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2 CO₂ Snow Deposition in Antarctica to
3 Curtail Anthropogenic Global Warming
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Abstract

A scientific plan is presented that proposes the construction of CO₂ deposition plants in the Antarctic for removing CO₂ gas from the Earth's atmosphere. The Antarctic continent offers the best environment on Earth for CO₂ deposition at 1 bar of pressure, and temperatures closest to that required for terrestrial air CO₂ snow deposition, 133°K. This plan consists of several components, including: (a) air chemistry and CO₂ snow deposition, (b) the deposition plant and a closed-loop liquid nitrogen refrigeration cycle, (c) the mass storage landfill, (d) power plant requirements, (e) prevention of dry ice sublimation and (f) disposal (or use) of thermal waste. Calculations demonstrate that this project is worthy of consideration, whereby 446 deposition plants supported by 16 1200-MW wind farms can remove 1 B tons (10¹² kg) of CO₂ annually (a reduction of 0.5 ppmv), which can be stored in an equivalent "landfill" volume of 2 km x 2 km x 160 m (insulated to prevent dry ice sublimation).

The individual deposition plant, with a 100m x 100m x 100m refrigeration chamber, would produce approximately 0.4m of CO₂ snow per day. The solid CO₂ would be excavated into a 380m x 380m x 10m insulated landfill, that would allow one year of storage amounting to 0.00224B tons of carbon. Demonstrated success of a prototype system in the Antarctic would be followed by a complete installation of all 446 plants for CO₂ snow deposition and storage (amounting to 1B tons annually), with wind farms positioned in favorable coastal regions with katabatic wind currents. .

1. Introduction

Since the beginning of observations of atmospheric CO₂ at the Mauna Loa Observatory in 1958, which established the famous Keeling curve for CO₂ increases (see Bacastow et al. 1985), there has emerged an unprecedented scientific concern (and alarm) regarding climate change attributed to fossil fuel emissions by the industrialized world. Pre-industrial CO₂ values of 295 ppmv have risen to the current global average of 392 ppmv and the more recent trend of CO₂ increase is illustrated in Figure 1 at 1.88 ppmv per year. Trenberth (1981) has determined that 1 ppmv of CO₂ increase amounts to 2.13×10^{12} kg, and therefore the 1.88 ppmv represents about 4 billion (B) tons of carbon added per year (based on the 2000-2009 decadal average). Global surface observations of air temperature, coupled with climate model simulations, support the conclusion that CO₂ is the principal greenhouse gas (GHG) responsible for much of the 1°C rise in temperature during the 20th century (see numerous scientific references in the Fourth Assessment Report of Working Group I, Intergovernmental Panel on Climate Change, aka IPCC, 2007, Cambridge University Press). Further, climate model simulations through the 21st century (through different scenarios of continued CO₂ increase) show additional global warming increases from 1°C to 5°C, which would result in unprecedented modern day geophysical and economic disasters.

To date, several efforts have been made to address this global emergency, from the Kyoto Protocol (1997) to the Copenhagen summit in December 2009; from national and state and city planning for mitigation (e.g., due to sea level rise), to calls for CO₂ sequestration. The social and economic impacts of global warming are too numerous to discuss in this paper, and the reader is referred to the various Working Group reports prepared by the IPCC. One particular effort that is relevant to this proposal is the Virgin Earth (VE) Challenge (see <http://www.virgin.com> or

earth.challenge@virgin.co.uk), a \$25 million (M) prize initiated and financed by Sir Richard Branson. The requirement of this challenge is to remove 1 B tons of CO₂ from the atmosphere per year, for a 10-year period. The concept presented in this paper was not submitted for competition, since the deadline for submission was 8 January 2010. Nonetheless, the VE prize is a simple illustration of the perceived importance of removing CO₂ from the atmosphere (with \$5 M awarded at the beginning and \$20 M at the end of a successful decade of removal). As of 2 November 2011 there were no winners, however, 11 leading organizations with promising ideas were announced at the Global Clean Energy Conference in Calgary to establish next steps for the Virgin Earth Challenge. It is noted, however, that 1 B tons per year is ~ 0.5 ppmv of CO₂ removal, and thus represents only a 25% decrease in the rate of increase.

2. The Idea

NASA's Mars Global Surveyor and Odyssey missions have revealed the presence of a CO₂ ice cap on Mars' South Pole (see Figure 2), which is annually subjected to deposition and sublimation. The presence of this CO₂ ice cap triggered the idea to consider the possibility of terrestrial air CO₂ deposition at the Earth's South Pole, considering that this is the coldest location on Earth and the energy required to sequester CO₂ from the atmosphere (and to maintain insulated storage) might be within the scope of reality. A depositional plant constructed on Antarctica could conceivably pull air into a refrigerated chamber, where sufficient cooling could result in CO₂ snow deposition. To pursue this idea, it is first noted that N₂, O₂ and Ar all would remain in the gas phase as terrestrial air CO₂ is brought down to its depositional temperature. Since the atmosphere is only 392 ppmv of CO₂, the Clausius-Clapeyron Equation, in conjunction with the CO₂ vapor pressure curve, can be considered to calculate the atmosphere's depositional temperature for CO₂. Appendix I is presented to show that the relevant depositional temperature

for terrestrial air CO₂ snow is 133°K, an achievable chilled temperature for the deposition plant. Alternatively, one could consider placing the ambient air under 10 bars of pressure, and the depositional temperature would increase to 152°K. It is noteworthy that liquid N₂ has a very high efficiency as a cooling agent at this depositional temperature (considering that pure N₂ at 10 bars of pressure condenses at 105°K). A more reasonable target for deposition is the use of liquid N₂ at T = 120°K (under a pressure of P = 29.61 bars), within a closed loop vapor-compression refrigeration system. This will be discussed in a later section.

3. Antarctica

The coldest surface air temperature ever measured on Earth was at the Vostok Station in 1983 (see Figure 3), a reading of T = -89.2°C (or 184°K), which is reasonably close to CO₂ snow deposition temperature of 133°K (1 bar) or 152°K (10 bars). In fact, much of Antarctica has been getting colder (largely attributed to the O₃ hole, see Thompson and Solomon, 2002), although the Western Antarctic Ice Sheet (WAIS) is warming (also see Stieg, et al. 2009; and Franzke, 2010). The mean annual temperature of the Antarctic interior is approximately $\bar{T} = 226^{\circ}\text{K}$ (-57°C), and this continent will continue to be the most favored location for implementing the proposed CO₂ sequestration methodology. It is further noted that the vastness of the Antarctic interior with multiple international scientific participation (see Figure 3) lends itself to the global theme of this paper. The Antarctic Treaty (see <http://www.nsf.gov/od/opp/antarct/anttrty.jsp>) provides a forum for international governance and scientific cooperation. As discussed later in this paper, the construction of CO₂ snow deposition plants that are supported by wind farms, offer the opportunity for unique international expertise to join forces to develop the CO₂ sequestration facilities that can substantially curtail the effects of anthropogenic GHG warming.

