WISCONSIN ICECUBE
PARTICLE ASTROPHYSICS CENTER

IceCube Upgrade
Project Execution Plan (PEP)

2021-001.26

Approval

Principal Investigator	Kael Hanson	
Project Director	Vivian O'Dell	
Project Manager	Farshid Feyzi	

Change Log

Rev	Description : Author	Date
-	Original document : J. Haugen	1/24/18
1	Initial Pre-award PEP: K. Hanson, J. Haugen, C. Vakhnina, M. DuVernois, R. Paulos, T. DeYoung	7/9/18
2	Second draft PEP: K. Hanson, J. Haugen, C. Vakhnina, M. DuVernois, R. Paulos, T. DeYoung, J. Yeck. WBS to level 4, improved risk and contingency	8/22/18
3	Third draft PEP: K. Hanson, J. Haugen, C. Vakhnina, M. DuVernois, R. Paulos, T. DeYoung, J. Yeck. Updated summary tables on p.17-18 and 42, and text on p.46	8/27/18
4	Revised PEP: J. Madsen. Removed WBS Dictionary and provided link to updated WBS Dictionary, Updated Organization Charts to be consistent with new WBS, Removed cost by WBS item and added description of Cost Book, Updated personnel, added EV reporting description, Updated the Design Flow Matrix and a Draft Risk Management Plan in the appendix	2/12/19
5	Revised PEP: J. Madsen. Added Section 1.5 Technical baseline (p.8-10), Updated Organization chart (Fig. 2, p. 11). Aligned 2.1.2 Project Office Senior Staff description with Org. chart (p.12). Removed associate director from list of responsibilities of host institution (p. 14). Added L1 and L2 Milestones (p.18-21). Updated Summary of Total	3/1/2019

	Project Definition, Non-NSF Funding Table to be updated (p.22). Updated US Funding profile by institution (p.29).	
6	Revised PEP: J. Madsen. Update 2.2.3 ICNO description and added information on MOUs and how they are used to describe in-kind contributions (p.14), Updated Development Schedule items (p.17-18), fixed links for NSF IceCube Upgrade Review, Updated Design Flow matrix Appendix 1	3/5/2019
10	Revisions to address comments and recommendations from March 2019 project review panel. J. Madsen: Added Section 1.1.3 IceCube-Gen2 R&D. Updated Fig.2 removing IDF and adding surface junction box, removed IDF from text in Section 1.2.3, Improved text in section 3 opening paragraph. Removed IDF references in Milestones and added SBJ. Moved Upgrade design flow matrix from appendix 1 to where it is referenced in 3.1.2 and eliminated the appendix. Removed section heading 4.5.1 Risk Register but kept text. Updated 2.1.2 Production Manager title corrected to Production Coordinator, 2.1.1 Updated to include Farshid Feyzi as PM, Updated reporting section 11. 3 to reflect monthly reports rather than quarterly as previously described. Updated link and text in 6 to refer to IceCube Upgrade Risk Management and Mitigation Plan (previous text said this was under development) and removed the redundant appendix. M. DuVernois: 1.2.3 Removed reference to IDF and added surface junction box, added sentence in 2.1.2 clarifying Technical Coordinator duties and in 2.1.4 about face-to-face meetings of Tech Board at Collaboration Meetings, Updated roles and responsibilities table in 2.3 for UW–Madison and Penn State, Reformatted personnel organization in 5 Staffing Plan. Updated information on major acquisitions in 8.1. Updated internal reviews Section 11.1 clarifying Subsystem Technical Reviews Configuration Board Meeting descriptions. Added Section 13.1 Physics, Calibration, and R&D Success Key Performance Parameters. Added Section 13 Reliability. F. Feyzi: Reorganized to follow guidelines of Major Facilities Guide. Edited for content and updated plans.	8/30/2019
11	Edited by J. DeMerit and F. Feyzi	9/25/2019
12	M. DuVernois, general edit, addition of 1.1.3, modifications for "transition to operations," improved figures 6 & removed the old figure 7, and clarifications is section 13. Edited by Feyzi	9/28/2019
13	Edits by K. Hanson: scientific requirements, risk management plan removed and referenced to external document	10/04/2019
14	Updated section 4.2 per PY2 detail plan. Reissued with name change to 2019001-14 for comments by NSF, all revisions up to 13 are designated as archival. F. Feyzi	10/11/2019
14a	Updated figure 1 and financial tables in section 4 based on comments from NSF. F. Feyzi	11/1/2019

15	Updated per additional comments from NSF. F. Feyzi	11/22/2019
16	Updated per additional comments from NSF. F. Feyzi	12/4/2019
17	Updated to address additional comments from NSF. F. Feyzi Fixed revisions notes for rev 10 to ensure section numbers correspond to those after reorganization, which was done during rev 10. Section numbers and pages referenced in rev notes prior to rev10 are no longer current. Recommendation re. calibration added to section 12. Reissued as 2020001-17	1/12/2020
18	Updated tables 6, 7 and 9 per changes in Cooperative Agreement Inserted Appendix 4: Contributions in Kind F. Feyzi	1/20/2020
19	Updated to address additional comments from NSF. F. Feyzi	1/29/2020
20	Updated for Project Year 3 (October 2020, September 2021), includes a stand-alone PY3 plan as appendix and notice of intent to re-baseline. Organization chart updated. Other updates as needed. Reissued as 2021001-20 and entered for approval	12/9/2020
21	Update for Project Year 4 (October 2021, September 2022), includes a stand-alone PY4 plan as appendix. Organization chart updated. WBS responsible persons at level 4 added. Cost estimation and cost uncertainty plan separated into stand-alone documents. Reissued as 2022001-21 and entered for approval F. Feyzi	10/1/2021
22	Reworked for rebaselining, following the latest Research Infrastructure Guide (Dec. 2021) and updating references to key IceCube Upgrade documents (CEP, KA, RMP,SMP). Need to update with results from risk modelling and overall budgets. V. O'Dell	2/5/2022
23	Updated with milestones, costs to go from latest schedule / budget. V. O'Dell	3/12/2022
24	Update with latest schedule and risk information for the NSF rebaselining review. V. O'Dell	4/6/2022
25	Incorporated comments; general cleanup. V. O'Dell	4/10/2022
26	J. Madsen, V. O'Dell. Updated org charts. Updated key personnel descriptions. Updated risk section. Updated budget numbers to agree with latest cost workbook.	7/23/2022

THIS PAGE INTENTIONALLY LEFT BLANK

1 Introduction and Overview

The IceCube Phase I Upgrade, hereafter the IceCube Upgrade, seeks to enhance the scientific capabilities of the existing IceCube Neutrino Observatory at the South Pole station with a modest deployment of seven additional "strings" of advanced optical sensor instrumentation evolved from the highly successful IceCube digital optical module (DOM) design. IceCube encompasses 10^9 tons of optically transparent glacial ice that serves simultaneously as a massive target for neutrinos of atmospheric and astrophysical origin and a Cherenkov radiator medium producing the light detected by the array of optical sensors. IceCube, with an inter-string spacing of 125 meters and a spacing of 17 meters between sensors along the string, was originally optimized for detection of neutrinos in the energy range of 1 TeV to 1 PeV. During construction of IceCube, which we refer to as "Gen1," a DeepCore infill array was deployed inside the IceCube strings to reduce the energy threshold to several tens of GeV. The IceCube Upgrade continues the trend by lowering the energy threshold to 5 GeV with the scientific objectives explained in the next section. The array geometries of IceCube, DeepCore, and the IceCube Upgrade are shown for comparison in Figure 1. For more details of the current IceCube "Gen1" detector see (1).

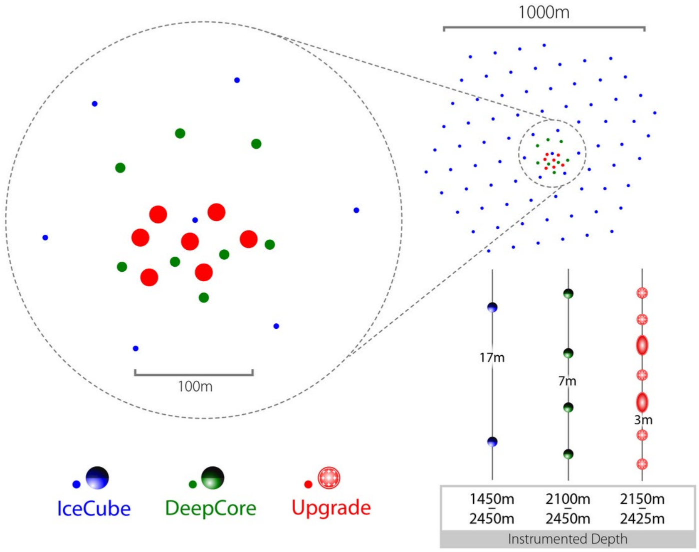


Figure 1: Deployment geometries of IceCube, DeepCore, and the IceCube Upgrade.

1.1 Scientific Objectives

1.1.1 Neutrino Properties

The indirect observation of neutrino mass by reactor, accelerator, and astrophysical oscillation experiments requires additional physics beyond the Standard Model. IceCube DeepCore has demonstrated its capabilities in the domain of neutrino oscillation physics, and the IceCube Upgrade will increase scientific knowledge in the still mysterious neutrino sector. Precision measurement of the atmospheric neutrino mixing parameters may provide clues to new symmetries and new phenomena. The tau neutrino mixing parameters are poorly constrained in current oscillation experiments. However, the ν_τ appearance signal from atmospheric muon neutrinos oscillating in transit through Earth is in the middle of the IceCube Upgrade's sensitivity region. More precise measurements of this column of the neutrino mixing matrix, the so-called PMNS matrix, could test the unitarity of this matrix, with failure of the unitarity condition indicating the presence of additional, sterile neutrinos.

1.1.2 Recalibration and Reanalysis of IceCube Data

The imperfect knowledge of the optical properties of the ice, which forms an integral part of the IceCube detector, limits the angular resolution of event reconstructions. At high energies where the additional information content of the signal should continue to improve angular and energy resolutions, reconstructions reach a resolution floor. The IceCube Upgrade presents an opportunity to deploy additional devices to measure ice properties that benefit from a decade of experience operating IceCube. The resulting advancements in-ice models are expected to improve angular resolutions significantly (approximately a factor of 2) and are applicable to IceCube archival data.

1.1.3 IceCube-Gen2 Research and Development

A third high-level goal of the IceCube Upgrade is to serve as a research and development platform for a potential high-energy extension of the IceCube Detector, the IceCube-Gen2 Project. Advances being made for the Upgrade are assessed for their applicability to the Gen2 effort.

Additionally, promising novel in-ice optical module designs will be included in small quantity R&D (“special devices”) deployments on the Upgrade strings. This will allow for a straight-forward evaluation of the detector technologies of potential interest in Gen2 *in situ* and in coincidence with IceCube neutrino and cosmic-ray events. These detector elements include the WOM (Wavelength-shifting Optical Module, a revolutionary step in gaining effective collecting area without increased photocathode size and cost), the FOM (Fiber Optical Module, a similar cost saving strategy but employing fibers deployed into the drill hole), the LOM (Long Optical Module, a more evolutionary module based on the mDOM construction but elongated to fit into a smaller diameter cylindrical or egg shaped housing which could dramatically reduce drilling costs), and test deployments of fiber optic cables to as an alternative to copper wires for communicating with the in-ice electronics.

The new Ice Communications Module (ICM) and the FieldHub surface communications boards are designed with an eye towards Gen2 logistics needs for lower-power in-ice modules, ease of integration by separating development work, and distributed surface electronics. The drill design for the Upgrade is an admixture of the original IceCube Enhanced Hot Water Drill and the design for a fully mobile Gen2 Hot Water Drill. Acoustic pingers are being tested in the Upgrade to understand the analysis of their positioning information in the deep ice for the wider string spacing of a Gen2 detector.

1.2 Scientific Requirements

The principal scientific mission of the IceCube Upgrade is the determination of the $U_{\tau 3}$ element of the PNMS mixing matrix: better than 10% relative uncertainty on the ν_τ normalization and exclusion of no ν_τ appearance at $10\,\sigma$ after 1 year of data taking. The Upgrade will also be a powerful instrument for measurement of neutrino oscillation parameters and low-energy searches and secondary goals include: 2% relative uncertainty (68% CL) on Δm^2_{32}; 12% relative uncertainty (68% CL) on $\sin^2\theta_{23}$ if maximal mixing; 6% relative uncertainty (68% CL) on $\sin^2\theta_{23}$ if non-maximal mixing; sensitivity to octant of atmospheric mixing angle; excluding maximal mixing at $3\,\sigma$; determination of the neutrino mass ordering at $3\,\sigma$ in 3-8 years (dependent on value of θ_{23} and ordering); sterile neutrino limit of $|U_{\tau 4}|^2 < 0.6$; extend neutrino search from solar WIMP annihilation down to WIMP masses > 5 GeV.

High-energy astrophysics goals are as follows: significantly improve angular resolution of *existing IceCube* data. These goals drive requirements on the ice characterization: DOM optical efficiency determination *in situ* < 3%; reduce uncertainties of angular acceptance of IceCube DOMs by a factor of at least 2; measure optical photon scattering in bulk and hole ice to achieve high-energy objectives.

Finally, the restart of deep-ice drilling opens the possibility to field test the functionality and reliability of new sensor instrumentation for the next generation facility and retire risk at an early stage.

The summary flow down from scientific objectives to technical requirements is shown in Appendix 1: Flow Down from Scientific Objectives to Technical Requirements.

1.2.1 Management Context of Physical Facilities

The IceCube Upgrade project will be part of the IceCube Neutrino Observatory at the Amundsen-Scott South Pole Station, one of the two dozen major research facilities operated by the National Science Foundation (NSF). Under the NSF Cooperative Agreement OPP-2042807, Management and Operations of the IceCube Neutrino Observatory 2021-2026, the Wisconsin IceCube Particle Astrophysics Center (WIPAC) at the University of Wisconsin–Madison (UW–Madison) oversees the ongoing daily, monthly, and annual maintenance of the IceCube facility.

1.2.2 Infrastructure Overview

The IceCube Upgrade will take advantage of the existing infrastructure at UW–Madison and the United States Antarctic Program (USAP)-managed South Pole station. UW–Madison maintains dark freezer optical test facilities for characterization of the sensor modules, a high-fidelity single-string implementation of IceCube, and associated computing infrastructure as well as the software repository, hardware spares, and documentation archive for the project. At the South Pole, the existing IceCube Laboratory (ICL) will provide infrastructure, power and computing, to operate the Upgrade strings. USAP contracts with Leidos via the Antarctic Support Contract (ASC) to provide station operations, logistics, medical support, information technology, construction, maintenance, and more at the South Pole station. The Amundsen-Scott South Pole Station is located 841 statute miles inland from McMurdo, at the geographic South Pole, and can accommodate a maximum of 160 people during the austral summer. Two winterover scientists dedicated to IceCube on-site detector operations are among the 40-50 people who remain at the South Pole during the winter. Astronomy and astrophysics are the primary scientific work carried out at the South Pole.

