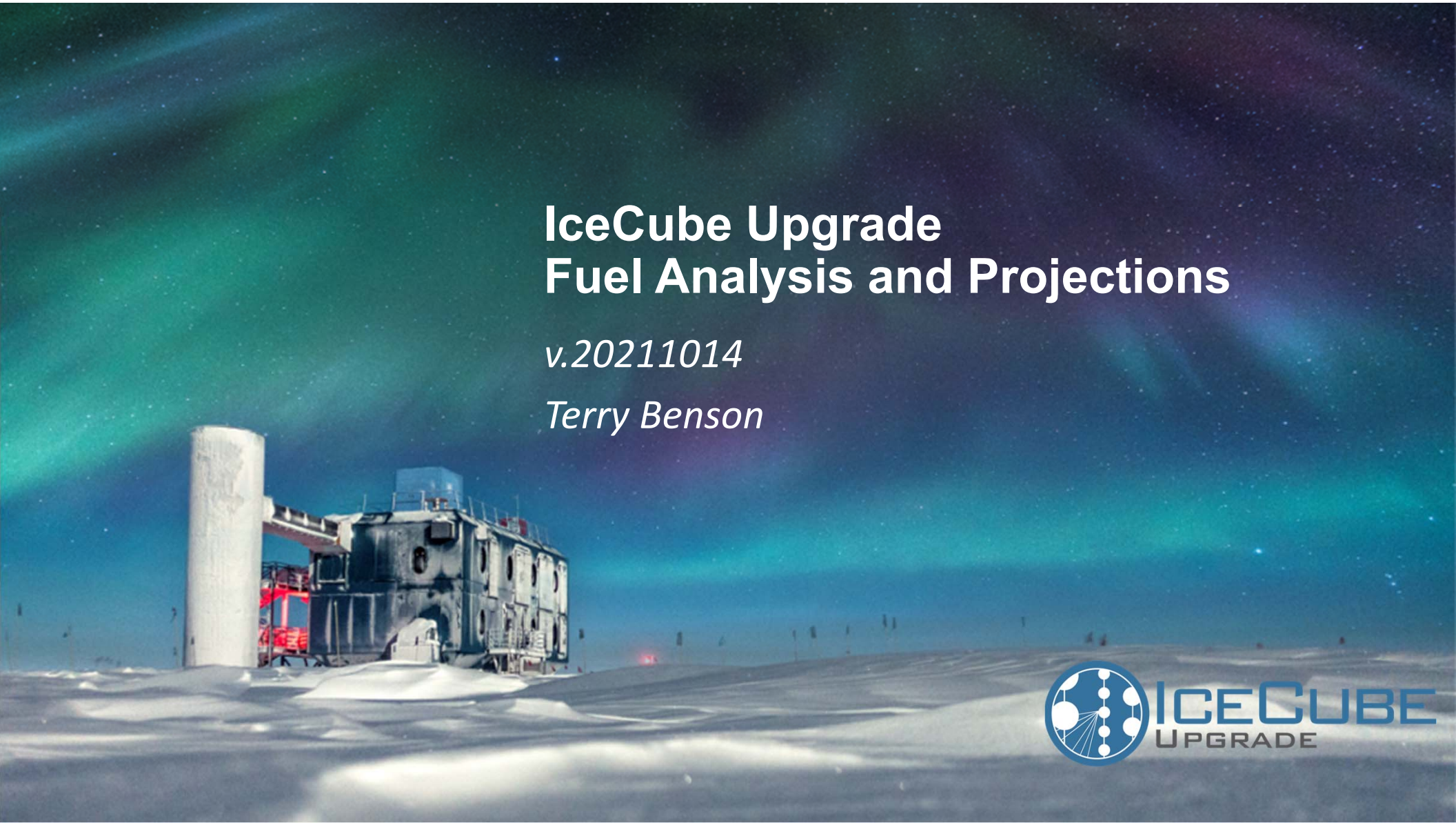

IceCube Upgrade
Fuel Analysis and Projections

v.20211014

Terry Benson

IceCube Upgrade Fuel

Units = Gallons
(A) = Actual

	18-19	19-20	20-21	21-22	Field Season 1	Field Season 2	Field Season 3	Total
						9 firn holes	7 deep holes	
Deep Drilling			X	X			53583	**53583**
Firn Drilling						3900		**3900**
Base Fuel	250 (A)	1000 (A)			3643	12346	17584	**34823**
Winter Heating						4305		**4305**
Total	**250 (A)**	**1000 (A)**			**3643**	**20551**	**71167**	**96612**

