funding for reaching mature designs that IceCube-Gen2 is proposing has been invested both by NSF as part of the current IceCube Upgrade Project (with a Total Project Cost of $40M), and by the University of Wisconsin ($5M). Our international partners in Germany and Japan are beginning to receive funding to prepare for IceCube-Gen2 as well. Substantial investment in the Radio Neutrino Observatory - Greenland is ongoing by our European collaborators (mainly Belgium, Sweden, with a small NSF contribution). We are also investigating additional opportunities for international engagement, potentially reducing the overall cost and/or risk of the Project to the NSF. The technical design of the Project is well beyond the Conceptual Design phase as defined by NSF. Additional investment is needed to refine the cost, schedule, and build the Project Office to prepare for an NSF Preliminary Design Review.

16 Quality Assurance and Reliability

The Quality Assurance, Quality Control (QA/QC), and Configuration Management systems within IceCube have been developed over the last 20 years for the IceCube construction project, the IceCube Upgrade project, and IceCube M&O programs. These systems have been extremely successful, as evidenced by the high uptime and reliability of the current detector. By using lessons learned at each stage of detector building, installation, and operation, we continue to improve our QA/QC and Configuration Management.

16.1 Reliability and overall performance of IceCube-Gen2

The IceCube detectors' (including IceCube, IceCube Upgrade, and IceCube-Gen2) unique operating environment and total inaccessibility of major in-ice system elements following deployment place a high priority on careful reliability engineering. The optical detector installation in IceCube-Gen1 occurred over 6.5 South Pole Field Seasons (between 2005 - 2010), when 86 strings of 60 Digital Optical Modules were installed in the ice. The observatory has been extremely reliable, with 98.3% of the optical detectors functional and routinely sending data. Figure 57 shows the fraction of Digital Optical Modules reliably operating as a function of year. In order to achieve this level of reliability, all modules are subjected to rigorous testing before shipping to Pole and modules are retested at Pole before installation to insure no damage occurred during transport. This same process is being followed by the current IceCube Upgrade project, which will install a handful of IceCube-Gen2 modules in the ice for testing. All in-ice failures are reviewed, along with testing results, with an eye to refining testing requirements to further improve detector reliability.

16.2 Reliability Key Performance Requirements

Success of the project's hardware installation effort is defined for each detector component. In general, the Key Performance Parameter for each hardware system is that >95% of the components remain functional throughout science runs. The definition of functional is described below for each of the components separately.

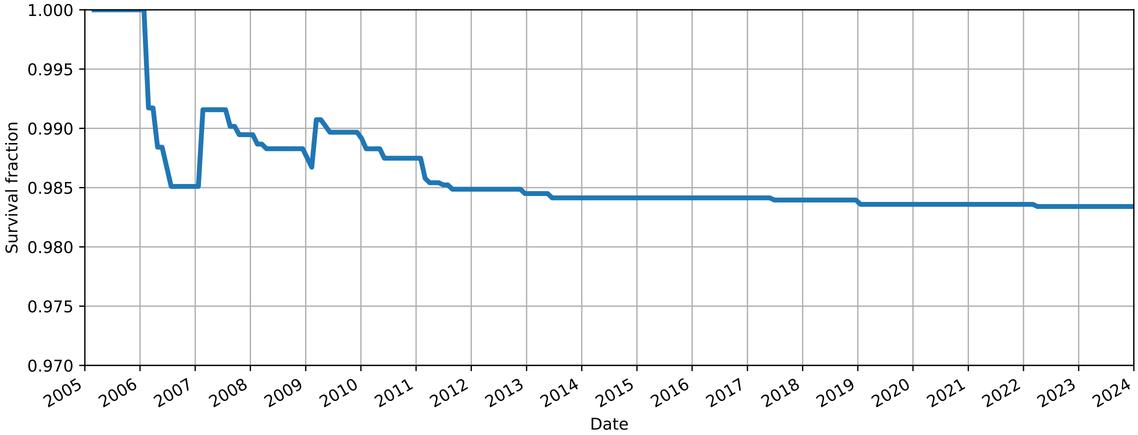


Figure 57: Fraction of good Digital Optical Modules as a function of year for the IceCube Neutrino Observatory. The fraction is measured during string commissioning after the string is installed in the ice, hence the jagged shape in the plot during the detector construction years. The fraction has been very stable since the completion of the detector.

For the **optical detector**, >95% of the in-ice optical modules shall be functional throughout the science run. In addition to any that fail completely, individual optical modules are considered to have failed if they have less than 75% nominal acceptance. For calibration success, it is required that >90% of all flasher-to-optical module transmission measurements be performed and that camera imagery exists for both freeze-in and post freeze-in hole ice.

For the **in-ice radio array**, success is achieved if >95% of the radio station channels are fully functional. A channel is considered fully functional, if the received thermal noise power is within 15% of the expected value and no self-induced noise contamination is observed.

For the **surface array**, all surface stations should be operational, and all individual detectors operational directly after installation. The surface radio antennas are considered operational, if they detect the Galactic noise modulations, and the scintillation detectors are considered operational if they detect the MIP peak of air-shower muons. All detectors and electronics of the surface array are elevated and can therefore be replaced in case of rare failures. As with the optical and radio arrays, >95% of the surface detectors should be fully functional during the lifetime of IceCube-Gen2.

16.3 Reliability Methodologies

The IceCube Neutrino Observatory has developed and refined its approach to ensuring detector reliability as more data on failures or degradations have become available. Because instruments installed in the ice cannot be exchanged or serviced, it is important to extensively test the detector components in advance to ensure high reliability.

For example, for the optical modules, this testing includes several weeks per module of temperature cycling, high voltage cycling, and optical testing and measurements before packing the modules to ship to Pole. Acceptance testing is done at Pole to ensure no damage occurred during shipping. After installation in the ice, any failed modules are studied for the root cause of the failure and tests that could address or predict the failure mode are reviewed and updated. Details of the testing can be found in the relevant sections in Part II of this Technical Design Report.

16.3.1 Physics of Failure

Physics of failure (PoF) is an approach for the development of reliable products that uses knowledge of root cause failure processes to prevent product failures through robust design and manufacturing practices. The basic premise is that it is equally important to understand how equipment works and how it fails in the environment in which it is expected to operate.

Unlike statistical analysis, which requires a prior database of comparable experience, PoF methods can be applied effectively in unique environments such as IceCube. By carefully understanding the sources, types, and levels of available energy that may cause harm, one can readily identify the system elements most at risk. Applying this insight into how the design interacts with environmental stressors enables a proactive risk response and results in significantly higher reliability.

16.3.2 Statistical Analysis

Statistical analytical methods are used as a supplement and extension of PoF reliability analysis whenever appropriate source data is available or can be reasonably developed using probabilistic methods. Failure rate estimates will be made for purposes of system availability estimation assuming a 15-year life span of the detector array, and the definition of functional as described above. Data collected during developmental and production testing will be captured for analysis and predictive value.

16.3.3 Failure Modes and Effects Analysis (FMEA)

Every system element in the detector will be examined in terms of possible failure modes and root cause—an activity closely integrated with PoF reliability philosophy and methods. As each failure mode is identified, the anticipated effect is determined and associated with a criticality level. This information is central to reliability modeling activities and to creating designs that are fault tolerant or at least fail gracefully through gradual degradation rather than exhibiting outright loss of functionality. Additional hazards analyses, considering both personnel and equipment safety, will be conducted for the procedures of drilling and installation.

16.3.4 System modeling

System modeling tools such as MIL-HDBK-217 and Telcordia (Bellcore) are limited in their direct applicability on a project such as IceCube due to its unique operating conditions, but are still useful for generating a baseline model. We will utilize the MIL-HDBK-217 approach to develop a system reliability model that will extend to the component level for critical system elements, in particular the high-voltage generators, and the in-ice module main electronics boards. This baseline model will be extensively applied during design for reliability allocation and estimation purposes.

16.3.5 Failure Review and Corrective Action

Although the IceCube-Gen2 detectors will be new, they build on current successful designs. As discussed in the introduction to this chapter, the in-ice modules have been extremely stable, however there were cases of "infant mortality" as the modules were being installed in the ice. For example, because of the extremely dry climate at Pole, protecting the modules against Electrostatic Discharge (ESD) during deployment is essential; this was the cause of infant mortality in several modules during installation in IceCube, and we now have more stringent controls in place to prevent similar losses in the future. As much as possible, we have performed thorough root-cause analyses for all module failures, even after the modules were installed in the ice.

16.3.6 Parts, materials, and process selection

In accordance with the PoF methodology, parts that have a limited usable lifetime such as aluminum foil wet electrolytic capacitors, materials that are not tolerant of low temperature exposure (freezing and cracking), and assembly and manufacturing processes that adversely affect the reliability of components and materials are excluded from our critical in-ice subsystems. During IceCube-Gen1 construction, NASA's Glenn Research Center (with expertise in low-temperature electronics) was consulted to provide guidance in component and material selection.

