Implications of Liquid Air as an Energy Storage Vector in Deep Mining

By

Dr. Daniel L Cluff
P.Phys. P.Eng. C.Eng.
B.A. Hon. B.Sc. M.Sc. M.Eng. PhD

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Genesis of idea

2008 MIRARCO

Thermodynamic modelling - Creighton Ice Chilling Concept

Could Deep mine Ventilation be supplied by Liquid Air?

Ruled out as too costly and too cold

2011 Highview Power Storage 350kW pilot project

Liquid Air for grid balancing – game changer for mining?

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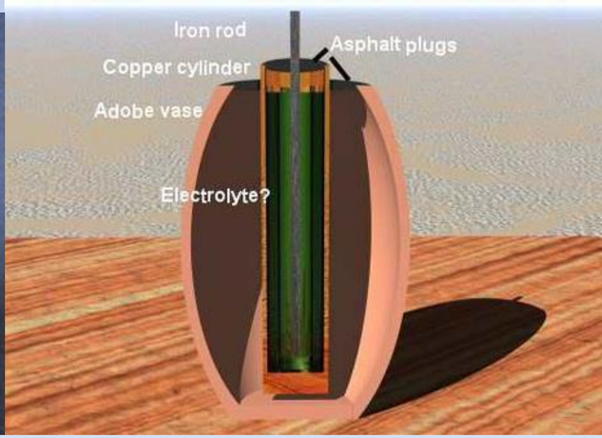
We have had the idea that energy storage is a valuable concept since the beginnings of understanding of electricity or perhaps even prior

Allesandro Volta

The original voltaic pile consisted of a pile of zinc and silver discs and between alternating discs, a piece of cardboard that had been soaked in saltwater.

The Baghdad Battery, a device unearthed in Khujut Rabu, near Baghdad, in 1936. A small clay jar with an iron rod suspended inside of a copper cylinder.



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Energy Storage Vector

An energy vector

- typically considered to be a means of transferring energy through space - electricity
- To include the transfer of energy through time as well requires storage – many

Yes we do need an energy storage vector

- Changes in the energy system brought on by decarbonisation
- Reduction in the use of coal, oil and gas that are easy to store and transport
- Shifting to renewable generation such as wind and solar
- Wind and solar produce energy rather than controllable power
- The key to a smart grid system is storage
- Improves the potential of developing a distributed energy system

Security of energy supply

- Energy storage provides the most flexible means of grid balancing
- Energy storage via LA coupled with gas turbine cogeneration plants increases efficiency
- Gas turbines operating on natural gas are reliable
- Cost effective compared to diesel especially when the cogeneration aspect is involved
- Natural gas is usually available during a power outage

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Energy storage vs. other grid balancing methods

Flexible Generation
- Peaking capacity for low wind periods
- Flexibility for short term variability
- Increased flexibility of generation for renewables

Increased Interconnection
- Connection to neighbouring markets (industries or countries)
- Full use of network to reduce wind curtailment
- Transmission reinforcement (link wind availability to demand)

Demand Side Responsiveness
- Incentives for peak demand reduction or lull usage
- Peak price increases to improve peak avoidance
- Heat electrification with potential for flexibility
- Flexibility in charging patterns for Electric vehicles
- Demand Reduction for balancing services

Electricity Storage
- Energy export for low wind/solar periods
- Energy import during high wind/solar periods
- Storage at point of generation reduce line losses
- Full use of network to reduce wind curtailment
- Storage of electrified heat
- Storage linked to Electric vehicles
- Provision of national or local for balancing services

On the 2003 grid failure

"A cascade of disaster due to a mix of human error and equipment failure, until by 4:10 p.m. that day more than 50 million people had lost power in parts of Ontario and eight U.S. states"

"The best bet would be a more distributed grid, with more local generation chiefly via solar and wind with local storage"

Energy storage is the most flexible form of grid balancing

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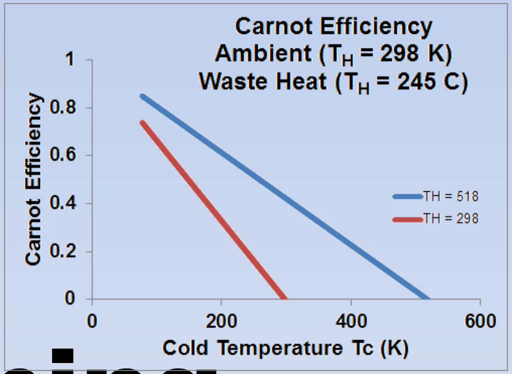
Storing Energy Providing Power

- **From wind**
- **Solar**
- **Arbitrage**

- Out of synchronization with demand
- Intermittent energy production
- Meet peak demand
- Off set global adjustment costs

Waste Heat increases the conversion efficiency

Large temperature difference between Liquid Air and ambient air
Is sufficient to provide efficient conversion to electricity



$$\eta = \frac{Q}{Q_H} = 1 - \frac{T_c}{T_H} = 1 - \frac{78}{300}$$

Other uses in mining

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Renewable Energy Actually Installed at Mines

Raglan

- Harper Announces $720,000 to TUGLIQ Energy Co. and Xstrata Nickel Inc.
    - Cut out 2.5 million l of diesel per year or 5% of the diesel volume
    - With plans to reach 50% of the mines power demand by incorporating LNG
    - Reduce greenhouse gas emissions
    - Obtain energy at a lower cost
- Quebec investes another $6.5-million to help Glencore install wind farm
- Glencore will test a 3-prong storage system
    - electrolyser stacks to generate hydrogen with flywheels and fuel cells
    - The hydrogen will be compressed and stored, available as long as 20 hours later.

Diavik

- Wind farm began delivering power to the mine's grid on 28 September 2012.
- Cut out 3.8 million l diesel in 2013
- provided 8.5 per cent of the mine's power needs
- Reduced Diavik's seasonal winter road fuel haul by approximately 100 loads
- No energy storage system

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Energy storage systems

- **Batteries solid state or flow**
- **Hydro-electric power – dams**
- **Pumped water reservoirs**
- **Compressed Air**
- **Thermal**
- **Hydrogen**
- **Liquid Air**

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Solid State Batteries

Lithium ion

- **1991** Sony and Asahi Kasei
- From a few kilowatt-hours in residential systems with rooftop photovoltaic arrays to multi-megawatt containerized batteries for the provision of grid ancillary services.

Nickel Cadmium

- Commercial production since the 1910’s
- **2003**: Golden Valley Electric Association BESS, capable of 27 MW for 15 minutes
- 2010: 3 MW system on the island of Bonaire

Sodium sulphur

- Ford Motor Company in the **1960’s**
- Uses Molten sulphur 300 ºC to 350 ºC
- Demonstrated at over 190 sites in Japan
- 270 MW of stored energy suitable for **6 hours of daily peak shaving**
- The largest is a 34-MW, 245-MWh unit for wind stabilization in Northern Japan

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Flow Batteries

Redox Flow Batteries

Separation of power and energy, which is stored in the volume of electrolyte

A few KWH to 10’s of MWH depending on the **size of the storage tanks**.

A few % of the total amount of **electrolyte flows between the plates** during discharge

Discharge at rated power for 2 hrs. to 8 hrs.

Iron- Chromium (ICB) Flow Batteries

NASA, 1970 - 1980 and by Mitsui in Japan.

Telecom back-up at the 5 kW for about 3 hrs.

Vanadium Redox (VRB) Flow Batteries

University of New South Wales,1980, commercially operating for about 8 years.

Suitable for 100 kW to 10 MW systems with storage durations in the 2-8 hour range

Zinc-Bromine (ZNBR) Flow Batteries

Exxon as a hybrid flow battery system in the early 1970s.

Now being tested by utilities, mostly in Australia.

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Compressed Air Energy Storage Methods

Compressed Air Energy Storage (CAES)

Compressed from atmospheric pressure to a storage pressure of about **70 bar**

A realistic alternative to pumped-hydro power plants

The capex and opex for the already operating diabatic plants are competitive

Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)

Not possible to store the CA at **the very high temperatures** reached during compression

Traditional CAES dumps the heat requiring and injection of heat prior to re-expansion

AA-CAES aims to store it separately, then re-inject the heat at the expansion stage

Isothermal CAES

Without intercooling the air heats **up to 900K**, difficult or expensive to process and store

Isothermal CAES is technologically challenging since it requires heat to be removed continuously from the air during the compression cycle and added continuously during expansion to maintain an isothermal process.

Project to recondition a mine shaft for CAES was part of the LOWCARB project, UK

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Heat Hydrogen and Kinetic

Pumped Heat

Pumped Heat Electrical Storage uses electricity to drive a storage engine connected to two large thermal stores.

The engine takes heat from the hot store, delivers waste heat to the cold store, and produces mechanical work.

When recovering electricity the heat engine drives a generator.

Hydrogen

Electricity creates hydrogen by electrolysis, Proton Exchange Membranes more flexible

The hydrogen can be then stored and used to supplement fuels, re-electrified

Efficiency today is as low as 30 to 40%, but high energy density (120 MJ/kg)

There are two full size hydrogen caverns in operation

Flywheels

Kinetic energy of a mass spinning in a nearly frictionless enclosure

Short-term backup power soothes fluctuations or losses

The rotational inertia of the rotor is converted to electricity

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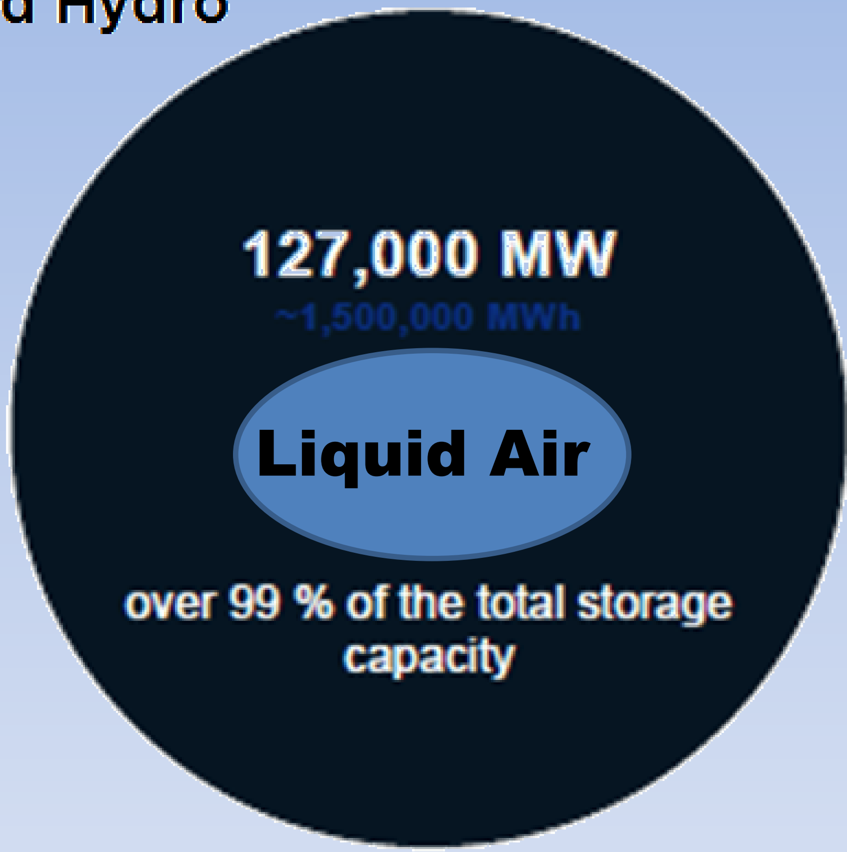
Installed capacity of Electrical Energy Storage systems used in electricity grids

Pumped Hydro



- Compressed Air Energy Storage
  440 MW 3,370 MWH
- Sodium Sulphur Battery
  316 MW 1,900 MWH
- Lithium Ion Battery
  70 MW 17 MWH
- Lead Acid Battery
  35 MW 70 MWH
- Nickel Cadmium Battery
  27 MW 6.75 MWH
- Flywheels
  25 MW 0.4 MWH
- Redox Flow Battery
  3 MW 12 MWH

International Electro-technical Commission 2011

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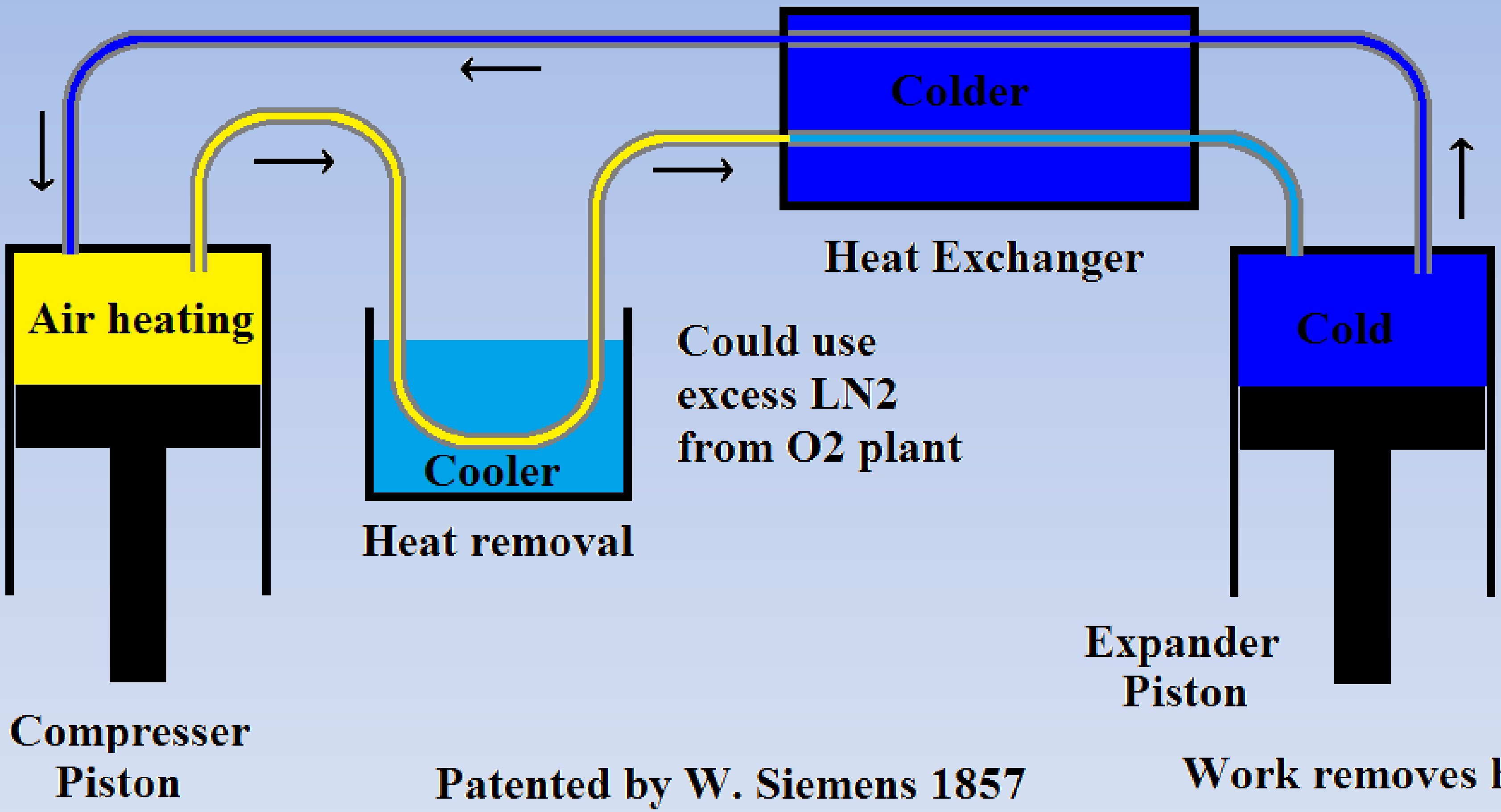
Liquid Air Production
is based on mature technology



