Deep Mine Cooling

ADMIRA DHES INC.

GUPEX

CanMIND

Cryogenic-based Chilling for Mines
Patent Pending Hybrid Cryogenic Technology

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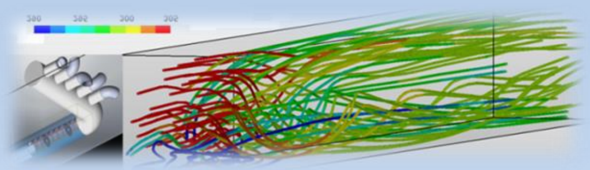
Big Picture of Underground Cryogenics

Large UG Equipment
Powered by Dearman Engines

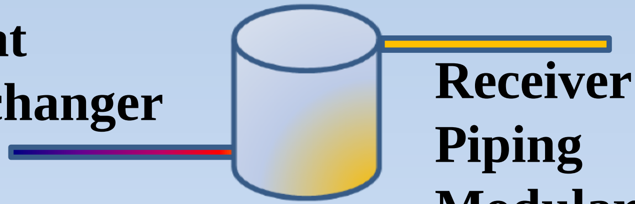
UG Cryogenic
Piping and Storage

Cryogenic Chilling
CFD Modelling



Compressed Air System Design

Heat
Exchanger

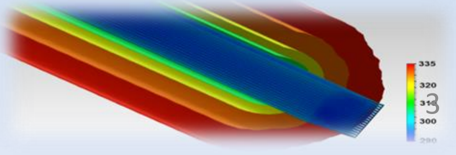


Receiver size
Piping
Modularity design

Power/chilling co-generation

8 MWr + 5 MW$_e$

Rapid Response Chilling on Demand



Why Liquid Air Energy Storage (LAES)
A Zero Carbon Green Energy Technology
EVERY TIME YOU DO SOMETHING WITH LiqAir IT ABSORBS HEAT !!

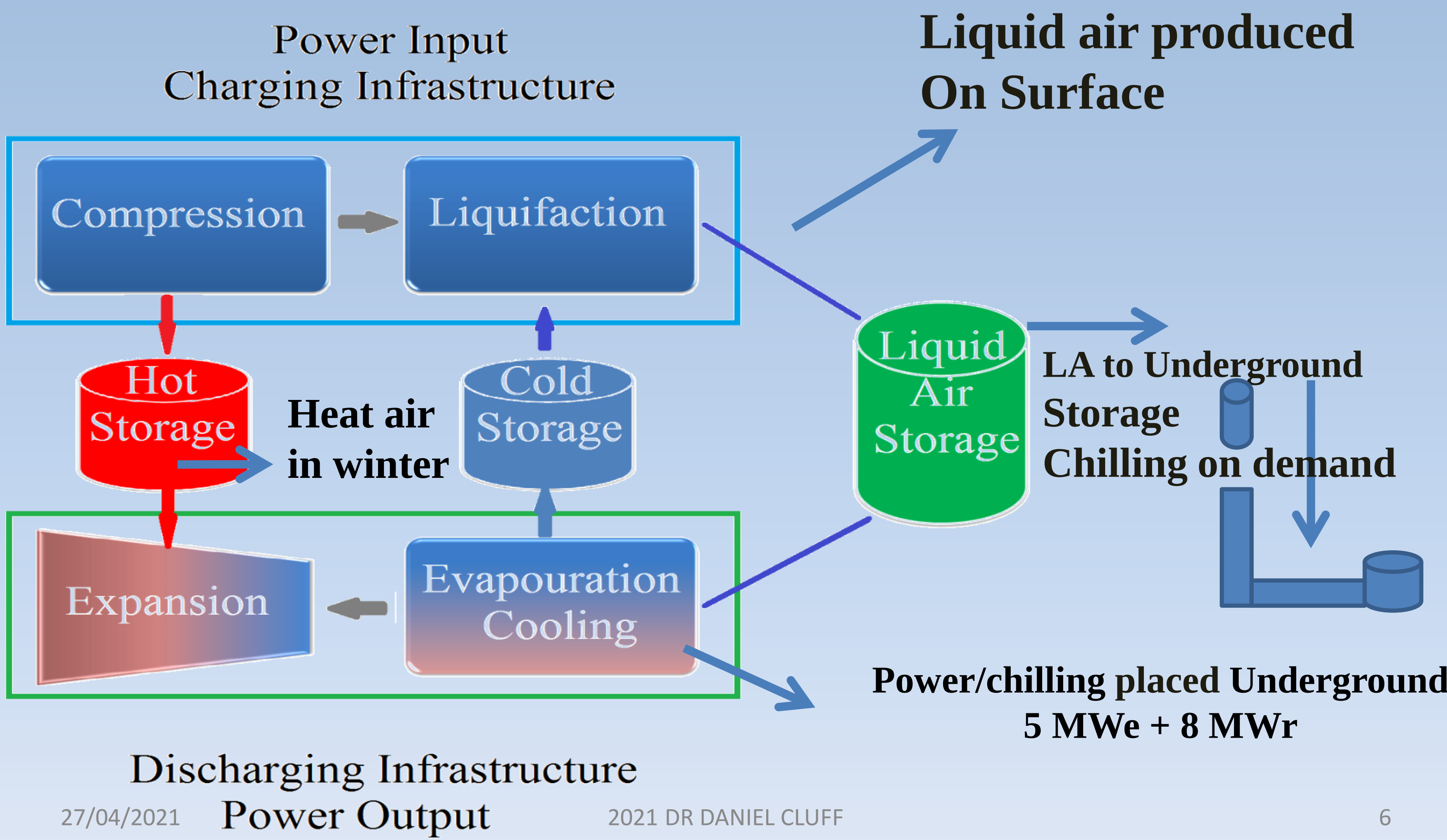
- The cryogenic liquids are produced on the surface in a standard cryogenic liquefaction plant or underground.
  - Heat rejected on or to surface

- Surface LAES System provides economy of scale, marketable byproducts, Ar, O_2, N_2
- Cryogenic liquid is delivered 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

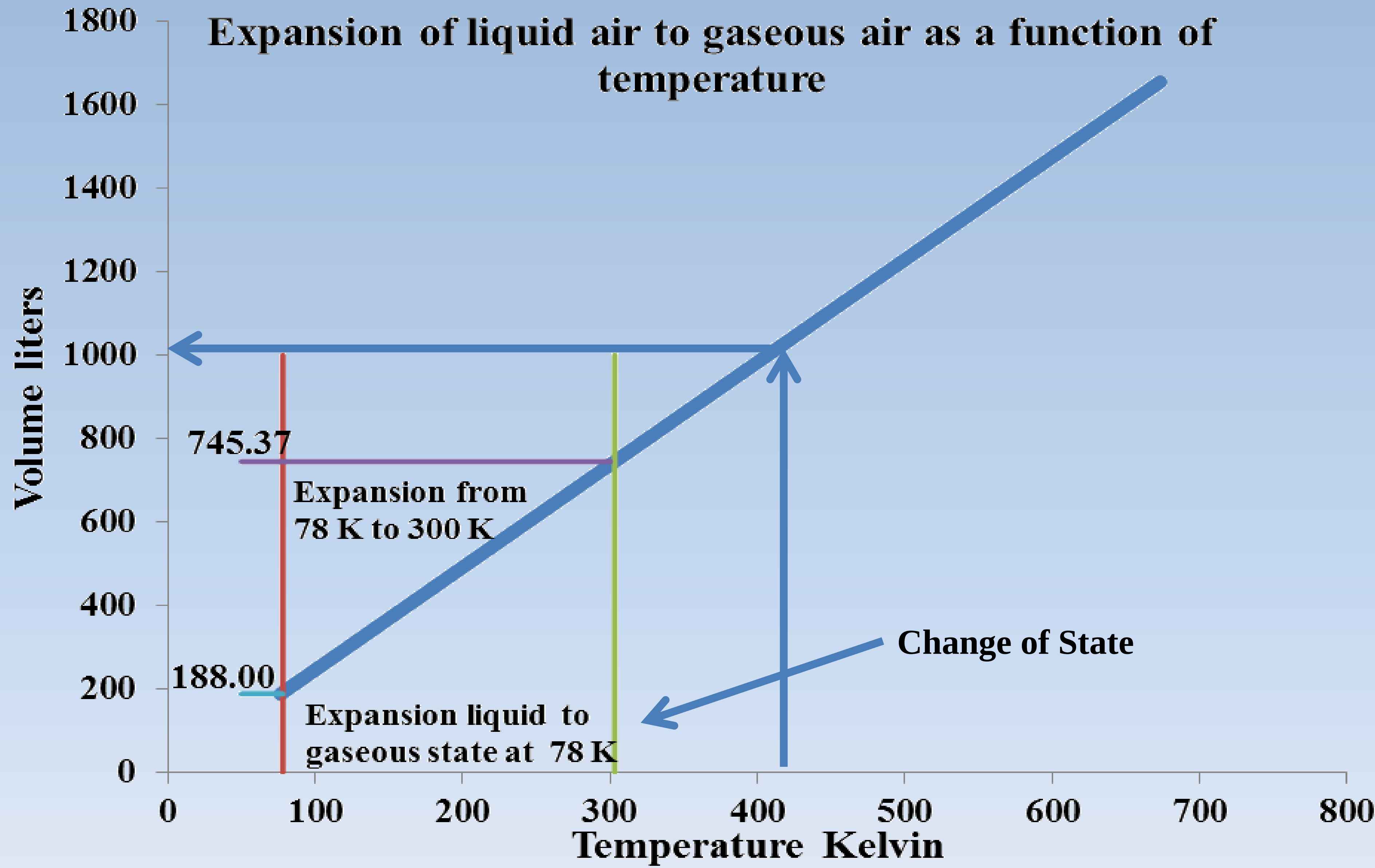
LAES Process

- 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
  - We create a mix of O_2 and N_2 appropriate to the conditions and use
- 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.

Simplified LAES Schematic



700⁺ ℓ Gaseous Air Per 1 ℓ Liquid Air



Cold Storage in a Liquid

1) **Latent Heat** = ΔQ_L = mass x L_v $L_{v\,=}$ 205 kJ/kg

2) **Expansion Heat** = ΔQ_a = mass x $C_p \Delta T_g$

The specific heat capacity of air C_p = 1.007 J/kg-K

$$\Delta Q_T = \Delta Q_{L} + \Delta Q_a$$

$$\Delta Q_T = m(L_v + C_p \Delta T_g)$$

and for a mass = 1 kg, 1kg(205 kJ/kg + 226.13 kJ/kg)

≈ 430 kJ/kg

The total heat absorbed by 1 kg due to change of state and expansion is 430 kJ/kg so 1 kg/s of liquid flow provides 430 kWr of cooling.