16.4 Quality Assurance

Quality systems for the IceCube-Gen2 project are a vital component in the delivery of successful hot-water drilling and instrumentation deployment. A quality and safety manager, who has the technical skills and background to address the issues in the context of the IceCube-Gen2, will manage the effort. Quality systems, as applied to the IceCube-Gen2 project, encompass nonconforming materials, incoming inspections, document control, audits, and corrective and preventive actions. It is an integral part of the design, procurement, fabrication, and deployment phases. The program objective is to ensure the completion of a high-quality, reliable, and advanced detector. Achieving this goal requires all project participants to employ accepted and sound engineering practices and to comply with all applicable procedures. Quality functions are integral to the entire IceCube-Gen2 team, allowing for a seamless approach and the institutionalization of quality into the project. The document “IceCube-Gen2 Quality Plan” describes the details of the quality systems program.

The design baseline content is stored in a documentation database instance in Microsoft SharePoint which allows for collaboration-wide contributions, editing, and reviewing. This is then moderated with a full available history of edits, and a document control system which allows the uncontrolled documents held in common by the collaboration to develop into controlled and approved documents. The transition from uncontrolled to controlled documentation is managed by the Quality & Safety Manager with approvals from the Technical Board following internal engineering reviews. System engineering is handled through the use of multiple defined document types for each baseline configuration item. Configuration items are stored hierarchically from the “IceCube-Gen2” level down to low level hardware and software items such as cable assemblies, electronics boards, and glass pressure housings. Each configuration item has the following documents:

- Configuration Management Document (CMD) : Links the hierarchy of configuration items and bill of materials for bottom level configuration items
- Engineering Requirements Document (ERD): Details the engineering requirements, and often how those requirements hook to science requirements, how the requirement is verified, and how the requirement was set.
- Interface Control Document (ICD): Covers the interfaces (electrical, mechanical, optical, etc.) between this configuration item and any other configuration items affected.
- Design Status Document (DSN): This presentation formatted document carries the current status of the design, photos of parts, links to manufacturers and software repositories as needed, and generally forms an evolving repository of documentation of the design process of the individual configuration item.

These documents are owned by the respective L3 (or lower level) managers until the documents are controlled via successful review. Engineering requirements are derived from the higher-level science requirements via science-engineering requirements flow-down matrix described in Part I of this Technical Design Report.

16.5 Failure review & corrective action

Although failures are always unwelcome, they offer a wealth of information that can be used to modify the design or environment to address the underlying causes of problems. Thorough root cause analysis often identifies corollary risks with much higher potential impact than the one prompting the analysis. This valuable information is lost if the circumstances cannot be recreated for analysis, such as when the user has tried to repair or hide the failure. In the event of any failure, the failed item will therefore be carefully maintained in its "as failed" state until root cause analysis can be completed. The results of the analysis will be used to determine the root cause of the out-of-specification condition, and a corrective action to eliminate the cause will be developed and implemented. Periodic checks after implementing the corrective action will be made to assess the effectiveness of the corrective action, and to further evaluate other actions that could improve the effectiveness and efficiency of the process, component, or material.

16.6 Manufacturing & manufacturability

Having a design that can be efficiently and cleanly manufactured is an important criterion for the Project. As discussed above, COTS equipment would be used as much as possible. IceCube will also work with potential vendors to clearly communicate technical requirements and testing protocols.

16.6.1 Vendor selection and relations

Vendor selection criteria are based on the successes of IceCube-Gen1, the IceCube Upgrade, and IceCube M&O. Each facility engaged in procurement must have a purchasing process that ensures that every product received meets its specifications.

Requirements for vendor selection, guided by experience with previous projects, include the following:

1. The evaluation and selection of vendors shall be according to defined criteria and shall be documented. These criteria shall be based in part on the vendor’s ability to meet product specifications, previous experience, ability to meet the project schedule and the capability of their quality system.
2. Vendors should be reviewed yearly by the purchasing institution to ensure they are still suitable to supply products for IceCube. These reviews can be accomplished through a combination of the following activities:
   - Review of inspection records of the product received.
   - Review of vendor’s quality system (ISO) certification.
   - Quality surveys.
   - On-site quality audits.
   - Other mutually agreed upon metrics of determining the suitability of the vendor for IceCube.
3. Each purchasing institution shall maintain records of approved vendors for use by the IceCube-Gen2 collaboration team in selecting appropriate vendors.
4. Where the same product is used at multiple facilities, the Project Office shall determine:
   - Which facility(ies) is responsible for vendor selection’
   - Whether the product should be purchased through one facility’
   - What facility is responsible for conducting the vendor review.

16.6.2 Test planning and spares policy

Test planning refers to acceptance testing of individual parts and for the final acceptance testing of a completed device. Test planning, and success criteria, is defined before approval for major parts purchasing, and during Final Design Reviews for integrated systems.

Spares policy varies depending on the devices: for example, devices that will be installed in deep ice cannot be repaired or exchanged; thus spares are needed only to ensure the full complement of devices are operational prior to detector installation. These devices are tested extensively before shipping, and then again at the South Pole (South Pole Acceptance Testing) and swapped out for spares if found non-functional. Spares for items installed in the IceCube Laboratory or above surface at the South Pole are more readily exchanged, and the exact spares policy for these items will be determined before manufacturing. Other items, such as the down hole cables, will not have spares – any damage to them in transit to the South Pole would have to be fixed on site. As with the test planning, the spares policy for each item is reviewed during the Conceptual Design Review and the Final Design Review.

The full bottom-up cost estimate done before the Preliminary Design Review will assume a spares policy informed by the ongoing M&O and Upgrade experience.

16.7 Environmental, Health & Safety (EHS) Program

The IceCube-Gen2 EHS program will build on the lessons learned from IceCube-Gen1 and IceCube Upgrade construction as well as the ongoing M&O program. The IceCube-Gen2 (EHS) program has the following specific objectives:

- To prevent personnel injury or loss of life during all phases of the IceCube-Gen2 project,
- To prevent environmental contamination during the construction, testing, or operation of the IceCube detector,
- To prevent damage to equipment caused by accidents during all phases of the project,
- To comply with all applicable federal, state, and local laws, rules, and regulations,
- To work together with the support contractor to establish and comply with all safety protocols in the field.

The Quality & Safety Manager administers the EHS program with the full support of the project. The safety policy lays out a foundation for project development and operations intended to establish a culture where the safety and health of personnel and equipment is of paramount concern. Individuals are empowered, and management encourages and promotes safety in all elements of the project. Details of the IceCube-Gen2 EHS implementation will be developed based on lessons learned, unique challenges for IceCube-Gen2, and any updates to safety protocols federally, internationally, and at the South Pole.

The EHS implementation will include the following elements:

- All Safety incidents will be reported, investigated, and corrective action plans will be created and implemented,
- SafeStart training, a behavior-based safety training that emphasizes mindset and hazard triggers and how to mitigate, will be taught to all deploying IceCube personnel,

- Advanced Safety Audits occur each summer and through the Pole season, throughout the project,
- Drilling and Installation Safety Manual and Procedures will be reviewed before each on-ice season,
- Process & Equipment Hazard's Analysis Review will occur during off-ice testing and procedure development,
- OSHA prescribed Training such as Fall Protection/Lock Out Tag Out/Confined Space is mandatory for all IceCube deployers,
- Hazardous Energy Training as required, such as Electricity, Welding, Burner, and Rigging.

The design and implementation of Safety equipment is the responsibility of the IceCube-Gen2 Quality & Safety Manager in concurrence with NSF and the Antarctic Support Contractor. Any modifications to the design and implementation of Safety equipment will go through the change control process and require approvals per IceCube-Gen2 Configuration Management Plan. On an annual basis, the Quality and Safety Manager reviews the Safety plan with all of the IceCube personnel who are deploying that season to the South Pole. This review is a part of the comprehensive deployment team training in August prior to deployment. The IceCube-Gen2 project reviews both the Quality plan and the Safety plan on an annual basis to incorporate revisions stemming from lessons learned or other revision sources.

16.8 Technical issue tracking

Another element in Quality Assurance is tracking all technical issues. The Project's Technical Coordinator is responsible for maintaining a list of technical issues as they are discussed at the weekly Technical Board calls, and for following up with the relevant experts until these issues are resolved. Elements of the risk register form part of the technical issues tracker; additional questions raised and followup actions to address them are also added. If the technical issues cannot be resolved within the technical board, and they risk the cost, schedule, or scope of the project, then they are added to the risk register along with potential cost, schedule, or scientific impacts.