Patented by W. Siemens 1857

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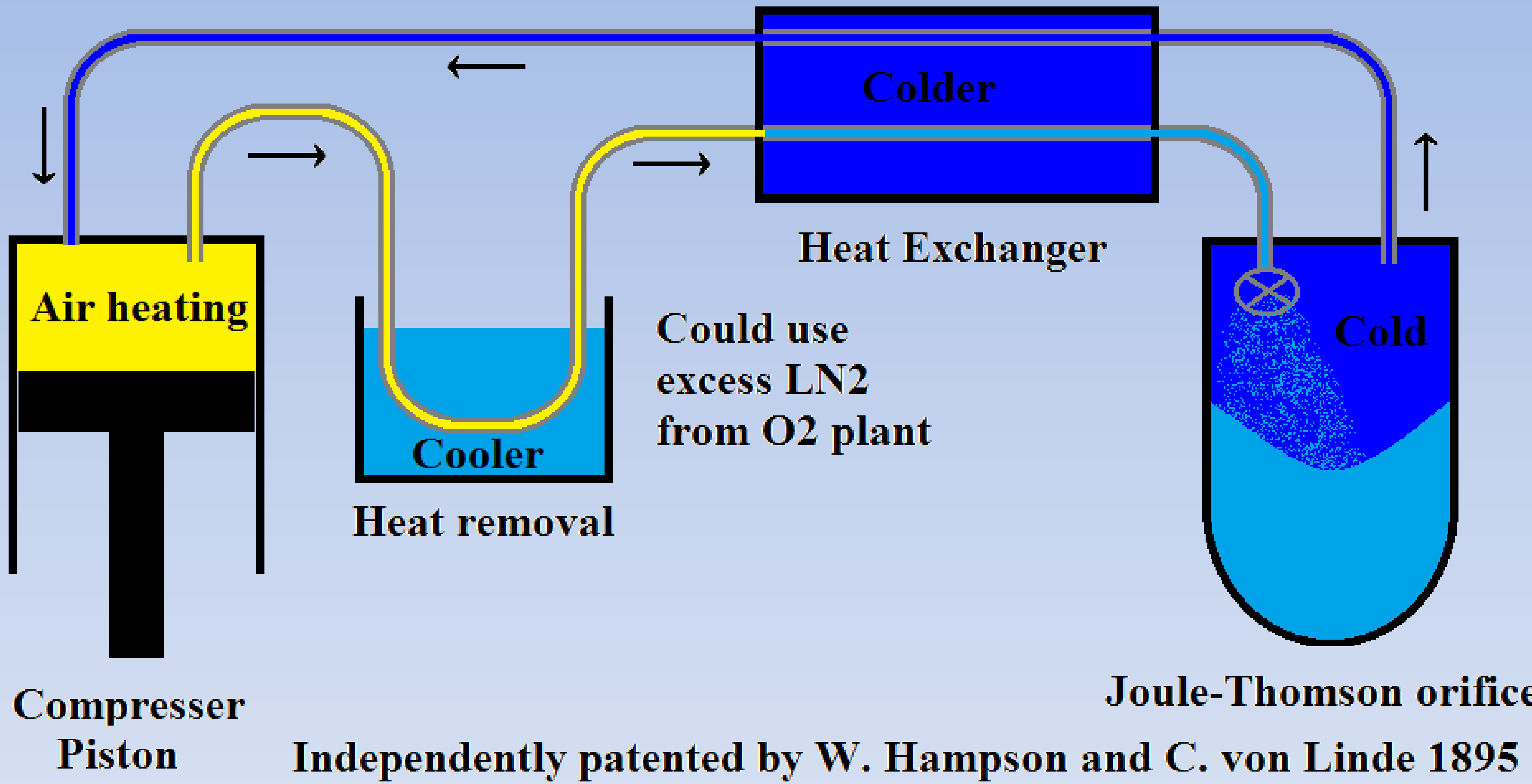
Liquid Air Production is based on mature technology



Independently patented by W. Hampson and C. von Linde 1895

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Production

of

Electricity

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Expected performance of a Cryogenset

Criteria	Performance	Comparison with incumbent technologies
Plant size (Net Power)	3-20 MW	Good – diesel generators typically a few MW's, Open Cycle Gas Turbines typically up to 50MW
Specific liquid air consumption	0.13 kWH/kg	4-5 kWH/kg diesel fuel. Liquid air has a lower energy density than fossil fuels
Start time to full generation (minutes)	< 10 minutes (prechilled cryo pumps)	Good – similar to diesel and gas turbines and in line with expected requirements for a reserve service
Expected mature capital cost at 10 -20 MW	£500 to £750/kW	Good – similar to typical Open Cycle Gas Turbine £600/kW or £450 to £750/kW for diesel generator
Expected availability	96%	Good – typical for the power industry
Expected reliability	99%	Good – typical for the power industry
Expected minimum life	➢ 30 years	Good – typical for the power industry
Site flexibility	Flexible	Good – important for the device to be installed at the optimal place in the network

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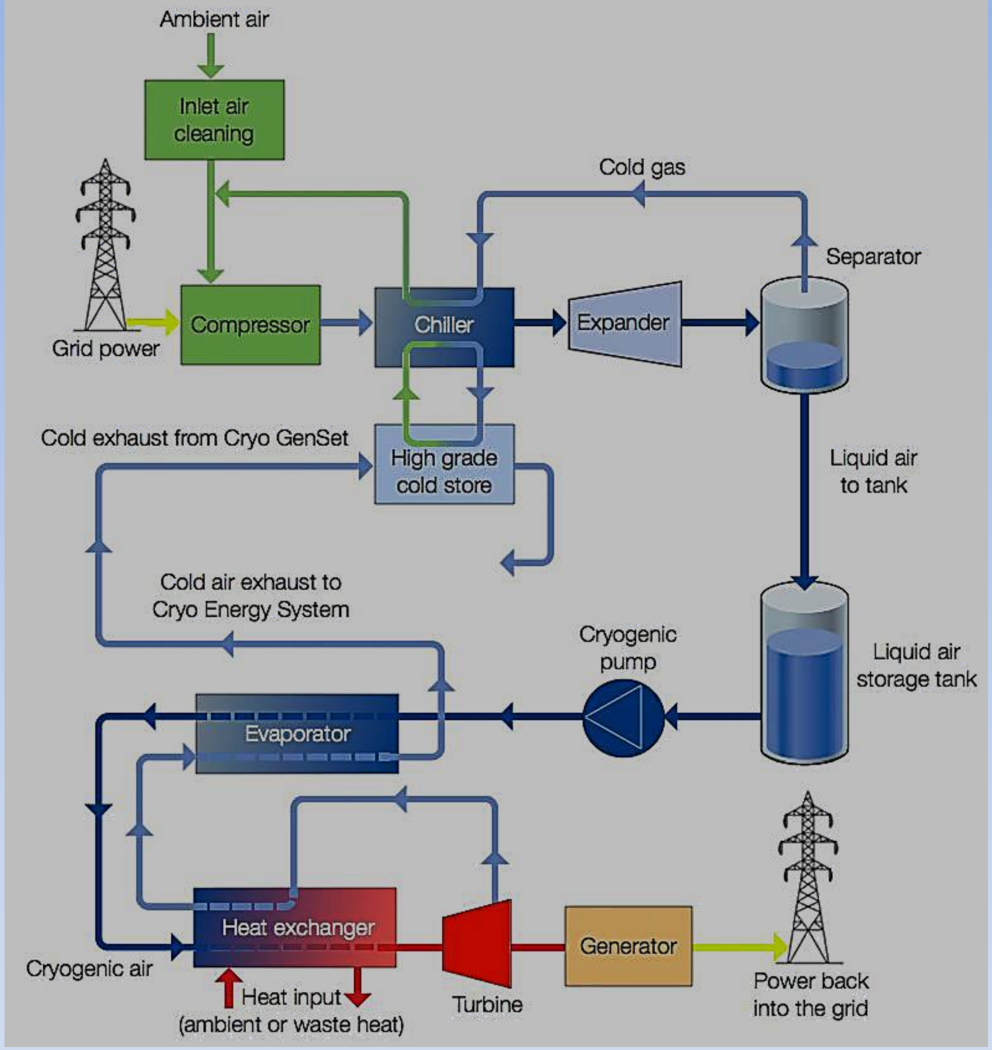
Highview Power



[Highview Plant at Slough UK]
Video excerpt

Schematic of a Liquid Air Energy Storage system. Courtesy of Highview Power Storage

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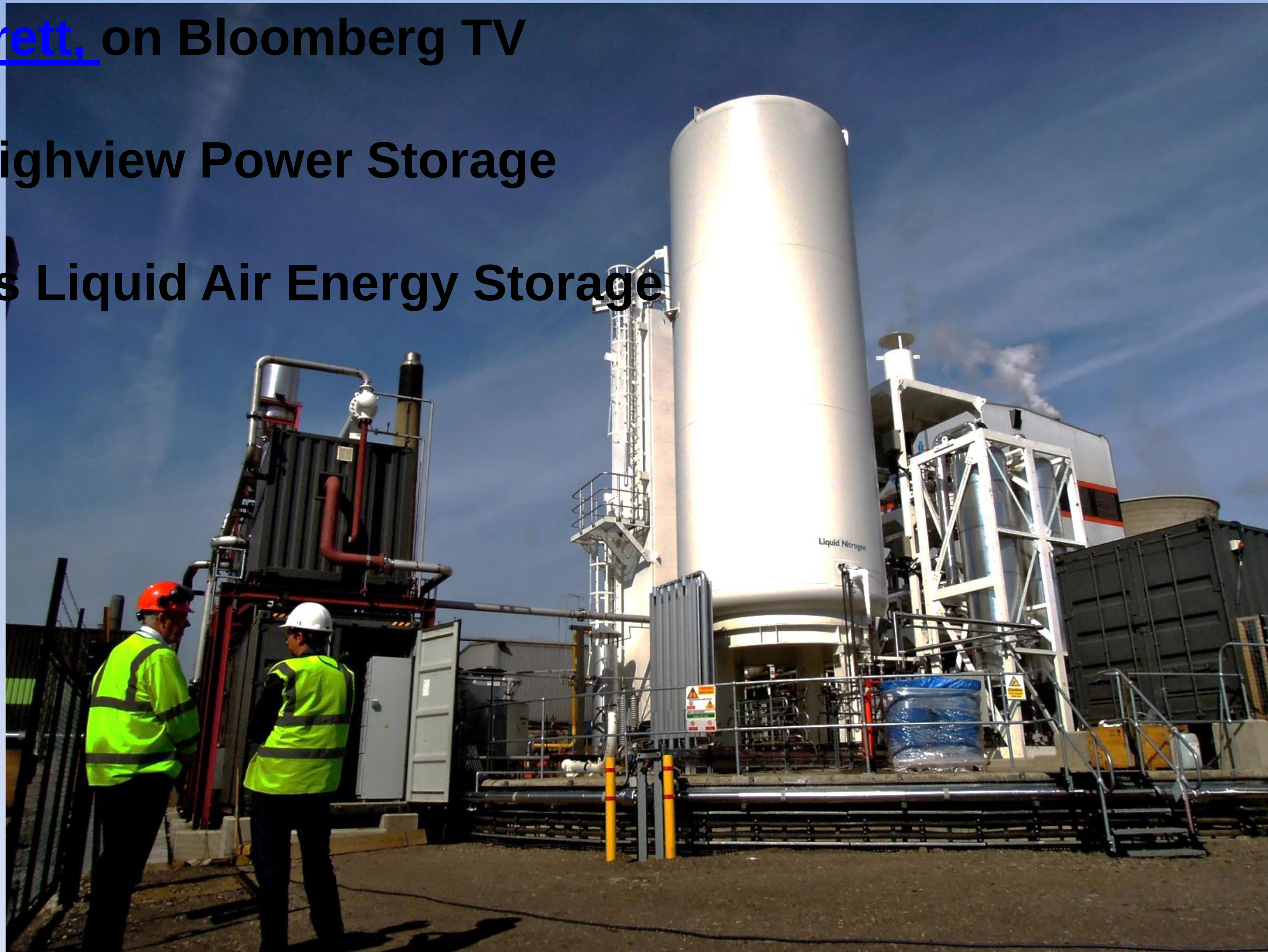
Gareth Brett, on Bloomberg TV

CEO of Highview Power Storage

discusses Liquid Air Energy Storage



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Liquid Air Energy Storage pilot demonstration at Slough, United Kingdom
Courtesy of Highview Power Storage

The point is that installation of a

Liquid Air Energy Storage System

Will provide a source of Liquid Air at the site

The Liquid Air has other uses

that may be a game changer for

Deep Mining

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Auto-compression

Heat

Dissipation

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Calculating the heat balance

Liquid Air Mass Required $m_{(LA)}$ At 2000 m

Latent Heat of vaporisation of LA $L_f = 205$ kJ/kg

Auto-compression $T_{ac} = 0.981(2000/100) = 19.62$ ºC

Surface temperature $T_s = 29$ C

Target underground temperature Tt = 28 ºC

$\Delta T_A = T_s + T_{ac} - T_t = 29 + 19.62 - 28 = 20.62$ ºC

$\Delta T_L = T_s - T_c = (273.15 + 29) - 78 = 224.15$ K

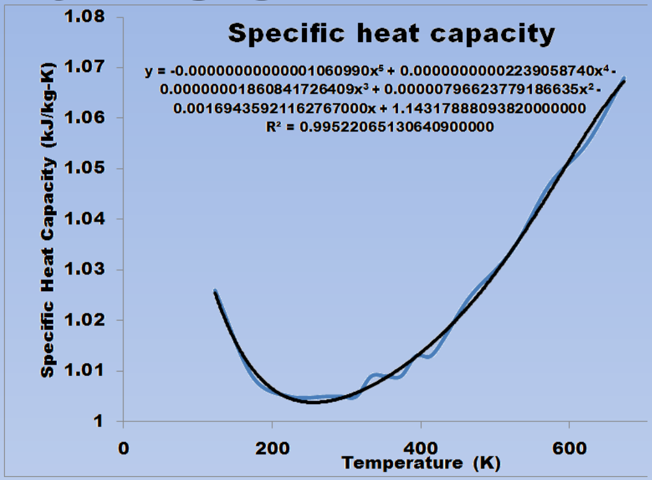
$\Delta Q_{(Air)} = m_a Cp\, \Delta T_A$

$\Delta Q_{(Liquid\ Air)} = m_{LA} L_f + m_{LA} Cp \Delta T_L$

$m_{LA} = m_a Cp\, \Delta T_A / (L_f + Cp \Delta T_L)$

$Vol_{int} = 171$ l **Change of state** (1 litre Liquid to 171 litres gas)

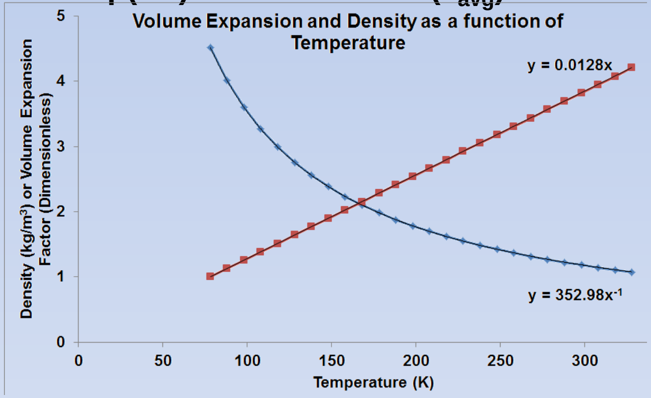
$Vol_{final} = 4.2 \times Vol_{int}$ **Temperature expansion from 78 K**



Specific Heat Capacity used

Cp(AIR) = 1.005 kJ/kg-K

Cp(LA) = Formula(T_{avg})



$4.2 \times 171 = 718.12\ (l_{air}/l_{liq})$ (slight temperature dependence)

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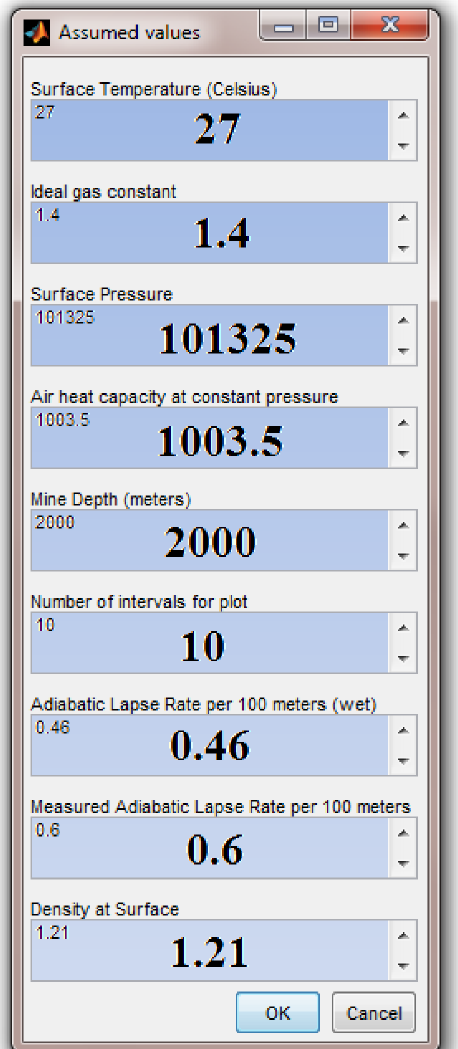

