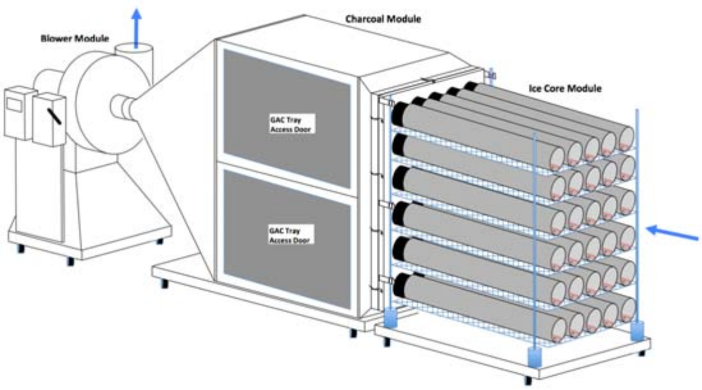
Dry Core

Ice Core Drill Fluid Evaporation & Odor-Capture System

Basis of Design



November 25, 2015

Research Sponsored By

University of New Hampshire (UNH)

With Technical Assistance From

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Summary

This document forms the Basis of Design for “Dry Core”, an ice core drill fluid evaporation and odor capture system. The primary purpose of the proposed system is to remove Estisol-140 (E-140) drill fluid residue and its objectionable odor from the South Pole Ice Core (SPice) ductile cores and brittle-ice cores, although ice cores from other projects may also be used in the drying system if the core diameter is not larger than approximately 4.1 inches. The South Pole ice core drilling camp is shown in Figure 1.

Figure 1 - South Pole Ice Core (SPice) Drilling Camp

The portable Dry Core ice core drying system is designed to operate at the National Ice Core Laboratory (NICL) -24°F “exam room” freezer in Denver, Colorado, but its use is not limited to that facility. Dry Core is designed to simultaneously dry 30,1-meter long ice cores within 8 hours using a 20-horsepower blower which pulls airflow over them in a controlled manner; the E-140 vapor and its odor is then captured by in-line activated granular charcoal (GAC) filters. Exam room chilled makeup air is not required during Dry Core operation since the Dry Core airflow cycle is “closed loop” within the exam room. The NICL exam room freezer has adequate cooling capacity for the additional thermal load of the blower motor/impeller operating in the room. A small-scale

Dry Core feasibility test at NICL has proven the merit and success of the design concept on un-netted (ductile) and netted (brittle) ice cores coated with E-140.

The purchase cost of the proposed full-scale (30 core) Dry Core system — including NICL electrical upgrade for a blower circuit — is estimated at approximately $33,000. The electrical operating cost for Dry Core's blower is approximately $15 per day (8-hour sessions), and the cost to cool the heat generated by the Dry Core blower operating in the NICL freezer is also approximately $15 per day. The activated charcoal is replaceable in the filter housings and will likely need replacement after drying approximately 900, 1-meter long ice ice cores (depending on E-140 film thickness); the charcoal replacement cost is $468 and the replacement work can be done at NICL or at the equipment vendor's factory.

Despite its objectionable smell, E-140 is not considered a hazardous or controlled waste, so "used" charcoal that is loaded with E-140 can be disposed of as common garbage (bagged in polyethylene bags for odor control), or it can possibly be regenerated ("refreshed") in the sun or with another source of heat and reused.

The Dry Core system is designed for ease of use and portability at NICL, and can also be shipped to other locations for ice core drying projects.

A Dry Core sealing gasket material that is compatible with E-140 and the -24°F operating temperature (-36°F storage temperature) is still being investigated and tested at this time prior to material selection.

Background

Ice cores are sometimes drilled using an in-hole lubrication fluid to compensate the pressure in the borehole so that it remains open at deep depths, to decrease chatter at the ice core and drill bit interface, to allow for efficient ice chip removal from the bore, to allow for faster drilling times, and to reduce stress on the ice core and drilling equipment. For the SPice drilling project which uses EstiChem A/S (Denmark) Estisol-140 drill fluid — 2-ethylhexyl acetate synthetic mono ester — some of the odorous, oily, low-volatility fluid remains on the surface of the ice core as it is wrapped in polyethylene plastic (Figure 2) and stored at the drill site or in the -36°F "main storage" ice core freezer at NICL.

Figure 2 – Estisol-140 Residue on Example of Greenland Ice Core and Storage Bag

When the coated cores are subsequently unwrapped for slicing into sample specimens in the “warmer” -24°F processing “exam room” at NICL, the strong, unpleasant smell of the E-140 — some core drillers have described it smelling similar to strong insect repellent, while EstiChem calls it “fruit-like” — could make handling and cutting of the cores an uncomfortable experience. In a report released by Ice Drilling Design & Operations in June, 2015, IDDO personnel comment on “possible headaches, smarting of the eyes, mild lung irritation, and other discomforts”, when using E-140 and EstiChem notes that E-140 is a mild lung and skin irritant). Thus it is desirable to remove as much E-140 as possible from the core surface and surface pores (common on brittle-ice core specimens) without affecting the various types of scientific data contained within the core.

Existing methods tested at NICL and various drill sites to remove the E-140 fluid from ice cores include wiping it off with an absorbent cloth (paper towel), pre-wiping the E-140 residue with Isopar-K drill fluid (to thin the layer and reduce the “tackiness” of the cold E-140) and then wiping both off with an absorbent cloth, displacing and suctioning the fluid off the cores with a high-force “air knife” fluid extraction device (FED) and, with a variant drill fluid (Isopar-K – different vapor pressure and not malodorous), evaporating the surface film using an semi-closed-loop airflow chamber (i.e., 85% air recirculation, with 15% fresh intake makeup air to help expedite the Isopar-K evaporation rate). However, each existing method has its limitations regarding complete removal of the drill fluid film, as well as with E-140 odor control. Further discussion of these previous and ongoing E-140 (and Isopar-K) removal techniques are described in later sections of this document.

After researching several improved E-140 removal and odor abatement solutions based on prior and new information, it was decided that an evaporation and odor-capture method was the best and most effective approach, and which has been subsequently proven with a small-scale feasibility test in 2015 at NICL (discussed in a separate section of this document).

Using the positive results from that feasibility test, the design of a full-scale Dry Core system is proposed based on the goal of drying at least 30, 1-meter long SPice ice cores per day (ideally within 8 hours) at NICL. As well, the drying system must not be in the way of the sequenced ice core processing operations at NICL, and in fact should be designed as part of the sequenced handling and processing regimen.

Proposed Dry Core System

The proposed full-scale, 30-core Dry Core unit is a portable, modular fluid evaporation and odor capture system that uses fast, turbulent airflow in a controlled airspace around each of 30, 1-meter long ice cores to evaporate residual E-140 fluid from the ice surface and surface pores. The E-140 fumes are then captured in granular activated charcoal (GAC) “scrubber” filters, thereby allowing the ice core processing technicians to section the dried cores into scientific samples without the unpleasant, irritating odor of E-140. The system is designed for use in the

-24°F ice core processing “exam room” at NICL (Figure 3) and could be used in other suitable cold locations as well. The system’s airflow is “closed loop” within the exam room, which means it requires no fresh, chilled makeup air into the room; this is beneficial to freezer performance, operating costs, and maintenance.

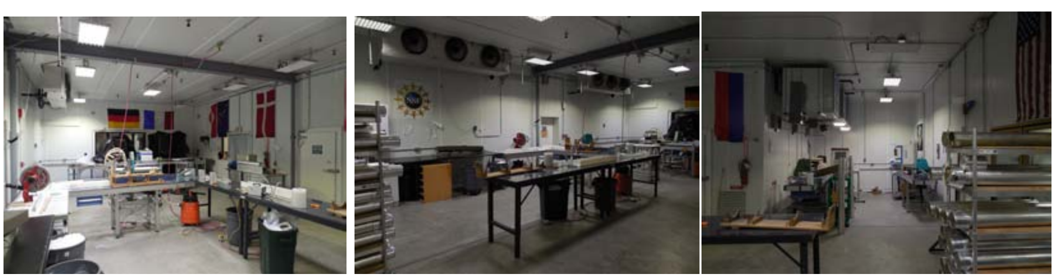


Figure 3 - Various Views of the NICL Exam Room

Dry Core is specifically designed to dry 30, 1-meter long SPice ice cores simultaneously within approximately 8 hours (one daytime work shift, or during the night when there are no people in the exam room). This quantity derives from the goal of drying and processing (cutting into pieces) a total of 950 “wet” South Pole ice cores in serialized sequence over the span of two years (for 1 to 2 months per year), with allowance for work flow interruptions. The preliminary drying and processing schedule for the SPice cores at NICL is shown in Figure 4.

Year Drying To Be Performed	Drying Location	Qty of Ductile Cores (un-netted)	Qty of Brittle Cores (netted)
2016	NICL	200	150
2017	NICL	100	500

Figure 4 - South Pole Ice Core (SPice) Drying and Processing Schedule at NICL (Qty = Meters of Ice Core)

585 meters of the SPice un-netted ductile ice cores have been returned to NICL and are stored in the -36°F main storage freezer; 555 meters of those ice cores were processed in the exam room in 2015, while the remaining 30 meters are in the freezer awaiting processing with the netted and un-netted SPice cores that will be returned in 2016. Note that netted brittle-ice cores at South Pole are allowed an over-wintering “resting” period (Figure 5) to help relax (anneal) and strengthen the brittle cores which came from deep, high-pressure zones in the ice sheet; this helps prevent broken or shattered ice cores.

Figure 5 - South Pole Brittle-Ice Cores "Relaxing" at South Pole Drill Site

The NICL exam room is full of equipment and people during ice core processing periods; the NICL exam room layout for SPice core processing is shown in Figure 6, with the Dry Core system superimposed in the image (left side of large area; not the final location). The lack of extra space in the exam room is evident in this view.

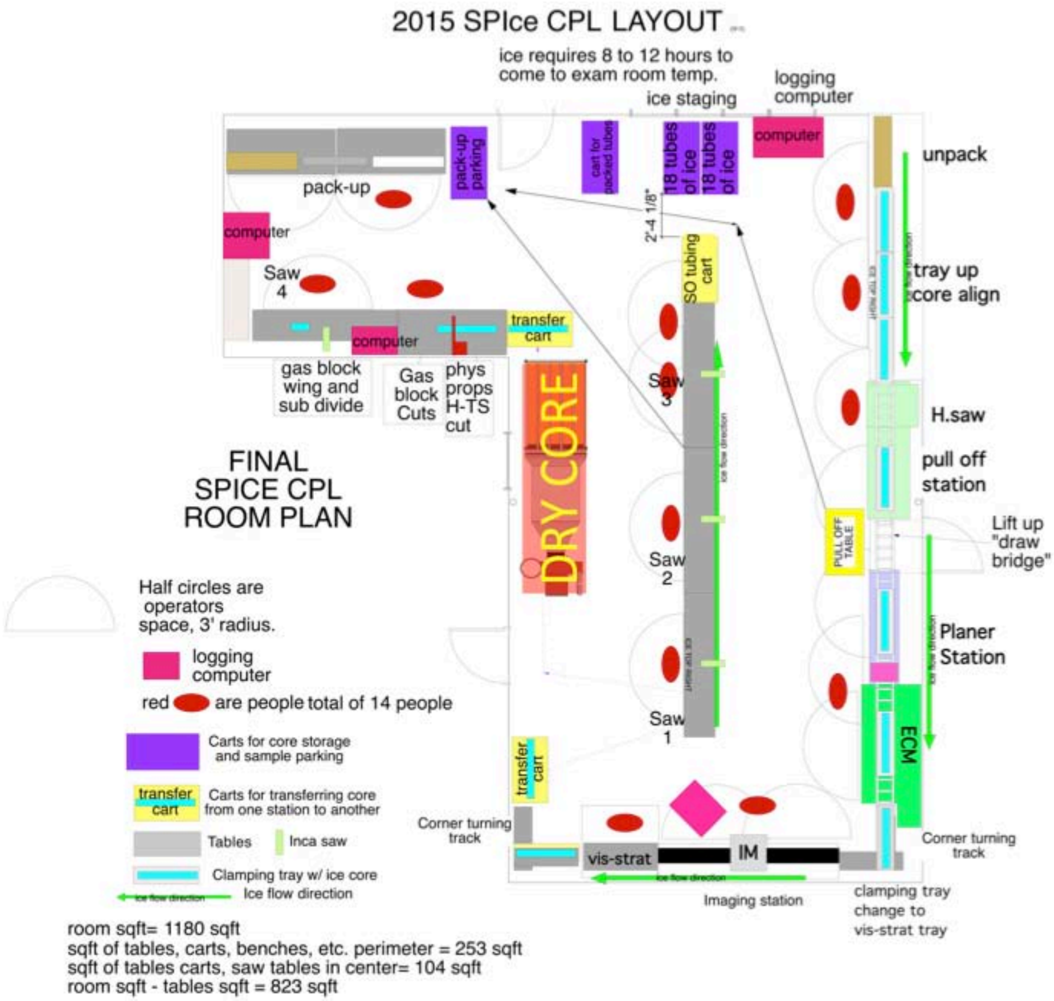


Figure 6 – NICL Exam Room Layout Ice Core Processing for SPice Ice Cores, with Dry Core System Shown for Scale (Plan View)

The Dry Core system can be installed and operated during the daytime in the NICL exam room while ice core processing is occurring or, alternatively (due to space constraints and noise allowance limits in the occupied room) it can be operated unattended at night in the exam room when the staff and processing crew has gone home (and once NICL staff gains confidence in Dry Core's operation and performance).

