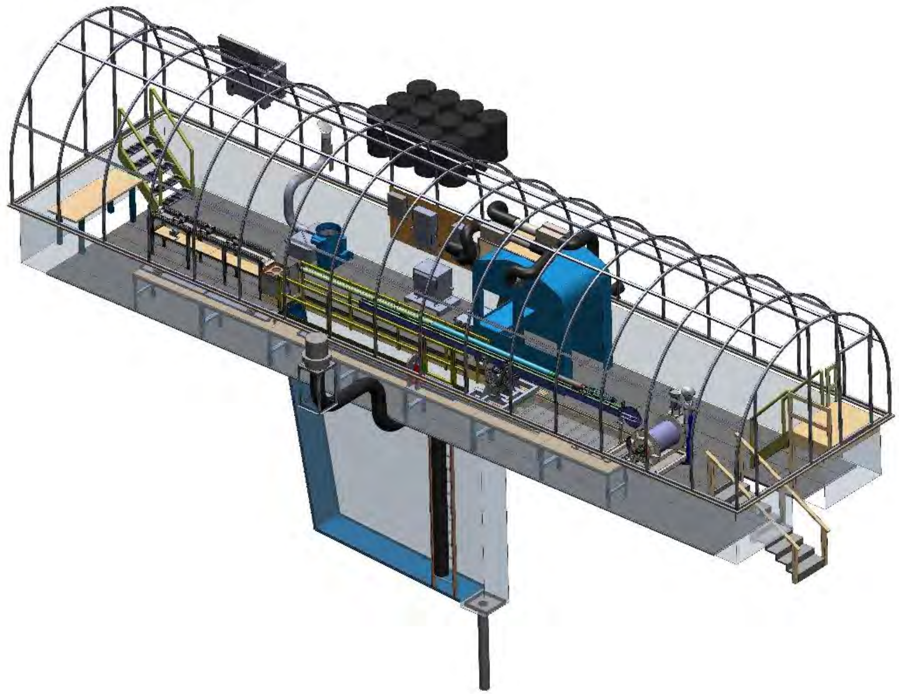
Foro 3000 Drill

Design Review

September 25, 2018



Science Requirements

1. Target depths: from the surface to 3,000 m depth
2. Ice core diameter: 98 mm +/- 3mm
3. Minimum core length: Core length per run should be designed to facilitate drilling to 3,000 m in three field seasons (assuming 40 drilling days each season with 24-hour operations).
4. The drill should be operable in ice temperatures down to -53°C to 0°C.
5. The surface equipment should be operable in ambient temperatures from -40° to +5°C.
6. Transport type: prefer Hercules LC130 or ground traverse
7. Drill should be compatible with existing fluids Isopar K and Estisol 140; compatibility of other fluids would be vetted by the science community prior to use.
8. Core quality requirements:
   1. Core recovery over the entire borehole, as close as possible
   2. Ice pieces to fit together snugly without any gaps
   3. In non-brittle ice, the packed core should have no more than 12 pieces of ice per 10 m section of core
   4. In brittle ice, there may be a lot of pieces in a single core segment, but the pieces must fit together, retaining stratigraphic order; more than 80% of the ice volume must be in pieces that each have a volume > 2 liters
9. Absolute borehole depth measurement accuracy: 0.4% of depth
10. Borehole inclination should be less than 6 degrees
11. Drill design and electronics should be forward-compatible with a future replicate coring and deviation system capable of deploying a removable and orientated whipstock to preserve the full borehole logging record.
12. The drill will be a complete system which includes a drilling structure and ice-core processing equipment. The drill structure will be appropriate for moderate accumulation rate sites (<15 cm per year), recognizing that specific sites may require additional specifications. Additional logistical equipment is permissible for drill site set-up and tear-down, for example a tractor with 3,000 lb. fork capacity for moving equipment and bucket or snow blower for drill trench excavation and site maintenance.

Scientific Features desired but not required

1. Ability to break multiple 1-m sections during a drill run to reduce the need to cut brittle ice at the surface.
2. Ability to measure inclination of borehole and azimuth of drilled cores
3. Ability to replicate core with a removable or drillable whipstock. Deviation drilling would preferably occur on the uphill side of the borehole to allow passage of logging tools in the main borehole.

*Items in blue text were added as part of revision 2

Safety

Safety of personnel using this drill is paramount:

- Hazardous nature of the operations
- Severe environmental conditions at the field sites
- Extremely long travel times to advanced medical care and life support facilities
- Small mishaps may have severe consequences in this environment

Safety Requirements:

- Create a safety plan that defines how key issues for the project will be identified, managed, assessed and addressed during the system development.
- Conduct a Failure Modes and Effects Analysis (FMEA) to identify and manage mechanical/physical/chemical and personnel hazards for the system.
- Provide operational and safety trainings, as identified by the FMEA, to address **safety** hazards.
- Provide operational and safety trainings, as identified by the FMEA, to address **quality** issues.
- Provide hardware and/or software protection devices to prevent damage to the equipment due to overloads in the system, such as torque limiters, over-current protection, and limit switches.
- Provide appropriate Personal Protective Equipment (PPE) for operating the drill system and handling drilling fluids, as identified in the FMEA.
- Minimize environmental impact of the drilling operations through mitigations identified in the FMEA.
- Provide identification of and protection from dangerous voltages.
- Provide safety interlocks (Lock-Outs) to prevent the in-advertent operation of equipment that would endanger personnel.
- Provide emergency stop and emergency power-off systems to respectively halt and power-off the equipment in the case of an emergency. The emergency power-off systems in some cases must have fail-safe brakes such that the removal of the power will engage the brakes. (Examples include the winch or tower mechanisms, which must engage the brakes and hold their last position in case of a loss of power.)
- Create an operations plan and procedures for normal drilling and surface operations of the system.
- Create safety and maintenance check lists that will be completed at defined intervals to verify safety equipment is in place and the drill system is in proper working order.

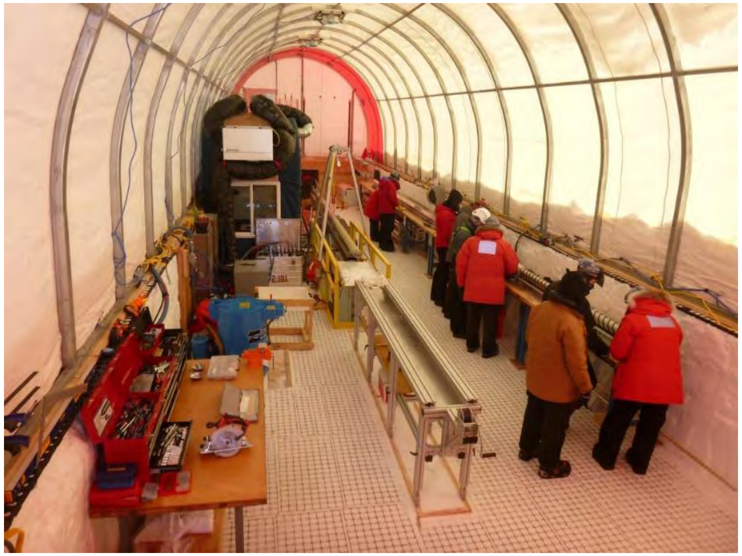
Background and Design Decisions

Extend the depth capacity of the Intermediate Depth Drill (IDD) system rather that build a complete new drill system

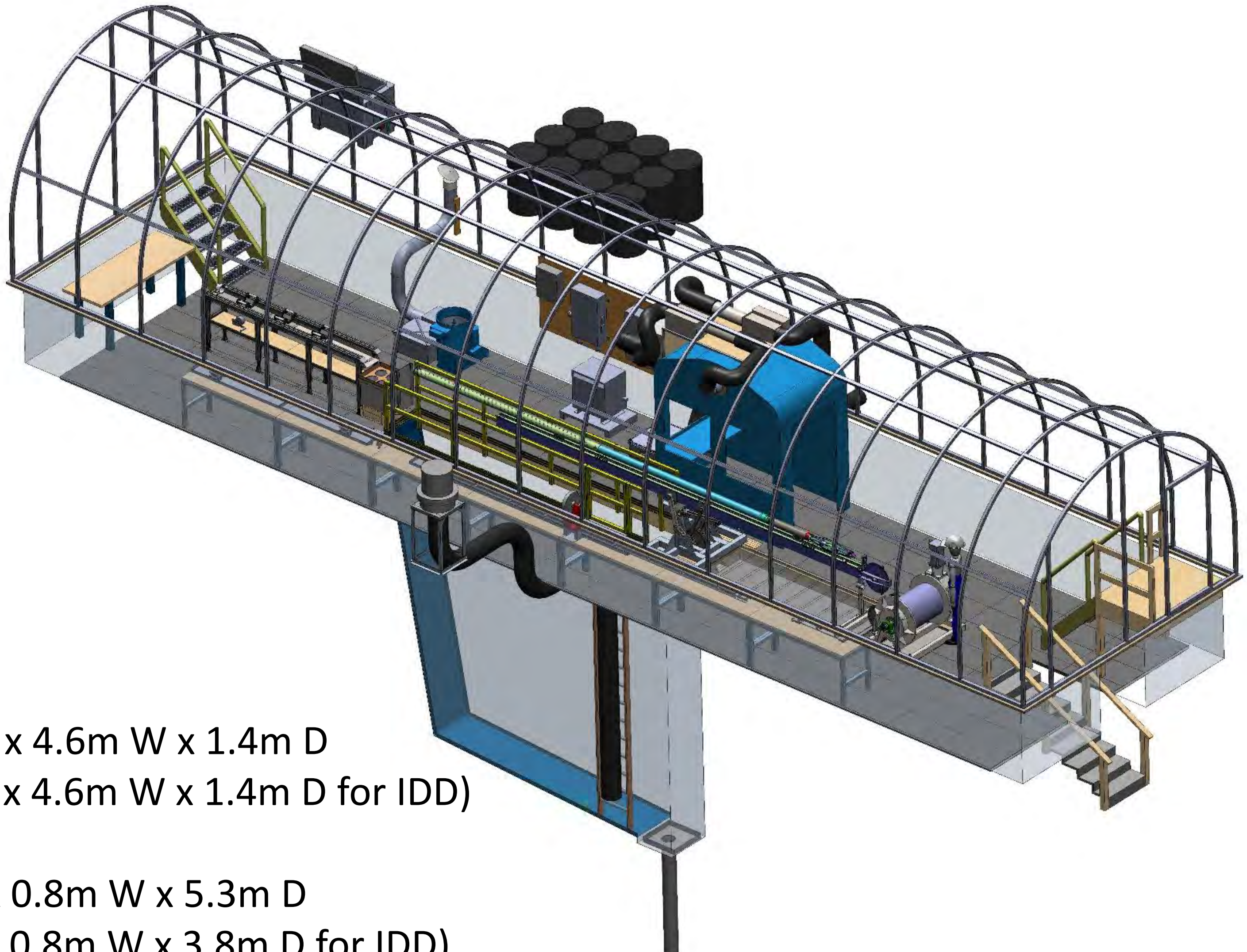
- Reuse as much of the existing system as possible
- All modifications must be reverse compatible
  - System can be configured for a max depth of either 1,600 or 3,000 m