4. Design of the CO₂ sequestration facility

The components of the proposed Antarctic facility are illustrated in Figure 4, which shows environmental air (A) entering the right side of the depositional chamber (B). Refrigeration is powered by wind farms that drive a closed loop liquid N₂ cooling facility. CO₂ snow deposition, at rates of approximately 40 cm per day (falling to the bottom of a 100 m x 100 m x 100 m chamber; see Fig. 5), is excavated into the insulated dry ice landfill (D). Appendix II shows the appropriate calculations and design criteria that would remove 1 B tons of CO₂ per year, which could be accomplished by approximately 16 1200-MW wind farms. Most individual wind turbines in Midwest USA wind farms, are 1MW to 3MW, however more powerful turbines could be considered but are not necessary. An example of a wind farm that exists in Antarctica can be found at <http://www.antarcticanz.govt.nz/scott-base/ross-island-wind-energy>. Appendix III shows the calculations and design criteria for meeting the energy requirements to support the depositional plants.

5. Engineering Design and Operations

The *refrigeration cycle* and energy requirements for CO₂ snow deposition are illustrated in Fig. 5, based on a “Closed Loop Liquid-Vapor Cooling System.” Liquid nitrogen is the refrigerant of choice and is effective at the required depositional temperature for CO₂ in terrestrial air. Engineering details regarding “compressor” size and “expansion valve” size are under consideration. Similarly, for the size of the “heat exchanger.” Multiple components of smaller size (e.g., the compressor) might reduce the energy requirements. Current plans for a 45-MW wind farm (15- 3MW towers) will run one prototype deposition plant. The wind farm should be designed to expand to 1200-MW to supply energy to 28 deposition plants. The CO₂

snow landfill for this prototype plant will be 380m x 380m x 10m (for each year of CO₂ snow deposition).

The schematic diagram for the *CO₂ snow deposition chamber* is given in Fig. 6. This chamber consists of a 100m x 100m x 100m cubical volume on four support pillars with reversible air intake and exhaust fans for the refrigeration process of the ambient air. The front and back sides of this chamber will have embedded coils of liquid nitrogen coolant. The “floor” of the depositional chamber will be allowed to open for excavation into an insulated CO₂ landfill. The prototype system will process ambient air at a depositional rate of 0.4m of snow per 24-hour operational day. This amount of solid CO₂ can be stored in an insulated CO₂ snow landfill that is 380m x 380m x 10m, which amounts to 0.00224B tons. The intake-exhaust fans will allow reversed air flow to permit the chamber to operate with the ambient wind direction (although typically there will be katabatic flow from the ice sheet to the coastal region). It is further noted that five insulated landfills (380m x 380m x 10m for each) will be constructed in a semicircle in close proximity to each deposition plant to accommodate for five years of CO₂ sequestration (one landfill filled per year at each deposition plant).

Figure 7 is an illustration of the landfills (per deposition plant), and they will be insulated with polyisocyanurate (effective down to 93°K). Snow cat excavators will operate in groups of five to move the dry ice rapidly into the insulated landfills. A partial vacuum or even refrigeration could be some alternative considerations for maintaining solid CO₂.

6. Summary and Conclusions

A plausible scientific plan has been presented for removing annually 1B tons of CO₂ from the atmosphere through refrigeration of terrestrial air and CO₂ snow deposition. The CO₂ snow will be stored in insulated landfills onsite in the Antarctic, and the energy for deposition

plant operations will be provided by wind farms (that will be positioned appropriately for both logistics and katabatic wind currents). The basic scientific concepts presented here are viewed as plausible, while additional engineering details can be provided as the project goes forward. Consideration will also need to be given to other related topics, such as modeling of CO₂ global diffusion to the Antarctic (once a CO₂ “hole” is created by the deposition plants). It is also noted that diffusion of global CO₂ to the Antarctic region should increase as the CO₂ is depleted.

Finally, a global partnership is envisioned and required to solve the global problem, and the Antarctic is the perfect location.

Appendix I Depositional Temperature for Terrestrial Air CO₂

1. Clausius-Clapeyron Equation

$$\frac{dP}{dT} = \frac{L}{T \Delta V} \quad (1) \quad \begin{array}{l} L \equiv \text{Latent heat of phase change} \\ T \equiv \text{temperature; } \Delta V \equiv \text{specific volume} \end{array}$$

$$P\alpha = RT \text{ or } \alpha = \frac{RT}{P} \quad (2)$$

$$\text{Now } dp = \frac{L}{\alpha} \frac{dT}{T} = \frac{L(P)}{RT} \frac{dT}{T} \text{ or}$$

$$\boxed{\frac{dP}{P} = \frac{L}{R} \frac{dT}{T^2}} \quad (3) \text{ mR} = R^* \equiv \text{universal gas constant}$$

2. Solution for CO₂ deposition in the Earth's atmosphere $\equiv T_{\text{dep}}$ (P = 1 bar)

a) $R^* = 8.314 \text{ J/mole } ^\circ\text{K}^{-1}$ and $m = 44 \text{ g/mole}$

$$\text{thus } R_{\text{CO}_2} = 0.1889 \text{ J/g } ^\circ\text{K}^{-1}$$

$$\text{or } R_{\text{CO}_2} = .1889 \text{ kJ/kg } ^\circ\text{K}^{-1}$$

b) The enthalpy for sublimation of CO₂ (gas-solid):

$$L = 25.5 \text{ kJ/mole or } L = 571 \text{ kJ/kg}$$

c) From the Chemical Engineering Research Information Center (CHERIC), one can obtain the equilibrium curve for equilibrium temperatures of CO₂ vapor over solid CO₂ (see Figure A1.):

From the equilibrium curve, one can choose $T_1 = 20^\circ\text{C} = 293.15^\circ\text{K}$ and $P_1 = 56.5 \text{ atm}$

d) Next, to solve for $T_{\text{dep}} (\equiv T_2)$, one knows the partial pressure of CO₂ in the terrestrial atmosphere is $P_2 = 3.9 \times 10^{-4} \text{ atm}$