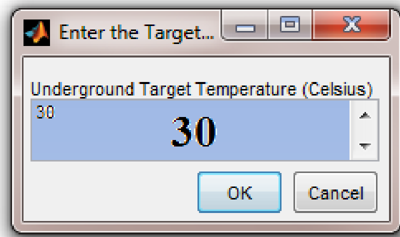

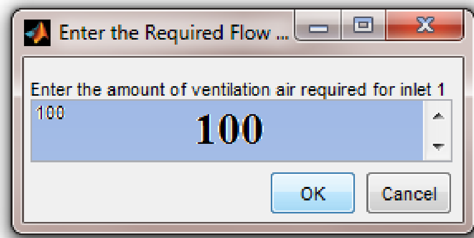

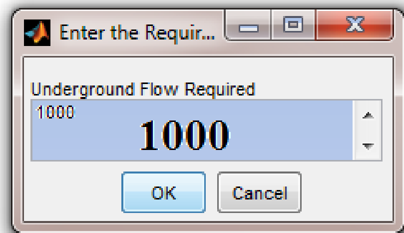

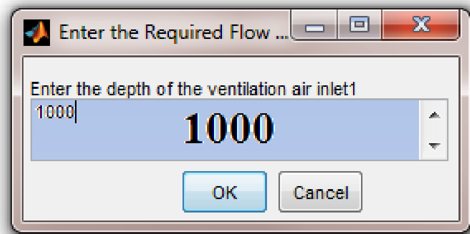

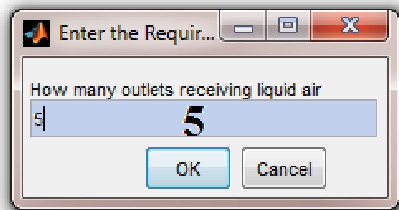

Input Screens For Auto – compression program

These inputs can be derived from sensors
So the program can adjust flows

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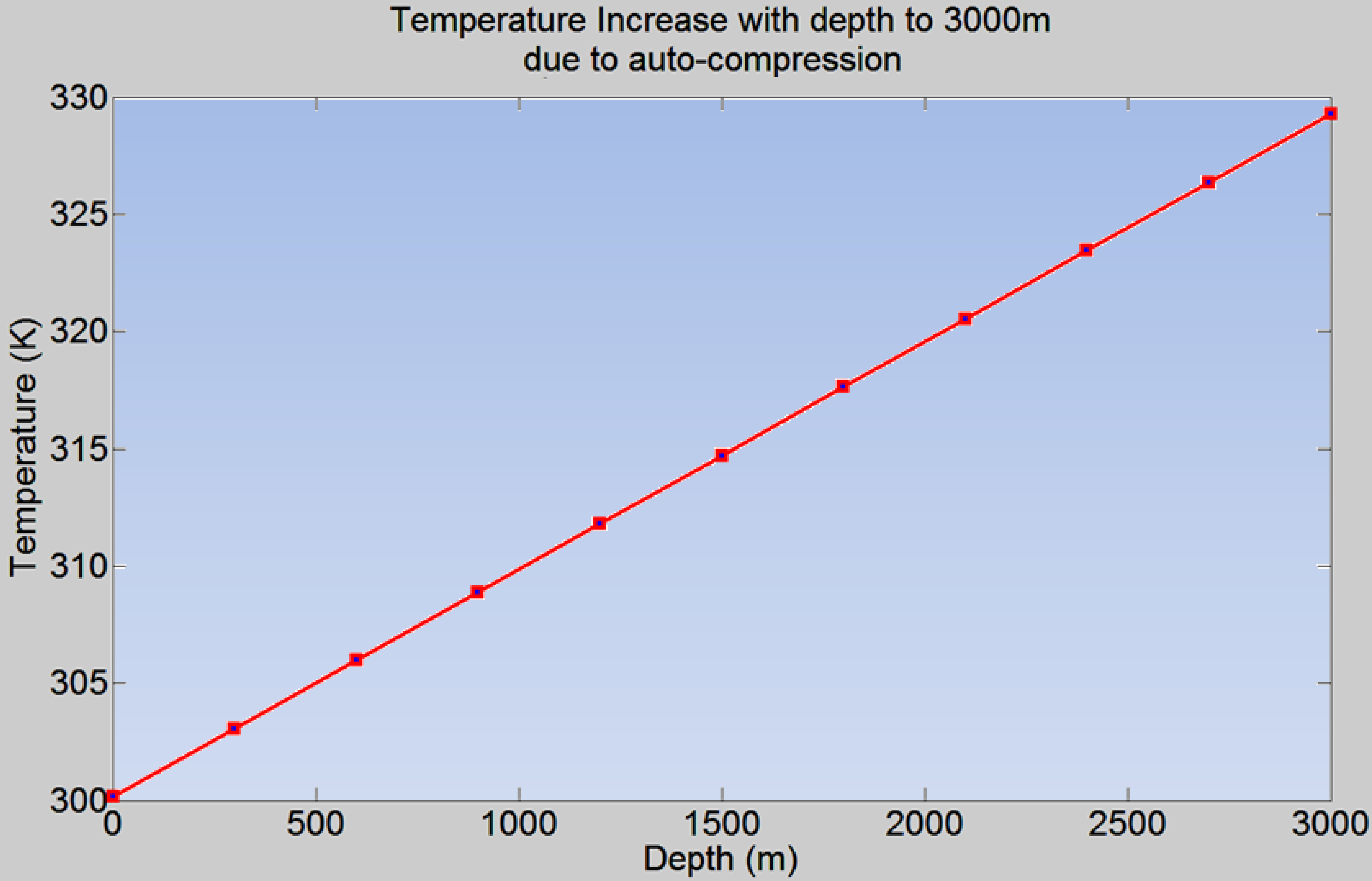
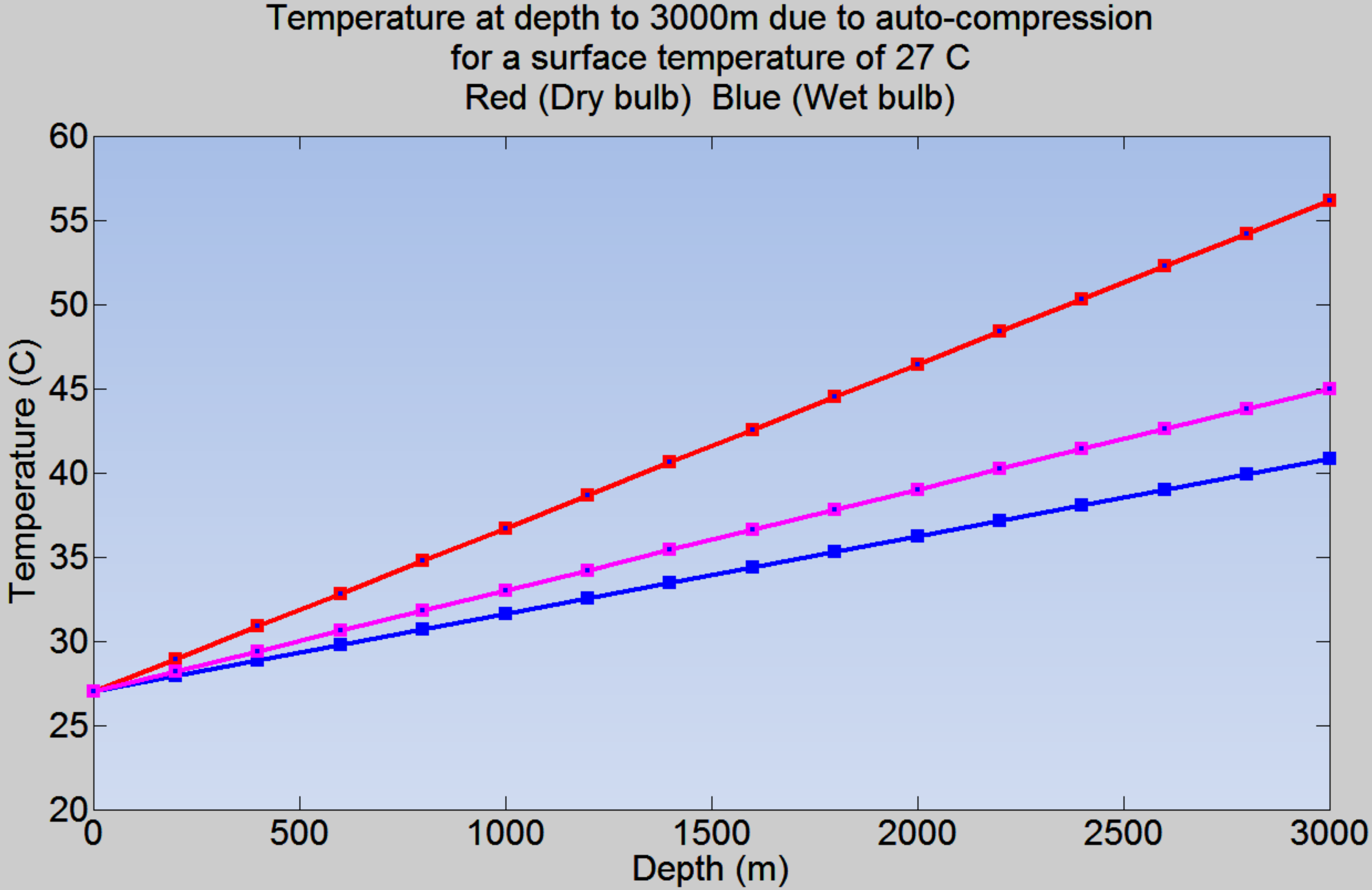

Temperature Increase with depth to 3000m
due to auto-compression
Temperature (K)
330
325
320
315
310
305
300
0
500
1000
1500
2000
2500
3000
Depth (m)



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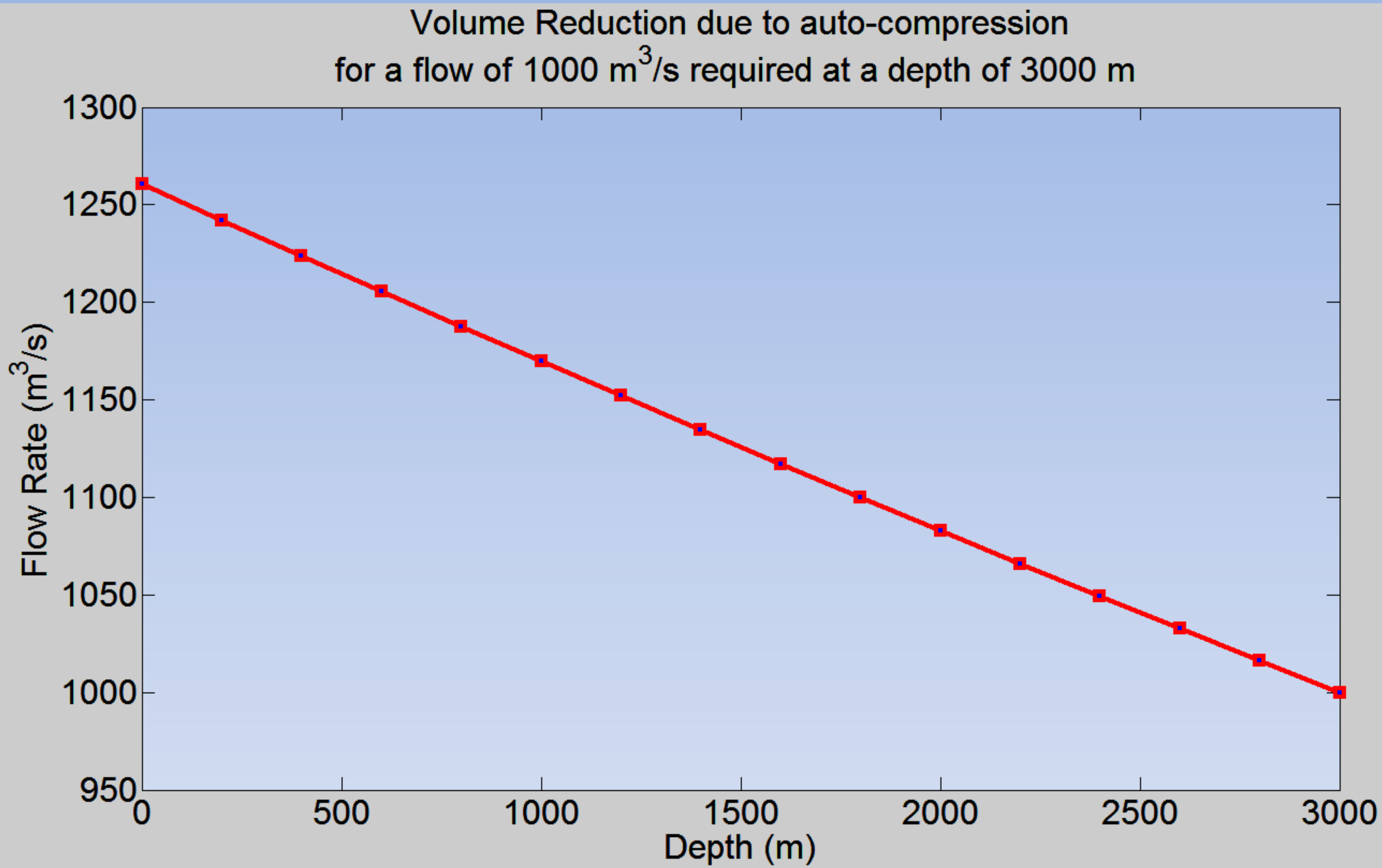

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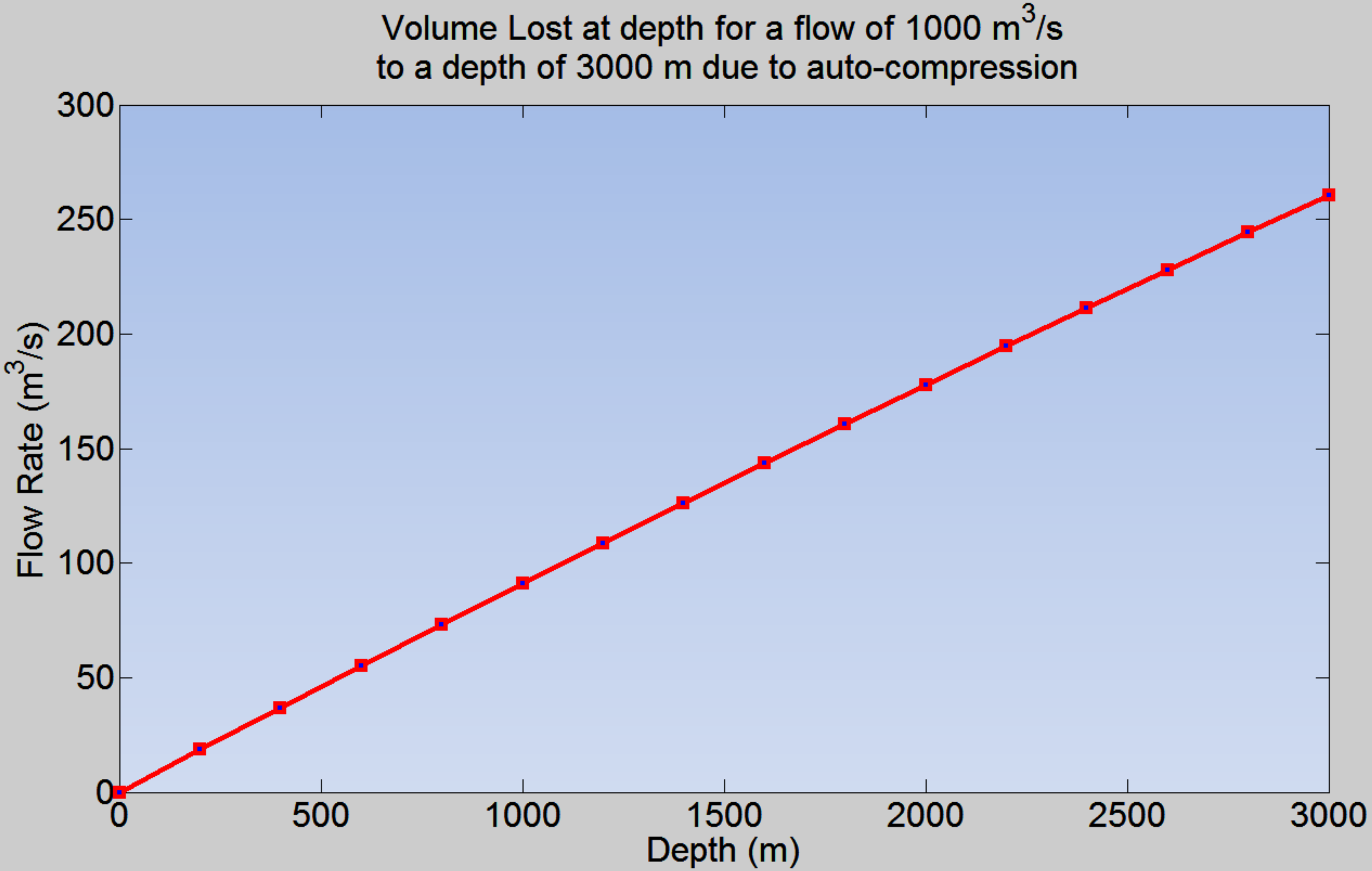

