Cryogenics based chilling, energy supply and services for deeper or hotter mines.

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CanMIND GLENCORE CEMI UDMN ULTRA DEEP MINING NETWORK

Interrelations

Glencore

- Funding
- Engineering Critique
- Real Mine Design

CanMIND Associates

- Principle Investigator
- Physics Engineering
- Concept Development

Highview Power

- Liquid Air Energy Storage
- Pilot plant
- 5 MW plant

CEMI

- Project Management
- Business Acumen

Dearman Engine Co.

- Engine Development
- Techno-economic Analysis
- In Kind Contribution

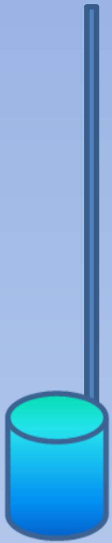
UDMN

- Funding
- Industry Network
- Commercialisation

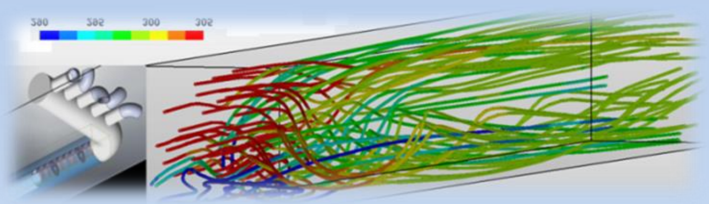
Project Elements

Large UG Equipment
Powered by Dearman Engines

UG Cryogenic
Piping and Storage

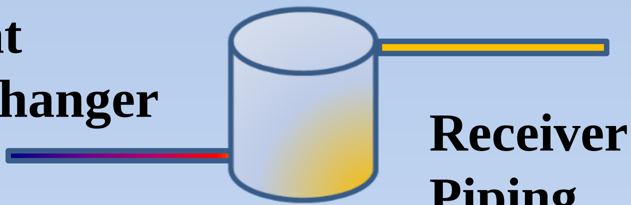


Cryogenic Chilling
CFD Modelling



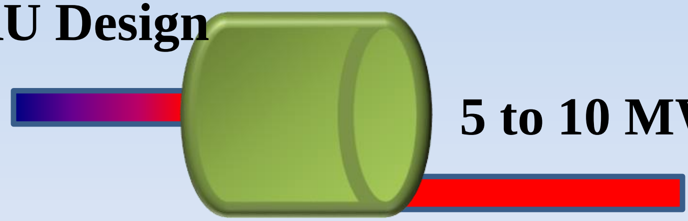
Compressed Air System Design

Heat Exchanger



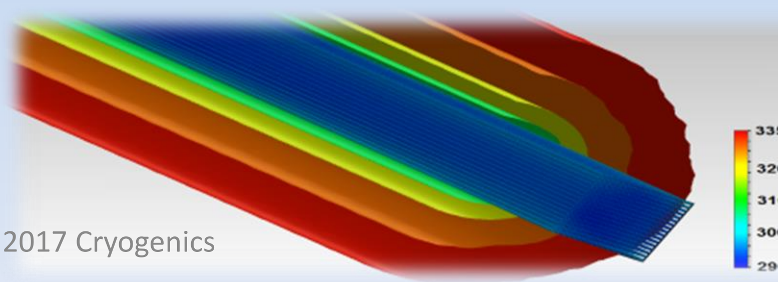
Receiver size
Piping
Modularity design

PRU Design



5 to 10 MW_e

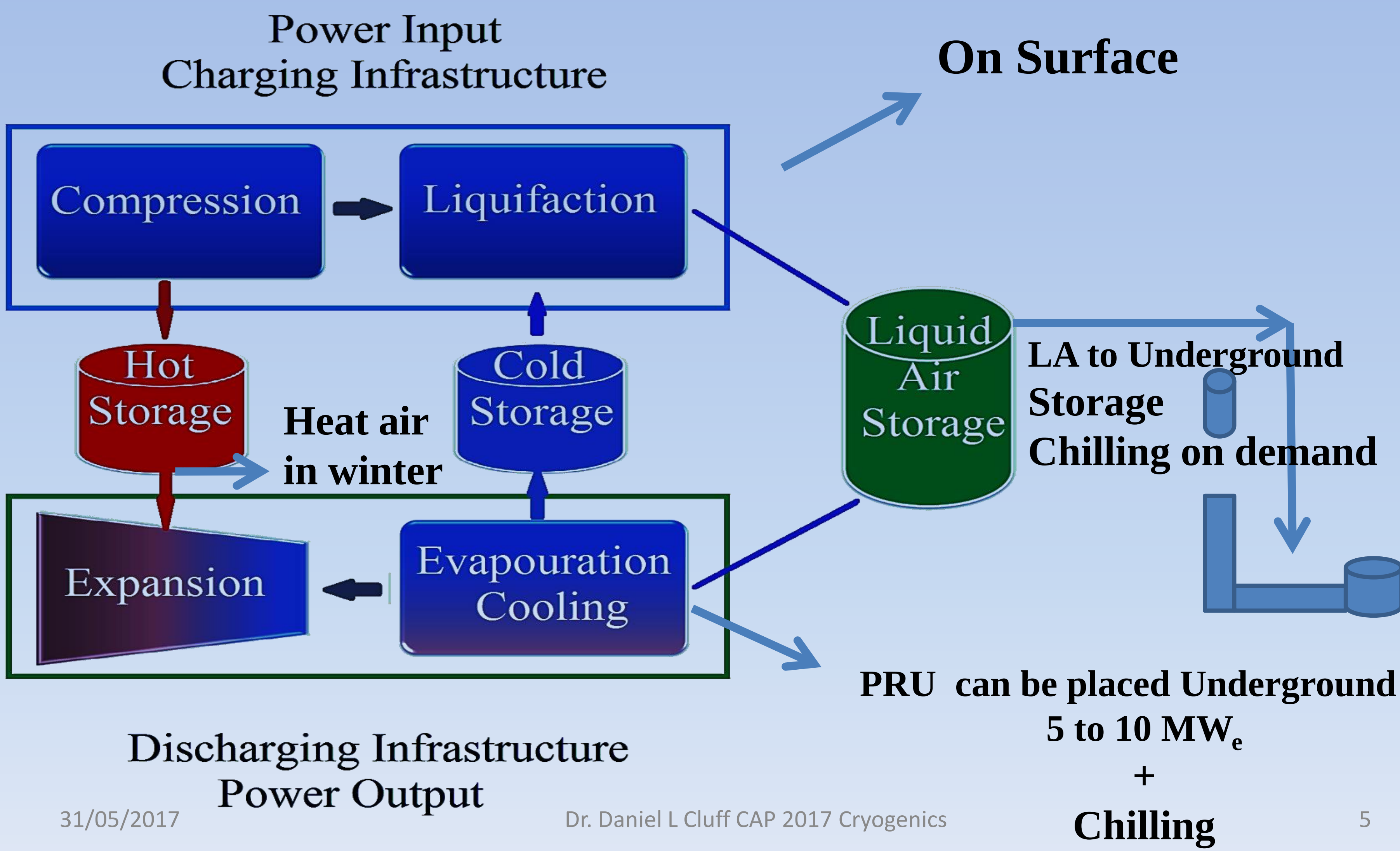
Rapid Response Chilling on Demand



Why LAES

- LAES technology provides plant size economy of scale
- Energy storage is an emerging technological niche
- The cryogenic liquids are produced on the surface in a standard cryogenic liquefaction plant.
- Cryogenic liquid is piped to the depth required
  - Depends on mine design decision
  - Sent to a central location and chill air in downcast shaft
  - Sent to individual levels to chill on demand