Thus, Eq. (3) becomes

$$\int \frac{dP}{P} = \frac{L}{R} \int \frac{dT}{T^2}$$

$$\ln\left(\frac{P_2}{P_1}\right) = -\frac{L}{R} \left[\frac{1}{T_2} - \frac{1}{T_1} \right] \quad (4)$$

Substituting into Eq. (4) for (P₁, T₁) and (P₂, T₂) one obtains,

$$\ln\left(\frac{3.9 \times 10^{-4}}{56.5}\right) = -\frac{571 \text{ kJ kg}^{-1} \text{ K}^{-1}}{.1889 \text{ kJ kg}^{-1} \text{ K}^{-1}} \left[\frac{1}{T_2} - \frac{1}{293.15 \text{ K}} \right], \text{ or } T_2 \equiv T_{\text{dep}} = 136.1 \text{ K}$$

- e) For the mean Antarctic surface Temperature, $\bar{T} = 226 \text{ K}$, the CO₂ snow deposition temperature becomes T_{dep} = 133 K. Please note that a difference in the enthalpy for sublimation from 293.15 K (vapor to solid) versus sublimation from 226 K, accounts for a slightly lower value of the deposition temperature.

APPENDIX II

Deposition of Snow Layer on Floor of Chamber (Refrigerator)

1. Chamber volume: $(100\text{m})^3 = 10^{-3} \text{ km}^3 = 10^6 \text{ m}^3$
2. Atmospheric CO₂ gaseous content: % by weight: 0.046
3. Density of terrestrial air:
T = 226°K: $\rho_{\text{air}} = 1.534 \text{ kgm}^{-3}$
 $\bar{T}$ for Antarctica $\cong 226^\circ\text{K}$
4. Density of CO₂ in terrestrial air at 226°K:
 $1.534 \text{ kgm}^{-3} \times 0.046 \times 10^{-2} = 0.071 \times 10^{-2} \text{ kg m}^{-3}$
5. Mass of CO₂ in 100m x 100m x 100m chamber in Antarctica:
 $(0.071 \text{ kg m}^{-3}) \times (10^{-2}) \times (10^6 \text{ m}^3) = 7.1 \times 10^2 \text{ kg}$
6. One chamber flush per 10 sec $\Rightarrow 6 \times 60 \times 24$ flushes/day
Total flushes per day = 8,640
7. Total CO₂ mass flushed per day:
 $(7.1 \times 10^2 \text{ kg}) \times (8,640) = 6.13 \times 10^6 \text{ kg/day}$
8. Density of dry ice = $1.561 \times 10^{12} \text{ kg km}^{-3}$
9. Surface area of chamber bottom = 10^4 m^2
10. CO₂ snow depth: $\frac{6.13 \times 10^6 \text{ kg}}{1.561 \times 10^{12} \text{ kg km}^{-3}} = 3.93 \times 10^{-6} \text{ km}^3$
Now, $3.93 \times 10^{-6} \times 10^9 \text{ m}^3 \div 10^4 \text{ m}^2 = .393\text{m}$
11. Bottom chamber cumulative depth per hour = $.393\text{m} \div 24 = .0164\text{m/hr}$
12. CO₂ snow depth per day = .393m

APPENDIX III

ΔCO_2 Mass:

1. According to Trenberth (1981), the total mass of the atmosphere is 5.137×10^{18} kg, and 1 ppmv of CO_2 gas is 2.13×10^{12} kg of mass.
 2. Based on global atmospheric CO_2 values from 2000-2009, the $\Delta\text{CO}_2 = 1.88$ ppmv/year.
 3. ΔCO_2 mass added to the atmosphere per year is $(1.88) \times (2.13 \times 10^{12} \text{ kg}) = 4.004 \times 10^{12} \text{ kg}$ (Note: 1 B tons of $\text{CO}_2 = 10^{12} \text{ kg}$)
 4. Virgin Earth Challenge: 10^{12} kg per year
 $\Rightarrow \Delta\text{CO}_2 = 1 \div 2.13 = .47 \text{ ppmv}$
- General Summary: 4 B tons of CO_2 gas into the atmosphere annually increases the atmosphere content by ~ 2 ppmv and the VE challenge would reduce the annual increase by $\sim 25\%$ (~ 0.5 ppmv).

Deposition Plant:

1. Volume = $(100 \text{ m})^3 = 10^6 \text{ m}^3 = 10^6 (10^{-3} \text{ km})^3$
 $= 10^6 (10^{-9}) \text{ km}^3 = 10^{-3} \text{ km}^3$
2. Mass of CO_2 in the depositional chamber
 $7.1 \times 10^2 \text{ kg}$
3. 360 chamber flushes per **hour**: (for sidewall exhaust velocity = 10 ms^{-1})
Mass of CO_2 processed in one hour =
 $(360) \times (7.1 \times 10^2 \text{ kg}) = 2.56 \times 10^5 \text{ kg}$
4. Depositional plant mass/year =
 $(24) \times (365) (2.56 \times 10^5 \text{ kg}) = (8.76) (10^3) (2.56 \times 10^5) \text{ kg}$
 $= 2.24 \times 10^9 \text{ kg} = 0.00224 \text{ B tons}$
5. Number of plants for $\Delta\text{CO}_2 = 4.004 \times 10^{12} \text{ kg} \div 2.24 \times 10^9 \text{ kg} = 1.787 \times 10^3 = 1,787$
 - a) $N = 1,787$ for 4 B tons
 - b) $N = 446$ for 1.0 B tons (Virgin Earth Goal)

APPENDIX IV

Energy and Power Plant Requirements

1. 617 Joules per g (CO₂ deposition at 136.1°K)

2. ΔCO_2 (1.88 ppmv): $1.88 \times 2.13 \times 10^{12} \text{ kg} = 4.004 \times 10^{12} \text{ kg}$

3. Energy = $(617 \times 10^3 \text{ Joules kg}^{-1}) (4 \times 10^{12} \text{ kg}) = 2.47 \times 10^3 \times 10^{15} \text{ kg}$
 $= 2.47 \times 10^{18} \text{ Joules}$

4. Time in seconds / year:

$(60) (60) (24) (365) = (6) (6) (2.4) (3.65) (10^5) \text{ sec}$
 $= 315.36 \times 10^5 \text{ s} = 3.1536 \times 10^7 \text{ seconds}$