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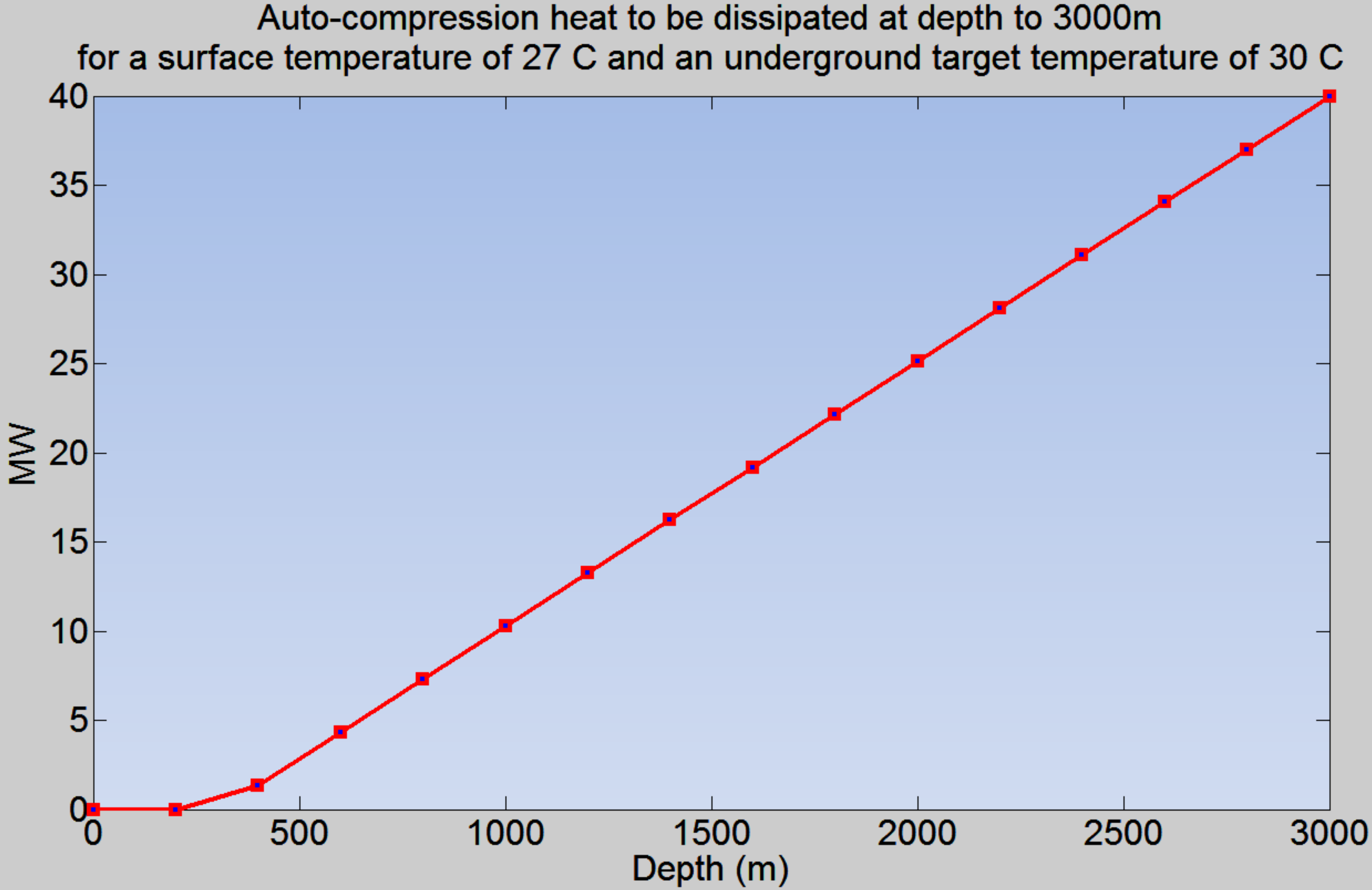

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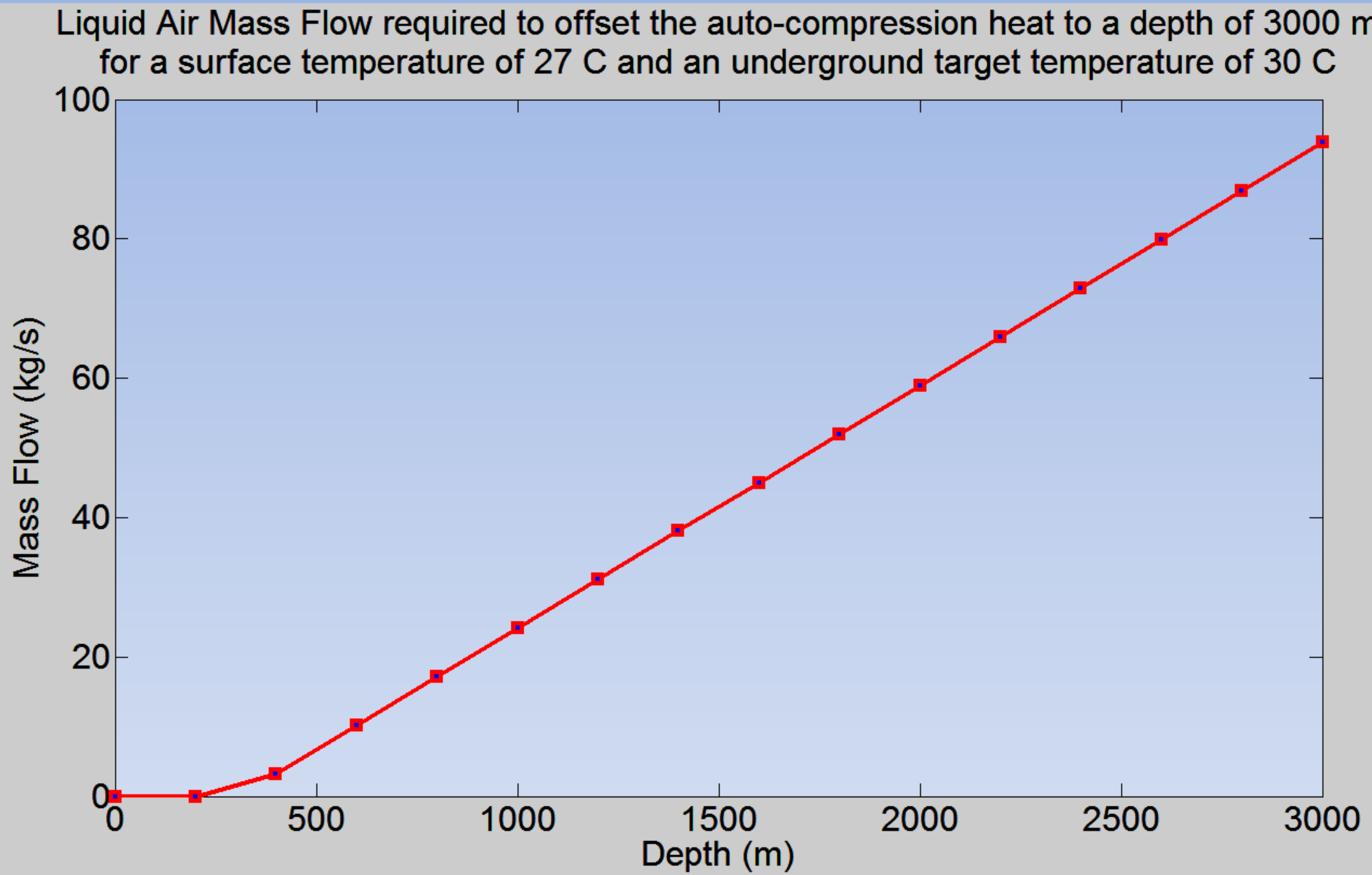

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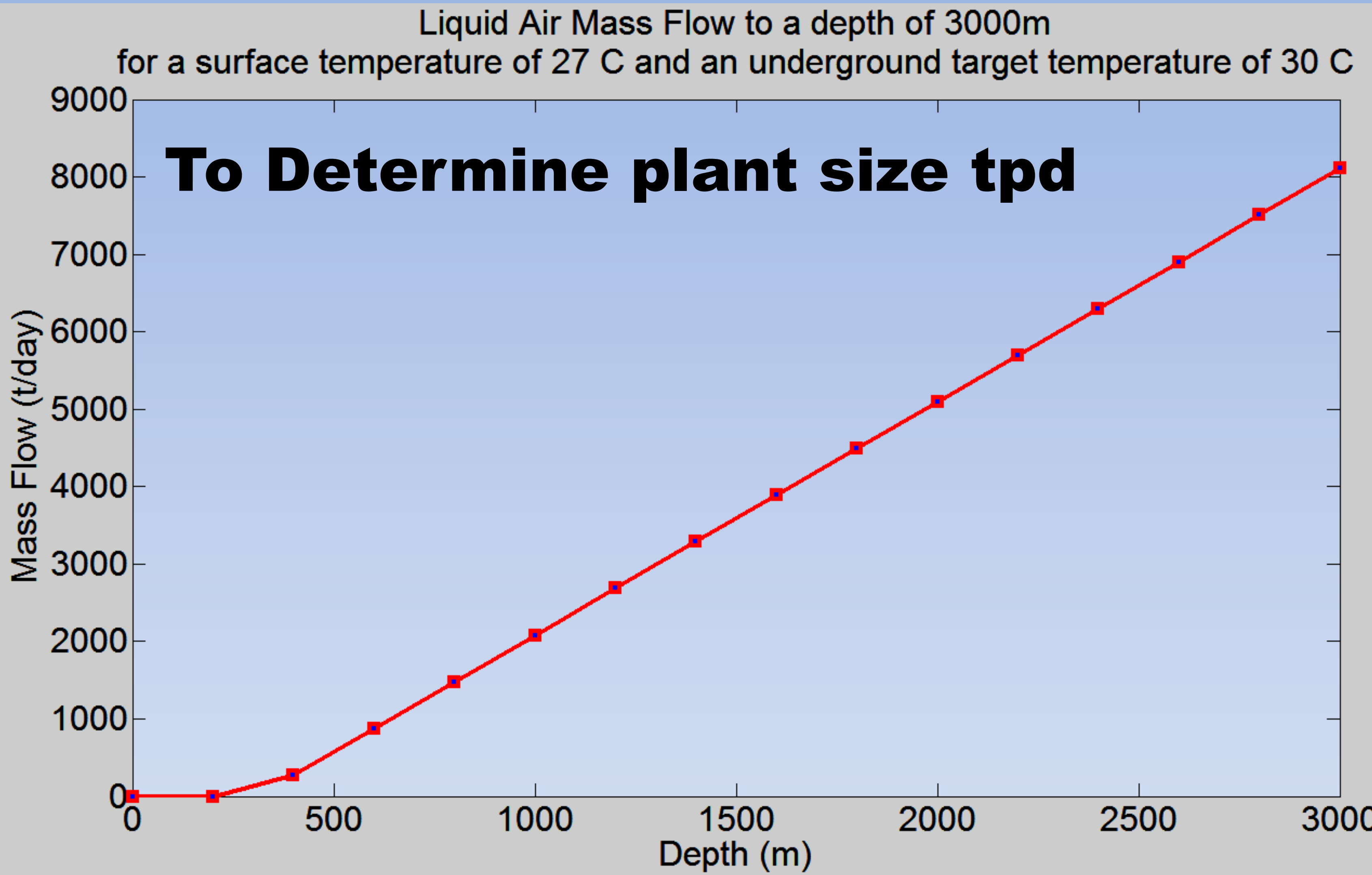

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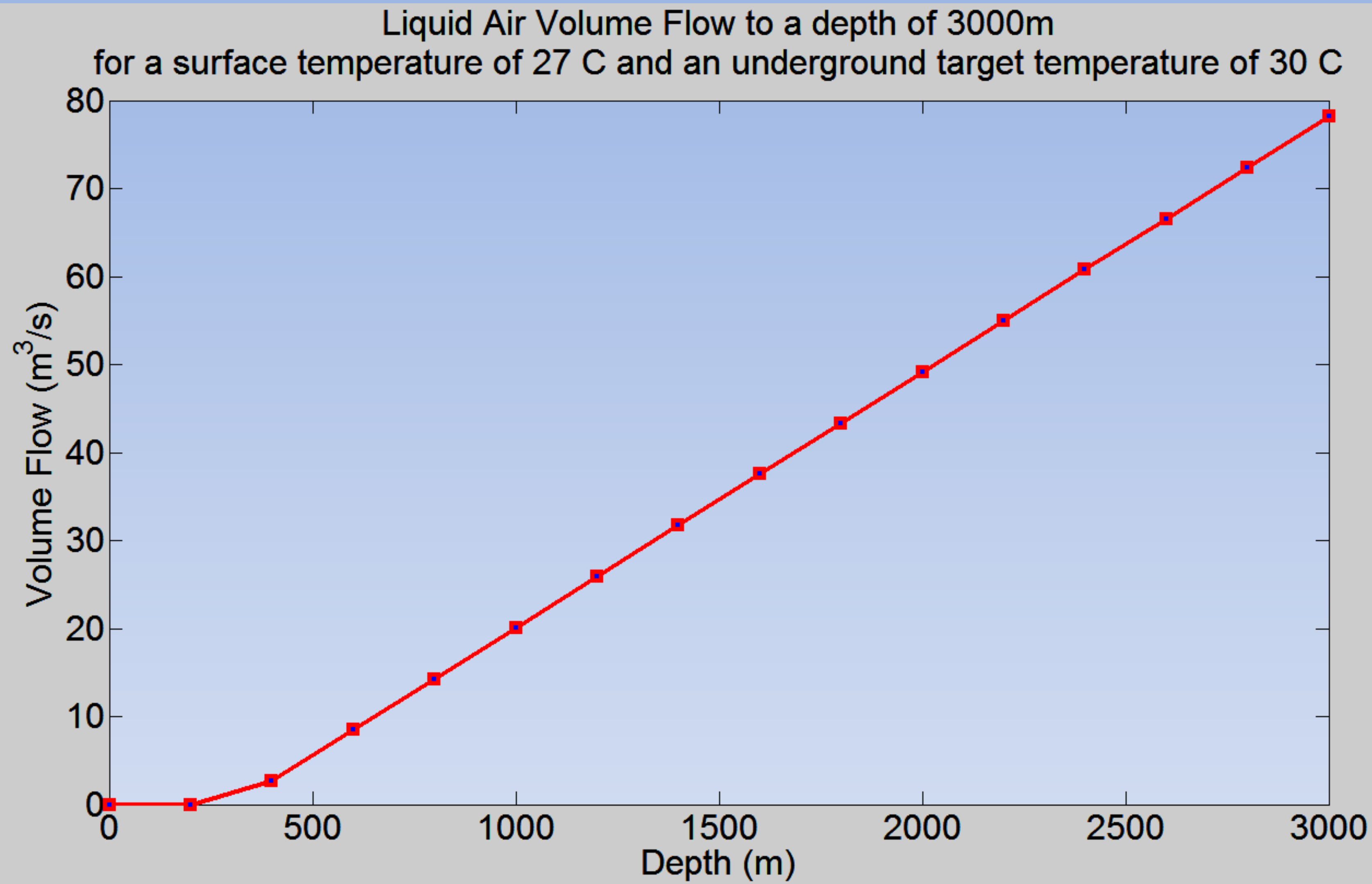

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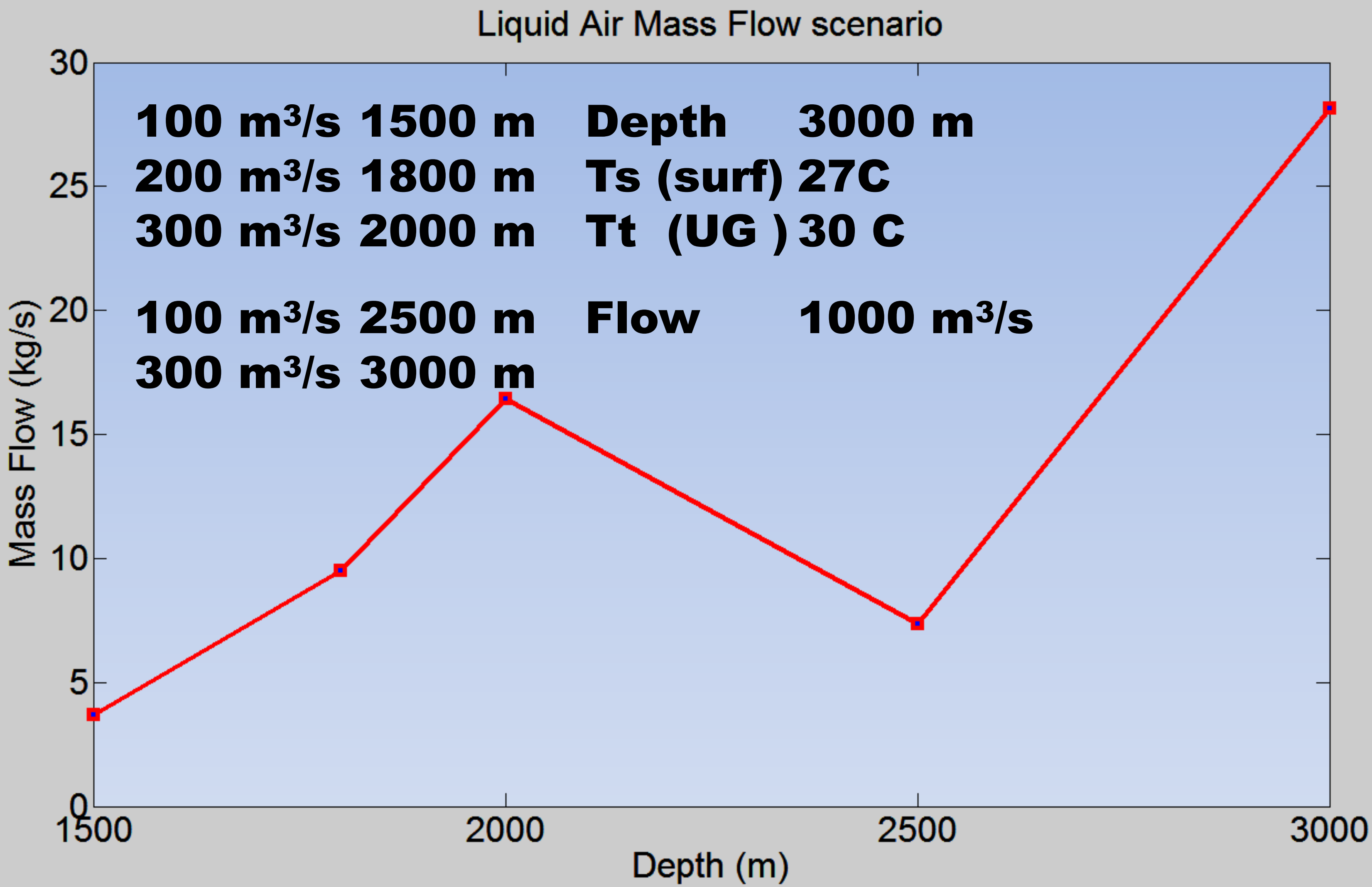
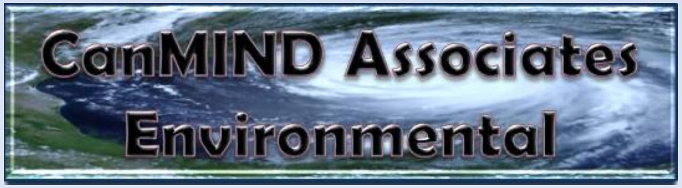