LAES Simplified Schematic



350 kW 2.5 MWH Pilot Plant

Highview Power Slough UK

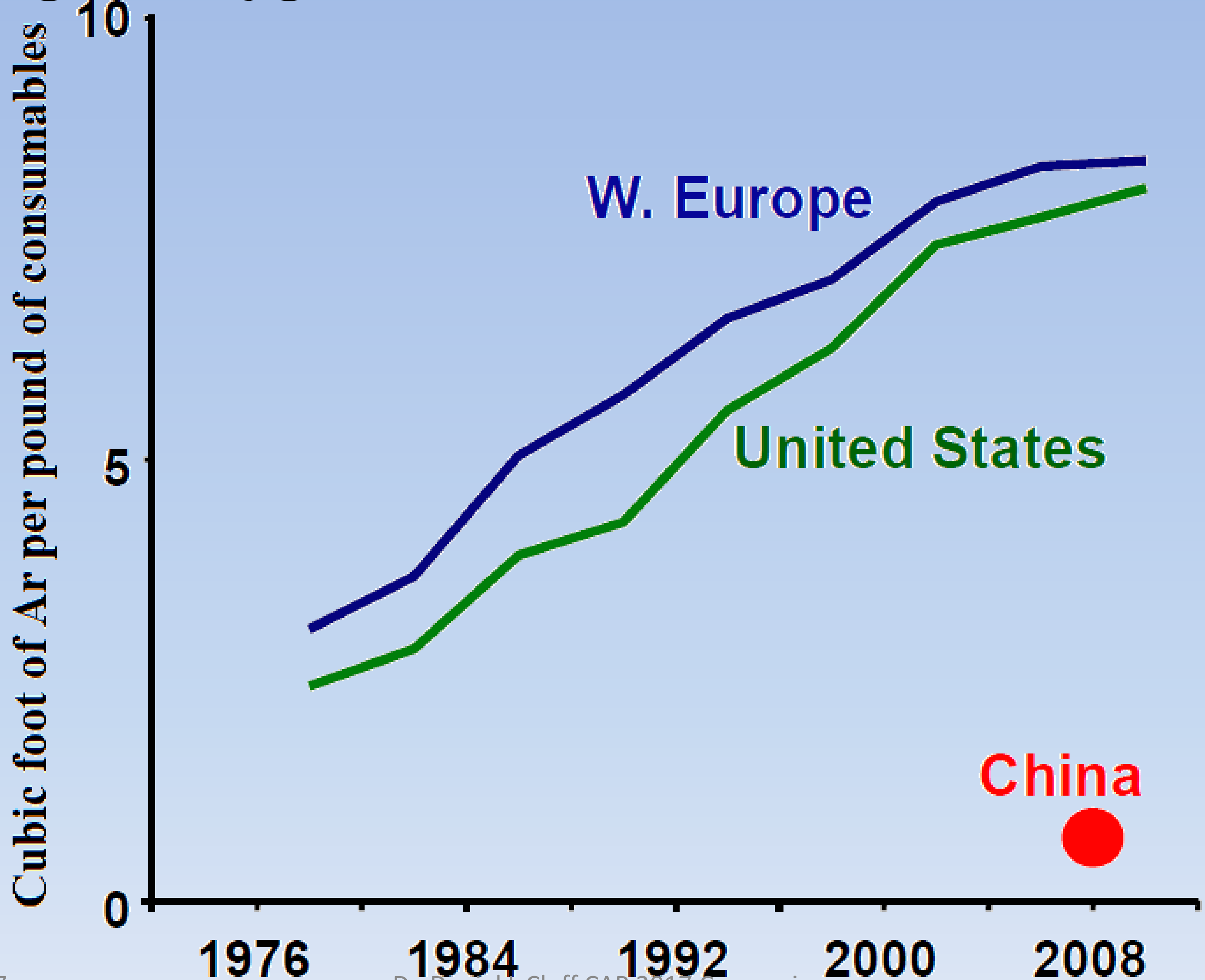
Six 3600 tpd O_2 plants in China

LAES Process

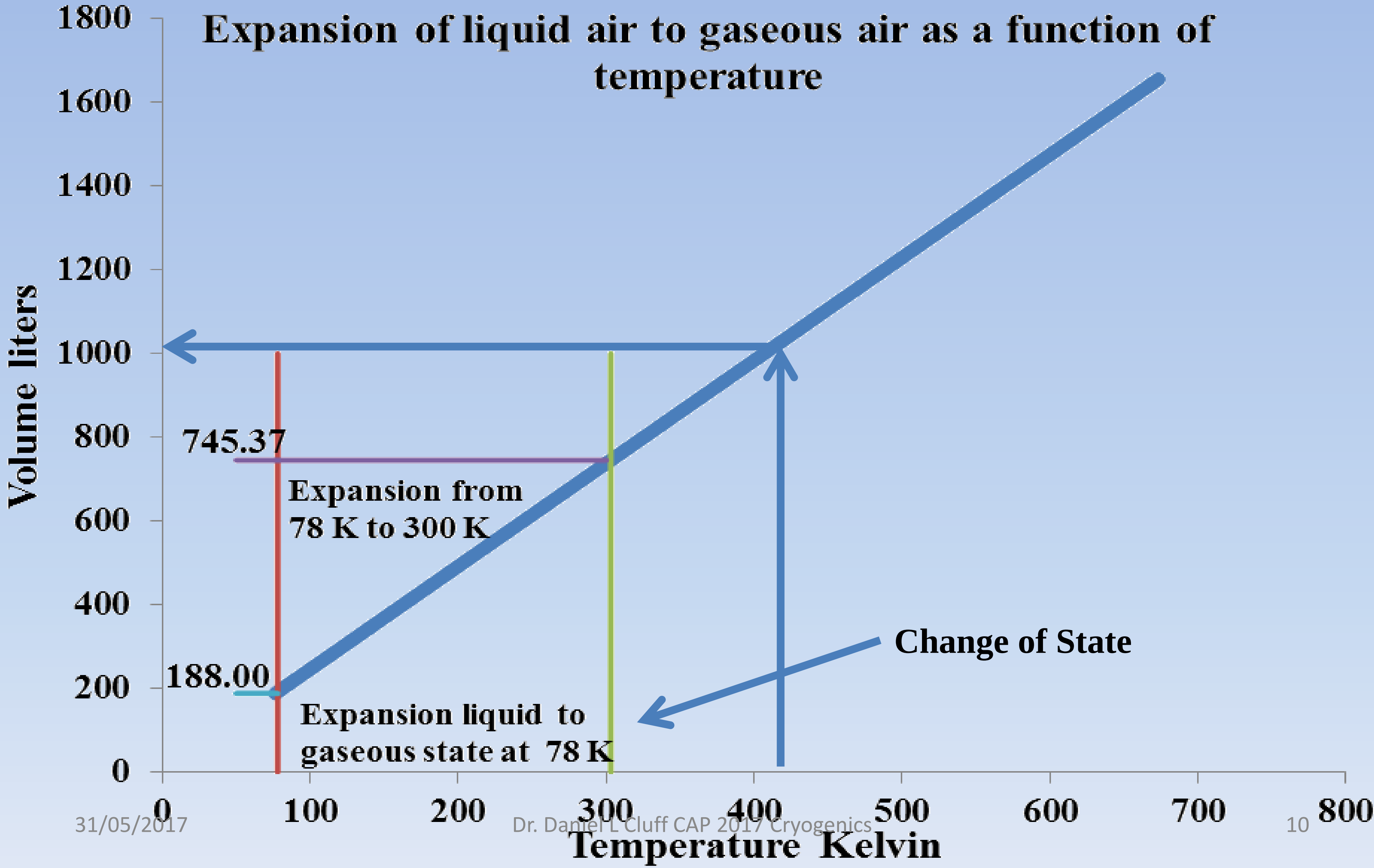
- A Liquid Air Energy Storage (LAES) system is comprised of a **charging system**, an **energy storage section** and a **discharging system**.
- Standard industrial air liquefaction plant
  - the electrical grid or a renewable energy project supply the electrical energy.
- Air drawn from the ambient environment.
  - The process creates liquid air a cryogenic liquid at temperatures near -196^{o}C (78 K).
- The liquid air is stored in a low pressure insulated tank.
  - Easily accessed energy storage repository
  - Low risk to the environment
- When power is required
  - liquid air is pumped to a high pressure and evaporated through a turbine system.
- Capable of providing the pressure necessary
  - to power a piston engine or turbine resulting in useful work
  - to generate electricity or drive a cryogenically powered vehicle.

Ancillary Economics Includes

Argon, Oxygen Markets Both Continue to Grow



700+ ℓ Gaseous Air Per 1 ℓ Liquid Air



A Basic Calculation to Illustrate the Heat Absorbed on Change of State

The heat absorbed per kg of liquid air:

Ambient $\mathbf{T_a = 29.85^oC\ (273.15 + 29.85 = 303K)}$

Cryogenic $\mathbf{T_c = 78\ K}$

Latent Heat of vaporisation $\mathbf{L_v = 205\ kJ/kg}$

Step 1: The mass "**m kg**" absorbs ΔQ_L,

Becomes a gas at or near T_c

$\Delta Q_L = \mathbf{m}L_v = \mathbf{(m\ kg)(205\ kJ/kg) = (m\ kg)205\ kJ/kg}$

Change of state is approximately $\mathbf{180\ell_{(gaseous)} / 1\ell_{(liquid)}}$

A Basic Calculation to Illustrate the Heat Absorbed on Expansion

Step 2: Very cold air (≈ 80 K) warms up to T_a

Expansion with heat absorbed ΔQ_a.

$$\Delta T_g = T_a - T_c = 303 - 78 = 225 \text{ K}$$

change in gas temperature

$$\Delta Q_a = mC_p\Delta T_g = (\text{m kg})(1.005 \text{ kJ/kg-K})(225 \text{ K}) = 226.13 \text{ kJ/kg}$$

Heat absorbed due to change in gas temperature

$$\Delta Q_T = \Delta Q_L + \Delta Q_a = mL_v + mC_p\Delta T_g = (\text{m kg})(451.13) \text{ kJ/kg}$$

Total heat absorbed due to change of state and expansion

For 1 MW_r Chilling

So let ΔQ_T = 1 MJ

The total heat absorbed by the ambient air

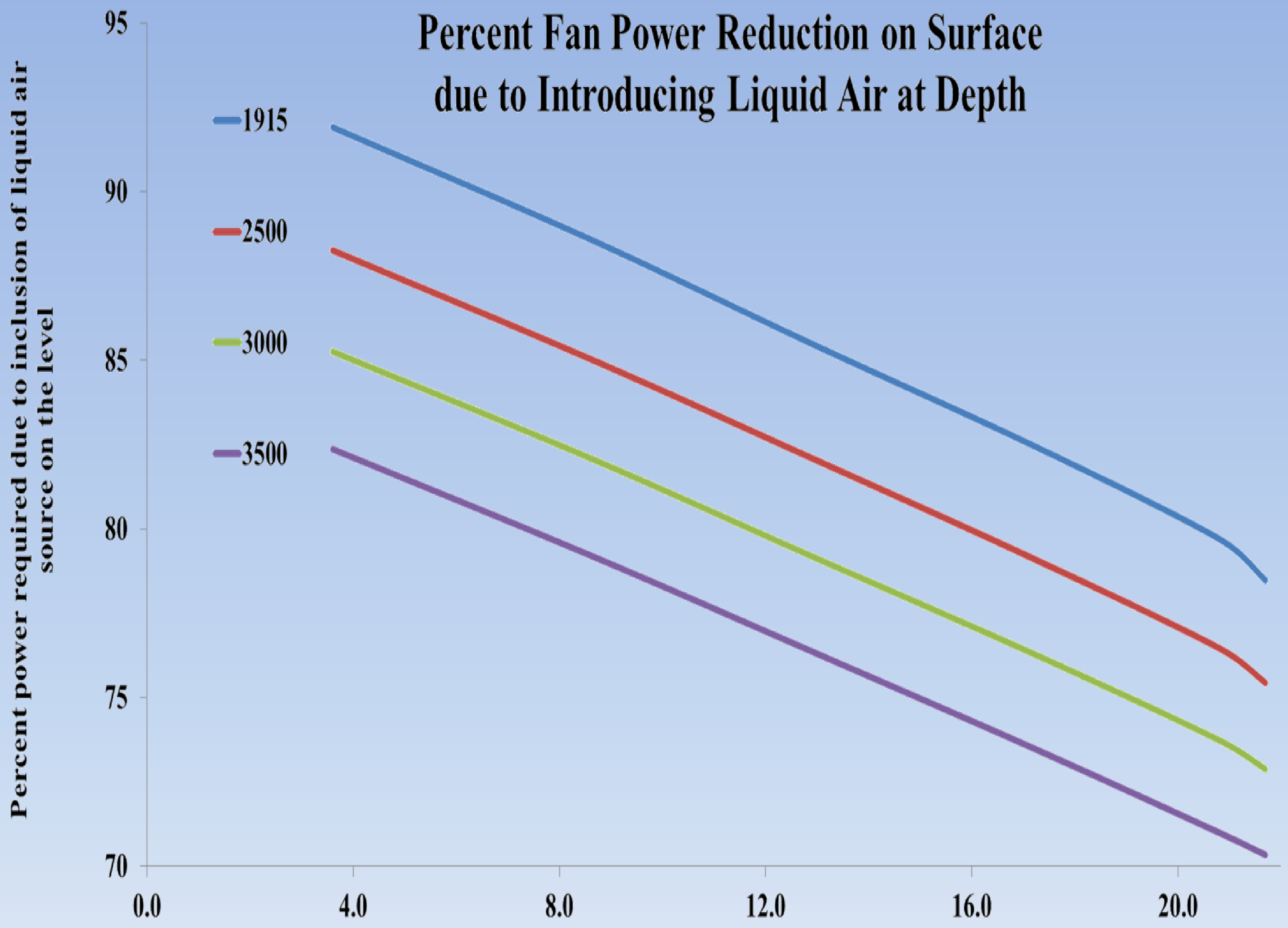
The mass of liquid air required is **2.217 kg**