Increase the core length recovered per run

- Make it feasible to drill a 3,000 m borehole in 3 drilling seasons
- The longer drill and core processing system must fit within the existing tent



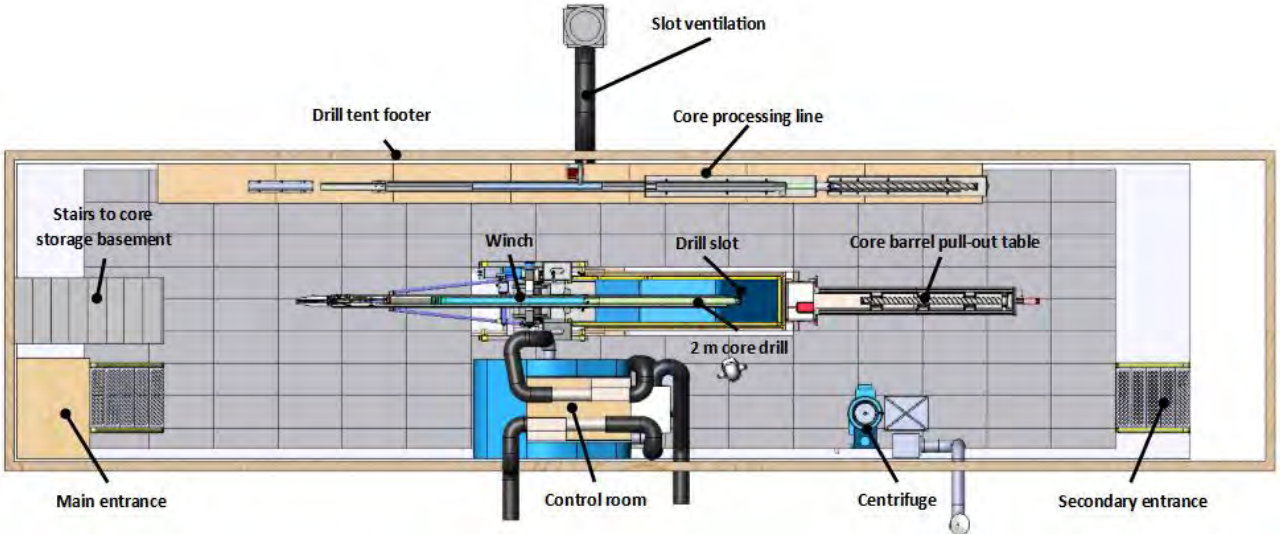
Drill Tent Layout



Trench:
- 19.3m L x 4.6m W x 1.4m D
  (18.3m L x 4.6m W x 1.4m D for IDD)

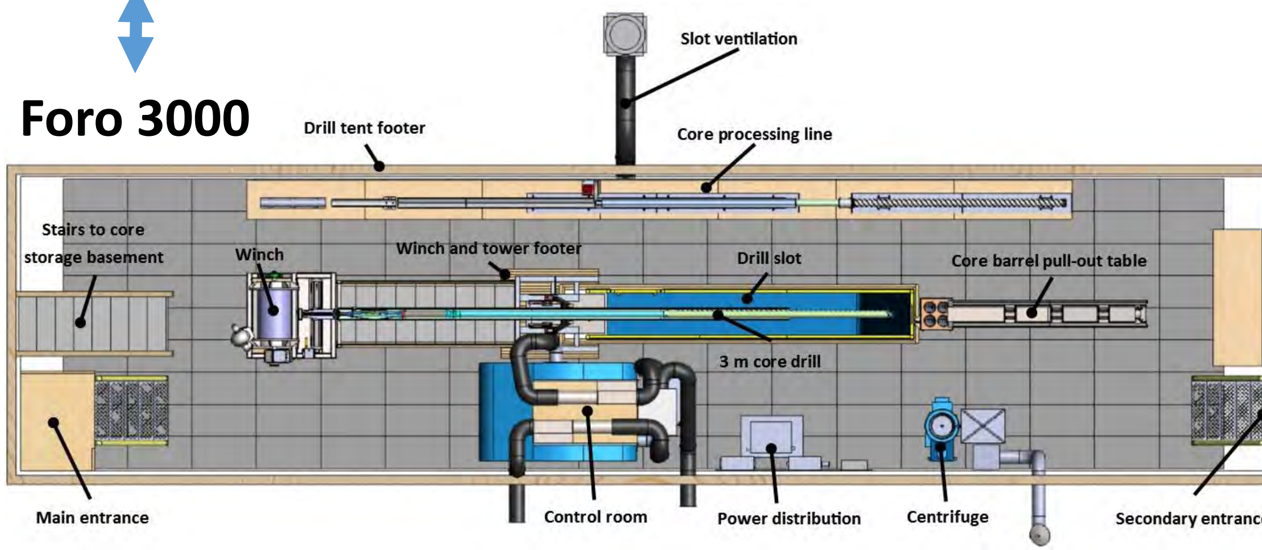
Slot:
- 5.4m L x 0.8m W x 5.3m D
  (3.7m L x 0.8m W x 3.8m D for IDD)

Drill Tent Layout- Comparison with IDD



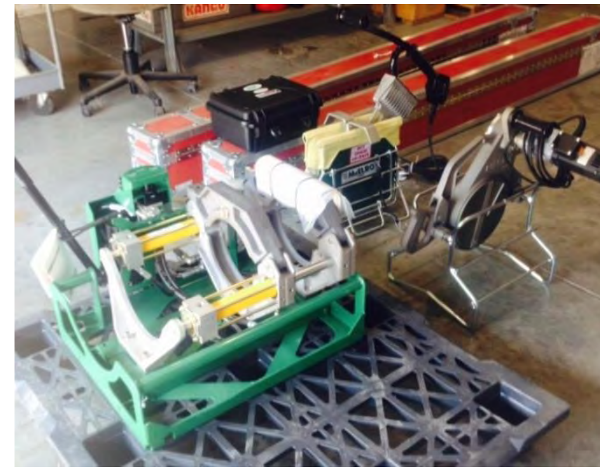
IDD

Foro 3000



Casing

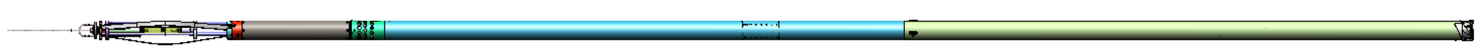
- In 2015, IDDO acquired a HDPE pipe fusion welding system for welding casing pipe joints
- Purchasing pipe without the threaded ends saves $8,400 on a 100 m length
- Welded joints are leak tight
- Weld is as strong as the base material
- Weld area will need to be pre-heated if ambient temp is below -20° C
- Procedures for welding below -20° C need to be developed and tested



Sonde Overview

- The core length has been increased from 2 to 3 m
  - Chips chamber length was increased by 1 m
  - Core barrel length was increased by 1 m
  - Increased the overall drill length by 2 m, from 6.4 to 8.4 m
    - ❖ Core lengths longer than 3 m would require the size of the subsystems and tent to increase

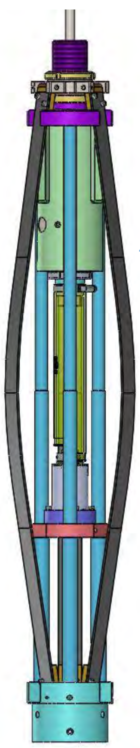
Drill with 2 m long core capacity, 6.4 m long overall



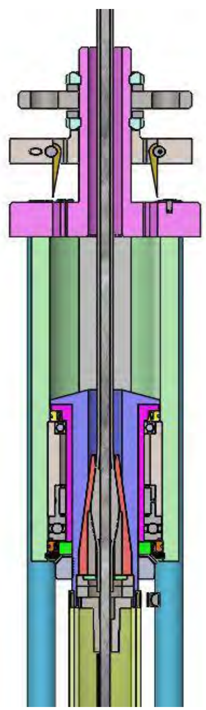
Drill with 3 m long core capacity, 8.4 m long overall

Anti-Torque

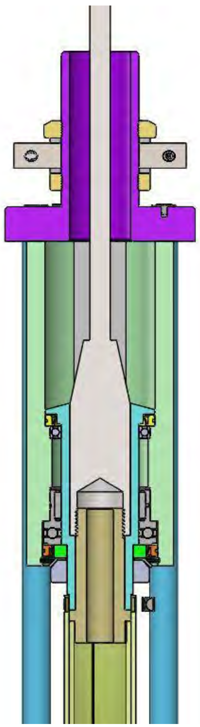
- The cable termination has been upgraded with a simplified design
    - Fewer parts
    - Quicker to install and remove than the previous design