1.2.3 Detector Overview

A high-level overview of the main components of the IceCube Upgrade project are shown in Figure 2. It consists of an enhanced hot water drill (EHWD), the surface junction boxes (SJB) that provide communication from the IceCube Lab (ICL), which houses FieldHubs and power from main station power distribution, the downhole cables and breakout cable assemblies (BCA), and the deep-ice sensor modules. A northern test station will be built at Michigan State University to reproduce a slice of the system from the SJB (Surface Junction Boxes) to the BCA allowing full testing of all components.

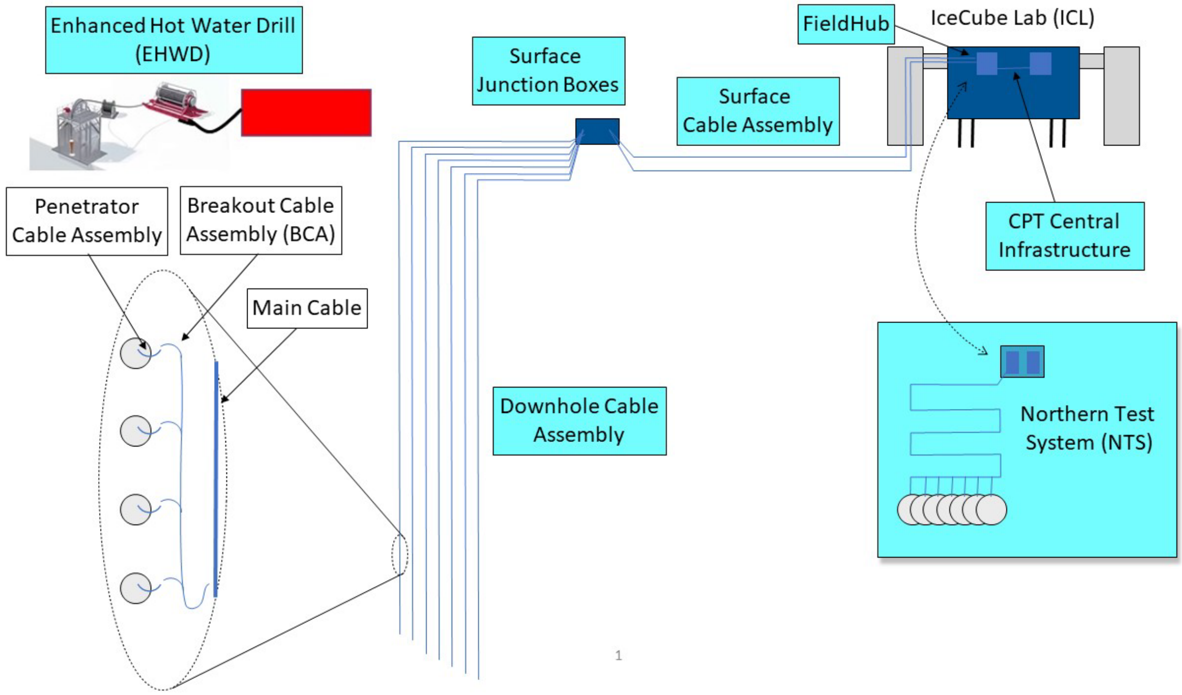


Figure 2: A high-level representation of the IceCube Upgrade.

1.2.4 Detector Design

The IceCube Upgrade consists of seven detector strings, as illustrated in Figure 3, installed in hot water drilled holes of a 50-cm minimum diameter. The core physics region, for precision neutrino oscillation and tau appearance measurements, consists of 90 optical modules (52 mDOM and 38 D-Egg sensors) over the 275-m vertical distance from 2150-2425 meters below the surface, where the clearest ice for precision measurements lies. At shallower and deeper depths (down to 2600 meters below the surface), a smaller number of optical modules (the mDOMs, D-Eggs, and pDOMs, which are similar to Gen1 DOMs) and calibration sources (POCAM, pencil beam, and radio) are deployed primarily for calibration purposes. The original IceCube Gen1 extends from 1450 to 2450 meters and surrounds these strings. Additional research and development of various types of modules (including the LOM, FOM, and WOM) to study potential sensor technologies for a high-energy IceCube-Gen2 extension are also deployed above the primary physics region.

The deep-ice sensor modules, whether they are PMT-based optical modules, stand-alone calibration devices, or R&D packages, are all connected via breakout cable assemblies to the main downhole cable. Both cable types are derived from IceCube Gen1 experience and the deep ocean industry. All downhole modules additionally communicate to the IceCube DAQ via the IceCube communications protocols (“all modules speak DOM”), receive power over the same communication wire pairs, and host the dedicated electronics to perform those communications (ICM = ice communications module).

The downhole cables terminate in a surface junction box under the snow surface to reduce drifting. Inside, there are connections to horizontal feeder cables that lead back to the IceCube Lab, carrying the data and power on the same wires.

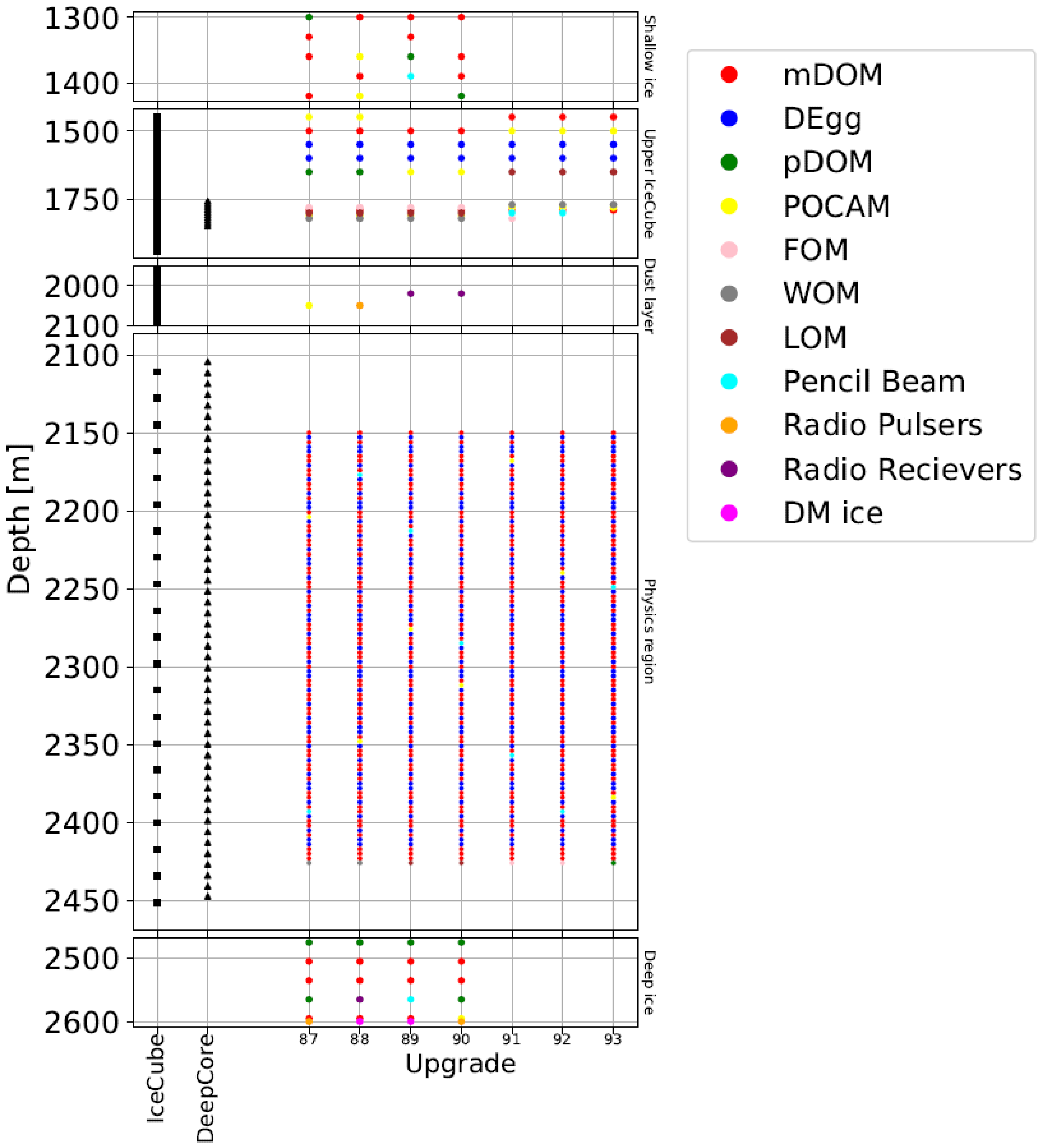


Figure 3: The configuration of the deep-ice sensor modules.

Inside the IceCube Lab, the IceCube Upgrade data is read out in rack-mounted FieldHubs (containing ICMs for the cable communications). The IceCube Upgrade event data is then combined with the IceCube Gen1 data at a low level to permit cross-triggering and full inclusion of the new strings in the data stream: the data appear at the analysis stage as a single, fully integrated experiment. Active calibration devices are controlled by the overall data acquisition system and are interlocked against any unintentional "light in the detector" during normal data taking. Passive calibration devices and R&D special devices are also managed, with their data routed appropriately.

1.2.5 IceCube Enhanced Hot Water Drill (EHWD)

The heart of the Upgrade Project is the refurbishment and upgrade of the IceCube-Gen1 EHWD. The EHWD was used successfully during the seven deployment seasons of IceCube, reaching a peak delivery rate of twenty holes per season. An engineering study was completed in 2015 by the University of Wisconsin Physical Sciences Laboratory (PSL) yielding a concept design for a next generation mobile hot water drill, traversable over the Antarctic plateau from McMurdo and able to deliver a comparable number of holes per season as the EHWD over the much larger footprint envisioned for the expanded South Pole neutrino observatory. This study has been re-analyzed for the current IceCube Upgrade scenario, and a feasible intermediate drill system has been identified that satisfies the requirements of this first phase and simultaneously delivers a platform which can extended to an eventual next generation drill. Additionally, the drill places significantly lower demands on the logistical infrastructure at South Pole than the original IceCube drill did.

1.2.6 Drilling and Installation

The implementation of the seven strings optical sensors in the ice are the largest effort for which support is requested. A challenging task is the drilling of the holes of 0.6 m diameter to a depth of about 2600 m. The drilling will be performed using the IceCube Enhanced Hot Water (EHWD) drill which produces a jet of hot water (200 gpm, 1000 psi pressure) of about 5MW thermal power to drill at a speed of 130m/hour. The drill was mothballed 6 in 2011 to be excavated from deep snowdrift in the first field activity of the IceCube Upgrade project in 2019/20. Significant components of the drill need to be replaced entirely, such as: drill hose, drill cable, generators and the complex control system. Other parts need maintenance such as: the main heating plant, high pressure pumps, water tanks, tower operations structures, hose reel.

The requirements for the IceCube Upgrade holes are more demanding than for IceCube. The required diameter is larger and the water filled holes are required to stay open for a longer period of time (50h vs. 35h) to ensure that strings can be deployed safely. The Upgrade strings are populated with almost twice as many instruments as a regular IceCube string. In addition, the mDOM optical sensors are larger in diameter and heavier and there is a larger variety of sensors and devices that needs to be accommodated. All factors included, the drill time per hole is projected to about 53 hours, compared to a full production IceCube hole drill time of 34 hours. The preparation for drilling can be categorized in two major tasks: a) planning, re-building and in some cases redesign of subsystems in the North, b) shipping of equipment, and c) refurbishing of subsystems, recommissioning of the drill, and finally drilling operations on the ice. The drill control system includes the readout of more than 300 sensors. All of these get readout to a central control center which includes complex safety functions and an emergency stop that can be initiated from any subsystem. Approximately 75% (by weight) of the drill equipment has been shipped by February 2022.

It is hard to overstate the importance of the field experience of IceCube construction for the planning of the field seasons and the eventual execution. The drill refurbishment, the redesign and fabrication of the control system is all done at UW-Madison's Physical Sciences Laboratory that designed and constructed the drill for IceCube, and largely lead the drilling operations. Similarly, the installation effort relies on the collective experience of 86 strings deployed. The field effort in this project is planned for three seasons which typically last from November 15 until the end of January. The main tasks by field season are:

- Field season 1 (2023/24): Repair and re-fit EHWD subsystems. Commission the Independent Firn Drill (IFD) and the Antarctic Rodwell Apparatus (ARA Drill). Set-up the Seasonal Equipment Site (SES)
- Field season 2 (2024/25): Complete the SES set-up and remaining interconnects. Integrate and test the drill sub-systems including Generator and PDM, system integration, and verification and testing. Perform control system testing and ”wet-testing” of EHWD subsystems. Firn drill all holes and install surface cables.
- Field season 3 (2025/26): Deep drilling of all seven holes; Install all seven detector strings; Commission the new strings, integrate in data acquisition and data handling; Drill system decommissioning and storage/retrograde.

1.2.7 Baseline Documentation

The technical baseline design of the IceCube Upgrade is maintained and documented on the IceCube Upgrade SharePoint site as a directory of design files (configuration management documents, engineering requirements document, engineering design notes, and interface definition documents). The project baseline can be altered using an official change request form along with discussion on the weekly technical board call and the weekly WBS Level 2 manager and change control board call. Change requests are logged and once approved by the project manager are routed to project resource coordination for budget and schedule alterations. This documentation can be accessed and improved by all collaborators. Controlled versions of the documents are created when items are sent to production. Progress is assessed by a mixture of milestones, the EVMS, and the system of reviews, with the design flow through those reviews detailed in Figures 6 and 7.

1.3 Facility/Infrastructure

1.3.1 Laboratory Facilities

Multiple laboratory facilities are available for electronics and detector development, mechanical fabrication, testing and qualification, and clean room processing. The labs are outfitted with standard test equipment including oscilloscopes, environmental chambers, spectrum and network analyzers, power supplies, data acquisition, and computers. Specialized facilities include a large walk-in shielded anechoic chamber for ultra low noise measurements on radio antennas and instrumentation as well as emissions and susceptibility testing, and two smaller chambers for emissions measurements. For South Pole hardware, there are a number of chest and walk in freezers capable of temperatures down to -80C. Specific to the IceCube Experiment, a high-fidelity model of an IceCube string is maintained, with detector elements cold, for temperature-sensitive timing studies, and for final development work on software or firmware before deployment to the South Pole System. Extensive machine shop and electronics shop facilities are housed near the lab spaces. Extensive assembly and high-bay spaces are available with total floor space up to 10,000 square feet covered by overhead cranes.

