How Decision Making Enables the Essential Connection Between Potential and Product

INCOSE Healthcare Working Group Webinar
February 23, 2018

Randall C. Iliff
randall@eintllc.com

Eclectic Intellect, LLC
www.eintllc.com

Today's Thought Menu

- Decisions in Development
- Real-World Decisions on IceCube
- Summary of Universal Insight

Development Decisions

- Who are the stakeholders?
- What do they actually need?
- How do those needs interact?
- How should the effort be structured?
- Where should attention be focused?
- Which decision methods should you use?

Please Note

This material is based upon work supported by the National Science Foundation under Grant Numbers OPP-9980474 (AMANDA) and OPP-0236449 (IceCube).

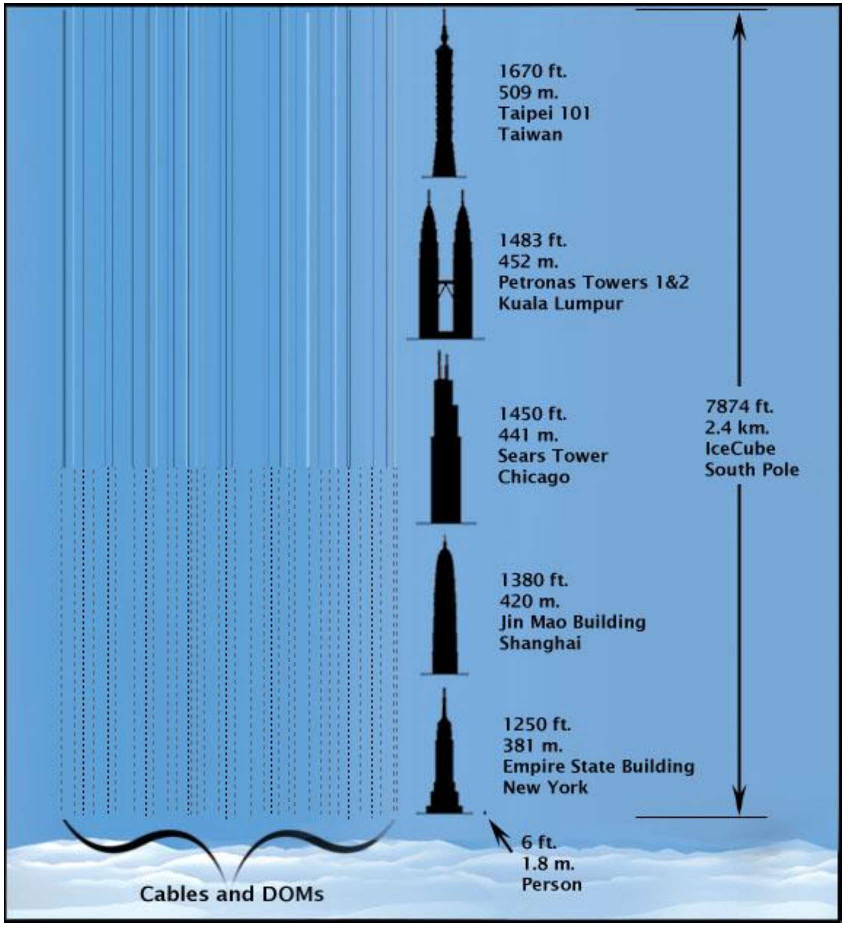
Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

So, What’s an IceCube?

“IceCube” is a cubic kilometer scale “Discovery Class” research instrument now operating at the South Pole.

Funded by the National Science Foundation and collaboration partners in Germany and Sweden, the project is managed by the University of Wisconsin in Madison.

>5,000 Sensors, 1 kM^3 Volume of Ice



DOMs are less accessible than spacecraft once they are deployed in deep ice...

IceCube

To Physicists:

- World’s most powerful neutrino telescope
- Nearly unlimited potential for discovery
- A possible Nobel Prize

To Engineers:

- A massively complex effort
- Little or no prior art
- Anonymity if it works
- Blame if it doesn’t

Stakeholders

What Did They Want?

- 300 Physicists agree on virtually nothing
- All had different research goals in mind
- We "binned" these into 8 primary groups

		SCIENCE OBJECTIVES - THE ICECUBE "MISSION"							
	ATTRIBUTE	Search for sources of cosmic rays that generate neutrinos	Search for steady and variable sources of high energy neutrinos, e.g. Active Galactic Nuclei or Supernova Remnants	Search for high energy neutrinos from transient sources such as Gamma Ray Burst and Supernova bursts	Search for neutrinos from the decay of superheavy particles related to topological defects	Search for WIMPs which may constitute dark matter. "Neutralinos"?	Search for magnetic monopoles and other exotic particles like strange quark matter	Monitor our Galaxy for MeV neutrinos from Supernova explosions and operation within SNEWS	Search for unexpected phenomena
PRIMARY SCIENCE REQUIREMENTS	Event Energy Range	TeV to PeV	TeV	to 100 TeV	PeV to EeV	10 GeV to PeV	TBD eV	MeV	TBD eV
	Expected Detectable Event Rate	TBD events/yr	TBD events/yr	"few" to 100 events/km^2-yr	1 to 100 events/km^2-yr	TBD events/yr	TBD events/yr	TBD events/yr	TBD events/yr
	Desired Angular Resolution	< 1 degree at TBD eV (Driven by desire to resolve the specific cosmological source.]			TBD Degrees [Do we care, other than just being able to have sufficient data for overall event reconstruction?			N/A	TBD degrees
	Waveform	sufficient duration / resolution to distinguish event signatures (TBD ns duration, TBD dynamic range, TBD sample rate)						1 to 3 ms?	TBD s
	Time Resolution	5 - 10 ns with initial degradation experienced at lower event energies						1 to 3 ms?	TBD
	Operating Life	Fifteen year instrument design life allows for 10 year fully configured operational period plus multi-year deployment.							

How do the Needs Interact?