Anti-torque assembly



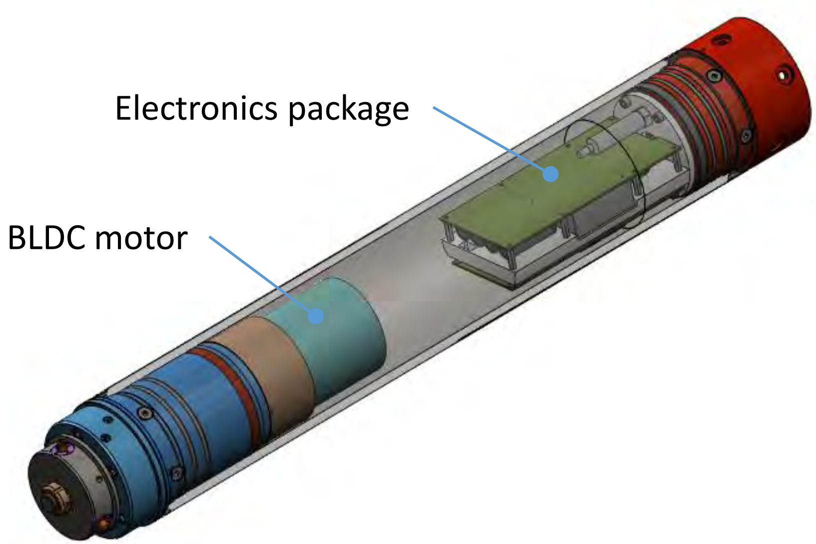
IDD cable termination



Foro 3000 cable termination

Sonde Motor Section

- The motor section electronics package will be upgraded as part of the Foro 3000 build to include sensors required to meet the Science Requirements.
  - Navigation module and motor resolver will be added
    - Azimuth of drilled cores
    - Directional orientation of a whipstock

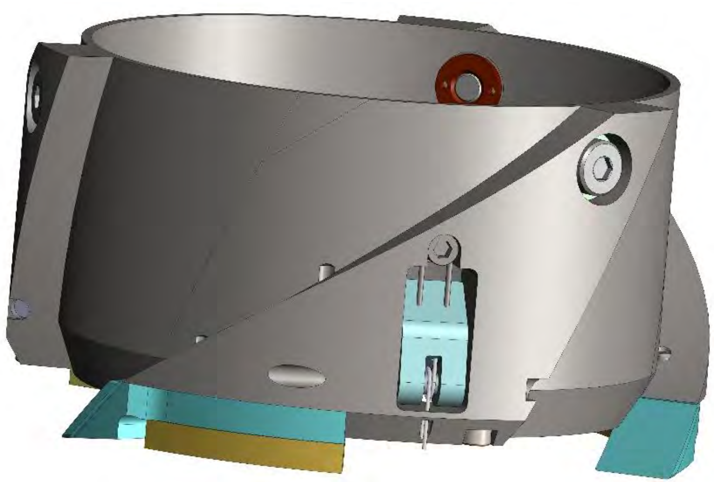


Electronics Package Features:
- PWM motor controller
- Pressure sensors; borehole and internal
- Temperature sensors; borehole, internal, and motor
- Inclination sensor
- Accelerometer (for sensing A-T slip)
- Navigation module
- Resolver

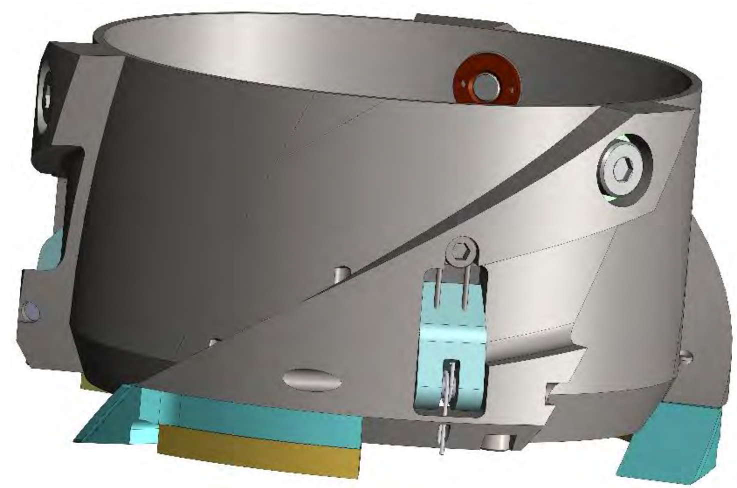
Cutter head

The motivation to revisit the cutter head design was driven by the science community's desire to be able to break multiple 1 m sections during a drill run to reduce the need to cut brittle ice at the surface

- During testing of the IDD in Greenland, the success rate was 60% with the standard cutter head design.
- Ice packing in the core dog windows during core break, preventing them from being able to retract, was identified as the most likely reason for not being able to drill a second core.
- New cutter head design has improved chip flow from the core dog window area that should allow ice build up to clear.



Standard cutter head

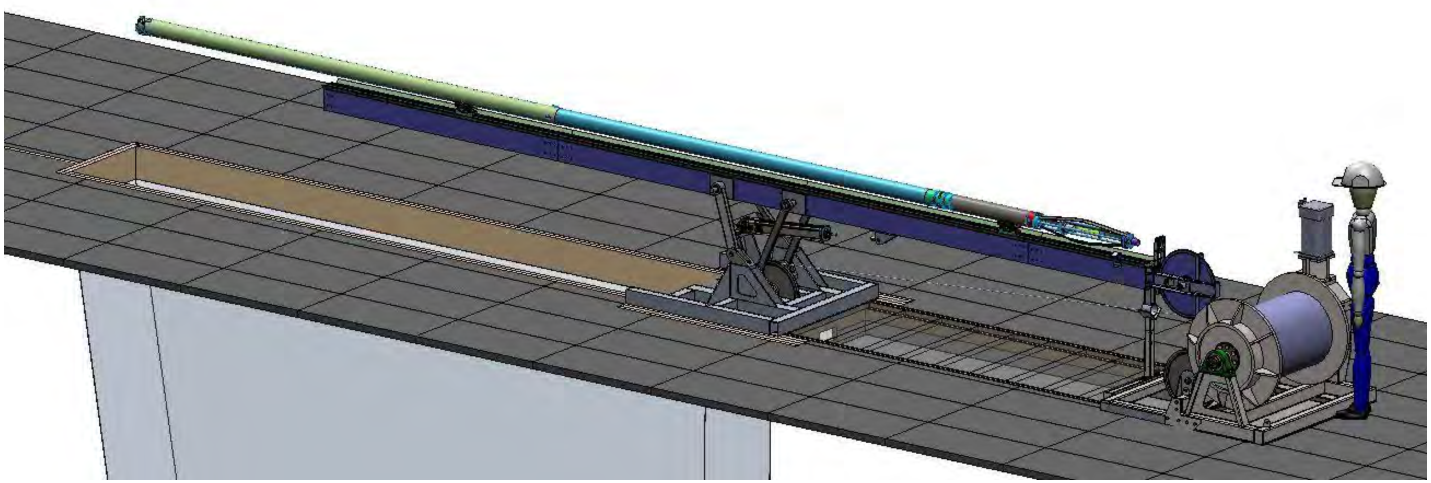


Cutter head with vented core dog windows

Winch and Tower Overview

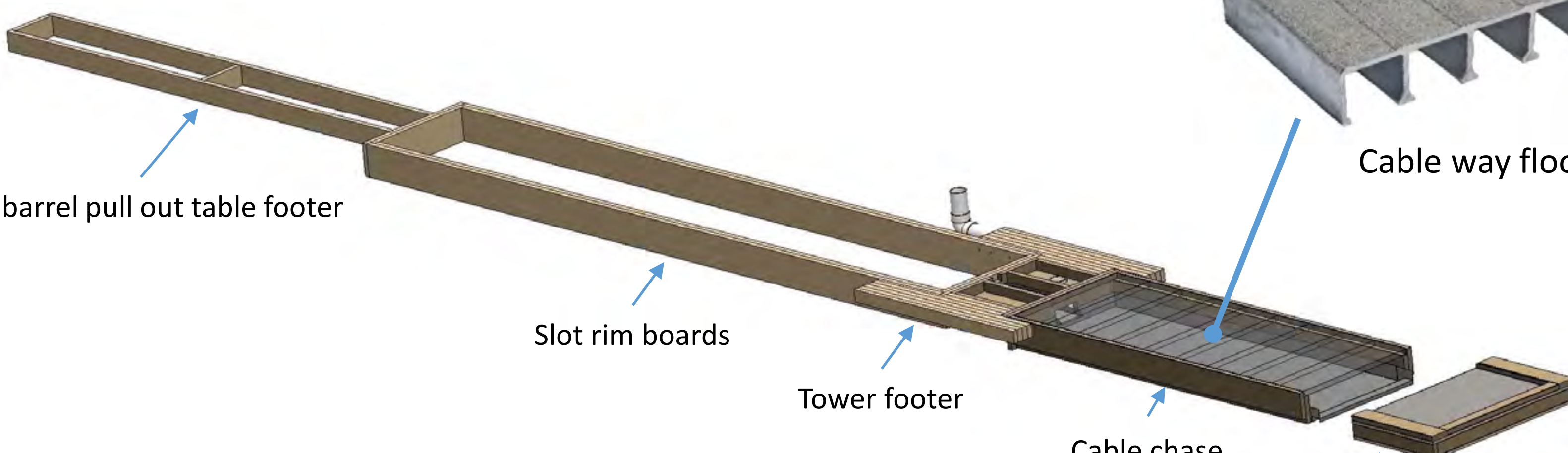
In order to accommodate a larger winch drum (3,100 m cable capacity), the winch and tower base were designed as separate units.