Mine Cooling Via Cryogenics

So for 1 MW of cooling

The mass flow of liquid air required = **2.2 kg/s**

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

The liquid flow of liquid air required = **2.6 l /s**

The final gaseous volume is **1.9 m^3 of air**

Cooling, Electricity and Compressed Air
Three Incremental Cases for Glencore OPD

- **Stand Alone Simple chilling**
  - Liquid air released directly to airflow
    - 2.6 l/s (liq) → 1.9 m^3/s (air) → 1 MWr
- **Chilling plus Electrical Power**
  - Liquid air exhaust directed through turbine
    - 1043 tpd → 5 MWe plus 8 MWr 24 hrs/dy
- **Chilling, Electricity and Compressed Air**
  - 5000 cfm (2.4 m^3/s) → 1.2 MWr

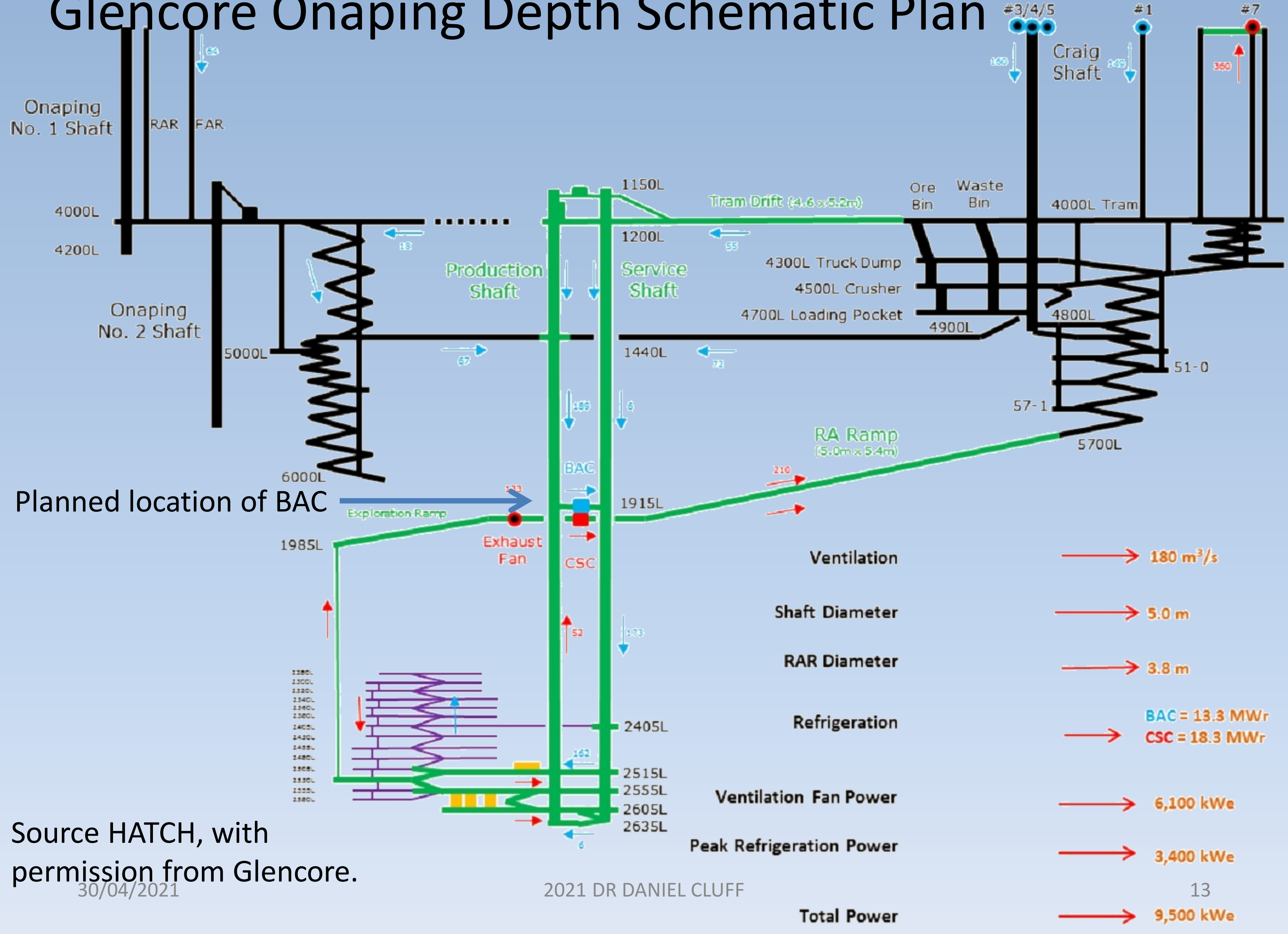
Bulk Air Chilling vs Cryogenics Comparison for Glencore Onaping Depth

- The CAPEX of both the LA and BAC are similar
- Significant OPEX reductions are possible based on selected LA option
- LA is a fast response “Chilling on Demand”™ (COD™) system
  - able to offset an abrupt heat influx in a lower air flow i.e. all electric mine.
- Optimal surface plant size is 2000 tpd with a 600 t storage facility allowing multiple options for Glencore OPD:
  - Energy storage
  - Electricity/chilling cogeneration production of 5 MWe with 8 MWr
  - Compressed air/chilling cogeneration of 2500 cfm with 600 kWr
  - Off-sales of surplus oxygen and argon
  - Powering vehicles

Key Concepts in Glencore OPD Study

- LA demand was correlated to 30 year environmental data.
- Cryogenic liquid is a form of stored energy.
- 2000 m Level bulk release chills sublevels (approximates BAC).
- Design condition: $12^{o}/12^{o}$ (DB/WB) at 2000 m from $28^{o}/19^{o}$ (DB/WB), provided by HATCH
- LA COD™ allows for daily cooling cost calculations.
- Underground cryogenic chilling system produces Electricity
- Compressed air/chilling cogeneration eliminates the compressed air plant and piping from the surface.
- Economic statements are accurate to +/- 25%.
- The 20 year NPV is calculated at a discount rate of 10% including both CAPEX and OPEX.

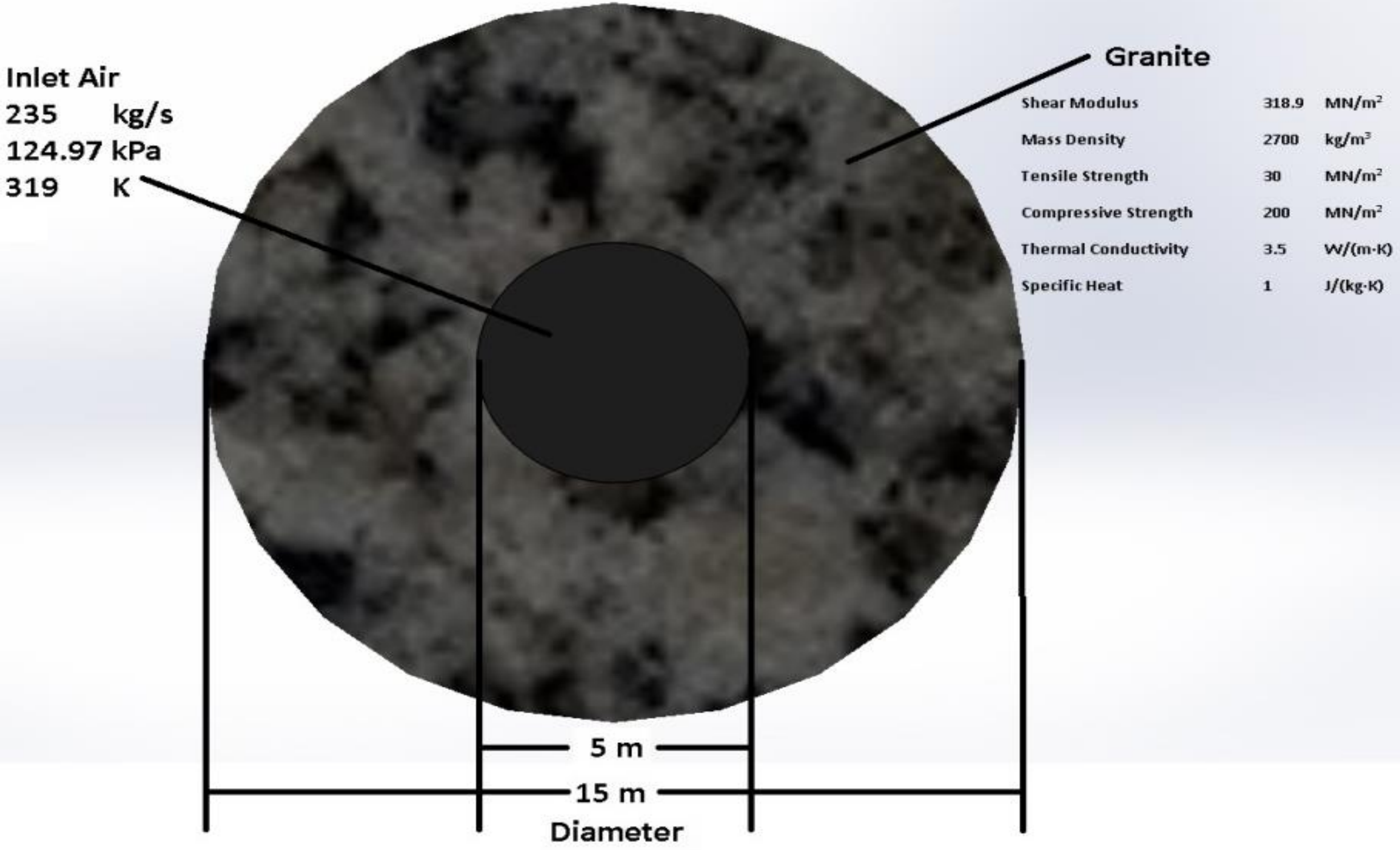
Glencore Onaping Depth Schematic Plan



Planned location of BAC

Source HATCH, with permission from Glencore.