- Some planning already had been done
- Science requirements for the instrument

PRIMARY SYSTEM REQUIREMENTS	Overall Inice Sensor Array	Instrumented Ice Volume	1 cubic kilometer (nominal)
		Array Shape	Polyhedral consisting of parallel upper and lower planes with hexagonal cross section.
		Effective Volume	TBD cubic kilometer at TBD eV and TBD arrival angle (varies with energy level and event orientation)
		Number of Strings	80
		Digital Optical Modules (DOM) per String	60
		Total Number of DOM	4800
		DOM Spacing - Horizontal	125 meters (efficient means to instrument the required volume of ice, provides good resolution for higher energy levels)
		DOM Spacing - Vertical	16.7 meters (provides highest resolution for vertical traveling particles)
		Detector Depth	1450 - 2450 meters (optical properties of ice improve with depth, limiting factor is boundary to surface shear effects)
	Ice-Top Array	Total Station Count	1 IceTop station at each hole location, nominally 80 station sets.
		Tanks per Station	2 tanks at each station provide operational redundancy, local veto capability.
		Effective Tank Volume	(TBD- simple look up and load entry)
		Digital Optical Modules (DOM) per Station / Tank	Two DOM in each tank are used to provide greater dynamic range, resulting in a total of four DOM per IceTop Station set.
		Total Number of DOM	320
		DOM Spacing - Horizontal	Within the tanks, spacing is 1 meter.
		DOM Spacing - Vertical	IceTop array is positioned roughly 1,450 meters above the topmost In-Ice DOM.
		Detector Depth	Tanks are installed to be flush with grade when covered, additional snow accumulation at roughly 1 foot per year thereafter.
	Individual DOM Performance	Sensitivity of DOM	Single Photo Event (SPE)
		DOM Photon Event Dynamic Range	SPE -> 200 PE / 15 ns (Note- two DOM are used in a high / low gain mode to support the IceTop Dynamic Range Requirement.)
		DOM Field of View	Hemispherical with [TBD] fov at [TBD] fall off
		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

How do the Needs Interact?

- Some derived requirements were obvious
- Most required complex decisions and trades

DERIVED SYSTEM REQUIREMENTS		
Calibration & Commissioning	Establish DOM Physical Location	Determine x, y, z coordinates to within .5 Meter (TBR)
	Establish optical characteristics of Ice along all inter-DOM paths	Primarily path loss, although scattering and other effects may also be noted.
	Establish operating characteristics of each DOM	Gain, noise rate, FOV, pedestal characteristics, others.
	String Commissioning	Determine that newly deployed string is acceptable to add to the body of operational instrument.
Event / Background Discrimination (Noise Reduction)	DOM Noise Rate	< 850 hits / second
	DOM Data Processing	Initial waveform capture and digitization in DOM, context sensitive compression of data prior to transfer
	Local Coincidence Function	User selectable, three modes: Off; Soft - Reduced data set for marginal probability events; Hard - Discriminator function requiring "m of n" confirmation from vertically adjacent DOM.
	Event Trigger Function	String and Global 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	TBD Buffer / Archive Capacity & 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 Meg / day
	South Pole High Volume Data Transfer	31 Gig / day
	Northern Hemisphere Data Warehouse	TBD Buffer / Archive Capacity & Redundancy Requirements
Operation & Maintenance	Power	Essential to minimize South Pole power consumption wherever practical.
	Master Time Reference	Internal reference consistent with overall < 5ns timing error budget allocation, conversion to UTC based on GPS reference.
	Experiment Monitoring	Built in monitoring capabilities are essential for managing inaccessible devices (such as the DOMs) but also help minimize South Pole headcount needs.
	Experiment Control	Experiment control is needed to managed the state of individual system elements as well as closely establish and control operational parameters during a given data taking session.
	Personnel Safety	Safety is a universal design consideration, but particularly for operations that must be conducted under difficult working conditions at the South Pole.
	Instrument Security	On site and remote access controls, user account management, and general IT safeguards to ensure undisturbed operation.
	Data Integrity	"Chain of custody" confidence in data from first capture through analysis and publication.
	System Growth Provisions	As a discovery instrument, there is a greater than normal responsibility to provide future flexibility for expansion or reconfiguration.

How to Organize the Effort?

- At the highest level this choice was simple
- IceCube has five major subsystems

SUBSYSTEM ALLOCATION				
Sensor Subsystem	Ice Cube Laboratory (ICL)	Northern Hemisphere Data Center	Software Subsystems	Enabling Systems