- Winch is located off the end of the tower
  - Winch cable runs in a cable chase under the floor to eliminate a trip hazard
- Winch is structurally connected to the tower base through the sub-floor footer
- Design makes it possible to reuse the IDD tower actuator and winch motor
  - Reduced design time and cost by reusing existing components
  - Existing winch/tower control system can be used without modifications
- The extra drill length is being accommodated by making the lower portion of the tower longer and deepening and lengthening the slot.



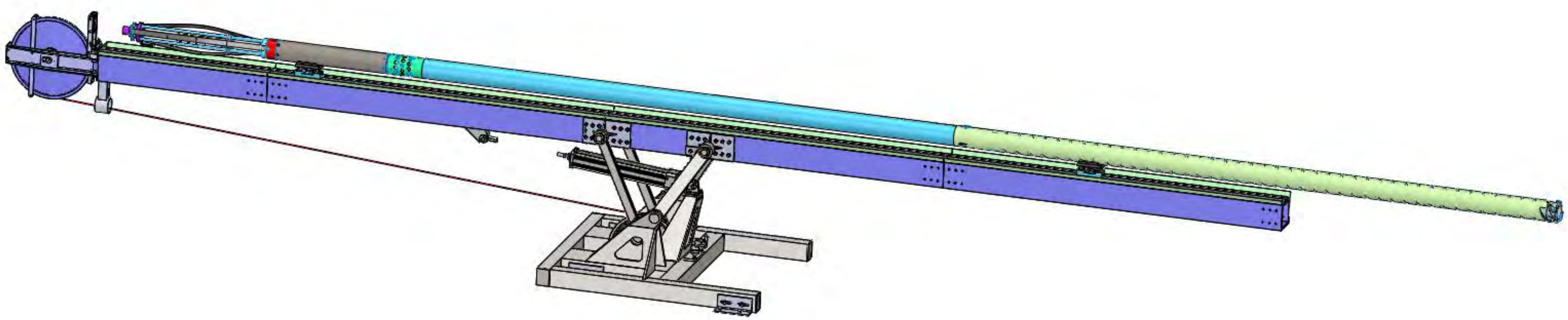
Footers and Cable Chase

- Wooden footers are required beneath the winch tower to disperse the load
  - Modular fabrications from standard framing materials and plywood
  - Snow loading is no higher than 2 psi
- Winch footer has integral drip pan
- Cable chase contains the winch cable and electrical cables for the winch
  - Cable chase is lined with fuel bladder material to contain any drill fluid that drips off the cable
- Cable chase is covered with removable aluminum plank flooring
  - 0.3 m (12") wide sections
  - Solid surface with non-skid coating
- Rim board around the slot stabilizes the snow opening



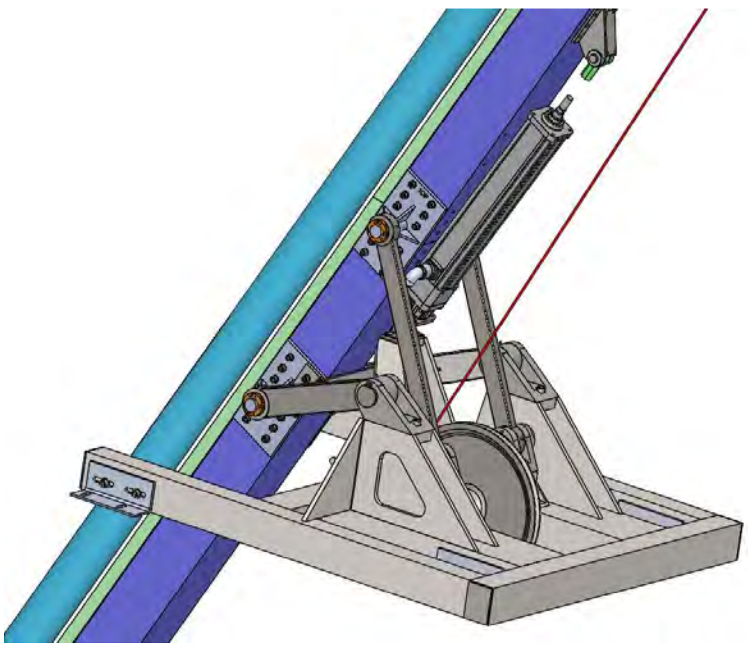
Tower

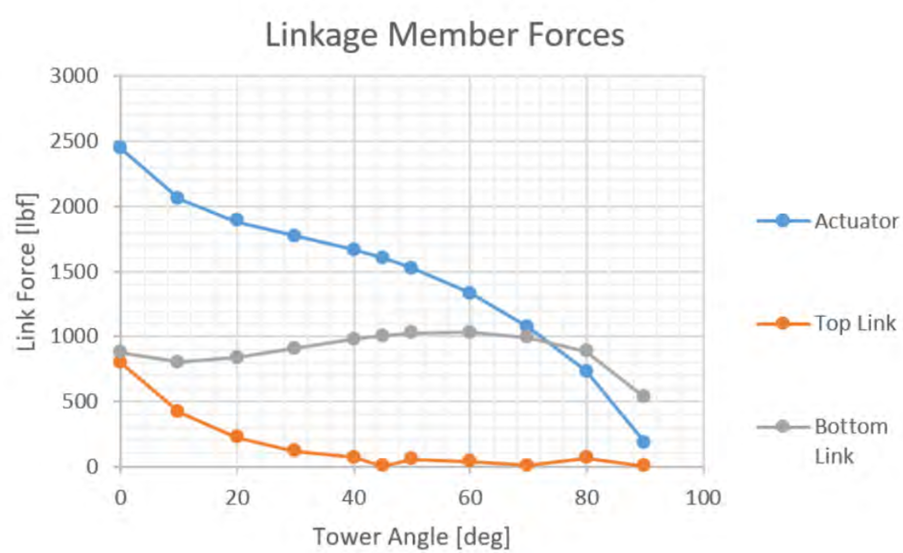
- The upper portion of the tower is the same length/height, 3 m, as the IDD
- The lower portion of the tower is 1 m longer than the IDD tower
- The IDD tower sections and drip pans will be reused
- The drill will extend past the end of the tower approximately 1 m
- The IDD crown sheave frame will be reused and fitted with a new sheave to accommodate the larger cable



Base

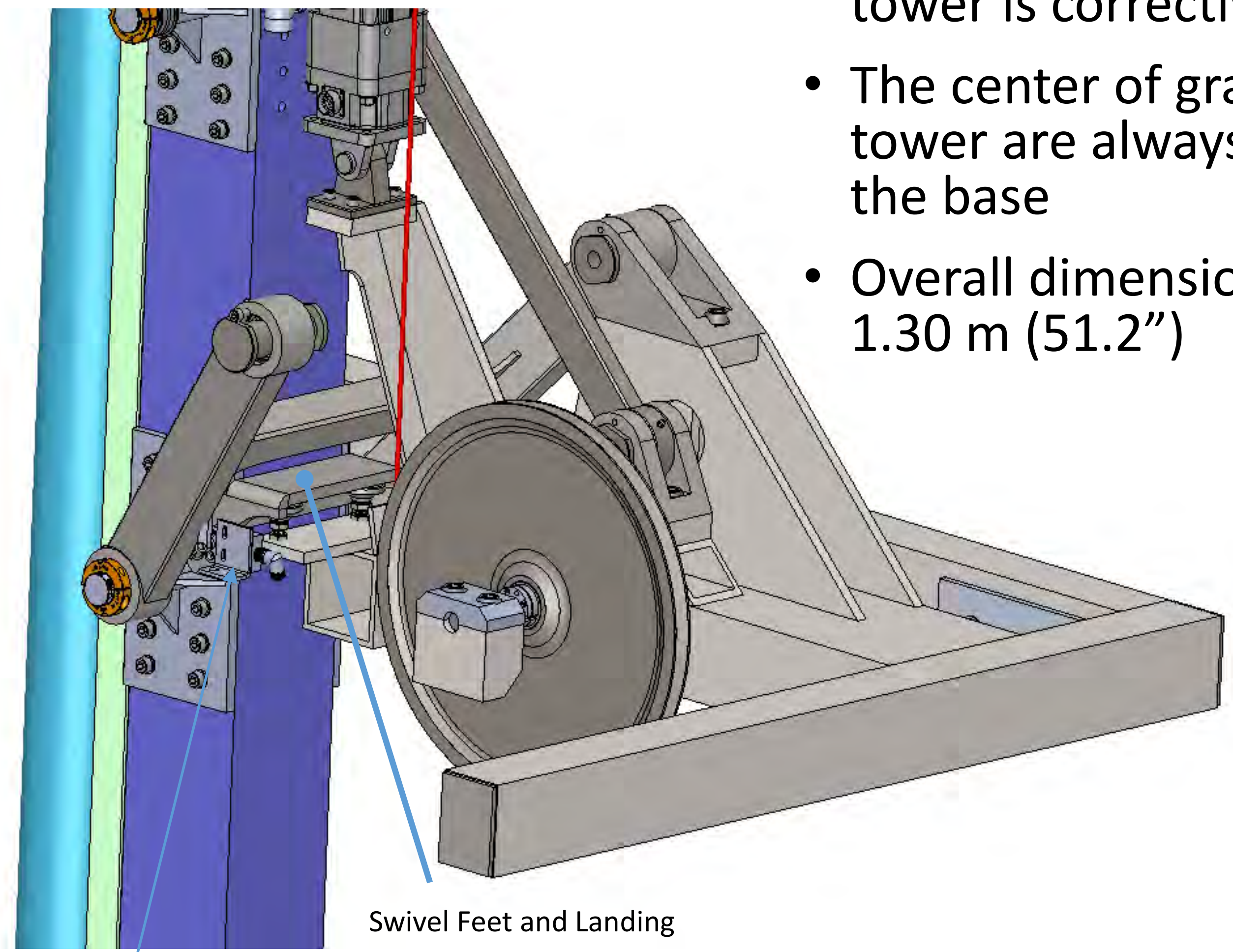
- The tower base was designed with linkage arms to prevent movement of the sonde along the tower during tilting
  - The tower shifts down as it rotates into the horizontal position to account for cable wrap around the reaction sheave
- Rotation from horizontal to 2 degrees past vertical
- Welded tubular steel frame – 218 kg (480 lbs.)
- Welded tubular steel linkage arms with spherical bearings – 15 kg (32 lbs.) [bottom] and 6 kg (14 lbs.) [top]

