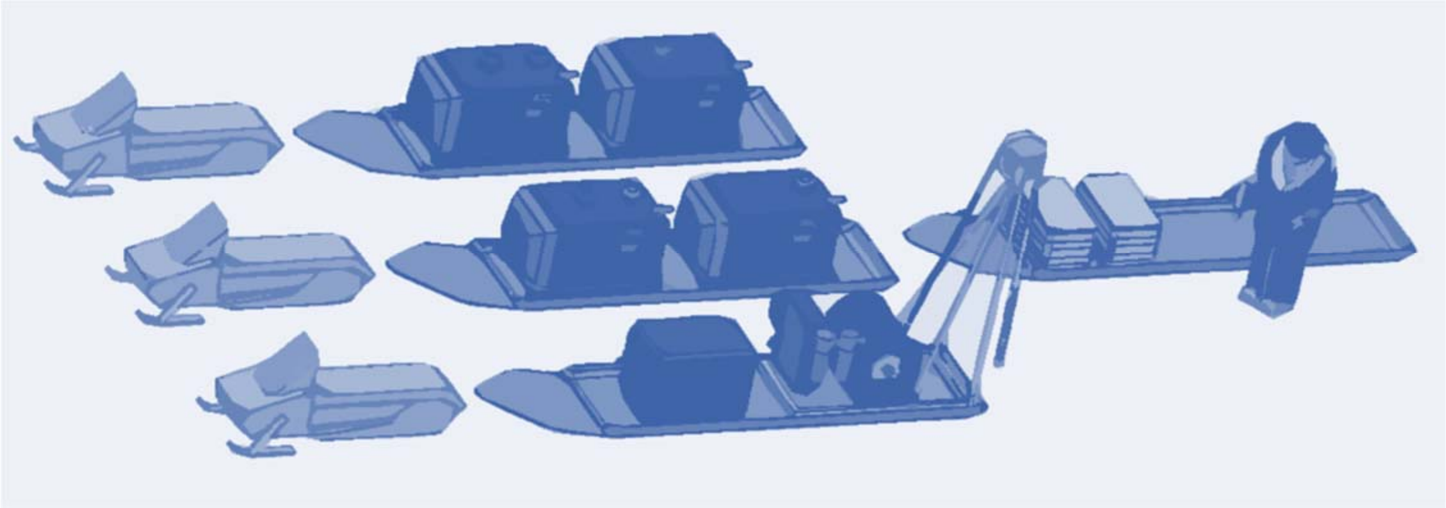
Rapid Air Movement Drill Upgrade
Concept Overview

Revision 8/8/2017



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INTRODUCTION and REQUIREMENTS

The U.S. Ice Drilling Program Long Range Science Plan 20117-2017 identified science goals for ice drilling that spanned a wide range of science targets. For field projects with limited logistical support where geophysical information is needed, an agile, scientist-operated, shot hole drill is needed to rapidly create holes in firn to depths of approximately 40-100 m depths. From discussions organized by IDPO with iterative discussions between IDPO, scientists, and IDDO staff, the following are the science requirements for the drill [1]:

Science Requirements

1. The Drill should produce holes in firn for a 10 cm nominal hole diameter in the top 40-100 m of a wide variety of firn types, including use in West Antarctica or Greenland. A minimum hole diameter of 7.5 cm is needed, in order to freely pass a cartridge of 5.5 cm diameter and 124.5 mm long to the bottom of a hole that is 100 m deep. The system may include modular hoses/winch/compressor subsystems to allow for access to either only the top 40 m, or to drill to the full max depth of 100 m, with reduced logistics needs for the 40 m system configuration.

2. The goal for the drilling rate should be to produce 15 ten-centimeter diameter holes to 100 m depth in 6 hours or less of drilling (not including drill transport time between sites). The longest acceptable drilling time per 100 m hole is 40 minutes.

3. The drill should have stand-alone capability for operation at small field camps at remote sites with no heavy equipment.

4. The drill should be operable in cold ambient temperatures down to -30 C (+/- 5 C) and winds of up to 25 knots. The firn and ice are expected to be frozen.

5. Drilling depth should be available during drilling.

6. The modules for transport shall be sized appropriately to be easily handled by 2 people with loading assist equipment provided with the drill. The goal for the total system weight with aircraft packaging is to be less than approximately 4,000 lb.

7. The drill should be very field portable, with the ability to be towed over rough terrain. It is a goal that the 40 m system should be towed ideally by a single snowmobile, and the 100 m system towed by several snowmobiles or by a Tucker.

8. If towing the 40 m system by a single snowmobile is not achievable, then a modular system is desired that be easily separated for transport (and subsequently reconnected). Consider a “power plant/ compressor” sled and a drill sled that are only connected by few hoses/cables.

9. The drill control should be simple and intuitive for use in the field by a scientist who has had training before going into the field. Two personnel (one trained and one other) should be able to set up and do the drilling operations in the field.

10. Setup time for the drill should be within 8 hours after initial unpacking on site.

11. Drill operations shall be such that two fit people can raise and lower the hose and drill head for a full day without excessive fatigue. Consider providing a mechanical assist to lessen fatigue during drilling operations.

12. Drill storage in the field at the end of the day should be planned and designed, in the case of an anticipated storm. The SOP should be designed for storms with 30-40knot winds and blowing snow.

13. The drill should be maintainable in the field by scientists, and instructions and parts for maintenance in the field should be included with the drill.

14. No more than 1 drum of one type of fuel should be required for 12hr operation.

15. Engineers should design an SOP for retrieving stuck drills or clogged exhaust hose. Possible ideas may include glycol bombs, or attaching a bullet heater to the air line, or heat tape integrated in the hose and head that can be turned on in an emergency, or other. The generator must be appropriately sized for these emergency situations, or else include a requirement for a 2nd “emergency/backup/spare” gen. A failure mode and effects analysis shall be performed and the drill system shall include documentation, tools, equipment and spare parts required to address high-risk situations in the field.

Safety

Safety of personnel using this drill is paramount due to the hazardous nature of the operations, severe environmental conditions at the drilling locations and the extremely long travel time to advanced medical and life support facilities. Even small mishaps may have severe consequences in this environment. In addition to the safety of personnel, preventing damage to the equipment is important because of the difficulty and cost of repairing the equipment in the field. The failure of a single piece of equipment that cannot be field-repaired could potentially cause the loss of an entire drilling season. The following are safety requirements for the drill system.