Needs, Requirements, Structure

Group	Subgroup	ATTRIBUTE	Search for sources of cosmic rays that generate neutrinos	Search for steady and variable sources of high energy neutrinos, e.g. Active Galactic Nuclei or Supernova Remnants	Search for high energy neutrinos from transient sources such as Gamma Ray Burst and Supernova bursts	Search for neutrinos from the decay of superheavy particles related to topological defects	Search for WIMPs which may constitute dark matter. "Neutralinos"?	Search for magnetic monopoles and other exotic particles like strange quark matter	Monitor our Galaxy for MeV neutrinos from Supernova explosions and operation within SNEWS	Search for unexpected phenomena	Sensor Subsystem	Ice Cube Laboratory (ICL)	Northern Hemisphere Data Center	Software Subsystems	Enabling Systems
PRIMARY SCIENCE REQUIREMENTS		Event Energy Range	TeV to PeV	TeV	to 100 TeV	PeV to EeV	10 GeV to PeV	TBD eV	MeV	TBD eV					
		Expected Detectable Event Rate	TBD events/yr	TBD events/yr	"few" to 100 events/km²-yr	1 to 100 events/km²-yr	TBD events/yr	TBD events/yr	TBD events/yr	TBD events/yr					
		Desired Angular Resolution	< 1 degree at TBD eV (Driven by desire to resolve the specific cosmological source.)			TBD Degrees [Do we care, other than just being able to have sufficient data for overall event reconstruction?			N/A	TBD degrees					
		Waveform	sufficient duration / resolution to distinguish event signatures (TBD ns duration, TBD dynamic range, TBD sample rate)						1 to 3 ms?	TBD s					
		Time Resolution	5 - 10 ns with initial degradation experienced at lower event energies						1 to 3 ms?	TBD					
		Operating Life	Fifteen year instrument design life allows for 10 year fully configured operational period plus multi-year deployment.												
PRIMARY SYSTEM REQUIREMENTS	Overall InIce Sensor Array	Instrumented Ice Volume	1 cubic kilometer (nominal)								√		√	√	
		Array Shape	Polyhedral consisting of parallel upper and lower planes with hexagonal cross section.								√	√	√	√	
		Effective Volume	TBD cubic kilometer at TBD eV and TBD arrival angle (varies with energy level and event orientation)								√		√	√	
		Number of Strings	80								√	√	√	√	√
		Digital Optical Modules (DOM) per String	60								√	√	√	√	√
		Total Number of DOM	4800								√	√	√	√	√
		DOM Spacing - Horizontal	125 meters (efficient means to instrument the required volume of ice, provides good resolution for higher energy levels)								√	√	√	√	
		DOM Spacing - Vertical	16.7 meters (provides highest resolution for vertical traveling particles)								√	√	√	√	
		Detector Depth	1450 - 2450 meters (optical properties of ice improve with depth, limiting factor is boundary to surface shear effects)								√	√	√	√	√
	Ice-Top Array	Total Station Count	1 IceTop station at each hole location, nominally 80 station sets.								√	√	√	√	√
		Tanks per Station	2 tanks at each station provide operational redundancy, local veto capability.								√		√	√	√
		Effective Tank Volume	(TBD- simple look up and load entry)								√		√	√	
		Digital Optical Modules (DOM) per Station / Tank	Two DOM in each tank are used to provide greater dynamic range, resulting in a total of four DOM per IceTop Station set.								√		√	√	
		Total Number of DOM	320								√	√	√	√	√
		DOM Spacing - Horizontal	Within the tanks, spacing is 1 meter.								√	√	√	√	
		DOM Spacing - Vertical	IceTop array is positioned roughly 1,450 meters above the topmost In-Ice DOM.								√	√	√	√	
		Detector Depth	Tanks are installed to be flush with grade when covered, additional snow accumulation at roughly 1 foot per year thereafter.								√		√	√	√
	Individual DOM Performance	Sensitivity of DOM	Single Photo Event (SPE)								√		√	√	√
		DOM Photon Event Dynamic Range	SPE -> 200 PE / 15 ns (Note- two DOM are used in a high / low gain mode to support the IceTop Dynamic Range Requirement.)								√		√	√	√
		DOM Field of View	Hemispherical with [TBD] fov at [TBD] fall off								√		√	√	√
		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								√	√	√	√	√
DERIVED SYSTEM REQUIREMENTS	Calibration & Commissioning	Establish DOM Physical Location	Determine x, y, z coordinates to within .5 Meter (TBR)								√	√	√	√	√
		Establish optical characteristics of ice along all inter-DOM paths	Primarily path loss, although scattering and other effects may also be noted.								√	√	√	√	√
		Establish operating characteristics of each DOM	Gain, noise rate, FOV, pedestal characteristics, others.								√	√	√	√	√
		String Commissioning	Determine that newly deployed string is acceptable to add to the body of operational instrument.								√	√		√	
	Event / Background Discrimination (Noise Reduction)	DOM Noise Rate	< 850 hits / second								√	√		√	√
		DOM Data Processing	Initial waveform capture and digitization in DOM, context sensitive compression of data prior to transfer								√	√		√	
		Local Coincidence Function	User selectable, three modes: Off; Soft - Reduced data set for marginal probability events; Hard - Discriminator function requiring "m of n" confirmation from vertically adjacent DOM.								√	√		√	
		Event Trigger Function	String and Global 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	TBD Buffer / Archive Capacity & 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 Meg / day									√		√	
		South Pole High Volume Data Transfer	31 Gig / day									√		√	
		Northern Hemisphere Data Warehouse	TBD Buffer / Archive Capacity & Redundancy Requirements										√	√	
	Operation & Maintenance	Power	Essential to minimize South Pole power consumption wherever practical.								√	√	√	√	√
		Master Time Reference	Internal reference consistent with overall < 5ns timing error budget allocation, conversion to UTC based on GPS reference.									√		√	
		Experiment Monitoring	Built in monitoring capabilities are essential for managing inaccessible devices (such as the DOMs) but also help minimize South Pole headcount needs.								√	√		√	
		Experiment Control	Experiment control is needed to managed the state of individual system elements as well as closely establish and control operational parameters during a given data taking session.								√	√	√	√	
		Personnel Safety	Safety is a universal design consideration, but particularly for operations that must be conducted under difficult working conditions at the South Pole.								√	√	√	√	√
		Instrument Security	On site and remote access controls, user account management, and general IT safeguards to ensure undisturbed operation.								√	√	√	√	
		Data Integrity	"Chain of custody" confidence in data from first capture through analysis and publication.								√	√	√	√	√
		System Growth Provisions	As a discovery instrument, there is a greater than normal responsibility to provide future flexibility for expansion or reconfiguration.								√	√	√	√	

Traceable to Every Config Item

PRIMARY SYSTEM REQUIREMENTS vs. PHYSICAL SUBSYSTEM ALLOCATION

Sensor Subsystem

Group	FUNCTION	SENSOR SUBSYSTEM	Detector String	In-Ice DOM	PMT	DOM Main Board	PMT H/V Power Supply	Delay Board	Pressure Sphere	Penetrator Assembly	Optical Gel	Mu-Metal Shield	Flasher Board Assembly	DOM Harness Assembly	Surface to DOM Cable Assembly	IceTop Station	IceTop DOM	Surface Cable Assembly	Surface Junction Box
Overall Inice Sensor Array	Instrumented Ice Volume	√																	
Overall Inice Sensor Array	Array Shape	√	√												√			√	
Overall Inice Sensor Array	Effective Volume	√																	
Overall Inice Sensor Array	Number of Strings	√														√		√	√
Overall Inice Sensor Array	Digital Optical Modules (DOM) per String	√	√	√						√				√	√			√	√
Overall Inice Sensor Array	Total Number of DOM	√	√	√											√				
Overall Inice Sensor Array	DOM Spacing - Horizontal	√	√	√	√								√			√			
Overall Inice Sensor Array	DOM Spacing - Vertical	√	√	√	√									√	√				
Overall Inice Sensor Array	Detector Depth	√	√	√					√	√					√				
Ice-Top Array	Total Station Count	√														√		√	√
Ice-Top Array	Tanks per Station	√														√			
Ice-Top Array	Effective Tank Volume	√														√			
Ice-Top Array	Digital Optical Modules (DOM) per Station / Tank	√														√	√		
Ice-Top Array	Total Number of DOM	√														√	√	√	√
Ice-Top Array	DOM Spacing - Horizontal	√														√	√		
Ice-Top Array	DOM Spacing - Vertical	√														√	√		
Ice-Top Array	Detector Depth	√														√	√		
Individual DOM Performance	Sensitivity of DOM	√		√	√	√	√	√	√		√	√							
Individual DOM Performance	DOM Photon Event Dynamic Range	√		√	√	√	√	√											
Individual DOM Performance	DOM Field of View	√		√	√				√			√							
Individual DOM Performance	Digitization Rate: Waveforms < 400 ns	√		√	√	√													
Individual DOM Performance	Digitization Rate: Waveforms > 400 ns	√		√	√	√													
Individual DOM Performance	Absolute Amplitude Calibration Accuracy	√		√	√	√	√	√					√						
Individual DOM Performance	Timing Accuracy	√		√	√	√		√											