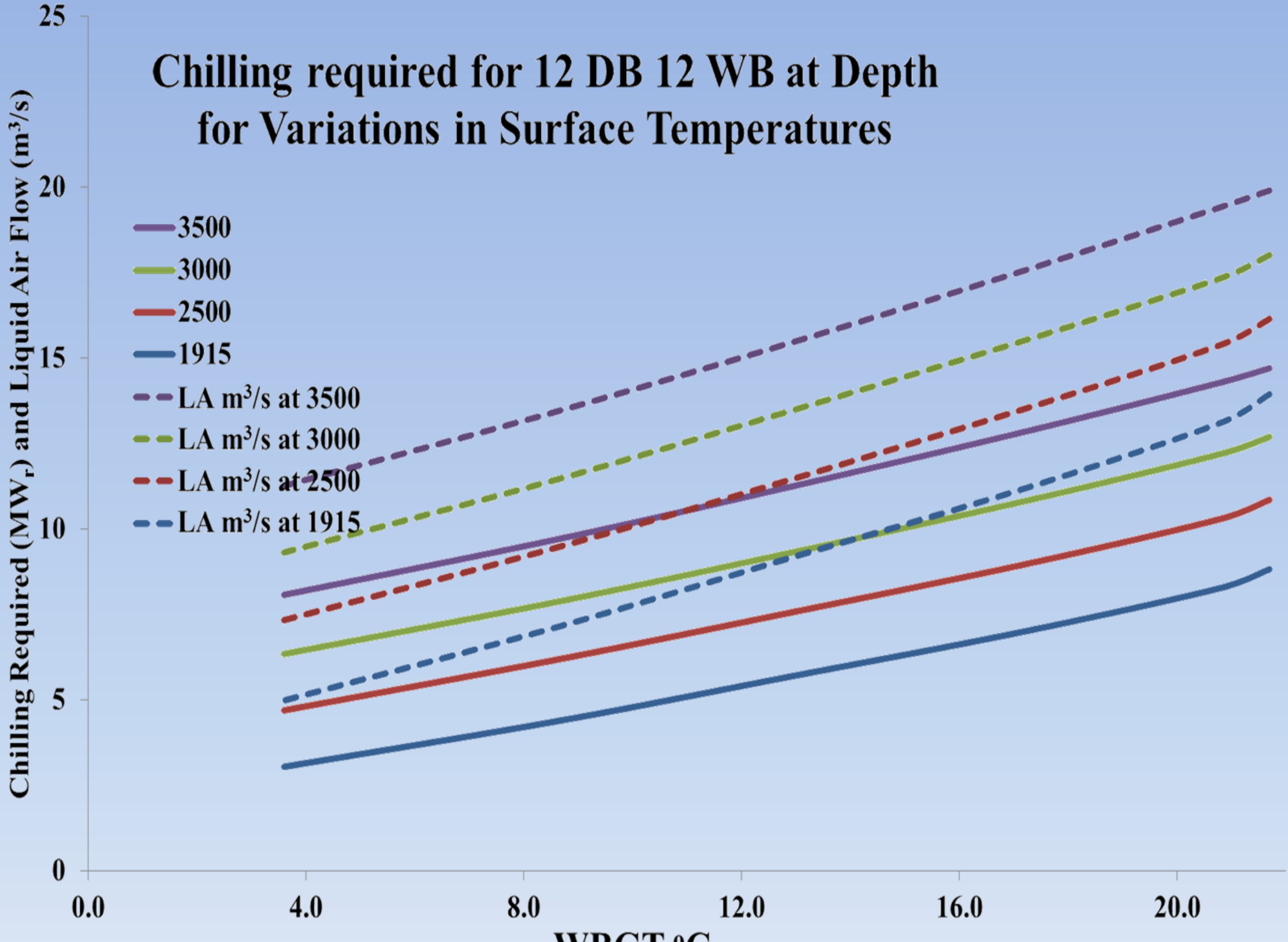
So a liquid flow **2.217 kg/s** will provide **1 MW_r** chilling.

The density of liquid air is about **870 kg/m^3**

So a flow of about **2.55 ℓ $_{(liquid)}$** provides **1MW_r**

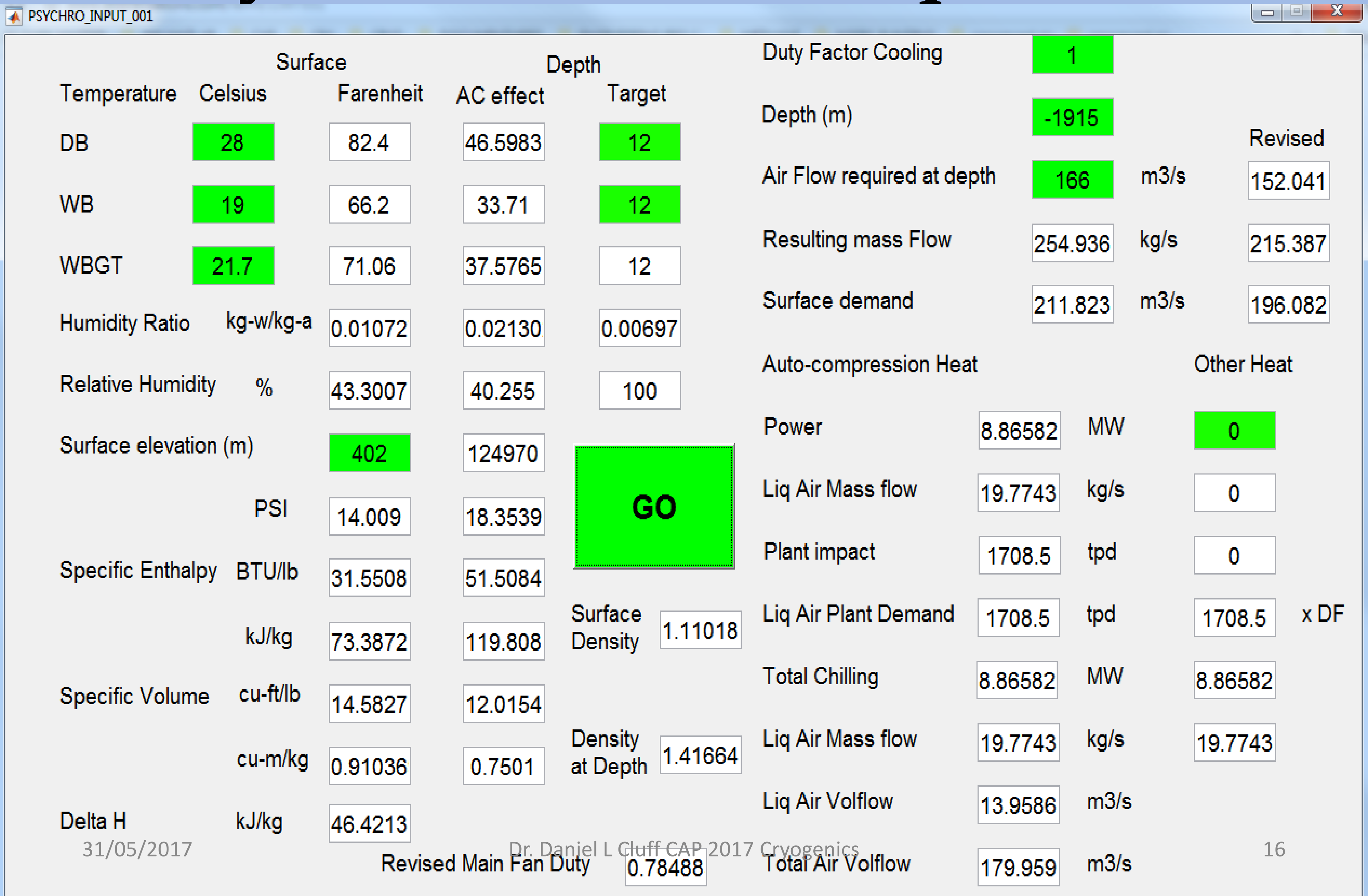
Final gaseous volume **1899.42 ℓ $_{(gaseous)}$ or 1.9 m^3**


Percent Fan Power Reduction on Surface due to Introducing Liquid Air at Depth
1915
2500
3000
3500
Percent power required due to inclusion of liquid air source on the level
95
90
85
80
75
70
0.0
4.0
8.0
12.0
16.0
20.0
WBGT °C



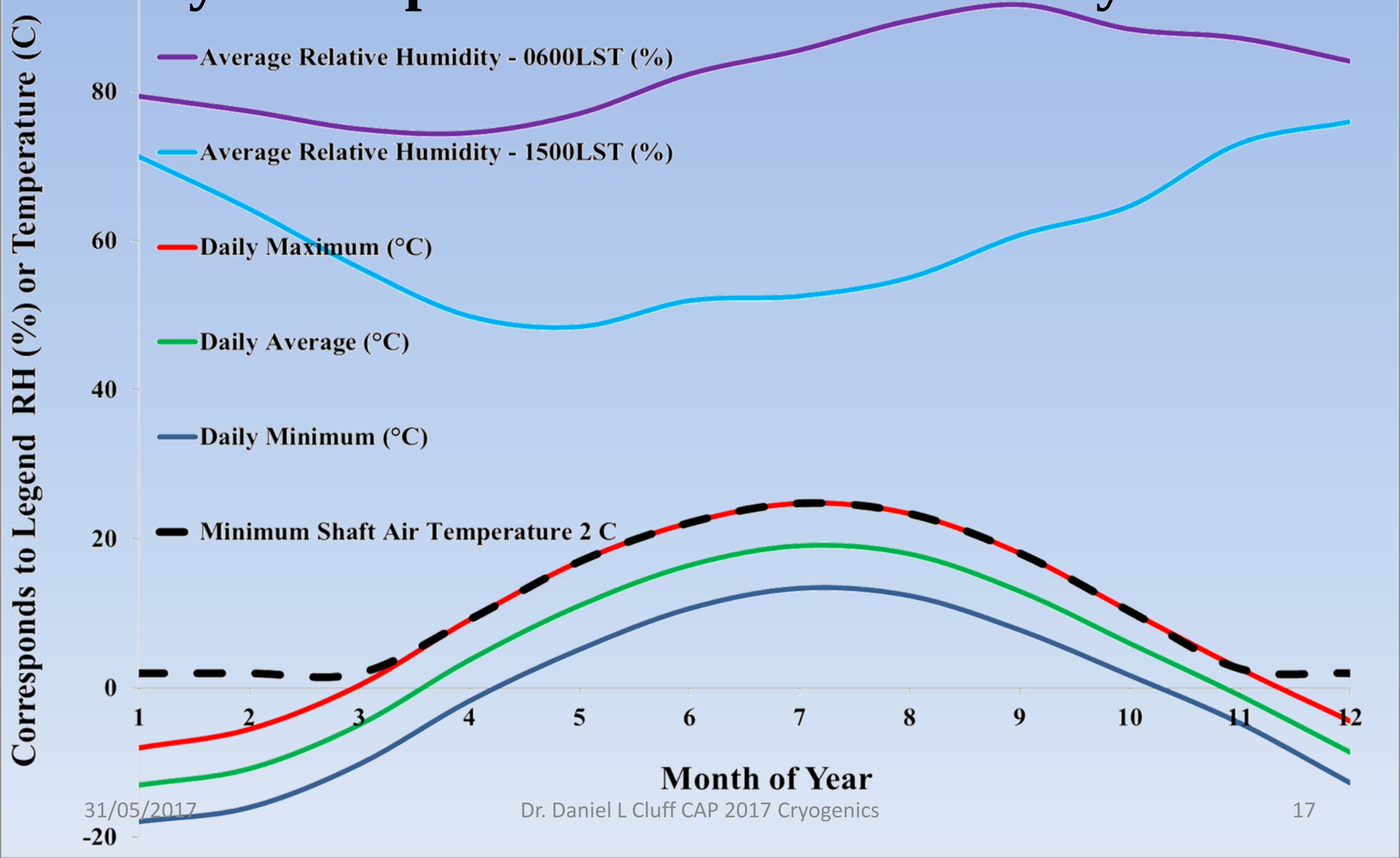
Chilling required for 12 DB 12 WB at Depth for Variations in Surface Temperatures
Chilling Required (MW$_r$) and Liquid Air Flow (m^3/s)
WBGT °C
3500
3000
2500
1915
LA m^3/s at 3500
LA m^3/s at 3000
LA m^3/s at 2500
LA m^3/s at 1915
25
20
15
10
5
0
0.0
4.0
8.0
12.0
16.0
20.0