To perform night-time Dry Core drying operations in the exam room, it may be necessary to move some of the ice core processing equipment out of the way each night, but that is relatively easy to do as the processing equipment is on wheels. The Dry Core system is also on wheels so it can be rolled into the exam room and placed in the desired location when needed, and then moved out of the way or entirely out of the exam room when not needed.

To provide maximum flexibility for transport, use and storage, Dry Core system is designed as three separable modules — Ice Core Module, Charcoal Module, and Blower Module (see Figures 7 and 8) — and each module is mounted on a wheeled “dolly” base so that they can be separately rolled through 36”-wide exam room freezer doorways at NICL and placed in the desired location.

The modules connect to each other with toggle clamps, while suitable interface gaskets and flexible couplings create a sealed system to keep the E-140 odor within the airstream until absorbed by the in-line charcoal filters. The blower is located at the end of the system so that it draws air through the drying tubes and charcoal filters; even if a gasket joint leaks during a drying session, the slight vacuum (negative pressure) created inside the Dry Core system prevents E-140 odors from escaping before it is adsorbed by the charcoal media.

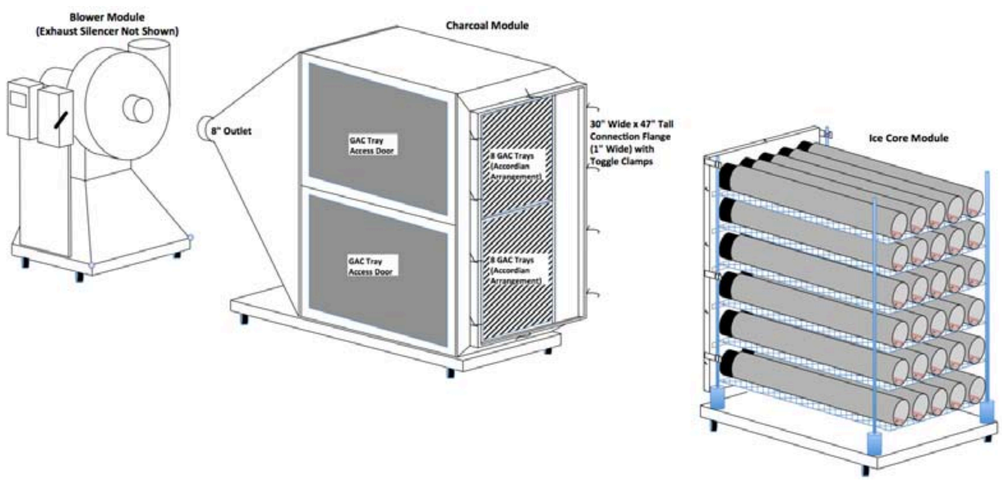


Figure 7 - Separated Dry Core Modules

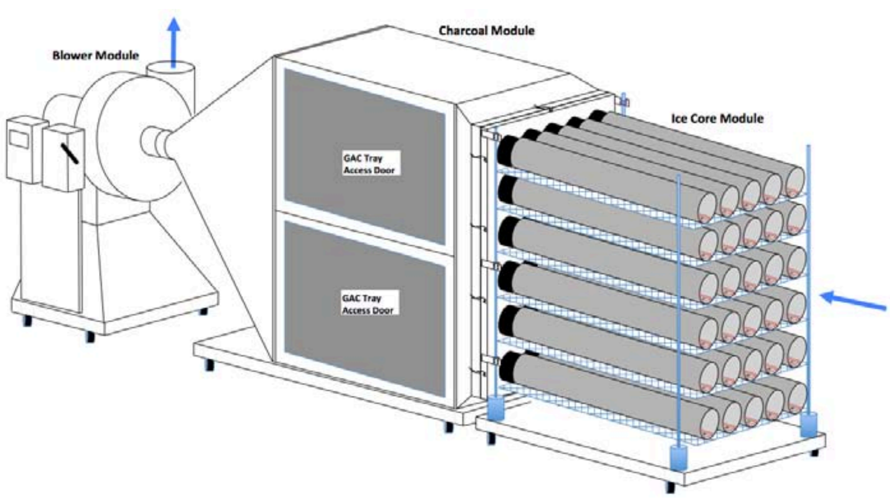


Figure 8 - Connected Dry Core Modules

Ice Core Module

The Ice Core Module is a 6-shelf metal rack (Metro) affixed with 30, 1-meter long metallized cardboard “drying” tubes that contain the ice cores; the tube material and construction (Chicago Paper Tube and Can Co.) is typical of most NICL ice core tubes, and the proven aluminum foil covering (inside and outside) prevents moisture degradation of the cardboard. A custom-made vertical sheetmetal “port plenum” (Progressive Manufacturing Inc.) is permanently bolted to two posts at the end of the Metro shelves, and flexible PVC couplings (Fernco) permanently connect the 30 tubes to the 30 open ports (which are butted end-to-end with negligible gap at the butt joint to minimize E-140 exposure to the flexible coupling). Once assembled the Ice Core Module remains assembled at all times unless a component is damaged and needs replacement. Each 1-meter long ice core is placed concentrically inside each “drying” tube to promote controlled, equal and uniform airflow conditions for all the cores (see Figures 9-12). The 5-inch inside diameter of each drying tube is sized specifically to create an air-gap annulus of 0.57 inches around the 3.86-inch-diameter South Pole ice cores, thus achieving evaporation-enhancing turbulent airflow over the core surface at the specified airflow rate of 110 CFM (cubic feet per minute) per tube; the estimated pressure drop in the tube is 5-6” inches water-column (WC) at this flow rate, and each tube and port is sturdy enough to withstand this suction. The u-channel on the bottom of each tube cradles and centers the core because the uniform air annulus helps ensure uniform ice core drying; the u-channel has a beveled entrance end to help prevent ice core impact damage (i.e. chipping or shattering) when sliding the cores into the tubes. The drying tube length is designed to accommodate a core as long as 41.5 inches. The Ice Core Module dimensions are approximately 34”W x 54”L x 76”H, and fully loaded with ice cores the Module (including 4-wheeled dolly with 2 brakes) weighs approximately 1000 pounds and can be rolled and maneuvered by 1-2 people.

It was observed during the small-scale feasibility Dry Core trials that the ice core needs to protrude slightly from the tube entrance for best drying on the initial “entrance zone” surfaces (due to entrance air deflection caused by the core’s blunt end); this protrusion distance will need to be confirmed on the final Dry Core system but it will likely be approximately 1-2 inches.

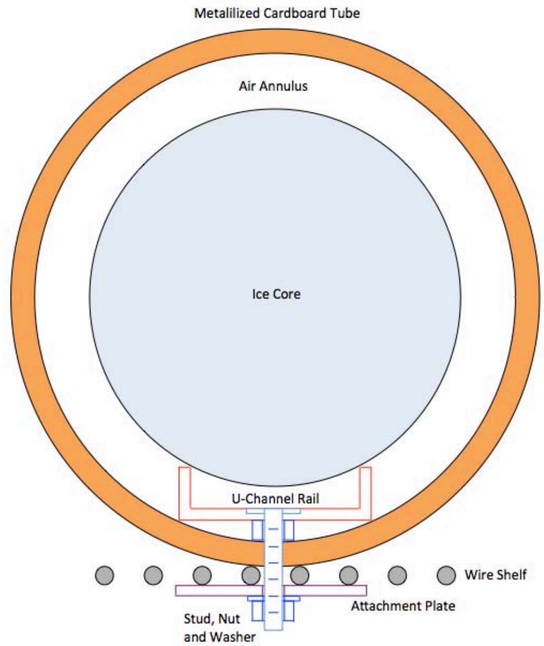


Figure 9 - Cross Section of Typical Ice Core Located Concentric In A Drying Tube

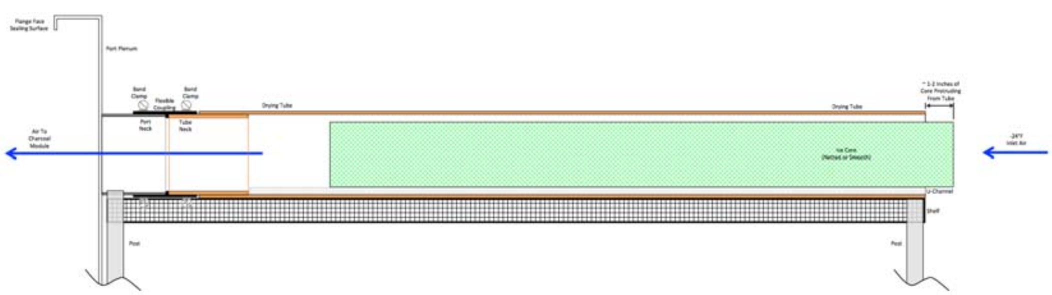


Figure 10 – Section Side-View of Ice Core In Drying Tube On A Shelf, Connected To Port

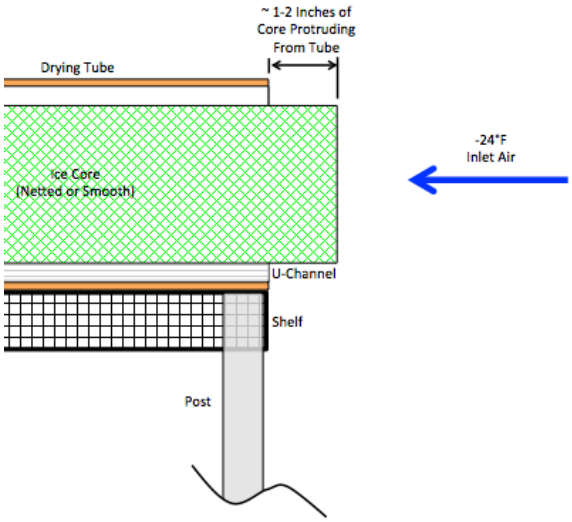


Figure 11 - Entrance End of Drying Tube

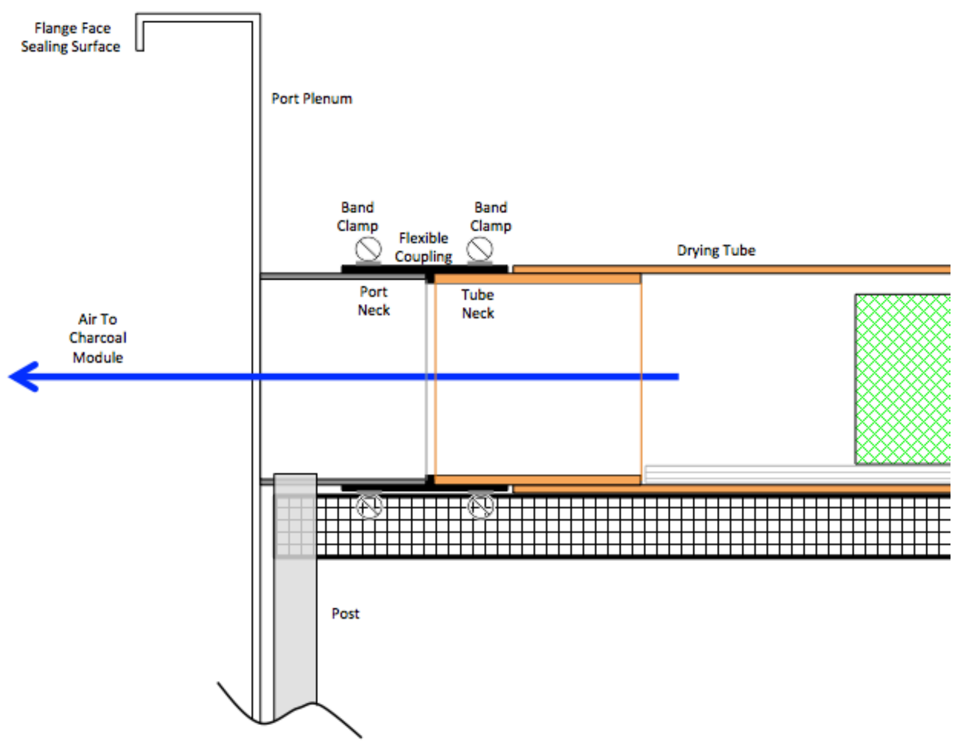


Figure 12 - Exit End of Drying Tube

It is important to note that any tube that has no ice core must instead have a "proxy" ice core (e.g., cardboard, wood, metal, plastic, etc., of the same diameter and length) or an end cap with a proper-diameter air-bleed hole to create the required air pressure drop caused by a real ice core in the tube. Otherwise air will “short-cut” through the empty, open tube, which will reduce the airflow rate and slow down the drying time in all the other tubes. Simply capping off an empty tube to block airflow will increase the airflow rate in all the other tubes and possibly cause excessive ice sublimation or other problems unless the airflow rate is re-adjusted.