5. Power plant: 1200-MW = $1.2 \times 10^9 \text{ Joules s}^{-1}$

1 year = $3.1536 \times 10^7 \text{ secs} \Rightarrow$

One plant for one year: $(1.2 \times 10^9) (3.15) (10^7) \text{ Joules}$
 $= 3.78 \times 10^{16} \text{ Joules}$

6. Number of power plants (N*) needed = $\frac{2.47 \times 10^{18} \text{ Joules}}{3.78 \times 10^{16} \text{ J}} = 0.653 \times 10^2 \cong 65.3$

a) N* = 65 for 4 B tons

b) N* = 16.2 for 1.0 B tons (Virgin Earth Goal)

N $\equiv$ Number of depositional plants(446); 43-MW per depositional plant

N* $\equiv$ Number of power plants (16) 1200-MW wind farms; 28 deposition plants per
wind farm

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Figure captions

Figure 1. Global mean value of CO₂ (January 1979 - March 2010) depicting the greater than linear increase from 1998 to March 2010. The line is fit to the period January 1979-December 1997, and extrapolated forward in time for comparison. The annual increase in CO₂ for the 2000-2009 decade is 1.88 ppmv. (Data provided by the Earth System Research Laboratory, NOAA – Boulder, Colorado.)

Figure 2. CO₂ ice cap over the South Pole of Mars, as revealed by NASA's Mars Global Surveyor and Odyssey missions (2005).

Figure 3. The International arena of Antarctica. Potentially favorable locations for CO₂ sequestration facilities are along the coastal regions, with favorable katabatic winds and supporting research stations that can benefit from the excess thermal waste of the cooling plants.

Figure 4. Proposed scientific-engineering system for global removal of atmospheric CO₂ in Antarctica. System components A, B, C, D and E are appropriately labeled.

Figure 5. Closed Loop Liquid-Vapor Cooling System, depicted as an adiabatic cycle. The design of this thermodynamic cooling system is based on operational conditions in Antarctica. CO₂ gas in terrestrial air changes to solid CO₂ ("snow") at a temperature of 133°K. Waste heat from the heat exchanger can be used to heat base facilities. Wind farms are designed to supply electrical energy to drive the compressor.

Figure 6. The proposed CO₂ deposition plant. The chamber box for terrestrial air intake is 100m x 100m x 100m. The bottom floor opens for solid CO₂ excavation to nearby insulated landfills. Liquid nitrogen is the coolant for the front and back side

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358 Obtained from the Chemical Engineering Research Information Center.

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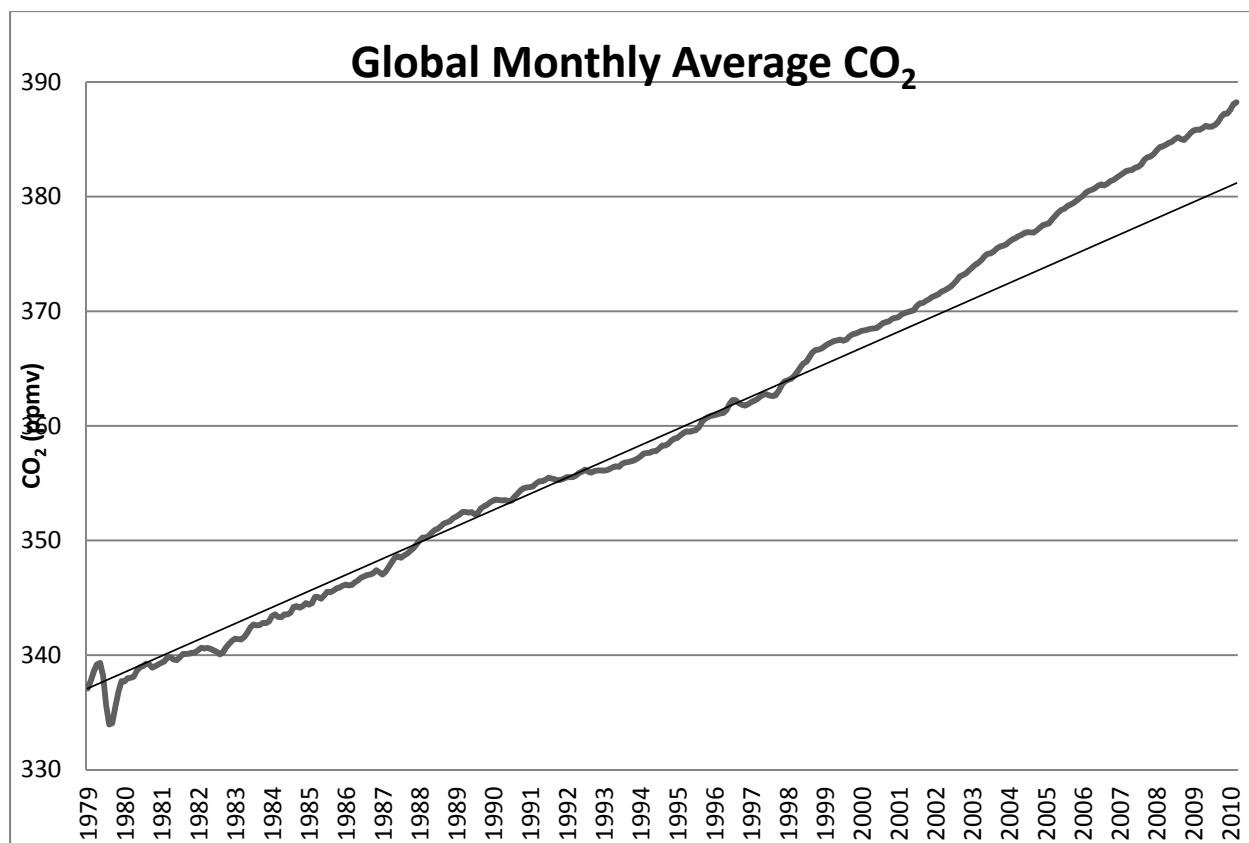
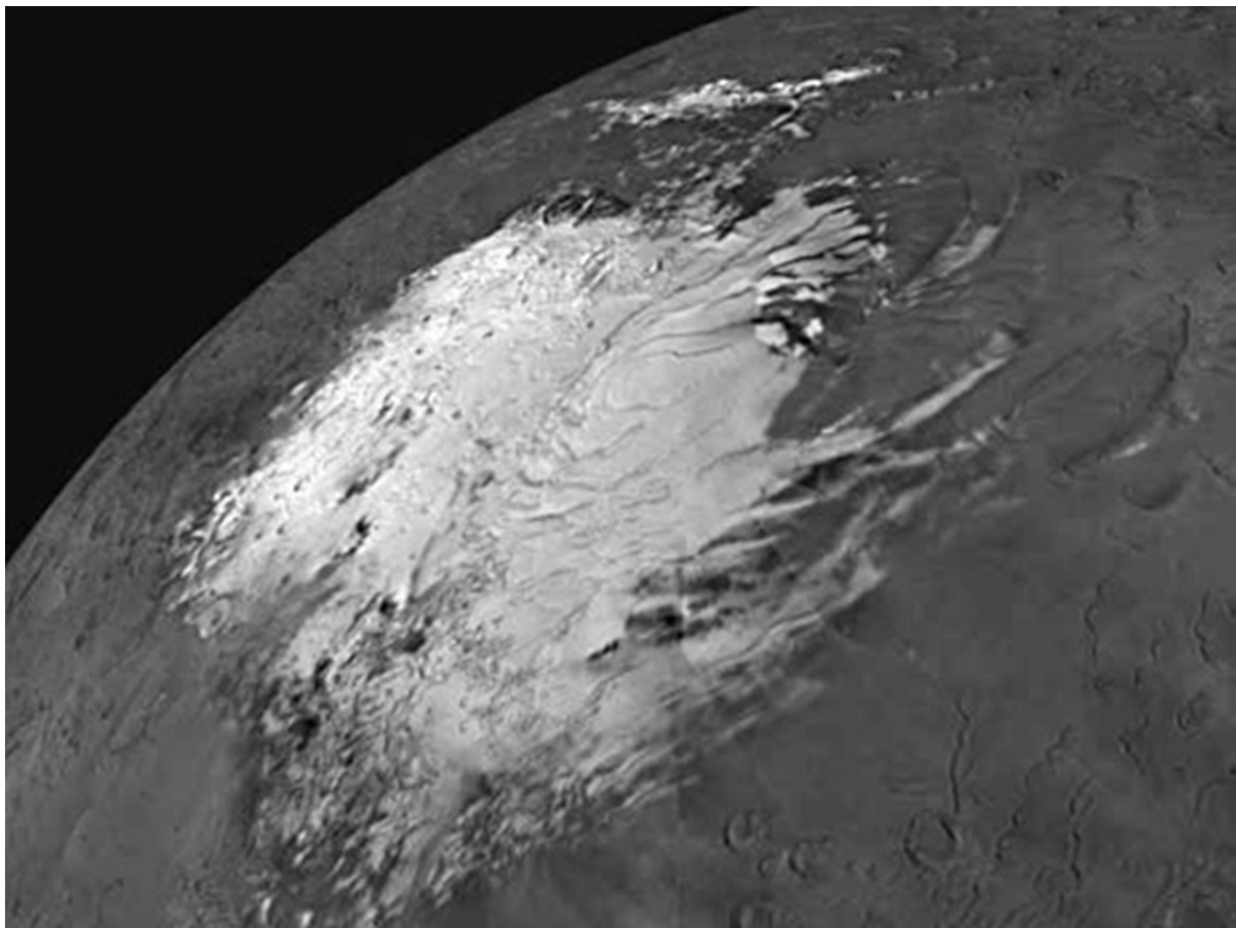