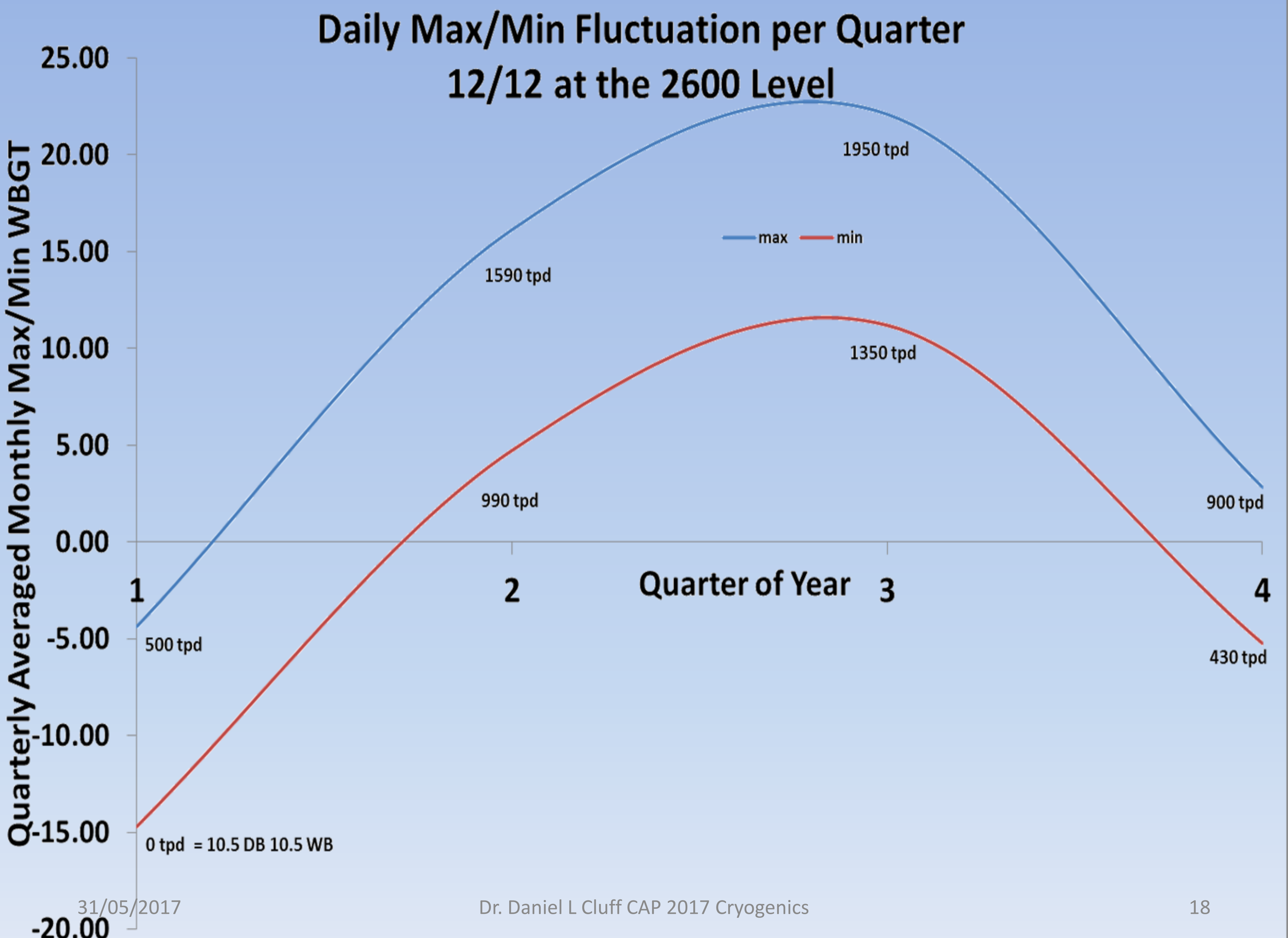
Psychrometrics to Liquid Air



Chilling on Demand

Yearly Atmospheric Conditions Sudbury Ontario

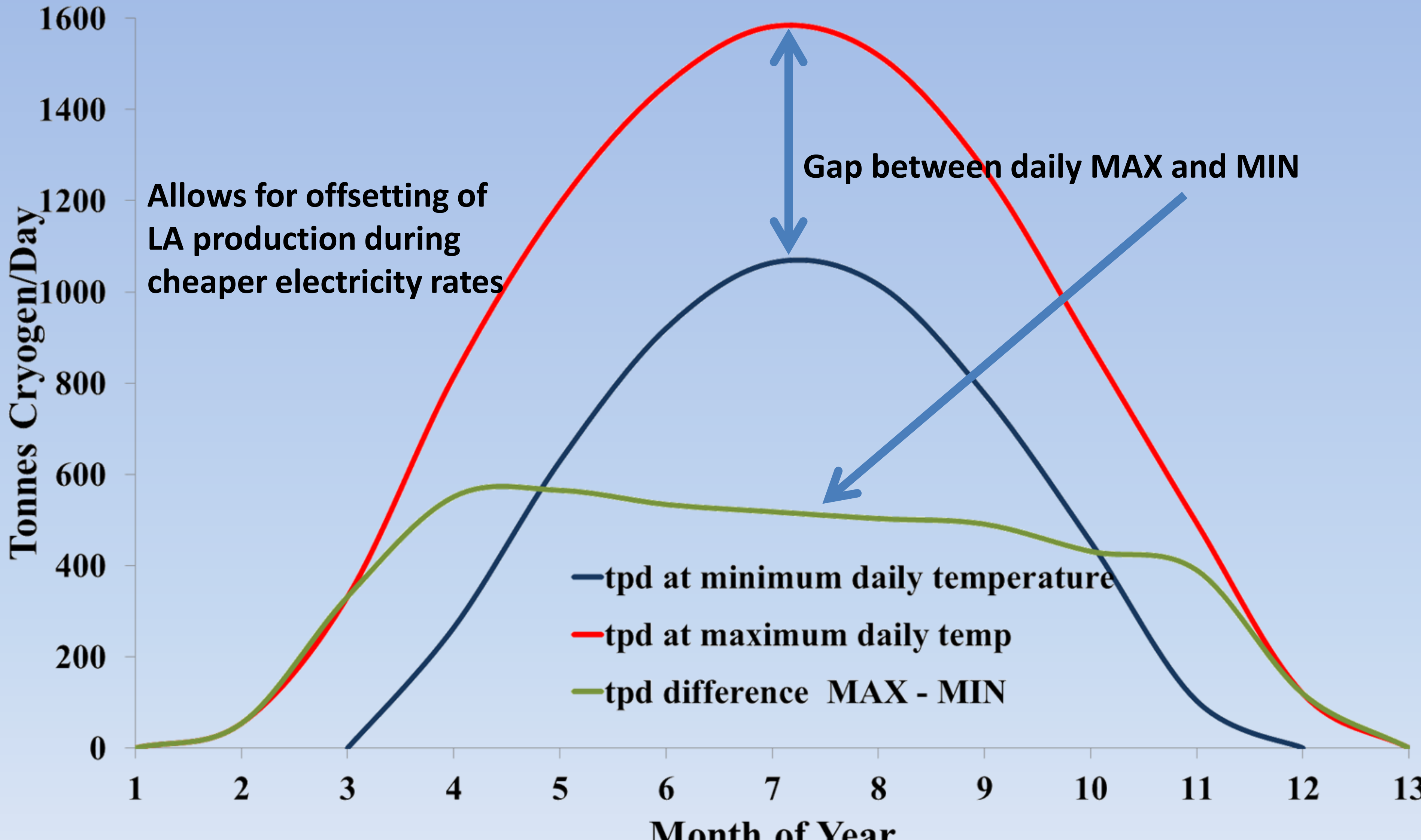




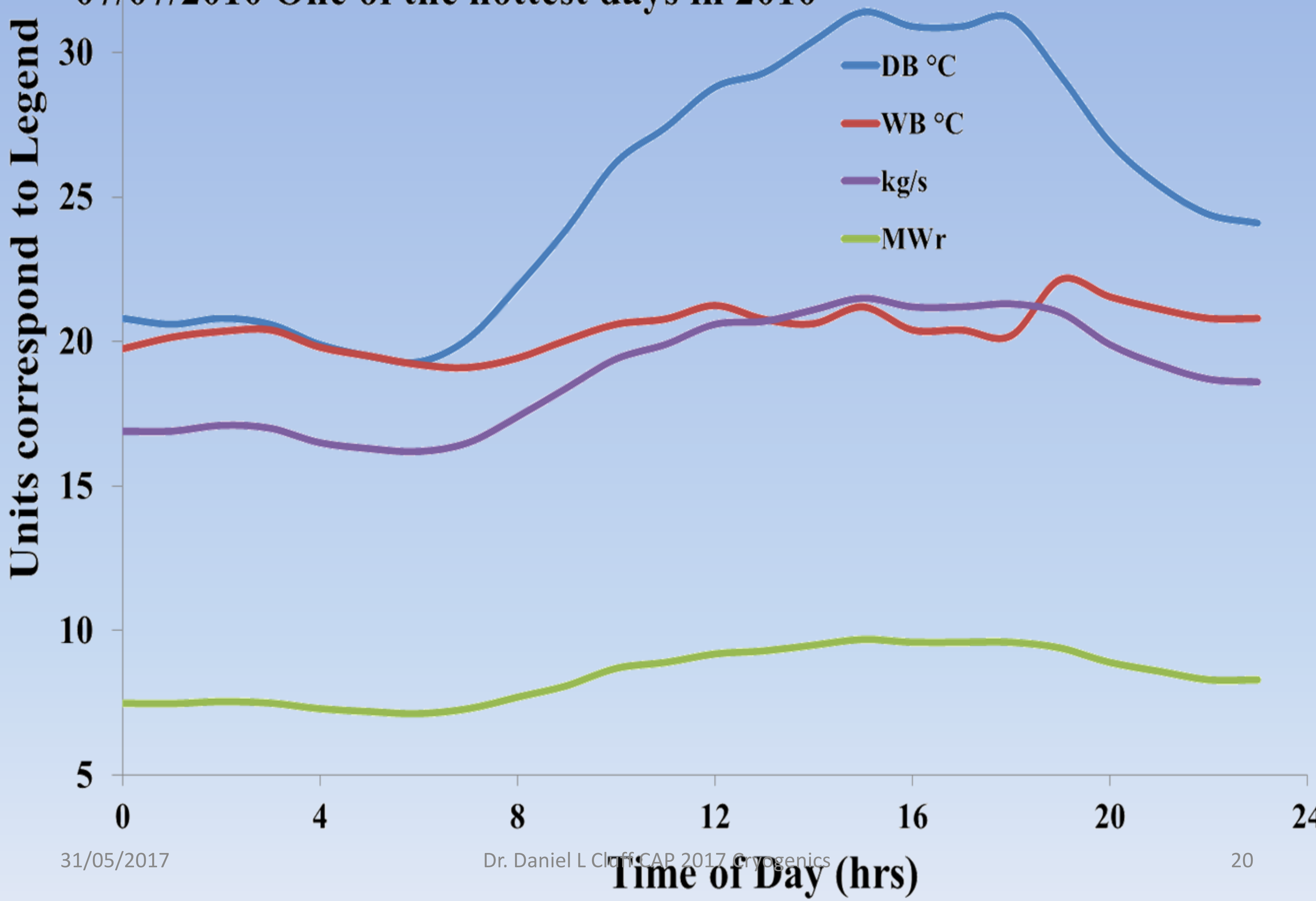
Daily Max/Min Fluctuation per Quarter
12/12 at the 2600 Level
Quarterly Averaged Monthly Max/Min WBGT
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
max
min
1950 tpd
1590 tpd
1350 tpd
990 tpd
900 tpd
500 tpd
430 tpd
0 tpd = 10.5 DB 10.5 WB
Quarter of Year
1
2
3
4