1.3.2 Computing Resources

The Wisconsin IceCube Particle Astrophysics Center (WIPAC) hosts the main computing facilities of the IceCube project as well as for smaller projects. The IceCube data center at WIPAC includes over 6000 TeraBytes of disk storage, 5000 CPU cores, and 400 GPU compute nodes. WIPAC and UW-Madison provide the facilities and power to run this data center including infrastructure to power and cool about 170 kW of IT equipment. IceCube scientists can access both IceCube-specific and several UW-wide computing clusters that are linked by the HTCondor software and together represent more than 20,000 CPU cores. Several IceCube collaboration institutions provide resources at their clusters as well to contribute to the Collaboration-wide simulation production effort. Finally, WIPAC can also tap into computing resources from the Open Science Grid (OSG) in an opportunistic manner. OSG is an expanding alliance of more than 120 universities, national laboratories, scientific collaborations, and software developers that enables efficient resource sharing. Both IceCube IT personnel and the WIPAC Computer Helpdesk provide support for IceCube computing services.

1.3.3 Office Space

The University of Wisconsin leases office space at 222 West Washington Avenue in downtown Madison for WIPAC. In addition, faculty and students have office space at the UW-Madison Department of Physics, and those involved with hardware work have additional office (and lab) spaces at the Physical Sciences Laboratory in nearby Stoughton. Administrative, accounting, purchasing, computing helpdesk, and human resources support are locally provided by WIPAC.

1.3.4 DESY

The DESY campus in Zeuthen hosts mechanical and electronics engineering groups with long standing experience in large-scale particle and astroparticle physics experiments (Baikal, AMANDA, IceCube, H.E.S.S., CTA, ATLAS, H1, and others). Both groups have workshops on campus at their disposal where prototypes and small batch series of detectors can be manufactured. The IceCube group at DESY produced 1330 Digital Optical Modules for the IceCube Observatory. The production facilities are still available and can be reactivated. The Dark Freezer Laboratory, that can hold up to 64 DOMs for final acceptance testing, is still in operation. Further, the group is developing calibration setups to calibrate selected modules with high precision.

1.4 Scientific and Broader Societal Impacts

The availability of a deep-ice drill presents several opportunities to enhance the existing IceCube infrastructure for research and education. The ice at the bottom center of IceCube is an excellent environment for experiments requiring extremely low cosmic ray background such as the DM-Ice direct dark matter experiment. Deep ice drilling also allows for the possibility of deploying next-generation optical sensor technology prototypes for ultimate use in a fully-realized IceCube-Gen2 Neutrino Observatory. Such an opportunity to retire risk at an early stage of development would shorten the design phase and provide a pathway for utilization of novel and potentially game-changing photodetection technology.

Working within the existing IceCube operations framework of education, outreach, and communications, this project presents new opportunities for international student exchanges throughout instrumentation development and production. The combination of astrophysics and the extreme polar climate attracts wide popular interest; this project is ideally situated as an example of NSF cross-directorate participation between the divisions of MPS/PHY and GEO/PLR, highlighting the diversity of science activities supported within these units to the scientific communities, the general public, and policymakers.

1.5 Facility Divestment Plan

The Project will become part of the IceCube Neutrino Laboratory and is expected to be operational over at least the next two decades (i.e. until ~2045). The IceCube Neutrino Observatory is operated by NSF under a separate Management and Operation grant. At the end of the ICNO operations, the M&O program would remove the parts of the ICNO that are accessible, and leave the rest, e.g. the buried sensors, in place. Details on the cost and scope of the facility divestment can be found in the "Divestment Plan for the IceCube Neutrino Observatory" (2).

2 Organization

2.1 Internal Governance, Organization, and Communication

The IceCube Upgrade project internal governance is shown in Figure 4. Specific Roles and Responsibilities of key project personnel and governing bodies are described in Section 2.4.

The University of Wisconsin – Madison is the host institution for the Project, and the Vice Chancellor's office has formal authority over the project and ensures that the project is well governed and appropriately staffed. The Office of the Vice Chancellor oversees regular reviews of the project.

The Project Director (PD) is the primary contact to the NSF. The PD is responsible for completing the project within the budget and schedule agreed upon by NSF. The PD delegates the responsibility of running the project to the Project Manager (PM) (see Section 2.4), but tracks the progress of the project, reports the progress to the NSF, and has authority to bring in additional resources or reallocate resources as needed for the successful execution of the project.

The PM runs the project, and chairs the Change Control Board, as well as appoints (in consultation with the PD) key management positions in the Project. The Project Advisory Panel participates in regular reviews of the project and advises the project.

NSF is responsible for oversight of the project, which is shared between the NSF Division of Physics and Office of Polar Programs.

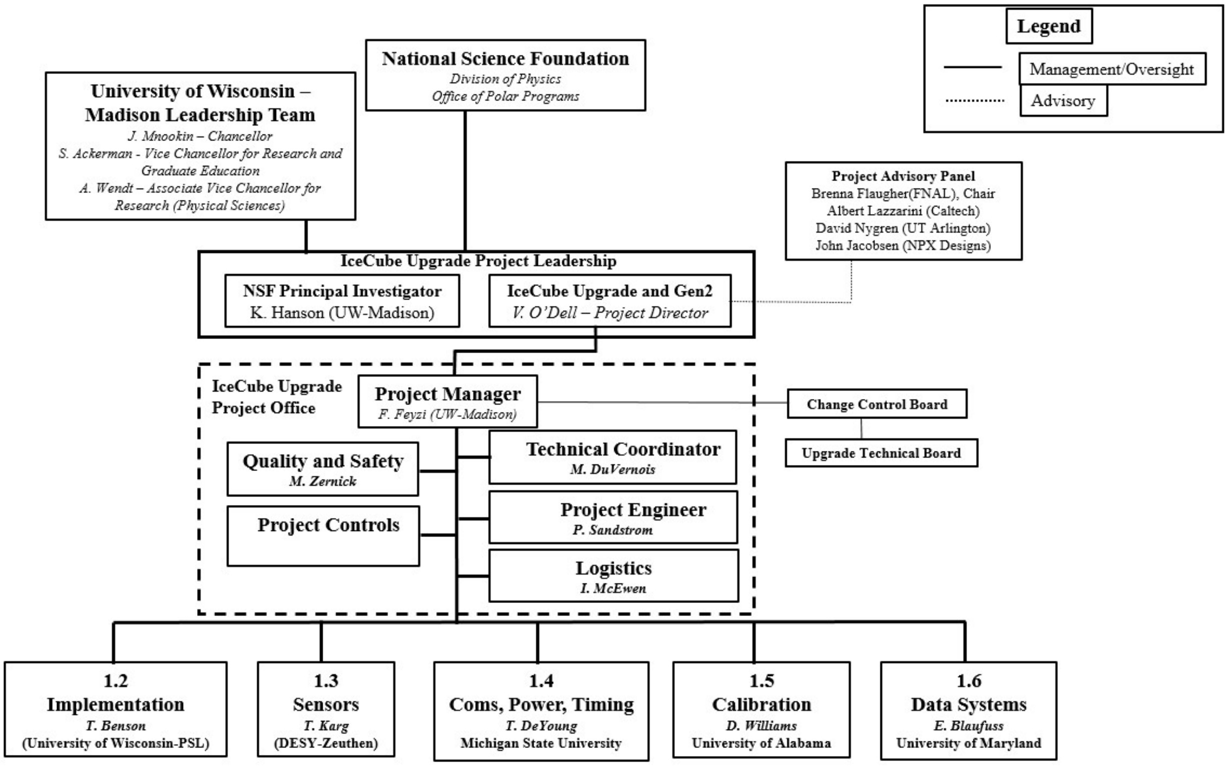


Figure 4: IceCube Upgrade organizational structure.

2.2 External Organization and Communication

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.

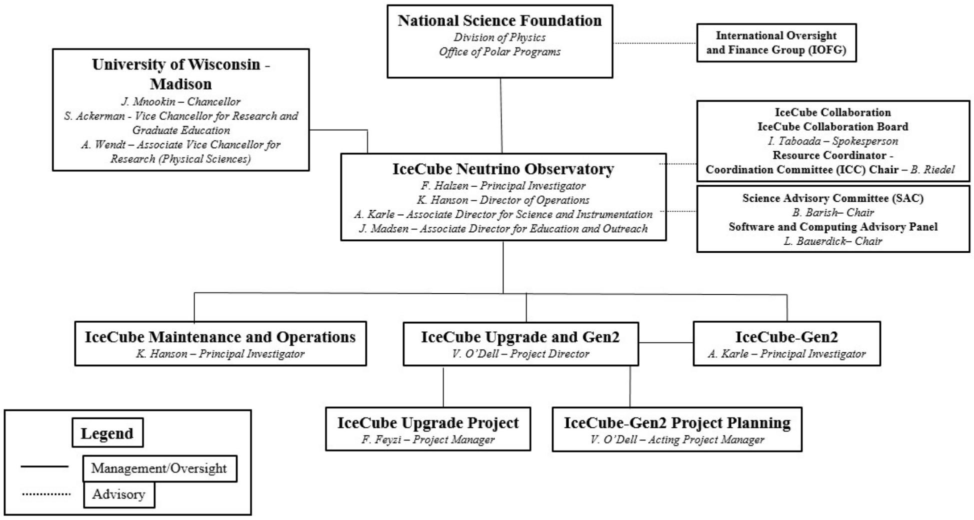


Figure 5: IceCube Neutrino Observatory global organizational structure.

2.2.1 National Science Foundation

The NSF is the executive agent responsible for seeing that the IceCube Upgrade meets its baseline requirements of cost, schedule, scope, and technical performance. The NSF has a special role in the IceCube Upgrade because of its host laboratory responsibilities in managing the logistical operations of the Amundson-Scott South Pole Station. These responsibilities include safety; physical qualification of project staff; environmental protection; transport of personnel, fuel, and equipment; and the provision of housing, food service, support personnel, logistical support, IT support, and general infrastructure support.

2.2.2 International Oversight and Finance Group

The International Oversight and Finance Group (IOFG), already in place for IceCube, provides oversight and financial support for the IceCube Upgrade project. The IOFG organizes annual oversight reviews of the construction project and meets annually to discuss project performance. The IOFG also sets policies for receiving periodic progress reports on all aspects of the project and by all the performers in the project.

2.2.3 IceCube Neutrino Observatory

The IceCube Neutrino Observatory is governed by an established and effective collaboration of institutions (IceCube Collaboration) with considerable experience delivering in-kind contributions to the IceCube-Gen1 MREFC and steady-state M&O programs. The responsibilities of all collaborating institutions are defined in MoUs executed between UW–Madison, as the project host institution, and the individual collaborating institutions. MoUs are updated twice a year prior to collaboration meetings. MoUs with institutions with in-kind deliverables required for the success of the IceCube Upgrade project include an appendix defining the in-kind deliverables, on a timeline consistent with the IceCube Upgrade project master schedule.

The PM is responsible for signing off on the in-kind deliverables outlined in the MoUs and project schedule. The recipient of the in-kind good or service will confirm when the in-kind deliverable is made, and the Level 2 managers will track delivery dates. The PM uses the tracking spreadsheet to confirm in-kind goods or services were delivered as outlined in the MoUs and project schedule. The tracking spreadsheet is available on SharePoint for the project office to view (3).

2.2.4 Host Institution

UW–Madison is the host institution for the IceCube Upgrade and the home university of the NSF IceCube Upgrade PI. The responsibilities of the host institution include:

- Providing internal oversight for the project
- Appointing the PD and PM (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 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 (4)

The IceCube Upgrade project office is headquartered at WIPAC. 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 future additions such as 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.

2.3 Partnerships

Table 1 shows the national and international partners in the design and construction of the IceCube Upgrade, categorized by NSF-funding status. The responsibilities of each partner are listed.

Table 1: NSF/non-NSF-funded national and international partnerships, roles, and responsibilities.

NSF-Funded Upgrade Institutions	**Roles**	**Responsibilities**
UW-Madison	Host institution, Project Office, Hot Water Drill System, level 1 and 2 management, WBS 1.1 and 1.2	Project management, PDOM production, data acquisition hardware, firmware, and software, high voltage electronics, CPT system components, pencil beam calibration module, construction and deployment of drill, installation of strings and optical modules
Michigan State University	Level 2 management WBS 1.4	Communications, power, timing, detector simulation, North. Test System
Penn State University		Data acquisition electronics, firmware
University of Alabama	Level 2 management WBS 1.5	Calibration management, coordination, commissioning
University of Maryland	Level 2 management WBS 1.6	Data filtering, software and integration
Non NSF-Funded Institutions (see Appendix 4: Contributions in Kind for more information)		
DESY–Zeuthen, Germany	Level 2 management WBS 1.3	mDOM production, data acquisition electronics, cables, ICMs
Karlsruhe Institute of Technology		Photomultiplier tubes (PMTs) acquisition for mDOM
Universität Münster, Germany	Level 3 management WBS 1.3.1	mDOM mechanical design and integration
Tech. Univ. of Munich, Germany	Level 3 management WBS 1.3.5	Precision Optical Calibration Module (POCAM)
Sungkyunkwan University, South Korea		In-module camera system
Chiba University, Japan	Level 3 management WBS 1.3.2	Optical sensors, D-EGG design, integration, and production
Michigan State University (in-kind)	Level 2 management WBS 1.4	mDOM production, cable production
Rheinisch-Westfälische Technische Hochschule Aachen		PMT characterization and acceptance testing, acoustic sensors, mini-mainboards

2.4 Roles and Responsibilities

This section describes the Roles and Responsibilities of key project personnel and governance groups.

2.4.1 Project Director

The IceCube Upgrade PD is appointed by the PI, subject to concurrence of the IceCube Executive Board and approval by UW Leadership and the NSF. The PD is responsible for setting the overall direction and goals of the project, and for coaching the project team on project requirements. The PD oversees and has authority over technical and managerial aspects of the project and is responsible for completing the project within the budget and schedule approved by the project and NSF. The PD is the main point of contact between NSF and the project. The PD establishes the detailed Project Execution Plan, and other project documentation to ensure the project follows best practices. The PD retains responsibility for technical and managerial oversight of the project but delegates the running of the project, according to the established project plans, to the PM.