Charcoal Module

The Charcoal Module (General Carbon Corporation) is a stainless steel box with 16 charcoal-filled stainless steel filter trays (“scrubber” filters) mounted inside on gasketed tracks in an accordion-like manner (Figures 13-15). This pleat-like tray layout creates a large amount of tray “facial area” (32 ft^2) to minimize the pressure drop of the 3300 CFM total air flow rate through the box (110 CFM per tube x 30 tubes), and also creates the desired air velocity at each charcoal tray’s inlet face so that the air/charcoal contact time allows for complete E-140 odor adsorption. Pressure drop through the charcoal module at 3300 CFM is estimated to be 1 inch WC, and the manufacturer states that the metalwork system can withstand the estimated total vacuum of 8-inches WC created by the airflow resistance of the combination Charcoal Module and Ice Core Module operating in series airflow.

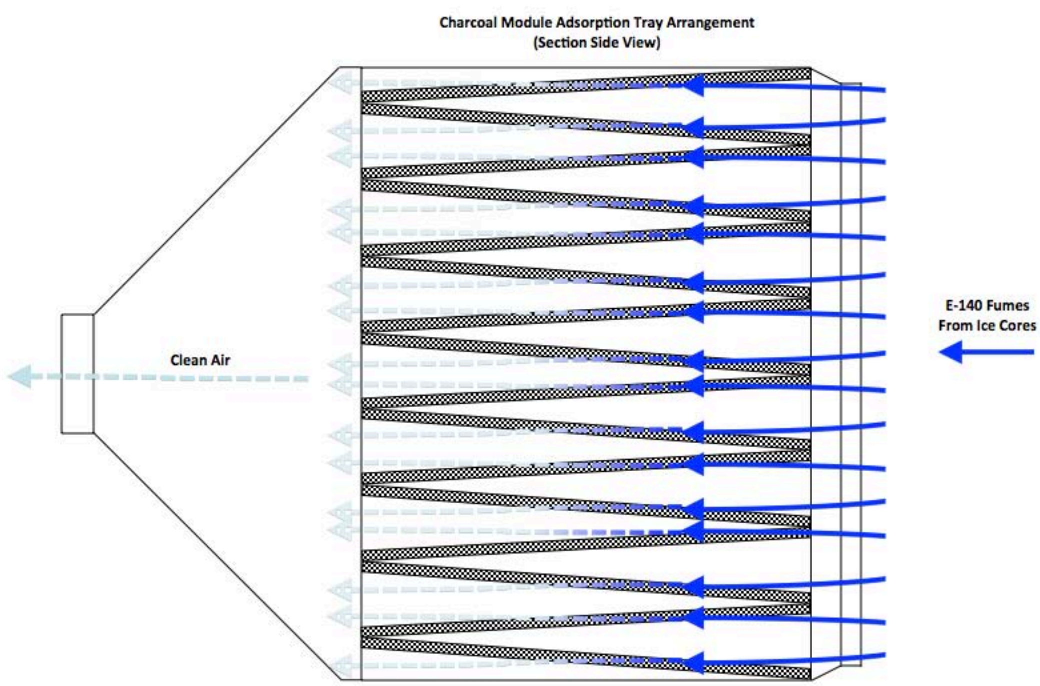


Figure 13 - Accordion-Like Charcoal Tray Arrangement In Charcoal Module (Side View)

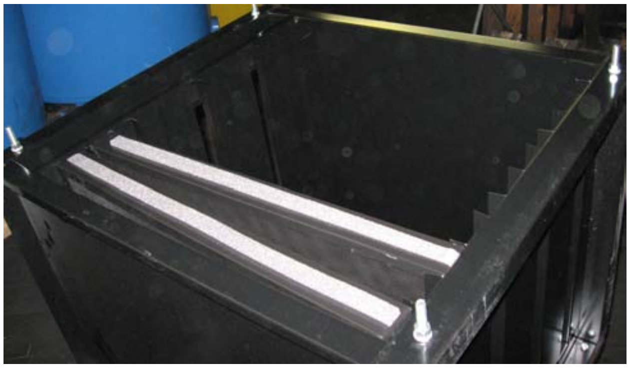


Figure 14 – Example of Charcoal Trays in Their Tracks (Track Gaskets Not Shown)

Figure 15 – Typical Tray Air Inlet Area, and Edge Openings For Charcoal Refill

Stainless-steel sheet metal inlet and outlet transitions (also manufactured by General Carbon Corp.) are bolted and sealed on each end of the charcoal box. The inlet transition flange mates and seals against the Ice Core Module flange with toggle clamps and a replaceable gasket (gasket material to be determined), and the outlet transition seals to the blower intake neck with a round, flexible PVC coupling (Fernco) using band clamps. The 16 charcoal trays within the box can be easily removed through the side access doors for bulk-pour charcoal replacement via the trays' edge-fill openings. The trays are made of stainless steel (4 pounds empty) and can be reloaded many times with new charcoal (refill = 18 pounds of charcoal per tray, and bulk refill bags of granular activated charcoal weigh 55 pounds each), although it is estimated that a new filling of charcoal will be able to adsorb the E-140 vapor from at least 900 ice cores before reaching a conservative 20% odor-breakthrough loading limit. The Charcoal Module dimensions are approximately 32"W x 74"L x 66"H, and fully loaded with charcoal trays the Module (including the 4-wheeled dolly with 2 brakes) weighs approximately 1200 pounds and can be rolled and maneuvered by 1-2 people.

Blower Module

To evaporate the E-140 from the ice cores within the 8-hour time limit desired by NICL staff, the Dry Core system is designed (based on the feasibility test results) to have turbulent and equivalent 110 CFM airflow in each tube and then reasonably uniform airflow streamlines beyond that to minimize further pressure drop and to avoid excessive "air stall" and turbulence zones after the tubes. A

3300 CFM suction blower will create the desired 110-CFM vacuum airflow rate in each of the 30 tubes, though the airflow rate may need slight adjustment in the final, full-scale Dry Core system and thus the Blower Module provides for that adjustment. The Blower Module consists of a 20-horsepower centrifugal blower capable of generating 3300 CFM with 8 inches of WC inlet suction. Also included is a hand-operated airflow damper plate (Howden American Fan) and a variable-frequency drive (VFD) speed controller box (Yaskawa). For noise reduction there is an optional blower motor/impeller sound-reduction jacket (various brands) and an optional 3-foot-long, flow-through blower exhaust silencer (Fan Tech). All components are mounted on a wheeled base. The blower's mechanical inlet damper plate provides course airflow adjustment of the Dry Core system during initial system setup, while the electronic, harmonic-free VFD motor controller allows course and fine adjustment of the airflow and pressure drop during initial Dry Core setup and trials, and also allows adjustment of the airflow to accommodate the pressure drop in the tube annulus created by slightly different ice core diameters from other drilling projects. The VFD controller also allows the user to easily compensate for the air density (airflow) at operating conditions different than NICL's 5500-feet elevation and -24° exam room (where the air density correction factor is 1.01). The blower is estimated to produce a noise level of 81 dBA at 16 feet, and the two noise reduction options (blower jacket and/or exhaust silencer) are each estimated to reduce the sound level by 10-15 dBA. The Blower Module dimensions are approximately 32"W x 28"L x 57"H (without exhaust silencer), and the Module (including 4-wheeled dolly with 4 brakes) weighs approximately 800 pounds.

The individual Dry Core Modules are shown in Figure 16, and the complete, connected Dry Core system is shown in Figure 17. The complete Dry Core system is approximately 13-feet long x 34-inches wide (at the widest component).

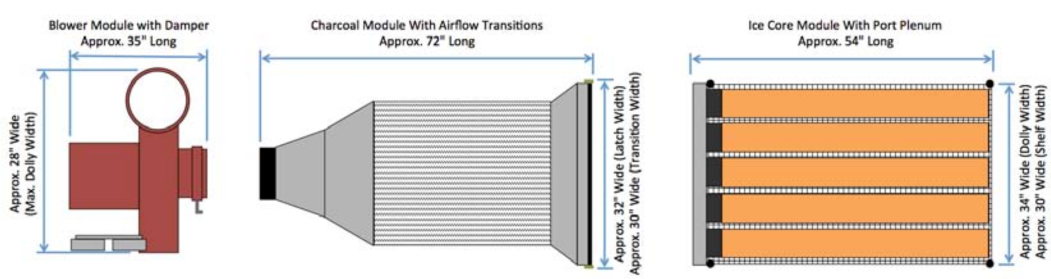


Figure 16 - Top View of Separated Dry Core Modules

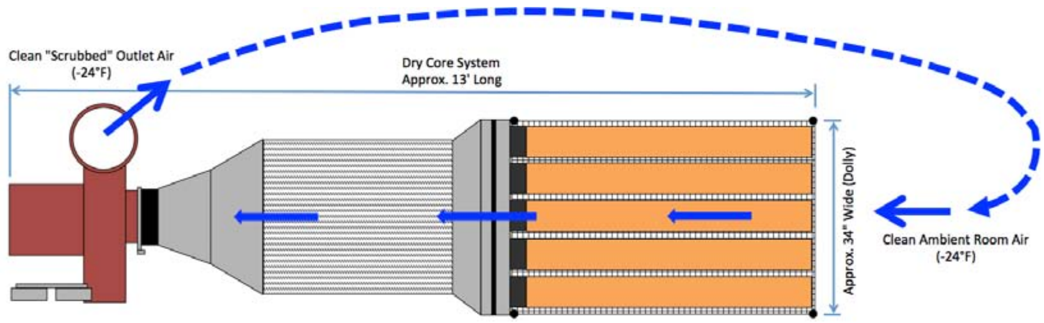


Figure 17 - Top View of Connected Dry Core Modules

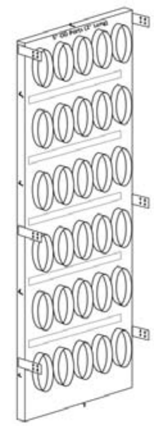
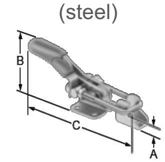
Dry Core System Cost

Dry Core is a combination of standard off-the-shelf components and custom fabrications; one complete Dry Core assembly is estimated to cost $28,923, and there is also an estimated $4,000 of NICL electrical upgrades (40-amp 460/3-phase circuit breaker wired to a 30-amp NEMA-style outlet in the exam room) required before Dry Core can be used there. These costs do not include the engineering time to create the detailed Dry Core equipment drawings and write the Procurement Specification.

The Dry Core Bill of Material is shown below for each Module, for optional items and for NICL electrical upgrades. The suggested suppliers, components, and pricing estimates are based on research performed in 2015. The blower lead-time is approximately 8-12 weeks at receipt of order; other items listed in the BOM are available sooner to begin assembling into a Dry Core system while awaiting receipt of the blower.