Demand for Liquid Air (tpd)

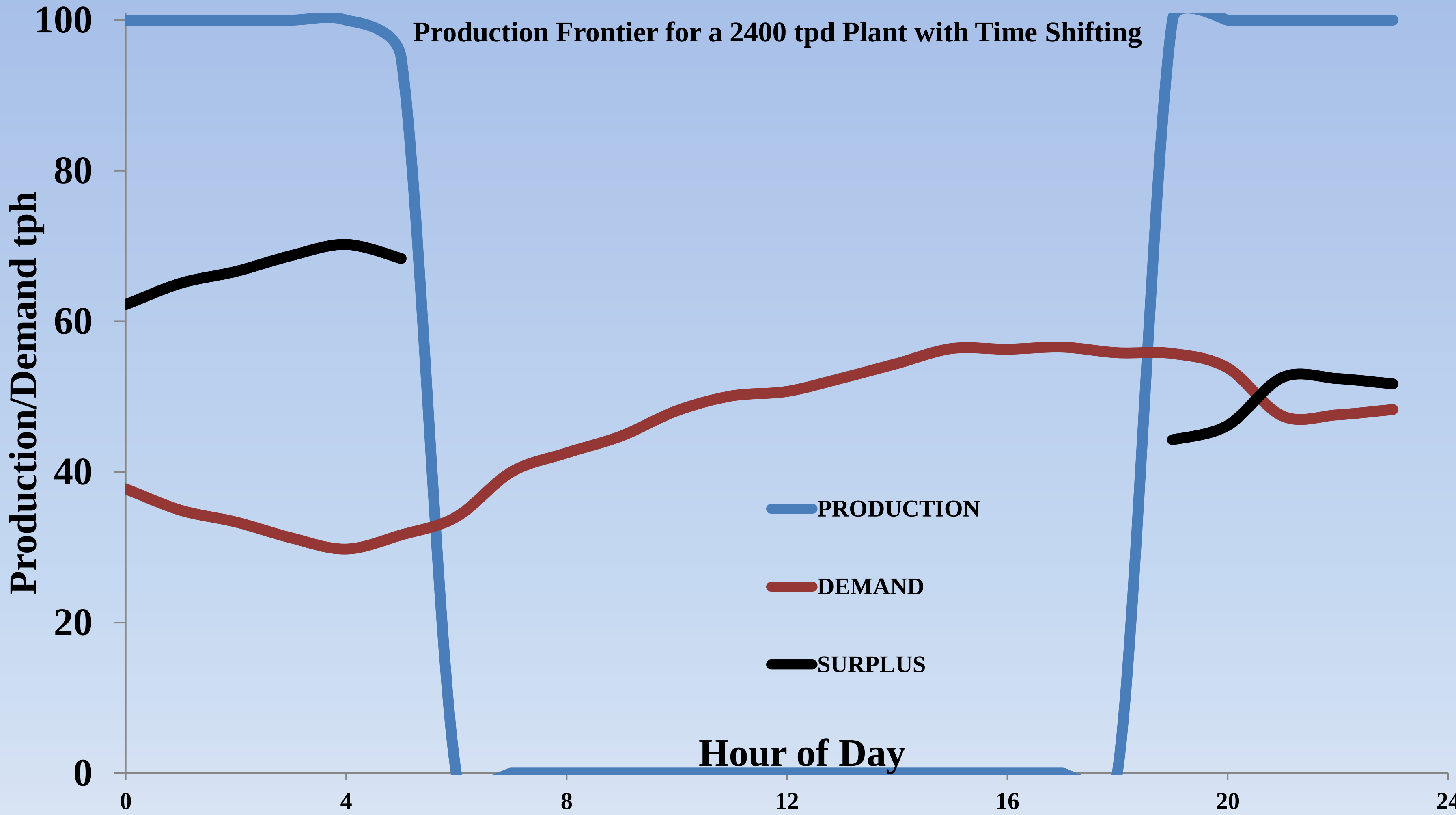
to Create a 12/12 DB/WB ºC Environment at 1915 Depth



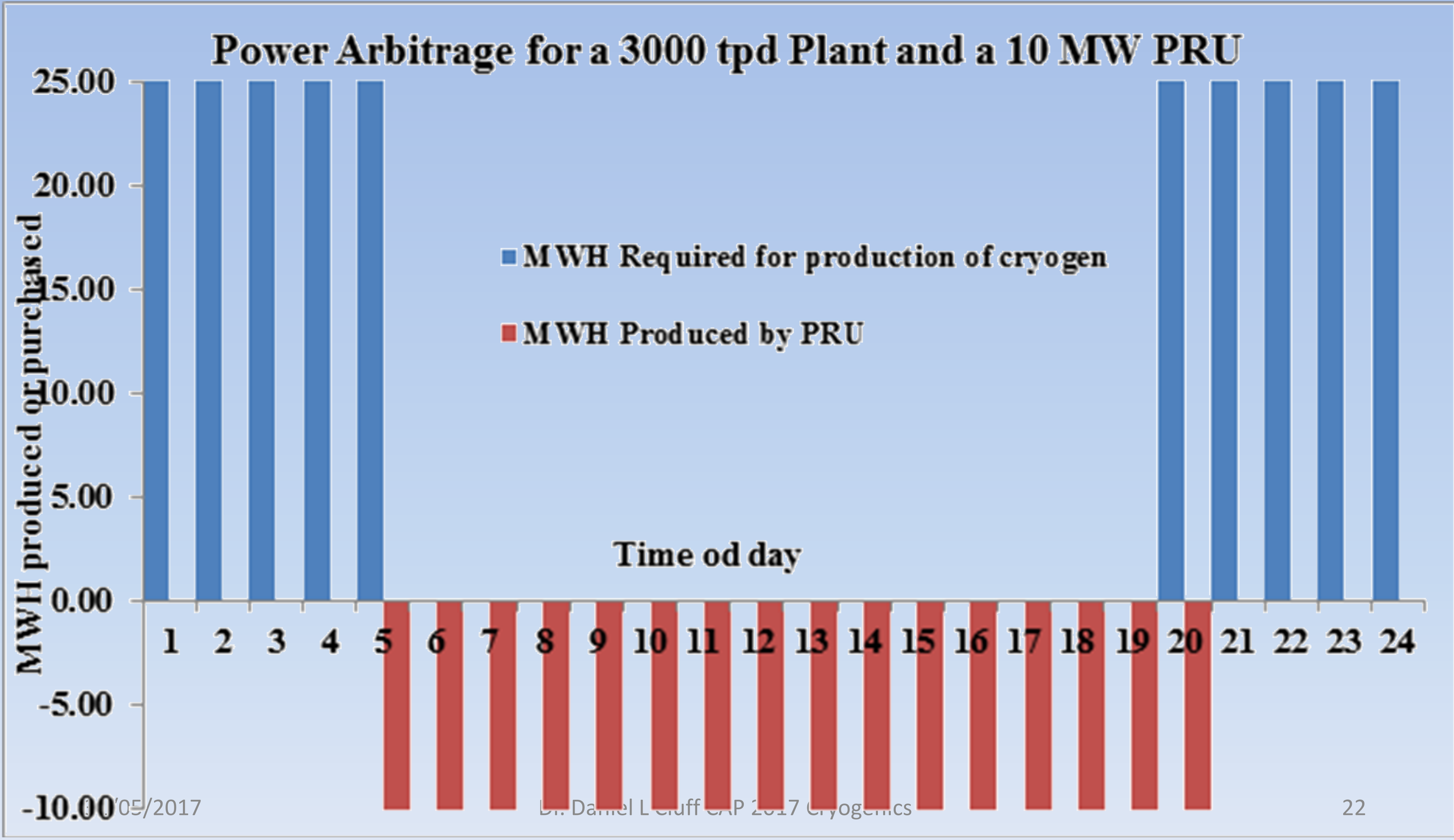
Cryogenic Chilling for Actual Temperature Fluctuations 07/07/2010 One of the hottest days in 2010



A 2400 tpd plant production frontier when the surplus produced over the least expensive energy cost is redistributed to the peak time cost



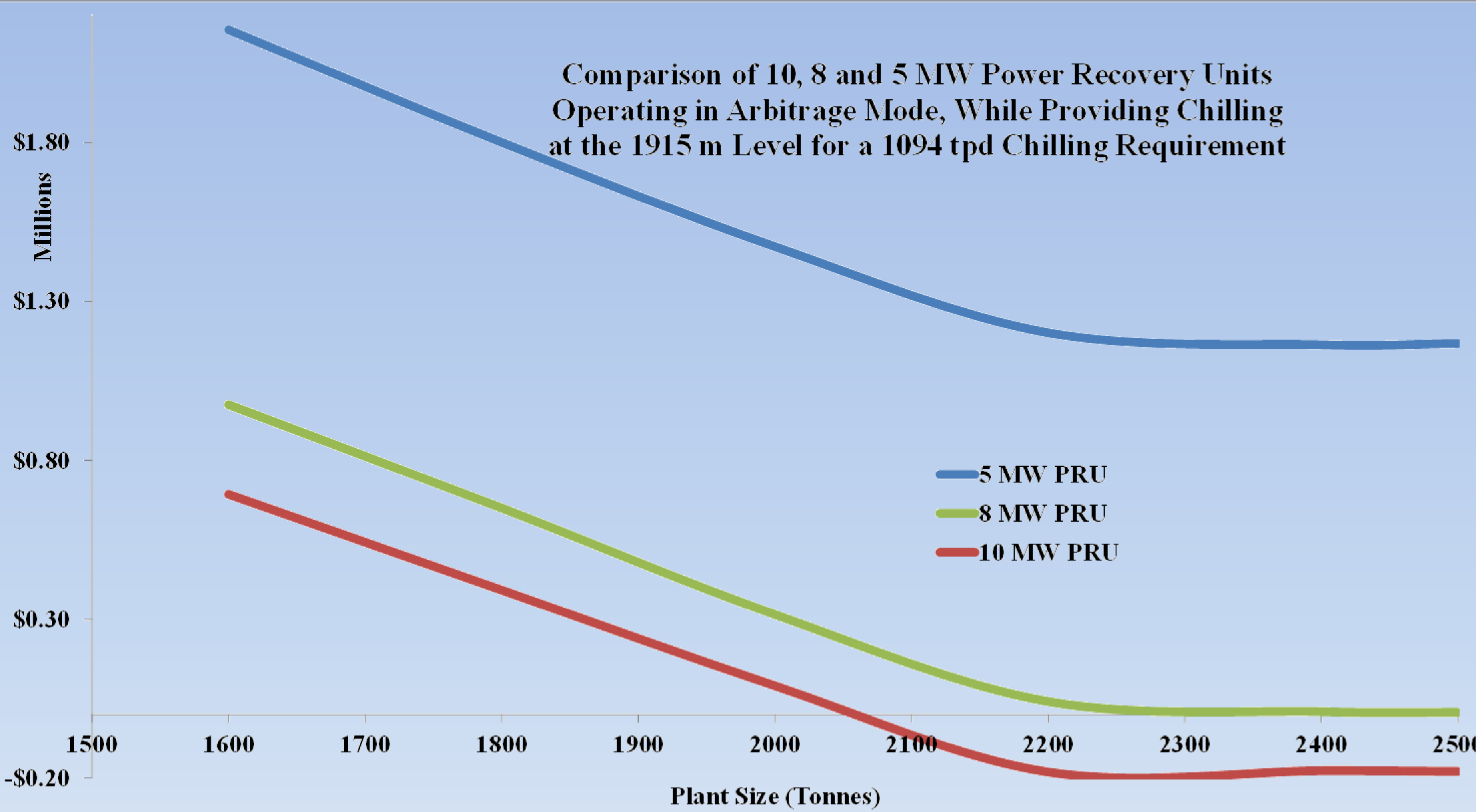
Summary of the cryogen production and power production