1. Create a safety plan that defines how key issues for the project will be identified, managed, assessed and addressed during the system development.
2. Conduct a Failure Modes and Effects Analysis (FMEA) to identify and manage mechanical/physical/chemical and personnel hazards for the system.
3. Provide operational and safety trainings, as identified by the FMEA, to address safety hazards.
4. Provide operational and safety trainings, as identified by the FMEA, to address quality issues.
5. 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.
6. Provide appropriate Personal Protective Equipment (PPE) for operating the drill system and handling drilling fluids, as identified in the FMEA.
7. Minimize environmental impact of the drilling operations through mitigations identified in the FMEA.
8. Provide identification of and protection from dangerous voltages.
9. Provide safety interlocks (Lock-Outs) to prevent the in-advertent operation of the equipment that would endanger personnel.
10. 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.)
11. Create an operations plan and procedures for normal drilling and surface operations of the system.
12. 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

Existing Rapid Air Movement Drill System:

The following provides a summary of the high-level Rapid Air Movement (RAM) system specifications as deployed in West Antarctica from 2002 to 2010.

- Rotary Screw Compressor (Qty 2): 400cfm/200psi; 174HP Cummins Diesel Engines; 5200lbs each
- Hose Reel Sled: 12’ High Assembled
- Hose: 1.5 inch ID/2.1 inch OD Hose, Min. Bend Radius of 24”, 1.07 lbs/ft, 325ft (99m)
- Sonde: 4 Blade Powered by two 1.6HP/2400RPM Air Motors
- Bore Diameter: 4”
- Deployed System Weight: >20,000lbs

The existing RAM system has been deployed to West Antarctica in multiple field seasons and to South Pole for testing with the Askaryan Radio Array (ARA) project. The lessons learned and data collected from these deployments are summarized below and serve as an invaluable reference for developing this concept and for future design decisions.

South Pole Testing 2010-2011 [2]:

A series of 12 test holes were created with 3 Compressors. Depths achieved were 44m on average with a 37m minimum and 5m standard deviation. Separately, a Pitot tube was used to measure exit velocity in holes of varying depth. Measurements showed exit velocities of 59 ft/sec in a 30m hole and 35 ft/sec in 45m hole. Based on data from the series of 12 test holes, assuming a standard distribution, we would expect about 50% of holes would fail at 45m and <2% of holes to fail at 30m, suggesting 59ft/sec would be a reasonable target value for minimum exit velocity. This value is consistent with previous estimates made for the RAM drill and with rock drilling norms [3].

With the objective of going deeper in South Pole firn, it was recommended that further studies of borehole permeability and casing the borehole be made.

West Antarctic Field Data (500+ holes, 2002-2010):

In the Onset D field season, 2002-2003, a number of useful parameters were recorded for more than 200 holes. In subsequent seasons in West Antarctica, drill logs provide basic data from over 300 holes.

Based on measured compressor performance at the University of Wisconsin Physical Sciences Lab, adjusted for conditions at Onset D, the estimated volume of air provided during drilling at Onset D was 590scfm. From this value, the exit velocity, assuming no loss to firn would have been 150 ft/sec in the annular space between the hose and the 4” borehole. Relative to the Pitot tube values of 35ft/sec and 59ft/sec, this suggests as much as 60% to 75% air loss to the firn in West Antarctica.

Onset D data also included average supply air temperature measurements of 8°C (46°F), a 14°C (26°F) rise relative to ambient. This is a higher temperature than the design target and indicates that improvements may be achieved by improved air cooling.

Data recorded in West Antarctica showed that in certain areas 90m depths were achieved consistently for several holes in a row. Also notable, average overall drill times were 0.40 m/minute and diesel consumption recorded was 5.5 gal/hole including that used by the Tucker Snow Cat.

The following highlight relevant recommendations during these field seasons.

2007 RAM Review Notes [4]:

- Evaluate the possibility of using more efficient compressors.
- Specify and deploy a larger generator for use with heaters.
- Design and implement a new hose reel.

2008-2009 End of Season Report [5]:

- The hose reel sled was damaged and it was recommended that the hose be removed during long traverses.
- Clogging appeared to be an issue and ethanol supply air temperatures were adjusted. Testing and fine tuning on location may be necessary in the future.

2009-2010 End of Season Report [6]:

- Simple level wind for hose reel to allow size reduction on a simplified assembly.
- Evaluate possible injection of ethanol up stream of after coolers. Install larger after coolers.
- Evaluate the possibility of using more efficient and lighter compressors.
- Implement minor mechanical improvements to the drill sled.

Given this data, it is interesting to consider what limits the performance of the RAM drill. Initially, it is clear that air flow is more than adequate with a 6’-10’ plume of ice chips and very few failures above 30m. Presumably, air losses increase in porous firn to depths of 70m. If this were the only contribution to hole failure, we would expect drilling to continue indefinitely beyond this depth, but this is not the case.

Erosion seen at the top of the hole was investigated as a possible contributor, but casing and other efforts seemed to have little effect. However, the possibility that the bore wall may erode over time at greater depths still exists. Expanded flow paths in these areas may cause recirculation of chips or simply lower velocities.

Another contributing factor is likely related to “snow balls” seen near the end of drilling. It seems likely that ice chips sticking together tend to clog the return path over time. This points to potential gains being achieved by adjustments to air temperature, ethanol injection, recirculation, and particle size.

Air-flow Model:

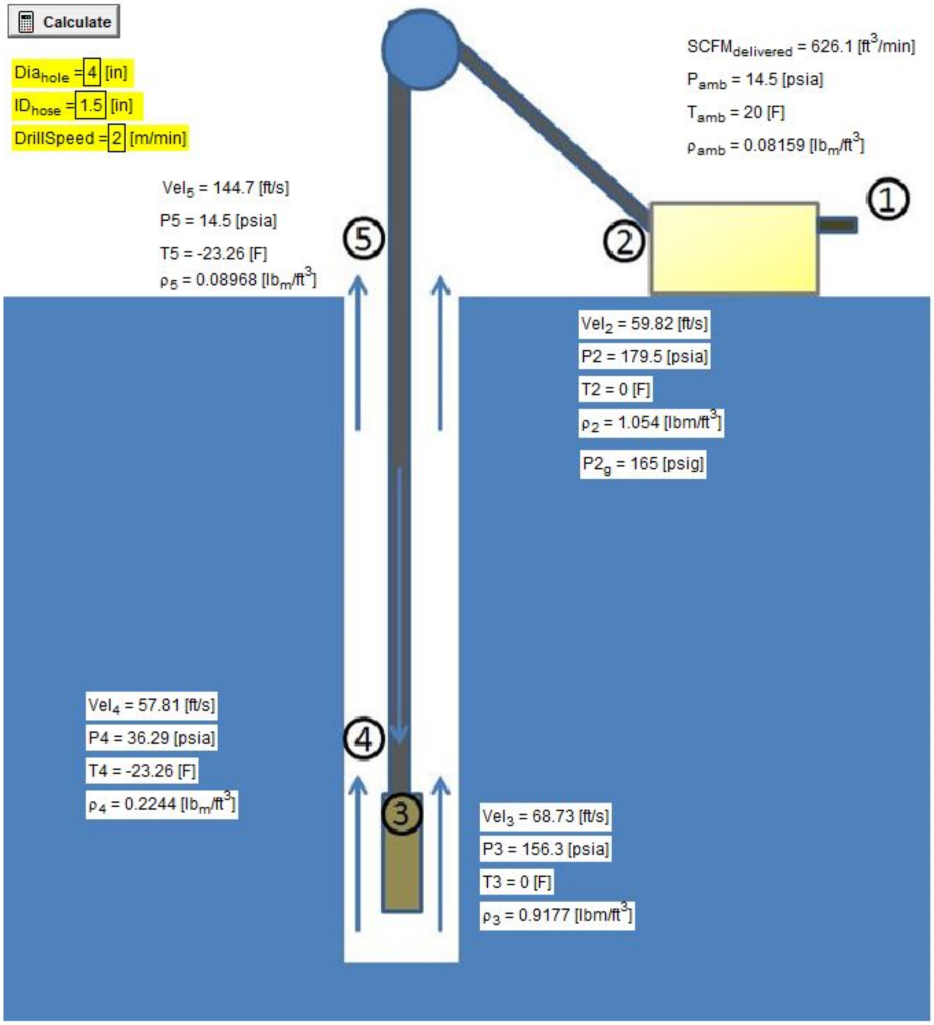
In order to have a better understanding of the performance of the existing system and to explore impacts of potential changes to the system, a model was developed based on empirical equations for air flow and solids conveyance [7, 8, 9, 10].