Ice Core Module - Bill of Material

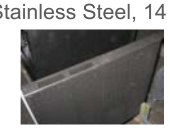
	Item	Vendor	Distributor/Rep. Contact	P/N	Quantity	Cost Each (List)	Cost Extended (List)
	30”W x 48”L Metro 6-Shelf Assembly on 34” x 52”Dolly	Metro	CO: Dave Difolco 720-556-9856 NH: Bryan St. Onge 978-973-7386	3048NS 6 Erecta Shelves (30”x48”) 74PS Staked 4 Posts (74”L x 1” Diam.) D3048NCB (1 Dolly Plate, 34”x52”) B5PR (2 rigid non-breaking casters) B5PB (2 swivel breaking B-casters) Dolly rated for 1200lb Casters have -30°F grease 	1 Unit	$3458	$3458
	Port Plenum	Progressive Manufacturing	Patrick Moynihan 603-298-5778	Custom Sheetmetal Plenum (incl. CAD work): 30”W x 47”T x 3”D, 11G 304SS with (30) 16G 5.0” OD Ports (rolled), and	1	$3900	$3900

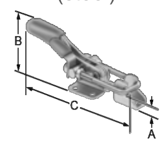
				10 perimeter toggle clamp catches 			
	Toggle Clamp (install only the catch on Ice Core Module)	McMaster-Carr	330-995-5500	5071A51 (steel) 	8	$0	$0 (see Charcoal Module for cost)
	Metallized Cardboard Tubes	Chicago Paper Tube and Can Co.	Bob Dudlak 773-283-9500	46"L (+/- .38") x 5.4" OD x 5.0" ID (with Neck on one end 5.0" OD x 4.5" ID with 2" protruding and 3" inside). Aluminum foiled in/out. Open both ends. 	30	$19.80	$594

	U-Channel (for inside cardboard tube)	McMaster-Carr	330-995-5500	1630T29 2”W x 1”H x 60”L 6061 Aluminum. (Machined to 2.0”W x 0.55”H x 42.5”L) 	30	$20	$600
	Mounting Plate (for U-Channel & Tube to Shelf)	Not Specified	Not Specified	2” x 2” x 0.125” with 0.265” Hole, 304SS 	60	$0.75	$45
	Pemstud (for U-Channel)	McMaster-Carr	330-995-5500	93580A640 Flush Pemstud FHS0424-24, ¼-20 x 1.5”, 18-8 SS 	60	$40.95	$57
	Nut (for Pemstuds)	McMaster-Carr	330-995-5500	91845A029 ¼-20 Hex Nut, 18-8 SS 	120	$0.05	$6
	Washer (for Pemstuds)	McMaster-Carr	330-995-5500	92141A029 ¼”, 18-8 SS 	120	$0.03	$4
	Pipe Strap	Eaton	Green Mtn Electric 603-298-7113	B2400-3/4ZN	6	$7.70	$46

							
	5” Diam. Fernco Couplings	Fernco	F.W. Webb	1060-44 (5.01” x 5.01” ID) 	30	$28.90	$867
	Polyethylene Tape	Grainger	800-472-4643	LB13012-2BL (9KFM7) 1” Wide x 36yd Roll 	1	$10	$10
						Ice Core Module Total	$9,587

Charcoal Module - Bill of Material

	Item	Vendor	Distributor/Rep. Contact	P/N	Quantity	Cost Each	Extended Cost
	Stainless Steel GAC Dual-Stacked Boxes with Inlet and Outlet Transitions	General Carbon	Kristen Ascione 973-523-2223	Dorex 2000S2 (2 boxes stacked, Buna-N (TBD) track gaskets No GAC trays 304 Stainless Steel, 16 Gauge 	1	$6113	$6113
	GAC Tray with Charcoal Fill	General Carbon	Kristen Ascione 973-523-2223	Tray Pre-Filled with 18 lbs of CG4x8S Charcoal 304 Stainless Steel, 14 Gauge 	16	$93	$1488
	1"W x 1"H Inlet Gasket with Acrylic PSA (bulb-shape or flat shape TBD, and more research	TBD	TBD	TBD 	13 feet	$8/ft (est.)	$104 (est.)

	needed for compatibility with E-140)						
	Toggle Clamp (install only the handle on Charcoal Module)	McMaster-Carr	330-995-5500	5071A51 (steel) 	8	$15.75	$126
	GAC Dolly	Custom	Tom Bonardi Bonardi Steel, Inc. 603-632-7400	30" x 70" Aluminum C-Channel and Plate Urethane Caster Wheels Low-Temperature Grease	1	$1840	$1840
						Charcoal Module Total	$9,671

Blower Module - Bill of Material

	Item	Vendor	Distributor/Rep. Contact	P/N	Quantity	Cost Each	Extended Cost
	Blower, 20HP, VFD-Ready, Steel Wheel and Housing	Howden American Fan	John John Bonardi Associates 603-527-8218	AF-18-R16550-8-10, 20HP, Steel Housing and Wheel (per NICL), 460VAC 3PH, Direct Drive, VFD-Ready, 23FLA, 256T Frame, Inlet Damper	1	$4737	$4737

							
	VFD Blower Speed Controller	Yaskawa	John Bonardi Associates 603-527-8218	4A0031FAA 	1	$2575	$2575
	Fusible Disconnect Switch (Local, Within Sight)	Square D	Square D	CH362RB Rated at 600V, 60A, 3 Pole, Fusible, Type 3R (Install 30A Fuses) 	1	$845	$845
	Power Cable (Portable)	CerroWire	Home Depot	SOOW, 600V, 6/4 (6 AWG, 3C & G)	25	$4/ft	$100
	Power Plug (Male)	Hubbell	Hubbell	To Be Determined	1	$50	$50

	Fernco Coupling (8” Blower Inlet)	Fernco	F.W. Webb 603-448-1980	1001-66WC (8.01” x 8.01” ID) 	1	$9	$9
	Fernco Coupling (10” Blower Outlet)	Fernco	F.W. Webb 603-448-1980	1001-88WC (10.0” x 10.0” ID) 	1	$29	$29
	Blower Dolly	Custom	Tom Bonardi Bonardi Steel, Inc. 603-632-7400	28” x 32” Aluminum C-Channel and Plate Urethane Caster Wheels Low-Temperature Grease	1	$1320	$1320
						Blower Module Total	$9,665

Dry Core System Total $28,923

Electrical Upgrade at NICL

	Electrical Upgrade at NICL For 460VAC 20HP Blower	NICL Electrical		40A 460V 3-PH Circuit Breaker, Conduit, Wires, 30A NEMA Outlet,	As Required	$4000 (est.)	$4000 (est.)

	Circuit to NICL Exam Room	Contractor		etc.)				

Replacement Charcoal (replacement required after ~1000 cores are dried, depending on ice core wetness)

	Replacement Charcoal (Bulk)	General Carbon	Bob 973-523-2223	GC4x8S (Bulk)	275 lbs (in 55-lb bags)	$1.70/lb	$468	

Optional Items

	Air Flow Meter	TBD	TBD	Anemometer in Metering Tube (Rated for -24°F use) 	1	$500 (est.)	$500 (est.)
	Blower Exhaust Silencer (est. 10-15 dBA reduction)	Fan Tech	800-747-1762	LD 10, Galv. Steel with Fiberglass 14" OD x 35.5"L, 10" OD Cuffs 	1	$300	$300
	Blower Sound Jacket (est. 10-15 dBA reduction)	Howden American Fan	John Bonardi Associates 603-527-8218	Loaded Fiberglass, Teflon/Vinyl Cloth	1	$680	$680

Electrical Operating Cost and Freezer Make-Up Air

The 30-tube Dry Core system requires a 20-horsepower blower (460 volt, 3-phase) to supply the required system airflow for effective evaporation, and drying a batch of 30, 1-meter long ice cores in 8 hours would add approximately $15 to the NICL electric bill (at $0.10/kWhr); the blower electrical bill for drying 900 1-meter long cores (30 batches of 30 cores) would be $450.

Importantly, the Dry Core system does not require any chilled make-up air to enter the -24°F NICL freezer because, as the offensive E-140 fumes are evaporated from the ice cores, they are immediately sequestered by Dry Core's in-line activated charcoal filters. This is considered a closed-loop system in that there are no freezer penetrations required for the E-140 evaporation/capture process, thus avoiding considerable chilled makeup air costs and also avoiding possible freezer condensation or frost issues.

However, it is estimated that approximately 59,000 BTU/hr (5 tons) of additional freezer cooling capacity will be required to offset the heat produced by the Dry Core blower motor (with closed-loop Dry Core airflow pattern) operating in the freezer during each drying session; this additional freezer electricity bill would also be approximately $15 per batch of 30, 1-meter long cores, or $450 per 900, 1-meter long cores. According to NICL refrigeration experts the NICL exam room's chilling system is currently at approximately 10% capacity, and with the Dry Core blower operating in the room (without people) the chillers would then be operating at 68% capacity during the usage period. If 15 people were also in the exam room at the same time (during typical day-time work), the chilling system would be at approximately 76% capacity (cooling the people and the Dry Core blower). Though daytime Dry Core operation still allows ample cooling capacity margin, night-time drying sessions with Dry Core are recommended for several reasons, as explained below.

Dry Core Operation at Night

When ice cores are being processed at NICL during the daytime the exam room is typically full of equipment and technicians, leaving little open space for the Dry Core equipment. Also, the extra noise from the Dry Core blower (estimated at 81dBA at 16 feet) added to existing ambient noise could exceed the room's total allowable noise limit (per OSHA) during the day. As well, the additional people in the exam room (sometimes as many as 15) during the daytime adds to the thermal load that needs to be chilled, reducing the margin on the exam room's cooling system capacity.

One option around these concerns is to dry the ice cores during the night. As suggested by NICL personnel, it is feasible each evening to roll some of the exam room's processing tables and equipment out of the way to make room for Dry Core. Then the Dry Core Modules, with damp ice cores already loaded in the tubes in the desired sequence, would be rolled out from the -36°F storage room and connected together in the exam room. After the blower is energized and the airflow in several tubes are spot-checked with an airflow meter (mounted in a separate metering tube that butts up to the entrance of the drying tube), the night-drying session on batches of 30 cores can be done unattended (once comfort with the system is gained) without impacting daytime processing operations. To prevent operating the Dry Core blower longer than 8 hours (which might cause excessive ice sublimation), the blower motor's VFD controller can provide a timed airflow shutoff or slow down the motor for significant airflow reduction. Once dried, the ice cores remain in the exam room on the Dry Core shelves until morning. At the start of the day shift the Ice Core Module remains in the -24°F exam room and the un-needed Dry Core Charcoal Module and Blower Module are wheeled out of the exam room for temporary cold storage in the -36°F storage room, out of the way of all operations. Then the technicians can process the dried ice cores in sequence directly from the Ice Core Module tubes. Regardless of daytime or night-time Dry Core operation, one technical aspect still to be resolved is to find a gasket material (the interface between the Ice Core Module and the Charcoal Module) that remains flexible and resilient at -24°F and -36°F, and is also resistant to E-140.

Outdoor ISO Freezer Option

To avoid adding Dry Core blower motor heat load to the exam room freezer, day or night, there is an option to operate the Dry Core system in a rented "blast-freezer" shipping container (Klinge Corp., York, PA) that would be parked in the NICL parking lot at the docking door. The rented freezer unit would be plugged into the 460V 3-phase power outlet at the docking door (usually used for the unrelated Safe Core ISO freezer container system). The Klinge freezer system can be set to maintain -24°F inside regardless of outdoor temperature. It has its own circulation dryer blower for drying the ice cores in lieu of using the modular Dry Core blower, but does not have a VFD speed controller to dial in the required Dry Core airflow rate; for that adjustment, a course flow-control damper plate could be installed on the Dry Core Charcoal Module outlet neck. The daily rental cost for the Klinge blast-freezer unit is $129/day for long-term rental, including the flatbed chassis. While the Klinge blast freezer is parked at the primary loading door near the docking ramp, any other incoming ice core shipments could be unloaded at the secondary loading door near the rear of the main storage freezer. Other appropriate blast freezer units besides the Klinge brand may also be available.

E-140 Odor Control During Dry Core Module Storage

When not in use in NICL's -24°F exam room, any of the three Dry Core Modules can be rolled out to create more floor space in the room. However, the interior of the metallized-cardboard drying tubes, metal plenum, and metal transitions *may* (to be determined) pick up and retain traces of E-140 odor, and certainly the charcoal media, by design, will have adsorbed the E-140 odor although it should "hold" the odors within the charcoal matrix. Regardless, any Module that smells when moved to a room warmer than -24°F should instead be moved to a colder room (such as the -36°F Main Storage Room) to dramatically reduce any potential E-140 off-gassing odor.

Alternatively (if needed), if any of the Modules are rolled to a room warmer than -24°F and an E-140 odor is noticed, polyethylene plastic wrap or other suitable material can be used to block the Module openings to prevent odors from evaporating and mixing into the room air. If desired or if it's easier, the charcoal trays can be removed from the Charcoal Module and placed in polyethylene bags if they are the only Dry Core component emitting E-140 odors in the warmer space.

Another option is to remove the E-140-loaded charcoal pads and dry them in the warm sun in the NICL parking lot for several hours per day for several days, thus "refreshing" the charcoal instead of replacing it. Note that this method does not dry the metalwork or other parts of Dry Core that might have retained the E-140 odor, and that the outside drying timing and location of the charcoal filters will need to be done with care to prevent odors from annoying NICL neighbors. Since E-140 fluid and fumes are not considered hazardous air permits are not required for "refreshing" the charcoal, but to be a good neighbor it would be wise for NICL staff to located the drying area to avoid annoying others.