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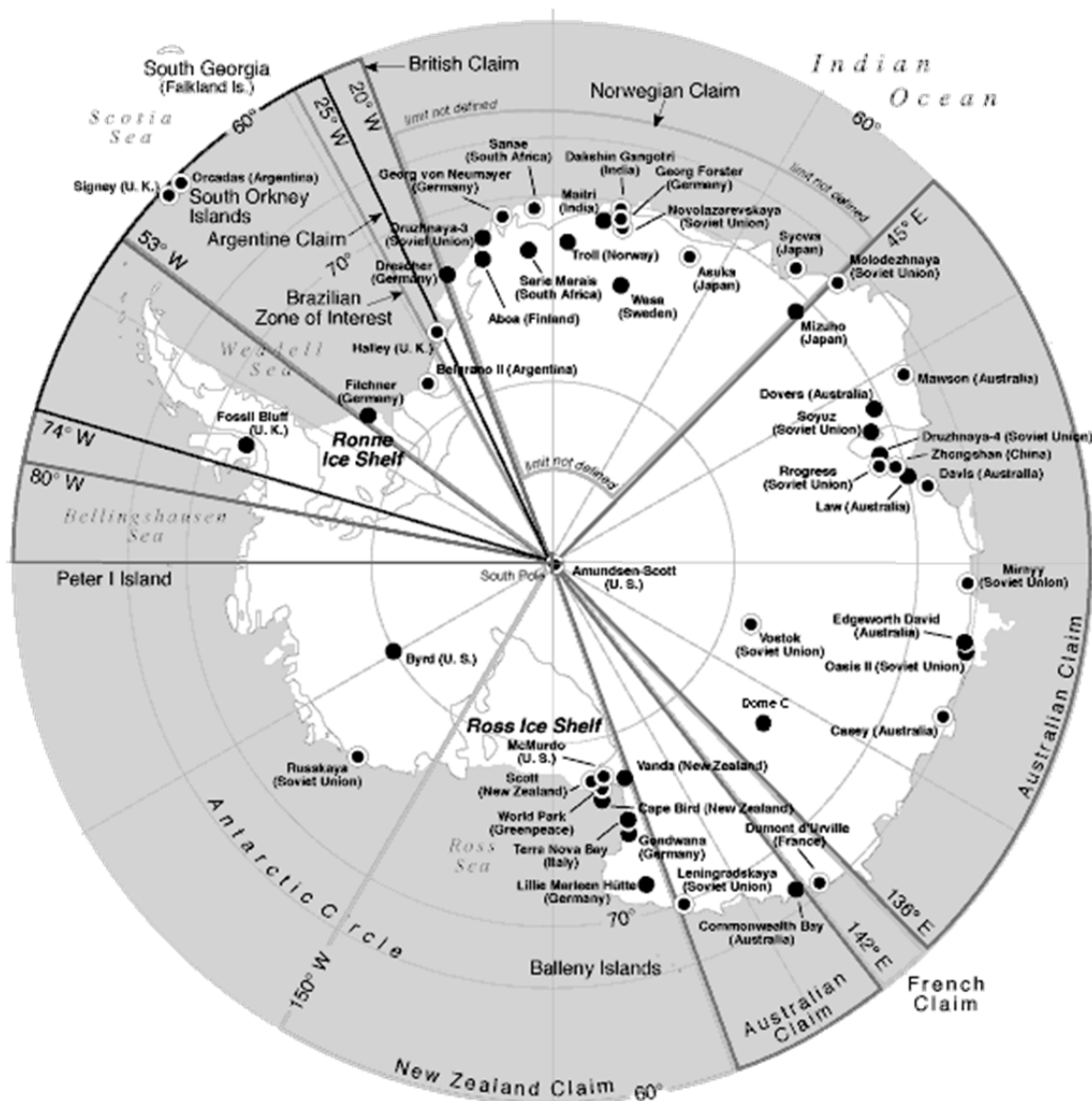
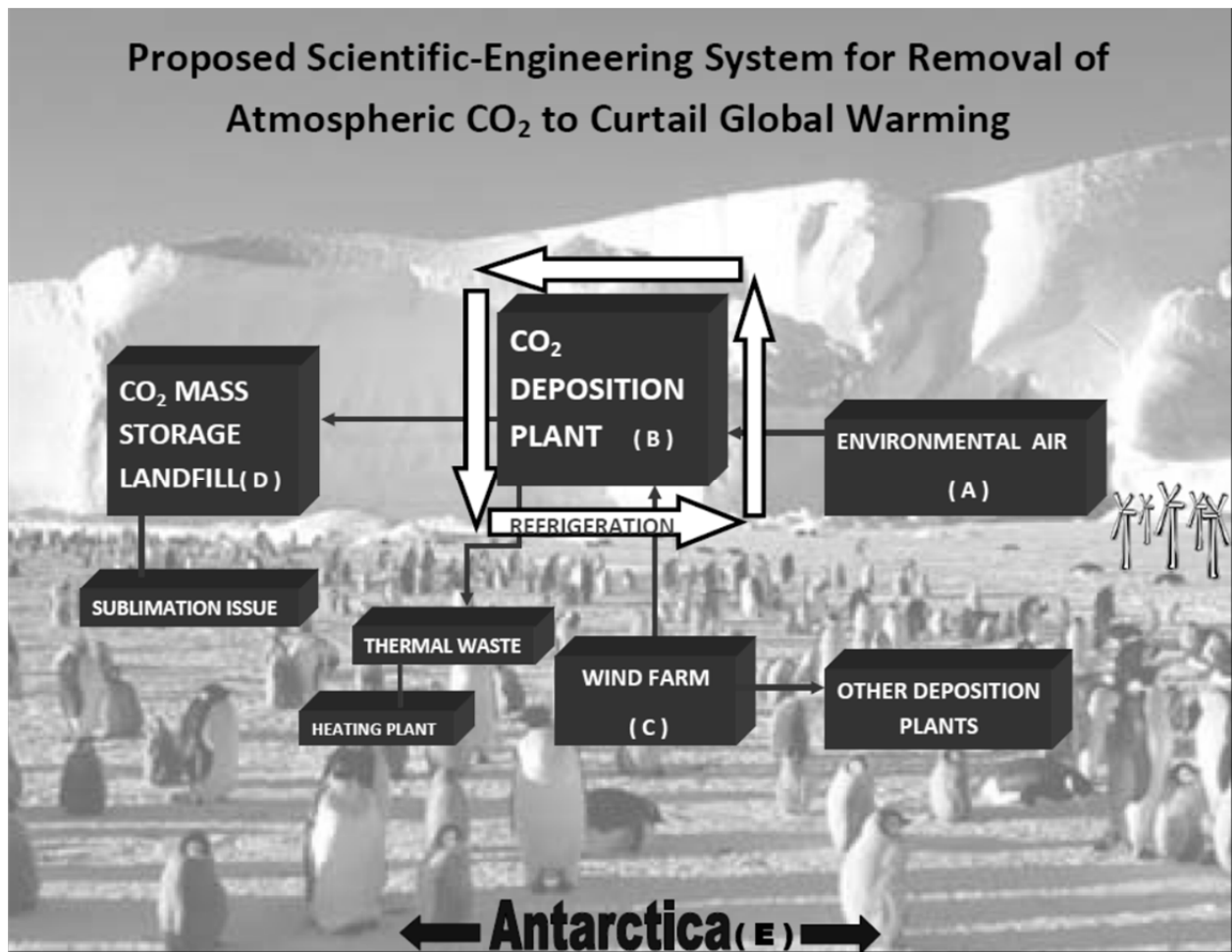