Liquid Air Mass Flow scenario
100 m³/s 1500 m Depth 3000 m
200 m³/s 1800 m Ts (surf) 27C
300 m³/s 2000 m Tt (UG) 30 C
100 m³/s 2500 m Flow 1000 m³/s
300 m³/s 3000 m
Mass Flow (kg/s)
Depth (m)
0
5
10
15
20
25
30
1500
2000
2500
3000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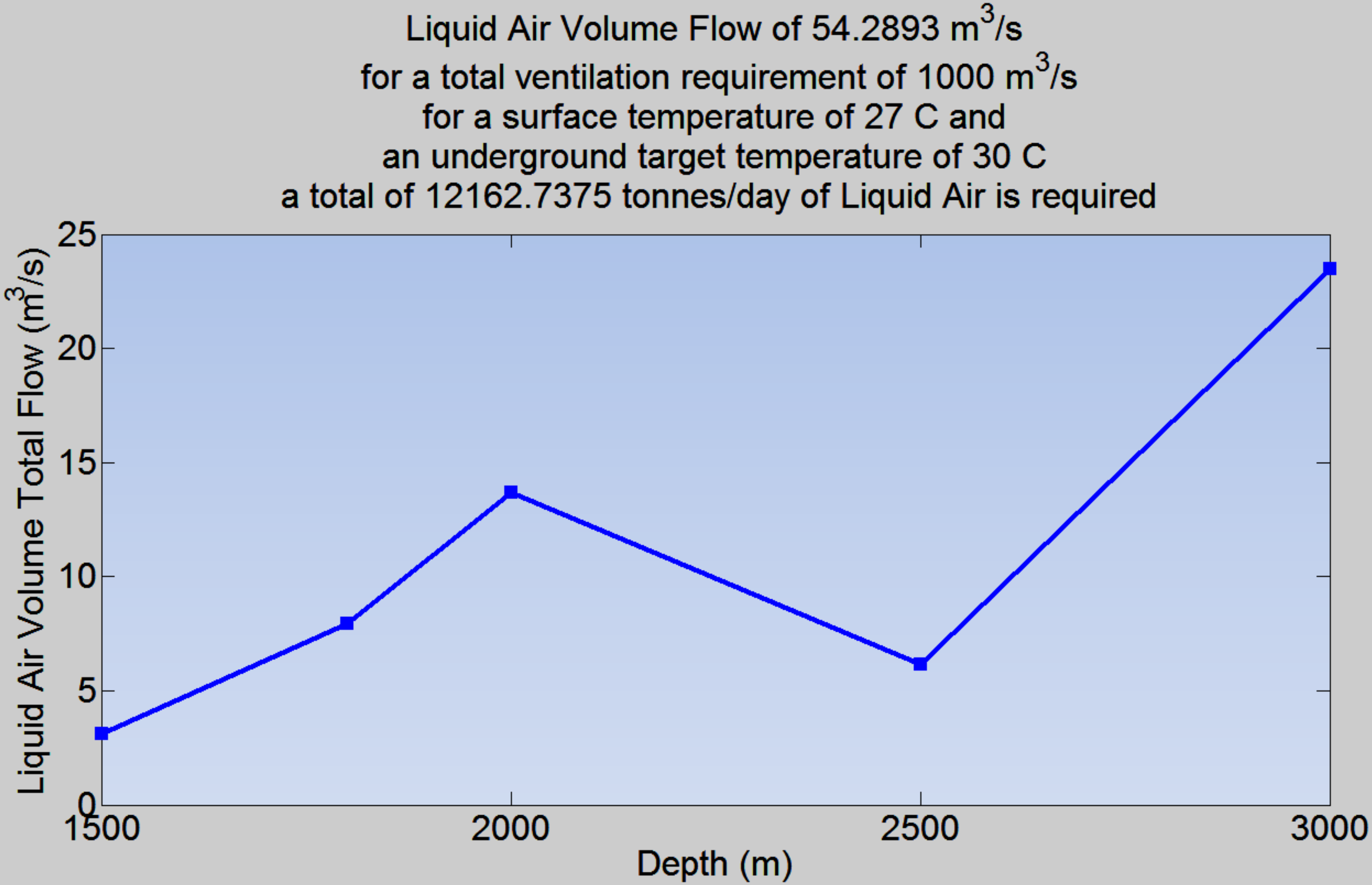

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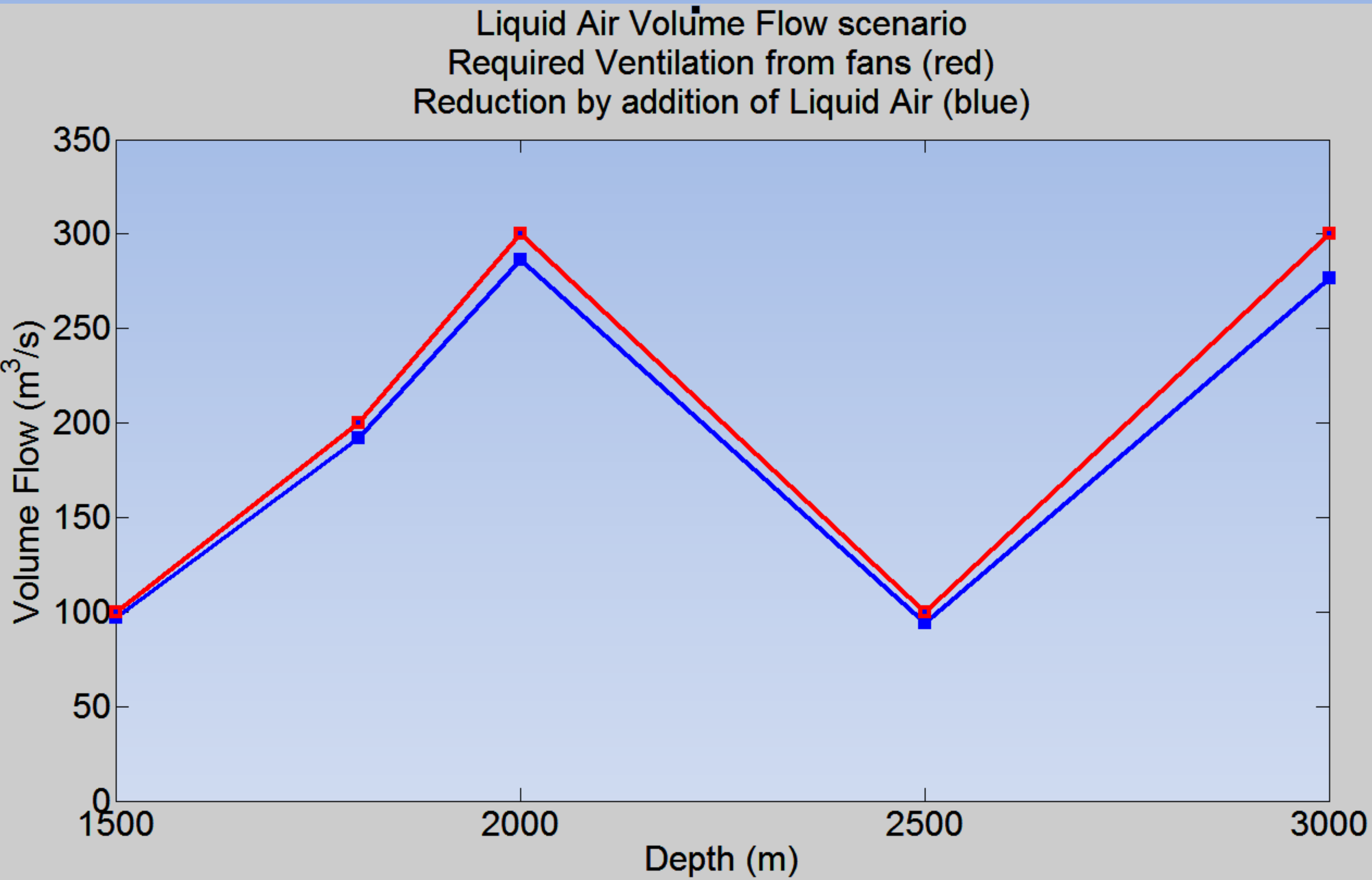

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Comparing Liquid Air to Ice or Water cooling

Increasing fan speed by 10% may increase the quantity of air by 10%, but the power requirement will increase by 33%.

Chris Hall

For quantities exceeding 700,000 cfm (330 m^3/s), it is usually economical to twin the ventilation fans.

William Meakin
https://www.minewiki.org/index.php/HRMH_-_Ventilation_and_Air_Conditioning[08/09/2014 18:24:06]

The downside of pumping chilled water through four kilometres of piping is the enormous expense, "Any reduction in required flow is an attractive proposition.
This is especially true if there are other associated benefits,"

Greg Will
Xstrata Copper's senior commercial advisor (utilities)

Deep mine achieves high efficiency, EcoLibrium® June 2007

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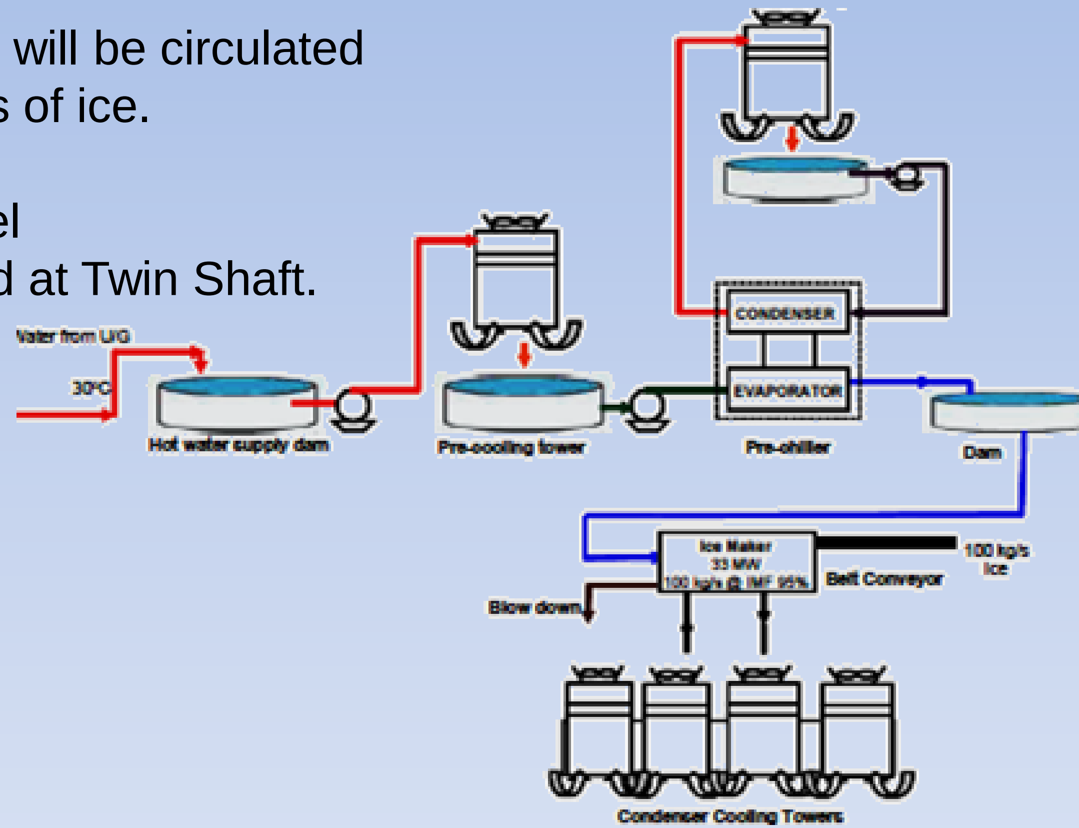
South Deep Gold Mine is a key asset for Gold Fields and the flagship growth project in South Africa

The underground air coolers utilise chilled water produced by a combination of refrigeration machines, located underground, and ice produced on surface and sent underground where it is melted.

1200 l/s of chilled water at about 4 °C will be circulated
500 l/s will be produced from 100 kg/s of ice.
100 MW of refrigeration
30 MW on surface, 40 MW at 94 Level
30 MW by an ice making plant located at Twin Shaft.



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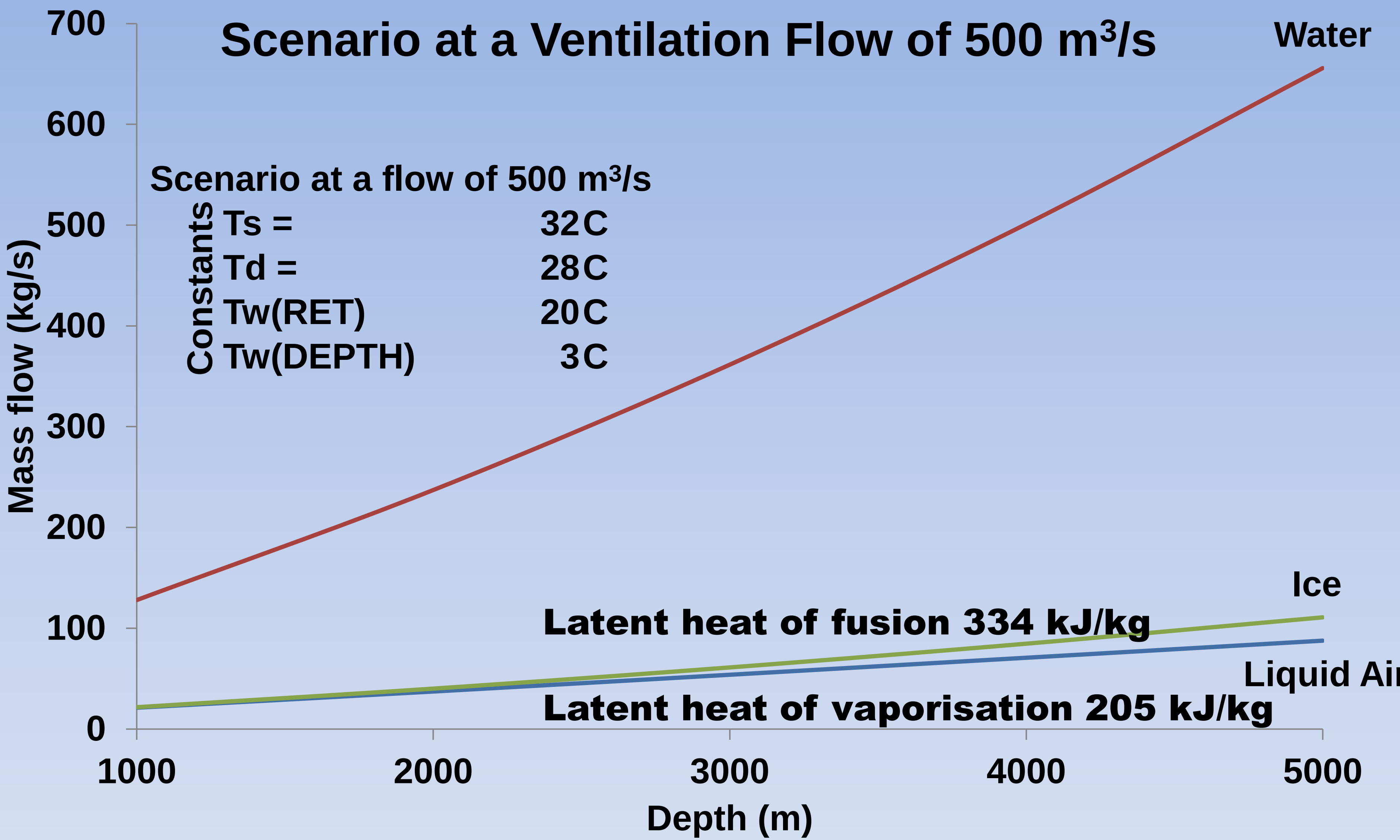