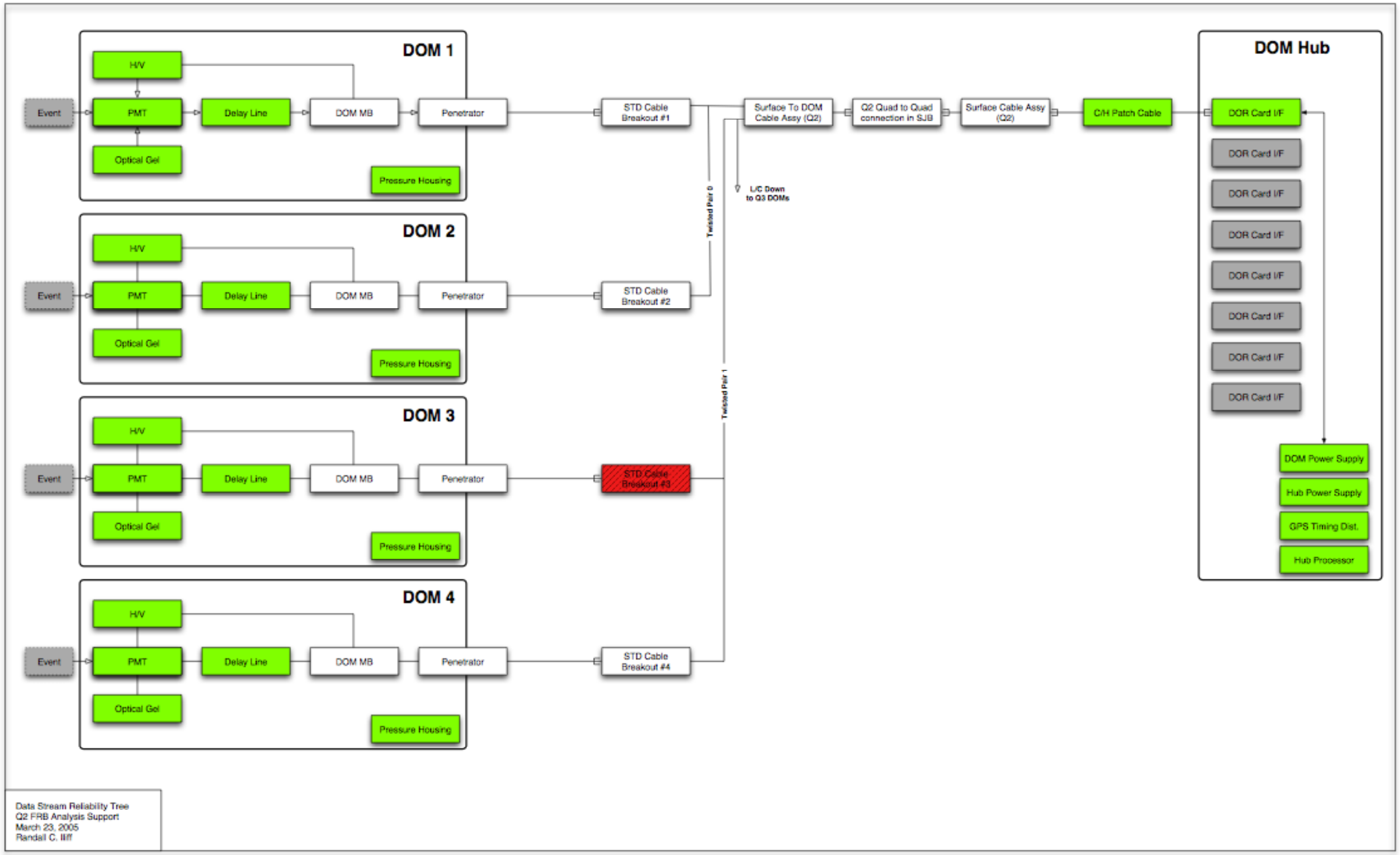
IceCube Laboratory (ICL)

Group	FUNCTION	ICECUBE LABORATORY (ICL)	ICL Facility	ICL Facility Improvements	Power Conditioning	EMI Entrance Panel	Bonding & Shielding	Cable Management	Operations & Support Area	DAQ Hardware	DOM Hub	DOR Card	DOM Power Supply	DSB Card	String Processor	In-Ice Trigger	Global Trigger	Event Builder	Master Clock Unit	Monitor & Control	Cable Patch Panels	Patch Cables	Signal Conditioning Filters	Data Handling Hardware	South Pole Archiving	Online Filter	Satellite Transfer
Overall Inice Sensor Array	Instrumented Ice Volume																										
Overall Inice Sensor Array	Array Shape	√	√	√		√		√																			
Overall Inice Sensor Array	Effective Volume																										
Overall Inice Sensor Array	Number of Strings	√	√	√		√		√		√						√	√	√		√	√	√					
Overall Inice Sensor Array	Digital Optical Modules (DOM) per String	√	√	√		√		√		√	√	√	√	√	√												
Overall Inice Sensor Array	Total Number of DOM	√		√	√	√	√	√		√	√	√	√	√		√	√	√	√	√	√	√	√	√	√		√
Overall Inice Sensor Array	DOM Spacing - Horizontal	√																									
Overall Inice Sensor Array	DOM Spacing - Vertical	√								√	√	√		√	√												
Overall Inice Sensor Array	Detector Depth	√								√		√	√										√				
Ice-Top Array	Total Station Count	√								√	√	√			√		√	√			√	√	√				
Ice-Top Array	Tanks per Station																										
Ice-Top Array	Effective Tank Volume																										
Ice-Top Array	Digital Optical Modules (DOM) per Station / Tank																										
Ice-Top Array	Total Number of DOM	√															√	√		√	√	√	√	√			√
Ice-Top Array	DOM Spacing - Horizontal	√																									
Ice-Top Array	DOM Spacing - Vertical	√																									
Ice-Top Array	Detector Depth																										
Individual DOM Performance	Sensitivity of DOM																										
Individual DOM Performance	DOM Photon Event Dynamic Range																										
Individual DOM Performance	DOM Field of View																										
Individual DOM Performance	Digitization Rate: Waveforms < 400 ns																										
Individual DOM Performance	Digitization Rate: Waveforms > 400 ns																										
Individual DOM Performance	Absolute Amplitude Calibration Accuracy	√								√	√	√															
Individual DOM Performance	Timing Accuracy	√		√	√	√	√	√		√	√	√		√					√								