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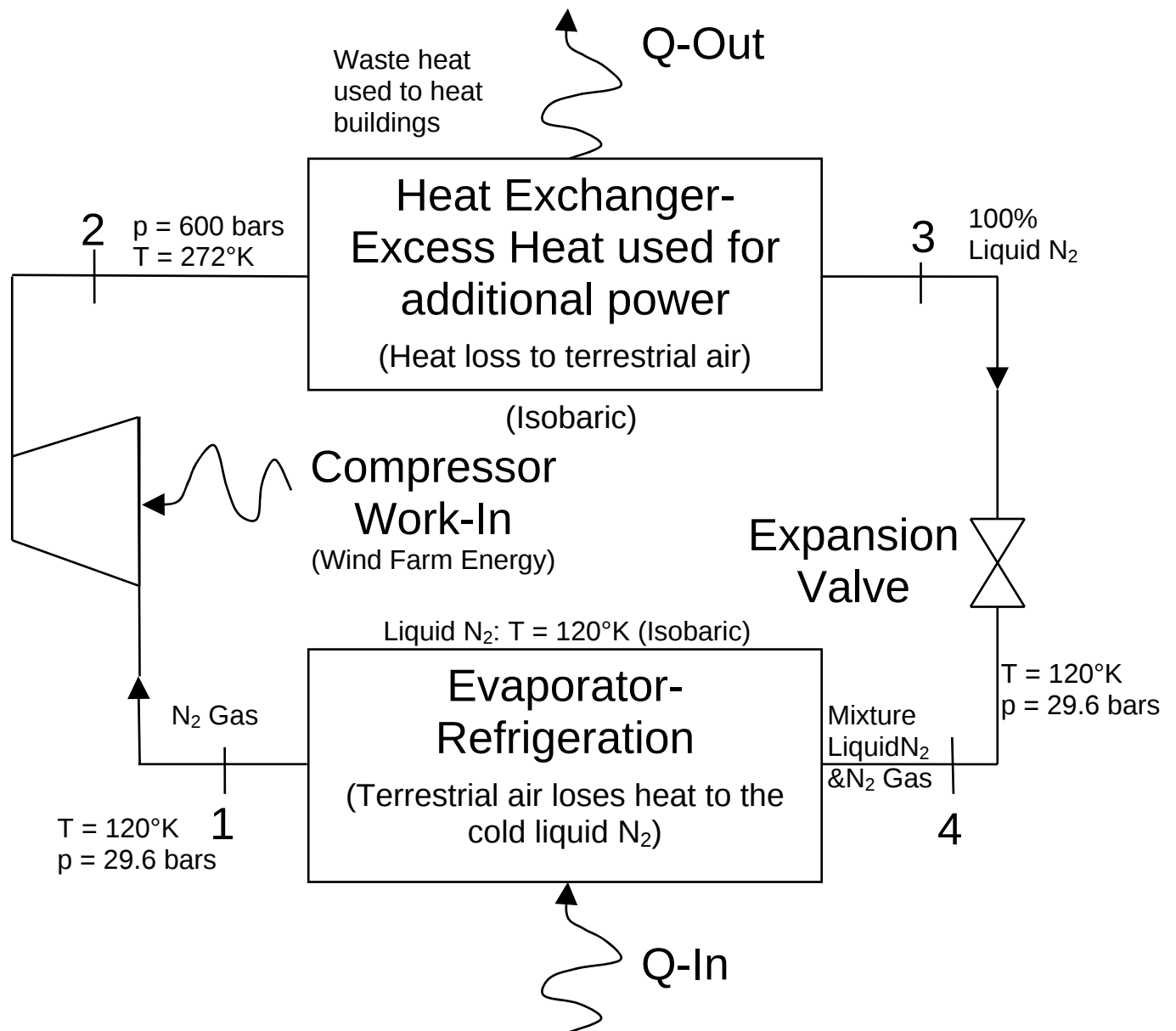
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