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



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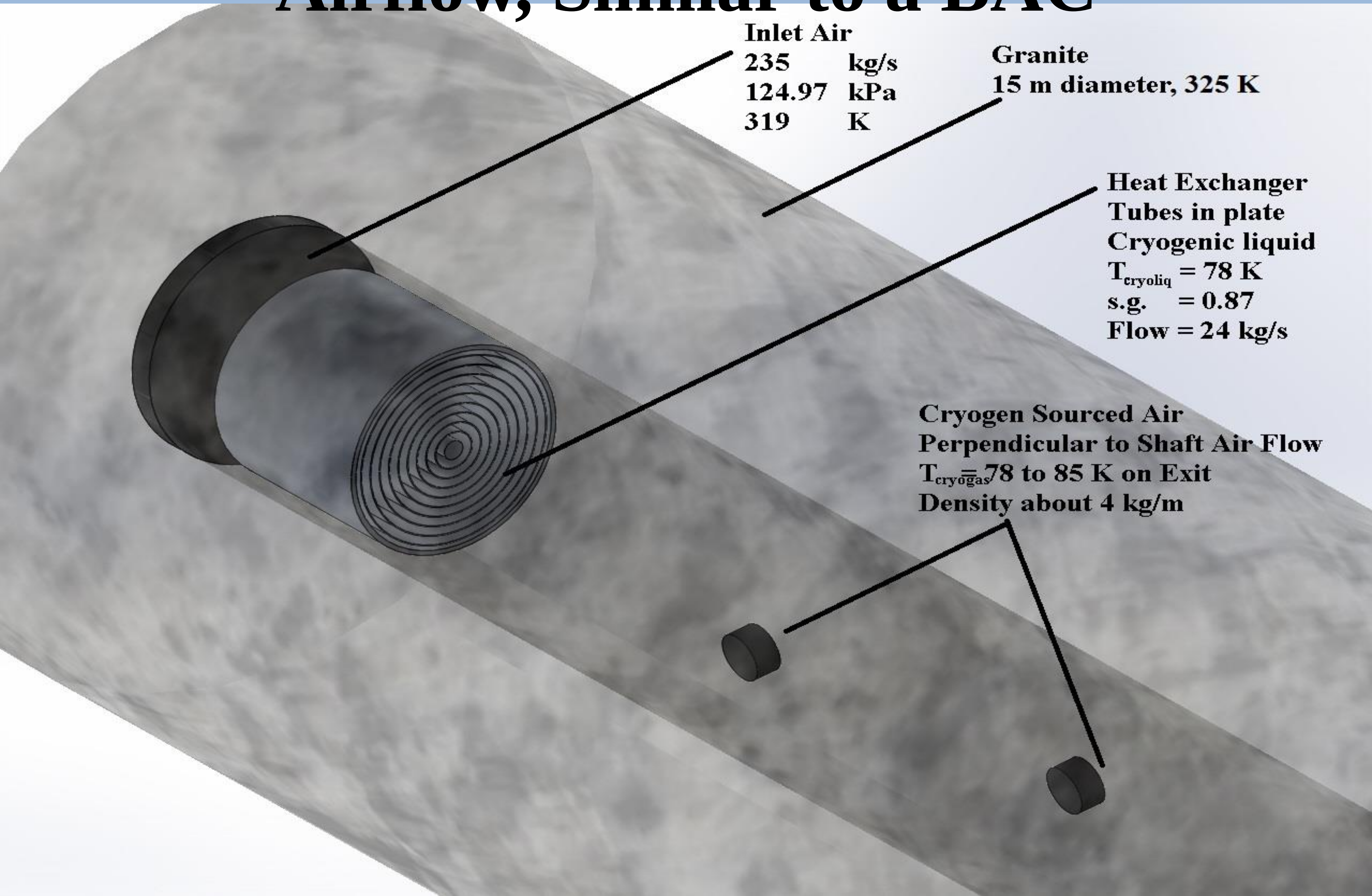
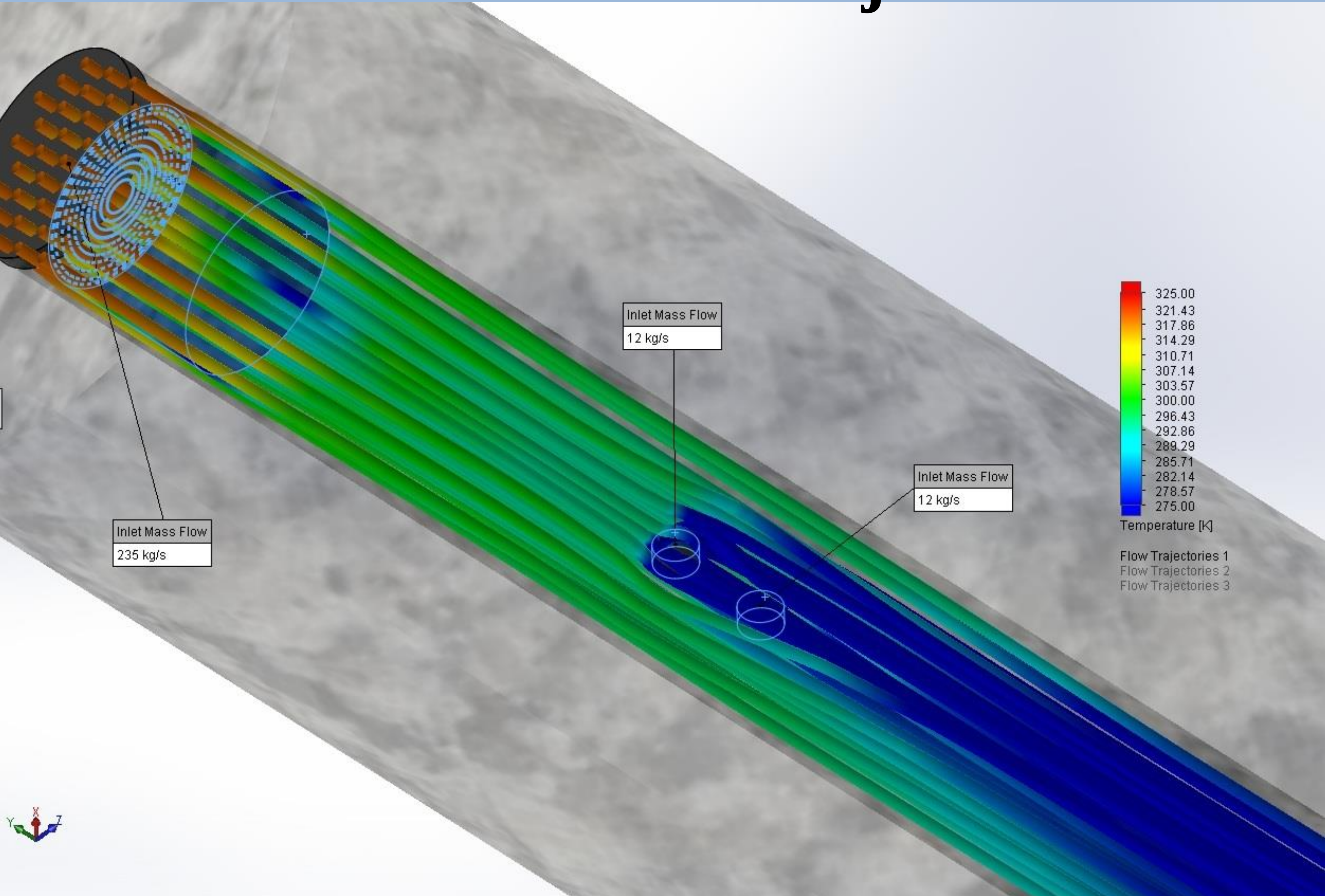
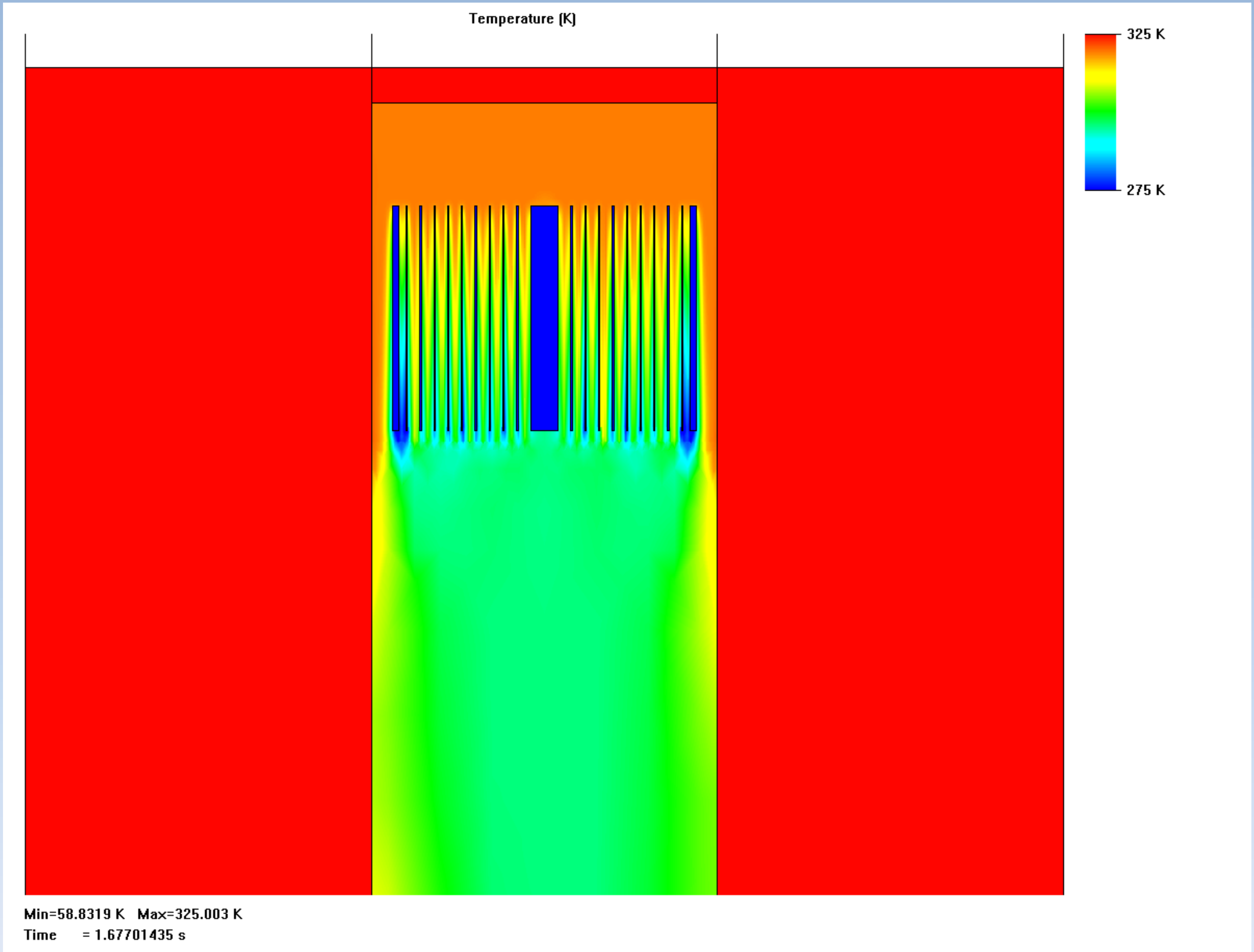