Based on the field data above, a reasonable target exit velocity of 59ft/sec was used in calculating pressure loss in the return path. With ambient pressure at the outlet of the borehole, pressure in the annular return path is comprised of friction of the air and ice chips against the bore wall and hose, ice chip particle interactions, and static pressure of ice chips [7].

Additional pressure drop across the drill head is typically set to 110psi at the surface during RAM Drill operation, an additional 5-10 psi is estimated for exit head losses when cutting.

Supply hose losses are given by an equation for isothermal compressible gas flow in long pipeline [9] with hose roughness factor estimated from RAM testing at University of Wisconsin Physical Sciences Lab.

Figure 1 below shows an example of the output from the model with a cased hole; firn losses are taken to be 60-75% mass flow supplied for a 4” hole based on Pitot tube test data above. Pressure loss through air treatment components (air chiller, oiler, air dryer) is 5-10psi based on manufacturers’ specifications.



Dia_{hole} = 4 [in]
ID_{hose} = 1.5 [in]
DrillSpeed = 2 [m/min]

$SCFM_{delivered}$ = 626.1 [ft^3/min]
P_{amb} = 14.5 [psia]
T_{amb} = 20 [F]
ρ_{amb} = 0.08159 [lb_m/ft^3]

Vel_5 = 144.7 [ft/s]
P5 = 14.5 [psia]
T5 = -23.26 [F]
ρ_5 = 0.08968 [lb_m/ft^3]

Vel_2 = 59.82 [ft/s]
P2 = 179.5 [psia]
T2 = 0 [F]
ρ_2 = 1.054 [lbm/ft^3]
$P2_g$ = 165 [psig]

Vel_4 = 57.81 [ft/s]
P4 = 36.29 [psia]
T4 = -23.26 [F]
ρ_4 = 0.2244 [lb_m/ft^3]

Vel_3 = 68.73 [ft/s]
P3 = 156.3 [psia]
T3 = 0 [F]
ρ_3 = 0.9177 [lbm/ft^3]

Figure 1: EES Model Output

Basic System Upgrades:

With no major change to the drill head and well established cutting performance, it is possible to make significant changes to reduce the weight of the system. Modular and light weight compressors could reduce compressor weight by 30-45%. The existing hose reel could be reduced in size to be assembled in the field by two people. Fuel usage, however, would not be reduced significantly.

This approach, while low risk and less costly, does not nearly achieve the fuel requirement or weight goals defined in the science requirements for this drill. Additional modifications are necessary.

Borehole Casing:

Given significant air losses to the firn, the potential benefit of casing the hole was explored.

Reducing total volume of air by the full amount lost to firn is not possible because adequate lift is necessary at base of the hole. Lift on ice chips varies with air density.

$$Lift=1/2C_D*\rho*v^2*A$$

Slower, higher-density air at bottom of bore hole has less lift. At the bottom of the hole with a pressure of 15psig, 2 times additional air volume is required to achieve equivalent lift. As such, the air flow reduction potentially achieved by casing is estimated to be 50%.

IDDO has performed a significant amount of analysis and testing of casing options given the large potential benefits. Results of some of the casing options explored follows. Many of the options are impractical due to the complexity added to procedure and very fast penetration rate required. None provide a solution that achieves the science requirements without significant risk in operations.

Custom Light-Weight RC Rod is a typical solution for compressed air drilling but is heavy and deployed much too slowly for this application. With assembly/disassembly of each 3m rod section, a 100m hole would require approximately 77 minutes of drilling time.

A **Fabric Sock** casing made of a material similar to parachute fabric held promise and was tested. Again, recovery rates were slow and there was a high likelihood of complication in the recovery process including a significant risk of a stuck drill. In testing in ideal conditions, recovery of the sock achieved a rate of only 5m/min. Presuming descent times similar to the existing RAM drill and no issues on recovery, a drill time of 55 minutes is estimated, Table 1.

Table 1: Trip Time Estimates

Trip Times		40m No Sock	100m No Sock	100m w/ Sock
Depth	m	40	100	100
Speed @ Top	m/min	6	6	6
Speed @ Bottom	m/min	2	2	2
Return Speed	m/min	20	20	5
Set-up/Tear-down Between Holes	min	5	5	5
Return Time	min	2	5	20
Descent Time Total	min	12	30	30
Total Trip	**min**	**19**	**40**	**55**

Partial Casing deployment was also considered. The most promising approach would be to deploy the fabric sock through the most porous firn only (approximately 35m) while drilling to the full depth of 100m. In ideal conditions, this would put drill times in the range of the 40 minutes dictated in the science requirements, but this approach comes with an unacceptable risk of complications and a stuck drill.

Umbilical Hoses were considered consisting of multiple hoses combined to contain both supply and return air paths. Potential solutions were explored with multiple manufacturers. An umbilical would likely provide drill times close to those required, but this approach has other drawbacks including: risk of wear and clogging on a long circuitous chip return path, weight, bend radius and sticking of a relatively inflexible hose. Perhaps the most significant of these is the overall impact to the weight size of the system. It is estimated the weight of the 3 1/2 " hose similar to that shown in Figure 2 is nearly 3 times larger than the existing RAM hose totaling nearly1000lbs. At 28", the bend radius of this hose is also greater than that of the existing RAM drill requiring a larger goose neck and a very large hose reel. Assuming multiple wraps, the hose reel would weigh approximately 900lbs. In total, this hose, with a suitable hose reel, tower and goose-neck would add more than 2000lbs to the system significantly offsetting weight savings that might be achieved from a smaller compressor.