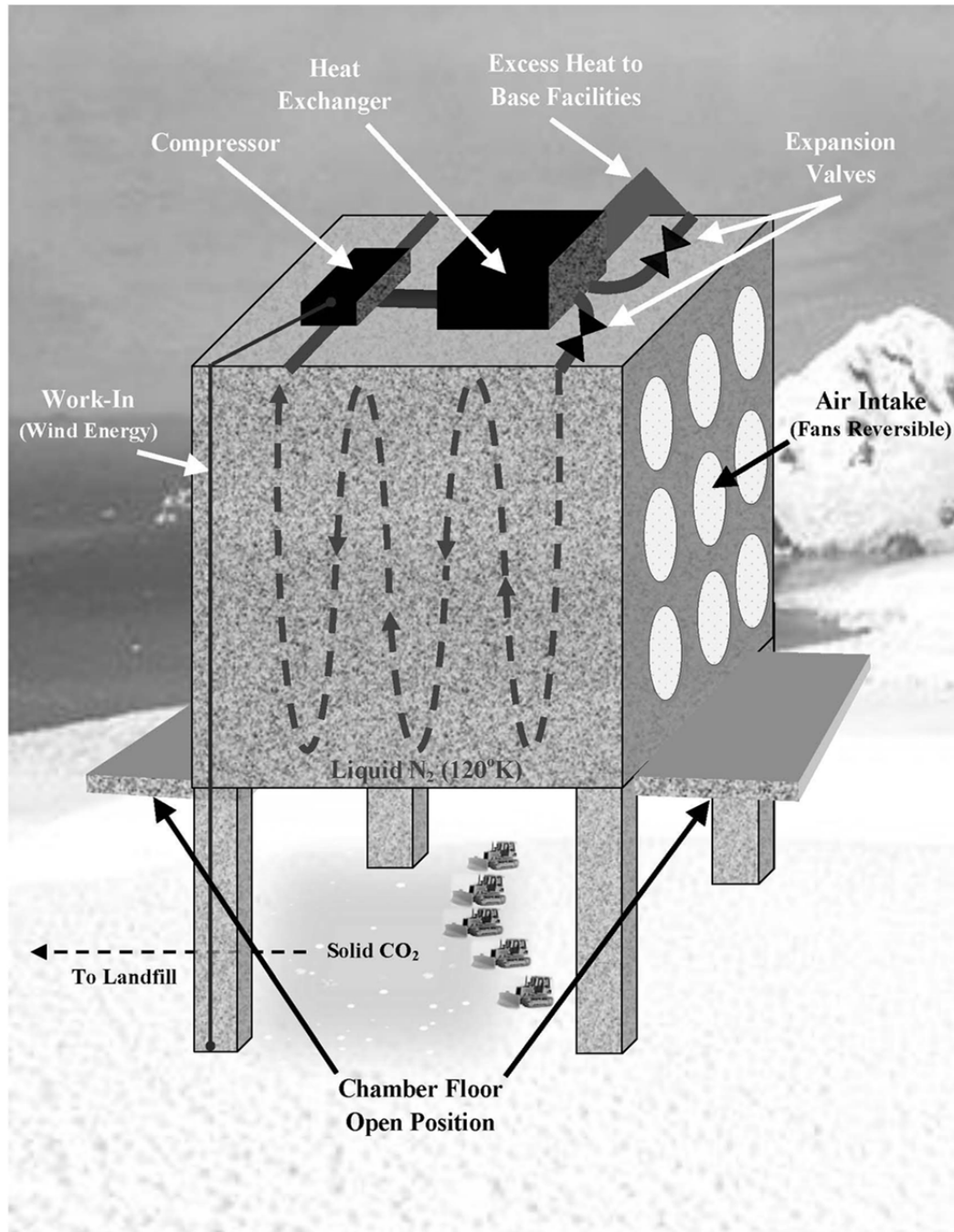
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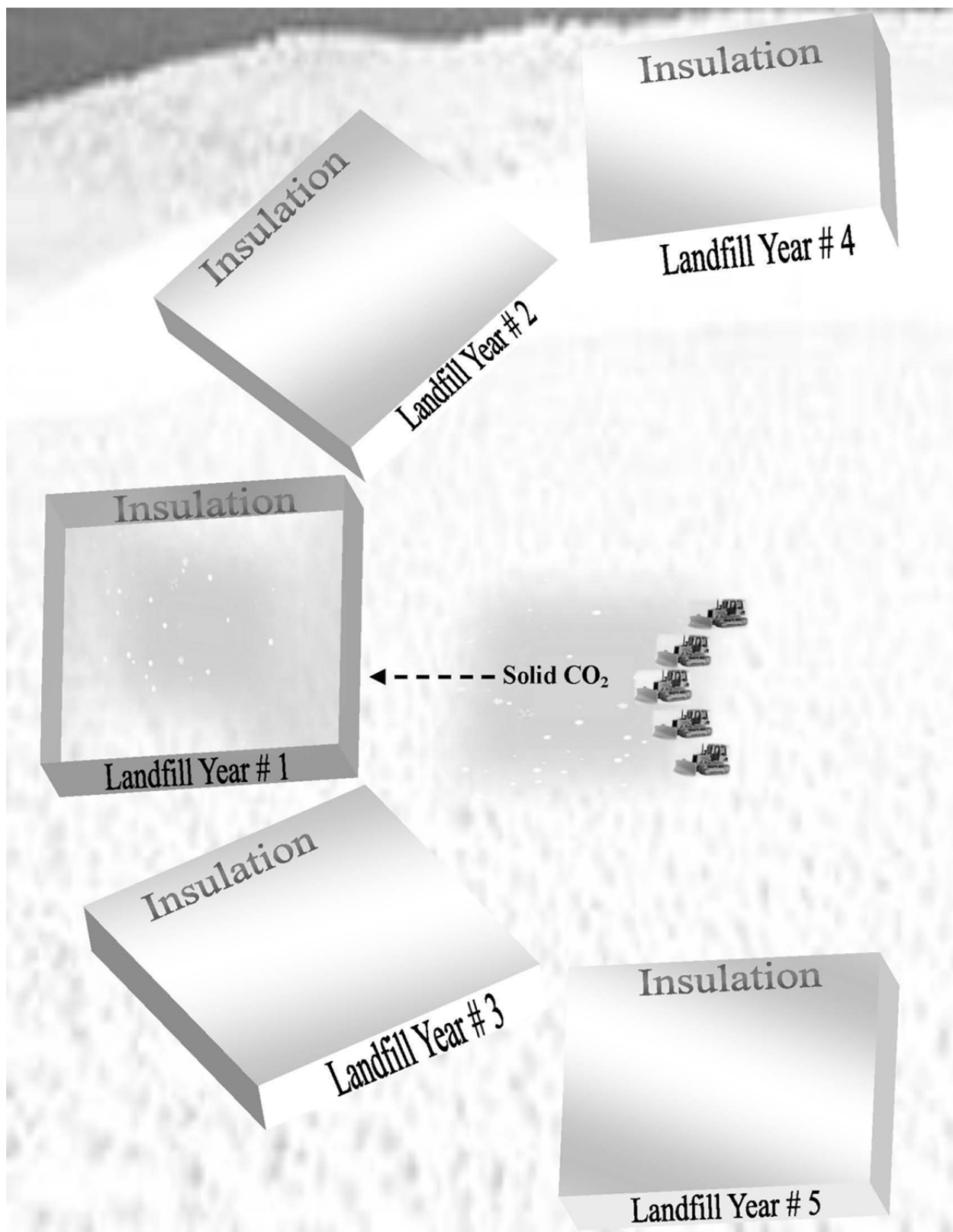