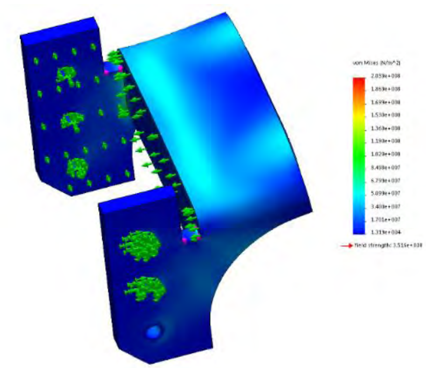




Base

- Adjustable feet support the tower during core break loads
- Limit switches (from IDD) ensure the tower is correctly positioned
- The center of gravity of the drill and tower are always within the footprint of the base
- Overall dimensions of 1.10 m (44.0") x 1.30 m (51.2")

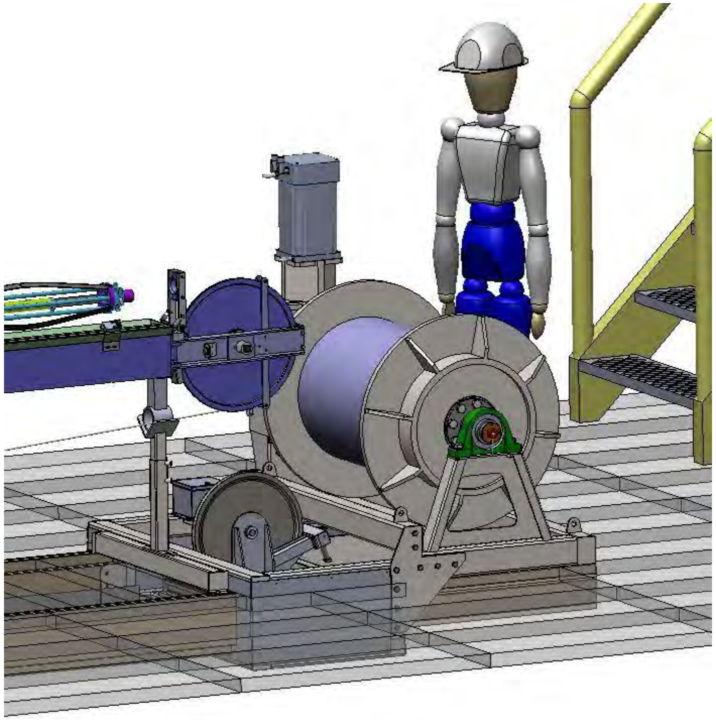


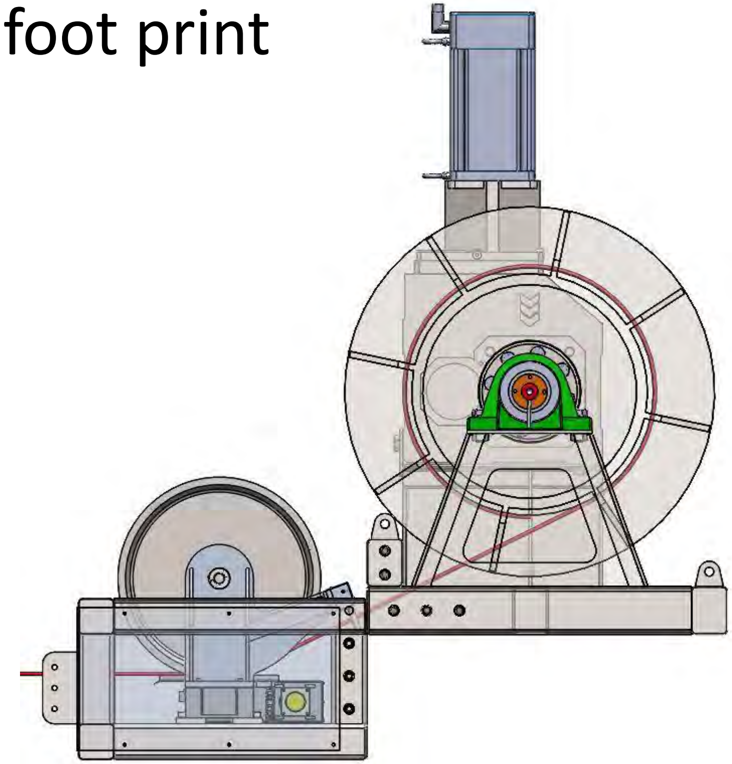


FEA results of the landing designed to support the tower during core breaks

Winch and Level Wind

- Winch and level wind separate for shipping
- Winch cable routes off the bottom of the drum, under the level wind sheave, and under the floor
- 1.4 m (55”) L x 1.5 m (59”) W foot print

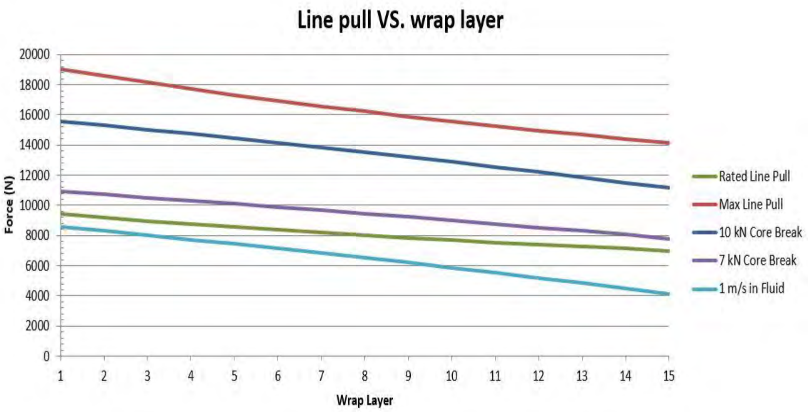




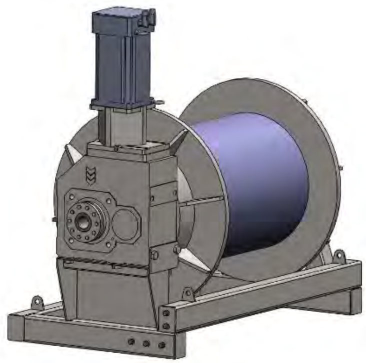
Cable routing path shown in red

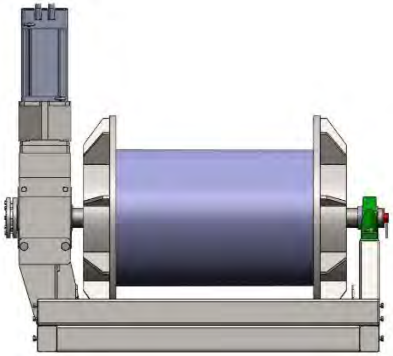
Winch

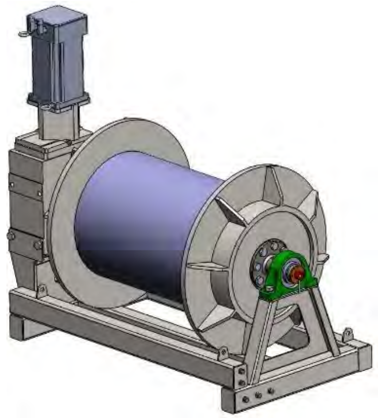
- Welded 3” x 4” tubular steel frame
- Gearbox and bearing mount are fabricated plate steel assemblies
- Removable winch drum with Lebus groove
- Design reuses the IDD winch motor
- 57:1 helical bevel gearbox
- Drum capacity is 3,100 m of 7.2 mm (.282”) Ø cable
    - 105 wraps x 15 layers
- Drum is 0.79 m (31”) Ø x 1.02 m (40”) wide
    - 0.76 m (30”) between flanges
- Overall dimensions of 0.77 m (30”) L x 1.50 m (59”) W x 1.33 m (52”) H
- Max line speed of 1.2 to 1.6 m/s depending on cable layer



Estimated winch weight	
Component	**Kg (lbs.)**
Frame	125 (275)
Winch drum	771 (1,700)
Gearbox	156 (344)
Motor	39 (85)
Cable (3,100 m)	626 (1,380)
Total Weight	**1,716 (3,784)**