Another solution for warm-space Dry Core storage is to roll the entire Dry Core system to an appropriate warm location, connect the three Modules together, power the Dry Core blower motor and run it at a slow speed (using the VFD controller), and vent the exhaust to outside the occupied space via a wall or roof vent, or as deemed suitable by NICL staff. If the warmer storage space is outside of a freezer zone (such as in NICL's main warehouse) then room-temperature makeup air (not freezer makeup air) will suffice for this low-flow odor-control storage setup. As with the sun-drying method, the outside vent location and the timing of the venting process outside the NICL building will need to be done with care to prevent odors from annoying NICL neighbors. After some time (duration to be determined), the E-140 residue should be completely evaporated from all the warm surfaces and the blower can be de-energized and the odor-free Dry Core system further prepared for long-term storage.

As noted previously, at this time there are no known Denver or Colorado regulations that preclude “airing out” the E-140 odors retained in the charcoal trays or the entire Dry Core system to the outdoor air, but NICL staff will need to investigate this further to ensure compliance with regulations that may exist on this matter.

With proper preparation such as this, the odor-free Dry Core system can be crated and transported by truck, aircraft, or vessel to other sites, even under warm conditions.

Gasket and Coupling Material Selection

The Dry Core design includes a flexible gasket mounted on the inlet side of the Charcoal Module’s inlet transition perimeter flange; this seals against the Ice Core Module’s port plenum perimeter flange. As well, each Charcoal Module tray sits on a track lined with a polymer gasket to prevent air from bypassing the trays. Any gasket exposed to the airstream upstream of (before) the charcoal filters must withstand E-140 vapor flowing past it without excessive degradation of its properties or loss of air seal at the interface. It must also be conformable and resilient enough so that it can seal when compressed at -24°F (on the inlet transition flange) and also rebound back to its original thickness when the Ice Core Module is detached from the Charcoal Module at -24°F. Research is underway to find a suitable gasket material that meets these criteria.

EstiChem provides a polymer compatibility chart for E-140 (Figure 18) showing that most “usual” gasket materials (Neoprene, Viton, Nitrile (Buna-N), natural rubber, silicon rubber, and EPDM) are poor choices with E-140 fluid, and field experience by American, Australian, Danish and other ice core drilling teams, and staff at NICL, verify that, indeed, most of those “unsuitable” materials either dissolve or dramatically swell or soften when in contact with E-140. Surprisingly, the EstiChem Material Safety Data Sheet (MSDS) for E-140 lists Nitrile gloves as a “somewhat” suitable material for handling liquid E-140 despite the field evidence that Nitrile dissolves in E-140. From field experience (and per EstiChem’s chart) polyvinyl chloride (PVC) is known to work well with E-140 fluid, and field experience shows that EPDM is reasonably resistant (only slight material swelling) to E-140 despite the EstiChem’s poor rating of

EPDM. Part of the material compatibility conflict is that there are so many slight variations of the generic version of Nitrile or EPDM or any other polymer; there may in fact be one exact polymer formulation that works well with E-140, and perhaps many other polymers with the same name, but made by other manufacturers, that fail.

ESTICHEM

PRODUCT INFORMATION

Polymer Compatibility
Synthetic Esters

Description

The data in the table below are based on the percentage volume increase after contact with the solvent for [illegible] h at room temperature[illegible] The amount of swell gives an indication of compatibility[illegible] Specific plastics should be tested individually[illegible]

Polymer Swell Properties

Polymer	ESTISOL 140	ESTISOL 150	ESTISOL 165	COASOL	D60	D100	A III
PMMA	A	–	–	A	A	A	A
NBR	C	C	B	C	B	A	A
EPDM	E	A	A	C	E	E	E
Neopren	E	A	A	C	E	E	E
Silicon rubber	E	A	A	B	E	E	E
PP	A	A	A	A	A	A	A
PE	A	A	A	A	A	A	A
PC	A	A	B	A	A	A	B
PS	A	B	A	A	A	A	A
PVC	A	C	A	A	A	A	A
PA-6	A	A	A	A	A	A	A
Natural rubber	E	B	A	E	E	E	E
Viton	E	E	E	D	A	A	A

D60 = De-aromatised hydrocarbon with flash point 60°C,
D100 = De-aromatised hydrocarbon with flash point 100°C
A III = White Spirit with flash point >55°C.

PMMA = polymethyl methacrylate, NBR = acrylnitrile butadiene rubber, EPDM = ethylene propylene diene rubber, PP = polypropylene, PE = polyethylene, PC = polycarbonate, PS = polystyrene, PVC = polyvinyl chloride, PA-6 = polyamide-6.

Compatibility levels in % v/v swell or shrinkage:
A = 0-5
B = 6-15
C = 16-30
D = 31-50
E = > 50
– = dissolved

Page [illegible] of [illegible]

Figure 18 - EstiChem Material Compatibility Chart

So with charts and field evidence somewhat in conflict, additional material compatibility tests are being performed at NICL at this time on various types of polymers from several manufacturers. The long list of “unsuitable” polymers is not discouraging however, as the Dry Core gaskets and couplings will not be immersed in the E-140 fluid but rather will experience a low-concentration E-140 vapor when it flows out of the evaporation tube and past the flexible coupling and sealing gasket. Therefore it is likely that the very small amount of coupling area and gasket area exposed to the passing airflow might experience only a small amount of E-140 misting or slight wetting, at most. This minimal gasket exposure area combined with low E-140 vapor concentration and the cold temperature helps minimize the chemical compatibility effects.

The flexible PVC clamp-on coupling (Fernco) proposed for use between the cardboard tube and the metal plenum port ring has been tested at NICL in E-140 liquid and exhibited some swelling when immersed in E-140 fluid and knowing this, the port-tube interface will be a tightly-fitted butt join to minimize E-140 contact with the coupling, and could also include a protective polyethylene tape wrap over the interface gap prior to installing the Fernco coupling between the tube and port to create an additional barrier between the E-140 and Fernco coupling. The Fernco material did experienced decreased flexibility at -24°F but was still usable for the intended permanent seal, and it was hard at -36°F but was not damaged by the cold and recovered to usable flexibility again at -24°F. Therefore the Fernco-brand coupling (made of their proprietary formula of flexible PVC) has been selected for that seal; other brands of flexible couplings must be tested with E-140 prior to use.

Previous E-140 Removal Methods

Because of the undesirable odor (to some people) and the skin/lung irritation risk of the E-140 fluid, it is desirable to remove as much E-140 as possible from the ice core surface as well as surface pores (common on brittle-ice core specimens) without affecting the various types of scientific data contained within the core. There have been several methods tested at various sites to remove drilling fluid from ice cores; wiping off the fluid with an absorbent cloth (paper towel), blowing or suctioning the fluid off the cores (fluid extraction device – FED), and evaporating the fluid off the cores. The methods are discussed below.

Absorbent Wipe Method (Aurora Basin; E-140)

At the Australian Aurora Basin North (ABN) drill site in Antarctica, E-140 fluid was removed from ice cores by simply wiping them with dry paper towels, followed by a 24-hour air-dry in an open-air tent, followed by further wipe-down with paper towels. Though a faint E-140 odor still existed even at cold temperatures it was not reported as an issue by the people at that site. The wipe-down method generates many wet, smelly rags, though if the wet rags remain very cold (approx. -20°F to -36°F) the E-140 evaporation rate is slow and the smell is not overly extreme. But if the rags (or clothing that contacts the E-140) are warmed the smell becomes much stronger because the E-140 evaporation rate is dramatically increased. A benefit of enduring E-140 fumes evaporating from warm clothing and rags is that eventually the odor is gone from clothing or rags. In general, all used wipe-down rags and clothing with E-140 should be stored in an airtight container or bag as they await proper airing, cleaning or an approved method of disposal.

Absorbent Wipe Method (South Pole; Isopar K and E-140)

An absorbent cloth or paper towel with a solvent such as ethanol can be used to manually wipe off the oily E-140 from the surface of the cores, but it is known that the ethanol will infuse into the porous surface of brittle-ice cores and contaminate the purity of the core's scientific data (isotopic signatures, etc.). Researchers at the University of California-Irvine found in their lab that using data-safe, odorless, synthetic isoparaffin "Isopar-K" drilling fluid on a cloth to wipe off the offensive E-140 coating is effective at removing a large amount (though not all) of the surface residue, so this was performed on the South Pole (SPice) ductile ice cores. This method works for ductile ice cores that have no plastic netting on them, but for brittle-ice cores there is a protective plastic netting sleeve placed on each core before wiping can occur. There was no additional wiping or air-drying performed on any of the SPice cores. NICL reports that the first shipment of SPice ductile ice cores seemed relatively dry and odor free, but is expecting the upcoming shipment of netted brittle-ice cores to have a significant odor due to lack of wiping off the E-140.

FED Air-Knife Method (NICL and IDDO; Isopar K)

It is possible to remove a significant portion of the ice core's residual drilling fluid using a high-velocity air stream aimed at the core, with the displaced fluid then vacuumed away. An air-knife device called a FED (Fluid Evacuation Device) was designed and tested at NICL (Figure 19) with good results (up to 80-90% fluid removal); a slightly different and less effective IDDO FED was also tested at the South Pole drill site —

Figure 20 depicts the differences between the NICL and IDDO FED. The NICL FED is a long donut-shaped assembly with approximately 200 cubic feet per minute of cold air pulled into its entrance chamber at a given speed using a 3.5 horsepower single-stage regenerative blower (Republic HRB-500). An ice core is fed lengthwise into the opening of the FED's round hole. The core first passes through an area of moderate-speed airflow and then through a constricted space — the "Bernoulli ridge". This feature accelerates the air velocity between the ice core and the longitudinal array of air grooves such that the excess fluid is driven off the core's surface. The removed liquid and loose ice chips are then separated from the airstream in a deceleration separator tank, and the regenerative blower (vacuum) mounted after the tank exhausts the fume-laden air outdoors via a hose. The IDDO FED used at South Pole had a less powerful air knife effect than the NICL FED due to the location of the device's air entrance and exit ports and by the lack of the constricting "Bernoulli ridge" in the grooves near the ring of exit slots. Regardless, with the pre-removal of a large percent of E-140 from the core surface using either rags or the FED, more complete ice core drying can then be achieved using air-flow assisted evaporation of the E-140, as described below.

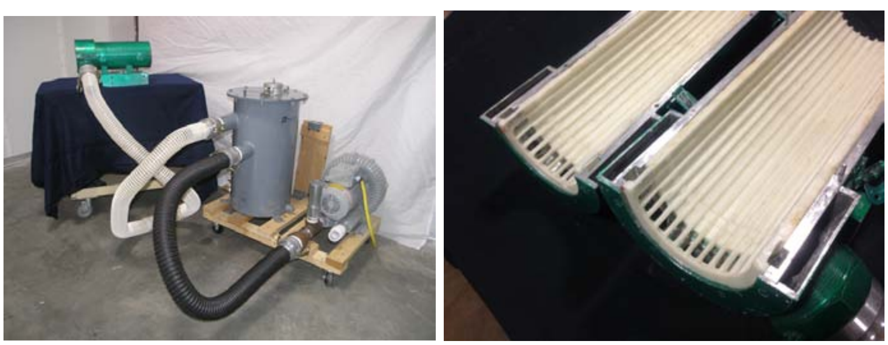


Figure 19 - Fluid Extraction Device (FED) System, and Detail of the NICL FED Air-Knife

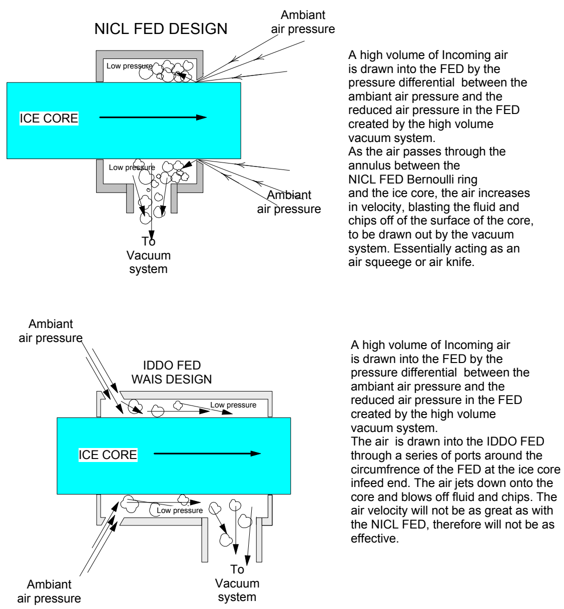


Figure 20 – Differences between the NICL FED and the IDDO FED

Evaporation Method (WAIS Divide; Isopar-K)

It is known that a fluid will generally evaporate into its gas phase more rapidly when there is airflow over it, with the rate of increased evaporation dependent on the fluid's chemical constituents, the concentration of vapor in contact with its liquid (i.e., its vapor pressure in the boundary layer), the temperature of the fluid, and the temperature of the airflow over the fluid. With this in mind, an induced-airflow ice core drying booth system (Figure 21 – three booths shown) was designed using these principles and operated at WAIS Divide with some success at drying a mix of Isopar-K and HCFC-141B drill fluid from the surface of ice cores. Though the Isopar-K does not have an offensive odor, it was still desirable to dry it from the ice cores as much as possible for handling and processing purposes.