Fuel Estimate Analysis Includes the following categories:

- **Deep Drilling** – Fuel consumed during deep drilling/reaming, calculated in conjunction with thermal hole modeling. Hole modeling produces a drill and ream speed strategy based on requirements of a given hole, and in turn yield drill and ream durations, from which fuel consumption can be calculated given a well established steady-state fuel burn rate at full system power.
  Ref. Greenler L and 6 others (2014) Modeling hole size, lifetime and fuel consumption in hot-water ice drilling. Ann. Glaciol., 55(68), (doi: 10.3189/2014AoG68A033)
- **Firn Drilling** – Fuel to support firn drilling, based on historical records.
- **Base Fuel**
  - *Startup and Rodwell development* – To commission the system, melt snow, and develop a mature Rodwell. Historical basis that is a function of number of deep holes and supported by estimate calculations.
  - *Shutdown* – After drilling operations are complete; camp idle, equipment operations, mothball activities; historical basis.
  - *Other* – General equipment operations, TOS furnace day tank fills, etc. Historical basis but also includes condensate bulb creation in FS2
  - *Testing* – Fuel specifically budgeted for planned system and subsystem tests in FS1 and FS2.
  - *Idle* – Fuel consumed during deep drilling campaign, but between holes. Also generator consumption during non-drill seasons. Historical supported by estimate calculations.
- **Winter Heating** – Electrical heating to sustain suitable storage temperature of DNF equipment and main drill hose during the winter after FS2

NOT INCLUDED *– Fuel at station to support population, fuel used to supply electricity when feeding drill equipment from Station power (i.e. @ Cryo), gasoline and premix for vehicles.*

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DEEP DRILLING:

PER HOLE - DEEP

Burn rates

Fuel consumption full heat (80C), gph	130	historic, see IceCube deep drilling fuel rate below
Fuel consumption low heat (12C), gph	37.5	scaled by (12/80)degC plus constant idle rate of 18 gph

Hole type / Hole requirements

FROM HOLE MODELING	IceCube	IceCube Upgrade				
Modeling results as of 1.29.2021 (JN)	reference	hot	hot + log	1000m cold shallow	500m cold deep	
Depth (m)	2450	2600	2600	2450	2600	*The Upgrade model actually calculates to 2650m*
Instrumentation Dia (cm)	41	47	47	47	47	*Includes xDOM and cable*
Lifetime Dia (cm)	45	52	52	52	52	*+10% over Instrumentation diameter*
Degassing Cold Ream (m)	none	none	none	1375-2450	2100-2450	
Hole Lifetime (hr)	37	45	55	50	50	*From hole lifetime budget and contingency worksheet*

These time estimates are provided by the thermal hole modeling runs

Drill Time, full heat (hr)	24.5	33.9	38.9	40.0	38.8	*From modeling (Nesbit Jan 2021)*
Cold Ream Time, low heat (hr)	0	0	0	9.3	5.6	*From modeling (Nesbit Jan 2021)*
Hot Ream Time, full heat (hr)	9.3	11.6	11.6	7.2	8.5	*From modeling (Nesbit Jan 2021)*
Total Drill Time (hr)	33.8	45.6	50.6	56.4	52.9	
Max Hole Pre-Ream Dia (cm)		65.5	69.4	74.8	68.5	*max dia drillhead can measure is 76 cm*

Drill/ream duration x burn rate

Drill Fuel, full heat (gal)	3185	4409	5059	5204	5038	*Full heat drill time x full heat consumption rate*
Cold Ream Fuel, low heat (gal)	0	0	0	347	208	*Low heat ream time x low heat consumption rate*
Hot Ream Fuel, full heat (gal)	1209	1513	1513	930	1110	*Full heat ream time x full heat consumption rate*
Fuel Per Deep Hole (gal)	4394	5923	6572	6481	6357	
Contingency — Deep + % (gal)	5273	7107	7887	7777	7629	1.2 *+20% contingency*
Number of each hole type		1	1	3	2	