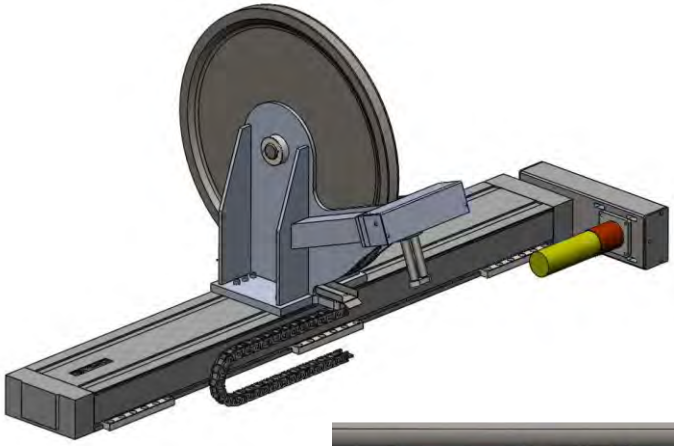


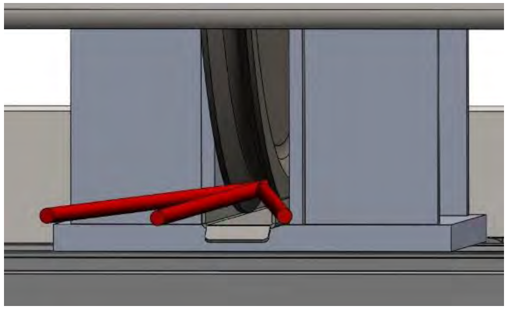


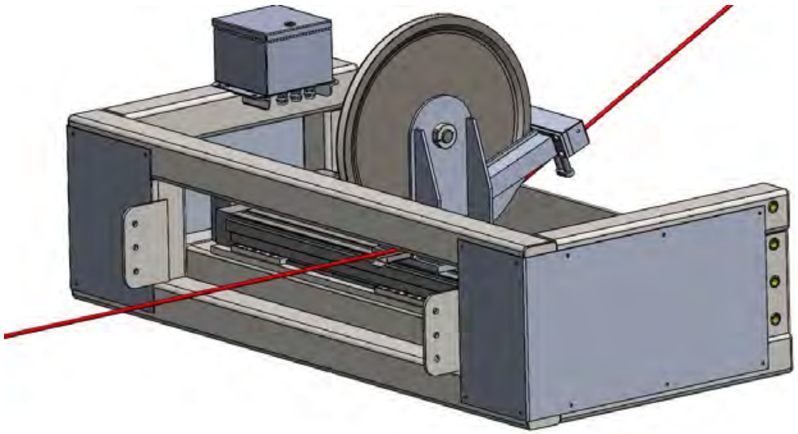


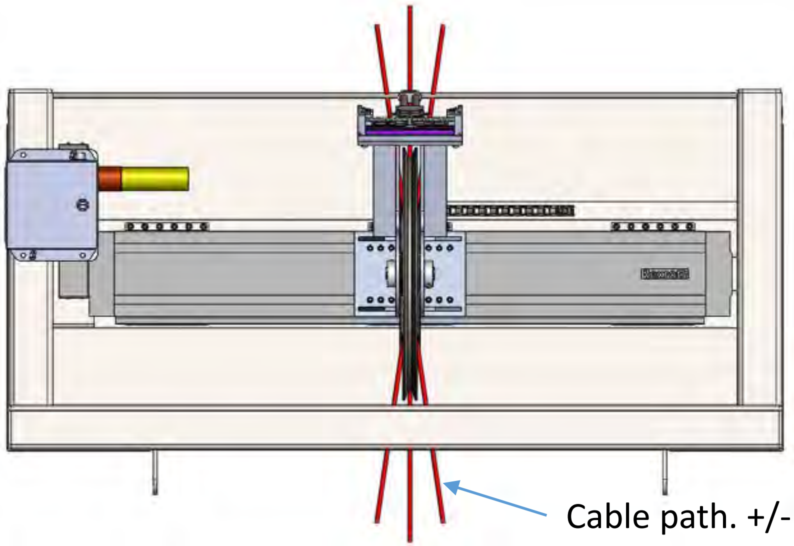
Level Wind

- Electronic auto-tracking system
- Welded 3” x 3” tubular steel frame
- 0.62 m (24”) L x 1.32 m (52”) W x 0.58 m (23”) H
- Estimated weight: 150 kg (330 lbs.)
- Built-in drill fluid containment
- Ball screw linear slide with timing belt side drive
  - 800 mm (31.5”) travel
  - magnetic reed limit switches
- 24 VDC, 150W BLDC motor
  - Same motor and control as used on the IDD level wind
- Designed to accommodate a +/- 8.3° fairlead angle
  - 6.1° required



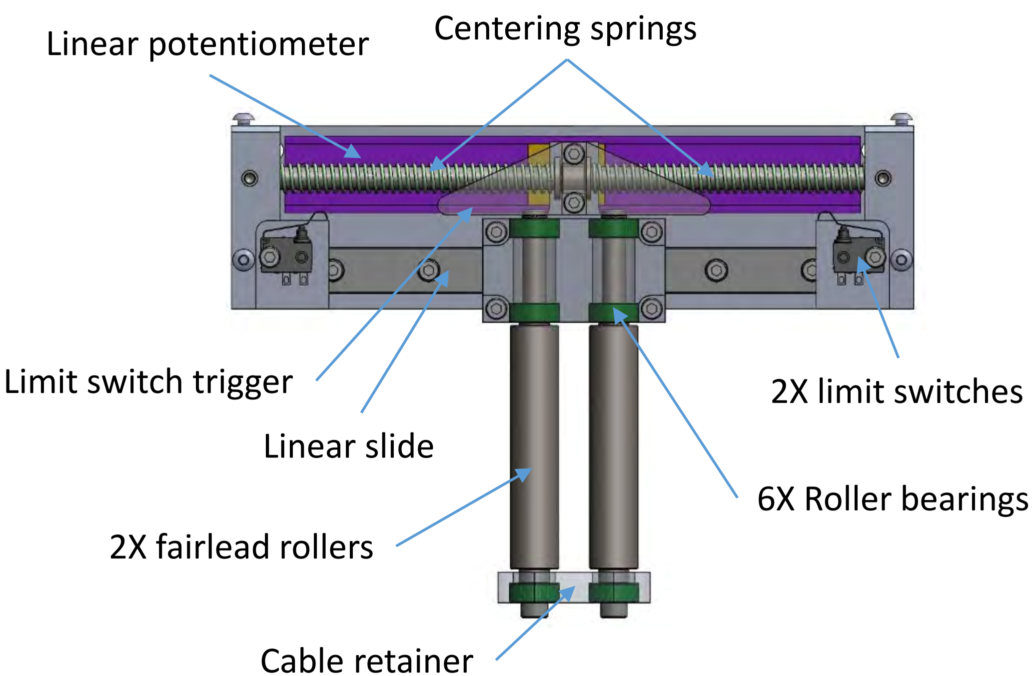


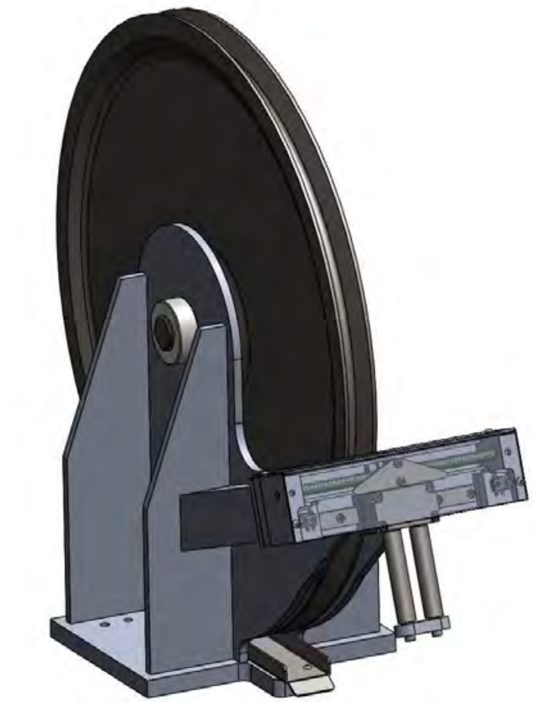




Level Wind Cable Angle Sensor

- Electronic auto-tracking system
- Fairlead rollers are mounted to a self-centering linear slide assembly
- Linear potentiometer senses cable position
- Limit switches will stop the winch if the level wind faults
- Modular self-contained assembly can be swapped out with spare unit for maintenance



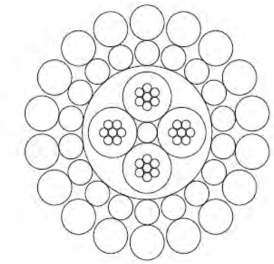


Winch Cable

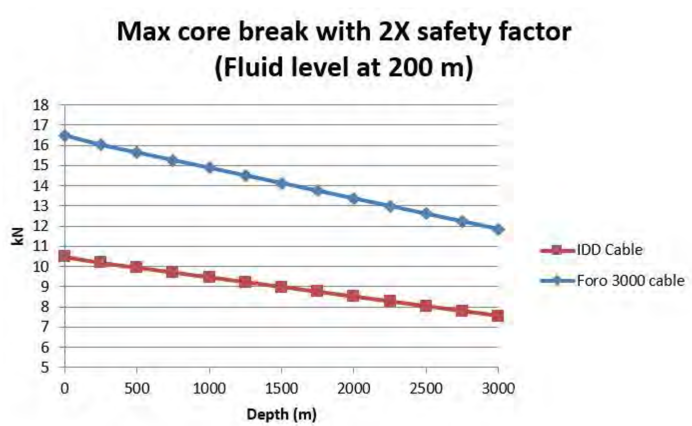
- Larger diameter cable required to maintain core break capacity at depth
  - 7.2 mm (.282”) Ø [IDD was 5.7 mm (.223”)]
- Four conductor cable
  - 2 dedicated conductors for communications
  - 2 conductors and the armor being used for power
- 3,100 m cable weighs 626 kg (1,380 lbs)