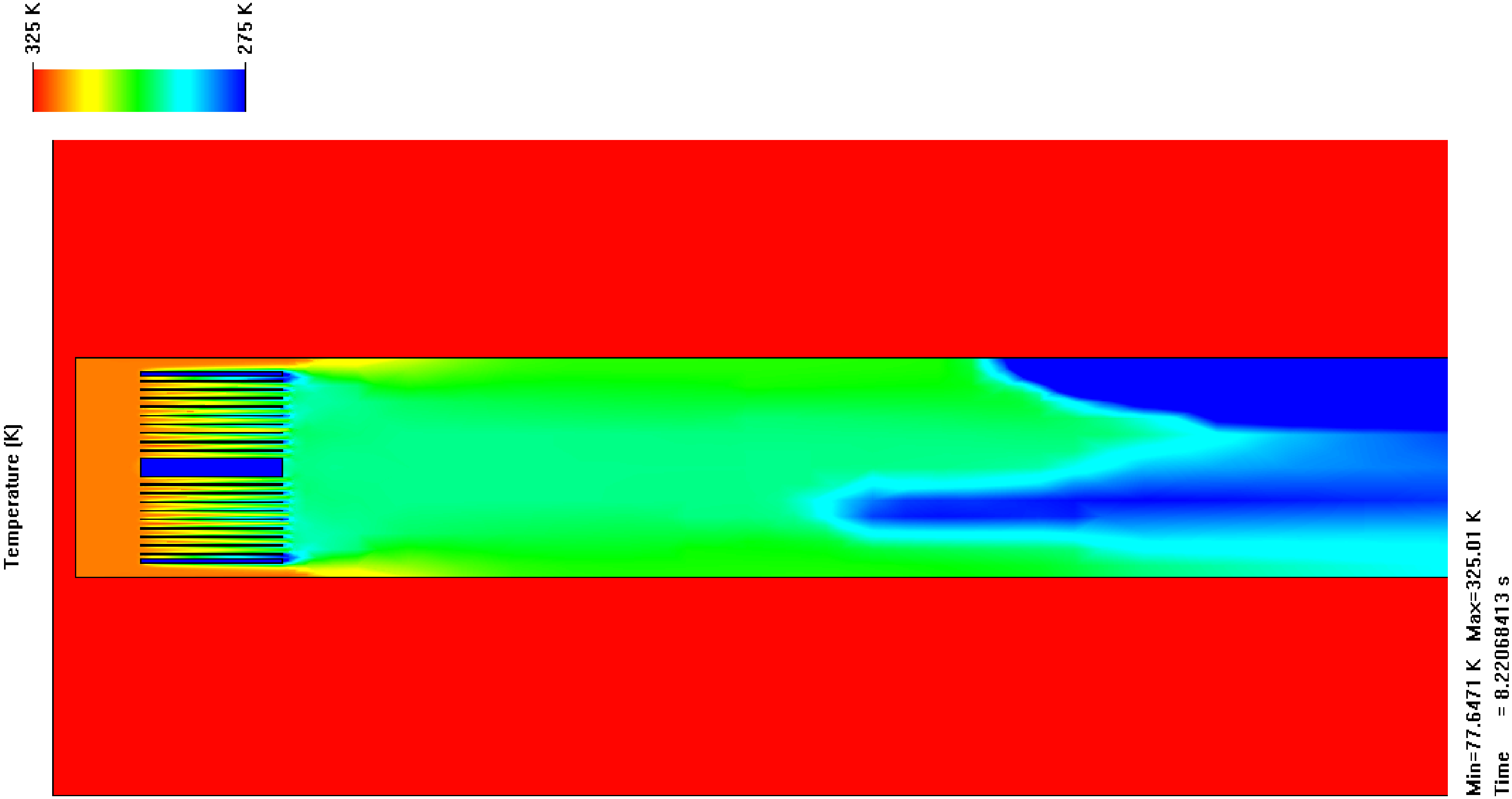
CFD Model Flow Trajectories



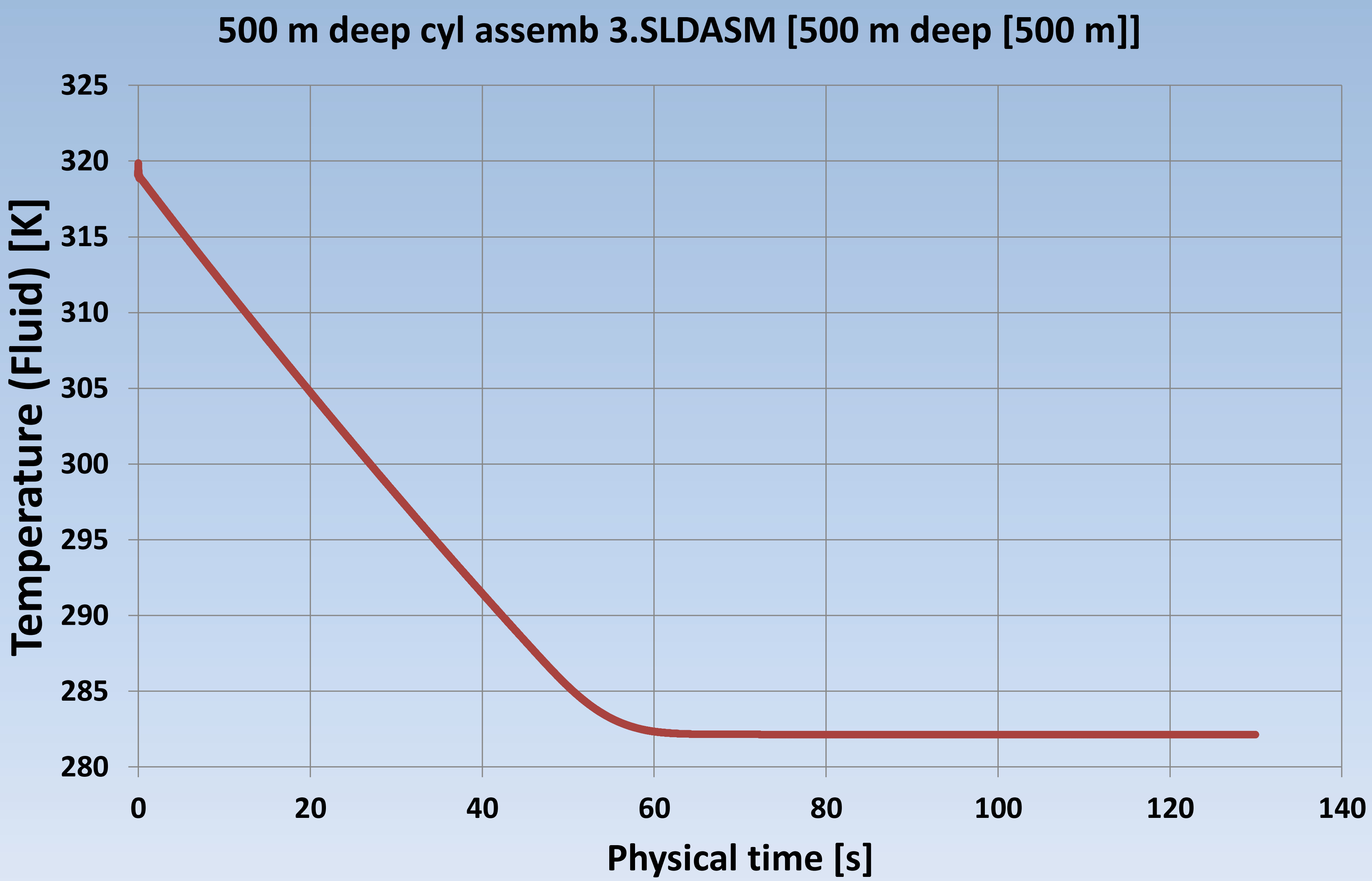
Close up View of Heat Exchanger 1.67 sec



Close up View of Heat Exchanger 8.2 sec



Average Temperature of Air in Shaft



NPV Comparison 2000 tpd Plant to BAC

Option 1: Base Configuration (Vaporiser Only)

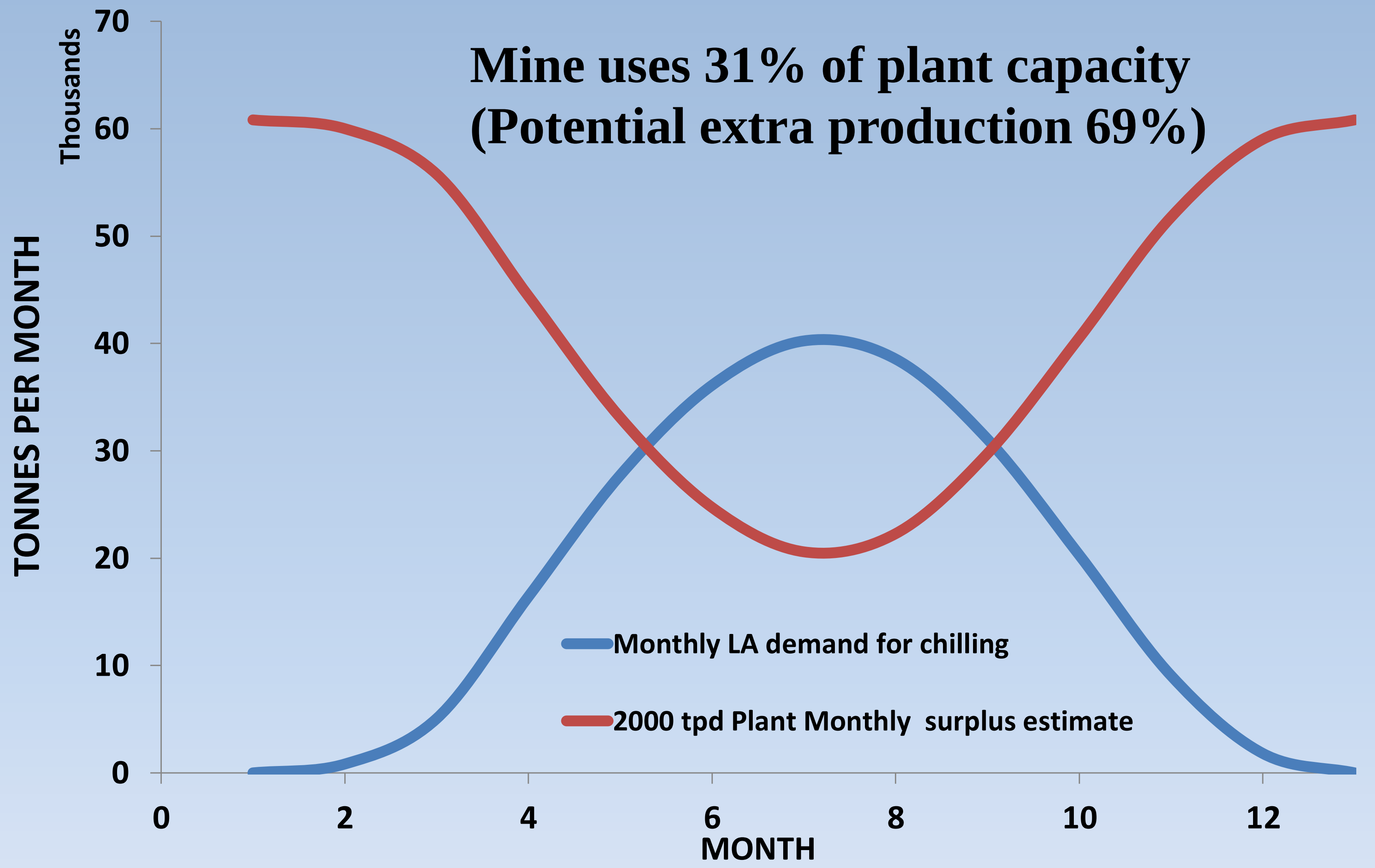
	CRYO ($M) CanMIND	BAC ($M) HATCH
CAPEX	$31.9	$31.4
OPEX/yr	$3.48	$3.22
NPV (10%)	-$61.60	-$58.80