2.4.2 Project Manager

The IceCube Upgrade PM is appointed by the PI in consultation with the PD, subject to concurrence of the IceCube Executive Board and approval by UW Leadership and the NSF. The PM is responsible for the technical execution of the project, and the PM oversees and has authority over technical and managerial aspects of the project. The PM:

- Appoints Level 2 (L2) managers (in consultation with the PI and PD) and approves Level 3 (L3) managers
- Establishes engineering standards and requirements
- Develops staffing plans and assists in recruitment and hiring
- Tracks project progress and reports to the PI and PD
- Develops and monitors subawards
- Chairs the IceCube Upgrade change control board

2.4.3 Project Office Senior Staff

Senior staff includes the technical coordinator, project engineer, quality and safety manager, project controls manager, and logistics manager.

The technical coordinator integrates the project scientific, engineering, and quality requirements, providing leadership in these areas and advice to the PM. Additionally, the technical coordinator manages the technical board, including holding weekly meetings on technical status and coordination and directing the project design reviews.

The project engineer 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.

The quality and safety manager is responsible 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.

The project controls manager is responsible for the overall project schedule and budget as well as earned value reporting.

The logistics manager is the main point of contact between the project and the Antarctic Support Contractor and provides a nexus for project leads to coordinate with the Antarctic Support Contractor for shipment of instrumentation and deployment of personnel.

2.4.4 Level 2 and Level 3 Managers

WBS Level 2 managers are appointed by the PM and have the authority and responsibility to manage activities and resources within their respective WBS Level 2 elements. Responsibilities include developing engineering requirements, managing budgets, schedules and change requests, and planning and accomplishing work. Level 2 managers define the scope of responsibility of the Level 3 subsystem managers and direct project engineering and project control activities within their areas.

Level 2 managers work principally at their home institution and are an important communication link between the project office and collaboration member institutions. Level 2 managers work in close coordination with both the PM and project office staff. WBS Level 3 managers are appointed by the Level 2 managers, subject to the concurrence of the PM and the technical board. Responsibilities of Level 3 managers include developing engineering requirements, managing budgets and schedules, and planning and accomplishing work.

Level 2 managers are also members of the change control board (CCB). Their responsibilities include: review of change requests by others, controlling the interfaces between subsystems resulting from the change, evaluation of cost schedule and technical impact of change on their own subsystems, and recommendations for approval to the PM. For additional information see Configuration Management Plan.

2.4.5 Technical Board

The technical board is chaired by the technical coordinator and includes the Level 2 and Level 3 managers and technical support staff. The PI, PD, and IceCube Collaboration spokesperson are ex-officio members. The technical board meets once per week, via conference call, to discuss project progress, problems, interfaces, potential changes, risk and risk mitigation strategies, and technical requirements, and in person as needed. The technical board also provides recommendations to the change control board and maintains the technical issue tracker.

2.4.6 Change Control Board

The configuration management process, defined in Section 7.2, is used to control changes to the technical, cost, and schedule baselines. A change control board (CCB) decides on these change requests. The CCB is chaired by the PM and consists of the technical coordinator, the project engineer, the quality and safety manager, the project controls manager, the L2 managers, the IceCube associate director for science and instrumentation, and the PD. The PI is an ex-officio member. The CCB is an executive decision-making body convened when the level of a proposed change to the budget, schedule, or scope of the project demands approval of this body as defined in the Configuration Management Plan.

2.5 Community Relations and Outreach

The IceCube Upgrade project is 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.

3 Design and Development

The design process for the IceCube Upgrade is guided by an overall philosophy of keeping as much IceCube Gen1 heritage hardware, design, and engineering as possible while also improving on the science returns. Therefore, infrastructure items such as the cable systems remain largely unchanged, while the optical modules that detect the incoming photons are being redesigned to increase performance and explore options for IceCube-Gen2 sensors. Successful, robust segments from the IceCube Gen1 data acquisition system remain the same, including the IceCube nanosecond timing system (RapCal) and general communications and power structures.

3.1 Project Development Plan

The design of the hardware, software, and procedures for the IceCube Upgrade is hosted by the IceCube Upgrade project office at WIPAC in close coordination with the WBS L2 managers and the co-PIs of the funded effort. The project office includes individuals with expertise from IceCube Gen1, the Pierre Auger Observatory, the HAWC Observatory, and NASA balloon experiment construction efforts.

The project office provides project management plans, including updates to this project execution plan, annual reports, supplier qualification documentation, configuration and interface control management, and a central repository for this documentation. The previous experience with the extensive IceCube project documentation guides this effort.

The project is divided into three stages: design, production, and deployment. Operations of the Upgrade detector will be subsumed into the ongoing IceCube Management and Operations program, as described in Chapter 15. The configuration management plan shows the requirements for moving from one design stage to another, up to and including production readiness. The Upgrade project benefits from a significant amount of design work that has taken place from the end of IceCube construction in 2010 to the start of this project. The design process portion of the project is driven by science and technical requirements along with well-defined interfaces between the optical modules (with significant design work to be done) and the cable system (much more defined at project entry) and between the IceCube Upgrade strings and the existing IceCube Neutrino Observatory.

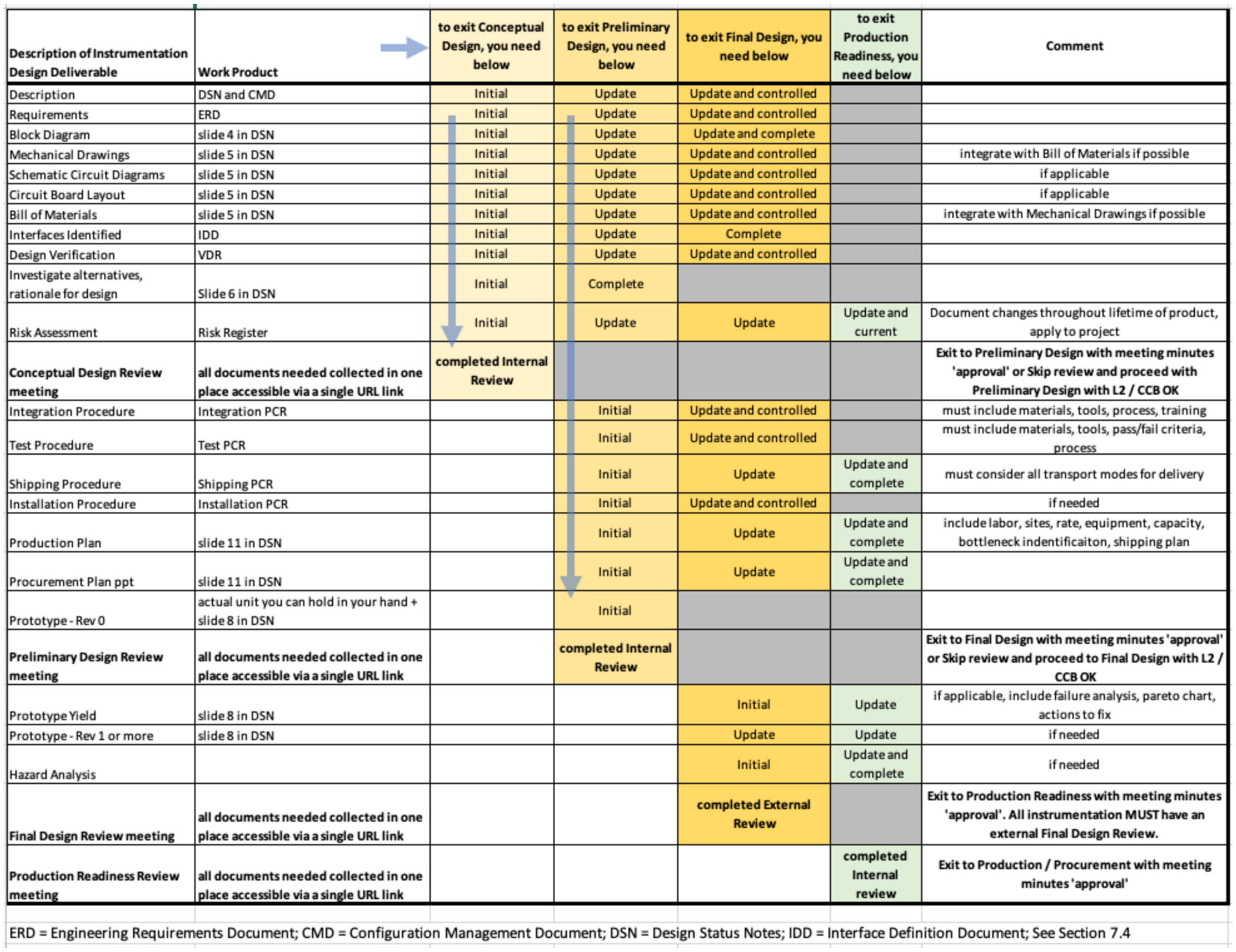
3.1.1 Design Verification

Design verification involves design reviews, including a final design review with requisite documentation to enter the production stage, as well as requirements satisfaction and device interoperability testing (see Figure 6). Demonstrating requirement satisfaction is the responsibility of the WBS Level 2 leads, and device interoperability testing falls under the northern test stand setup. This is a high-fidelity, cold-tested installation of optical modules and in-ice calibration devices, with the downhole cable quads read through the communications, power, and timing (CPT) system (defined later) and input into the IceCube northern test system.

To smooth the transition to manufacturing, early vendor visits for important parts such as cables, photomultiplier tubes, and a third-party industrial partner fabricating optical modules, were conducted. Prototypes are assessed for reliability, testability, and manufacturability with the engineering for these requirements, as much as possible, provided by the vendors and overseen by the project office. Due to the unique environment of the detector, two kilometers below the South Pole glacial surface, we expect to work closely with the vendors on testing requirements and manage deployment reviews ahead of South Pole field seasons. This includes detailed on-ice operational procedures, contingency plans, safety (equipment and personnel) plans, and structures that allow for field autonomy in real-time decision making.

3.1.2 Project Management Structures for the Design Phase

The WBS structures are in place for the design phase of the project. The WBS includes design elements as deliverables with ultimate responsibility through the L2 leads, the project office, and the co-PIs. The co-PIs, Level 2 managers, and the project office staff (project engineer, quality and safety manager, production coordinator, technical coordinator, PCMS manager) make up the L2 oversight group for the project, which manages design scope changes and interface control documents as well as engineering change requests in the latter phases of the project.



Description of Instrumentation Design Deliverable	**Work Product**	**to exit Conceptual Design, you need below**	**to exit Preliminary Design, you need below**	**to exit Final Design, you need below**	**to exit Production Readiness, you need below**	**Comment**
Description	DSN and CMD	Initial	Update	Update and controlled		
Requirements	ERD	Initial	Update	Update and controlled		
Block Diagram	slide 4 in DSN	Initial	Update	Update and complete		
Mechanical Drawings	slide 5 in DSN	Initial	Update	Update and controlled		integrate with Bill of Materials if possible
Schematic Circuit Diagrams	slide 5 in DSN	Initial	Update	Update and controlled		if applicable
Circuit Board Layout	slide 5 in DSN	Initial	Update	Update and controlled		if applicable
Bill of Materials	slide 5 in DSN	Initial	Update	Update and controlled		integrate with Mechanical Drawings if possible
Interfaces Identified	IDD	Initial	Update	Complete		
Design Verification	VDR	Initial	Update	Update and controlled		
Investigate alternatives, rationale for design	Slide 6 in DSN	Initial	Complete			
Risk Assessment	Risk Register	Initial	Update	Update	Update and current	Document changes throughout lifetime of product, apply to project
Conceptual Design Review meeting	**all documents needed collected in one place accessible via a single URL link**	**completed Internal Review**				**Exit to Preliminary Design with meeting minutes 'approval' or Skip review and proceed with Preliminary Design with L2 / CCB OK**
Integration Procedure	Integration PCR		Initial	Update and controlled		must include materials, tools, process, training
Test Procedure	Test PCR		Initial	Update and controlled		must include materials, tools, pass/fail criteria, process
Shipping Procedure	Shipping PCR		Initial	Update	Update and complete	must consider all transport modes for delivery
Installation Procedure	Installation PCR		Initial	Update and controlled		if needed
Production Plan	slide 11 in DSN		Initial	Update	Update and complete	include labor, sites, rate, equipment, capacity, bottleneck indentificaiton, shipping plan
Procurement Plan ppt	slide 11 in DSN		Initial	Update	Update and complete	
Prototype - Rev 0	actual unit you can hold in your hand + slide 8 in DSN		Initial			
Preliminary Design Review meeting	**all documents needed collected in one place accessible via a single URL link**		**completed Internal Review**			**Exit to Final Design with meeting minutes 'approval' or Skip review and proceed to Final Design with L2 / CCB OK**
Prototype Yield	slide 8 in DSN			Initial	Update	if applicable, include failure analysis, pareto chart, actions to fix
Prototype - Rev 1 or more	slide 8 in DSN			Update	Update	if needed
Hazard Analysis				Initial	Update and complete	if needed
Final Design Review meeting	**all documents needed collected in one place accessible via a single URL link**			**completed External Review**		**Exit to Production Readiness with meeting minutes 'approval'. All instrumentation MUST have an external Final Design Review.**
Production Readiness Review meeting	**all documents needed collected in one place accessible via a single URL link**				**completed Internal review**	**Exit to Production / Procurement with meeting minutes 'approval'**

ERD = Engineering Requirements Document; CMD = Configuration Management Document; DSN = Design Status Notes; IDD = Interface Definition Document; See Section 7.4

Figure 6: The IceCube Upgrade subsystem design flow matrix built on the System Engineering documentation for the Baseline Library and a series of engineering reviews.

The required steps for each item to proceed through the checkpoints from project design, production, and deployment stages are detailed. These gateways are controlled by the project office and the technical and change control boards.

3.2 Development Budget and Funding Sources

The IceCube Upgrade project is governed by and is managed in accordance to the requirements of the National Science Foundation Research Infrastructure Guide (RIG) (5). Per guidelines in the RIG, the scope of this project includes support for design activities of all major subsystems: drill, sensors, cables, calibration hardware, and computing through project life cycle up to the operation phase. Funding for these activities is integral to the overall project funding profile (see Section 4.6). In addition to NSF funding to support development activities, in-kind contributions from U.S. institutions and foreign funding from Japan, Germany, and South Korea also support these crucial facets of the project.