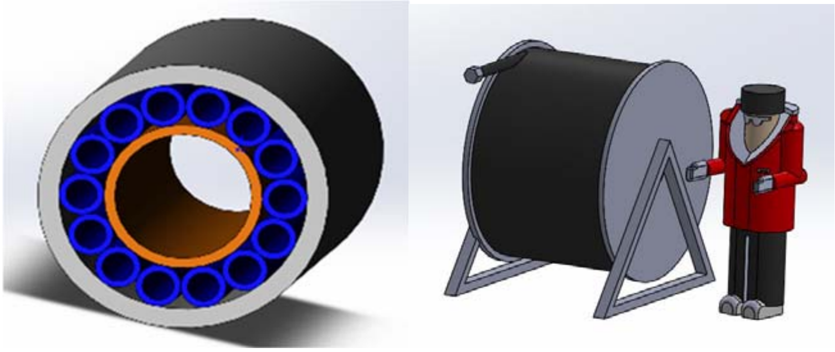


Figure 2: Umbilical Hose

Cross-section of a 3 1/2" O.D. umbilical hose (left). Conceptualization of the size of the hose reel with umbilical hose (right). Hose, reel and motor together would weigh well over 2000lbs. At 6' in diameter and 4.5' wide, significant assembly, disassembly and multiple trips would be required for transport by light air craft.

Other Possible Performance Improvements:

Other solutions in combination have the potential to impact the size of the system to an extent similar to that of casing the borehole.

Optimizing the air-flow path for the return chips has the potential to reduce air flow demand from the compressor.

Reducing clogging potential will help keep established flow from being cut-off over time. This may be possible through improved cooling, drying of input air; careful evaluation of ethanol use, and limiting borehole erosion especially below surface.

Finally, weight reductions are possible to directly impact logistics costs. These can be focused on drill equipment, support equipment and fuel consumption.

A combination of all of these is proposed and discussed in more detail in the following section.

SYSTEM DESCRIPTION

The figures below describe the upgraded system. Equipment lists are shown in Table 2 highlighting major components of the 40m and 100m configurations. The 40m system largely consists of all the components of the 100m system with the exception of the hose and hose reel which are replaced with a smaller version sized for 40m. The 40m configuration will also use just 3 of the 4 compressors. In total, the weight reduction for the 40m system is expected to be approximately 1000lbs. This may be significant in allowing both fuel and the drill equipment to be transported with 3 snow mobiles.