Cryogenic OPEX = maintenance 0.38M plus energy cost 3.1M

BAC OPEX = maintenance 0.82M plus energy cost 2.4M

Maintenance for cryo is low because it is tried and true started in 1900's

Option 1: Chilling/Surplus Estimate



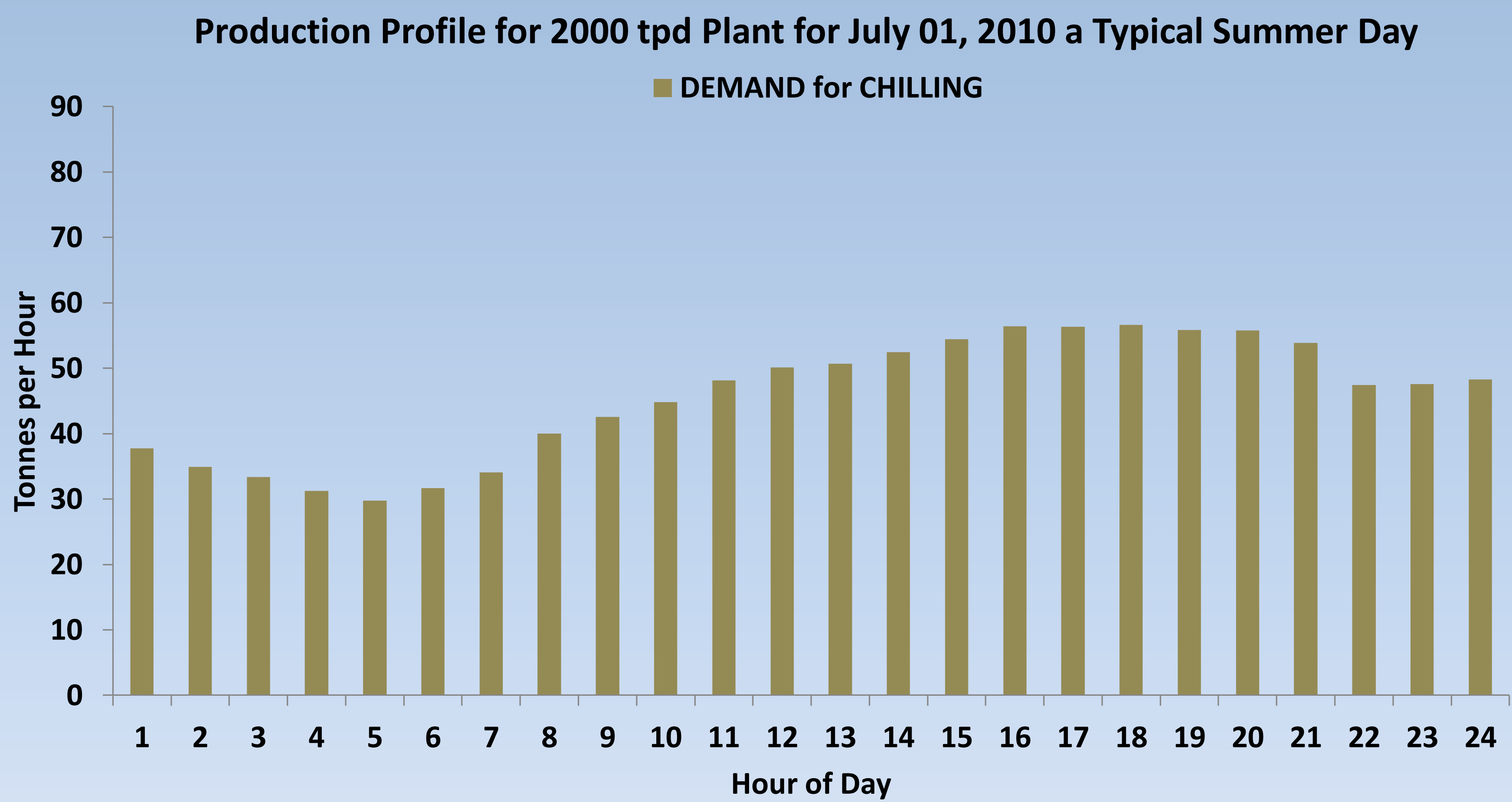
Option 2: Cogeneration

Simultaneous Production of Electricity and Chilling

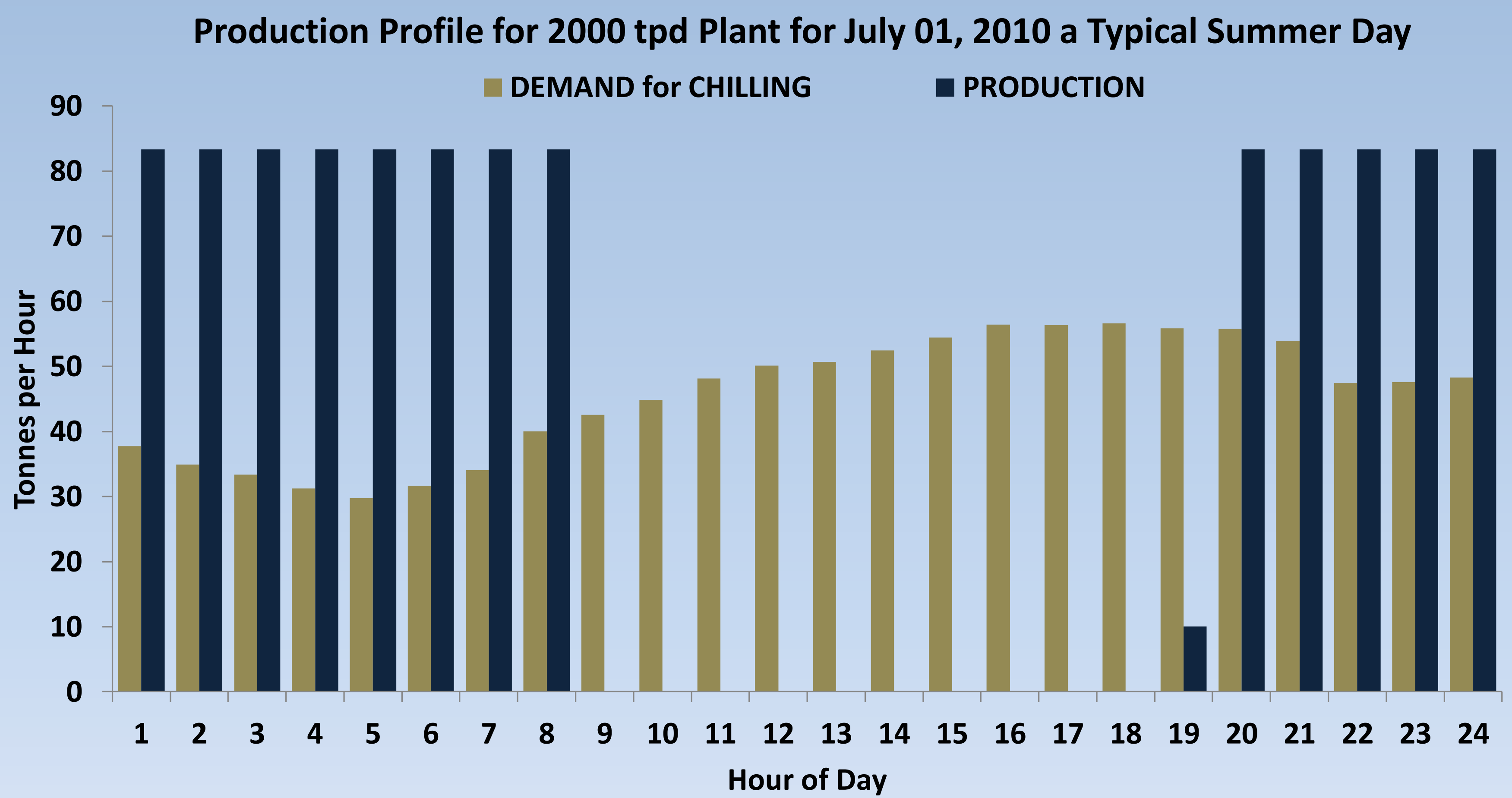
- Cogeneration Chiller:
  - 5 MWe operating for 24 hrs/day
  - 8 MWr min. to 14 MWr max. chilling
  - Consumes 1043 tpd
  - 2000 tpd Plant operates for 12.5 hrs/day drawing 16.7 MWe
  - Electricity generator operates for 24 hrs/day producing 5 MWe
- Requires hourly energy consumption/generation to calculate overall energy cost.
  - Mid-day is high cost recovery
  - Evening is low cost production

} Peak Power Cost Shifting

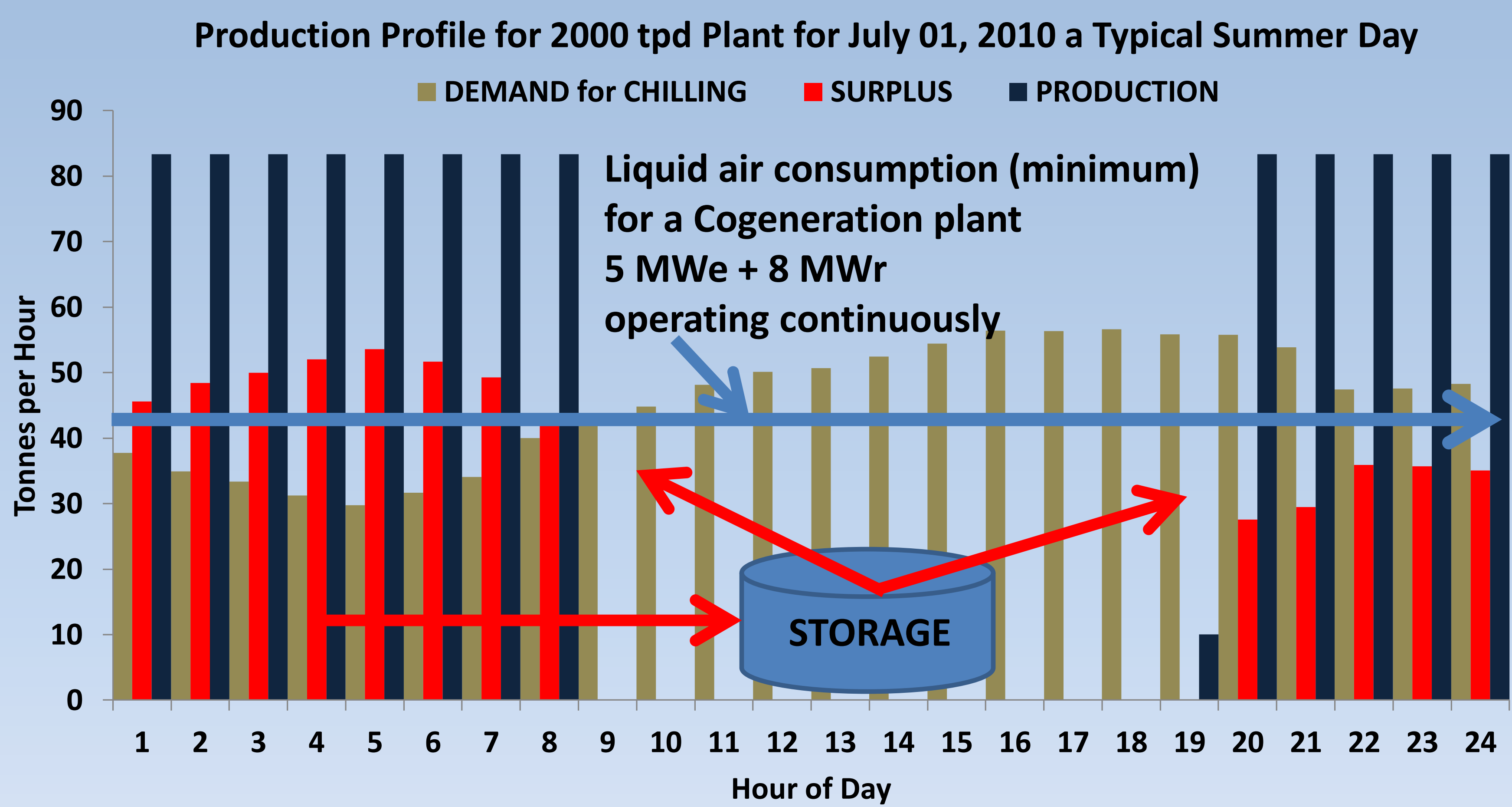
Cogeneration of 5 MWe Electricity/chilling



Cogeneration of 5 MWe Electricity/chilling



Cogeneration of 5 MWe Electricity/chilling



Option 2: Energy Cost Comparison

Cogeneration Electricity/Chilling vs BAC

	Energy Profile (MWH/yr)		Estimated Cost ($ M/yr)	
	CRYO	BAC	CRYO	BAC
Purchased	76193	20000	$6.5	$2.4
Recovered	-43800	0	-$5.3	$0
Supplemental chilling	4300	NONE	$0.48	Not Possible
Fan Energy Savings	-4000	0	-$0.45	No Savings
Total energy	32693	20000	$1.23	$2.4
Maintenance			$0.51**	$0.82
Total OPEX			$1.74	$3.22

It takes approximately 76000 MWH/yr to produce enough cryogen to operate a 5 MWe (24/7).
The 5 MWe cogeneration system produces 43800 MWH/yr.
The cost of the production of LA (during off-peak energy rates) versus that of the energy production (during peak electricity rates), results in an overall savings.

** needed to add $.13M for PRU re: CRYO maintenance option

Option 2: NPV Comparison
Cogeneration Electricity/Chilling vs BAC

$ millions	CRYO 5 MWe (24/7)	BAC
CAPEX	$44.7	$31.4
OPEX/yr	$1.74	$3.22
NPV (10%)	-$59.52	-$58.8

OPEX includes Electricity & maintenance costs

Option 3

5 MWe + 8 MWr Power/electricity Cogeneration

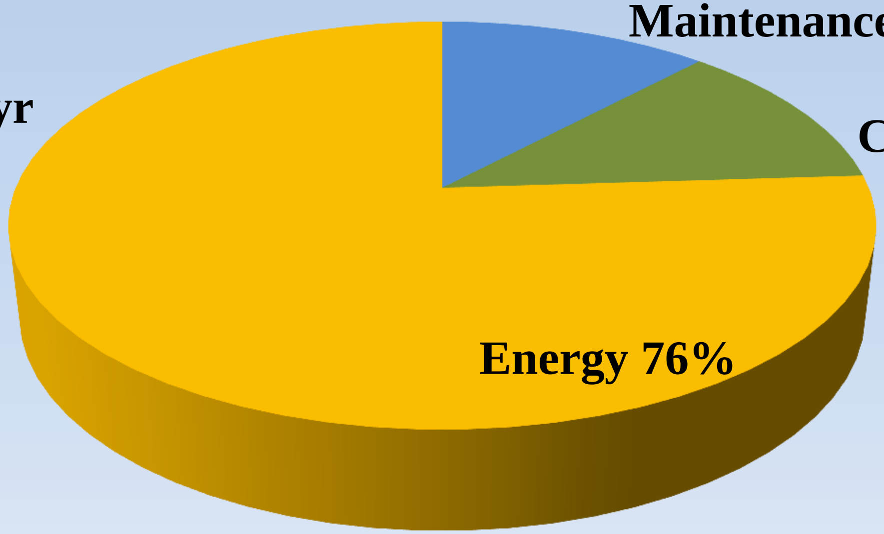
+

Add 5000 cfm (2.4 m^3/s) compressed air to the existing system

Cost Estimate: Typical 5000 cfm (2.4 m^3/s) System

	Cost Item	**$M/yr**	
Opex	Energy cost from industry standard formula	$0.9	**$1 M**
	Energy cost from Atlas Copco Calculator	$1.02	
	Maintenance = 12% of energy cost	$0.12	
	Equipment = 12% of energy cost	$0.12	
Capex	Piping installed <u>*one time cost*</u> (maintenance ?)	$5.00	

Compressed air costs/yr
Over ten year horizon



Option 3: Cost Comparison. Lair vs BAC

Cogeneration + Compressed Air 5000 cfm (2.4 m^3/s)

		Estimated Cost	
		CRYO	BAC
Total OPEX Cogeneration ($M/yr)		$1.74	$3.22
Supplemental chilling reduced		-$0.12	
Additional OPEX	Energy	$0.70	$1.00
	Maintenance	$0.15	$0.24
Total OPEX		**$2.47**	**$4.46**
CAPEX Cogeneration ($M)		$44.7	$31.4
Equipment (compressors etc.)		$0.70	$1.00
Piping + installation		$0.50	$5.00
Total CAPEX		**$45.9**	**37.50**

Option 3: NPV Comparison

Option 2 plus 5000 cfm (2.4 m^3/s) Compressed Air

$ millions	CRYO 5 MWe (24/7)	BAC
CAPEX	$45.9	$37.5
OPEX/yr	$2.47	$4.46
NPV (10%)	-$66.91	-$75.48

OPEX includes Electricity & maintenance costs

Financial Estimates

Vaporiser

($M)	CAPEX	OPEX
BAC	$31.4	$3.22/yr
CRYO	$31.9	$3.48/yr

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Financial Estimates

($M)	Vaporiser CAPEX	Vaporiser OPEX	Cogeneration CAPEX	Cogeneration OPEX
BAC	$31.4	$3.22/yr	$31.4	$3.22/yr
CRYO	$31.9	$3.48/yr	$44.7	$1.74/yr

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Financial Estimates

($M)	Vaporiser CAPEX	Vaporiser OPEX	Cogeneration CAPEX	Cogeneration OPEX	Compressed Air CAPEX	Compressed Air OPEX
BAC	$31.4	$3.22/yr	$31.4	$3.22/yr	$37.5	$4.46/yr
CRYO	$31.9	$3.48/yr	$44.7	$1.74/yr	$45.9	$2.47/yr

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Financial Estimates

($M)	Vaporiser CAPEX	Vaporiser OPEX	Cogeneration CAPEX	Cogeneration OPEX	Compressed Air CAPEX	Compressed Air OPEX
BAC	$31.4	$3.22/yr	$31.4	$3.22/yr	$37.5	$4.37/yr
CRYO	$31.9	$3.48/yr	$44.7	$1.74/yr	$45.9	$2.47/yr

20 year NPV Calculated at a discount rate of 10% ($M)

	Vaporiser	Cogeneration	Compressed Air
BAC	-$58.80	-$58.80	-$75.48
CRYO	-$61.60	-$59.52	-$66.90