Northern Hemisphere Data Center, Software Subsystem, Enabling Subsystems

Group	FUNCTION	NORTHERN HEMISPHERE DATA CENTER	Data Warehouse	Simulation	Analysis	SOFTWARE SUBSYSTEM	Production Software	South Pole Apparatus Management	Detector Operations	DAQ Dispatch	Data Handling	Simulation	Warehouse Reception	Data Warehouse	Data Requisition	Development & Support Software	ENABLING SUBSYSTEMS	Production STE	Packaging, Handling, Storage, and Transport	Deploymnet STE	IceTop Freeze Management	ESD Bonding / Cable Test Unit	DOM Leakage Current (freeze-in) Tester
Overall Inice Sensor Array	Instrumented Ice Volume	√		√	√	√						√											
Overall Inice Sensor Array	Array Shape	√		√	√	√						√											
Overall Inice Sensor Array	Effective Volume	√		√	√	√						√											
Overall Inice Sensor Array	Number of Strings	√		√	√	√	√	√	√	√		√					√					√	√
Overall Inice Sensor Array	Digital Optical Modules (DOM) per String	√		√	√	√	√	√	√	√		√				√	√					√	√
Overall Inice Sensor Array	Total Number of DOM	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√				
Overall Inice Sensor Array	DOM Spacing - Horizontal	√		√	√	√						√											
Overall Inice Sensor Array	DOM Spacing - Vertical	√		√	√	√						√											
Overall Inice Sensor Array	Detector Depth	√		√	√	√						√					√	√		√			√
Ice-Top Array	Total Station Count	√		√	√	√						√					√				√		
Ice-Top Array	Tanks per Station	√		√	√	√						√					√				√		
Ice-Top Array	Effective Tank Volume	√		√	√	√						√											
Ice-Top Array	Digital Optical Modules (DOM) per Station / Tank	√		√	√	√						√											
Ice-Top Array	Total Number of DOM	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√					
Ice-Top Array	DOM Spacing - Horizontal	√		√	√	√						√											
Ice-Top Array	DOM Spacing - Vertical	√		√	√	√						√											
Ice-Top Array	Detector Depth	√		√	√	√						√					√	√		√			
Individual DOM Performance	Sensitivity of DOM	√		√	√	√						√				√	√	√					
Individual DOM Performance	DOM Photon Event Dynamic Range	√		√	√	√						√				√	√	√					
Individual DOM Performance	DOM Field of View	√		√	√	√						√				√	√	√					
Individual DOM Performance	Digitization Rate: Waveforms < 400 ns	√		√	√	√						√				√							
Individual DOM Performance	Digitization Rate: Waveforms > 400 ns	√		√	√	√						√				√							
Individual DOM Performance	Absolute Amplitude Calibration Accuracy	√		√	√	√	√		√	√	√	√				√	√	√					
Individual DOM Performance	Timing Accuracy	√		√	√	√	√	√	√	√	√	√				√	√	√					