17 Risks and Opportunities

17.1 Introduction

Given the decades of experience in the building of IceCube and its extensions at the South Pole, most of the risks are well known and can be quantified. The highest level challenges to the project are primarily due to the extreme environment and short seasons at the South Pole, primarily in the areas of safety, logistics, and the training and retention of experienced personnel for drilling and installation of hardware. While risks also exist in the detector design and build, these risks are minimal in that the technology is thoroughly tested in the North, and prototypes will be installed in-ice during the IceCube Upgrade and the Radio Neutrino Observatory - Greenland (RNO-G) installation seasons.

In addition to risks that negatively impact the project, we also have opportunities to more efficiently build and deploy our detector. The cost and schedule uncertainties on the project are tied to both the technical maturity of the design, and the impacts of possible risk events, or future events that have impacts on the cost and/or schedule (both negative – threats, and positive – opportunities). In this chapter we will first describe the current technical maturity of the design, and then discuss the risks to the project. Finally we will describe the project's approach to risk to calculate the impact of identified risks on cost and schedule.

17.1.1 Technical Maturity

We are leveraging our experience in building the IceCube Upgrade to inform the design and prototyping for each major subsystem in IceCube-Gen2, as described below.

- **Digital optical modules:** The main elements of the IceCube-Gen2 optical sensors are the 4" class PMTs, the sensor electronics (HV supply, readout, data transmission, in-sensor calibration devices),and the mechanical support structure (pressure housing, cable penetrator, harness, and internal holding structure). The baseline sensors for IceCube-Gen2, the mDOMs are currently developed for a deployment in the IceCube Upgrade in the 2025-2026 Antarctic season. The final design was reviewed and approved in Spring 2022 with production beginning immediately afterwards. Over 400 mDOMs will be built and thoroughly tested before an anticipated final design review of IceCube-Gen2. Currently, mDOMs are in production in Germany (DESY-Zeuthen) and Michigan State University. Specifications for critical mechanical components of the mDOM closely match those of IceCube-Gen1 DOMs. The electronics have been redesigned for the mDOM to allow the simultaneous readout of 24 individual PMTs, and facilities designed to produce and exhaustively test about a dozen mDOMs per week over two sites. While the production capability would have to ramp up, adding more sites and possibly streamlining the production, producing 9600 detectors over ten years is not a huge jump in rate.

  In parallel to building the mDOMs for the IceCube Upgrade, design studies are on-going to re-package the mDOM in a smaller-diameter pressure housing, e.g., the housing of the D-Egg, also deployed in 2025-2026 as part of the IceCube Upgrade. This re-packaging will mostly affect less critical components, such as the internal holding structure and the layout of the electronics boards. About 10 prototype modules of this type are planned to be deployed with the IceCube Upgrade. The risks related to this re-packaging effort are therefore considered small.

- **Surface to DOM Cables:** The data will be transmitted via a custom designed communication to the surface via copper twisted pair cables packaged in quads. An advanced triggering system will permit only data associated with physics events to be sent to the surface. The data rate per string will be less than that in IceCube due to the higher energy threshold. The bandwidth and other performance requirements are therefore less stringent than those for IceCube, despite the larger number of sensors per string. Advances in technology will permit the use of lighter weight cables than those used in IceCube. Initial estimates show a reduction in the amount of copper by as much as a factor of three compared to IceCube. At the surface the FieldHubs are connected to the central data acquisition infrastructure via optical fiber and provided with power cable.
- **Surface Detectors:** IceCube's surface array, IceTop, has proven to be a very valuable component of the detector, providing veto and calibration functionality for the in-ice neutrino measurements in addition to unique contributions to cosmic-ray physics. For similar reasons, the IceCube-Gen2 high-energy array will include a surface detector station at the top of each deployed string. The conceptual design of this array will be similar to the enhancement for IceTop that will mitigate the issue of snow accumulations. Lessons learned have been incorporated in the design, e.g., the detectors are elevated and extendable. A complete prototype station of eight elevated scintillators, three elevated radio antennas, and an elevated fieldhub has been operating for three years at the South Pole, successfully detecting air showers. No major issues occurred and minor issues, such as small light leaks, were mitigated by corresponding improvements of the design.
- **Data Acquisition:** The major elements of the surface Data Acquisition hardware are: the FieldHubs that communicate with and read out the DOMs via the main copper cable and provide DOM-to-DOM time synchronization; the White Rabbit optical fiber communication and timing system, which provides precision time synchronization and network connectivity to the IceCube Laboratory (ICL); and the DOM power system, which provides DC power to the DOMs via the FieldHubs. First prototypes of the FieldHub have been manufactured in late 2019 for the IceCube Upgrade. The IceCube-Gen2 FieldHub will be nearly identical, but deployed in the field at the surface instead of inside the ICL. To facilitate this, the Upgrade FieldHub will be designed for extreme low-temperature operation. The White Rabbit timing and communication system is widely used in high-energy and astro-physics instrumentation. In IceCube, a White Rabbit timing system has been deployed in the field since early 2018 as part of the prototype IceTop surface array enhancement, using modified hardware designed for low-temperature operation. The same hardware will be used in the IceCube Upgrade. The DOM power system delivers the DC voltage required to power the DOMs. In both IceCube and the IceCube Upgrade, these are commercially available AC-to-DC converters, located inside the IceCube surface laboratory. For IceCube-Gen2,where these units will reside in the FieldHub enclosure and be inaccessible during the austral winter, special attention must be paid to adequate cold-testing and redundancy.

The detectors and readout systems for IceCube-Gen2 are intentionally conservative, and will be tested in-situ at the South Pole as part of the IceCube Upgrade. While there are still optimizations on-going in the design and planned fabrications, the technical designs are mature and allow us to estimate the cost and schedule with a high degree of confidence.

17.2 Risks

The general themes that drive our major risks are:

- **Personnel safety:** The drilling and deployment operations that will take place over multiple seasons at the South Pole involve high temperature water, liquid fueled heaters, high-current electricity distribution, and large moving equipment in an extreme and uncompromising environment. The health and safety protocols for drilling and detector installation are built into every operation on the ice. They are instilled in each deploying individual from when they start work with the project, and are a foundational part of the project culture. Awareness of safety risks, providing training to mitigate them, and making safety the top priority is crucial to the project's success.
- **Logistics:** The challenge of bringing equipment, instrumentation, project personnel, and support staff to the South Pole during the limited austral summer working season, in the face of weather and aircraft delays, is significant. At the South Pole, housing and general support are currently inadequate for the expected science populations of multiple large experiments; however, this has been managed successfully in the past, and we will actively work with the NSF and its South Pole contractors to mitigate this risk.
- **Training and Retention of Experienced Personnel:** As described in Chapter 15 during IceCube-Gen1, the efficiency of the drilling and detector installation operations increased with each subsequent drilling season as both the hardware was made more reliable, and the drilling team gained experience.

17.3 On-Ice Season Risks

Based on the extensive experience with IceCube construction and ongoing Management and Operations, the critical factors to ensure success of the on-ice seasons are:

- **Logistical Support:** The timely shipping of hardware and transport of personnel to the South Pole are dependent on scheduling of military airlift and some of the most extreme weather on the planet. Airlift capability between Christchurch and McMurdo, and McMurdo to South Pole to maintain timely delivery of all drill, detector, and personnel is critical. Due to the lack of storage space (including "Do Not Freeze" or "Do Not Deep Freeze") at the South Pole, much of the detector equipment and cables rely on "just in time" scheduling from McMurdo to the South Pole. Delays in equipment or personnel arrival can have significant impacts on the schedule. The short South Pole deployment season is a significant concern each year, and the logistics chain to get equipment from the North to the South Pole means shipping must be done well in advance (typically, especially for heavy equipment, a year in advance). Additionally the support of the living and working arrangements for the on-ice teams, and the contractor support personnel is critical.
- **Retained Experience:** Drilling and installation operations require professionals with unique and specific skills along with a broad-base of practical problem solving talents able to work in a extreme conditions. The IceCube-Gen2 hot water drill is a one-of-a-kind custom configuration of technical systems, operating in the most unique environment in the world. Retaining experienced personnel, starting with the current IceCube Upgrade and continuing throughout IceCube-Gen2 is a high priority.
- **Project Support:** The project requires on-site direct support from the Antarctic Support Contractor including all aspects of living and working at the South Pole such as equipment oper-

ations, trades-support, and cargo/fuel delivery, and general station support for housing and meals.

- **Loss of a South Pole season:** There are a number of failures (e.g., a personnel injury, major equipment failure or fire, or other serious safety incidents) in the field which could essentially cause the project to “lose" a South Pole drill and deployment season. Though these risk will be strongly mitigated by our safety staff and a strong safety culture, we will maintain contingency specifically to cover such an incident.

17.4 Optical Detector Risks

Within the optical instrumentation, the largest risk is in manufacturing and production of the 9600 Optical Modules. On the order of quarter million photomultiplier tubes will be required for the instrumentation. This is a major portion of the world production of tubes for several years, and there are only two identified vendors for these parts. We work closely with both Hamamatsu Photonics (Japan) and NNVT (China) but we are reliant on their production for our sensors.