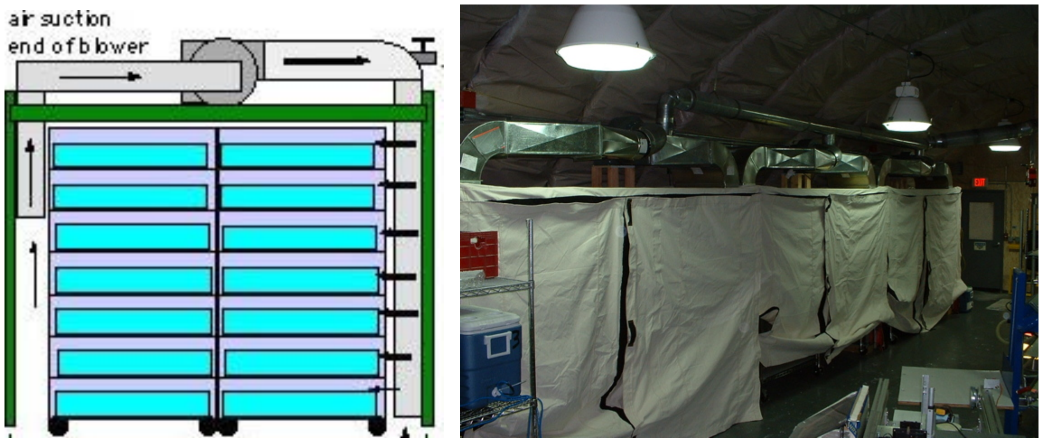


Figure 21 – Isopar-K Drill Fluid Evaporation System Unit Operating at WAIS Divide

The 850-CFM drying booth was designed as a recirculation system to save heating/cooling energy in the -25°F booth. However, to help prevent drill fluid vapor saturation at the ice core boundary layer and to help keep a negative pressure in the booth for odor containment, the ducting was designed so that approximately 10-15% of the airstream's volume was ported outdoors via ducting while cold (approx. -24°F to -28°F), fresh makeup air from the room (with some amount of resulting energy loss) was allowed to enter into the drying booth at the bottom of its canvas sidewalls. Because the Isopar-K odor is not very strong or bothersome to people there was no attempt to capture or eliminate any odors in the exhausted air or around the drying booth. It was discovered that if pre-drying of the cores (using the FED) was not adequate due to FED clogging or other reasons, it was perceived by some that the drying booth was not functioning because it took much longer to dry the core than the 8-12 hours that it took for properly pre-dried core. The intake and exhaust ends of the WAIS Dive drying booth had a manifold plenum with mesh diffusers to force airflow along a prescribed horizontal path over each horizontal layer of ice cores; this arrangement helped to prevent "dead zones" of low-flow air so that more uniform drying of the cores was achieved. The 4-shelf booth held a total of 16 ice cores (4 per shelf with them butted end-to-end).

The air speed over each ice core was not measured due to a malfunctioning airspeed gage, but is estimated to have been no more than 100 CFM/core, on average. Though the air speed around each core was likely not uniform it was estimated to be an average of 15 FPS (feet per second) and was thus fully turbulent airflow for that setup and location; thus the boundary layer of air around each core was relatively well mixed with fresh air and not overly saturated with Isopar-K. This provided reasonable (if not a bit slow) evaporation results; i.e., the cores were found to be reasonably free of fluid residue after 24 hours of drying, though it was found that the Isopar-K evaporation using this booth arrangement was not uniform on each ice core due to non-uniform air gaps and airflow patterns around and along each of the cores. Despite the non-uniform drying the trial did show that reasonable evaporation of Isopar-K was possible in cold conditions, though it shed no light on how well or how quickly the Estisol-140 drill fluid would evaporate under similar conditions, since there is no formal evaporation data on the E-140 chemical at cold temperatures (but there are estimates from ice core scientists based on similar chemicals).

Feasibility Test at NICL for E-140 Evaporation and Odor Absorption

Feasibility Test Summary

A simple, small-scale E-140 evaporation and odor-capture feasibility test system was assembled at the National Ice Core Laboratory (NICL) facility in April, 2015. It consisted of on-hand components — blower with integral activated charcoal filter, flexible air duct, metalized cardboard tube, large u-channel, small u-channel — to create vacuum airflow passing over an E-140-coated Greenland ice core (collected during testing of the drill used at South Pole), with the core centered in a cardboard tube to create an annulus and the air flowing into an activated charcoal filter (Figure 22 and 23). The feasibility test was performed in the -24°F NICL exam room. A more elaborate one-tube drying system concept is shown in Figure 24, but the specific equipment shown in Figure 24 was not available at NICL at that time so the ad hoc test was performed with the equipment noted and shown in Figures 22 and 23.

Figure 22 – Ad Hoc Feasibility Test at NICL (GAC Filter is Inside Blower Housing)

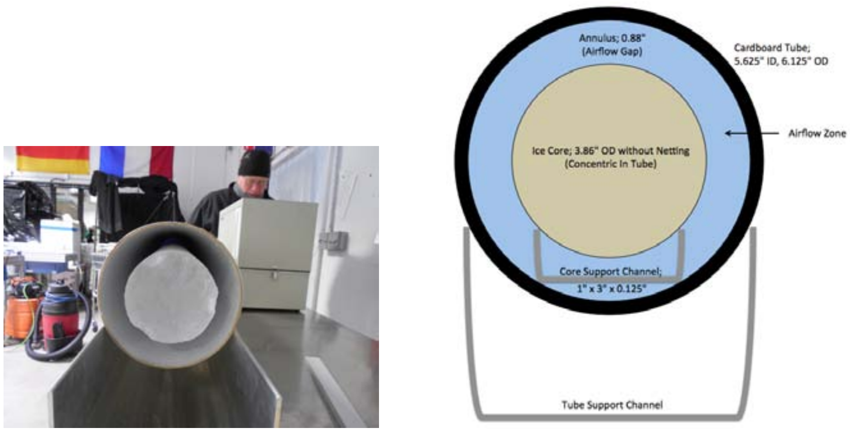


Figure 23 - Ice Core Concentric In Tube for Feasibility Test

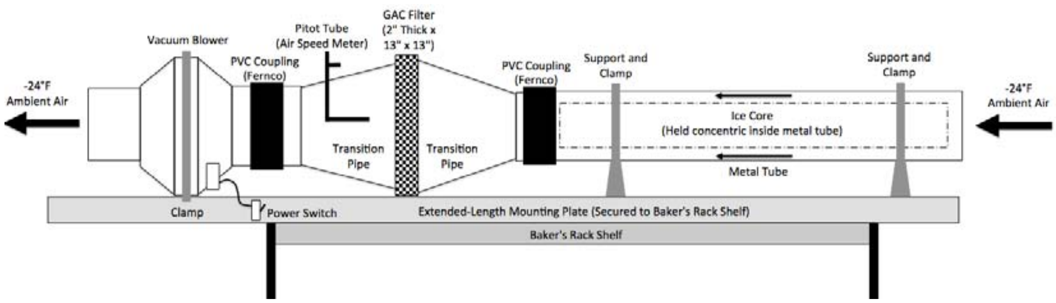


Figure 24 – Conceptual Layout (One Blower and GAC Filter per Ice Core)

Unknown at the start of the test was how fast the E-140 would evaporate from the ice core at the 110 CFM airflow rate produced by the available blower, and whether the thin (2-inch) activated charcoal filter pad that was available at NICL would adsorb the E-140 odor at that airflow rate at the -24°F ambient air temperature. The vapor pressure of E-140 at various cold temperatures was estimated and extrapolated by ice core scientists based on a similar (proxy) fluid manufactured by BASF, known as 2-Ethylhexyl Acetate M5849-e; see Figure 25), but there was no calculated or empirical data indicating how well and how quickly E-140 would actually evaporate from an ice core, regardless of its estimated vapor pressure. Empirically, at NICL it was known that a core with E-140 at -36°F did not smell very much, but once place in a -24°F room it did smell much worse due to the vaporizing E-140 at the warmer temperature, without any airflow moving over it.

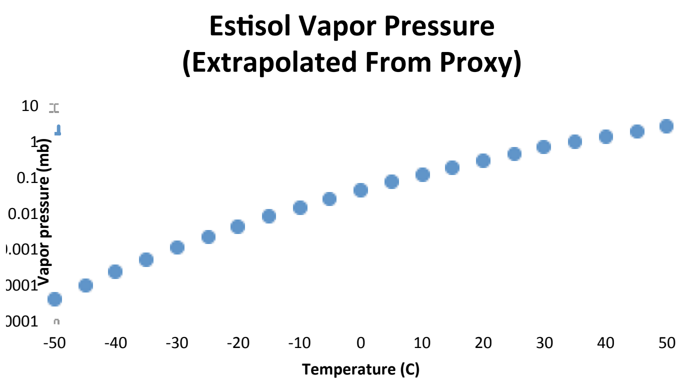


Figure 25 - Estimated Vapor Pressure for Estisol-140 Based on a Similar Compound

The feasibility test performed at NICL did prove that, in fact, the E-140 drill fluid did evaporate from the surface and surface pores of 39-inch-long un-netted (3.86-inch OD) and netted (3.88-inch OD) Greenland ice core specimens after 6-8 hours of drying time in the -24°F room, leaving the ice core surface with no noticeable E-140 residue or offensive odor. As well, the -24°F activated charcoal filter did indeed trap the evaporated E-140 odors, as verified by subjective "sniff" tests downstream of (after) the filter while in the cold room, as well as by surface wetness observation and by paper-blotting the ice core surface. The plastic netting on the brittle-ice core did create some superficial ice sublimation at the netting interfaces that is explained later in this section.

Importantly for this E-140 evaporation project, the discovery that the E-140 fumes are effectively sequestered by the cold activated GAC filter was great news because it suggested a way to save freezer operation costs and frost build-up problems at the freezer doorways and freezer vacuum relief ports, since the cleaned, cold air exiting the GAC filter remains within the -24°F freezer airspace and thus no pre-chilled freezer makeup air is required for Dry Core use.

Feasibility Test Details

From past field drill site (Australia's Antarctic Aurora Basin North ABN, USA's South Pole SPice) and NICL laboratory experience, the E-140 fluid is known to evaporate slowly at low temperatures if there is minimal or no airflow over the ice core, but increasing the airflow does hasten E-140 evaporation. Thus the E-140 evaporation rate for the -24°F NICL feasibility test was increased by using a small vacuum blower (Airfiltronix HS3000 with one port blocked) to pull 110 CFM of airflow over an E-140-

coated ice core (3.86-inch diameter). The core was placed concentrically inside a larger (5.63-inch inner diameter) metalized-cardboard airflow tube and the calculated air speed in the resulting negative-pressure annulus between the tube and the core was approximately 14 MPH (miles per hour).

As the E-140 evaporated into the turbulent airstream (calculated Reynolds number of ~ 17,000) surrounding the core, the air was then flowed through an in-line granular activated charcoal (GAC) filter "scrubber" pad at -24°F to determine if the adsorptive van der Waals force between the cold charcoal and E-140 fumes could sequester the E-140 odor to the charcoal.

The 2-inch thickness of the 10-inch x 17-inch charcoal filter pad (with 6 pounds of a cocoanut/coal charcoal blend) allowed for 0.1 seconds of air-charcoal contact time as air flowed through it, and indeed the cold charcoal proved to effectively capture and retain the offensive E-140 odor based on a "sniff test" of the air after the filter. The GAC filter manufacturer (Airfiltronix) noted that this particular filter (FR-4) effectively removes odorous vapors until approximately 33%-50% of its own charcoal weight is adsorbed (depending on the type of vapor, temperature, humidity and other variables). Making a more conservative estimate, if the maximum loading of this test filter's 6 pounds or charcoal is assumed to be only 20% of its own weight, then 1.2 pounds of E-140 can be captured from the airstream before the E-140 odor might "break through" this filter and become noticeable in the freezer. Further, assuming a conservative (overly thick) E-140 film thickness on the ice core of 0.005 inches (i.e., the average thickness of a human hair or a sheet of paper), one Airfiltronix FR-4 charcoal filter could dry 30 ice cores to the conservative 20% loading limit. From observation it appears that the E-140 film thickness on the ice core is much less than 0.005 inches and that the 6-pound test filter likely would last much longer than 30 cores before it becomes 20% loaded (at which point it would be disposed of per standard E-140 disposal protocol).