4 Construction Project Definition

4.1 Summary of Total Project Definition

The baseline IceCube Upgrade physical deliverables are approximately 700 optical sensors, and associated calibration devices, deployed along seven instrumentation cables in the deep ice along with the necessary firmware, software, and computing systems required to bring data from these devices into analyzable form in the Northern Hemisphere data warehouse of the IceCube Neutrino Observatory. To realize the deployment of such an array deep in the ice, a drill capable of producing 2600-m deep holes in the glacial ice is required. The total project scope along with scope options is described in (6).

4.2 Work Breakdown Structure (WBS)

The IceCube Upgrade project uses a detailed work breakdown structure (WBS) as the basis for both scheduling and costing. The IceCube Upgrade WBS is divided into six major elements that are detailed to Level 4 in the WBS dictionary. The WBS at Level 3 is graphically shown in Figure 7 below.

4.3 WBS Dictionary

Figure 7 shows the IceCube WBS structure to level 3. The WBS dictionary to all levels can be found in Reference (7).

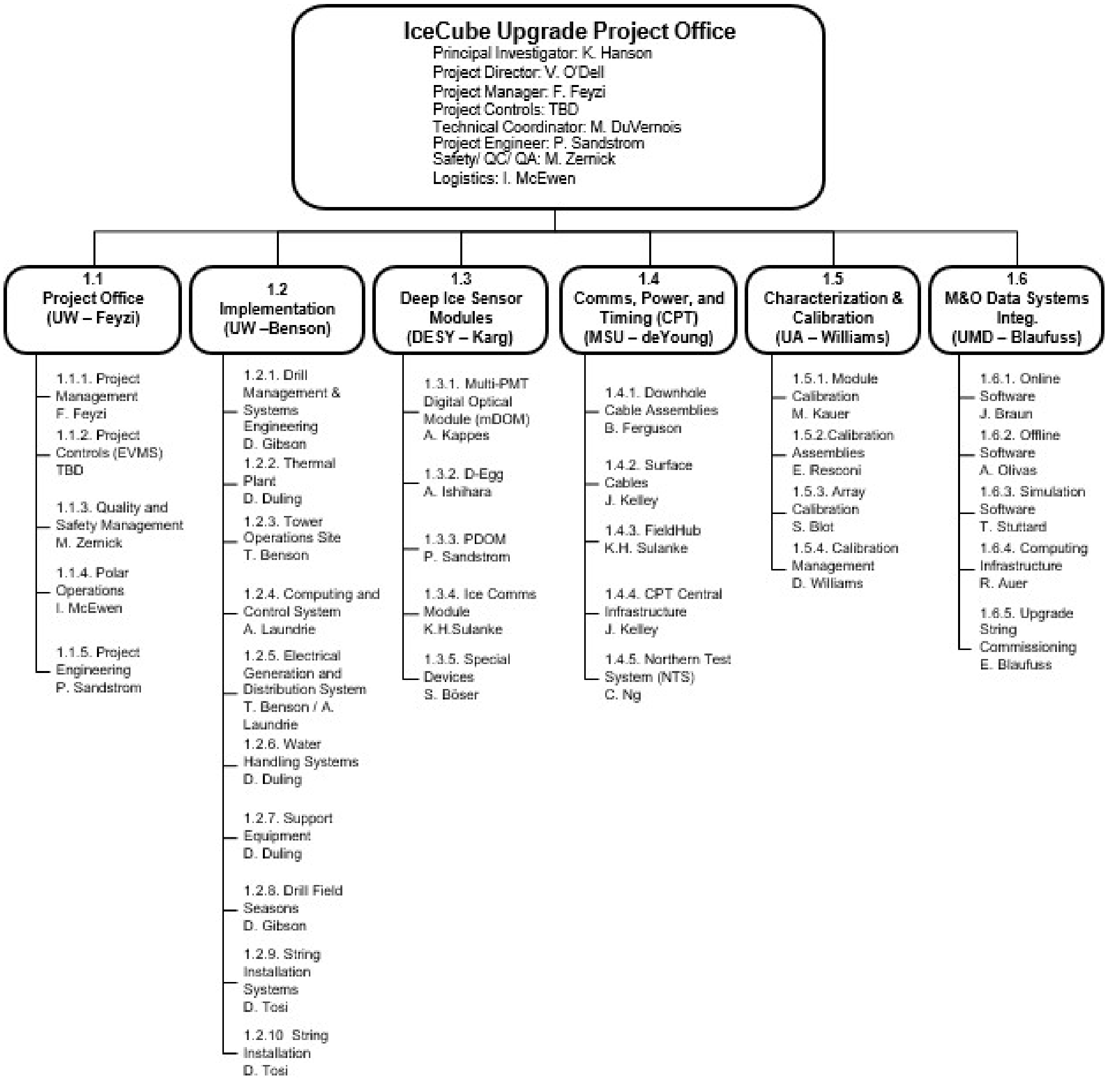


Figure 7: The Work Breakdown Structure to level 3.

4.4 Scope Management Plan and Scope Contingency

The Upgrade Project has identified the baseline scope and scope contingency, which can be found in the *Scope Management Plan for the IceCube Upgrade* (6). Scope contingency is carried by the project to either save money or schedule, and additional scope is proposed in the case that the project is on track to successfully complete without spending all funding or schedule contingency. All scope contingency usage, whether increased or decreased scope, is agreed upon in advance with the NSF program managers.

4.5 Cost Estimating Plan, Executive Summary, and Baseline Budget

Budget planning was performed bottom-up and documented in the Projects Basis of Estimates. The costs were entered into the Projects Resource Loaded Schedule. Labor, materials, equipment, and travel estimates were made based on the tasks in the schedule provided by L2 and L3 WBS managers. Current labor rates as well as up-to-date fringe and overhead rates are available from the NSF-supported institutions.

Details of cost estimation methodology are found in the Cost Estimating Plan (8). Assumptions in the cost estimation are captured in the Key Assumptions Document (9).

The overall costs by WBS L2 is given in Table 2.

L2 WBS	**Base Cost To Go (PY5-PY8)**
1.1 Project Office	$5,485,228
1.2 Implementation	$7,993,431
1.3 Deep Ice Sensor Modules	$375,710
1.4 Comms, Power, and Timing	$1,177,605
1.5 Characterization & Calibration	$616,605
1.6M&O Data Systems Integration	$1,018,365
Projected total	$16.719,946
Contingency (EU+Discrete Risks)	$4,761,183 (28.5%)
Total Base + Contingency	**$21,481,128**

Table 2: Overview of Project Cost

4.6 Budget Contingency

Contingency has been estimated as arising from one of two sources: (a) identified risks (threats or opportunities) and (b) cost uncertainties related to the maturity level of cost estimate. Estimates for both sources were constructed using input from subject matter experts, in general with expertise from the IceCube Gen1 Project. Cost uncertainties (b) are documented in the Upgrade Project's Basis of Estimates using project-wide methodology laid out in the *IceCube Upgrade Cost Estimating Plan* (8) and the *IceCube Upgrade Key Assumptions Document* (9).

Risks, and their resulting cost and schedule impacts, are identified and estimated by subject matter experts as discussed in Chapter 6. The derivation of the contingency contribution from sources in category (a) above is captured in the *IceCube Upgrade Risk Register* (11) and managed per the *IceCube Upgrade Risk Management Plan* (12).

4.7 Cost Book, Cost Model Data Set, and Basis of Estimate

The Project Cost Book can be found here (13) and consists of all costs by WBS areas of the project. The Basis of Estimates that document the costs can be found here (14).

4.8 Funding Profile

	PY5	PY6	PY7	PY8	TOTAL
Baseline	$5,309,870	$4,295,967	$4,336,434	$2,777,675	$16,719,946
Contingency	$820,604	$1,816,903	$1,828,325	$295,351	$4,761,183
Total (PY5-PY8)	$6,130,474	$6,112,870	$6,164,758	$3,073,026	$21,481,128
% Contingency	15.5%	42.3%	42.2%	10.6%	28.5%

Table 3 Anticipated total funding profile and contingency allocation

4.9 Baseline Schedule Basis Document and Integrated Schedule

The project master schedule baseline was assembled from individual WBS L2 schedules. The schedule comprises NSF and non-NSF deliverables which together form the full project scope. The schedule encompasses all activities and deliverables needed to complete the project scope, as described by the Project's WBS hierarchy, and is technically driven, i.e. the baseline schedule does not contain any schedule contingency. The schedule is fully resource loaded.

Scheduling tools are used for planning a detailed schedule for all years of the project (15). They are also used to track percent complete by task level and subsequent progress against the plan. The project office maintains control of the master schedule and updates actual progress reported by L2 managers every month as part of the NSF reporting cycle.

The schedule includes effort for system integration, commissioning, acceptance, and transition to the ongoing Maintenance and Operations program for the IceCube Neutrino Observatory. A high-level table of the Level 1 milestones is shown in Table 4.

Date	Milestone
2022 Q4	mDOM Production Readiness Reviews

2024 Q3	Sensors (D-Eggs/mDOMs) for first two strings shipped
2025 Q1	9 Firn Holes Drilled, Covered and Flagged
2025 Q3	Final sensors (D-Eggs/mDOMs) shipped
2025 Q3	Drill Readiness Review (PSL)
2025 Q4	EHWD System Ready for Drilling
2026 Q1	Drilling & Installation Complete
2026 Q2	Detector complete and handed off to M&O

Table 4 High Level Project Milestones, ordered by date.

4.10 Schedule Contingency

The best estimate duration for each activity is entered into the schedule, without any padding of the estimate to account for duration uncertainties. In general, the critical path runs through the logistics and on-ice tasks; the project is responsible for ensuring that the project's off-ice deliverables have sufficient contingency before entering the USAP logistics chain. This is done by monitoring critical "ready to ship" milestones at least monthly. Schedule float is determined by the time between a deliverable ready to ship and when it must ship according to the logistics plan and the "Required On Site" dates. This information is contained in the *IceCube Upgrade Master Cargo Spreadsheet* (16) which is used in communicating our plans and needs with USAP.

4.11 Project Year Detail Planning Process

At the end of each project year, detail planning for the next project year is conducted. Actual costs for prior year, the detail plan for upcoming year and projected cost for future years are compared with obligated and anticipated funds in order to plan the upcoming year work. Plans for the upcoming year are adjusted to fit within the project obligated amount.

In addition, remaining risks and remaining cost uncertainty are compared with remaining contingency. At the time of detail planning, any change in contingency, whether it results in a decrease or increase in contingency, is evaluated and communicated to NSF. The process for contingency use and approval follows the provisions of the Cooperative Agreement and the Research Infrastructure Guide.

5 Staffing Plan

This section includes key IceCube Upgrade project office staff and their responsibilities and qualifications.

5.1 Hiring and Staff Transition Plan

5.1.1 Key Personnel

5.1.1.1 Principal Investigator

The Principal Investigator (PI) is responsible for the scientific, technical, and budgetary aspects of the award and is ultimately responsible for all aspects of successfully executing the project, including ensuring that it meets its scientific and technical objectives and interfacing with NSF and the broader science community.

5.1.1.2 Project Director

The Project Director is responsible for the day-to-day management of the project and, along with the Principal Investigator, is the primary contact to the NSF. The Project Director is responsible for completing the project within the budget and schedule agreed upon by NSF. The PD delegates the responsibility of running the project to the PM (see Section 2.4), but tracks the progress of the project, reports the progress to the NSF, and has authority to bring in additional resources or reallocate resources as needed for the successful execution of the project.

The PD has expertise in NSF Project Management guidelines and in the principles of Project Management in general, including managing scope, cost, schedule, risk, change control, quality and safety, and other important facets of project management. Vivian O'Dell was appointed PD in December, 2021, and has experience in NSF and DOE project management as well as PMP certification.

5.1.1.3 Project Manager

The PM is the central figure coordinating and making decisions on all technical and managerial aspects of the project execution. The complexity and risks associated with this project require the following qualifications from this individual: experience as PM or deputy with a construction project of similar scale and similar technical background; engineering or scientific background with advanced degree; familiarity with NSF and/or DOE project organization and technical progression; and experience working in a project environment distributed across multiple institutions and working with multiple funding sources, possibly international.

Farshid Feyzi was designated as the Upgrade project manager effective July 1, 2019. Feyzi has extensive experience managing large instrumentation projects funded by DOE and NSF with multiple national and international collaborators, including overseeing the construction of the IceCube Gen1 hot-water drill.

5.1.2 Project Team

5.1.2.1 Project Controls Manager

The project is searching for a full time project controls manager. Qualifications for this position include experience with project planning, budgets, and schedules; resource coordination; MoU and subaward management and tracking; performance tracking; and knowledge of earned value management. Temporarily the position is being split between a Financial Accountant (Barb Witt) and a Project Controls Specialist (see below).

5.1.2.2 Technical Coordinator

Michael DuVernois is the technical coordinator. He has held scientific and technical leadership roles in both NSF- and NASA-supported projects. These include the Pierre Auger Observatory, the High-Altitude Water Cherenkov (HAWC) Telescope, the ANITA, HEAT, CREAM, and CREST balloon payloads, and High Energy Telescope (HET) on the Ulysses spacecraft. He has led fieldwork at McMurdo, the South Pole, high-altitude sites in Mexico and Chile, and remote sites in Argentina, the US, and Canada.

5.1.2.3 Project Engineer

Perry Sandstrom serves as project engineer. He has been a member of the IceCube project for many decades, serving in a similar capacity during the construction and operations phases.

5.1.2.4 Logistics Coordinator

Ian McEwen serves as logistics coordinator, providing logistics support and acting as liaison to the Antarctic Support Contractor. He has been a member of South Pole management team and has extensive and direct experience applicable to the project.

5.1.2.5 Safety and Quality Manager

Michael Zernick has been hired as the safety and quality manager. Zernick worked as safety officer during IceCube construction.

5.1.2.6 Project Controls Specialist

The project controls specialist must be qualified in project planning, scheduling, performance tracking, and knowledge of earned value management. Currently we have contracted with an expert in our current project tools (SmartSheets), Jim Lowe, who has expertise in the project management tools, in the overall schedule, and in earned value management. He holds an MBA, and has more than 18 years of experience in project management. His principal duties are: development and maintenance of the master schedule and cost database, communication with cost account managers to track project progress, generation of earned value metrics for project monthly reports, and assisting with cost and schedule planning.

The project is in the process of migrating from the current project tools (i.e. SmartSheets) to enterprise level tools (i.e. Primavera P6, Deltek Acumen) in order to build a system that is more maintainable, performant, and interoperates cleanly with the Antarctic Services Contractor. This migration will be completed and commissioned by Fall, 2022. At this point we will also transition our controls specialist to a contractor who has expertise in these tools.