The primary technical issues within the instrumentation design and production are relatively minor compared to the manufacturing risks, but are noted here:

- **Sensor geometry calibration:** The IceCube optical modules located each other through light pulses seen on nearby strings. The increased string spacing puts this calibration into an untested regime, so additional acoustic positioning sensors (to be demonstrated in the Upgrade) are planned for IceCube-Gen2.
- **Manufacturing reliability issues:** We hold a requirement that >95% of in-ice sensor modules will operate throughout the lifetime of the experiment. This imposes reliability and testing regimes on the optical modules that more closely resemble spacecraft qualification than consumer device standards. Even relatively rare production flaws could start to compromise this requirement.
- **Inherently conservative design:** With the instrument heritage in IceCube, and the high reliability requirements, there is an inherent conservatism in the hardware design. Two problems are possible as a result: the loss of availability of a well-tested component could result in a significant amount of effort to replace and properly certify the new technology; and there is a considerable hurdle to any new, transformative technology for the in-ice sensor were such technology to appear.

17.5 Radio Array Risks

For the in-ice radio array, the largest risks stem from the large area that has to be covered during installation.

- **Installation Project Support:** The installation effort of the radio array will cover a large area, which includes stations at a distance of up to $25\,\mathrm{km}$ from the South Pole Station. Small teams will work in parallel to drill and install a shallow station within less than a day and a hybrid station within less than two days. Such a highly mobile installation will require thorough planning and on-ice logistical support.
- **Radio drilling:** The mechanical drill planned for the holes for the hybrid station is based on the drill for RNO-G. This drill, however, has yet to achieve design specifications, in terms of drilling speed. Before the start of IceCube-Gen2 additional drilling seasons in Greenland

are planned, which will be used to further test the drill. Should the speed not be achievable, a mitigation strategy is to replace hybrid stations with shallow stations that do not require drilling, which, however, increases the total number of stations in the array.

17.6 Surface Array Risks

Within the surface instrumentation, the greatest risks are production related. Installation risks exist, but are less critical than for in-ice instrumentation, and it is unlikely that a season would be lost completely:

- **Logistical & Project Support:** Shipping and transportation risks are similar to the other detectors. However, the deployment for the surface array allows for some flexibility. In case of delays, shipment of cables can be prioritized over the surface detectors. While the surface array cables need to be deployed together with the other surface installations, the actual detectors could be deployed at a later time in case of delays.
- **Scintillator Panel Production:** The production of scintillator panels currently relies on specific suppliers, and while the production is straightforward, there is a low risk of significant delays that may require an update of the design of the scintillation detectors or of the complete array.
- **Surface Detector Radio Antenna Manufacturer:** The baseline design for the radio antenna in the surface detector uses the same instrumentation as the Square Kilometer Array experiment. It is possible that during the procurement of these detectors that newer versions become available. Swapping to a newer antenna version during deployment will not impact the performance significantly, but it will lead to an inhomogeneous array that requires additional calibration efforts.
- **Surface Array Electronics:** Supply chain issues and parts availability can cause delays in the production of the surface DAQ electronics and/or require changes of the electronics design. Since the fieldhubs remain accessible after deployment, in the worst case, the DAQ electronics can be deployed in a later season, delaying the operation of the corresponding surface stations.

17.7 Data Acquisition and Surface Infrastructure Risks

Risks for the data acquisition and surface infrastructure include similar logistical considerations as the rest of the project, but specific risks exist related to the power delivery capacity of South Pole station.

- **Downhole Cable Supplier:** The component 4-conductor quads of the downhole cable must meet stringent crosstalk requirements that allow precise timing and parallel high-bandwidth communications with the existing IceCube Upgrade communications protocol. There is currently a single identified manufacturer for the downhole cable, Hexatronics. In order to mitigate this single vendor risk, we have identified protocol changes that could be implemented to relax the cable requirements. Additionally, we are working to identify other potential vendors.
- **Power Infrastructure Capacity:** During IceCube-Gen2 construction, the power consumption of the operating detector will exceed current South Pole power generation capacity. Delays in an upgrade of the station power plant could delay commissioning and operation of the detector

during this period. To mitigate this risk, we are examining the possibility of supplementing the power in the IceCube Laboratory with the drill microturbines when the drill is not in use.

- **Shared Cable Topology Risk:** In order to simplify the downhole cable design for the optical array, up to 6 devices share the same wire pair. Certain DOM failures (e.g. an electrical short) could result in the loss of all modules on that wire pair. To mitigate this risk, we will analyze and minimize the failure modes that could result in such a multiple-module loss.
- **Large Power and Communications Grid for the Radio Array:** The large scale grid of power and communications wiring for the radio array is unlike anything previously built at the South Pole. We believe it to be a manageable construction, but it will require significant time, effort, and specialized equipment to realize.

17.8 Programmatic Risk

About 50% of the IceCube-Gen2 optical sensors are foreseen to be funded and delivered from non-US groups, with major contributions from Germany and Japan. This is similar to the arrangement for IceCube, where about 40% of the optical sensors were assembled in Germany and Sweden. In IceCube, a very high reliability of the optical modules was achieved independent of the production site. In addition to the in-ice sensors, parts of the surface veto instrumentation (scintillation and radio detectors), calibration devices, and communications hardware for the data acquisition system will be delivered by international collaborators. Our experience in IceCube and the IceCube Upgrade is that our international partners are extremely reliable and committed to the delivery of their pledged contribution, however these in-kind contributions rely on non-U.S. funding agencies with differing funding cycles and time scales. We keep in close contact with all funding agencies engaged in the project with regular meetings of project leadership, national, and international funding agencies in order to carefully monitor and track any disruptions or constraints in outside funding. We continue to develop and expand the collaboration to mitigate the loss of any particular institution or funding agency.

17.9 Risk Analysis

We use an approach to risk analysis based on standard best practices as detailed in the U.S. General Accounting Office cost estimating guide [9], the National Science Foundation's Research Infrastructure Guide (RIG) [10], and the ANSI-standard and industry best-practice Project Management Body of Knowledge [11].

The project will maintain a risk register in accord with best practices and the NSF Research Infrastructure Guide. The risk register includes information as to the severity of the risk (both in cost and schedule), the probability the risk will occur, and the time frame within which the risk is active and/or the triggering event for the risk. Risk mitigation is built into the project cost and schedule baseline; the residual risk cost and schedule impact is modeled using a probabilistic Monte Carlo of all active risks using the project baseline cost and schedule as inputs.

As with the IceCube and IceCube Upgrade projects, dedicated risk workshops will be held regularly to identify new or emerging risks; likewise the risks in the risk register are reviewed monthly to ensure accuracy.

17.10 Contingency

The risk register provides one piece of the contingency estimate for the project. Financial contingency is estimated from the cost uncertainties all the cost estimates (detailed in their respective Basis of Estimates (BoEs)) and the risk cost exposure from the risk register. The impact of both areas are simulated using a probabilistic Monte Carlo as mentioned above. Similarly the schedule contingency is determined using a Monte Carlo that uses both the uncertainty of the time estimates in each line of the schedule, and the discrete risk schedule exposure.

While the Project has not yet performed a comprehensive cost and schedule risk analysis, the experience from IceCube and IceCube Upgrade allows us to set a top-down estimate for the contingency. For the IceCube construction project the U.S. total project cost was $242M and the final contingency used was $43.9M, or about 22.2%. The IceCube detector design is modular enough to allow for descoping of optical strings if necessary. This approach was taken in IceCube and in the end additional in-kind contributions were secured and no descoping was required to stay within the original contingency estimate.

We have used our experience from IceCube and the current IceCube Upgrade to estimate a top-down contingency amount by Level 2 area. Table 32 shows the results of this estimate. For more details on Project costs see Chapter 15.

Because we have more information and experience in the production, drilling, and installation of optical modules, we used a slightly lower number for contingency than the overall number used in IceCube construction. Prototype optical modules have been produced, and will be installed as part of the IceCube Upgrade detector. The radio design is also very advanced, with the installation in Greenland as part of the RNO-G project. Data systems, commissioning, and calibration areas are also very well understood technologies and processes.

Although we have more experience in hot water drilling than we did at the start of IceCube, the drill is undergoing a redesign to make it suitable for supporting the larger string spacings in IceCube-Gen2. Because of this, we assumed a larger contingency of 30% for this area. Project office work is mainly "Level of Effort" tasking, thus we gave it a lower overall contingency (15%). Finally the logistics estimate was done pre-pandemic, drawing on experience and costs

WBS	**Total** ($M)	**Contingency** ($M)	**Contingency** (%)
1.1 Project Office	38.41	5.76	15%
1.2 Implementation	82.37	24.71	30%
1.3 Instrumentation - Deep	118.63	23.73	20%
1.4 Instrumentation - Radio and Surface	30.45	6.09	20%
1.5 Data Systems	18.04	3.61	20%
1.6 Commissioning and Calibration	16.80	3.36	20%
1.7 ASC Coordination and Polar Support	72.73	50.91	70%
Total U.S. Costs	**377.42**	**118.16**	**31.3%**

Table 32: Total U.S. Project Costs with Contingencies. For more details on the project costs see Chapter 15.The overall contingency is estimated at 31.3%.

from IceCube. We believe the estimate is reasonable, but as we have little insight into current logistics costs, we put a contingency of 70% in this area.