The preliminary testing was performed on a non-netted ductile ice core as well as with a netted brittle-ice core, both drilled in 2012 at the Greenland NEEM ice core drill site. The 6-8 hour E-140 evaporation time and desired dryness results were similar on both, though the netted core exhibited some amount of ice sublimation in a diamond-shaped pattern (Figure 26) mimicking the netting contact zones on the ice where airflow was faster or more turbulent; this superficial "alligatoring" effect (differential sublimation that somewhat resembled rough alligator skin) was deemed insignificant by NICL staff as it is not part of the scientific specimen area (which is deeper inside the core). However, the amount of ice sublimation on netted cores would need to be watched, understood and controlled during the drying process on a full-scaled Dry Core system. There did not appear to be any abnormal amount of sublimation difference from one end of the core to the other end; i.e., it was uniform along the length of the netted ice core.

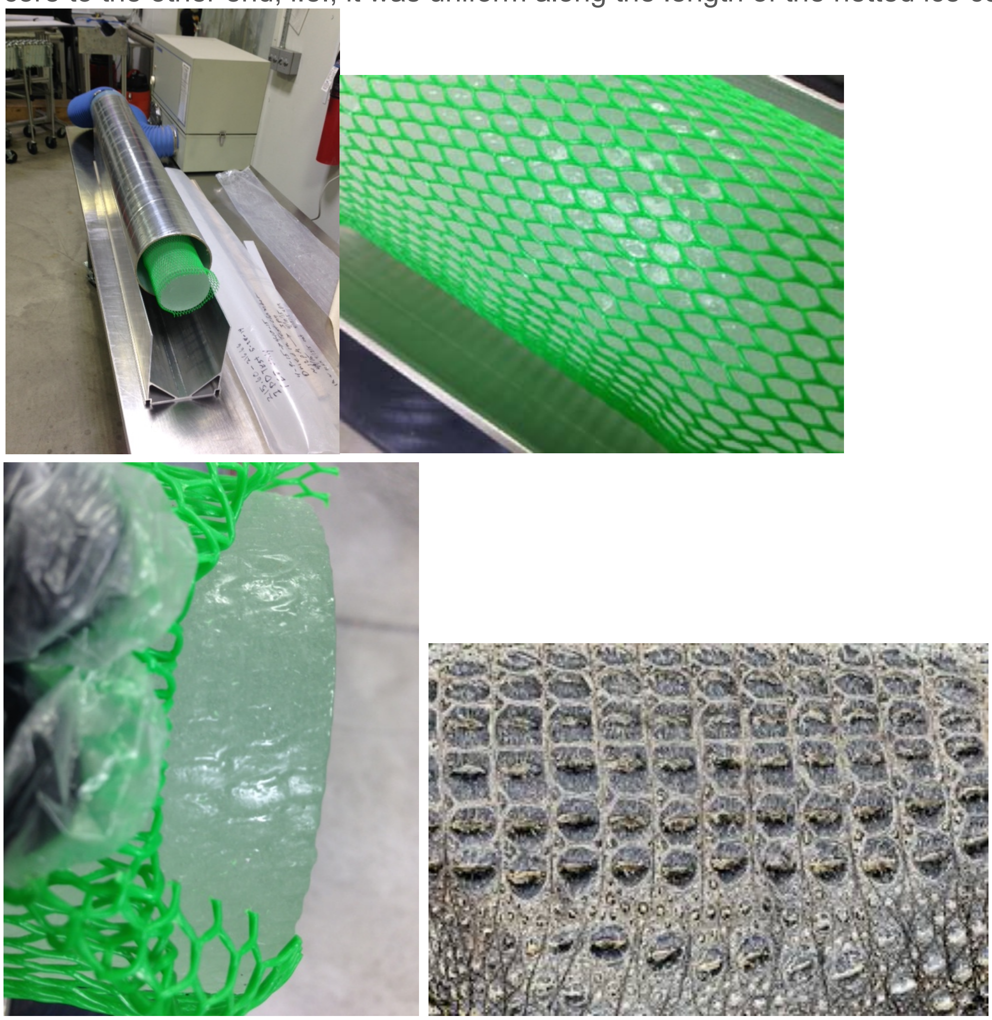


Figure 26 - Netted Core with "Alligatoring" of Ice Surface (Differential Sublimation), and a Photo of Alligator Skin

It was noted during the test that when the ice core's blunt end was located fully inside the drying tube, the first few inches of surface on that end of the ice core remained somewhat wet due to air deflection and eddies (and resulting slow or stagnant airflow) in that area. By pulling the ice core out from the tube so that it protruded 2-4 inches, the improved airflow streamlines at the tube entrance provided better drying at that zone (Figure 27). More testing of the optimal protrusion distance will need to be performed on a final Dry Core system, as it depends on several factors including tube inner diameter, core diameter, nearby airflow obstructions etc. Unequal ice sublimation from one end to the other end is not expected once the drying setup and process is fully defined.

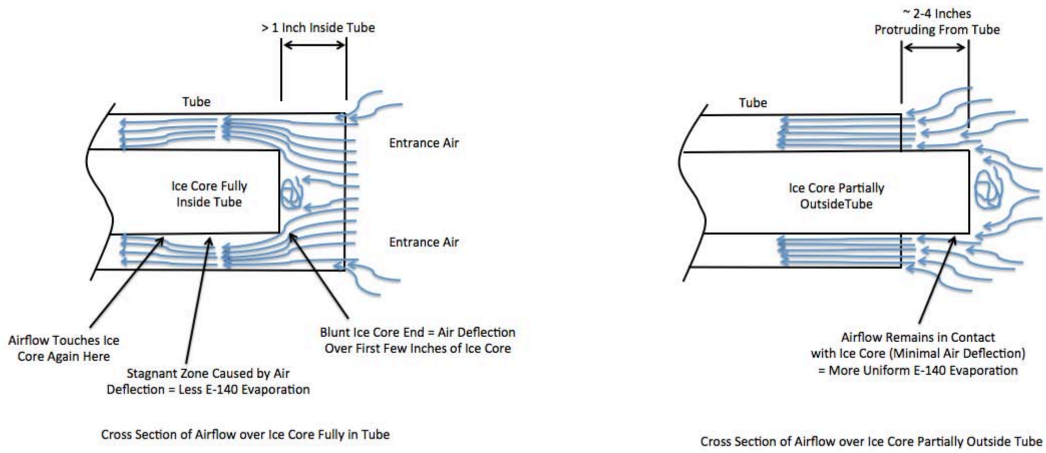


Figure 27 – E-140 Evaporation Uniformity Improvement with Ice Core Protrusion

Interestingly, when the ice cores were initially moved from the -36°F freezer to the -24°F exam room, unwrapped from their protective plastic bags, placed into the drying tube, and -24°F airflow started over the core, it was noted that additional moisture (apparently water) accumulated on the core surface, along with the existing E-140 coating. It is theorized that the higher relative humidity level in the -24°F exam room caused room moisture to condense onto the colder ice core, but as the core warmed to -24°F during the drying experiment the condensed moisture (along with the E-140) evaporated from the ice core surface.

Turbulent Airflow for Improved Evaporation (Liquid-Vapor Boundary Layer and Reynolds Number)

As has been discussed previously, the feasibility test single core used an open-ended metallized-cardboard round tube with an E-140-coated ice core located concentrically inside on a support channel; this concentric arrangement created a small, defined annular gap between the core surface and the tube's inner wall for uniform airflow over the core's length. For the test configuration at NICL the ice core had a 3.86-inch outer diameter and the metalized cardboard tube's inner diameter was 5.63 inches, providing a 0.88-inch annulus air gap shown in Figure 28.

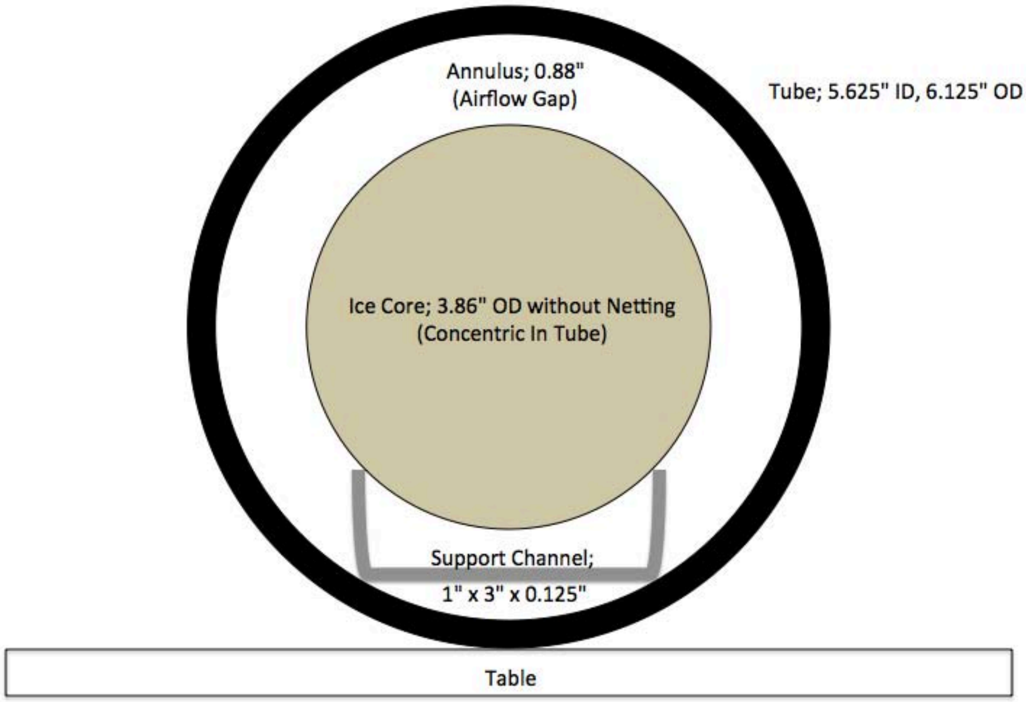


Figure 28 - Ice Core In Tube as Tested at NICL

In -24°F still air the E-140 liquid film evaporates from the ice core surface into surrounding very slowly, as there is a very thin (approximately 0.02-0.04 inch) boundary layer of air surrounding the entire ice core that becomes 100% saturated with the escaping E-140 molecules and slows the evaporation process. The same physics occur when water evaporates off asphalt on a foggy day - the saturated air at very close ground level dramatically slows the water evaporation rate from the asphalt.

For the ice core drying process, airflow at the saturated ice surface will increase the evaporation rate, but if the airflow is not fast enough and remains laminar (not turbulent) then the thin boundary layer will remain intact over the core and E-140 evaporation will still not be very rapid. But if the airflow is made to be fully turbulent (based on its Reynolds number), then the thin boundary layer of E-140-saturated air will mix into the turbulent surrounding air and the E-140 fluid film on the ice core can more readily evaporate into the unsaturated airstream above. So for the most efficient (rapid) E-140 evaporation process, the airflow rate through the tube/core annulus should be in the turbulent realm; airflow at a Reynolds number near 18,000 or higher (this is not an exacting value) is generally considered fully turbulent. The Reynolds number (Re) equation for airflow in an annulus using the hydraulic radius method is (showing the values from the feasibility test);

Re (dimensionless) = □hoV(OD-ID)/□u

Where:

V= air velocity (20.0 ft/sec)
□ho=air density (0.0664 lbs/ft^2)
□u=air dynamic viscocity (1.1465E-5 lb/ft-sec)
OD=core outer diameter (0.322 ft Greenland ductile core)
ID=tube inner diameter (0.469 ft in.)

Inserting the appropriate values from the feasibility test into the equation yields a fully-turbulent Re of 17,059 for this test, which is very close to the desired Re of 18,000.

As noted above, the desired Reynolds number of approximately 18,000 was calculated only after the NICL feasibility test was completed and, by luck, the available test blower's airflow rate and the tube/core diameter ratio (annulus gap) happened to provide a nice turbulent airflow of 17,059, which explains why the ice core's E-140 layer (which has a very low vapor pressure at -24F and is thus reluctant to evaporate) had completely evaporated after only 6-8 hours in the drying tube. This finding is a key factor in the proposed full-scale Dry Core system; the tube/core annulus must have turbulent airflow for efficient E-140 evaporation, as created by the interrelationship between airflow rate, tube inner diameter, and core outer diameter. As shown in Figure 29, the blue dot is the resulting Re number in the tube for the feasibility test setup, and the black square is the desired Re number for the proposed full-scale Dry Core system, (which will have a slighter smaller tube to obtain a slightly higher Re number, as well as to allow more tubes to fit on a 30-inch wide Metro shelf rack). Also seen in Figure 29 is that, for a given core diameter, using airflow rates less than 110-CFM lowers the Re number much more dramatically than using various tube diameters.