6 Risk and Opportunity Management

A risk is defined as a future event that may impact the cost, schedule, technical scope, quality, scientific objectives, or other aspects of the project. Risks are further divided into ***threats*** and ***opportunities***, where threats have negative impacts to the project and opportunities have positive impacts (e.g. lower cost, higher quality, etc.). The goal in risk management is to identify risks and develop strategies to reduce threats and amplify opportunities.

6.1 Risk Management Plan

The IceCube Upgrade Risk Management Plan is described in a separate document *IceCube Upgrade Risk Management Plan*. (12). This section briefly summarizes some key points from the document.

6.1.1 Roles and Responsibilities

The IceCube Upgrade Project does not have a dedicated Risk Manager, therefore the duties that would typically be undertaken by a Risk Manager are shared between members of the Project Office. These tasks include establishing the project's processes and systems for identifying risks, documenting them, analyzing their probabilities and impacts, developing mitigations and response plans, and monitoring them. They are responsible for maintaining the risk information in the risk register and performing a project-wide risk analysis using Monte Carlo or other techniques to aggregate cost and schedule impacts for the entire project. They also coordinate the preparation of risk reports to the combined Risk Management and Change Control Board and project oversight bodies. The exact breakdown of the duties is listed below.

Project Director (PD)

- Ultimately responsible for all aspects of project risk management
- Establishes the project's processes and systems for identifying risks, documenting them, and analyzing their probabilities and impacts
- Reports on risks to oversight bodies

Project Manager (PM)

- Implements the project's risk processes and systems
- Coordinates with the project team, the technical coordinator, and the quality manager to hold regular risk workshops
- Assigns a **Risk Owner** to each risk (see below)

Technical Coordinator (TC)

- Assists the PM and the project team in all aspects of risk management.
- Takes responsibility in documenting mitigation and response plans for risks, and monitoring them
- Maintains the risk and mitigation information in the risk register

Quality Manager (QM)

- Tracks risks and risk triggers
- Works with Risk Owners to ensure consistency of risk assumptions across the project
- Alerts CCB to upcoming risks / risk triggers

Project Controls (PC)

- Performs project-wide risk analysis using Monte Carlo techniques to aggregate cost and schedule impacts for the entire project. (This role is temporarily filled by the PD until the Project Controls team is firmly onboard).

Risk Owner

- Each risk has a risk owner, who is typically the subject matter expert (SME) who identified the risk. The risk owner helps to analyze the risk and develops and executes mitigation and response plans. In many cases this is the cognizant L2, or in some cases, a L3 SME.

Combined Change Control and Risk Management Board

The Combined Change Control and Risk Management Board is chaired by the Project Manager and consists of the PM, PD, TC, PC, the Project Engineer, the Project Safety and QA/QC officer, the logistics coordinator, the Associate Director for Science and Instrumentation, and the WBS L2 managers. Additional staff may be invited as needed for specific topics. The board meets weekly, while risks are reviewed at least quarterly.

L2 Managers and Cost Account Managers **(CAMs)**

WBS Level 2 Managers and CAMs are responsible for working with their teams and other stakeholders to: identify risks to their subproject; assess their probabilities and impacts; and develop and execute risk mitigation and response plans. L2 managers and CAMs report on risk-related issues to the Combined Change Control and Risk Management Board.

National Science Foundation

The National Science Foundation Program Officers ensure that the Project has established an appropriate risk management process, monitors its implementation, and affirms decisions of the Change Control and Risk Management Board. The NSF approves the use of risk contingency when the amount exceeds the spending authority of the PM.

Table 5 shows the risk management responsibility assignment matrix.

Process / Responsible	Project Director	Project Manager	Technical Coordinator	Project Safety/QA/QC Officer	L2 or Control Account Manager	Project Controls	Risk Owner	NSF
Plan Risk Management	Performs	Contributes	Contributes	Contributes	Contributes	-	Contributes	Reviews
Identify Risks	Accountable	Contributes	Contributes	Contributes	Contributes	-	Contributes	Reviews
Perform Qualitative Risk Analysis	Accountable	Contributes	Contributes	Contributes	Contributes	-	Performs	Reviews
Perform Quantitative Risk Analysis	Accountable	Contributes	Contributes	Contributes	Contributes	Performs	Contributes	Reviews
Plan Risk Responses	Accountable	Contributes	Contributes	Contributes	Performs	-	Performs	Reviews
Monitor and Control Risks	Accountable	Contributes	Performs	Performs	Performs	-	Performs	Reviews

Table 5 Risk Responsibility Matrix for the IceCube Upgrade Project.

6.2 Risk Register

The IceCube Upgrade Project's Risk Register is a controlled document, stored as an excel file in Sharepoint (11). The Risk Register contains risks characterized by:

- Unique risk ID and risk name;
- A summary description of the risk;
- Risk type, risk area (RBS), risk owner, and WBS area the risk pertains to;
- Risk status, start and end date period of risk validity, and conditions for closing the risk;
- Risk probability and technical, cost, and schedule impacts (and the basis for these estimates);
- Activities in the Resource Loaded Schedule that are impacted by the risk, and the risk trigger or causal factors;
- Risk mitigations in the base plan, and risk responses to be executed if the risk occurs; and
- Miscellaneous notes and links to supporting information.

The risk register determines the risk rankings based on the project's risk ranking matrix and the risk probability and impact values.

The categorization of the Risk Impact as agreed upon between NSF and the Project are shown in Table 4.

	Very Low	Low	Moderate	High	Very High
Technical Impact	No impact	Somewhat substandard	Significantly substandard	Extremely substandard	Scientific objectives in jeopardy
Cost Impact	Less than $10k	$10k - $50k	$50k - $250k	$250k - $1M	> $1M
Schedule Impact	Less than 1 week	1 month	3 months	6 months	Greater than 6 months
Scope Impact	Scope decreases barely noticeable	Minor areas of scope affected	Major areas of scope affected	Scope reduction unacceptable to sponsor	Project item is effectively useless
Quality / Performance Impact	Quality / performance degradation barely noticeable	Only very demanding applications are affected	Quality / performance reduction requires sponsor approval	Quality / performance degradation unacceptable to sponsor	Project item is effectively useless

Table 6 NSF / Project agreed upon definitions of impact scores with respect to cost or schedule.

6.3 Contingency Management

The PM manages risk contingency funds subject to the established change control process and the approval requirements. The PM is responsible for reporting on matters of risk to the Project oversight bodies. When risk opportunities occur and budget contingency is gained the PM will recover the funds to the project wide contingency pool. Any use of contingency funds must be associated with specific risks and documented in the change control documentation.

The project maintains a ’liens’ list of possible risk exposures to track the expected use of contingency funds. This list is used in making decisions about possible use of scope contingency to ensure the Project can be completed on schedule and within budget.

7 System Engineering and Configuration Control

7.1 System Engineering Plan

The primary scope of the IceCube Upgrade system engineering team 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 simulations.

Design documentation of the detector instrumentation uses four main templates to describe configuration items (“items”) at all levels, from the complete detector down to all its constituent sub-components. This provides a consistent format for capture and review of system dependencies, design status, requirements, and interfaces. The "Design Baseline Library" is the central cloud-based repository where these documents are created, modified and reviewed. Periodic technical reviews and change control operate on content in the Design baseline Library on an item-by-item basis. A separate "production" library is reserved for permanent archiving of fabrication drawings for "as-built" items and for any revisions to production items. A description of the templates used to establish the design baseline and their use is described in the **Design Documentation System** (17)**.**

7.2 Systems Engineering Requirements

Requirements are established on an item-by-item basis through an Engineering Requirements Document (ERD) spreadsheet for each item. There are four types of requirements: Environmental, Functional, Performance, and Interface. The spreadsheet captures details regarding rationales, validation (by subject matter experts), verification class (e.g., inspection, analysis, or test) and a link to appropriate evidence verifying that the item, as designed, meets each requirement. The ERD's for key items such as instrument packages and cables are subject to formal change control after the requirements are validated. This ensures a review of possible system-level conflicts or opportunities that may arise from changes made to key items.

7.3 Interface Management Plan

Interfaces are described using a common "Interface Definition Document" (IDD) Template. There are four types of interfaces defined for any item (electrical, mechanical, optical). All interfaces between items are defined in each item's IDD with detail sufficient to create the mating side on the "adjacent" item. The IDD for each item links to the IDD for each item that it interfaces with, providing a convenient cross-check of interface compatibility between items created by different designers or institutions. Each interface is also captured as a requirement in the ERD of the items involved, meaning that interfaces for key items are under change control and interfaces for all items are subject to design verification.

7.4 Quality Assurance/Quality Control Plans

Quality systems for the IceCube Upgrade project are a vital component in the delivery of successful hot-water drilling and instrumentation deployment. A quality manager, who has the technical skills and background to address the issues in the context of the IceCube Upgrade, manages the effort. Quality systems, as applied to the IceCube Upgrade 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 Upgrade team, allowing for a seamless approach and the institutionalization of quality into the project. The details of the quality systems program is documented in *the IceCube Upgrade Quality Plan* (18) .

The IceCube Upgrade 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.

8 Configuration Control

8.1 Configuration Control Plan

Configuration control of the IceCube Upgrade 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 Project's Configuration Management Plan (CMP) can be found in (19). This plan ensures that the schedule, budget, and performance impacts of changes to the baselines are tracked and recorded. It also 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 others who have an interest
- 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

8.2 Change Control Plan

The Project's Change Control system is also described in the Configuration Management Plan. Change Control is applied to technical and programmatic changes, where programmatic changes includes cost, schedule, scope, and science objectives. All proposed changes are documented and logged in the Project's Change Request (CR) log, All controlled documents must be signed off on by the relevant parties, and ultimately by the Project Manager. Changes in cost, schedule, scope, and/or science objectives must be approved by the Combined Risk Management and Change Control Board and by the NSF, where required. All changes are reported to the NSF.

8.3 Document Control Plan

The baseline design content is stored in a SharePoint library 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 be moved into controlled and approved documents when finalized. The transition from uncontrolled to controlled documentation is managed by the Quality Assurance Engineer with approvals from the Technical Board and internal engineering reviews.

System-level design engineering is handled using four defined document types for each configuration item ("item" is used as a shorthand). Items are stored hierarchically from the entire detector level down to all DOM assemblies and low-level hardware items such as cable assemblies, electronics boards, and pressure housings. Each item is specified by the following documents:

- Configuration Management Document (CMD); Establishes the hierarchy and production dependencies of configuration items and all the constituent sub-items and parts required to produce the item.
- Engineering Requirements Document (ERD): Names each of an item's requirements, the rationales for each, the date of validation of the requirement by subject matter experts, whether the requirement is to be verified by test, inspection or analysis, and a link to verification data ensuring that the item, as produced, meets each requirement. Requirements are of four types: environmental, functional, performance, and interface.
- Interface Definition Document (IDD): Details the interfaces (electrical, mechanical, optical, etc.) between an item and any other items. Links to the IDDs of adjacent items are provided here for easy comparison of both sides of each interface. All interfaces are also verified and controlled as a type of requirement.
- Design Status and Notes (DSN): This document shows the status of the design, photos of parts, links to developmental drawings and schematics, as well as links to manufacturer's web pages and internal talks. The DSN forms an evolving record of the design process for an item from conception through final production.

This configuration management system was built during the first year of the project and is well-populated with the systems and subsystems of WBS 1.3, 1.4, 1.5, and 1.6. The drill documentation is handled separately as the requirement of broad, international editing of the documents are not required for the drill. These documents are owned by the respective L3 (or lower) managers until the documents are controlled via successful review.

The engineering requirements have been derived from the higher-level science requirements via the science-engineering requirements flow-down matrix filtered through the hardware experiences from the Gen1 IceCube construction. This is especially important for the extreme environment of the deep, cold glacial ice of South Pole.

9 Acquisitions

9.1 Acquisition Plans

This section describes acquisition plans, processes, subawards, and contracting strategy, including evolving technologies and assumptions for design definition. It provides a time-based list of acquisitions and procurement actions.

9.1.1 Subcontract Management

Each participating U.S. institution has a subaward with UW–Madison (the host institution) that defines the cost, schedule, and performance requirements for the planned participation. The budget provides funds to UW–Madison, which then distributes them through subaward agreements to Michigan State University, Pennsylvania State University, the University of Maryland at College Park, and the University of Alabama at Tuscaloosa. In general, funds are divided such that the institution responsible intellectually for a specific deliverable, *e.g.*, a piece of equipment, is also responsible monetarily for it, and that institution's purchasing system provides the infrastructure for those purchases, ensuring they adhere to federal procurement standards.

The project controls manager is responsible for developing and maintaining the subawards with support from the institutional legal representatives.

10 Project Management Controls

10.1 Project Management Control Plan

A project management control system (PMCS) is maintained to track the budget, schedule, and resources necessary to complete the IceCube Upgrade. The PMCS contains the costs and schedule as well as the scope, resource allocations, work descriptions, the basis of estimates, and the activity-based risk assessment evaluation. The PMCS maintains data in the base year value as well as the then-year costs. The IceCube Upgrade project office has defined consistent cost and schedule baselines built on the foundation of a well-developed work breakdown structure (WBS) for development, implementation and commissioning of the IceCube Upgrade. The schedules include clearly defined milestones against which progress of major tasks is judged. A formal project management control system (PMCS) provides a wide variety of management products for effectively monitoring progress and assessing project health.

10.2 Earned Value Management System

The project office began implementing effective cost and schedule tracking tools, analyzing performance, and including this data in monthly reports March 2019. These reports include monthly comparisons of actual versus planned resource use in the categories of total cost, labor cost, non-labor cost, and full time equivalent (FTE) staff utilization. An earned value management system (EVMS) is implemented to comprehensively plan work and objectively assess cost and schedule performance. Cost and schedule data are collected at WBS Level 4 or lower and reports are generated for the total project, WBS Level 2, and WBS Level 3 on a quarterly basis. Summary reports are posted on the web to provide managers outside of UW–Madison with the means to follow the overall progress of the project.

Level 3 managers identify and mitigate risks associated with their tasks and take appropriate corrective action if a task falls behind schedule, consumes more resources than planned, or encounters technical difficulties. They communicate with Level 2 managers and project office staff on a continual basis and provide written quarterly status reports to their respective Level 2 managers.

Monthly status reports include cost, schedule, and technical progress for each active Level 4 WBS element. Data for these reports are generated by technical and financial managers at each participant institution, submitted via the internet, reviewed and quality controlled by project office staff, and input to a formal project management system. The updated project management system will be used to generate a wide variety of recurring reports for managers at all levels of the collaboration that are timely, internally consistent, and accurate.