We are also tracking our use of contingency during the ongoing IceCube Upgrade project, and this will add to our ”lessons learned” for risk and risk mitigation for IceCube-Gen2, although many of the Upgrade risks do not directly translate due to e.g. impacts of the COVID pandemic, having only one drilling season, and loss of experience and mechanical failures after not operating the hot water drill for more than ten years. Additionally, just as in the IceCube construction project, the IceCube-Gen2 project is highly modular with natural descoping scenarios if needed.

18 Project Management and Organization

Management and organization of the IceCube-Gen2 project will build on the very successful models of IceCube-Gen1 and IceCube Upgrade. This chapter describes the project management and organization approach for IceCube-Gen2.

18.1 Internal Governance, Organization, and Communication

The IceCube-Gen2 project organization is shown in Figure 58. Specific Roles and Responsibilities of key project personnel and governing bodies are described in Section 18.3. Major roles and responsibilities in the Project Office are described briefly below:

The Principal Investigator (PI) is directly responsible to NSF for the financial and scientific oversight of the project. The PI reports regularly to the National Science Foundation. The Project Director (PD) is appointed by the Principal Investigator, who holds the PD responsible for technical execution of the project. The PD oversees and has authority over technical and managerial aspects of the project and is responsible for completing the project within the approved budget and schedule as approved by the project, and NSF. The PD, with the concurrence of the PI, appoints the Project Manager (PM) to oversee the project and assume responsibility for implementing project processes. Control Account Managers (CAMs) are established at Level 2 in the Project Work Breakdown Structure (WBS): they are responsible for delivering the technical scope in their areas, for documenting baseline costs and schedule, for monthly updates in cost, schedule, and technical achievements, and for reporting on cost and schedule variances in their areas. The Project Office (PO) and L2 CAMs make up the Change Control and Risk Management Board (CCB), chaired by the PD, which meets weekly to review project progress, upcoming or retired risks, and decide on any Change Requests approved at the Technical Board (TB). The TB is chaired by the Technical Coordinator (TC), and meets weekly to review issues, risks, and proposed changes to cost, schedule, technical, or scientific requirements of the Project. Other important members of the PO are the Project Controls and Finance team who is responsible for keeping the baseline and current schedules, performing Earned Value

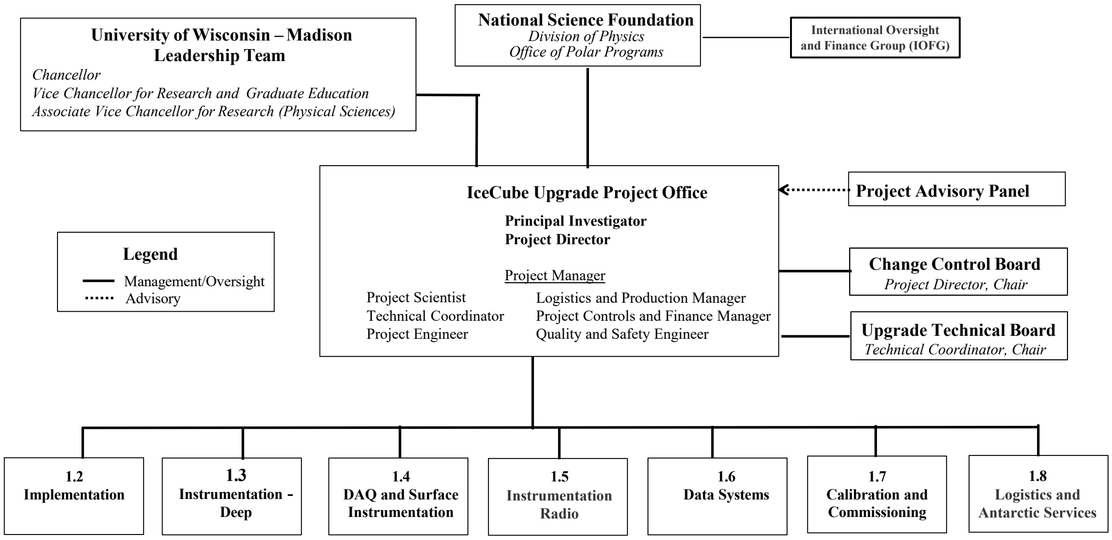


Figure 58: Overview of the IceCube-Gen2 Project Organization Structure

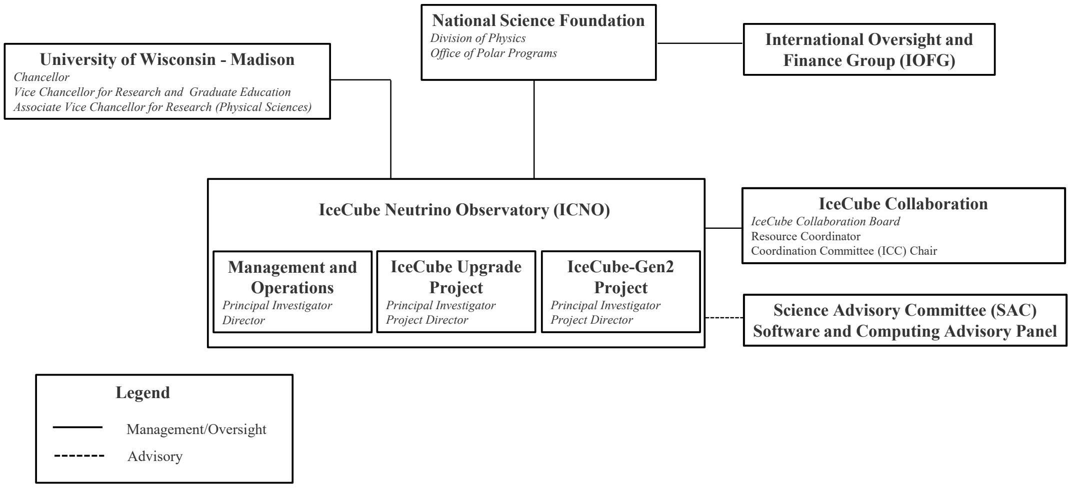


Figure 59: IceCube-Gen2 Project Organization Structure within the IceCube Neutrino Observatory

calculations, comparing Earned Value with Actual Costs, and running Risk Monte Carlos as needed; the Systems Engineer (SE) responsible for documenting, controlling, and reviewing system interfaces; the Quality and Safety (Q&S) Engineer who is responsible for documenting configuration control, quality assurance and quality control, and project safety aspects (both on- and off-ice); and the Logistics Coordinator who is responsible for interfacing with the Antarctic Services Contractor and coordinating equipment shipments, support requirements, and personnel needs at the South Pole. The Project Advisory Panel (PAP) is made up of experts in management, science, and South Pole logistics and is charged by the PI and PD to review the project regularly and report to the PI on their findings.

For details of the Roles and Responsibilities within the Project, see Section 18.3.

18.2 External Organization and Communication

The IceCube-Gen2 Project will be part of the IceCube Neutrino Observatory, which in turn is embedded in the Wisconsin Particle Astrophysics Center (WIPAC) at the University of Wisconsin, Madison. Figure 59 shows the IceCube-Gen2 project in context as part of the IceCube Neutrino Observatory (ICNO). In the sections below we describe in more detail the entities depicted in the figure.

18.2.1 National Science Foundation

The National Science Foundation (NSF) would be the executive agent responsible for seeing that IceCube-Gen2 meets its baseline requirements of cost, schedule, scope, and technical performance. The NSF will have a special role in the project because of its additional host laboratory responsibilities in managing the logistical operations of the Amundsen-Scott South Pole Station. The IceCube-Gen2 Project will work with the NSF and the NSF Antarctic Contractors to ensure the project requirements are well understood and can be supported, and that the project has budgeted adequately and accurately the cost and schedule needs for the required logistical support and on-site effort.

IceCube is supported and managed through both the NSF's Division of Physics and the Office of Polar Programs, which reflects the dual role of the NSF in approving and supporting physics projects at the South Pole. We anticipate that IceCube-Gen2 would operate in the same way.

18.2.2 International Oversight Finance Group

The International Oversight and Finance Group (IOFG), already in place, meets at least annually to approve MOUs or changes to MOUs and to review the status of the IceCube M&O program, the IceCube Upgrade Project, and planning for IceCube-Gen2. The IOFG is chaired by the NSF and comprises international and national funding agency contacts. The IOFG sets policies for receiving periodic progress reports on the IceCube program, and provides oversight and financial support.