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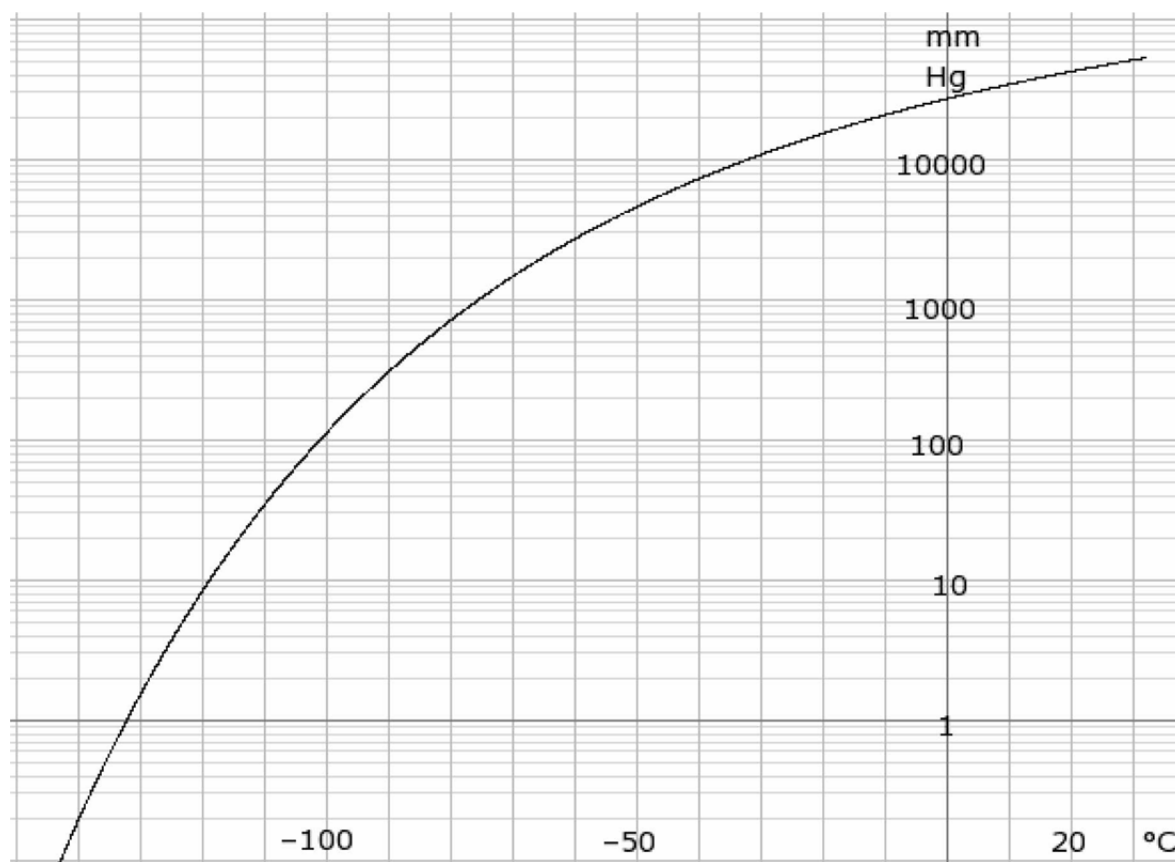


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