1x 7107
1x 7887
3x 7777
+ 2x 7629
53583

IceCube Upgrade Fuel

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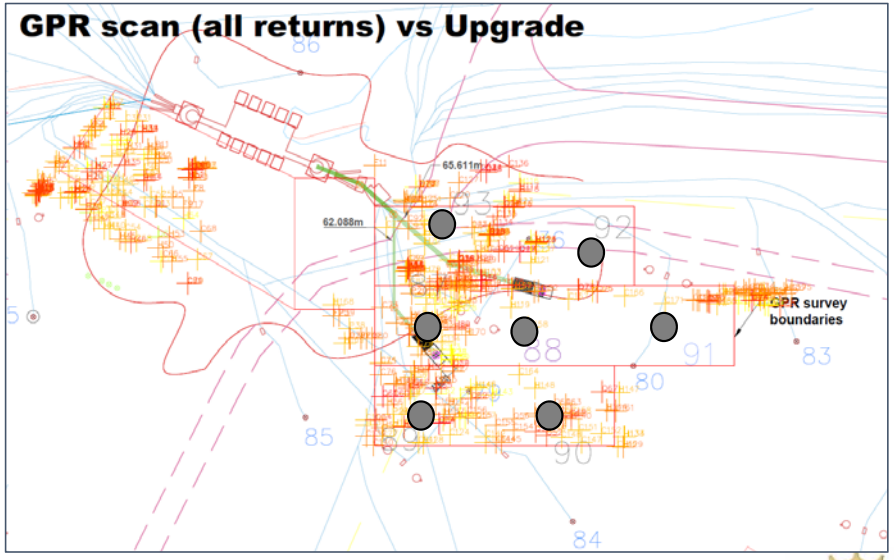
FIRN DRILLING:

- The Independent Firn Drill System debuted in the 07-08 Gen1 season
- Average fuel consumption over the following 3 remaining seasons of Gen1 was 250 gal/hole
- Add 20% contingency for system recommissioning and re-learning curve -> 300 gal/hole
- Plan on 4 additional re-tries due to potential buried obstacles (additional contingency, see right)
- 13 firn holes
  - 7 Deep holes
  - 1 Rodwell
  - 1 Condensate well
  - 4 Re-tries budgeted
- 13 x 300 = <u>3900 gal</u>



Map showing approximate hole locations and all GPR returns from 19-20 (gold and orange – these are potential obstacles).

IceCube Upgrade Fuel

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BASE FUEL:

	Field Season 1		Field Season 2		Field Season 3	
	Outfit, test, SES setup		9 firn holes, sys integrate/test, melt snow, condensate bulb		7 deep holes, melt snow, Rodwell develop, mothball	
Startup and Rodwell			1500	Estimate that includes ~400 gal to melt snow	7200	min 3000 gal for rodwell and melt snow, 6000 gal used in 10-11 for 7 holes, add 20% to that
Shutdown			1500	Roughly equivalent to gen1 shutdown during a standard season	4000	consistent with last (drill + mothball) season of Gen1 (5400 gal), but shorter duration
Other	1200	Consistent with Gen1 average, last 3 seasons	1800	1200 gal est + 600 gal for condensate bulb creation	1200	consistent with Gen1 average, last 3 seasons
Testing	523	Heater flushing. 39 Model 75s, 3.5 gph each, 2 hour hot flush each. Also 250 gal for gen testing	1066	Heater testing and full system test. 39 Model 75s, 3.5 gph each, 4 hour test each, + 4 hour full system @ 130 gph		
Idle	1920	Wht Gen Full load 20 kW ~ 2 gph 40d x 24hr/d x 2gph	6480	Blue Gen 50% load ~ 9 gph 30d x 24hr/d x 9gph	5184	Between holes only (rest of season captured in Startup/Shutdown). Assume 2 days between each hole (6 x 2d x 24hr/d) x 18 gph rate (historical)
BASE FUEL TOTAL	3643		12346	Ref. 15000 gal Gen1 04-05 season (1 hole)	17584	Ref. 14000 gal Gen1 10-11 season (7 holes)