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Financial Estimates

($M)	Vaporiser CAPEX	Vaporiser OPEX	Cogeneration CAPEX	Cogeneration OPEX	Compressed Air CAPEX	Compressed Air OPEX
BAC	$31.4	$3.22/yr	$31.4	$3.22/yr	$37.5	$4.37/yr
CRYO	$31.9	$3.48/yr	$44.7	$1.74/yr	$45.9	$2.47/yr
20 year NPV Calculated at a discount rate of 10% ($M)						
BAC	-$58.80		-$58.80		-$75.48	
CRYO	-$61.60		-$59.52		-$66.90	
Percent of Plant Capacity Required for Mine Chilling						
Mine	31%		55%		61%	
Surplus	69%		45%		39%	

Effect of adding heat to airflow and the impact of Chilling on Demand on the 3300 m level for a flow of 50 m^3/s at an initial temperature of 12/12 DB/WB^{o}C

Heat added	kW	Temperature DB/WB^{o}C	WBGT
Base amount	1100	25.9/25.2	25.5
+ 1 LHD	180	28.2/27.4	**27.7**
+ 2 LHD	360	30.5/29.6	**29.8**
+ 3 LHD	540	32.7/31.8	**32.1**

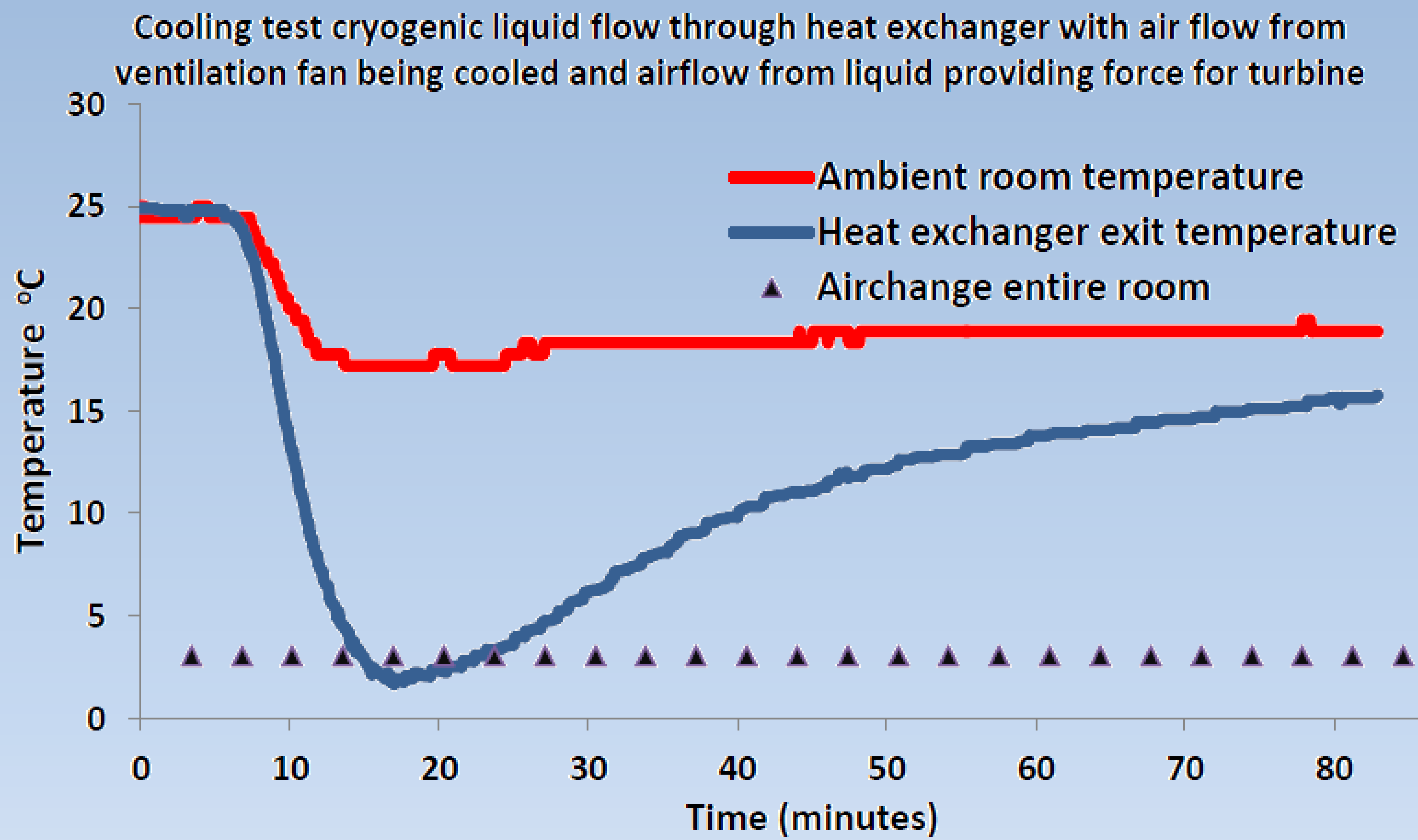
Increasing the cryogenic liquid air flow from 8.1 kg/s to 8.7 kg/s raises the chilling power from 3.73 MW_r to 4.0 MW_r

Total heat	1640	28.7/27.7	28

3300 level: the mass flow is 78.7 kg/s and density is 1.574 kg/m^3.

Mine Cooling Via Cryogenics

Prototype Testing Results



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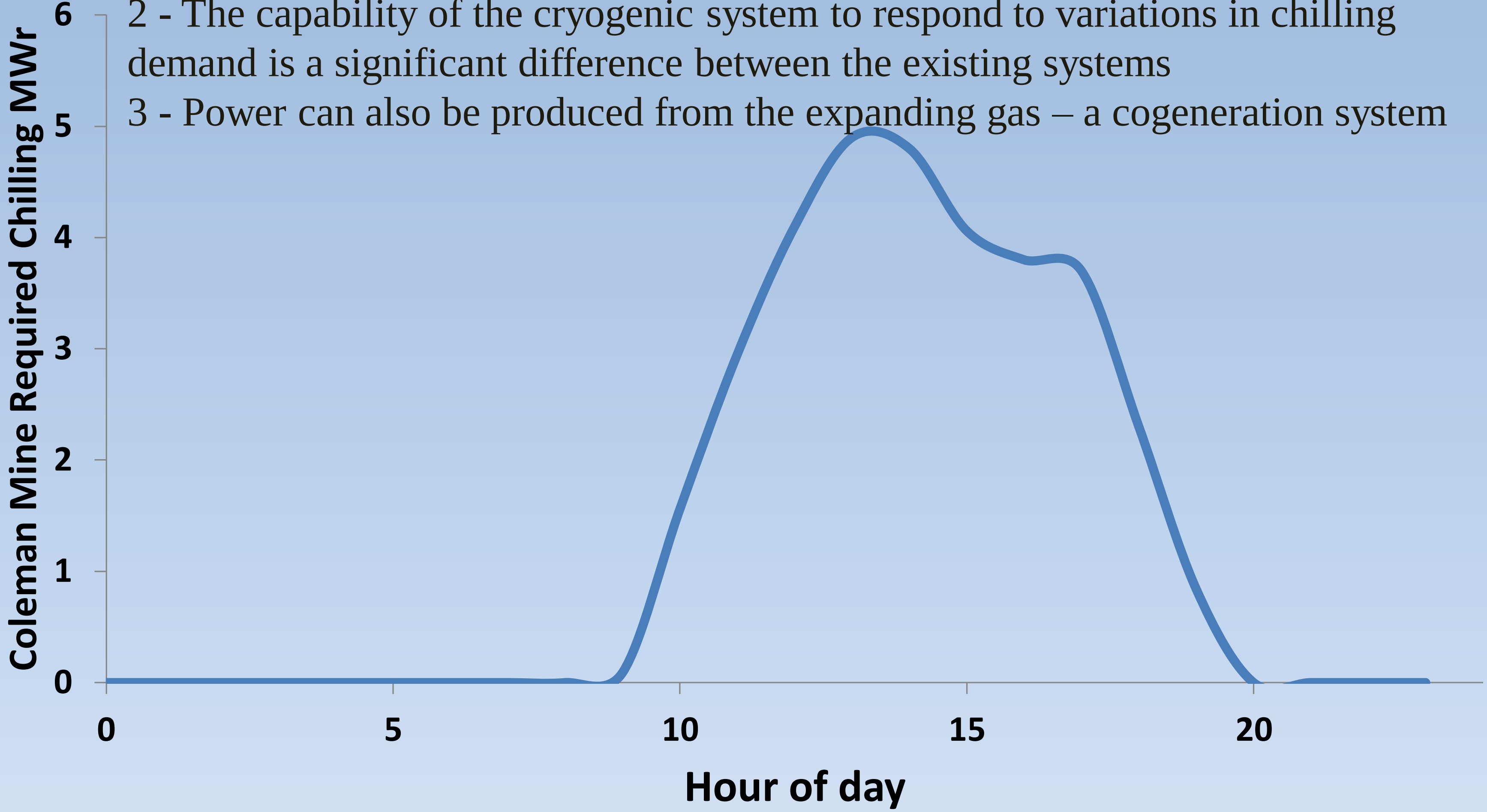
Mine Cooling Proposal for Coleman

1 - The average chilling demand over this day is 3 about MWr

2 - The capability of the cryogenic system to respond to variations in chilling demand is a significant difference between the existing systems