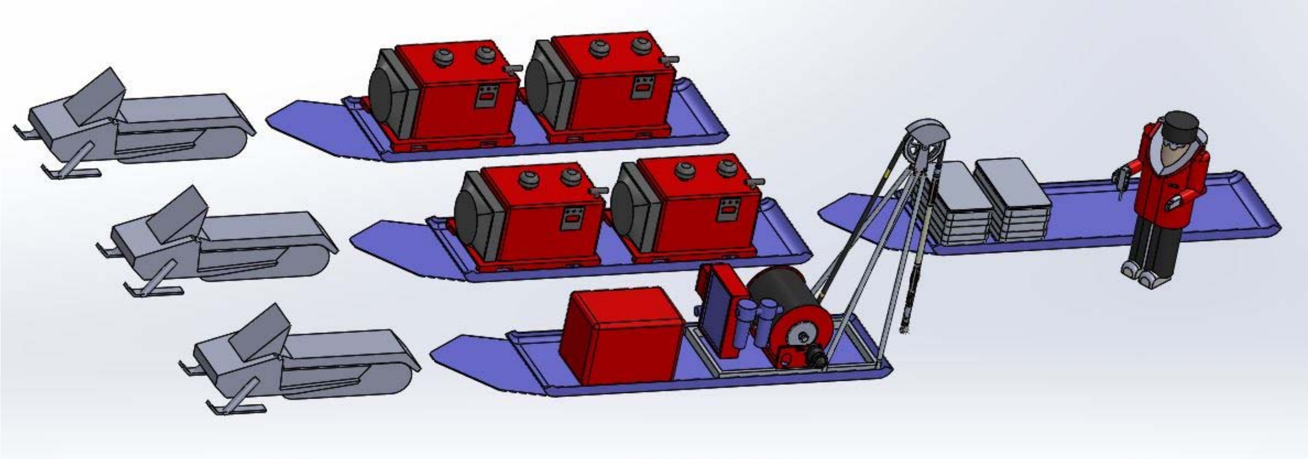


Figure 3: System-Level Concept

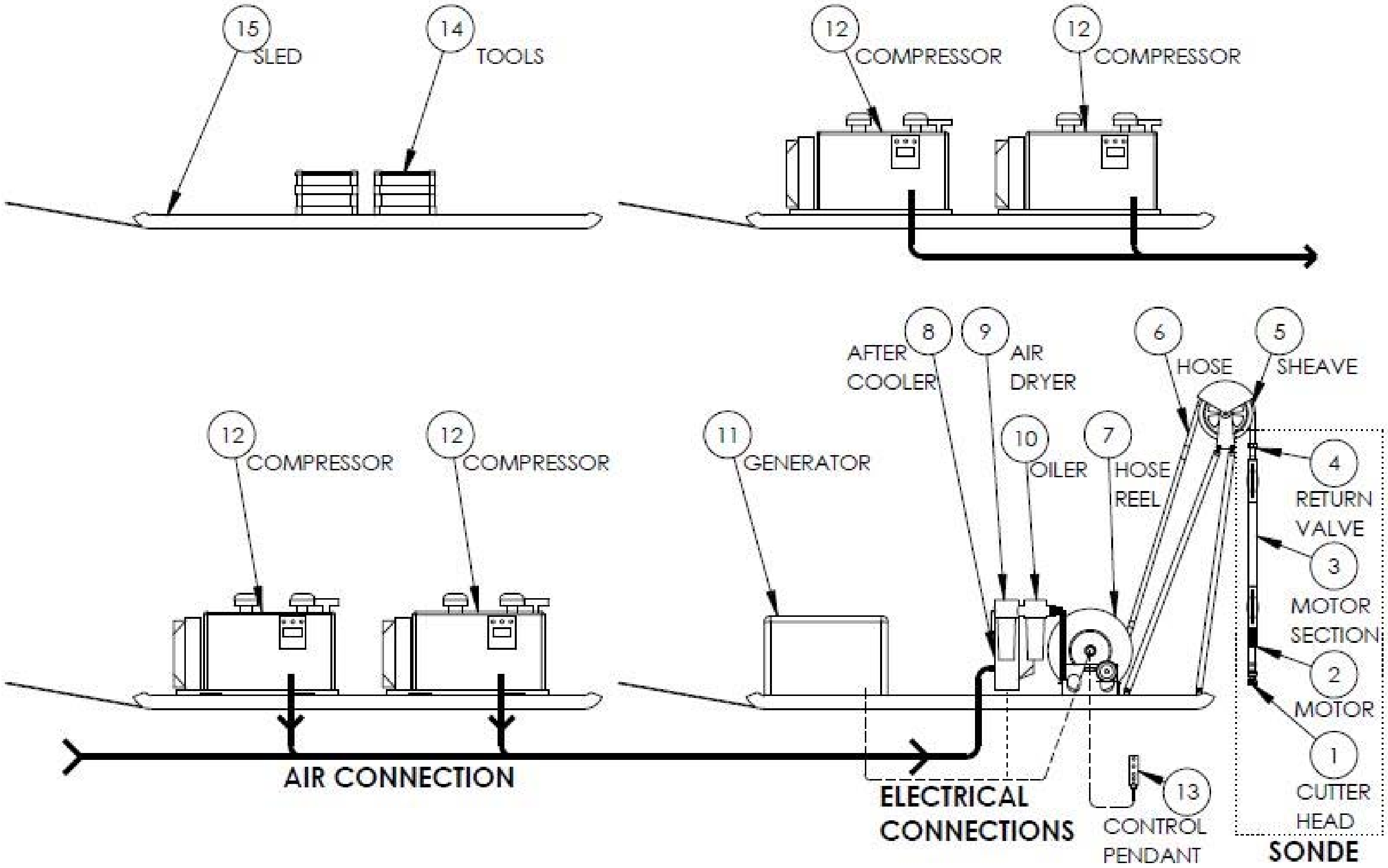


Figure 4: System Schematic

Table 2: High-level Equipment List

These are approximate values; both weight and cost are expected to vary +/- 10% from these values.

Qty	Descrpition	Weight Ea. (lbs)	Total-Weight (lbs)	100m Deployed Weight (lbs)	40m Deployed Weight (lbs)	Cost Ea. (USD)	Total (USD)
4	Custom 130scfm/100psi Compressor	800	3200	3200	2400	$ 32,000	$ 128,000
1	Air Interconnect Plumbing	80	80	80	80	$ 1,000	$ 1,000
2	1 1/4" Hose 110m ea	280	560	280	0	$ 4,500	$ 9,000
2	14Ga Cable 120m ea	20	40	20	20	$ 250	$ 500
1	Hose Reel w/ Motor	250	250	250	0	$ 4,000	$ 4,000
1	Tower w/Base	225	225	225	225	$ 3,000	$ 3,000
2	Pendant w/cable	10	20	10	10	$ 200	$ 400
2	Sonde Control Box w/cables	25	50	25	25	$ 1,500	$ 3,000
2	Sonde	150	300	150	150	$ 13,500	$ 27,000
2	Compressor Sled	120	240	240	240	$ 1,800	$ 3,600
1	Reel Sled	120	120	120	120	$ 1,800	$ 1,800
1	Fuel Manifold and Plumbing	40	40	40	40	$ 500	$ 500
1	Tools	150	150	75	75	$ 3,500	$ 3,500
1	Packaging/Covers	550	550	75	75	$ 5,000	$ 5,000
1	Spare Reel Motor	40	40	0	0	$ 300	$ 300
1	Spare Compressor Components	200	200	50	50	$ 4,000	$ 4,000
1	5kW Gasoline Generator	300	300	300	300	$ -	$ -
1	Fuel Sled	100	100	100	100	$ -	$ -
2	Oiler	15	30	30	30	$ -	$ -
2	Air Dryer	15	30	30	30	$ -	$ -
2	AfterCooler	150	300	150	150	$ -	$ -
1	Ancillary Components and Fabrications	800	800	400	400	$ 29,100	$ 29,100
1	40m Hose Reel w/Hose	330	330	330	330	$ 5,750	$ 5,750
	TOTAL		**7955**	**5850**	**4850**	**-**	**$ 229,450**

Note: Deployed weights represent materials that will likely be required for daily drilling operations. Total weight includes all drill equipment including packaging and spares not needed daily for drilling.

Sonde

Several improvements to the sonde will be implemented and are described below.

Reduced Diameter Bore

A borehole diameter reduced to as little as 75mm is possible given the science requirements for the upgrade and the necessity of accommodating only a 2" cartridge. This reduces the amount of chips that have to be transported by nearly 50%. With a reduced hose diameter as well, airflow volume can be reduced while maintaining the required return velocity. Additionally, air losses to the firn will be reduced given less bore wall surface area. Overall, the volume of air required to lift chips from a 75mm hole are estimated to be 30% less than that required for a 101mm (4") hole.

Efficient Electric Cutter Motor

An electric motor can operate more efficiently than the existing air motor. In order to drive the air motor of the existing RAM drill, all the air supplied downhole is maintained at 110psi relative to borehole pressure. An electric motor does not require this differential pressure. With no change seen in borehole pressure, the total demand at the compressor is reduced from 175-200psi to 80-100psi. This has a direct impact on horsepower required to drive the compressor, reducing engine size and fuel consumption. Using the following equation to calculate compressor horsepower [11] shows potential savings in engine power and fuel of more than 30%.