IceCube Upgrade Fuel

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Total	250 (A)	1000 (A)			3643	20551	71167	96612

WINTER HEATING:

	Calculated Fuel per Winter[1]	With 90% transmission efficiency assumed	Add 20% Contingency = TOTAL
Drill Control Center (DCC)	972	1080	1296
Tower Operations Structure 1 (TOS1)	361	401	481
Tower Operations Structure 2 (TOS2)	361	401	481
Drill Supply Hose Reel	1535	1706	2047
TOTAL	3229	3588	4305

1. See *IceCubeUpgradeWinterHeatingRequirement_20201216.pdf*

IceCube Upgrade Fuel Contingency

Units = Gallons
(A) = Actual

- Contingency is added into each major component of the fuel budget
  - Deep drilling: 20%
  - Firn drilling: 20% on fuel per hole, + 4 extra firn holes = 73% contingency
  - Base: Has many subcomponents estimated from engineering judgement. For purposes here, we will assume 0% contingency.
  - Winter heating: 20%
- We can back out an overall contingency:

	No Contingency	Contingency	With Contingency
Deep Drilling	44653	8930 (20%)	53583
Firn Drilling	2250	1650 (73%)	3900
Base	34823	0 (0%)	34823
Winter Heating	3588	717 (20%)	4305
Total	**85314**	**11298 (13%)**	**96612**

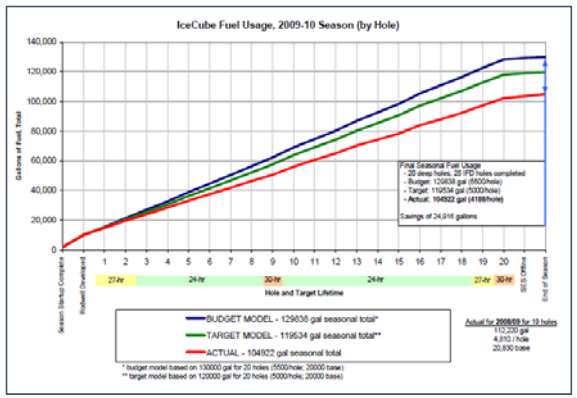
- And then distribute across each field season, for fuel left to go:

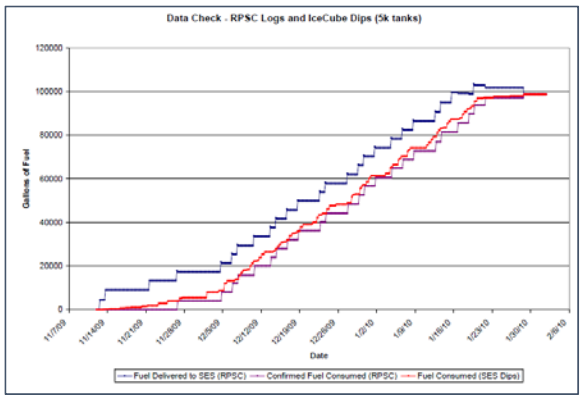
	Field Season 1	Field Season 2	Field Season 3
No Contingency	3191	18178	62694
Contingency	452	2373	8473
Total	**3643**	**20551**	**71167**

95361 gal to go

IceCube Fuel Projections and Tracking

- Strong fuel culture established during Gen1, this will be fostered for Upgrade
- Logs include:
  - 5k tank dip at start, bottom, end of deep drilling each hole
  - 5k tank dip at end of each shift
  - 5k tank dip when new tank arrives, or depleted tank is taken offline
  - ASC records
- IceCube and ASC records are cross checked throughout the season
- Reporting, for Upgrade:
  - Weekly internal updates to the drilling team and ASC fuels
  - 1 seasonal external final report
  - The weekly internal reports will provide real time status on actual vs. planned fuel usage
- See Gen1 example reports for what information may be included





	VALUE	ERROR	
Driller Dips			
Total for Season	104,922	0 (0%)	
SES	98,648	0 (0%)	
RPSC			
Total for Season	104,985	63 (0.06%)	Good!!!
SES	98,711	63 (0.06%)	Good!!!