18.2.3 Host Institution

The University of Wisconsin, Madison is the host institution for the IceCube Neutrino Observatory, and the UW Vice Chancellor's office has formal authority over the program and ensures that it is well governed and appropriately staffed. The University of Wisconsin, Madison will also be the host institution for IceCube-Gen2. The responsibilities of the host institution include:

- Providing internal oversight for the project,
- Appointing the PD (subject to concurrence of the NSF and IceCube Collaboration Board),
- Ensuring that the project office has adequate staff and support,
- Ensuring that an adequate management structure is established for managing the project and monitoring progress,
- Ensuring that accurate and timely reports reflecting full transparency of the project are provided to the NSF, IOFG, and the IceCube collaboration,
- Developing subawards with other U.S. collaborating institutions and providing appropriate funding,
- Establishing MoUs between UW–Madison and non-U.S. collaborators that define the non-U.S. institutional responsibilities.

The Wisconsin Particle Astrophysics Center (WIPAC) is the primary interface to the university administrative and support systems to coordinate the multiple roles of the university, such as lead and host institution for the IceCube construction project, for IceCube M&O, and for IceCube-Gen2. WIPAC provides administrative services such as accounting, purchasing, and human resources, coordinates E&O activities, and collaborates with the largest participating research group. It also supports engineering and computing needs for these projects.

18.2.4 IceCube Neutrino Observatory

The ICNO is governed by an established collaboration of institutions (IceCube Collaboration) with a successful history of delivering in-kind contributions to the original IceCube project, the IceCube Upgrade project, and the M&O program. The ICNO also enables planning for IceCube-Gen2.

The responsibilities of all collaborating institutions will be defined in Memoranda of Understanding (MOUs) executed between UW–Madison, as the project host institution, and the individual collaborating institutions, as is done for the current Upgrade project and for the M&O program. The schedule for deliverables for all in-kind items is included in the IceCube-Gen2 Integrated Master Schedule. All deliverables are subject to Project reviews, including Conceptual Design, Preliminary Design, Production Readiness Reviews as detailed in Section 18.6 to ensure they meet requirements and are thoroughly tested. The status of all in-kind contributions is reviewed weekly during regular management/CAM meetings, and monthly as part of the Earned Value, Schedule, and Risk reviews.

18.2.5 IceCube Collaboration

The IceCube Collaboration, through the IceCube Collaboration Board (ICB), governs the scientific activities of the Collaboration and advises the ICNO on detector operations for scientific investigations and maintenance. The ICB is composed of one voting person from each collaboration member institution. The ICB requests regular program progress updates, and is the main source of advise and resources from the collaboration.

18.2.6 Science Advisory Committee

The primary goal of IceCube is to ensure that the ICNO meets its high-level science goals and serves the collaboration in a changing environment. In consultation with the collaboration, the ICNO Principal Investigator and the IceCube Spokesperson appoint a panel of external experts, the Scientific Advisory Committee (SAC). The SAC's role is to meet regularly and review the performance of ongoing ICNO activities and make recommendations on scientific goals and other matters that may affect ICNO scientific activities, including future projects such as IceCube-Gen2.

18.2.7 The Software and Computing Advisory Panel

The IceCube Software and Computing Advisory Panel (SCAP) is composed of experts in the fields of software development and scientific computing. The SCAP advises the IceCube spokesperson, director of operations, global computing coordinator, and software coordinator on the most efficient and effective computing resources for IceCube, including online computing, online and offline data processing and filtering, offline computing facilities, simulations, and analysis tools support. The spokesperson and the director of operations appoint the SCAP members and chairperson.

18.2.8 Partnerships

The IceCube Neutrino Observatory is an international organization comprising more than 350 scientific authors in 14 countries and 58 insitutions. For the current IceCube Upgrade, non-NSF funding agencies contribute significant materials and expertise. In terms of hardware deliverables, while the U.S. and NSF are largely responsible for hot water drilling, logistics, and population at the South Pole, international institutions will continue to contribute the lion's share of instrumentation. The current IceCube-Gen2 Collaboration includes 15 countries and 64 institutions, and this number will grow as the IceCube-Gen2 project matures.

NSF principal investigators and non-NSF partners contributing significant resources to the project constitute the scientific leadership of the project and ensure that technical decisions are made in a manner that preserves the scientific viability of the instrument. IceCube Maintenance and Operations ensures compatibility with the existing infrastructure. The IceCube Collaboration Board ensures that the project efforts are transparent to IceCube collaborators.

18.3 Roles and Responsibilities

18.3.1 Principal Investigator

As described above, the Principal Investigator for the IceCube-Gen2 Project is directly responsible for the financial and scientific oversight of the project. The PI reports regularly to the NSF and to the University of Wisconsin leadership on project progress.

18.3.2 Project Director

The Project Director (PD) is appointed by the principal investigator (PI), subject to concurrence of the IceCube Executive Board and approval by the University of Wisconsin Leadership and the National Science Foundation. The principal investigator holds the PD responsible for technical execution of the project, and the PD oversees and has authority over technical and managerial aspects of the project. The PD establishes the detailed project execution plan, establishes the project office, appoints the Project Manager, and, along with the Principal Investigator is the main conduit between the Funding Agencies and the Project.

18.3.3 Project Manager

The PD appoints the Project Manager (PM) subject to concurrence of the PI. The Project Manager is responsible for implementing project processes and for the daily oversight of the project, as well as any duties delegated by the PD. The PM is tasked with reporting on the project's cost and schedule health and progress to the PD and PI, and for raising any issues promptly.

18.3.4 Project Scientist

The Project Scientist has a key role in all science related aspects of the project, and works with the Project Director and Systems Engineers, in tandem with In-Kind Contributers and the IceCube Gen2 Collaboration, to ensure that the design, implementation and science verification of IceCube-Gen2 achieves the science goals of the project. The Project Scientist is responsible for enunciating the primary scientific goals, and the science goal flow down to the science and technical requirements, for the project and ensure they are being met by the technical design. The Project Scientist advises the Project Director as to the scientific impact, if any, of significant management decisions (e.g. changes of scope) made at the L1 level, and advises L2 managers as to the scientific impact, if any, of significant technical decisions (e.g. technology choices) taken within the sub-projects. As a member of the combined Change Control and Risk Management Board, the Project Scientist advises the project on the scientific impact of pending change requests.

18.3.5 Level 2 and Level 3 Managers

WBS Level 2 managers control and direct their respective areas, and report to the PM. They are directly responsible for generating and maintaining the cost-estimate, schedule, risk, and resource requirements and providing regular status reports for their subprojects. They are responsible for meeting the requirements of their subproject within the accepted baseline cost and schedule. The L2 managers appoint, in coordination with the PM, the L3 managers. Each L2 area consists of several L3 areas that are managed by a L3 manager. The L3 managers are CAMs (Control Account Managers) and are responsible for the Earned Value Management on their assigned Control Account.

18.3.6 Project Technical Coordinator

The project technical coordinator (TC) is appointed by the PD and is tasked with integrating the scientific, engineering, and quality requirements, providing leadership in these areas and advice to the PD. Additionally, the technical coordinator manages the technical board, including holding weekly meetings on technical status and coordination and directing the project design reviews.

18.3.7 Project Systems Engineer

The project systems engineer is appointed by the PD and oversees the preparation of all key systems documents and approves technical changes. These documents include, but are not limited to, engineering requirements documents (ERD), interface control documents (ICD), verification and testing documents, and procurement specifications.

18.3.8 Project Controls and Finance

This area covers both the Lead Project Controls and the Lead Finance Officer.

The lead Financial Officer is responsible for budgeting, monthly cost reporting, invoicing, MoU and subaward management and tracking. He or she communicates and coordinates with accounting for gathering and reporting of financial data related to the project, and acts as liaison to accounting and management for all issues involving expenditures, funding, and collection of financial data. The Lead Finance Officer reviews data and verifies accuracy to prepare for interface with reporting tools and generation of reports for project stakeholder review and provides expertise in preparing, awarding, managing, and monitoring all aspects of subawards.

The Lead Controls Manager works with the PD, the PM, and L2/L3 Managers to develop the project schedule, implement the EVMS, and status the schedule monthly. He or she also generates any monthly reports necessary to track the project, including cost and schedule variances, and instructs any additional project controls personnel on the proper maintenance and oversight of the schedule. Project Controls is responsible for implementing any approved Baseline Change Requests and maintaining the project baseline.

18.3.9 Project Quality and Safety Engineer

As both safety and quality should be addressed during the design, procurement, production, and deployment stages, the quality and safety manager is a key member of the technical, change control, and risk boards, and takes responsibility for project systems quality assurance, document control, and, in conjunction with the project engineer, configuration management. The quality and safety manager also develops and maintains the safety plan and ensures compliance.