$$HP = [144\,N\,P1\,V\,k / 33000\,(k - 1)]\,[(P2 / P1)^{(k - 1)/N} *(k - 1)]$$

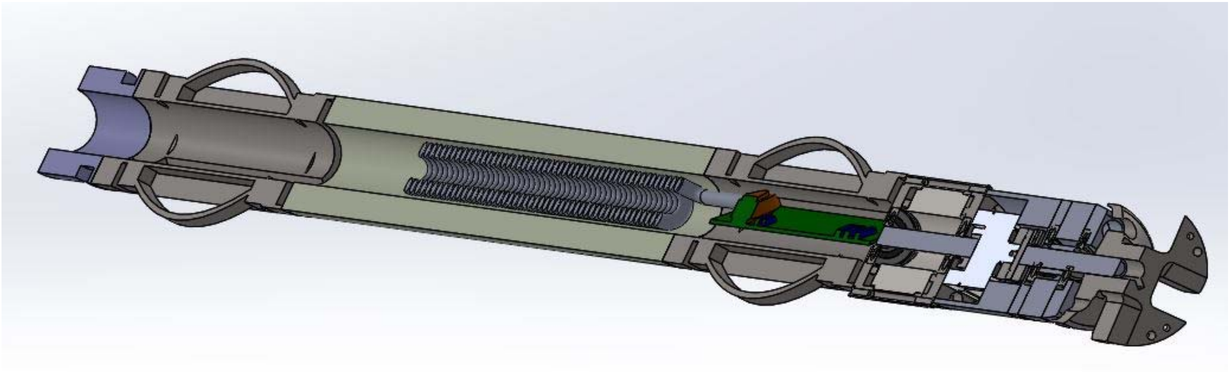
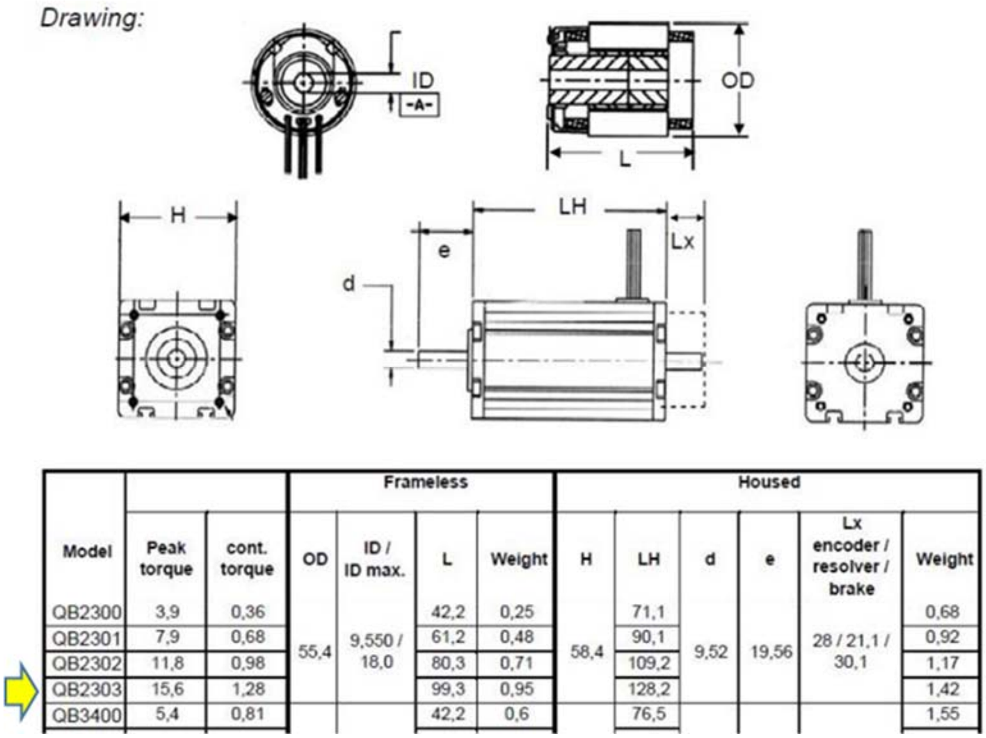


Figure 5: Reduced Diameter Sonde with Electric Motor



Model			Frameless				Housed					
	Peak torque	cont. torque	OD	ID / ID max.	L	Weight	H	LH	d	e	Lx encoder / resolver / brake	Weight
QB2300	3,9	0,36	55,4	9,550 / 18,0	42,2	0,25	58,4	71,1	9,52	19,56	28 / 21,1 / 30,1	0,68
QB2301	7,9	0,68			61,2	0,48		90,1				0,92
QB2302	11,8	0,98			80,3	0,71		109,2				1,17
QB2303	15,6	1,28			99,3	0,95		128,2				1,42
QB3400	5,4	0,81			42,2	0,6		76,5				1,55

Figure 6: Small Diameter Frameless DC Motor

Additional Sonde Modifications:

In addition to significant modifications to the sonde described above, other smaller adjustments will also be made. The cutter head will be very similar to the existing 4” head, but will be optimized for flow in the smaller diameter borehole. The design of the bypass valve at the top of the Sonde will be revisited to ensure discharged air is not eroding the borehole.

Hose and Hose Reel

With a smaller diameter bore hole, the hose must change from a nominal 1.5” hose to 1.25” hose. This maintains air velocity with little added back pressure.

The hose will be marked in increments to indicate depth. Having no encoder on the sheave simplifies the system.

Lower bend radius, weight, and tension resulting from the smaller hose allows for construction of a smaller hose reel. The much reduced hose reel also reduces the reel motor power required and allows for transport in light air craft i.e. Bell, Basler, Twin Otter. The proposed hose reel eliminates the need for heavy equipment in assembly. A mechanical level-wind mechanism will be included on the reel. Possible solutions include a diamond groove guide or a manual “Hose Boss” shown in Figure 7.

Figure 7: Possible “Hose Boss” Mechanism, includes integral motor control
(Credit: reelcraft.com)

Compressors

Purpose-built compressors similar to those used in exploration drilling have significant potential for weight savings, Figure 8. The primary components these compressors are the same as those of the rotary screw compressors used with the existing RAM drill. The weight savings comes primarily through packaging and matching engine with air end (screw assembly) for the specific performance required.

Figure 8: Purpose Built Drill Rig Air Compressor (Credit: Northspan)

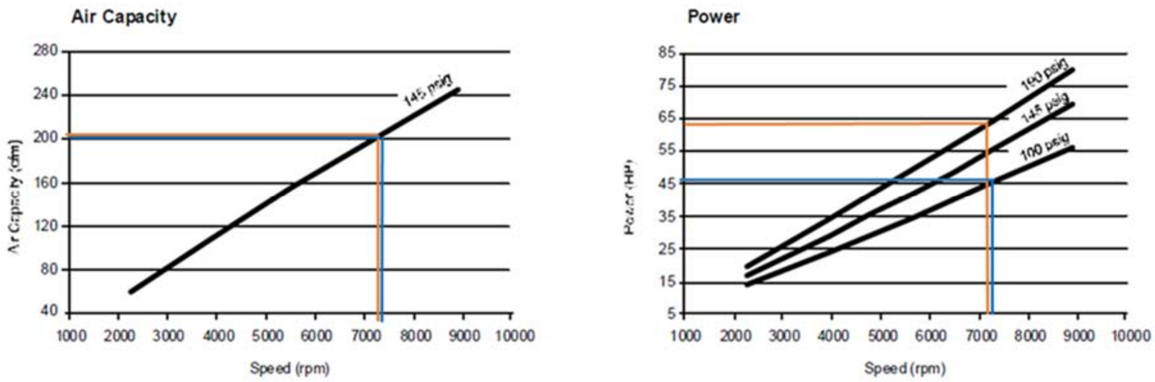


Figure 9: Air-end Sizing (TMC SPA10)

The air end sizing chart above clearly demonstrates the effect of lower pressure on compressor power. The blue lines represent performance at 100psi and the orange lines performance at 190psi. At 100psi, the compressor requires 45HP to achieve 200cfm, while at 200psi, nearly 65HP is required to achieve the same flow rate.