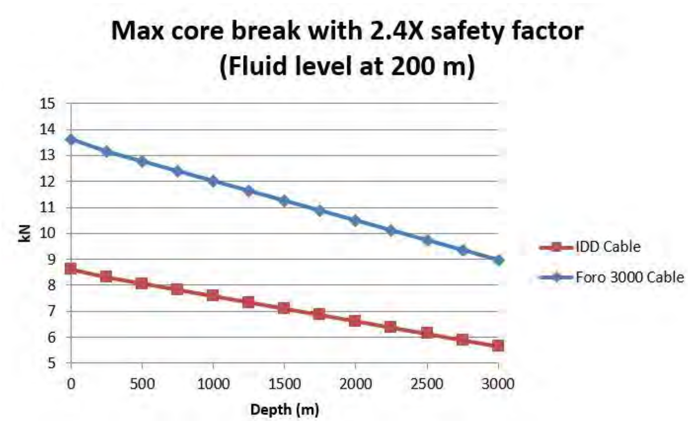
DATALINE®

Description	mm	Inch
CONDUCTORS (4) #22 AWG, 7/0.010" (0.25 mm) Bare Copper	0.76	0.030
INSULATION 0.015" (0.38 mm) Wall EPC	1.52	0.060
CORE 4 insulated cdrs twisted with fillers as necessary. Protective bedding over core.	3.76	0.148
ARMOR: Special GIPS Wire Inner: 18/0.028" (0.71 mm) Outer: 18/0.039" (0.99 mm)	5.18 7.16	0.204 0.282



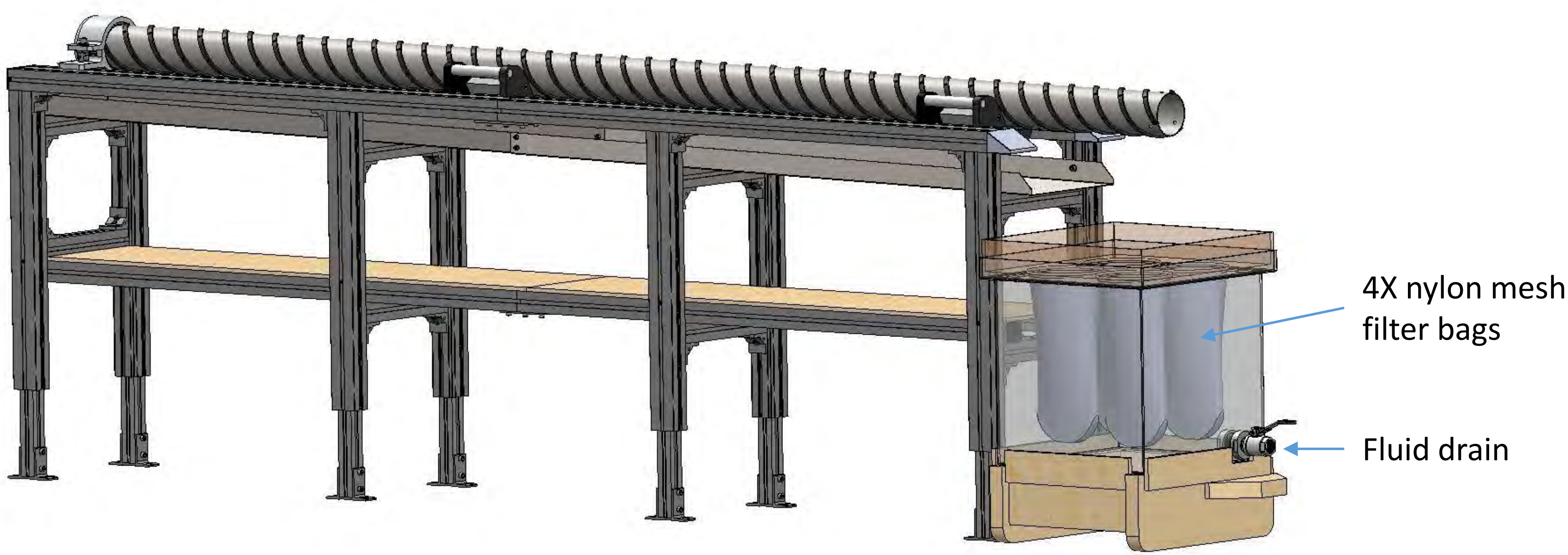
CABLE CHARACTERISTICS (Nominal Values @ 20°C)	Metric	English
PHYSICAL		
Overall Dimensions	7.16 mm	0.282 in
Weight in Air	202 kg/km	135 lb/kft
Weight in Freshwater	168 kg/km	113 lb/kft
Temperature Rating, normal	135°C	275°F
intermittent	149°C	300°F
MECHANICAL		
Breaking Strength	34.7 kN	7,800 lbf
Bend Diameter	40 cm	16 in
Elongation (approximate)	0.58 m/km/kN	2.6 ft/kft/klbf
ELECTRICAL		
Voltage Rating	600 Vdc	600 Vdc
dc Resistance		
cdr	54.5 Ω/km	16.6 Ω/kft
armor	10.3 Ω/km	3.1 Ω/kft
Insulation Resistance @ 500 Vdc	15,000 MΩ•km	50,000 MΩ•kft
Capacitance (cdr - armor)	115 pF/m	35 pF/ft
Velocity of Propagation @ 1 MHz	67%	67%





Core Barrel Pull-Out Table

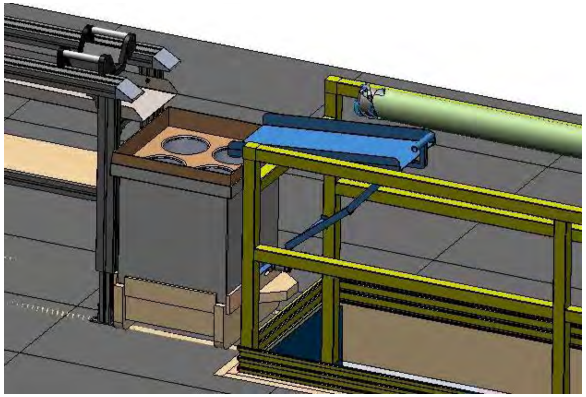
- No modifications to existing table - will accommodate a 3 m long core barrel
- New chips slurry tub with bag pre-filters to drain excess fluid from cuttings
  - Makes chips slurry easier to handle
  - Less material for the chip melter to process

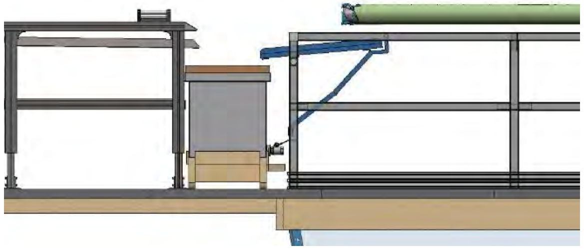


Core Barrel Drip Tray

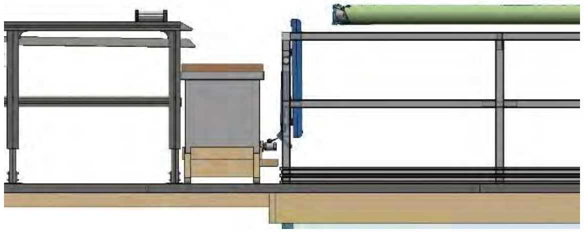
Folding drip tray directs the chips slurry coming out of the drill into the chips slurry tub as the core barrel and hollow shaft are pulled out

- Trip lever will fold the tray down if the drill runs into it

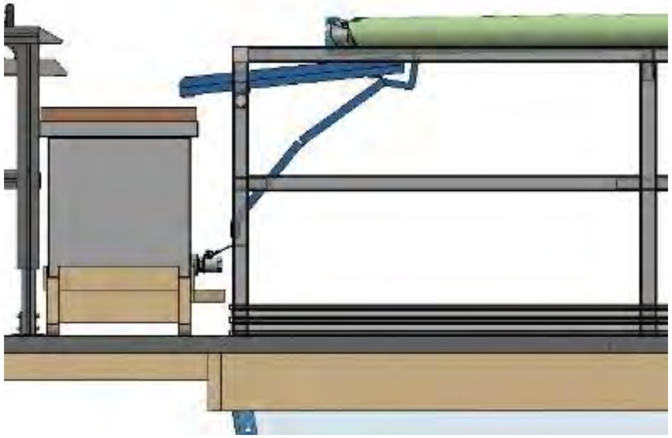




Tray in up position



Tray in stowed position



Drill actuating the trip lever

Chip and Fluid Processing

- Chip slurry will be heated to melt and separate the ice portion for improved drill fluid recovery
  - Centrifuge recovers only about 85% of the fluid from the cuttings
  - A melter system can recover nearly 100% of the fluid from the cuttings
  - Every 5% improvement in fluid recovery will save 10 drums of fluid for a 3,000 m deep borehole
- Electric powered chip melter has been selected over a system utilizing waste heat from the generators
  - Does not require generator modifications
  - System requires 2 kW of energy to keep up with a 60 m/day drilling rate
  - A load-shedding controller will be included
    - Allows melter operation only when generator loads are below a preset level
    - Reduces peak power demand
- Within ten minutes, Estisol 140 and water will separate enough that they can be recovered