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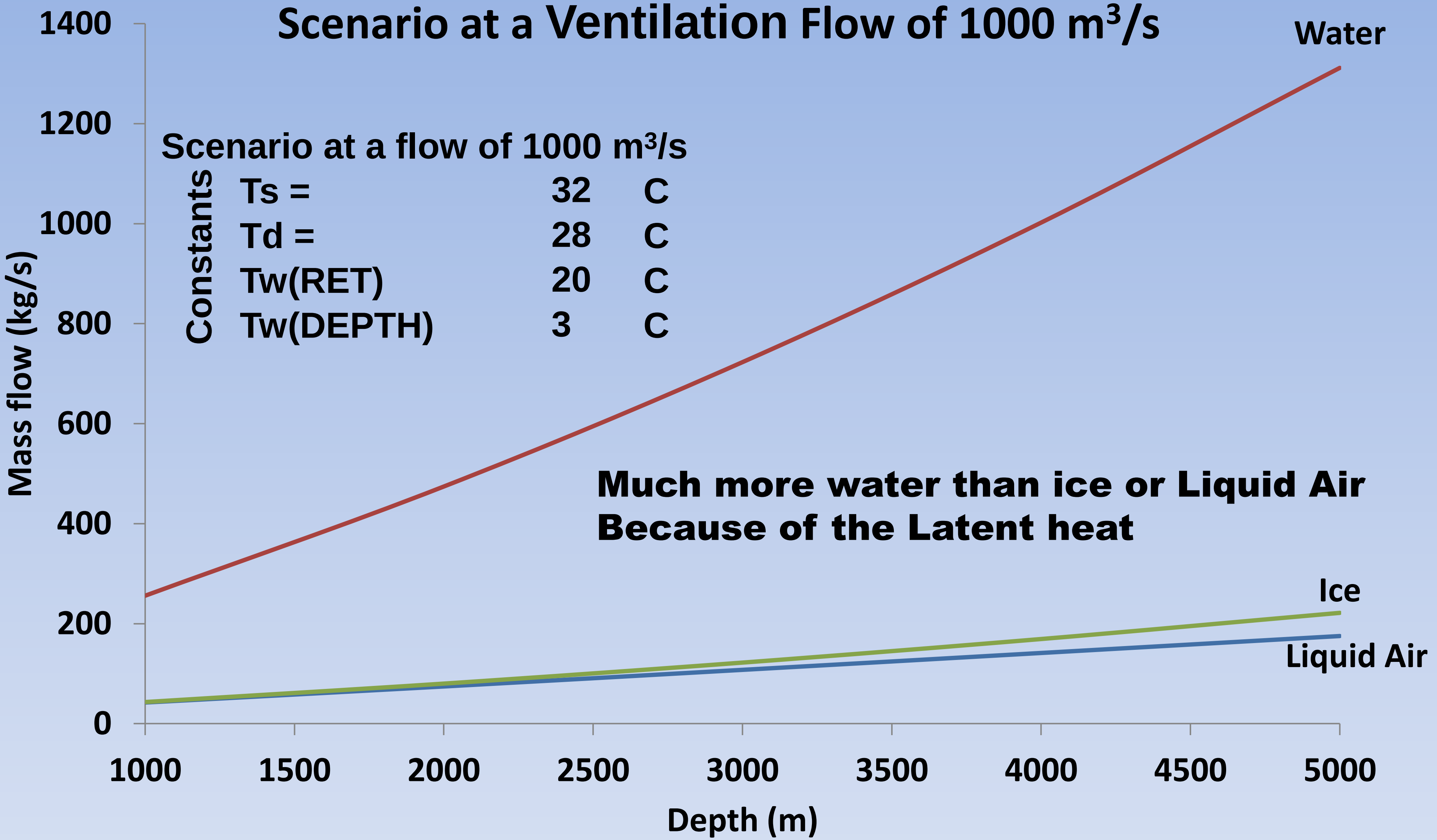
Scenario at a Ventilation Flow of 1000 m^3/s



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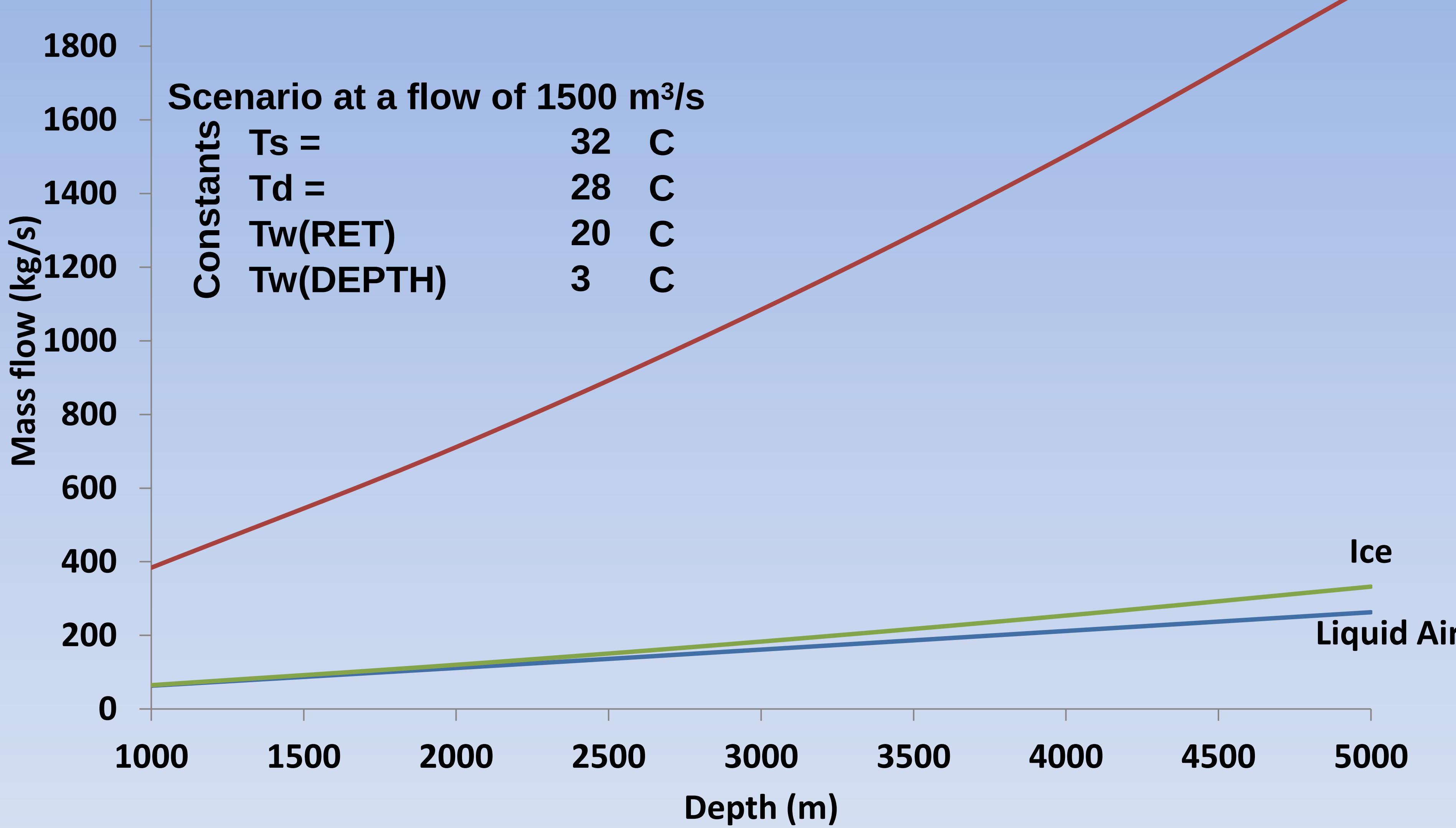
Scenario at a Ventilation Flow of 1500 m³/s



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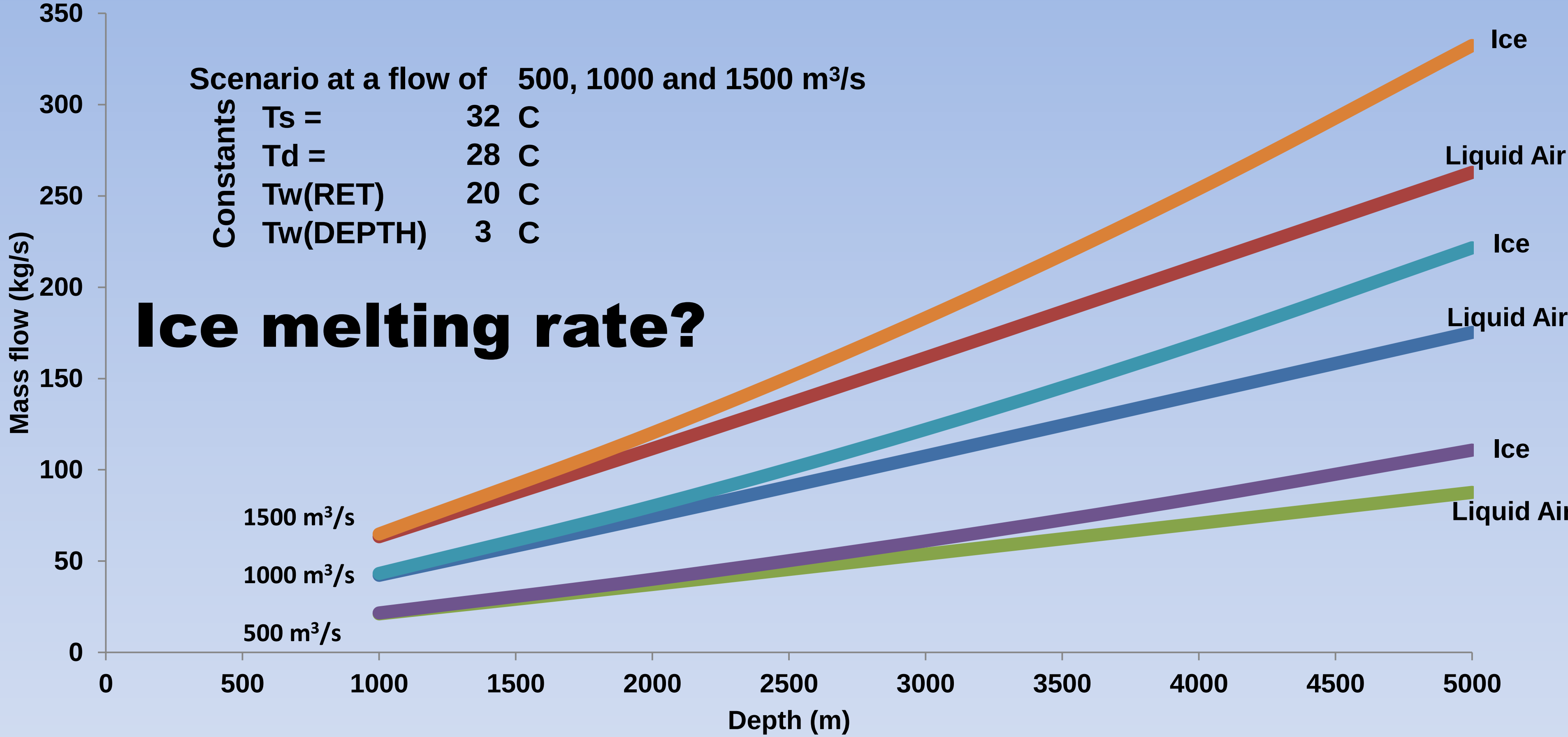
Gap widens as the depth and/or ventilation flow rate increases

Scenario at a Ventilation Flow of 500, 1000 and 1500 m^3/s



A lower temperature source could reduce the Amount of energy spent on chilling, these calculations are for a circulating system. I f lower temperature water is available, lake isotherm, the return may be discarded in favour of the lower temperature source. This does not change the amount required for underground chilling or the amount to be pumped.

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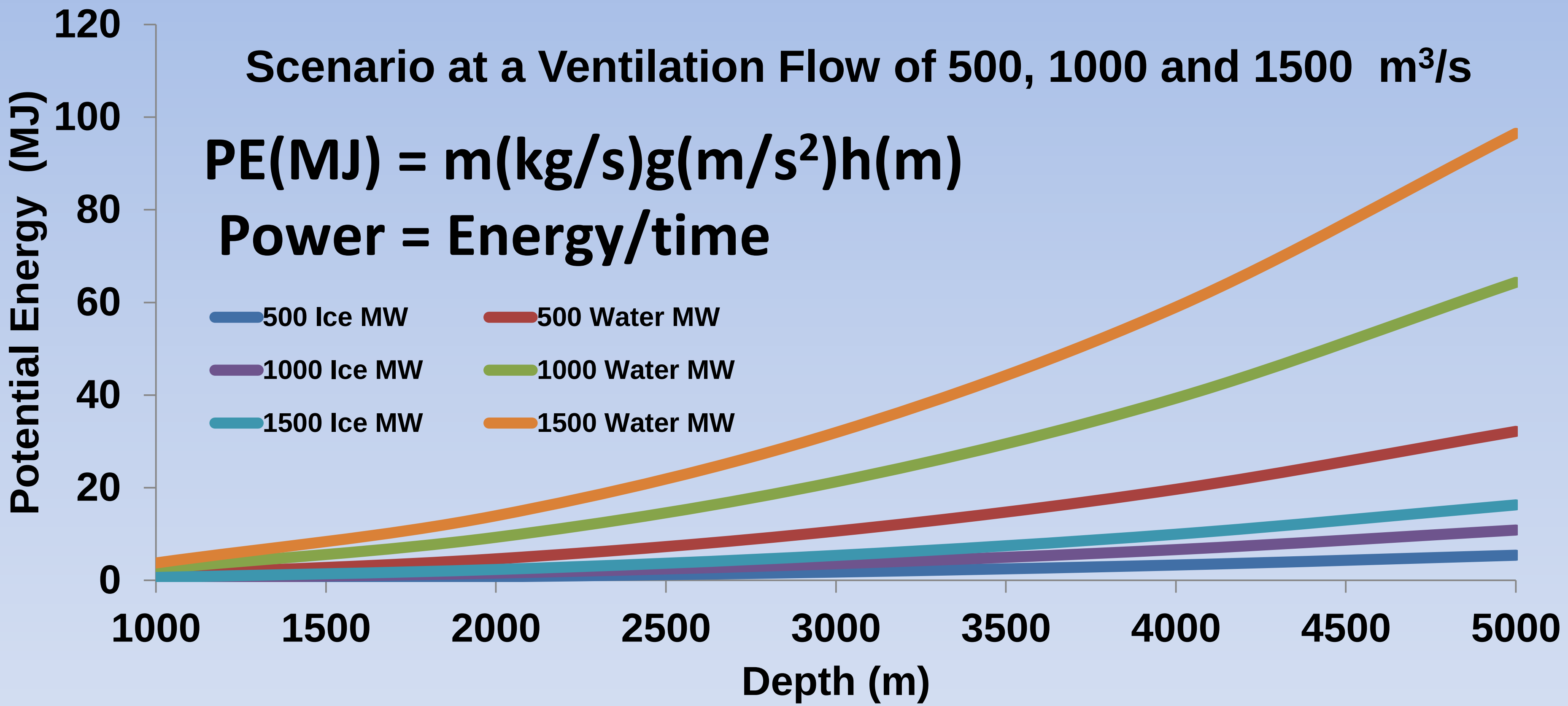
Liquid Air is a one way trip!!

Water or ice needs to be pumped back to the surface!