A gasoline engine is proposed as the power source for the compressor. Powering the air-end with a gasoline engine has many benefits relative to a diesel engine. The gasoline engine has better cold start ability and can be paired with numerous small gasoline generators including those supported by the Antarctic Support Contractor (ASC). Inherently lighter, the gasoline engine results in a weight reduction for the generator and the compressors totaling about 1000lbs. Although the weight savings for the season can be significantly offset by lower power density of gasoline, the elimination of 1000lbs of equipment from a daily traverse is very valuable and has the potential to eliminate the need for an additional snow mobile and driver.

Given lessons learned in the field, a preheater for the compressors is planned to address the potential issue of a compressor screw locked with frozen condensation at start-up. A fuel powered bullet heater, and 12VDC or 120VAC heater pads will be among options considered.

Although the specific compressor unit has not been selected, the following equipment specifications for one candidate compressor are a useful point of reference.

- Kubota WG1605-G-E3 57 HP gasoline engine
- 57 HP @ 3600 RPM
- 4 Cylinder
- Hayes bearing supported stub shaft assy.
- VMAC VR150 air compressor
- Output – 130 CFM @ 100 PSI
- Belt and pulley drive
- Separator tank w/ filtration
- 12VDC compressor cooler
- Engine & compressor control panel
- Aluminum frame
- Split module design
- Approx. total dry weight – 635 lbs.
- Estimated split module weights 425 lbs & 210 lbs

Tower

Reduced hose weight, bend radius, sonde weight all contribute to reduction in the size of the drill tower. The proposed tower assembly is compatible with Siglin sleds or a larger ASC traverse sled if used with a Tucker. The tower is mounted on a frame with the hose reel. The sheave includes no encoder or load cell.

Air Treatment

Improved air treatment has the potential to slow formation of larger ice chips that may block the return path.

The existing after cooler is somewhat undersized for the air flow of the existing system with a 14°C (26°F) average rise over ambient. With the reduced flow rate of the upgraded system, the same cooler will provide significantly lower temperature and contribute to better water separation.

The upgraded system will also continue to use the existing air dryer, and the potential of other drying methods will be explored.

An ethanol "oiler" is used to introduce about ½ quart of ethanol per hole to the air flow in the existing system. This oiler will be maintained as an option in the upgraded system initially. It has been demonstrated to address clogging from frozen condensation in the supply line but also has the potential to contribute to clogging in the return; this will be evaluated in testing. An evaluation will also be made of the possibility of moving the ethanol "oiler" up-stream of the cooler to help address icing and to further improve cooling.

Electrical Power Requirements

The system requires electrical power for the hose reel, after-cooler and down-hole motor. Per the table below, total power will be approximately 3890W and would be provided by a gasoline generator available from ASC. A 5kW generator rated to 4500W continuous will likely serve the purpose in most conditions.

Table 3: Power Budget

Power Budget	**Generator Demand**	
Module	**HP**	**W**
Hose Reel	0.75	559
Down Hole Motor (1.6HP motor w/ losses)	2.00	1491
AKG CC450-1 Aftercooler (4FLA @ 230VAC-1ph; 920W ea.)	2.47	1840
Total	**5.22**	**3890**

Drill System Set-up and Tear-down

The initial unloading and assembly of equipment onsite is performed by two people. Given the weight of the compressor modules, moving the modules will be limited to loading and unloading from the aircraft and sliding onto the Siglin or traverse sleds. Based on experience in recent drilling projects, this can be accomplished manually or with the assistance of a winch/"come-along" provided with the system. Module frames will include a solid base pan to facilitate sliding on firn. Once installed on the sled, the modules will be pulled by snow mobile for the remainder of drilling operations.

Some initial system assembly is also required. In most cases, the tower, air treatment, and hose reel with hose will be shipped as individual units and will need to be mounted on the tower frame. Interconnecting hoses and cables will also need to be installed. Initial assembly and tear-down will take less than 8 hours each in most field conditions. Modules will be easily sealed against blowing snow with enclosures. See Figure 10. Tear-down is performed in steps very similar to assembly.

Figure 10: ASIG Engine Covers:
Cover is sealed to drip pan on base with Dual-Lock industrial Velcro.
Outlet flaps, open during operation, are sealed for storage.

Drilling Operations

Drill operations will remain very similar to those with the existing RAM drill equipment. Given the improved mobility of the smaller system, fine adjustments to location of drill tower are made by simply positioning the sled. Interconnect hoses between sled trains will be installed at each drill site. The compressors and generator will be powered on and the drill head and winch motor will be controlled by a pendant.

A Stuck Drill procedure will be developed and will likely include the use of ethanol. The existing RAM drill has used application of ethanol inside and/or outside the hose to free a stuck drill.

Logistics

The upgraded system equipment can be transported in several trips by light aircraft (approximately 5 flights; Twin Otter or Bell Helicopter).

Fuel consumption running all four compressors and the electric generator continuously in the 100m configuration is 10.5gal/hr. Although, it may be possible to further conserve fuel during operation, based on these values, one 55 gallon drum of fuel would provide 5 hours of continuous operation. This would be sufficient time to drill fifteen 40m holes. It is estimated that fifteen 100m holes would require nearly 2 drums of fuel.

Given field experience in West Antarctica (D. Voigt, personal email exchange), it is expected that a large ASC snow mobile can pull a total weight of up to 2000lb over significant distances in most conditions. For the 40m system, it may be possible to transport fuel and drill equipment with 3 snow mobiles. However, with an estimated weight of nearly 6000lbs of drill equipment for the 100m system, at least 3 snow mobiles will be required for the drill equipment alone and fuel will need to be transported and cached separately or a 4th snow mobile used. In either case, an alternative would be to use a larger vehicle, e.g. Tucker Sno-Cat, and pull the equipment on one ASC traverse sled.

SCHEDULE and COST

Duration for the upgrades of the RAM Drill is expected to be eleven months. This includes time to complete the detailed design, fabricate components, assemble the system, complete functionality testing, and package the system for shipping. At the start of the project, a detailed project schedule will be created for the execution of the project and used in the management of the RAM Drill upgrades.

Table 4: Project Milestones

Milestone		Completion
PY17	Preliminary Testing and Analysis	4/1/2017
	System-Level Concept	8/15/2017
	Design and Purchase Sonde	11/1/2017
PY18	Specify and Purchase Compressors	3/1/2018
	System-Level Fabrication and Test	8/1/2018
	100m Configuration Ready to Ship	9/1/2018
PY19	Field Testing	12/15/2018
	Modifications and Upgrades	8/15/2019
	Fabricate and Test 40m Configuration	8/15/2019

Development will continue in PY17 and is expected to include the purchase of downhole equipment. The majority of work, however, will be performed in PY18, producing a 100m system ready for deployment for field test in Antarctica in the 2018-2019 field season. The PY18 project cost is expected to be **$450,000 to $550,000**. This includes all labor, equipment, materials and indirect costs.