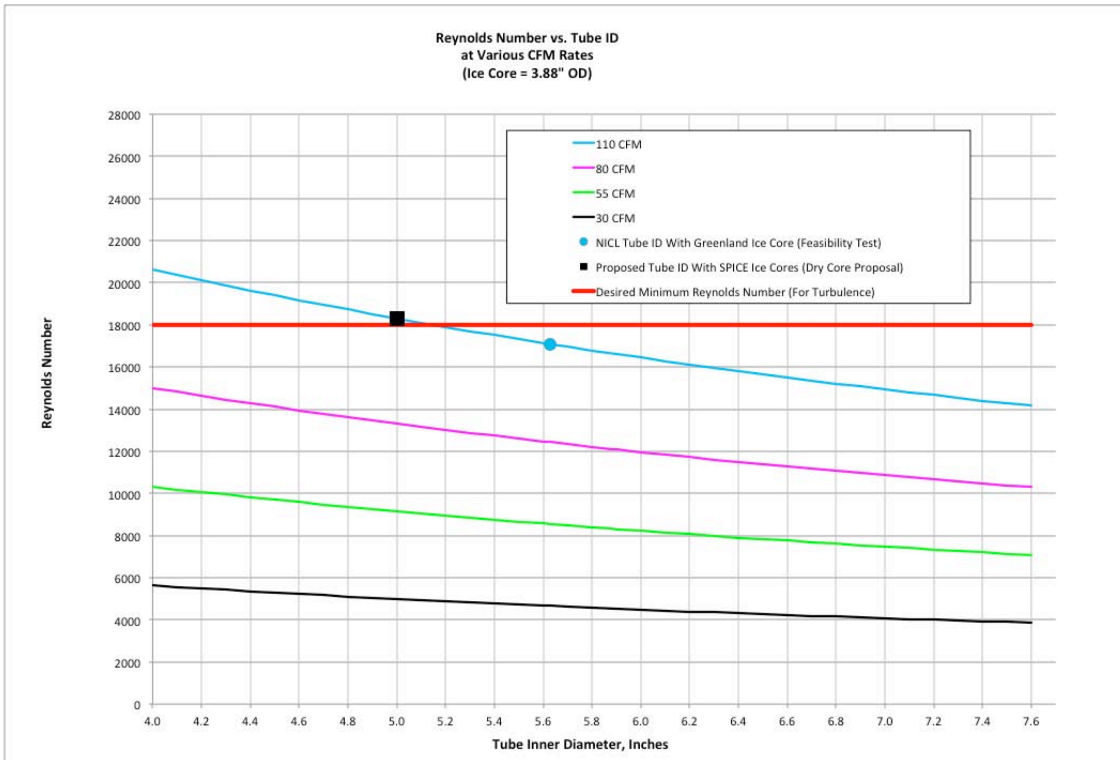


Figure 29 - Reynolds Number With Varying Airflow Rates and Tube Diameters

With this success and looking ahead to the proposed full-scale Dry Core design, if the drying tube inner diameter is set at 5 inches for reasons noted previously, and the airflow is set at 110CFM per tube, one might ask what other ice core diameters (besides the 3.86-inch diameter SPice ice cores) could be used in the Dry-Core system. The two graphs below help define this: Figure 30 shows the Reynolds number changing relatively slowly (and on a negative slope) as the ice core diameter changes, with the negative slope being due to the ever-smaller gap of larger cores in a 5-inch diameter tube increasing the air's viscous losses faster than it increases its inertial energy. So from a Reynolds number standpoint, the annulus gap between the ice core and the tube could actually vary from 0.5-1.5 inches without much effect on achieving full turbulence.

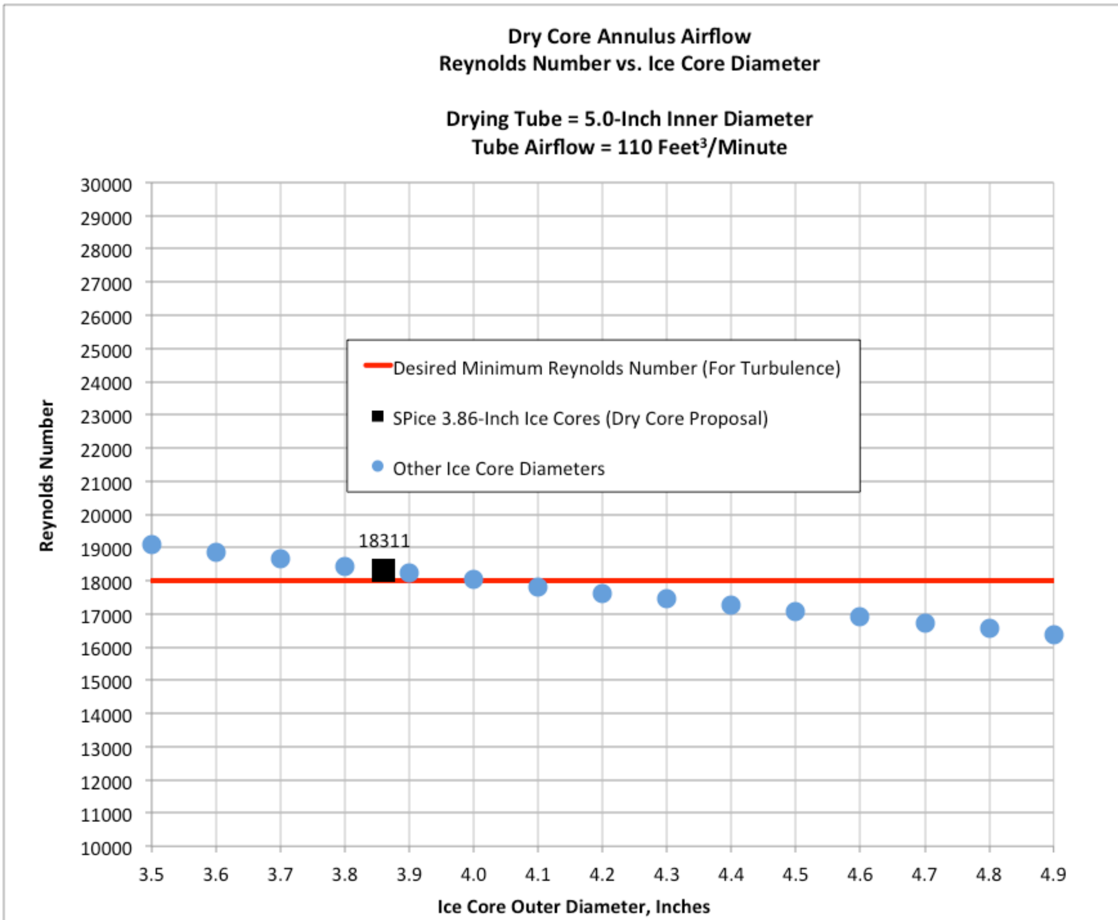


Figure 30 - Reynolds Number is Relatively Stable with Various Core Diameters in 5-Inch Drying Tube

However, as seen in Figure 31 the actual air velocity increases rapidly as the annular gap dimension becomes less, with the faster air velocity in the narrowing annulus air gap creating significantly higher air friction and thus a much higher pressure drop through the annulus.

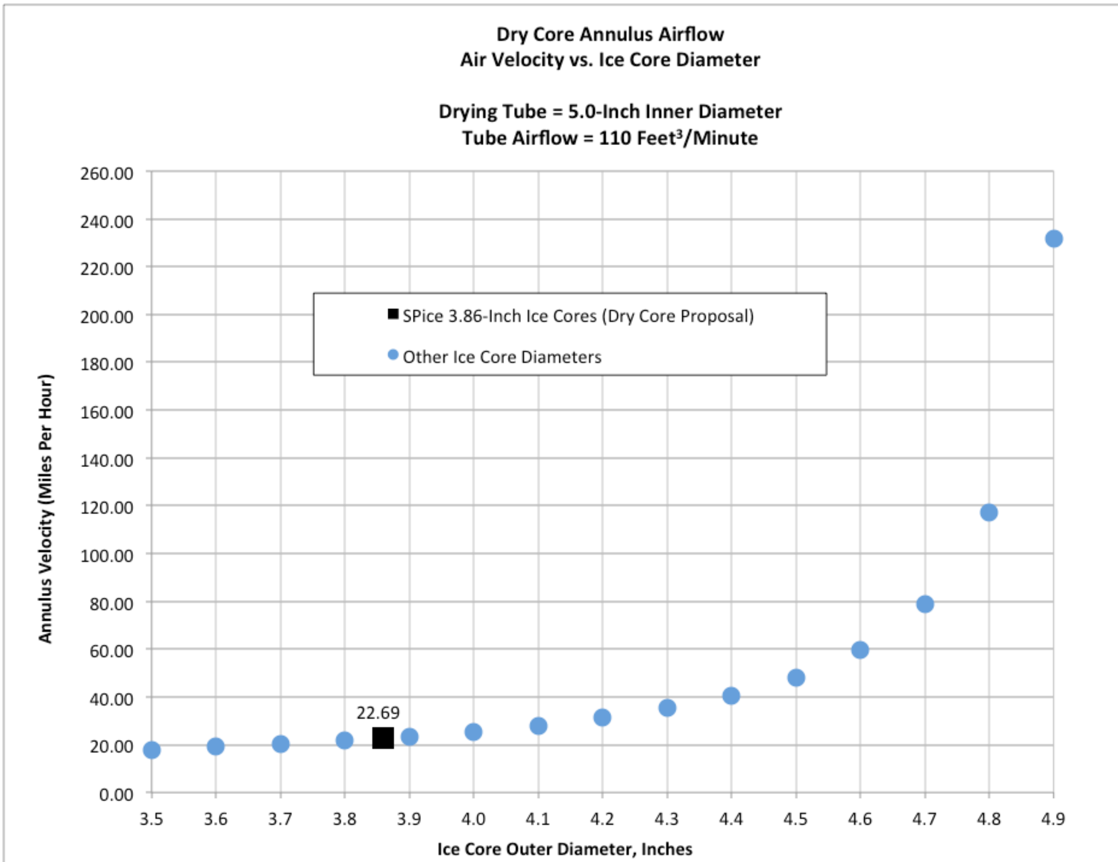


Figure 31 - Velocity Increases Dramatically with Various Core Diameters in 5-Inch Drying Tube. (Note: A 4.1-Inch Core Diameter is the Suggested Maximum in a 5-Inch Tube Due to Increasing Air Speed (i.e., Air Friction and Pressure Drop)

So, depending on the blower performance curve, a blower designed for an 8-inch WC pressure drop using a 3.86-inch core in a 5-inch tube might be overwhelmed if a much larger ice core (perhaps larger than 4.1 inches in this example) were placed in the same tube. That is, at a given motor speed the airflow rate is forced to reduce to the point that the larger pressure drop will match the blower performance curve at a new, lower airflow rate. This is not to say a slower airflow rate is not acceptable or the (likely) resulting slower drying times will be unacceptable to NICL personnel, but it does warrant mentioning the effect of using larger-than-designed-for ice cores in Dry Core. Of course, depending on the blower speed setpoint (using a VFD controller) when drying 3.86-inch cores, it may be possible to increase the motor speed and increase the drying speed on larger ice cores, even with the increased pressure drop in the tube annulus, as long as the metalwork, cardboard tubes and seals in the airflow system have been designed to not collapse or leak due to the higher pressure drop. With testing of the proposed Dry Core system at various temperatures, with different core diameters, with various thicknesses of E-140 film and other variables, it will be possible to establish a Dry Core SOP (standard operating procedure) and system guidelines for any number of ice core drying projects in the future, beyond the South Pole's ice cores.

Regardless of the core diameter, tube diameter, airflow rate or the exact Reynolds number, it is always best to keep the core centered in the tube to help ensure uniform drying all around the core along its length. As well, as experience with proposed full-scale Dry Core system is obtained it is important for the Dry Core operator to be aware and watch for excessive ice surface sublimation on any section or along the length of the ice core during the E-140 evaporation session.

Acknowledgements

The author wishes to express appreciation and gratitude to the following people who helped in many ways on concept discussions, feasibility testing, design details, suggested improvements, and the many nuances of the proposed Dry Core System Basis of Design:

Mark Twickler – University of New Hampshire, Durham, NH
Geoff Hargreaves – National Ice Core Laboratory, Denver, CO
Stan King (retired) – Sonic Enclosures, Delta, British Columbia, Canada
Henrik Klinge – Klinge Corporation, York, PA
Edward Moynihan – Integrity Integration, LLC, West Lebanon, NH
And numerous equipment manufacturers and distributors referenced in this document.