Summary of the cryogen production and power production implications for a 10 MW PRU

Plant Size tonnes	1600	1800	2000	2200	2400	2500
Energy Cost	$3,170	$2,345	$1,520	$775	$787	$781
Fan Savings	-$1,271	-$1,271	-$1,271	-$1,271	-$1,271	-$1,271
Final Cost	$1,899	$1,074	$248	-$496	-$484	-$490
YEAR at this rate	$693,071	$391,886	$90,701	-$180,987	-$176,752	-$178,869
MWH paid	218.84	218.84	218.84	218.91	219.04	218.98
10 MWH PRU recovered	-120.00	-120.00	-120.00	-120.00	-120.00	-120.00
FAN MWH recovered	-10.20	-10.20	-10.20	-10.20	-10.20	-10.20
TOTAL	88.64	88.64	88.64	88.71	88.84	88.77
Tonnes produced	1094.00	1094.00	1094.00	1094.33	1095.00	1094.67
Tonnes required	1094.12	1094.12	1094.12	1094.12	1094.12	1094.12
Power Generation	10	10	10	10	10	10
Operating Period	12	12	12	12	12	12
MWH Produced	120	120	120	120	120	120
Efficiency	54.83%	54.83%	54.83%	54.82%	54.78%	54.80%

Cost of Chilling When Time shifting and Using a Power Recovery Unit



Plant Configuration Costing

Plant Configuration	Waste heat	Standalone	Standalone	Waste heat
Liquefaction capacity (tonnes/day)	2500	3000	2000	1700
Power input (MW @ charge time)	21.4	25	16.6	14.3
Charge time hrs	6	6	8	8
Consumed energy MWH	128.4	150	132.8	114.4
Discharge time hrs @ 5 MW	18	18	16	16
Energy output (MWH)	90	90	80	80
Liquid air store capacity (tonnes)	570	570	510	510
Round trip efficiency	70%	60%	60%	70%
CAPEX (million $)	46	40	33	38
PRU (turbines/generators/grid)	8.15	8.15	8.15	8.15
Storage cost	3	3	2.7	2.7
Cost per kilowatt ($)	9285	8098	6569	7545
Cost per kilowatt-hour ($)	516	450	411	472

Ancillary Systems

- Chilling accounts for a major share of consumption
- There are a number of other services that can be implemented that provide a service while also simultaneously chilling as a side benefit.
  - Compressed air
  - Electricity production
  - Vehicles, pumps or fans that can be driven by liquid air

Compressed Air

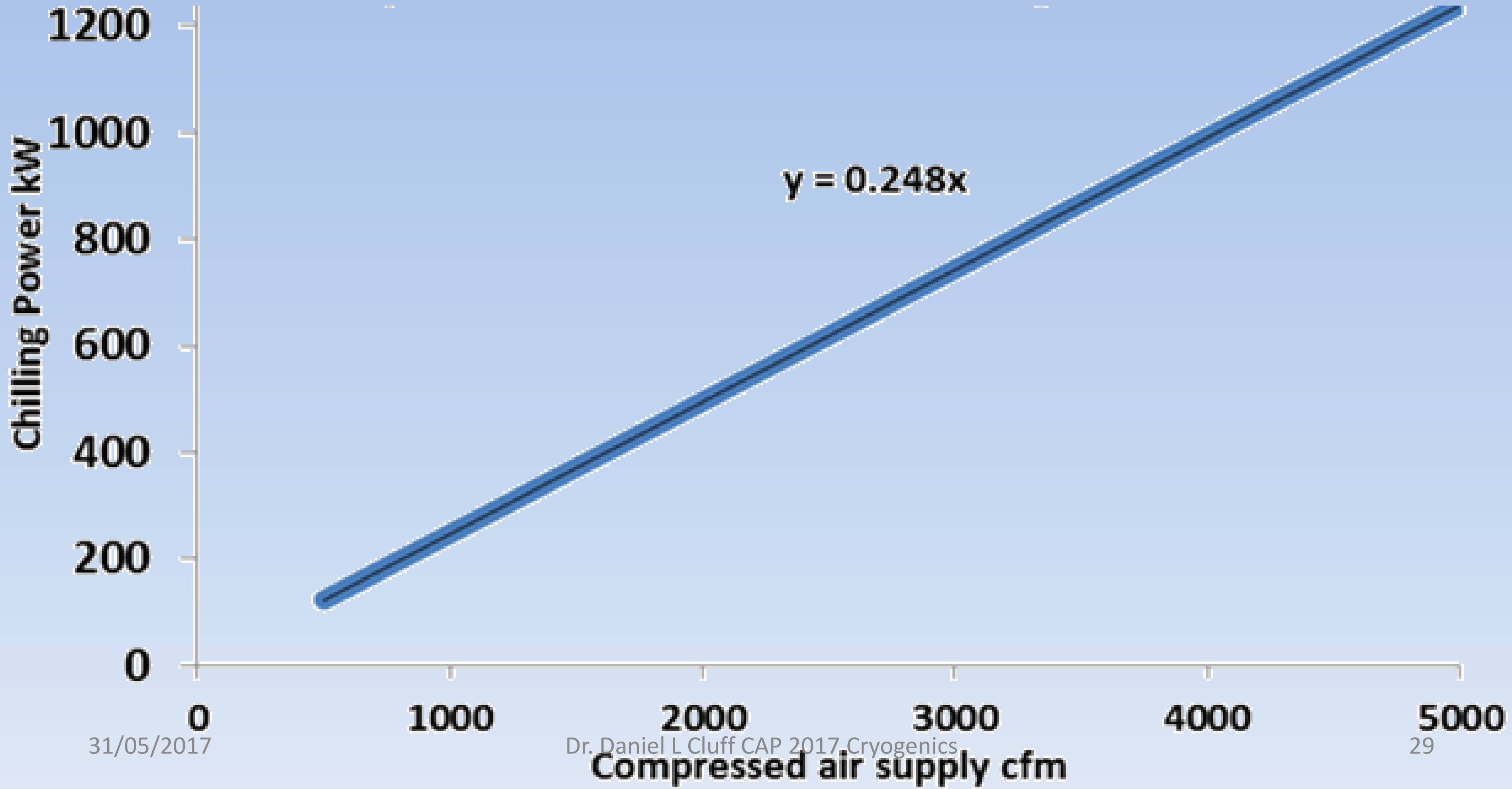
- The production of compressed air exploits the liquid nature of the cryogen, which is simply squirted into a receiver tank and allowed to reach ambient temperature – quickly!

Compressed Air Supply With Chilling Power

Compressed Air Consumption		Receiver Size	Chilling Power	<u>kW</u> ft³/min	Mass flow	Liq flow	Plant impact
ft^3/min	m^3/hr	m^3	kW		kg/s	l/s	tpd
500	850	1.79	124	0.248	0.29	0.33	25
1000	1699	3.6	248	0.248	0.58	0.67	50
2000	3398	7.28	496	0.248	1.16	1.33	100
3000	5097	11.06	744	0.248	1.74	2.00	150
5000	8495	18.54	1240	0.248	2.9	3.33	250

Assuming continuous demand the liquid air can be configured to provide a modular compressed air system which will simultaneously chill at the location the receiver tank is located akin to spot chilling.

Chilling Power as a function of the Compressed Air Supply



Recall the earlier LAES Simplified Schematic

- In the schematic it was indicated that the PRU could be placed underground.
- Part of the PRU process is to pump the liquid air to a pressure of about 1000 psi before evaporating and expanding through the turbomachinery.
- At 2000 m the pressure is about 2500 psi
- Sufficient pressure to eliminate the pumps

Recall the earlier discussion regarding the gap between the MAX and MIN daily temperature was about 500 tpd, Below for a 5 MW_e PRU