The addition of components for a 40m configuration as well as modifications and upgrades to the system based on field test results are currently planned for PY19.

CONCLUSION

As identified in previous reviews of the system [7], it is notable that a significant improvement to the logistical burden of the system can be achieved with relatively little development time, cost and risk. The hose reel can be significantly reduced from a logistics perspective without a smaller hose and bore hole. Compressors can also be improved in weight and modularity with little change to the basic design of the drill system.

Achieving reduction of weight and logistics burden consistent with goals and requirements defined in the RAM Drill Science Requirements document entails undertaking some additional upgrades, including changes to the basic functionality of the system i.e. change to bore size and conversion to an electric motor. As such, system upgrades according to this concept do include some additional cost, field testing and risk but provide a more useful and cost effective solution to the program in the future.

The following table summarizes expected performance of the upgraded system. The clarifications provided with each requirement define how the system will be built so there is a clear understanding with all parties involved. System validation will be performed with respect to the science requirements with these clarifications.

Table 5: Requirements Summary

Science Reqirement	Concept
1. The Drill should produce holes in firn for a 10 cm nominal hole diameter in the top 40-100 m of a wide variety of firn types, including use in West Antarctica or Greenland. A minimum hole diameter of 7.5 cm is needed, in order to freely pass a cartridge of 5.5 cm diameter and 124.5 mm long to the bottom of a hole that is 100 m deep. The system may include modular hoses/winch/compressor subsystems to allow for access to either only the top 40 m, or to drill to the full max depth of 100 m, with reduced logistics needs for the 40 m system configuration.	The proposed system is expected to achieve minimum Ø0.75mm hole to 100m depth. A weight-reduced 40m configuration is also included in the concept.
2. The goal for the drilling rate should be to produce 15 ten-centimeter diameter holes to 100 m depth in 6 hours or less of drilling (not including drill transport time between sites). The longest acceptable drilling time per 100 m hole is 40 minutes.	The proposed system is expected to achieve a 100m hole in 40 minutes including descent, return and set-up/tear-down. Goal Clarification: 15holes x 40minutes =10hrs. May require a 12hr shift or more to achieve 15x100m holes/day with transport time.
3. The drill should have stand-alone capability for operation at small field camps at remote sites with no heavy equipment.	The proposed system will require no heavy equipment for assembly or operation.
4. The drill should be operable in cold ambient temperatures down to -30 °C (+/- 5 °C) and winds of up to 25 knots. The firn and ice are expected to be frozen.	The proposed system will be operable in ambient temperatures down to-30 °C (+/- 5 °C) and winds of up to 25 knots.
5. Drilling depth should be available during drilling.	Drilling depth will be available during drilling. Indelible marking on hose will indicate depth.
6. The modules for transport shall be sized appropriately to be easily handled by 2 people with loading assist equipment provided with the drill. The goal for the total system weight with aircraft packaging is to be less than approximately 4,000 lb.	Modules will be easily handled by 2 people with loading assist equipment provided with the drill. Goal Clarification: 100m system is expected to weigh approximately 6,000lbs; 40m system approximately 5,000lbs configured for daily deployment.
7. The drill should be very field portable, with the ability to be towed over rough terrain. It is a goal that the 40 m system should be towed ideally by a single snowmobile, and the 100 m system towed by several snowmobiles or by a Tucker.	System will be very field portable and mounted on sleds suitable for towing over rough terrain. Goal Clarification: The proposed 40m system is expected to require 2 to 3 snowmobiles. The 100m system will require 3 to 4 snow mobiles or Tucker.
8. If towing the 40 m system by a single snowmobile is not achievable, then a modular system is desired that be easily separated for transport (and subsequently reconnected). Consider a "power plant/ compressor" sled and a drill sled that are only connected by few hoses/cables.	The proposed system is modular, towable by single snow mobiles, and interconnects can be made in less than 5 minutes.
9. The drill control should be simple and intuitive for use in the field by a scientist who has had training before going into the field. Two personnel (one trained and one other) should be able to set up and do the drilling operations in the field.	The drill control is similar to the RAM drill. Two personnel (one trained and one other) will be able to set up and do the drilling operations in the field. Requirement Clarification: Due to the inherently hazardous nature of drilling with compressed air, operation of this system will require an IDDO approved driller.
10. Setup time for the drill should be within 8 hours after initial unpacking on site.	Set-up of the proposed system will be less than 8 hours after initial unpacking.
11. Drill operations shall be such that two fit people can raise and lower the hose and drill head for a full day without excessive fatigue. Consider providing a mechanical assist to lessen fatigue during drilling operations.	Two people can raise and lower drill for 15 holes over the course of a day without fatigue. The proposed system includes a powered hose reel.
12. Drill storage in the field at the end of the day should be planned and designed, in the case of an anticipated storm. The SOP should be designed for storms with 30-40knot winds and blowing snow.	Design and SOP will accommodate of end of day drill storage in 30-40knot winds and blowing snow. Modules will include easily sealed enclosures to protect from blowing snow.

Science Reqirement	Concept
13. The drill should be maintainable in the field by scientists, and instructions and parts for maintenance in the field should be included with the drill.	The proposed system will be maintainable in the field by scientists, and instructions and parts for maintenance in the field will be included with the drill. Requirement Clarification: Due to the inherently hazardous nature of drilling with compressed air, operation of this system will require an IDDO approved driller.
14. No more than 1 drum of one type of fuel should be required for 12hr operation.	The proposed system will use 1 type of fuel. In the 40m configuration, the system will provide 7 hours of continuous operation using 1 drum of fuel. This is more than adequate to drill 15 holes in a 12 hour shift with an estimated 20 minutes of operation per hole, i.e. 5 hours total drilling time. Requirement Clarification: In the 100m configuration, the proposed drill system will provide 5 hours of continuous operation. Assuming an estimated 40minutes of operation per 100m hole, one barrel of fuel is sufficient to create approximately 7x100m holes. Depending on tranport time between holes, one drum may or may not suffice for operations over a 12hour shift.
15. Engineers should design an SOP for retrieving stuck drills or clogged exhaust hose. Possible ideas may include glycol bombs, or attaching a bullet heater to the air line, or heat tape integrated in the hose and head that can be turned on in an emergency, or other. The generator must be appropriately sized for these emergency situations, or else include a requirement for a 2nd "emergency/backup/spare" gen. A failure mode and effects analysis shall be performed and the drill system shall include documentation, tools, equipment and spare parts required to address high-risk situations in the field.	SOP for stuck drill and clogged hose will be created and adequate generator power will be provided. FMEA will be performed and the drill system will include documentation, tools, equipment and spare parts required to address high-risk situations in the field.

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