Level 3 managers are responsible for continually estimating remaining work on tasks, iterating on the schedule, budget, and requirements for an optimum balance, and communicating results to the project stakeholders. When cost or schedule problems arise, project office personnel will work with the appropriate Level 3 manager, or subcontractor, to correct the problem using the resources currently allocated for the task.

Level 2 managers approve plans, manage resources, and oversee all aspects of subsystem (Level 3) development within their areas of responsibility. They participate in weekly status meetings with the PM and project office staff, serve as primary members of the change control board, and provide written status inputs for monthly reports to the NSF.

If current resources are not sufficient, the Level 2 manager will make a recommendation to reduce the scope of the task, reallocate resources from another task, or apply previously unallocated management reserve funds. If scope is reduced, the PI advises the PM as to whether the proposed change adversely impacts the scientific objectives of the project.

10.3 Financial and Business Controls

Administrative, accounting, IT, and human resources support are provided by the Wisconsin IceCube Particle Astrophysics Center of UW–Madison. The IceCube Upgrade project office is a beneficiary of the robust UW–Madison human resources system and follows its personnel policies and procedures, which include strategies to recruit, develop, and retain a diverse workforce. UW–Madison is committed to hiring the right talent to ensure that the university continues to be a world-class institution of higher education. The university's goal is to provide opportunities for talented people from all backgrounds to help us maintain a highly productive, welcoming, empowering, and inclusive community. UW–Madison encourages women, minorities, veterans, and people with disabilities to apply for our vacancies. WIPAC will continue to strive to attract outstanding candidates from underrepresented groups.

The IceCube Upgrade will follow all generally accepted accounting principles (GAAP) and Code of Federal Regulations (CFR) Part 200 "Uniform Administrative Requirements, Cost Principles, and Audit Requirements for Federal Awards" as well as comply with all statutory and regulatory requirements. IceCube also adheres to UW–Madison financial policies and procedures, which are designed to ensure compliance. As a recipient of federal government funds, the IceCube Upgrade is subject to audit by federal agencies in addition to its outside independent auditors. As described in section 9.1, the PMCS system will be integrated with the WIPAC accounting system in such a way as to support earned value management and to provide timely performance reports of variances with respect to the baseline project plan. Detailed financial, accounting, and other policies may be found online on UW–Madison website.

11 Site, Environment and Logistics

11.1 Site Selection

The IceCube Upgrade instrumentation will be installed within the existing envelope of the IceCube neutrino detector at the South Pole. The South Pole environment presents an obvious set of design challenges to overcome; however, the successful completion of the IceCube Neutrino Observatory provides a framework to follow.

The IceCube Upgrade will work closely with ASC to mitigate the potential impacts of the extreme cold and low humidity at the South Pole. IceCube Upgrade project management is mindful of the unique environment in the Antarctic and will continue to advise all project participants to follow USAP policies and to work in a proper and safe manner.

11.2 Environmental Aspects

The IceCube Upgrade Safety Program is originally based on the NASA Safety Manual and incorporates much of the referenced documentation (OSHA and other standards) referenced by the NASA Manual. This Program is intended to be consistent with the ASC Standard Operating Procedures (SOP) and their referenced documents. For details on the Program, see the *IceCube Upgrade Safety Manual* (20).

This plan is mandated by, and meets the requirements, regulations, and the Health and Safety Policy of, the NSF/OPP Office of Polar Environmental Safety and Health (PESH); the Antarctic Conservation Act, as amended, 16 U.S.C. § 2401 et seq. (ACA), which implements the Antarctic Treaty and the Protocol on Environmental Protection to the Antarctic Treaty (Protocol); regulations on environmental impact assessment (e.g., 45 CFR 640 and 45 CFR 641); Master Permit requirements; applicable U.S. Occupational Safety and Health Administration (OSHA) regulations; and other applicable U.S. regulations.

The IceCube Upgrade will follow the guidance as stated in the Comprehensive Environmental Evaluation (CEE) that was prepared by the director of the Office of Polar Programs in 2004 for the original IceCube project. The IceCube Upgrade will work with ASC to compile an intermediate environmental evaluation (IEE) which will branch off from the IceCube CEE and will be focused on Upgrade activities only.

11.3 Logistics

The primary logistical challenges of the project revolve around deployment of equipment and people to the South Pole and the operation of that equipment in support of deploying IceCube Upgrade instrumentation. In addition, logistical challenges are created by the multisite production strategy for deep-ice sensors.

The IceCube Upgrade Implementation Manager, formerly ASC's South Pole Operations Manager, is managing cargo movement and collaborating with ASC on field planning. He has extensive experience with the USAP Transportation and Logistics and is well versed in supporting construction/field science at the South Pole. Support requirements will be detailed in the annual submission of the Support Information Package (SIP) each March. The yearly plan will be finalized in September by IceCube Upgrade's concurrence with the ASC-generated research support plan (RSP).

IceCube Upgrade will communicate and coordinate with internal and external agencies to ensure the smooth and timely shipment of personnel and equipment to the South Pole for successful startup of activities and work related to the main drilling season in 2025-2026. IceCube Upgrade will provide other detailed support for ongoing activities to enhance delivery of equipment and the smooth transition of personnel while acting as the central point of contact for quick resolution of logistics discrepancies to a ensure a successful drilling season at the South Pole.

12 Cyber Infrastructure

12.1 Cyber Security Plan

Computing for the IceCube Upgrade Project is supported through the ongoing Maintenance and Operations support for the IceCube Neutrino Observatory (ICNO). The information security program was developed and implemented and is maintained to provide an organizational environment to ensure appropriate information security and acceptable levels of information-related risk. This program entails ongoing activities to address relevant policies and procedures, technology and mitigation, and training and awareness.

A risk-based approach is used to secure ICNO systems. Information systems are evaluated in terms of sensitivity of information and availability requirements of the asset. Security controls are selected and implemented to reduce risk to acceptable levels. In addition, we inherit security controls from ASC for information systems at the South Pole station and UW security controls for information systems operated at UW--Madison.

12.1.1 Asset Protection

The IceCube detector is the single most valuable asset for the ICNO. As such, the primary concern is securing and maintaining the operational capability of the detector as well as day-to-day operations and data collection. This is followed closely by the data collected by the detector.

Access to the detector and its subsystems is restricted to IceCube personnel with a need to work on the detector itself. Remote access is limited to a small set of machines in the Northern Hemisphere. These machines are protected by ICNO-operated, network-based firewalls in the north and south. In addition, any access to the systems at the station must also pass through network firewalls and other security systems operated by ASC. Changes to station security controls are coordinated with ASC via the annual support information package process.

The data collected by the detector is the foundation of all science output. To avoid missing unique events, it is critical to collect and preserve these observational data as they are created. To reduce the likelihood of data loss, two copies of the raw data are written to disk at the Pole. These disks are shipped to UW--Madison during the austral summer. A filtered copy is written to disk at the Pole and a reduced data set, about 10%, is transferred north via satellite daily. The reduced data set is replicated to DESY in Germany daily when it reaches the north. The raw data are read from disk when they arrive at UW--Madison, where they are then replicated to NERSC. One copy is also physically stored offline in Madison.

The science data collected and maintained are not sensitive or regulated, and indeed are eventually published. In the course of operating the center, other information is generated and stored. This information is intended for internal use only. We only generate and retain the data necessary for executing administrative processes. This information is stored separately from all computing and research systems and uses normal IT controls to ensure the confidentiality of the data.

Where widely accepted security practices and standards are not workable, compensating controls are adopted to maintain an appropriate security level. For example, stateful, network-based firewalls have unacceptable performance impacts on large research data flows, and therefore data moving machines are frequently placed outside of such protections. To mitigate the risk, a ScienceDMZ architecture (21) is applied as a compensating control to apply equivalent protections.

12.1.2 Cybersecurity Standards and Adherence

ICNO follows standards, practices, and guidance from TructedCI (22) that are consistent with operations of NSF major facilities as well as UW–Madison campus policies and ASC policies at the station. ICNO participates in and contributes to NSF security communities via TrustedCI and the large facilities security team.

12.1.3 Cybersecurity Breach Reporting Policy

ICNO maintains an incident response plan which includes escalation and notification procedures. To summarize, breaches will be reported to the appropriate parties in a timely manner in accordance with the severity. For incidents with a scope beyond the home institution, external incident response staff will be engaged immediately. For breaches that may impact resources at the South Pole station, ASC and NSF program officers will be notified immediately. Significant breaches will be reported to NSF program officers within 24 hours. UW security personnel will be notified in a manner consistent with UW reporting policy.

ICNO maintains a list of security contacts for all collaborating institutions to facilitate notifications within the collaboration.

12.2 Code Development Plan

All software and firmware for the IceCube Upgrade is maintained and version controlled using industry-standard tools, primarily git. Access is controlled to the primary GitHub workspace; most instrumentation software / firmware repositories are private to the collaboration. Best practices are followed around issues and releases, with issues documented in issue-tracking systems, resolved issues documented in change logs, and repositories tagged with release versions. Key interfaces are documented for each subsystem to ensure interoperability, and subsystem integration is performed using existing test systems to exercise data flows during project development.

12.3 Data Management Plan

The IceCube Upgrade adds a negligible amount of extra data to the ICNO, and the data is readout and merged with the full IceCube Neutrino Observatory into one dataset. In the following sections, we describe the overall ICNO data management plan.

12.3.1 Research products and types of data

The process of turning IceCube's sensor data that is recorded at the South Pole into scientific results makes use of several intermediate internal data types. Over 300TB/year of raw data are produced, which are filtered in real time at the South Pole and reduced to a 36 TB/year stream that is transferred north daily via satellite. Once in the UW–Madison data center, the filtered data are further processed, first into a general purpose data set (Level 2) and then into high-level analysis- topical selected data sets (Level 3). Further data processing uses high-quality, resource-intensive reconstruction algorithms to produce science-ready data sets. The reconstructed data are further reduced into much smaller data sets that contain only the time, direction, energy, and quality information for each event. These reconstructed event sets are used in specific physics analyses and are one of the value-added data products publicly released by IceCube.

In order to extract science information from the collected data, it is necessary to produce an adequate amount of simulation data with accurate description of the underlying physics (e.g., cosmic-ray-induced and neutrino-induced events) and the detector response, including the ice op- tical properties. Simulation files at detector response level are equivalent to the experimental raw data and are subsequently filtered and processed exactly the same as the experimental data.

12.3.2 Data Products

Event data sets (few GB/year): IceCube releases event reconstruction information for the most interesting sets of data (e.g., astrophysical neutrinos) after separating events from the background of cosmic-ray muons. These value-added data sets contain the most useful information for scientists' analyses. These data sets contain a description of the data and an event list in ASCII format, with a table of reconstructed variables such as time, direction, energy, and quality information. Additionally, we are planning on publishing the data available on IceCube's website as part of NASA's HEASARC service (23).

Real-time alert streams: IceCube shares event information for the most interesting sets of events in a rapid manner with the international scientific community. These real-time alerts are shared using standard coordination tools of the scientific community, such as Astronomer's telegrams (Atel), SuperNova Early Warning Systems (SNEWS) alerts, Gamma-ray Coordinates Network (GCN) alerts, and the Astrophysical Multimessenger Observatory Network (AMON).

12.3.3 Software Product

IceCube makes several custom software packages freely available to the wider scientific community for use in other experiments. These packages include our core analysis framework (IceTray) and several particle interaction simulation and event reconstruction packages.

12.3.4 Standards for data and metadata format and content

Data released for public access are provided in easily accessible formats such as ASCII text or HDF5 and includes metadata information in ASCII format to provide a description of the contents of each of the data files in the release.

The rise of new sky surveys has seen the establishment of the VOEvent format for reporting and rapid follow-up of astronomical transient events. IceCube uses the VOEvent format in the product streams shared within alert networks.

12.3.5 Data access and data sharing practices and policies

Data will be made publicly available upon publication of results. The IceCube Collaboration has created a data release webpage that serves as the entry point for future data releases to the scientific community, http://icecube.wisc.edu/science/data. This page will be maintained for the entire duration of the project.

As mentioned above, IceCube is also sharing data by providing real-time alerts to the international community through the Astronomer's telegrams (Atel), SuperNova Early Warning Systems (SNEWS) alerts, Gamma-ray Coordinates Network (GCN) alerts, and the Astrophysical Multimessenger Observatory Network (AMON).

12.3.6 Policies and provisions for reuse, redistribution, and the production of derivatives

When reuse of IceCube data makes a significant contribution to a research project, users are requested to reference this URL, http://icecube.wisc.edu/science/data in resulting publications and journal articles where applicable.

No redistribution of data products by others is expected.

12.3.7 Archiving and preserving access to data

All of the data that are irreproducible, as well as the data products that go into publications or that are released to the public, are preserved in a long-term archive. This archive is managed by the IceCube M&O core group. A copy of all satellite-transferred and processed data is stored at an automated tape archive system at the DESY-Zeuthen (Germany). A copy of the raw data stream is stored on an automated tape archive system at the National Energy Research Scientific Computing Center (NERSC, California). These are large automated tape libraries that are operated and supported 24x7 and are used for archiving data for several other scientific experiments. The data management policies for DESY-Zeuthen and NERSC are available upon request. They include data preservation operations such as integrity verification and periodic tape media migration.

13 Environmental, Safety, and Health (ES&H)

The IceCube Upgrade environmental health and safety (ES&H) program has the following specific objectives:

- To prevent personnel injury or loss of life during all phases of the IceCube Upgrade project
- To prevent environmental contamination during the construction, testing, or operation of IceCube
- 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 comply with safety protocols on the field as established in cooperation with the support contractor

13.1 ES&H Plans

The safety manager administers the ES&H program with the full support of the PM. 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 Upgrade ES&H program are in the document *IceCube Upgrade Safety Manual* (20) . Details of the safety planning for each season at the South Pole are found in the IceCube Upgrade safety plan.

Design and implementation of safety equipment are the responsibility of the IceCube Upgrade safety manager in concurrence with NSF and support contractor. In the areas of drilling and deployment, the safety equipment are as designed and implemented during IceCube Gen1. Any modifications to the design and implementation of safety equipment will go through the change control process and with approval requirements per the Project Configuration Plan.

On an annual basis, the safety manager reviews the safety plan with all 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.

14 Reviews and Reporting

14.1 Reporting Requirements

The project office prepares monthly performance reports and an annual report. These reports are distributed within the IceCube project organization and collaboration, host institution, various IceCube advisory and oversight committees, and to the NSF.

14.1.1 Monthly Performance Reports

Monthly reports are submitted to the NSF. This report is prepared in accordance with the Cooperative Agreement and consists of a summary of work accomplished during the reporting period. The monthly report includes major scientific and technical accomplishments, an assessment of current status against the cost and schedule baselines, and an overview of current or anticipated problem areas. This report also includes management information such as changes in key personnel and other actions requiring NSF/IOFG notification.