Focus on Science Data Stream

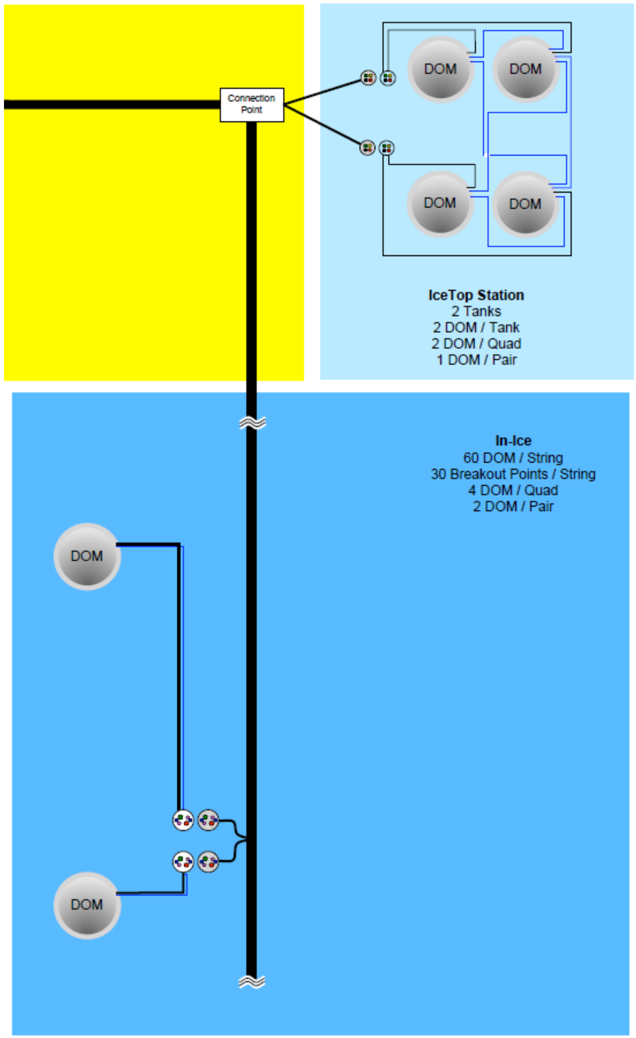


Science Data Stream FMEA

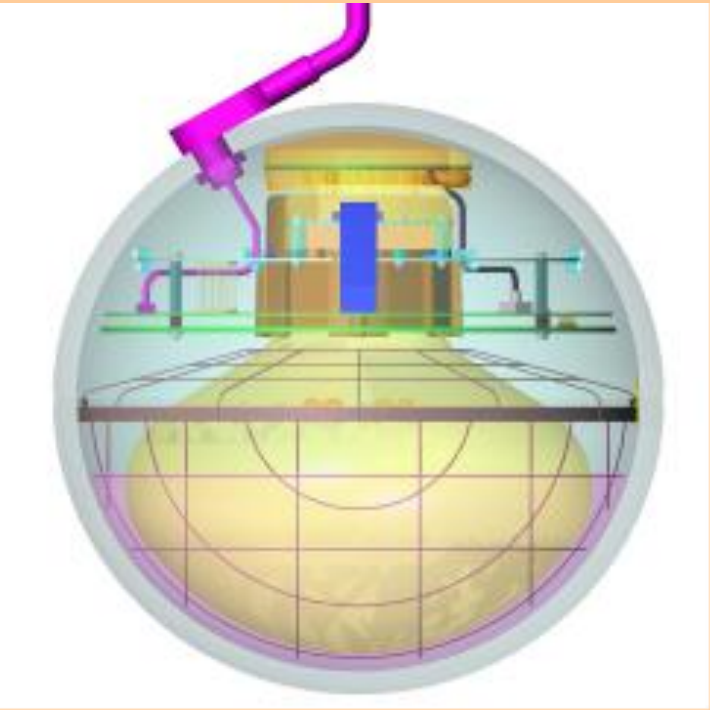
Functional Role	Key System Elements	Accessible?	Failure Effect	Criticality
Science Data Stream - Sensor Subsystem	In-Ice and Ice-Top DOMs, cables, connections	No	Permananent Loss of Science Data due to failed Channel(s) for the remainder of the instrument operational life.	Very High
			Permananent Loss of Science Data due to induced failure of Channel(s) for the remainder of the instrument operational life.	Very High
			Permananent Loss of Science Data from Channel(s) due to wear out, performance drift, or end of service life degradation effects in excess of user defined thresholds.	High
			Degraded Science Data from Channel(s) compared with specifications, but still deemed useful for scientific purposes such as Supernova detection and reporting.	Moderate
Science Data Stream - DOM Hub	DOM Hub, DOR Card, DOM Power Supply, Master Clock Distribution System	Yes	Permanent Loss of Science Data from unavailable channel(s) / string(s) during the interval between failure and system restoration following maintenance.	Moderate
Buffer Limited Trigger and Event Processing	Raw Data Storage, Raw Data Buffer, String Processor, Trigger, Event Buffer, Event Data Storage, Communications Buffer	Yes	Permanent Loss of Science Data from effected channel(s) / string(s) during the interval between buffer overflow and system restoration following maintenance.	Moderate
Off-Line Data Processing	All other system elements	Yes	User inconvenience prior to restoration, no loss of science data.	Low

Sensor Subsystem

- Cables
- Connections
- Digital Optical Modules



Digital Optical Module



Key DOM Decisions

- Pressure Sphere Specification and Margin
  - Life-cycle analysis to identify max / min pressure
  - Hydrostatic Pressure from 2,400 meters of water
  - Peak “re-freeze” dynamic pressure during install
  - Minimum pressure during transport
- Interior environment pressure and fill gas
  - Finite set of options to select from
  - Simple trade study analysis effort