3 - Power can also be produced from the expanding gas – a cogeneration system



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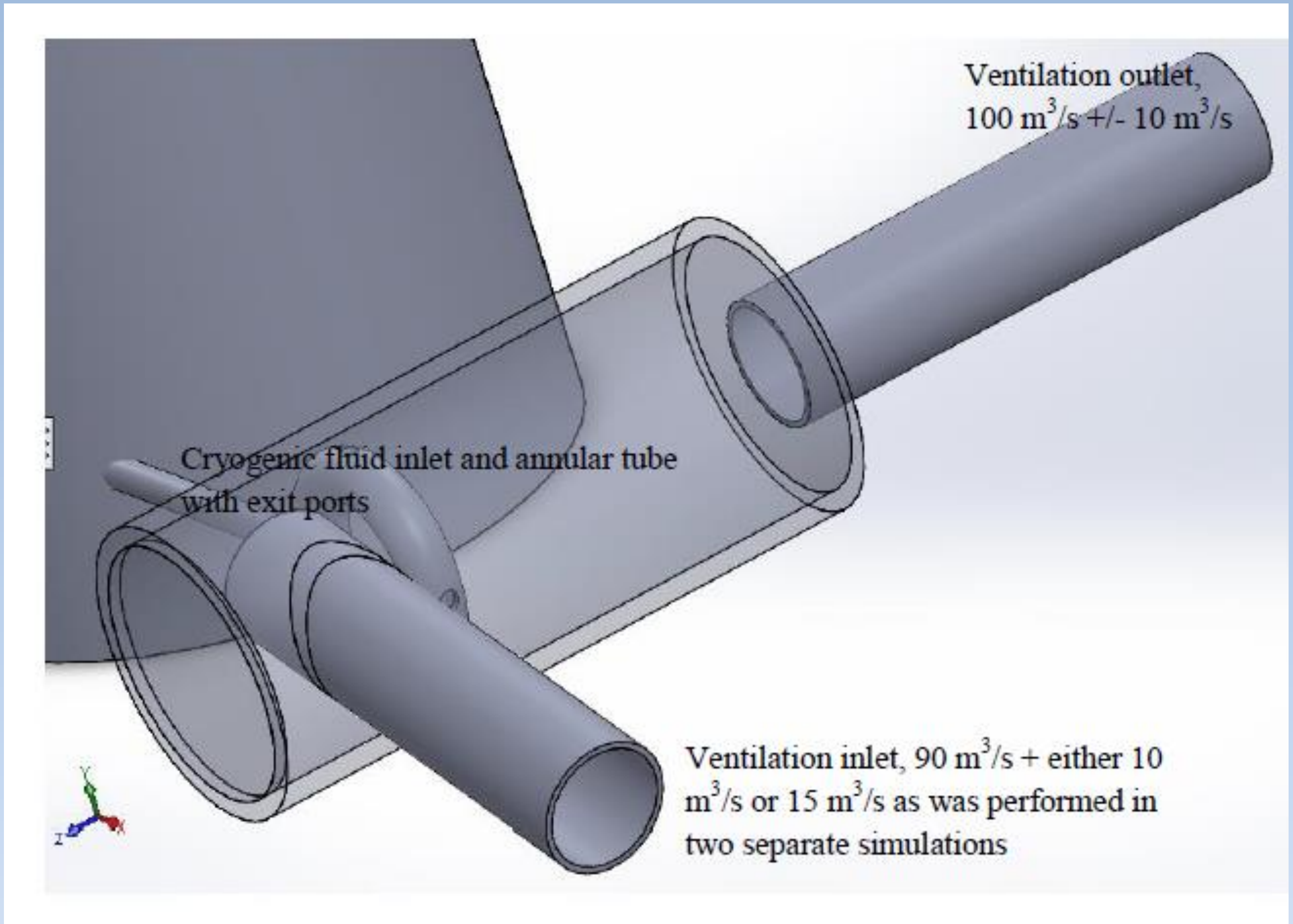
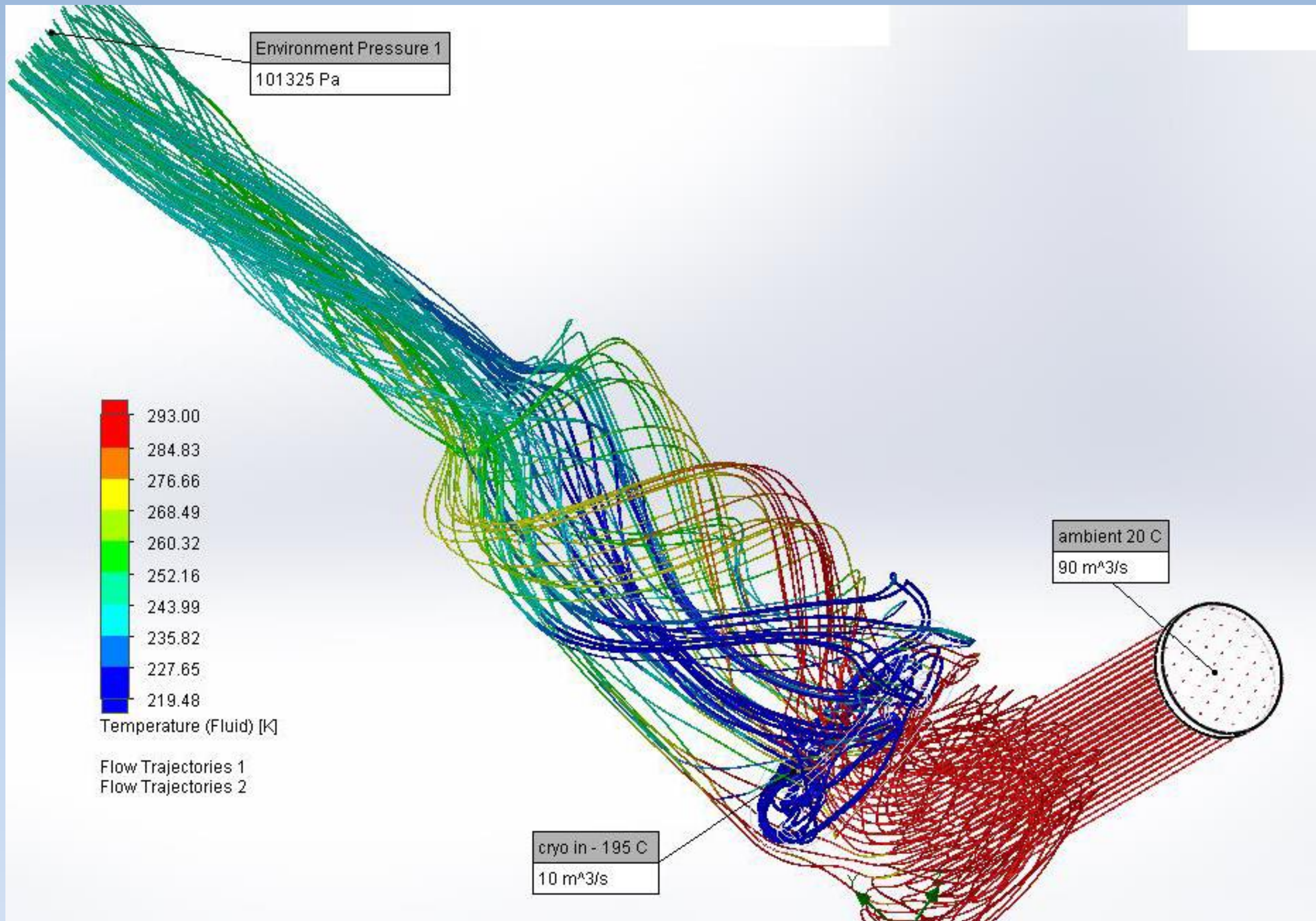
Conceptual Design for Coleman



Details of the mixing chamber where the ultra cold cryogenic liquid expands and mixes with ambient air to cool the mine

CFD Modelling for Coleman Design

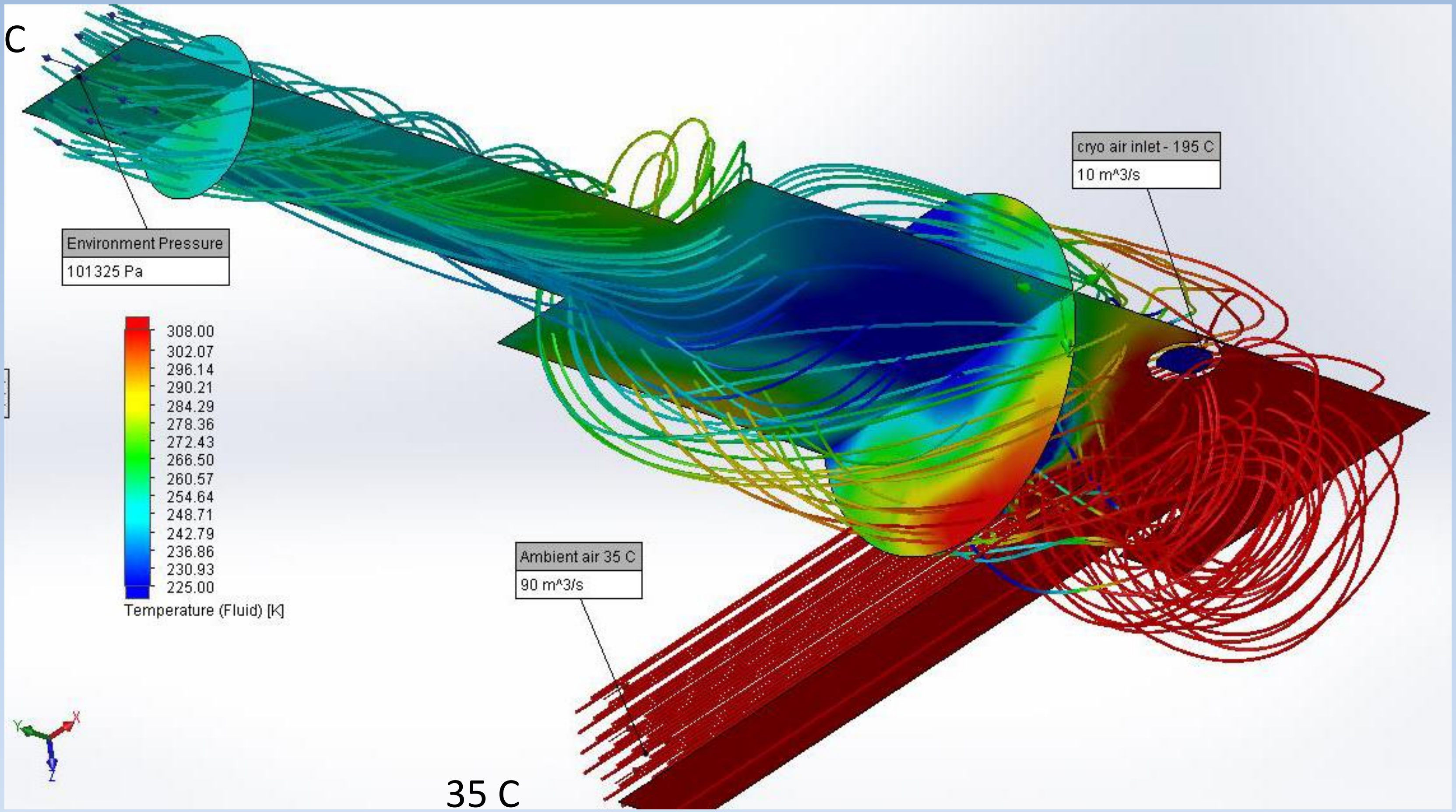
≈ -35 C



Flow trajectories of a simulation for incoming air temperature of 20 C at 90 m3/s and 10 m3/s of air created from the expansion of the cryogenic liquid to illustrate the mixing.