	Waste heat	Standalone	Standalone	Waste heat
Liquefaction capacity (tonnes/day)	2500	3000	2000	1700
Power input (MW @ charge time)	21.4	25	16.6	14.3
Charge time hrs	6	6	8	8
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Cost per kilowatt ($)	9285	8098	6569	7545
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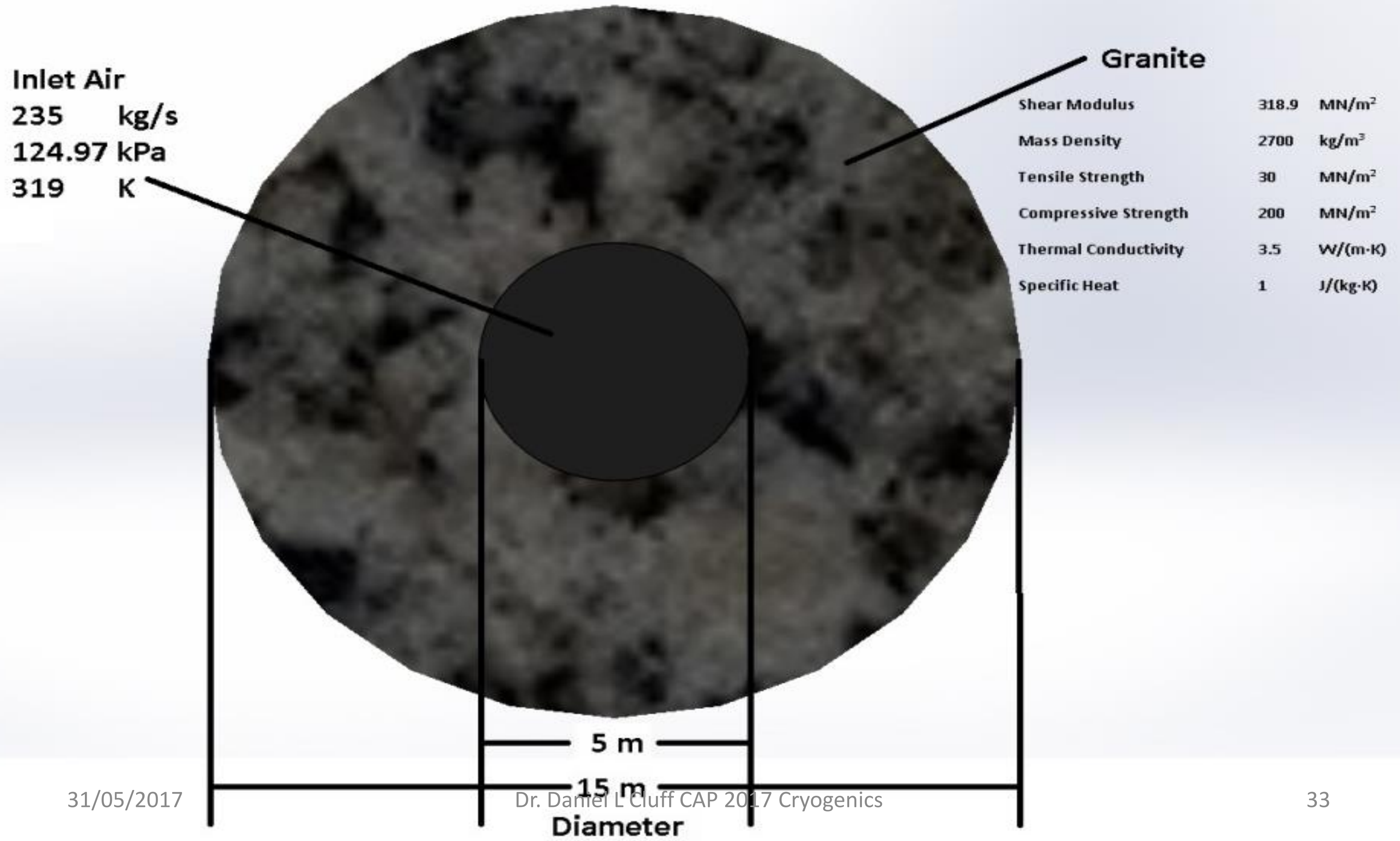
Typically the cold would be recycled to cold storage, but here it is absorbed by the air at depth

Exploitation of the Joule Thompson Effect

- With 2500 psi available as a forcing pressure the Joule Thompson Effect, which is part of the liquefaction process, can be exploited to provide further chilling commonly referred to as free expansion or a throttling process.
- $T_2 = T_1 - U_j(P_1 - P_2)$, $P_2 = 14.5$ psi, $T_1 = 25^oC$
- where U_j is the JT coefficient - ambient T_1 - contained P_1
- For a contained pressure of 880 psi, $U_j = 0.1815$
- $T_2 = 298 - 0.1815(880 – 14.5) = 140.9$ K $=-132.05^oC$

CFD Model for Chilling the Entire Airflow, Similar to a BAC



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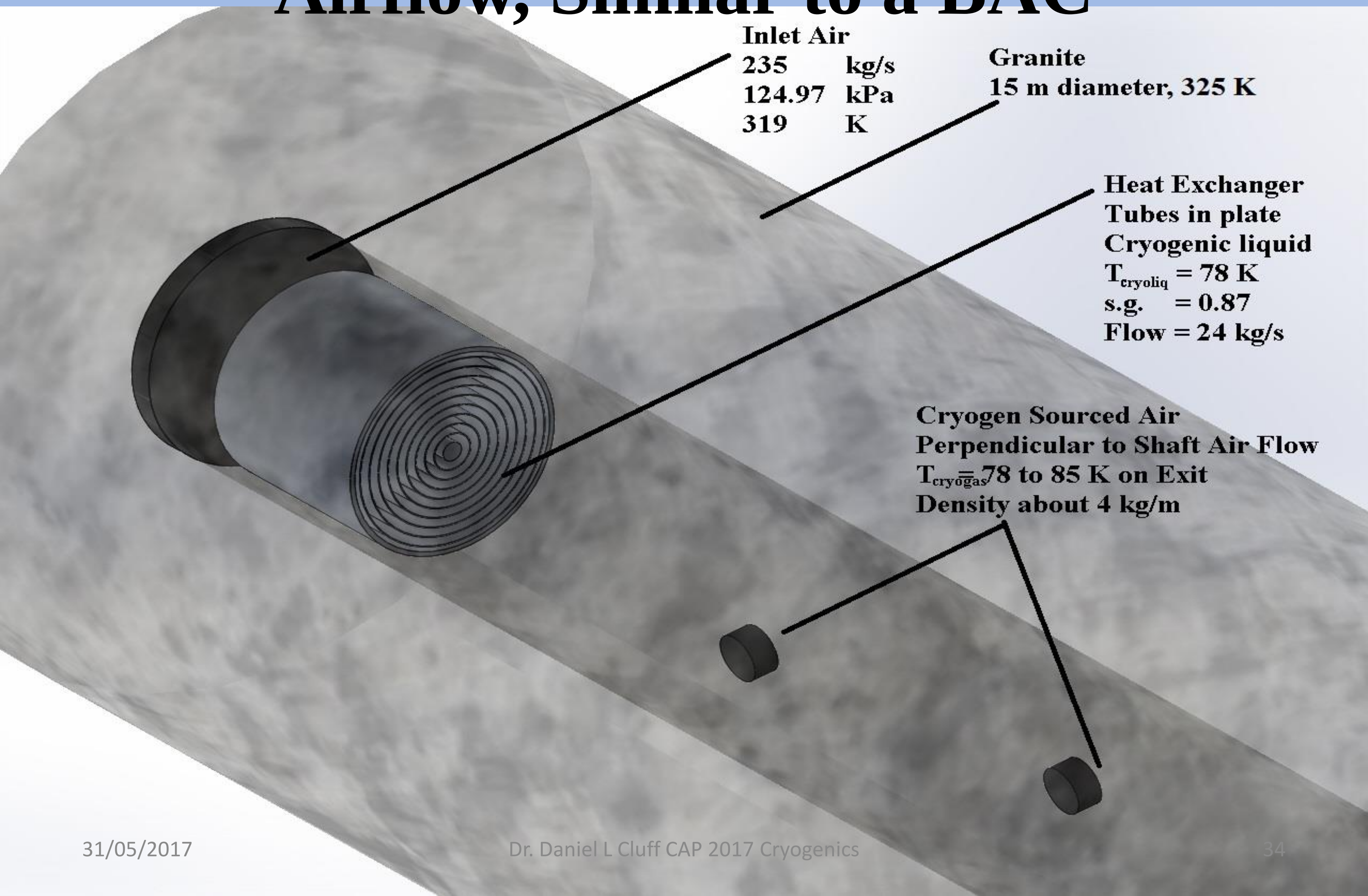
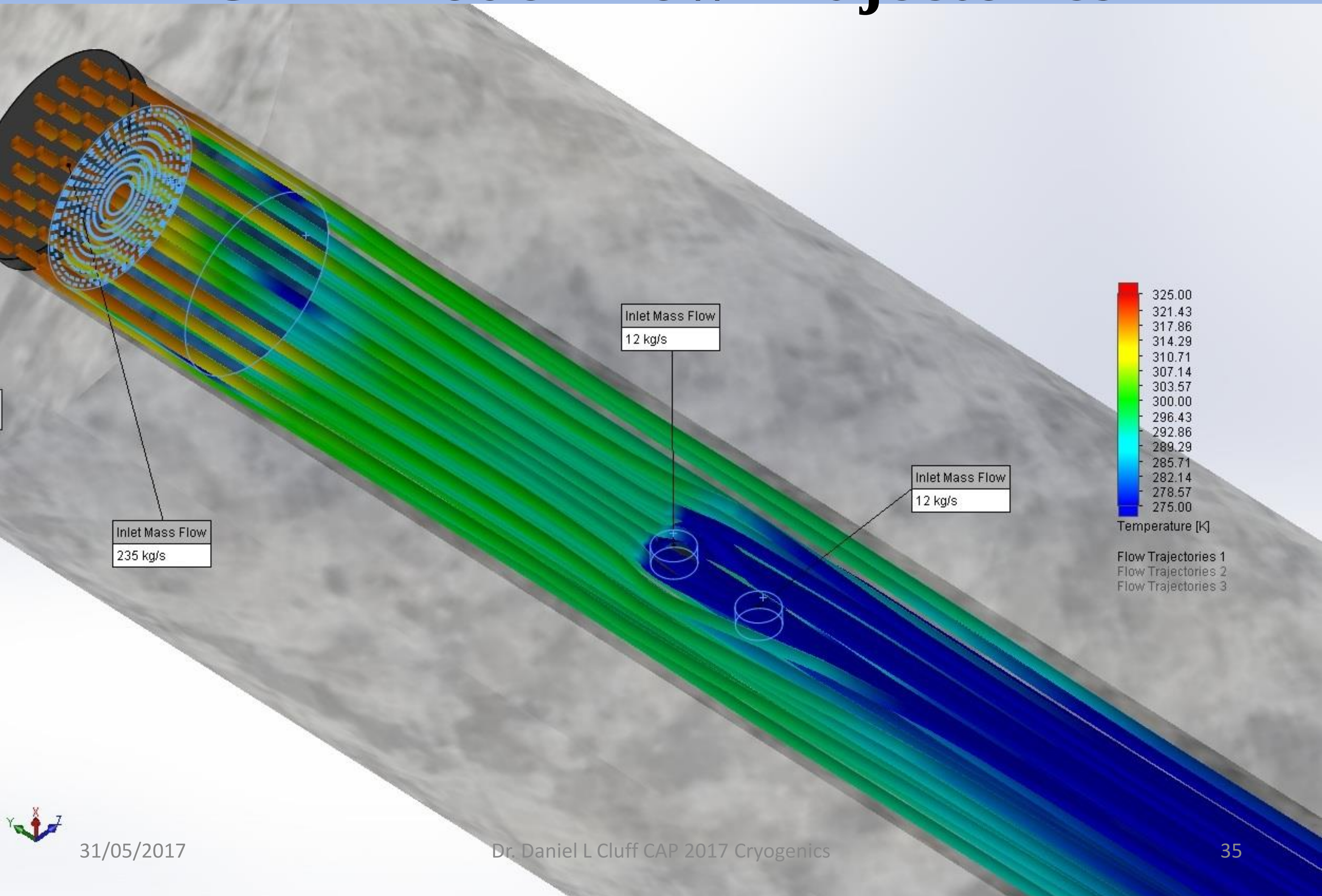
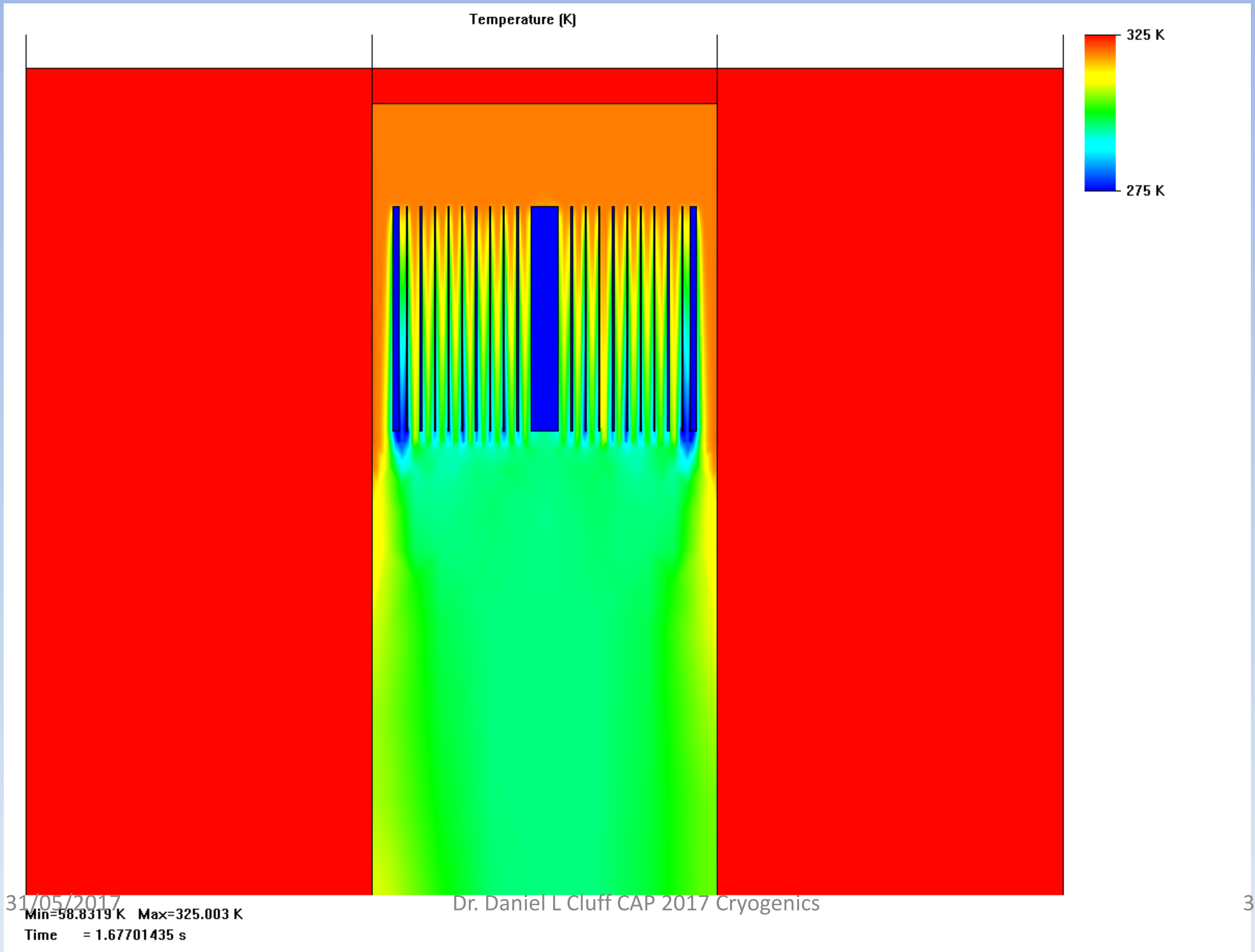