Load shedding panel

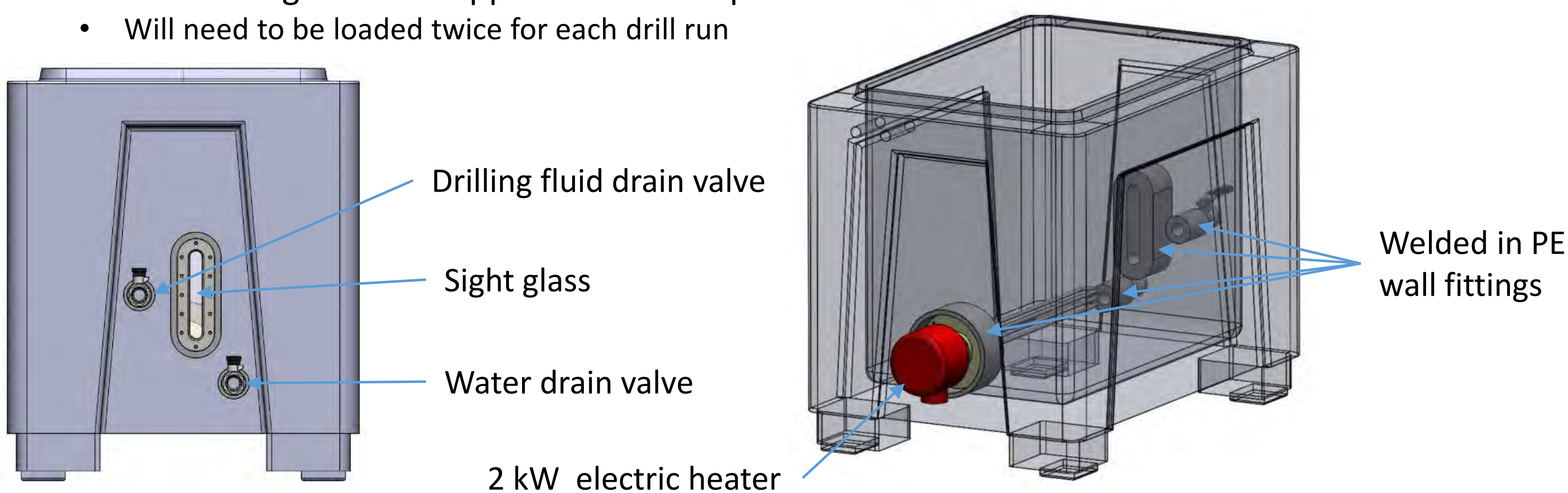
Estisol 140 & Water Separation Test

Time: 0min | Time: 2min | Time: 4min | Time: 8min | Time: 10min | Time: 20min

Chip Melter

- 306 L (82 gal) insulated double wall PE tank with hinged lid
  - OD: 1.1 m (42") L x 0.7 m (28") W x 1.0 m (39") H
- Melter system will be located outside the drill tent
  - Mitigates ventilation issues
  - Chip slurry will be transferred to the melter by hand in buckets
    - No more than 28 l (7 gal), 19.5 kg (43 lbs.) per drill run
- Water and drilling fluid are drained off through separate valves
  - Water will be discarded
  - Drilling fluid will be recovered and cooled before being reintroduced to the borehole
- Drilling fluid will be added to the borehole using the existing IDD fluid handling system
- The IDD centrifuge will be supplied as a backup
  - Will need to be loaded twice for each drill run

Chip melter system



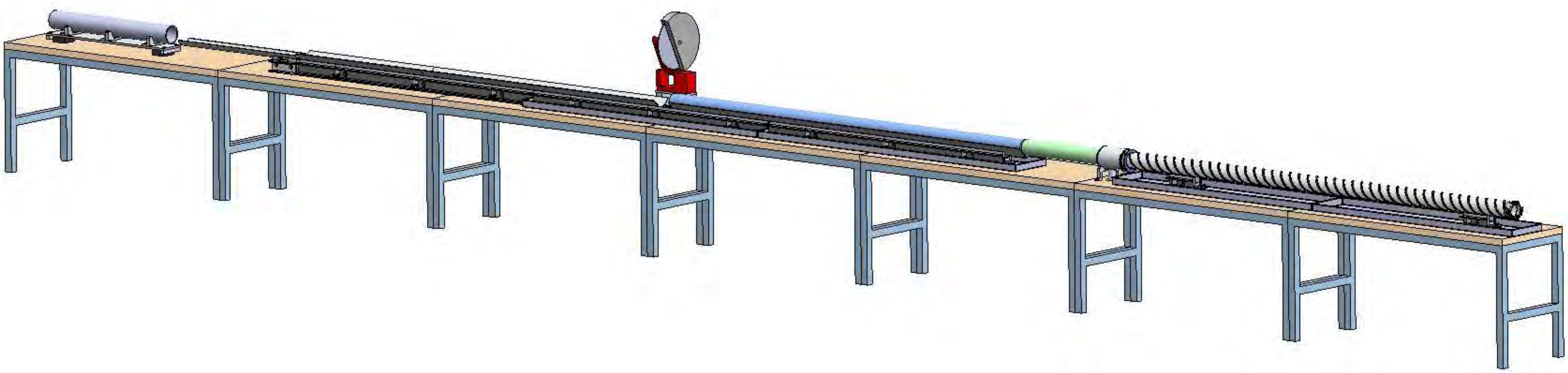
Drilling Fluid

- Drill system is compatible with Estisol 140 and Isopar K
- Recommend using Isopar K with a yet to be determined densifier over using Estisol 140
- Despite a determination that Estisol 140 is non-hazardous, many people experience negative side effects when exposed to Estisol 140
  - Headaches
  - Lightheadedness
  - Throat/eye irritation
  - Change in appetite
  - Loss of smell
  - Effected balance
- Suggest continued research and testing of other fluid options

Core Processing Line

The Core Processing Line required only minimal changes to accommodate a 3 m core barrel and space to process 3 m cores

- New core barrel rests for use with the longer core barrel
- Longer netting sleeve for the FED to accommodate the longer brittle ice netting
- Longer sliding core tray after the FED
- New fluid containment drip pans
- Reconfigured system fits on the existing 7 tables



Maintenance Shop

- A maintenance shop is a critical part of the drill system for minimizing downtime due to unforeseen maintenance issues and for necessary modifications
- Three options were investigated
- Each option has its strengths and weaknesses when evaluated for cost, logistics burden, and ease of setup/takedown on site
- Further discussion is needed to determine the best option

Panoramic view of the MECC shop

Maintenance Shop

MECC Shop

Bicon Shop

Tent Shop

	MECC Shop	Bicon Shop	Tent Shop
Transport size	20’ L x 8’ W x 8’ H	9’ 10” L x 8’ W x 8’ H	6’ 7” L x 4’ 2” W x 4’ H
Weight	19,140 lbs.	7,000 lbs.	2,200 lbs. (w/o tent)
Cubes	1280 ft^3	635 ft^3	110 ft^3 (w/o tent)
Floor space (expanded)	393 ft^2	154 ft^2	150 ft^2 minimum
Heat	Electric, 6000 W	Electric, 3000 W	Kuma Stove – JP8 fuel
Power feeds	208V 3ph and 460V 3ph	208V 3ph	220V 1ph
Materials Cost	$0	$77,980	$11,480 (w/o tent)

Power requirements

- The drill system will require a 55 amp 460V 3ph power feed
  - 35 kW generator
- The existing IDD power distribution system will supply power to the shop and all equipment in the drill tent
- Estimated to require 10,000 gallons of fuel to operate for 150 days (3 seasons)

50 kW generators used for the SPICE Core project

Operations

- Drilling and core processing operations will require a 10-person team
  - 24 hour/6 days per week operations
  - 3 people per shift (Two IDDO drill operators and one science team member)
  - 1 IDDO lead driller
- It is estimated to require approximately 120 drilling days to drill to 3,000 m

	Season 1 (days)	Season 2 (days)	Season 3 (days)	TOTAL (days)
Setup (one 10 hr. shift)	12	2	2	16
Pilot hole (two 10 hr. shifts)	5	0	0	5
Drilling (three 8 hr. shifts)	31	46	43	120
Pack up (two 10 hr. shifts)	2	2	4	8
Total operational days	**50**	**50**	**49**	**149**

- Timing is based on heavy equipment being used to move cargo, excavate the drill trench, and support drilling operations.
- It is recommended to plan for a fourth season in case drilling issues are encountered, especially in warm ice, or if delays due to weather or logistics and camp close-out are encountered.

Logistics

- The IDD system is currently packaged for transport by LC-130 or ground traverse
  - Tractor with minimum fork capacity of 4,000 lbs. is required to move crates
- Additional weight and volume considerations for the Foro 3000 are shown below

Estimated shipping weight

Current IDD system	Foro 3000 additions	Shop Option	Total Shipping Weight
28,800 lbs.	7,200 lbs.	MECC Shop = 19,140 lbs.	55,140lbs.
		Bicon Shop = 7,000 lbs.	43,000 lbs.
		Tent Shop = 2,200 lbs.	38,200 lbs.

Estimated shipping volume

Current IDD system	Foro 3000 additions	Shop Option	Total Shipping Volume
2,130 ft^3	120 ft^3	MECC Shop = 1,280 ft^3	3,500 ft^3
		Bicon Shop = 635 ft^3	2,855 ft^3
		Tent Shop = 110 ft^3	2,330 ft^3

High-Level Equipment List

- Does not include design/development/fabrication labor or indirect costs
- One of the shop options would be included in the final design
- Total project cost is expected to be $787,000 to $1,060,000
  - Includes labor, equipment, materials, and indirect costs
  - Portion of the cost range is due to shop option costs

Maintenance Shop Options	
MECC Shop	$0
Bicon Shop	$77,980
Tent Shop	$11,480

Winch and tower	
Winch with level wind and 3,100 m cable	$68,698
Second winch drum for spare cable	$21,000
Spare 3,100 m winch cable	$26,058
Tower base and tower modifications	$10,430
Sonde	
Extend IDD drill for 3 m long cores	$56,110
Anti-torque modifications for larger diameter cable	$5,150
Drill Recovery	
Glycol freezer and equipment	$5,094
Baler	
Extend baler 1 m and add weight stack	$4,388
Control System	
Longer cabling for winch	$500
Drill Slot	
Modifications for longer and deeper slot	$3,029
Casing Installation Tools	$550
Core Pull-Out Table	
Modifications to work with Foro 3000 layout	$1,127
Core Processing Line	
Modifications to work with 3 m cores	$2,455
Fluid Handling	
Longer hoses	$450
Chips Processing	
Chips Melter system	$4,284
Drill Tent	
Add vestibule to one entry door	$150
Shipping Cases/Crates	
Crates for new equipment	$3,765
Consumables	
Casing, 100 m of pipe	$2,672
Casing shoe	$575
Glycol for drill recovery	$222
Drill Equipment Total:	**$216,706**

Discussion