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Liquid Air in Mine Rescue Apparatus

Personal air and cooling

Compressed Air Produced Underground

Modular Underground Electrical

Deerman Engine

Liquid Air Booster Fan

Rapid cooling of drift for VOD

Local space cooling

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Liquid Air in Mine Rescue Apparatus
Nature, October 11, 1924

Brown and Mill's Aerophor

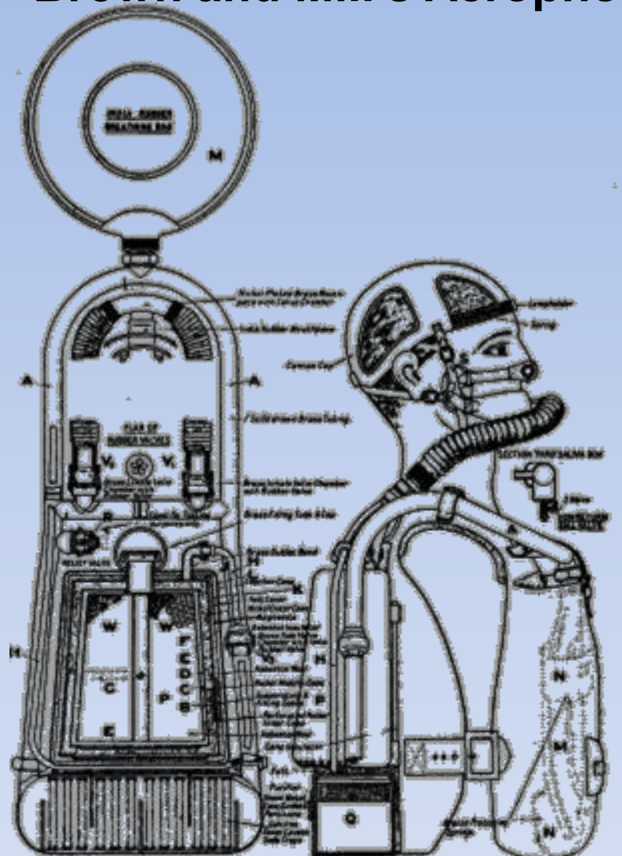

Fig. 1.—Brown and Mills aerophor. Reproduced, by permission of the Controller of H.M. Stationery Office, from the Third and Final Report of the Mine Rescue Apparatus Research Committee.

1924
Liquid Air
Emergency Rescue

2014
Cooling and air supply for an individual in a heat stressed environment

Emergency rescue

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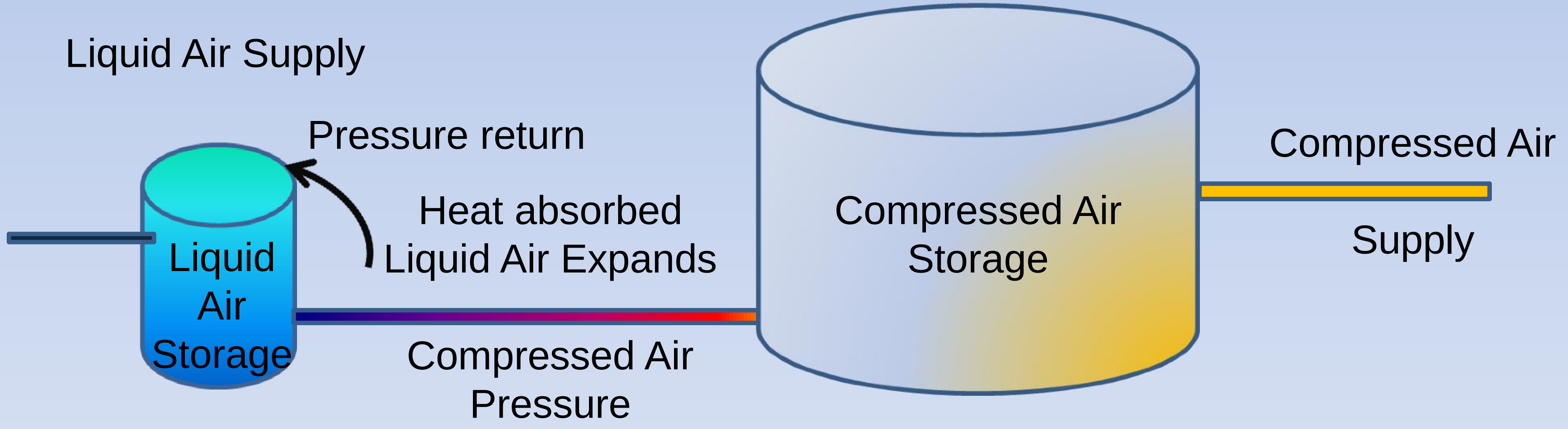
Compressed Air Produced Underground

- **Line loss**
  - **significantly reduced**

- **On site production as needed**

- **Provides net supplemental chilling as compressed air is produced**
  - **Opposite to the typical production of compressed air**



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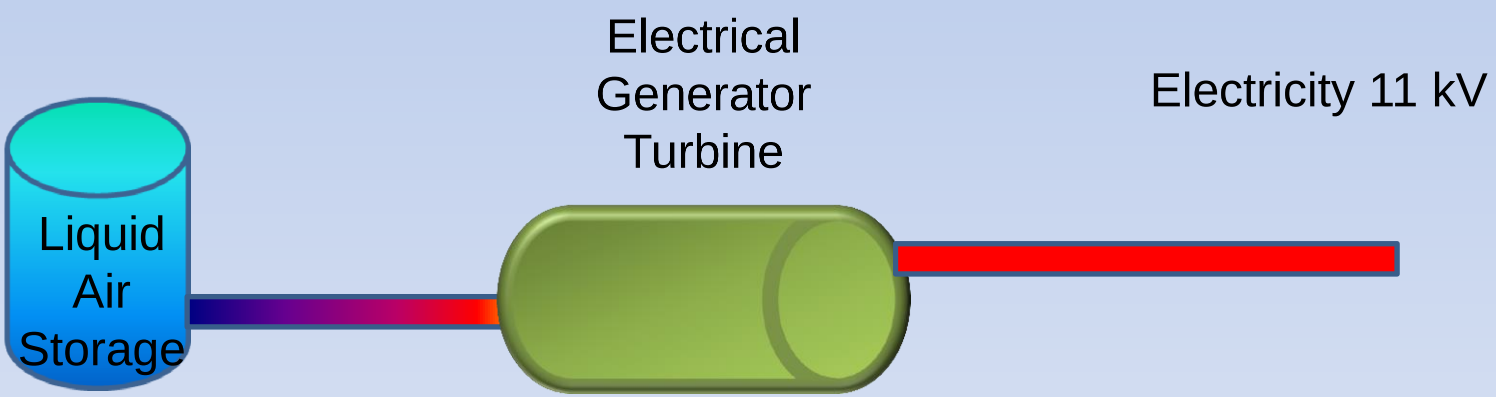
Modular Underground Electrical

Electrical generation demonstrated convincingly Highview Power

[Container size generator Liquid Air in – Steam heat – Electricity]()
1:00 to 3:06



Deerman Engine BBC

Imagine an engine that exhausts cool clean air underground

The use of a Deerman Engine, reduces the ventilation demand

Stirling or Deerman engines can also be used for stationary applications like pumping.

A Diesel LA hybrid reduces the amount of heat generated by equipment and the diesel consumption by 30 % to 50 %
A liquid fuel so all the same standard parts and quick fill-up
Rather that hours to charge a battery

Waste heat recovery at about 80 % efficiency!

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Liquid Air Booster Fan

Liquid Air Expansion:

Expansion through a turbine to power a fan

The potential exists for a booster fan design

The expanding Liquid Air
- **a) would absorb heat**
- **b) rotate a turbine to drive a fan**
- **c) Add cool air to the ventilation to reduce demand**

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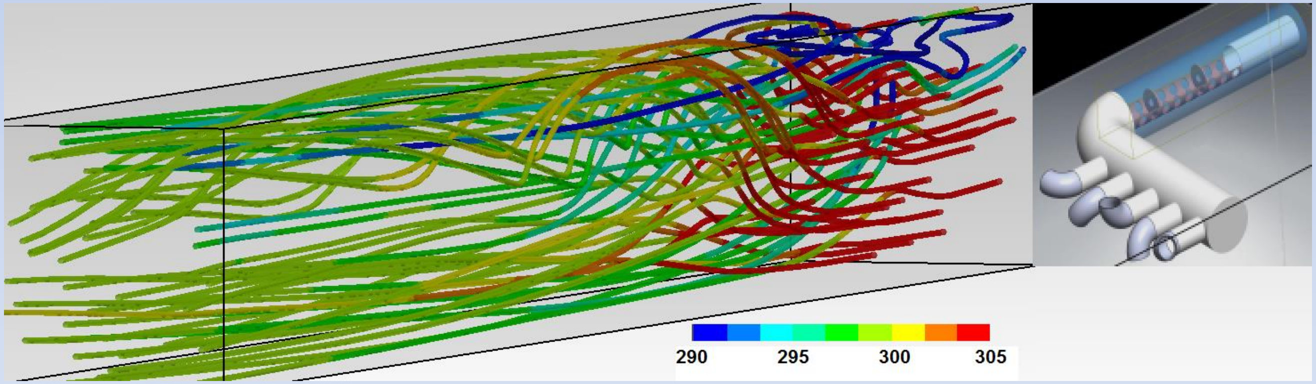
Local space cooling

- **Release of Liquid Air to a localised volume creates chilling**
- **The supply can be located nearby and replenished as needed**
- **No need for electrical connection**
- **Not simply displacing the heat, but provides actual cooling**
- **A simulation is shown with a preliminary booster fan concept**



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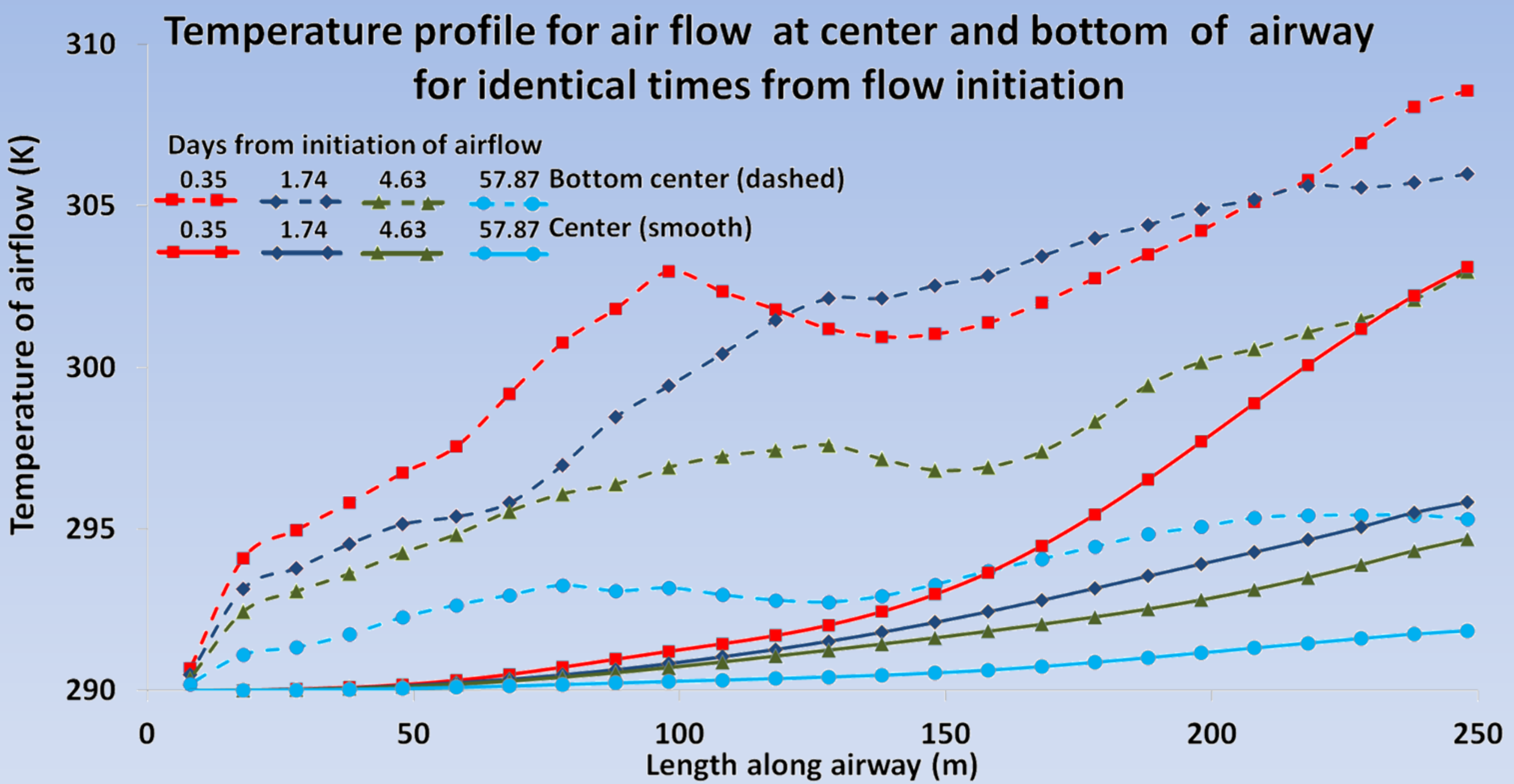
Rapid cooling of drift for VOD



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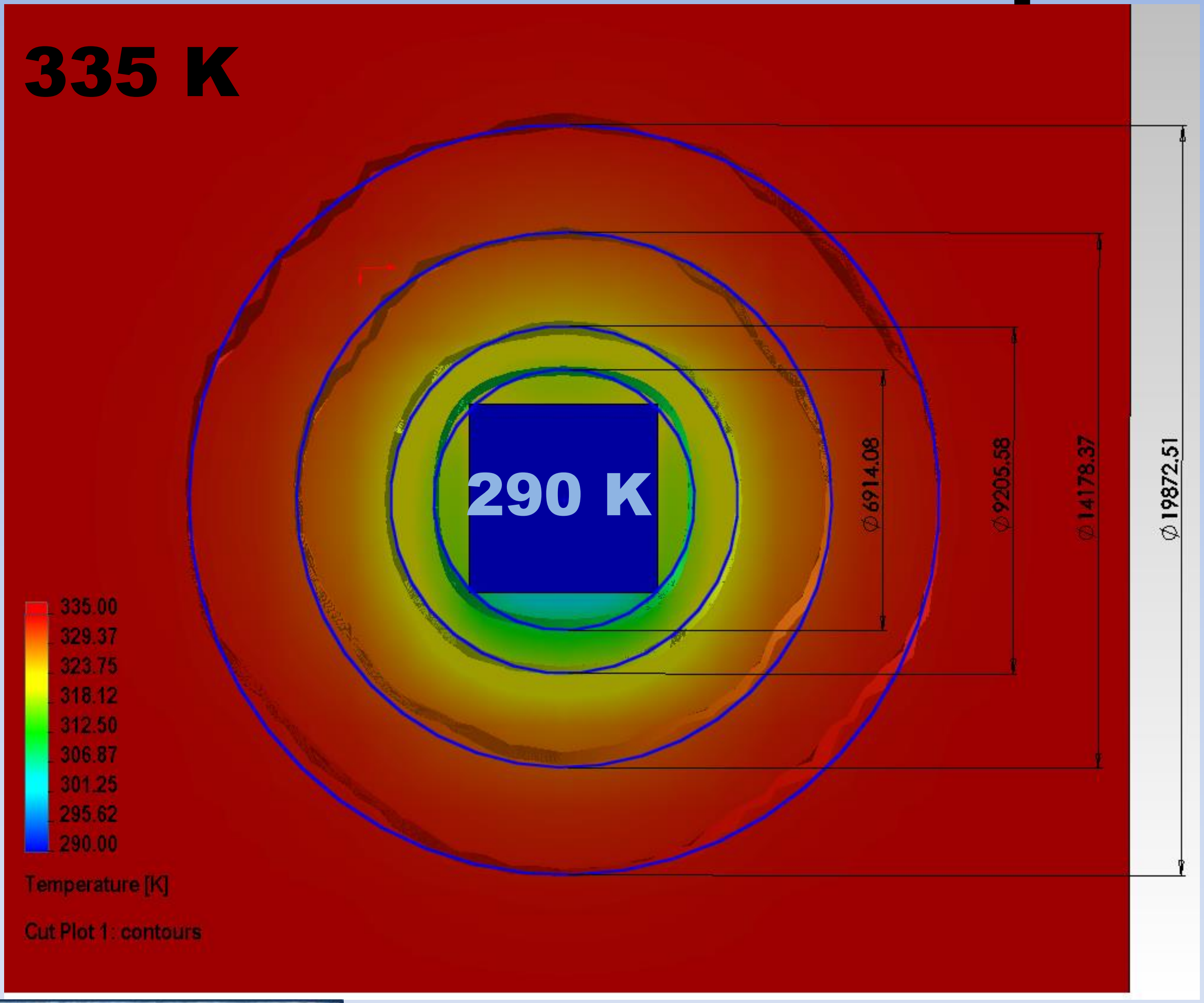
Simulation of Host Rock Temperature