18.3.10 Logistics and Production Manager

The Logistics and Production manager works with the quality and safety manager and Level 2 and Level 3 leads of areas involving significant procurements and manufacturing activities to ensure instrumentation is delivered on a schedule that fulfills engineering requirements. The production and logistics manager also provides a nexus for project leads to coordinate with the Antarctic Support Contractor for shipment of instrumentation and deployment of personnel.

18.3.11 Change Control Board

The Change Control Board (CCB) meets regularly and ratifies any change to the Project Baseline Cost, Schedule, or Scope. The CCB is chaired by the PD and consists of all members of the Project Office, the L2 managers, the PI, and the PD. Depending on the details of the changes, the full CCB may not be required; administrative or minor cost or schedule updates may be approved by a subset of the CCB responsible for maintaining the project baseline. Details will be documented in the Project's Configuration Management Plan and Project Execution Plan.

18.3.12 Technical Board

The technical board is chaired by the Technical Coordinator and includes the Level 2 and Level 3 managers, technical support staff, and other Subject Matter Experts. The PI, PD, and IceCube Collaboration spokesperson are ex-officio members. The technical board meets weekly to discuss project progress, problems, interfaces, potential changes, risk and risk mitigation strategies, and technical requirements. The technical board also provides recommendations to the change control board and maintains the technical issue tracker.

18.4 System engineering plan

The primary scope of IceCube-Gen2 system engineering is to define, establish, and control individual subsystem requirements and interface requirements between subsystems. System engineering is responsible for incorporating the various technical contributions into an integrated system through interface design and specification, modeling, and simulation.

18.5 Configuration control plan

Configuration control of the IceCube-Gen2 project requires an approach that allows tasks to be performed by a distributed network of collaborators while at the same time providing the necessary controls to ensure that the system configuration is maintained. The project office establishes the requirements for configuration management. Those requirements flow down to the organizations performing the actual tasks through MoUs and/or statements of work. Configuration requirements are reviewed and approved in accordance with the configuration management plan. It is the responsibility of each organization to use its existing configuration management system (if adequate) or institute one that complies with the IceCube configuration management requirements. Conforming to the configuration management plan is the responsibility of the Project Engineer and is monitored by the Quality and Safety Manager.

The detailed configuration management plan (CMP) will be developed before the project cost and schedule is baselined. This plan will describe how the schedule, budget, and performance impacts of changes to the baselines are tracked and recorded, and ensures that complete and accurate descriptions of the project's technical, schedule, and cost baselines are developed and maintained. The CMP provides:

- A mechanism for establishing the baseline,
- A process for identifying and managing changes,
- A method to verify proper implementation,
- Reports to notify the change to all stakeholders,
- Records of the change for historical reference,
- A central document library and document control system for project documentation including drawings, requirements documents, interface control documents, and manufacturing records.

18.5.1 Documentation management

All information needed to design, manufacture, test, install, and use systems and components developed for IceCube-Gen2 are defined in appropriate drawings and documentation. This includes information required to coordinate work, allocate resources, and monitor progress. The current documentation reflects the current configuration. Previous configurations are documented and archived. A flexible procedure exists to control preliminary drafts and/or items not requiring a formal release and control system while maintaining the necessary minimum format. Appropriate personnel must approve documentation before release. In general, documentation must be released before hardware is procured and built or before software is released or delivered. Exceptions can be made for good reasons, such as early procurement of long-lead items or fast track rapid prototyping schedules, but in such cases there must be timely follow up to assure documentation is completed as soon as possible. After release, changes are accomplished through a formal change procedure to assure that appropriate personnel have reviewed the proposed changes and that the impact on other system components and documents is taken into consideration and implemented.

The revision status of all IceCube-Gen2 documents must be clear and readily verifiable. Because of their nature, some documents generated for the project do not need to be controlled through a document control system, but do need to be archived. These documents include meeting minutes, internal design review reports, and e-mail messages. The current, released, and authoritative version of each document resides in the appropriate SharePoint library.

18.5.2 Change request management

Change request management is the process by which controlled documentation, project cost, schedule, and scope can be updated after the project baseline is established.

Documents under change control

It is the policy of IceCube-Gen2 that all controlled documents be changed through the Change Request (CR) Process. The originator (owner) of the change or a member of the change control board shall complete the CR form. The person completing the form gets a CR number from the CR Log, notes the changes to the document, and fills out the CR form.

After project baselining, a CR Log will be created, showing the CR number, originator, date the CR number was issued, and the document(s) being changed. The CR is then circulated for approval to all relevant parties and recorded in the CR Log.

Once approved, the changes are incorporated into the document(s) and the revised document(s) proceed through the approval process, as well. After all tasks related to a given CR have been completed, QA conducts a final review of the CR to ensure that the information contained in the CR is accurate; and, that all changes indicated by the CR have been implemented. QA then signs and closes the CR. After approval, the completed CR is filed, and the log is updated with the date the CR was approved and closed.

Cost, schedule and scope changes

IceCube, in consultation with the National Science Foundation, has defined three types of changes to cost, schedule, or scope that are adjudicated through the Change Request Process: Class 1, Class 2, and Class 3. The classes are weighted based upon the severity of the impacts of the change to budget, schedule, contingency, or science. Class 1 changes, the most severe changes, require NSF approval. The thresholds for these changes in terms of cost, schedule, scope, or scientific impact will be set by the NSF at the project baseline. Class 2 and Class 3 changes are set by the Project Director, in consultation with the NSF, and require approvals by the Project Director (Class 2) or the cognizant Level 2 manager (Class 3).

Change request approvals

All changes, except adminstrative changes, are first proposed in the weekly Technical Board call. The Technical Board can either approve, reject, or recommend further studies to ensure the project's scientific and technical objectives are met. Administrative changes are defined as those changes that are necessary to keep the cost, schedule, and documentation up to date, but have no or very small impact on the overall cost and schedule. Administrative changes can be decided by the relevant experts (typically Project Controls, Finance, and Project Director / Principal Investigator). Administrative changes are, by definition, Class 3 changes.

As mentioned above, the project change control board (CCB) will be convened to review Class 1 and Class 2 changes for the project after they are approved by the Technical Board. The CCB reviews proposed changes to project content (schedule, budget, scope), project/device design, or project documentation to determine the extent of the impact of the change upon the IceCube-Gen2 Project. The impacts could be in terms of revised cost, funding source, schedule, and scientific objectives. Class 3 changes are reviewed by the CCB at the discretion of the Project Director.

The CCB will convene at least weekly, but may be convened more frequently at the chairperson's discretion. All Class 1 and 2 changes shall be reviewed by the CCB prior to final QA sign-off. Changes will not be implemented before the CR is signed.

18.6 Review management

Reviews are a cornerstone to ensuring a robust project technical baseline and execution. To this end, IceCube-Gen2 plans to continue the successful suite of IceCube reviews, both internally and externally.

18.6.1 Internal reviews

Internal reviews are a key component of the successful IceCube projects. These reviews promote a robust project technical baseline and execution. In this section, we describe the suite of internal reviews used to ensure the success of the project. These reviews are overseen by the Project Technical Coordinator with significant input from the Project Scientist and the Project Systems Engineer, and the review panel consists of Subject Matter Experts from the collaboration.

- **Conceptual Design Review (CDR):** Once the initial design concept has been defined and the engineering studies between alternative approaches have been completed, a CDR is held to affirm the design approach before major investment is made in detailed design work. The inputs to the review are the requirements and the preliminary design drawings, parts lists, and supporting documents. Requirements are reviewed at this time.
- **Final Design Review (FDR):** After the design is complete and before fabrication begins, the FDR is held to affirm the design is complete, correct, and satisfies requirements. In addition, the design is reviewed for manufacturability. The FDR reviews the design documents (drawings, specifications, manufacturing plans, etc.) and prototype results.
- **Design Verification Test Review (DVTR)** Often combined with the Final Design Review, the DVTR is held to determine whether the prototyped design meets all of the requirements, and that the testing for determining this is sufficient. The inputs to the review are the design documents, test plans, and test results.
- **Pre-Production Review (PPR):** When a project plans to produce multiples of the same device, a PPR will be conducted. The purpose of the PPR is to ensure that all items required to produce the devices are available in the quantities needed. These items include: availability of raw materials/components, test hardware/software, assembly/test documents, drawings, production forms, device process qualification defined, production quality processes ready and training complete. A PPR may be conducted at the beginning of each yearly production cycle to ensure process consistency between the production sites including assembly/test documents, record keeping, test equipment and materials.
- **Pre-Ship Review (PSR):** The PSR is held after the testing is complete or nearly so and before the item is packed for shipment. The review is held to review the test results, failures, non-conformances, repairs, the packing and shipping plans, post-delivery support plans, and all previous review action items to verify all issues are closed and the item is ready to ship.