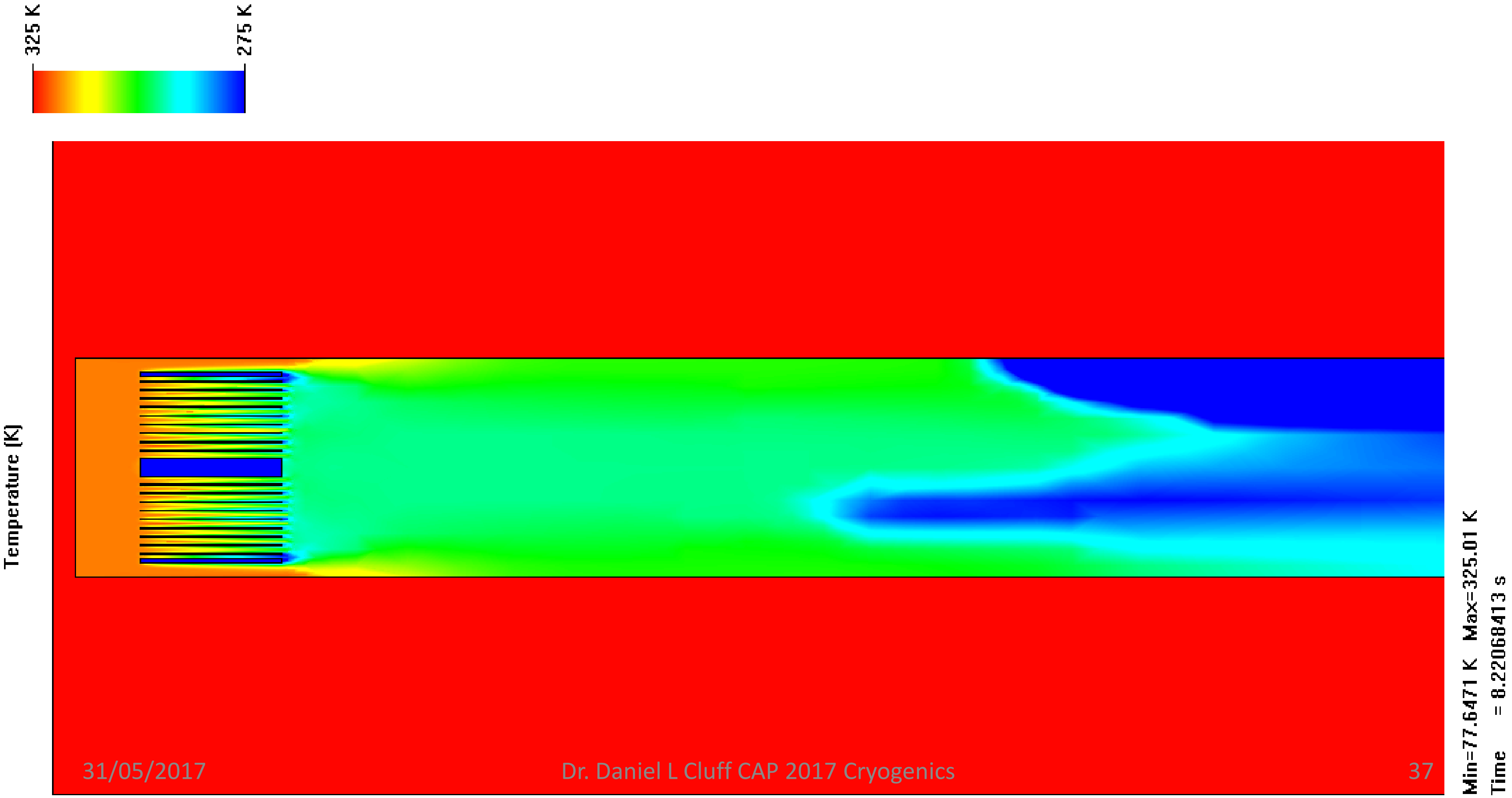
CFD Model Flow Trajectories



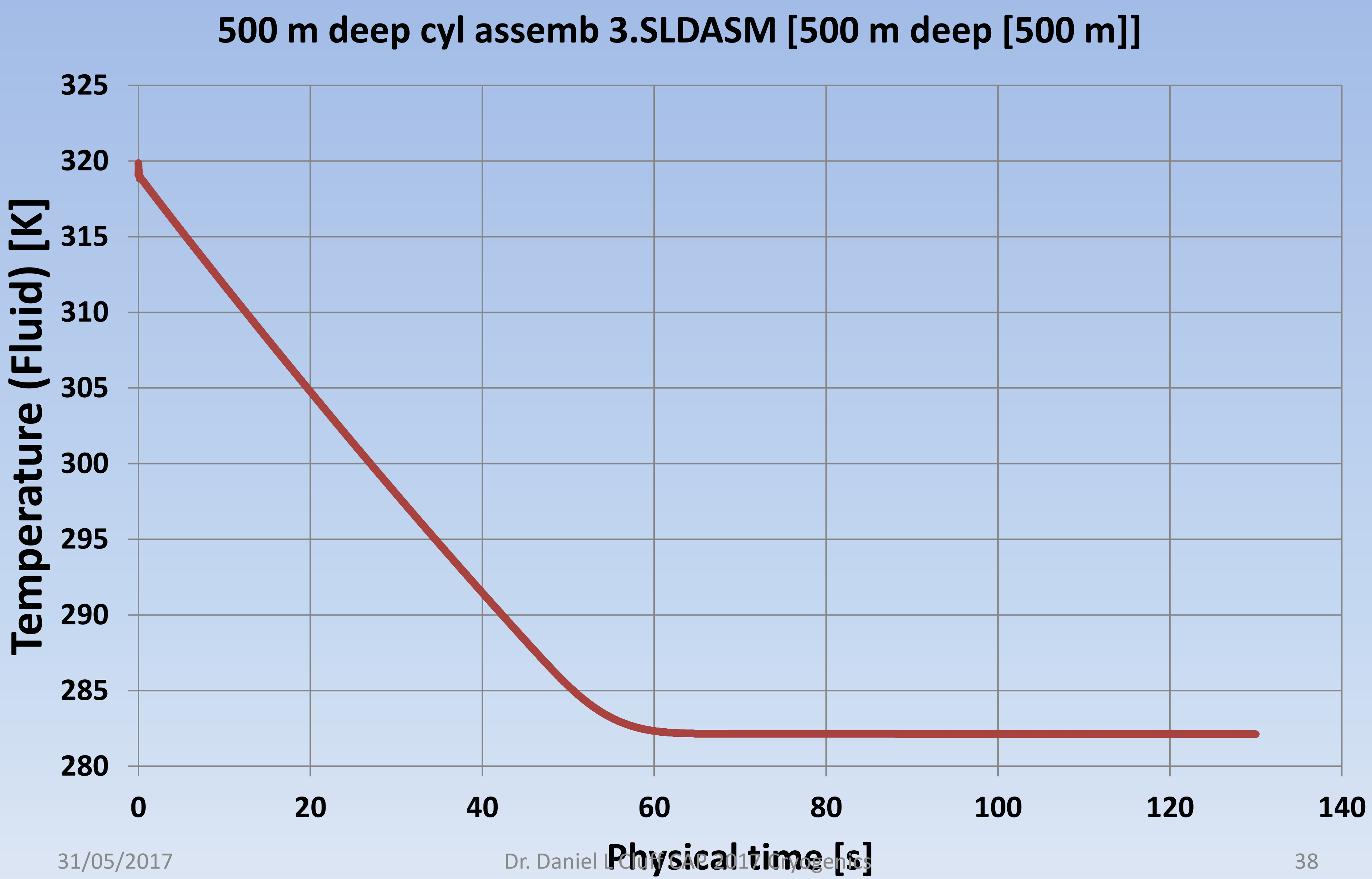
Close up View of Heat Exchanger 1.67 sec



Close up View of Heat Exchanger 8.2 sec



Average Temperature of Air in Shaft



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Thank you to:

Glencore for Financial Support and Engineering Excellence.

UDMN for financial support.

CEMI for business expertise and project management

Dearman Engine Company for Cryogenics expertise and technoeconomic analysis.

Highview Power Storage for LAES expertise and technical support.

Camborne School of Mines for academic support

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