DOM Fill Gas Trade Study

- Baseline plus 4 options
- Emphasis on info – not scores

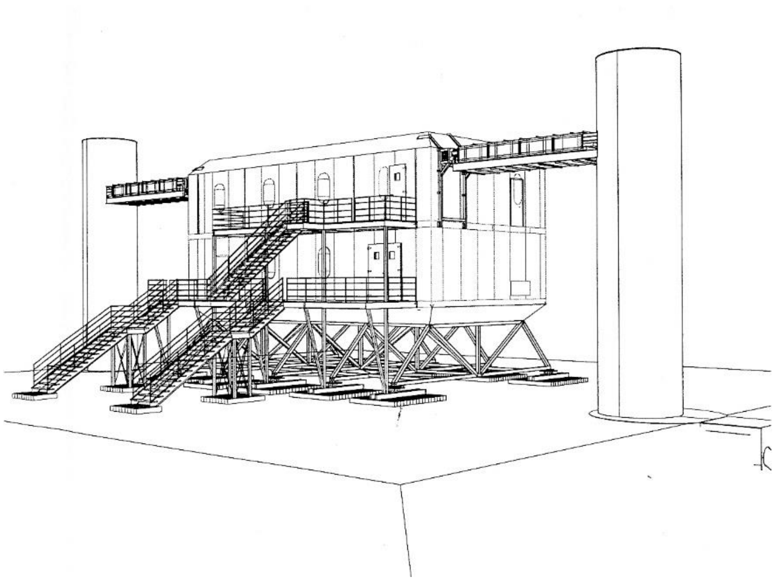
		Current Baseline	Alternative Concepts				
			1	*2*	*3*	*4*	
		Seal DOM in partial vacuum of ambient atmosphere.	**Clean Dry Air via in house compressor system**	**Compressed gas cylinder**	**Commercially available dry nitrogen.**	**Sulfur Hexafluoride**	**Comments**
Descriptive Information	**General Description**	No special steps taken to control and monitor particulates, trace gases, and dew point of the atmosphere sealed in the DOM.	House compressed air will have been filtered to remove large particulates, and the dew point reduced by 22 C from ambient by use of a refrigerated dryer.	Commercially bottled air will have a better controlled dew point, and lower concentration of particulates.	Purity and dew point requirements can be specified to supplier.	Sulfur hexafluoride is an excellent dielectric material for high voltage electronic applications.	
Reliability Information	**Atmospheric Contents**	Reactive Chemical Species Average Chlorine 0.001 ppm* Hydrogen Sulfide 0.01 ppm* Sulfur Dioxide 0.05 ppm* Nitrogen Oxide 0.05 ppm* Hydrocarbons 0.24 mgm/m3 Particulate Contamination 50 mgm/m3-24h *Measured by volume at 25 C and 760 mm pressure.	Reactive Chemical Species Average Chlorine 0.001 ppm* Hydrogen Sulfide 0.01 ppm* Sulfur Dioxide 0.05 ppm* Nitrogen Oxide 0.05 ppm* Hydrocarbons 0.24 mgm/m3 Particulate Contamination < 50 mgm/m3-24h *Measured by volume at 25 C and 760 mm pressure.	Purity ranges from 99% to 99.998%, water content range from 5 ppm for "high purity" product to unspecified for welding grade product. Particulates were not called out on supplier's spec. sheets.	99.999+% Nitrogen dew point < -100C.	99.99% Sulfur Hexafluoride	**Baseline and alternate approach 1 are not capable of delivering reliable performance throughout the 15 year project life.** **Alternatives #2 and #3 are most likely to provide a noncorrosive atmosphere throughout the 15 year project life.**
	Risk of corrosion on DOM PWB assemblies	**Extremely High**	**Very High**	**Very High**	**Very Low**	**Very Low**	
	Corrosion Mechanisms	Condensation due to high dew point, reactive atmospheric gases, corrosive particulates, Ozone due to combination of oxygen and high voltage (corona discharge). Ozone will also attack and degrade organic materials such as wire insulation.	Condensation due to high dew point, reactive atmospheric gases, corrosive particulates, Ozone due to combination of oxygen and high voltage (corona discharge). Ozone will also attack and degrade organic materials such as wire insulation.	Possible reactive atmospheric gases, reduced condensation concerns due to the lowering of the dew point in the "high purity" product, ozone due to combination of oxygen and high voltage (corona discharge). Ozone will also attack and degrade organic materials such as wire insulation.	As long as the atmosphere in the DOM has been purged prior to nitrogen backfill, there will be no atmospheric contribution to corrosion reactions. Ozone will not form because no oxygen is present inside of DOM.	As long as the atmosphere in the DOM has been purged prior to sulfur hexafluoride backfill, there will be no atmospheric contribution to corrosion reactions. Ozone will not form because no oxygen is present inside of DOM.	
	Possible trace radioactive gases	**Radon**	**Radon**	**Radon**	**None**	**None**	
	Reliability Impact	**Very Poor Reliability** Extremely high probability of corrosion effects on the PWBs, internal connectors, and ozone attack on base metals, electrical insulating materials, and possibly the optical gel.	**Poor Reliability** High probability of corrosion effects on the PWBs, internal connectors, and ozone attack on base metals, electrical insulating materials, and possibly the optical gel.	**Poor Reliability** High probability of corrosion effects on the PWBs, internal connectors, and ozone attack on base metals, electrical insulating materials, and possibly the optical gel.	**Highly Reliable** Only physics of failure mechanism (other than manufacturing defects) is metallic whisker growth. Consistent dielectric performance due to controlled purity and dew point.	**Highly Reliable** Only physics of failure mechanism (other than manufacturing defects) is metallic whisker growth. Consistent dielectric performance due to controlled purity and dew point.	
Performance Information	**DOM Performance Impact**	**None**	**None**	**None**	**None**	**None**	**No Impact**
	Possible trace radioactive gases	**Radon**	**Radon**	**Radon**	**None** Nitrogen is processed through molecular sieve and cryogenic separators in order to purify the gas. This process will eliminate contamination from other gases.	**None**	
Safety	**Safety Impact**	**Low Safety Risk** The atmosphere presents no safety issues, the evacuation equipment will require special operator training to ensure operator safety.	**Low Safety Risk** The atmosphere presents no safety issues, the evacuation equipment will require special operator training to ensure operator safety. The use of pressurized gases will again require special operator training to ensure operator safety.	**Low Safety Risk** The atmosphere presents no safety issues, the evacuation equipment will require special operator training to ensure operator safety. The use of pressurized gases will again require special operator training to ensure operator safety.	**Moderate Safety Risk** Nitrogen gas is inert and will not support life, therefore special precautions and operator training will be required. Training will also be required for operators to handle pressurized gases.	**Moderate Safety Risk** Sulfur hexafluoride is inert and will not support life, therefore special precautions and operator training will be required. Training will also be required for operators to handle pressurized gases. Under normal conditions sulfur hexafluoride is stable, but will decompose in an electric arc to form gaseous byproducts which includes fluorine gas. Fluorine gas, in the presence of moisture is very corrosive as it will form hydrogen fluoride. If an arcing event has occurred in a DOM, caution will need to be exercised when opening it. The use of standard safety equipment, including chemical resistant gloves and a face shield should be worn when any DOM is opened.	**All safety issues are manageable. Sulfur hexafluoride is the most significant issue**
Production / Programmatic Information	**DOM Manufacturing Impact**	**Least complicated production operation** The use of a glove box and vacuum chamber to control the atmosphere surrounding the DOM hemispheres during final assembly is assumed in all concepts.	**Moderately complicated production operation** The use of the glove box and vacuum chamber is still assumed. The need for a clean, dry air source drives the requirement for an air compressor with a refrigerated dryer and filter.	**Moderately complicated production operation** The use of the glove box and vacuum chamber is still assumed. The need for a clean, dry air source drives the requirement for an air compressor with a refrigerated dryer and filter, or cylinders of compressed air along with pressure regulators to control the final pressure	**Moderately complicated production operation** The use of the glove box and vacuum chamber is still assumed. The need for a dry nitrogen source drives the requirement for cylinders of pure, dry nitrogen along with pressure regulators to control the final pressure and flow.	**Moderately complicated production operation** The use of the glove box and vacuum chamber is still assumed. The need for a sulfur hexafluoride source drives the requirement for cylinders of sulfur hexafluoride along with pressure regulators to control the final pressure and flow.	**All controlled environment alternatives have comparable product impact**
	Repair / Rework Impact	**None**	**None**	**None**	**None**	**None**	
Logistics / Deployment Information	**Handling & Transport Impact**	**None**	**None**	**None**	**None**	**None**	**No Impact**
	Deployment Timeline Impact	**None**	**None**	**None**	**None**	**None**	
Secondary Impacts	**DOM PWB Assemblies Design Impact**	**None**	**None**	**None**	**None**	**None**	**No Impact**
	Software Design Impact	**None**	**None**	**None**	**None**	**None**	
Cost	**Cost**	**Lowest cost approach** Does not require any special materials.	**Low cost impact** If compressed clean dry air is available at the facility all that is needed is a pressure regulator (estimated cost $175.00) and associated plumbing to deliver the CDA to the glove box.	**Modest cost impact** Compressed air cylinders can be purchased at an estimated cost of about $120.00 for a 280 cubic foot cylinder, and a pressure regulator to deliver the air to the glove box - estimated cost $175.00. Compressed gas cylinder safety mounting hardware is about $75.00 per cylinder. Cost per DOM is $2.40 (ROM) for the bottled air, based on 50 DOMs per cylinder.	**Modest cost impact** Compressed nitrogen of specified purity and dew point can be purchased at an estimated cost of $170.00 for a 280 cubic foot cylinder of mid grade nitrogen. A pressure regulator is required to deliver the nitrogen to the glove box - estimated cost $175.00. Compressed gas cylinder safety mounting hardware is about $75.00 per cylinder. Estimated cost per DOM is $3.40 (ROM) for compressed nitrogen, based on 50 DOMs per cylinder.	**Modest to modestly high cost impact** Sulfur hexafluoride of specified purity and dew point can be purchased at an estimated cost of $400.00 per cylinder. A pressure regulator is required to deliver the sulfur hexafluoride to the glove box - estimated cost $175.00. Compressed gas cylinder safety mounting hardware is about $75.00 per cylinder. Estimated cost per DOM is $8.00 (ROM) for sulfur hexafluoride, based on 50 DOMs per cylinder.	
Other	**Other Considerations**	**TBD**		**TBD**	**TBD**	**TBD**	