14.1.2 Annual Reports

An annual report is prepared and submitted to the NSF and the IOFG. The annual report contains:

- A summary of major technical accomplishments compared to the proposed goals of the period
- Financial and schedule status information similar to that given in the monthly report
- A summary of any current problems and favorable or unusual developments
- A summary of work to be performed during the following year

14.1.3 Earned Value Management System (EVMS) Report

EVMS reports are updated monthly for discussion by the technical board. Actual costs are "estimated actuals" for the report month. These estimated actuals consist of some actual values for the early portion of the month (the first two weeks or so) and estimates for the last half of the month. To formulate earned value, L2 managers estimate percent complete at the lowest task level in their schedules. This information is collected by the project office for roll-up and reporting to the NSF and other stakeholders. An EVMS report consists of data sheets for each L2 that shows actual, earned, and planned values at L3. A summary sheet that rolls up overall earned value at L2 along with cost and schedule variance is compiled and reported in the monthly report.

14.2 Audits and Reviews

14.2.1 Internal Reviews

The project office conducts a variety of internal meetings to coordinate work and assess status.

14.2.1.1 Subsystem Technical Reviews

As subsystem elements progress from preliminary design to final design and on to production readiness, a series of technical readiness reviews will be held to ensure subsystem maturity is consistent with transition to the next phase. Panels for these reviews will comprise primarily internal subject matter experts along with external advisors selected as needed by the technical coordinator. NSF program officers are invited to participate in the reviews, and panel reports will be shared with the collaboration and the NSF.

14.2.1.2 Configuration Control Board Meetings

Configuration control board meetings are conducted weekly along with the L2 weekly updates to review and pass along recommendations on baseline change requests to the PM.

14.2.1.3 Project Advisory Panel Meetings

Project advisory panel meetings are held annually, and on an ad hoc basis as needed, to review project execution issues and recommend actions to improve efficiency and reduce risk.

14.2.1.4 Science Advisory Committee and Software & Computing Advisory Panel Meetings

The existing IceCube M&O advisory committee meetings are held annually or on an ad hoc basis and will have an additional agenda item to review and make recommendations on the IceCube Upgrade scientific goals, computing needs, and other matters that may affect the scientific activities of the neutrino observatory.

14.2.2 External Reviews

14.2.2.1 IceCube International Oversight and Finance Group Meetings

The International Oversight and Finance Group meets annually to approve MOUs or changes to MOUs and to review the current status of the IceCube project. The IOFG reviews and endorses the annual work plan, including budget, schedule, and technical objectives.

14.2.2.2 NSF Annual Reviews and Site Visits

The NSF conducts annual reviews in the fall of each year ahead of the deployment season. The review evaluates the following items:

- Annual bottom-up cost estimate
- Schedule and technical progress
- Management
- Annual readiness to proceed with deployment season

The NSF also conducts site visits and reviews in the spring of each year, including an external panel. The review evaluates the following items:

- Overall project status and business systems review
- Project technical progress and performance against baseline
- Technical achievements of field season

15 Commissioning

15.1 Integration and Testing Plan

The IceCube data acquisition and online filtering software was designed to support new instrumentation. During IceCube construction new strings were added annually, even the dissimilar legacy AMANDA strings were integrated into the IceCube online systems for a period of several years. Deployment of the Upgrade readout hardware will coincide with upgrades planned for the IceCube string readout systems, known as DOMHubs, to replace aging electronics and computing platforms. The combined system will be maintained under the existing IceCube operations infrastructure with little or no additional cost, a negligible increase in data volume, and less than 10% additional required power.

15.2 Operational Readiness Plan

The Upgrade detector elements will pass from the Upgrade Project to the ICNO after successful drilling, deployment of the sensors, freeze-in, and the initial commissioning of the detector systems. Calibration will continue afterwards, both to understand the Upgrade systems and to better calibrate the Gen1 IceCube, but the operations will be completely subsumed into normal ICNO operations.

15.3 Concept of Operations Plan

The existing IceCube Neutrino Observatory provides a natural framework into which the IceCube Upgrade, once operational, will transition. Sensor hardware, firmware, and software systems are designed with the IceCube interface taken into consideration to permit an efficient incorporation of the additional instrumentation in the current operational infrastructure requiring only minimal increase in operations scope.

We have considered how to incorporate the first analyses of the IceCube Upgrade data, including the important new calibration inputs to the analysis, in the final documents for the project. We will have the calibration goals of the Upgrade fully documented (on improvements both for the Upgrade sensors and for the Gen1 data) going into the commissioning of the new modules, and will deliver preliminary calibration results during the final year of the project. These will not be the final calibrations but will reflect the importance of in-ice calibration as one of the primary goals of the project. In practice these activities will be split between the IceCube Observatory normal operations and the Upgrade calibration team efforts.

15.4 Segregation of Funding Plan

The IceCube Upgrade Project is responsible for delivering, installing, commissioning and initial calibration of the Upgrade strings. At this point it is handed off to the ongoing IceCube Neutrino Laboratory M&O program that supports IceCube Operations.

16 Project Closeout

16.1 Project Closeout Plan

The project will be completed when all scope contained in the WBS dictionary has been delivered, installed, commissioned, and handed over to the operations program.

When the Project nears completion, a project close-out plan will be developed and implemented. The following activities will be covered in the close-out process:

- How all contract obligations, products, services, and deliverables have been completed and accepted,

- How excess equipment and associated components will be properly disposed,
- How subcontractors/vendors are notified of the close out, and a formal request is submitted to deobligate balances and/or accrue outstanding costs and resolve/deobligate outstanding balances. Deobligation and contract close out requires formal concurrence of vendors.
- How costs associated with closed charge codes must be cleared.

A completion report will be written and include how the project was completed within cost and on schedule, project lessons learned, and performance achieved at project completion.

17 Reliability and Overall Performance of the IceCube Upgrade

The IceCube Upgrade's unique operating environment and total inaccessibility of major in-ice system elements following deployment place a high priority on careful reliability engineering. The primary reliability engineering analysis for IceCube are based on a "physics of failure" assessment of the factors that introduce stress on system elements, supplemented by statistical analysis of failure rate predictions when meaningful data is available. Available IceCube failure history data are examined for insight, and experience from similar systems such as KAMLAND and Super-K will also be utilized where applicable. The goal of the reliability program is to maximize the number of functional sensors in the ice.

17.1 Physics, Calibration, and R&D Success Key Performance Parameters

The key metric for success of the project hardware installation is to have more than 95% of the in-ice optical modules (D-Eggs plus mDOMs) functional throughout the science run. (This is similar to the Gen1 requirement for success.) 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 more than 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. R&D modules are likely to have had less strict reliability and manufacturing controls, so for each special device type we would consider module operation a success if some of the modules performed to specification in the ice after freeze-in.

17.2 Physics of Failure Methodology

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.

17.2.1 Role of Statistical Analysis

Statistical analytical methods shall be 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 using as guides a 95% in-ice module survival and a 15-year life span of the in-ice detector array. Data collected during developmental and production testing will be captured for analysis and predictive value.

17.2.2 Failure Modes and Effects Analysis (FMEA)

Every system element in the critical downhole strings 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.

17.2.3 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 the 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 mainboards. This baseline model will be extensively applied during design for reliability allocation and estimation purposes.

17.2.4 Failure Review and 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 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.

17.3 Parts, Materials, and Process Selection

In accordance with the PoF methodology, we are not using 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, our group consulted with NASA's Glenn Research Center (experts in low-temperature electronics) to provide guidance in our component and material selection.

17.3.1 Determination of Prohibited Materials

Prohibited materials include compounds, components, and materials used in assembly and processing that can outgas elements that are corrosive to metallic components, cause delamination of PWBs, cause changes in the optical and mechanical properties of the optical gel, or cause degradation of the dielectric characteristics of the electronic assemblies. Also included are materials and processes that promote the growth of electrically conductive whiskers. The system-level ERD will contain the overall list of prohibited materials, and individual subsystem ERDs are free to impose additional restrictions as dictated by the application. Additionally, Antarctic treaty and best practices material restrictions (e.g., Styrofoam in shipping packaging) are observed.

17.3.2 Use of Commercial and Industrial Parts

The use of commercial off-the-shelf (COTS) products is becoming increasingly commonplace in high-reliability programs. Accelerating rates of COTS product enhancement is a major driver of this process. Wherever possible, we select electronic parts from "manufacturer high-reliability" parts or "industrial" parts qualified and screened in accordance with MIL-STD-883 or EIA/JEDEC approved test methods from manufacturers on the DoD Qualified Manufacturer List (QML) and NASA's Active Parts Core Suppliers Listing (CSL). By using QML vendors we leverage the system implemented by the DoD to ensure the availability of high-quality parts in a cost-effective manner. On an electronic component-by-component basis, we require an absolute minimum for industrial or automotive ratings or that parts are explicitly denoted as high reliability.

References

1. *The IceCube Neutrino Observatory: Instrumentation and Online Systems.* **IceCube Collaboration.** P03012, 2017, Journal of Instrumentation, Vol. 12.

2. **IceCube Neutrino Observatory.** *Divestment Plan for the IceCube Neutrino Observatory.*

3. **IceCube Upgrade.** *Spreadsheet of In-Kind contributions.*

4. **IceCube Upgrade Project.** *Institutional MOUs for the IceCube Upgrade Project.*

5. **National Science Foundation.** NSF Research Infrastructure Guide (RIG). [Online] December 2021. https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf21107&org=DBI.

6. **IceCube Upgrade Project.** *Scope Management Plan for the IceCube Upgrade Project.*

7. —. *IceCube Upgrade WBS Disctionary.*

8. —. *Cost Estimating Plan for the IceCube Upgrade Project.*

9. —. *Key Assumptions Document for the IceCube Upgrade Project.* 2021.

10. —. *IceCube Upgrade Risk Register.*

11. —. *IceCube Upgrade Risk Register.*

12. —. *IceCube Upgrade Risk Management Plan.*

13. —. *Project Cost Book.*

14. —. *Basis of Estimates for the IceCube Upgrade Project.*

15. —. *Project Management Tools for the IceCube Upgrade Project.*

16. —. *IceCube Upgrade Master Cargo SpreadSheet.*

17. —. *Design Documentation System.*

18. —. *IceCube Upgrade Quality Plan.*

19. —. *IceCube Upgrade Configuration Management Plan.* 2020.

20. —. *IceCube Upgrade Safety Manual.* 2018. rev A.1..

21. **Dart, Eli, et al.** The Science DMZ: A Network Design Pattern for Data-Intensive Science. *Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis.* s.l. : Association for Computing Machinery, 2013.

22. **TrustedCI.** [Online] 2021. https://www.trustedci.org/.

23. **National Aeronautics and Space Administration.** NASA's High Energy Astrophysics Science Archive Reasearch Center (HEASARC). [Online] https://heasarc.gsfc.nasa.gov/docs/archive.html.

Appendix 1: Flow Down from Scientific Objectives to Technical Requirements

		SCIENCE OBJECTIVES - THE ICECUBE UPGRADE						
		Tau Neutrino Appearance and the Unitarity of the PMNS Matrix (2.1)	Neutrino Oscillations (2.2)	Sterile Neutrinos (2.2)	Indirect Dark Matter (2.2)	Ice Characterization for better LE & HE flavor physics (2.3)		
PRIMARY SCIENCE REQUIREMENTS	Event Energy Range	few to 100 GeV	few to 100 GeV			TeV to >PeV		
	Expected Detectable Event Rate	Measurement in 2-3 years	5-10% tau measurement	Any detection/improved limit	Any detection/improved limit	100s / year		
	Desired Angular Resolution	<5 deg at O(20 GeV)						
	Time Resolution Within Event	2-5 ns	2-5ns					
	Absolute Time Accuracy					50 ns		

Inice Sensor Array Geometry	Instrumented Ice Volume	About 2 million cubic meters		√	√	√	√
	Array Shape	Compact		√	√	√	√
	Effective Volume	Varies with energy level and event orientation (derived from other properties)		√	√	√	√
	Number of Strings	7		√	√	√	√
	multi-PMT Digital Optical Modules (mDOM) per String	108 (90 in the dense physics region, others above and below for primarily calibration purposes) - 46 mDOMs, 38 D-Eggs, & 6 pDOMs		√	√	√	√
	Total Number of mDOM	~750 (photocathode area is key parameter here)		√	√	√	√
	mDOM Spacing - Horizontal	22 meters (compromise between closer and drill constraints)		√	√	√	√
	mDOM Spacing - Vertical	3.0 m		√	√	√	√
	Detector Depth	Physics region: 2150-2425m Upper region: 1450-2150 Deep region: 2425-2600m		√	√	√	√
Individual mDOM Performance	Sensitivity of mDOM	Single Photo Electron (SPE)		√	√	√	√
	mDOM Photon Event Dynamic Range	SPE to >200 PE / 15 ns		√	√	√	√
	mDOM Field of View	Spherical with <10% variation, except for cable shaddowing.		√	√	√	√
	Digitization Rate Waveforms < 400 ns	300 megasamples / second		√		√	√
	Digitization Rate Waveforms > 400 ns	40 megasamples / second		√		√	√
	Absolute Amplitude Calibration Accuracy	< 5 %		√	√	√	
	Timing Accuracy	< 5 ns		√	√	√	
Event / Background Discrimination (Noise Reduction)	mDOM Noise Rate	O(10kHz) total noise rate, <850 Hz per PMT				√	√
	mDOM Data Processing	Initial waveform capture and digitization in DOM, context sensitive compression of data prior to transfer		√		√	
	Local Coincidence Function	In mDOMs, might require N of 24 PMTs hit within time window to suppress noise.		√		√	
	Event Trigger Function	Global (surface) trigger logic to package event data and discriminate noise		√	√	√	√
	Veto Function	Surface Array (IceTop) allows identification and discrimination of downgoing background		√	√	√	√
Data Transport and Storage	Incoming Data Stream from Sensor Array	150 Gig / day		√	√	√	√
	Non-Volatile Storage at South Pole	1-2 Day Buffer / Archive Capacity & Full Redundancy Requirements	√			√	
	South Pole High Priority Communications	At all times, it must be possible to complete a minimum 10KB transfer to the Northern Hemisphere within 10 minute period. (SNEWS and GRB Reporting)	√			√	
	South Pole Medium Priority Communications	500 MB / day	√			√	
	South Pole High Volume Data Transfer	>30 GB / day	√			√	
	Northern Hemisphere Data Warehouse	Fully Buffered / Archive Capacity & Redundancy Requirements	√			√	