18.6.2 External reviews

In addition to internal reviews, the Project relies on external reviewers to scrutinize the cost, schedule, management, scope, logistics, and technical aspects of the Project.

- **Project Advisory Panel** A Project Advisory Panel (PAP) will be formed and will meet at least annually, and on an ad-hoc basis as needed, to review the Project and recommend actions to improve efficiency and reduce risk.
- **Science Advisory Committee** The Science Advisory Committee (SAC) was established during IceCube construction and advises the IceCube Neutrino Observatory to ensure IceCube meets its high-level science goals and serves the collaboration in a changing environment. Members of the CAC are appointed, in consultation with the collaboration, by the ICNO PI and

the IceCube spokesperson. The SAC's role is to meet regularly and review the performance of the current IceCube program (IceCube M&O and Upgrade) and is expanded to also review plans for IceCube-Gen2. The panel makes recommendations on scientific goals and other matters that may affect ICNO scientific activities. The current chairperson is Barry Barish from Caltech.

- **Software and Computing Advisory Panel** The IceCube Software and Computing Advisory Panel (SCAP) is composed of experts in the fields of software development and scientific computing. The SCAP advises the IceCube spokesperson, director of operations, global computing coordinator, and software coordinator on the most efficient and effective computing resources for IceCube, including online computing, online and offline data processing and filtering, offline computing facilities, and simulations and analysis tools support. The spokesperson and the director of operations appoint the SCAP members and chairperson. The SCAP meets semi-annually. The current chairperson is Lothar Bauerdick (FNAL). As the IceCube-Gen2 project ramps up, the Computing Advisory Panel will add additional agenda items to review and make recommendations on IceCube-Gen2 computing needs.
- **IceCube International Oversight and Finance Group (IOFG)**: The IOFG is a committee created in 2004 to provide oversight and financial support for the IceCube Neutrino Observatory (including Construction phase, Maintenance & Operations, Research, and ongoing and future detector upgrades). The IOFG comprises representatives of the funding agencies in partner countries supporting the construction and operation of the IceCube Neutrino Observatory and its current and future upgrades. The current composition includes funding agencies from Belgium, Germany, Sweden, and the United States, and is chaired by the National Science Foundation. The IOFG meets at least annually and reviews the progress of all aspects of the ICNO operations, science output, and upgrades.
- **NSF Annual Reviews and Site Visits:** After the Project is baselined, NSF will be responsible for conducting regular reviews. These reviews will evaluate the schedule and technical progress including any changes to the baseline plan, management, and plans for upcoming Field Seasons, including logistical support, work plans and scope, and risks.

  NSF will also conduct site visits and reviews which will serve to evaluate the overall project status and business systems review, Project technical progress and performance against baseline, and technical achievements.

18.7 Community Relations and Outreach

The project will be headquartered at WIPAC, which maintains a staff responsible for education, outreach, and communications for all hosted projects. Other institutions contribute effort and resources with support from WIPAC, such as by hosting high school students for internships and IceCube Masterclasses. Print and web resources including videos for the IceCube YouTube channel are produced to highlight significant results and promote activities through social media platforms, including Twitter, Instagram, and Facebook.

19 Glossary

AIL	Antarctic Infrastructure and Logistics, office within NSF
ASC	Antarctic Support Contractor. Contracted by the NSF to support Antarctic logistics. The current contractor is Leidos, located in Denver, CO
CCB	Change Control Board
CDR	Conceptual Design Review
CMP	Configuration Management Plan
COMAir	Commerical Aircraft transport of materials (to Christchurch, NZ)
COMSur	Commerical Surface Ship transport of materials
CONUS	Continental United States
COTS	Commercial Off The Shelf, not custom
DAP	Drill Advisory Panel
Dark Sector	Controlled light radio emission region near South Pole, for Astronomy
DAQ	Data Acquisition
DCC	Drill Control Center
DCS	Drill Control System
DNDF	Do Not DEEP Freeze, keep above about –35C (must be heated or stored inside at Pole, outside storage is fine at MCM), especially for IceCube cables and hoses
DNF	Do Not Freeze
DOM	Digital Optical Module, Gen1 optical module, or used generically for all modules
DSN	Design Status Notes, part of the Technical Baseline documentation
DVT	Design Verification Testing, to ensure the prototype fulfils the engineering requirements documented in the Engineering Requirements Documentation (ERD)
E-Stop	Emergency Stop for the drill
EHWD	Enhanced Hot Water Drill, the IceCube drill used for IceCube-Gen1 and refurbished for IceCube Upgrade
EMI	Electromagnetic Interference
ERD	Engineering Requirements Document, part of the Technical Baseline documentation
EVMS	Earned Value Management System
FAT	Final Acceptance Testing
FDR	Final Design Review
FieldHub	Surface readout electronics for the in-ice optical module support (DESY, Germany)
Firn	The top layers of partially compressed snow in the Antarctic, about 100m thick at the South Pole

FMEA	Failure Mode and Effects Analysis, typically much lower level and hardware-associated than the risks
HA	Hazards Analysis, includes personnel and equipment safety issues
ICL	IceCube Laboratory, at the South Pole
ICNO	IceCube Neutrino Observatory
IDD	Interface Design Document, part of the Technical Baseline documentation
IFD	Independent Firn Drill
IOFG	IceCube International Oversight and Finance Group, meets annually with membership from the national financial partners of the ICNO
IVT	Integrated Verification and Testing
M&O	Maintenance and Operations program for ICNO
MCM	McMurdo Station, Antarctica
MDS	Mobile Drilling Structure
MECC	Mobile Expandable Container Configurations, WeatherPort-built expanding building/shipping container
MHP	Main Heating Plant
Milspec	Military Specification, either an actual military specification or any parts built to such, contrast to COTS or truly custom
MoU	Memorandum of Understanding, institution-to-institution agreement for deliverables
MTBF	Mean Time Between Failures
MTTR	Meant Time To Repair
NASA	(US) National Aeronautics Space Administration, also the NASA-run satellite communications facility at MCM
NCM	Non-Conforming Materials
NCMR	NCM Report
NPX	South Pole Station, Antarctica
NSF	National Science Foundation
NTS	Northern Test System, high fidelity “slice” of the Upgrade detector
NZ	New Zealand
Operations Sector	Area near South Pole Station with vehicle activities, storage sites, and general operations and activity
PAP	Project Advisory Panel, external advisory panel for the project
PAX	Passengers, on plane or another vessel
PD	Project Director
PDM	Power Distribution Module, interconnects the drill generator units
PDR	Preliminary Design Review
PEP	Project Execution Plan
PI	Principal Investigator

Pisten Bully	Small (red) tracked, enclosed vehicle used on the ice
PLC	Programmable Logic Controller, SCADA interface to drill sensors and controllers
PM	Project Manager
PO	Project Office
POC	Point of Contact
PoF	Physics of Failure, physics-based modeling efforts for quality control especially on electronics
PRR	Production Readiness Review, often but not always connected to the FDR
PSL	Physical Sciences Laboratory at the University of Wisconsin—Madison, home of the IceCube drill
PTH	Port Huaneme, California, Antarctic shipping point for the CONUS
QA	Quality Assurance
QC	Quality Control
RFI	Radio Frequency Interference, also called EMI
RNO-G	Radio Neutrino Observatory in Greenland, under construction
SCA	Surface Cable Assembly, goes from the SJB to the ICL
SCADA	Supervisory Control And Data Acquisition, slow control system
SES	Seasonal Equipment Site of the drill
SEW	Seasonal Equipment Workshop of the drill system
SOP	Standard Operating Procedure(s)
SOW	Statement of Work
SJB	Surface Junction Box, interconnect between downhole cable and surface cables
SPAT	South Pole Acceptance Testing, go/no-go test at Pole for optical modules
SPF	Single Point of Failure
SPOT	South Pole Overland Traverse, currently three per year, called SPoT-1 through SPoT-3, carries fuel and cargo to the South Pole and returns waste materials from the Pole
SPS	South Pole Computing System (at South Pole), or Amundsen-Scott South Pole Station
SPTS	South Pole Test Computing System (in Madison, WI)
SW	Software
SWOT	Strengths, Weaknesses, Opportunities, and Threats, project planning tool
TB	project Technical Board, also the Technical Baseline which is kept and defined by the Technical Board
TOS	Tower Operations Site/Structure
TU20	winch used in drilling and deploying

USAP	US Antarctic Program
UTC	Universal Coordinated Time, the official time basis for astronomical timing, see also Zulu
VC	Vice Chancellor, UW Vice Chancellor of Research and Graduate Education
WBS	Work Breakdown Structure, project organizing framework centered on deliverables
WIPAC	Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin—Madison
WO	Over winter operator of IceCube, resident at South Pole
WT	(generic) Water Tank(s) used by the IceCube drill
Zulu	Greenwich Mean Time, see also UTC

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