CFD Modelling for Coleman Design

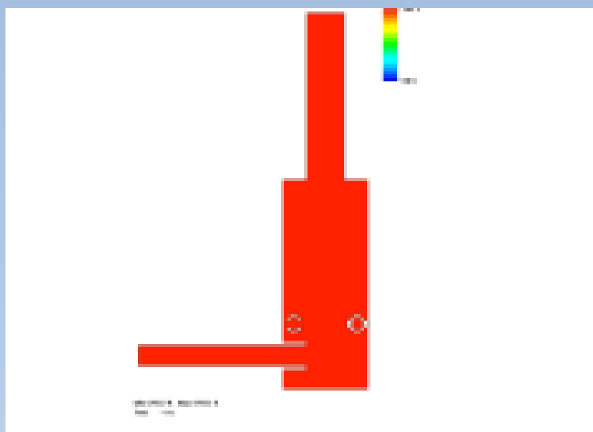
- 35 C



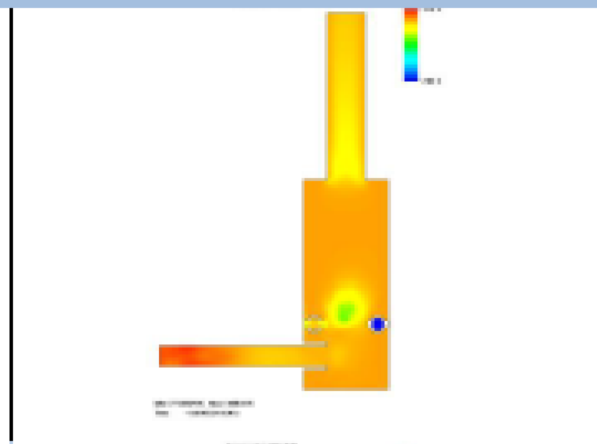
35 C

CFD of Flow vs Time 0 s to 10 s

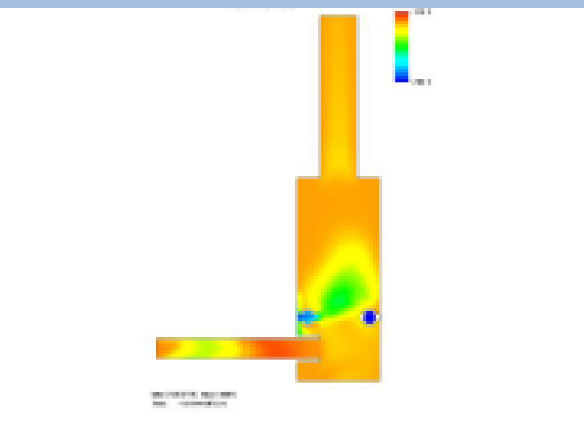
cryogenic flow initiation 0 s

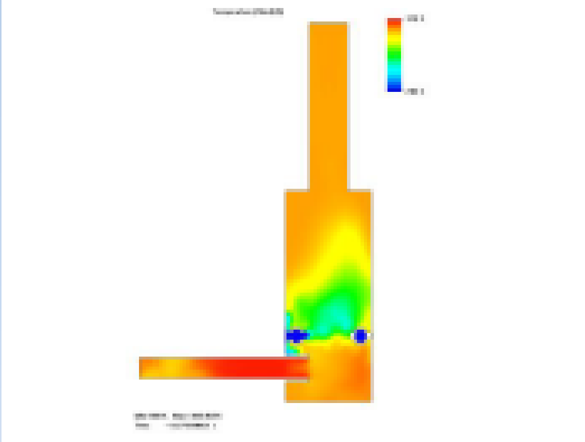


0.095 s from start of flow

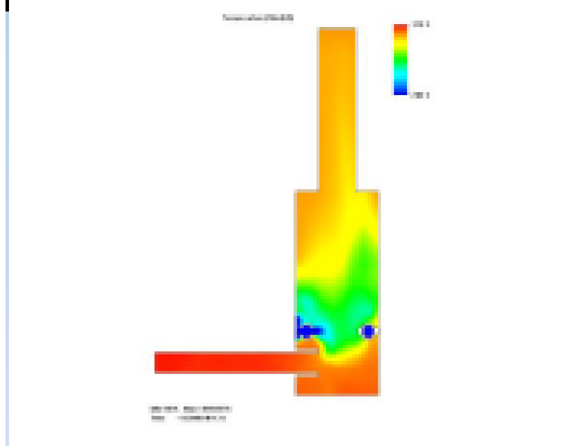


0.18 s from start of flow

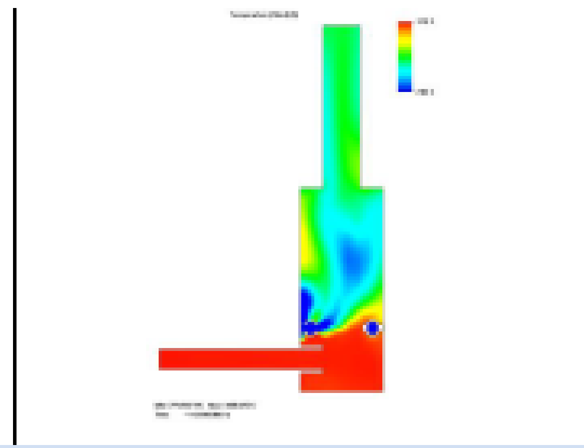




0.27 s from start of flow



0.4 s from start of flow



10.7 s from start of flow

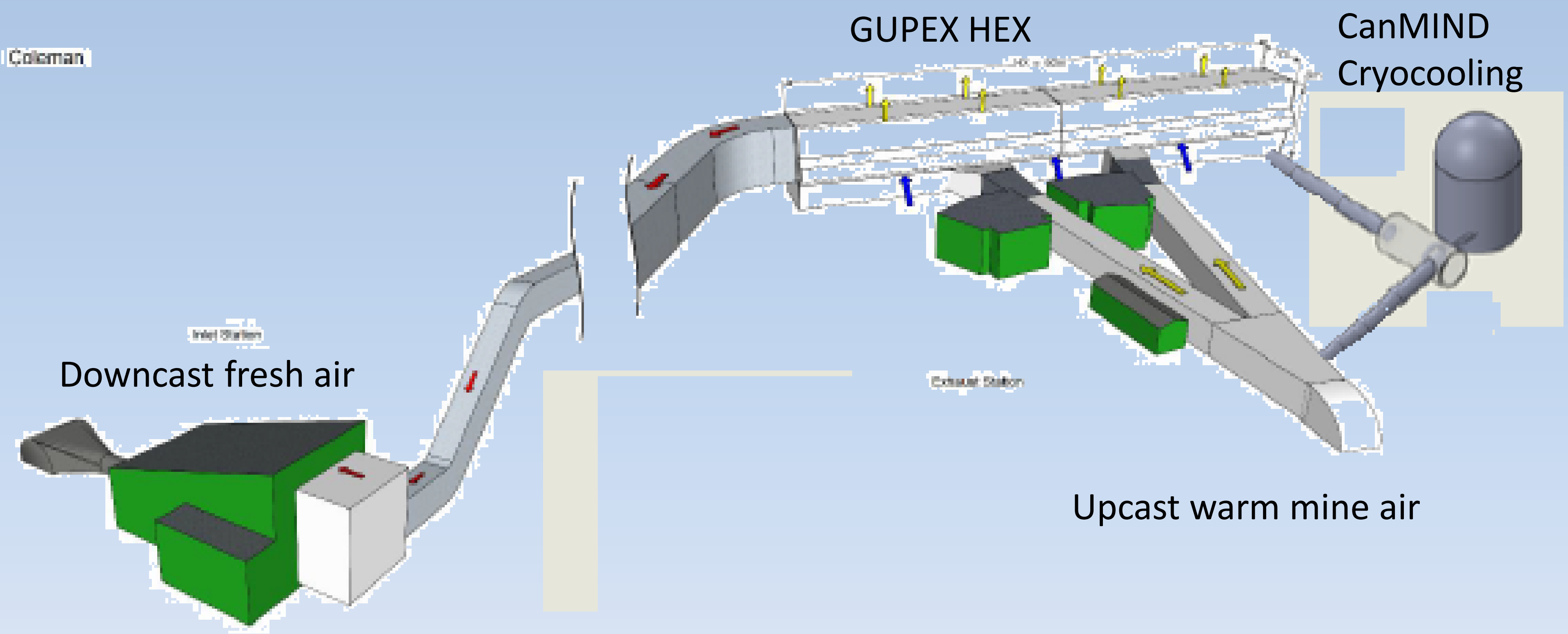
Easy assembly

Prefabricated components “building block system”

Inspection doors

Boliden

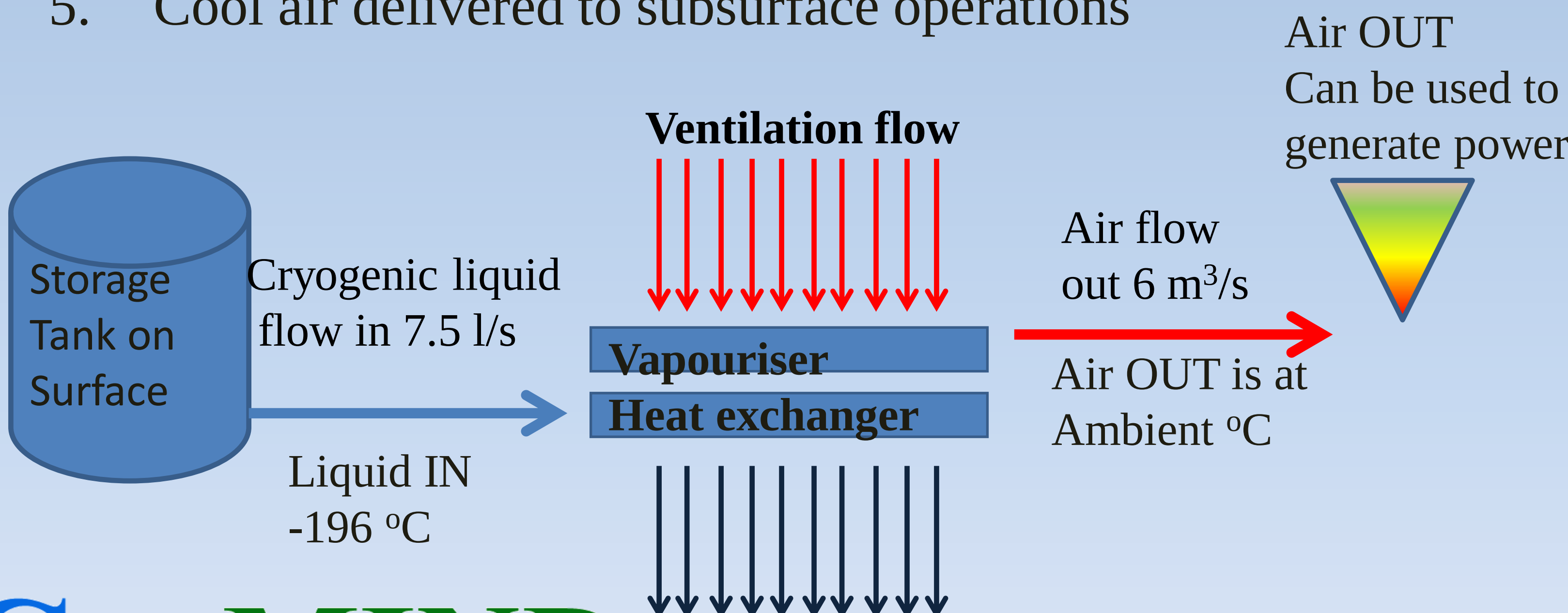
Conceptual Integration of Cryogenic Chilling with Gupex Heat Capture System



Mine Cooling Solution for Coleman

Simple Base Case Demonstration for Client Mine

1. Install a small liquid air plant
2. Liquid -196 °C enters vapouriser/heat exchanger
3. Air at ambient temperature exits vapouriser/heat exchanger
4. Heat is absorbed from airflow over vapouriser/heat exchanger
5. Cool air delivered to subsurface operations



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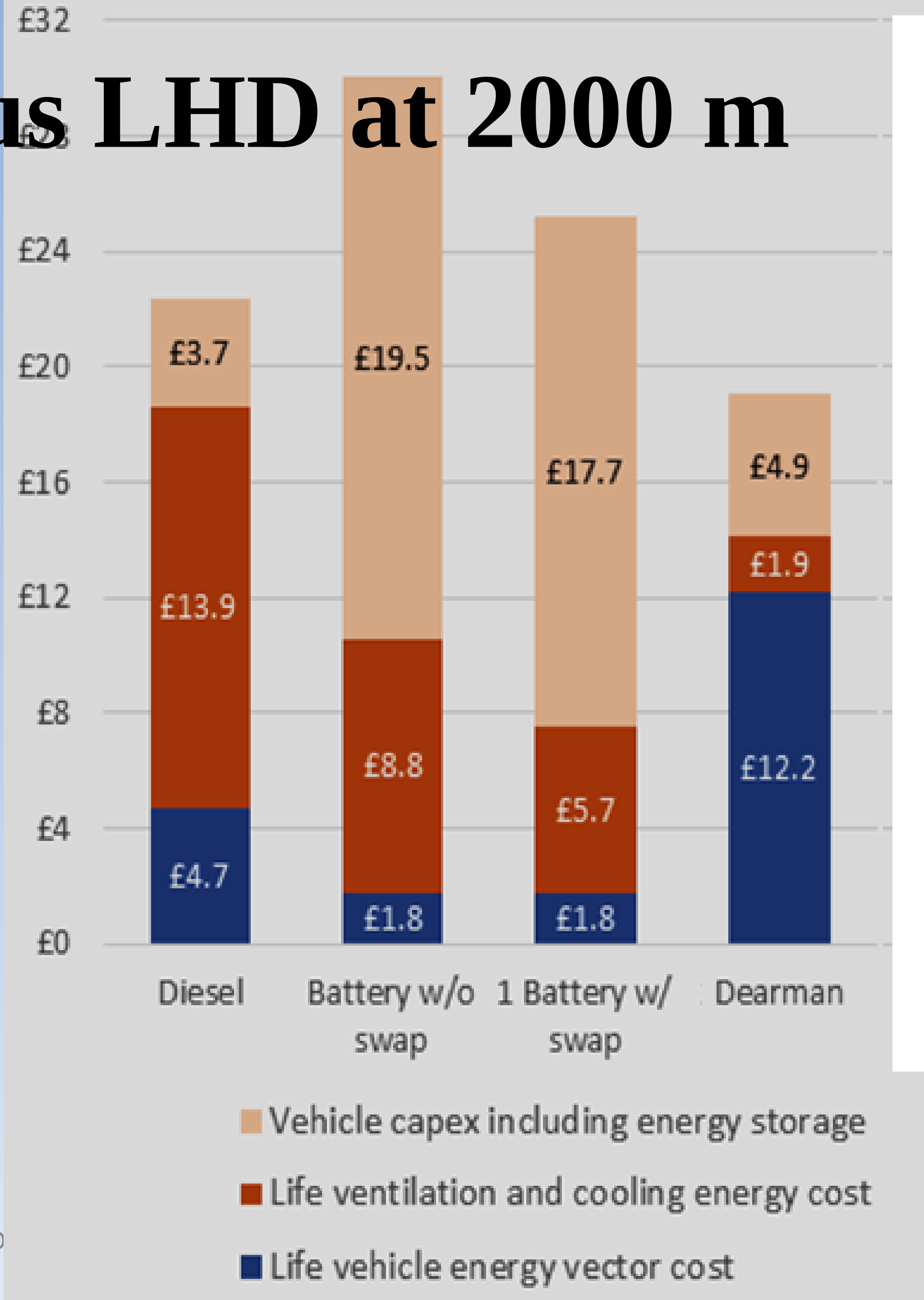
Dearman Engine CanMIND Study

- Engine uses liquid air instead of Diesel
- Larger fuel storage tank
- 1/3 power --- 2/3 cooling
  - 500 kW engine provides 1 MWr (670 hp)
- Liquid fuel
- Cold pure air as exhaust
- Competitive with Diesel and Battery TCO

TCO for Various LHD at 2000 m

Study does not include load shifting for production, economies of scale or chilling created by the vehicle



Advantages of Liquid Air Systems

Applied to mining, cryogenic technology offers

- Reduced ventilation requirements
- Underground cooling on demand
- Reduced power requirements for ventilation and cooling
- Underground compressed air
- Energy storage and load shifting
- Non-diesel underground motor power providing breathable air
- Exploitation of free geothermal power
- Commercialization of a suite of marketable technologies enabling mines to use cryogenics
- Green house gas emission reductions
- A model for remote projects/communities to have reliable renewable power and water supply

Thank You

Dr. Daniel L. Cluff

CanMIND Associates