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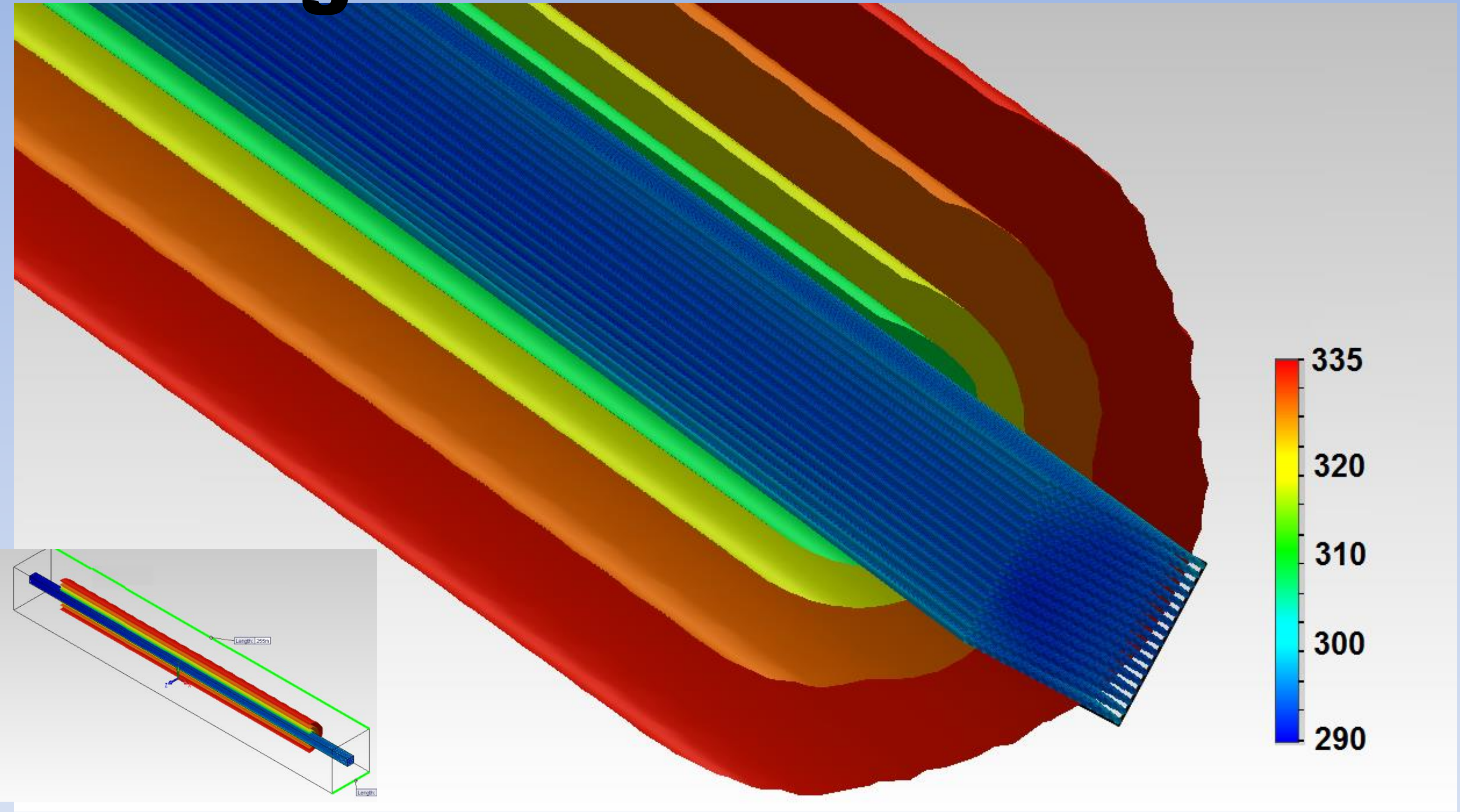
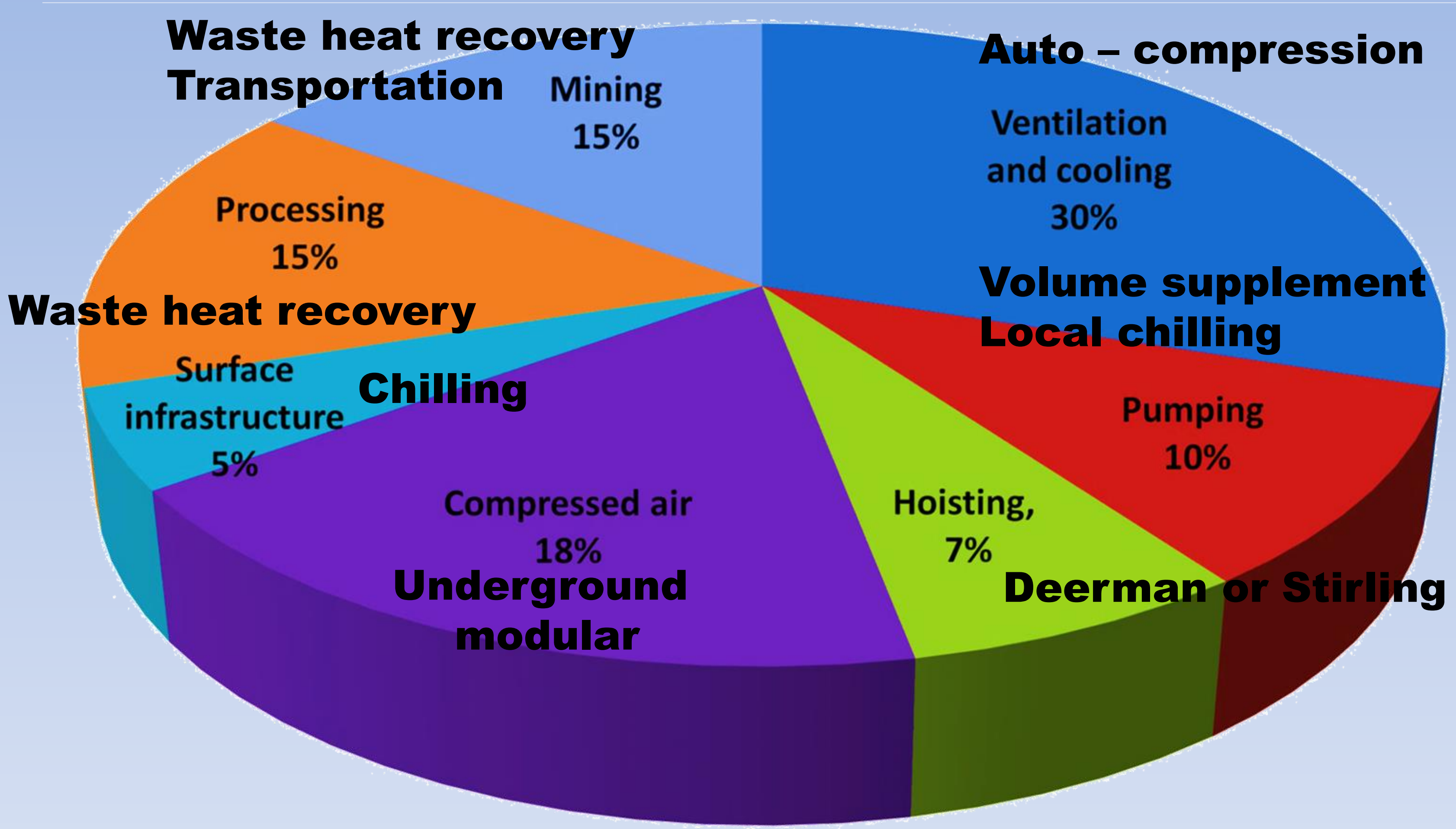
Chilling of host rock



Energy distribution for a deep mine, up to 5000 m, according to MinEcon mine costing model (AngloGold 1999)



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Natural gas LNG

America is now the worlds number one natural gas producer

Combined with LNG the production of Liquid Air is more efficient

Gas turbines waste heat is easily used to increase the electrical output efficiency

Natural Gas is usually available during a power interruption

Combined with a Liquid Air storage system the critical systems or perhaps even normal operations may be maintained

Gas turbines are efficient and reliable, can be used to operate the ventilation system in a co-generation configuration where the waste heat from electricity production is directed to increase the efficiency of the Liquid Air system or heat the dry.

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Summary

Liquid Air is emerging as a competitive energy storage vector

A source of Liquid Air at a mine

1. **Can provide efficiencies if renewable energy is installed**
2. **Convert waste heat to energy efficiently**
3. **Provide power arbitrage, peak shaving, global adjustment**
4. **Auto-compression heat dissipation**
5. **Reduces the ventilation air flow; thus, ventilation fan power – cubic**
6. **Underground modular production of compressed air**
7. **Rapid drift temperature conditioning**
8. **Personal environment for emergencies or heat stress abatement**
9. **Deerman or Stirling engines for various equipment or vehicles**
10. **Volume spot chilling, booster fan pressure for crews**
11. **Underground modular electricity production**
12. **Operate machines in a similar fashion as compressed air currently does**

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What is next?

Technical feasibility?   Costing comparisons.

For example,

pumping water and shipping ice underground to chill

Compared to the one way trip of liquid air to chill.

Design specifications for modular production of:
- **Electricity,**
- **Compressed air,**
- **Localised cooling**
- **Booster fans**

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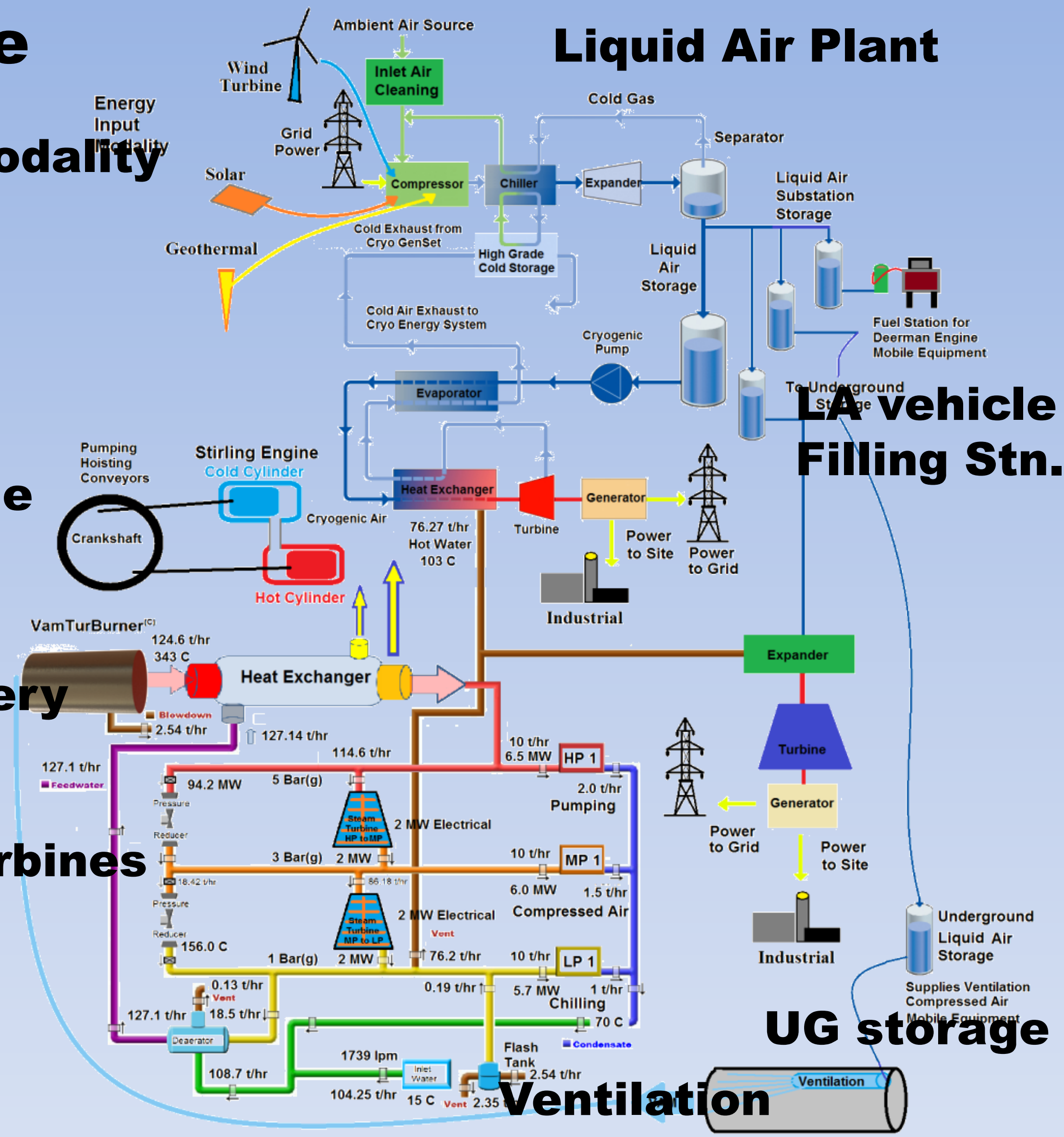
Implications at a mine

Energy modality

Stirling engine

Waste heat recovery

Steam Turbines



LA vehicle Filling Stn.

UG storage

Ventilation

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Highview Power Short

Highview Plant at Slough UK
Video excerpt

Container size electrical generator
Liquid Air in + Steam heat =
Electricity 1:00 to 3:06

Deerman Engine BBC

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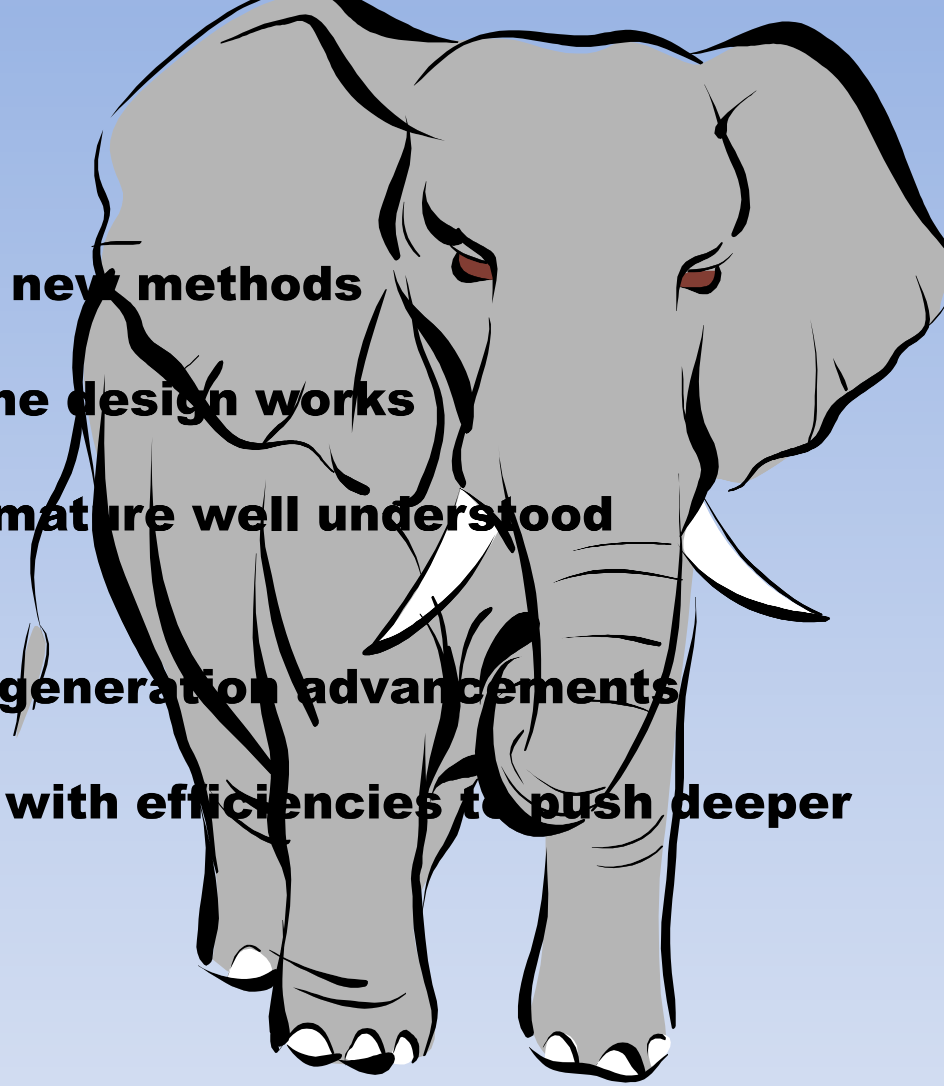
In Closing



Inertia in the system

We miners are not easily swayed to new methods

We like to see evidence that the mine design works

These technologies are built on all mature well understood Equipment and processes

Could bridge the gap between next generation advancements

Allow for the same mining methods with efficiencies to push deeper

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Emerging Technologies Seminars Deerman Engine Excerpt 1 from 6:16 to 8:50

Emerging Technologies Seminar excerpt 2 11:08 to 13:00 if time at end

Emerging Technologies Seminars Deerman Engine Excerpt 3 13:42 to 14:50

Deerman Engine BBC

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Gareth Brett CEO discusses the size of LAES technology 0:33

Pilot demonstrator January 2010 - February 2011 3:48

How Highview turns liquid air into power 0:33

Gareth Brett discussing the electricity market 1:03

Highview Power Storage: Liquid Air Energy Storage site visit 4:04

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[Hydrogen storage Linde Plant Magog, Quebec]

[Hydrogen storage Linde Plant Magog, Quebec excerpt]

[Hydrogen storage & Hydrogen videos]

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