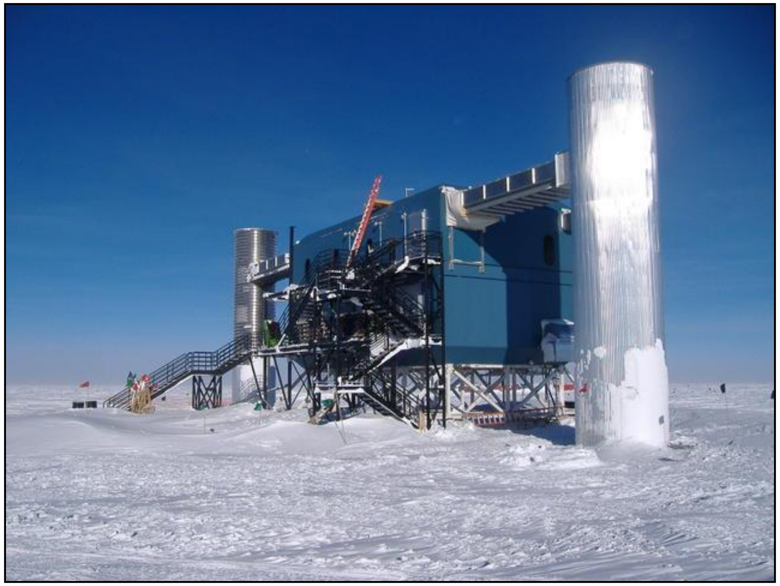
DOM Fill Gas Trade Study

- Yielded decision plus database of options
- Sample of Trade Study content

Low Safety Risk	Moderate Safety Risk	Moderate Safety Risk
The atmosphere presents no safety issues, the evacuation equipment will require special operator training to ensure operator safety. The use of pressurized gases will again require special operator training to ensure operator safety.	Nitrogen gas is inert and will not support life, therefore special precautions and operator training will be required. Training will also be required for operators to handle pressurized gases.	Sulfur hexafluoride is inert and will not support life, therefore special precautions and operator training will be required. Training will also be required for operators to handle pressurized gases. Under normal conditions sulfur hexafluoride is stable, but will decompose in an electric arc to form gaseous byproducts which includes fluorine gas. Fluorine gas, in the presence of moisture is very corrosive as it will form hydrogen fluoride. If an arcing event has occurred in a DOM, caution will need to be exercised when opening it. The use of standard safety equipment, including chemical resistant gloves and a face shield should be worn when any DOM is opened.

IceCube Laboratory





It Snows at the South Pole

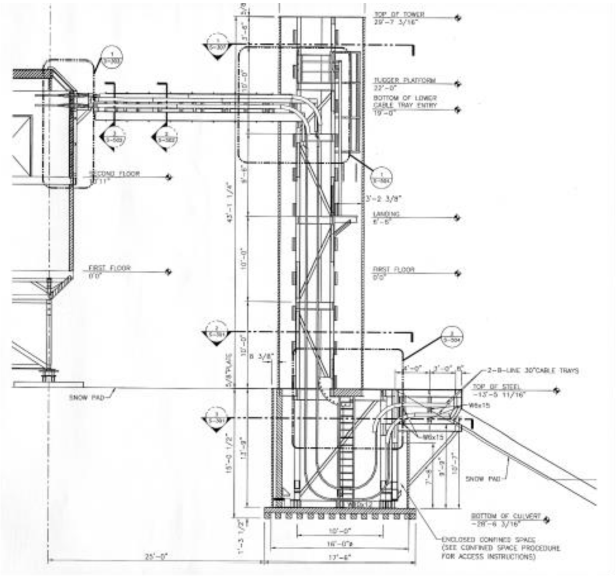
- Not much (1 ft/yr) but builds up over time
- Snow blows and drifts in very nasty ways
- Decisions:
  - How to keep the IceCube Laboratory useable?
  - How to manage over 80 huge cables?

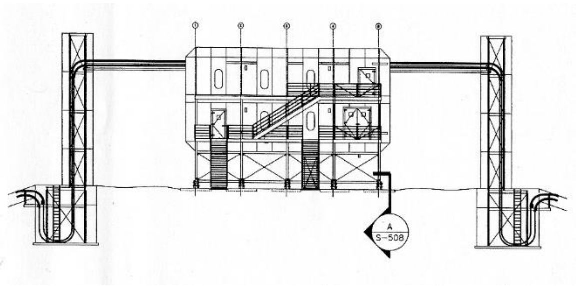
IceCube Laboratory

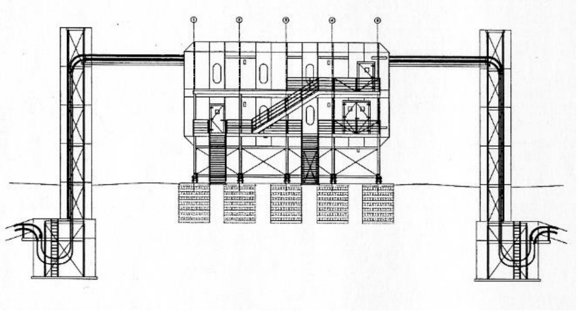
- Building Lift Operation
  - Applied proven South Pole Station precedent
  - CFD modeling to minimize vortices and deposition
- Cable Management
  - No prior precedent (80+ huge, very stiff cables)
  - Installed over multiple seasons
  - Wanted single entry panel, settled for two
  - Accepted complex logistical constraints
  - Accepted complex personnel task / training effort

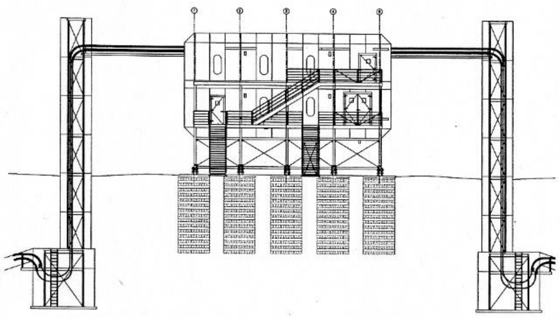
IceCube Laboratory

- Snow and Cable Solution
  - Stilts for the building
  - Towers for the cables
  - Periodic lift operation









Many Thousands of Decisions

- Data collection throughout multi-year build
- Component selection for extreme cold / hi-rel
- Extreme task simplification for installers
- Minimizing peak and total power consumption
- Logistics impacts (LC-130 load limits)
- International collaboration coordination
- Documentation and training support

Summary of Universal Insight

- The most critical decisions were those regarding stakeholders and needs
- Next was a system / sub-system / interface view that enabled simultaneous development
- Mission-level FMEA guided decision priority
- Decision method driven by available data, type of choice, need to communicate result
- Data is valuable, mere scores are dangerous

Thanks!