Iron Fertilization, Air Capture, and Geoengineering

Woods Hole, MA

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How Industry May Change Climate

The amount of carbon dioxide in the air will double by the year 2080 and raise the temperature an average of at least 4 per cent. The burning of about two billion tons of coal and oil a year keeps the average ground temperature somewhat higher than it would otherwise be. If industrial growth extended over several thousand years instead of over a century only, the oceans would have absorbed most of the excess carbon dioxide. Seas circulate so slowly that they have had little effect in reducing the amount of the gas as man's smoke-making abilities multiplied during a hundred years.

All this and more came out in the course of a paper that Dr. Gilbert N. Plass of Johns Hopkins presented before the American Geophysical Union. He found that man's industries add six billion tons of carbon dioxide to the atmosphere.

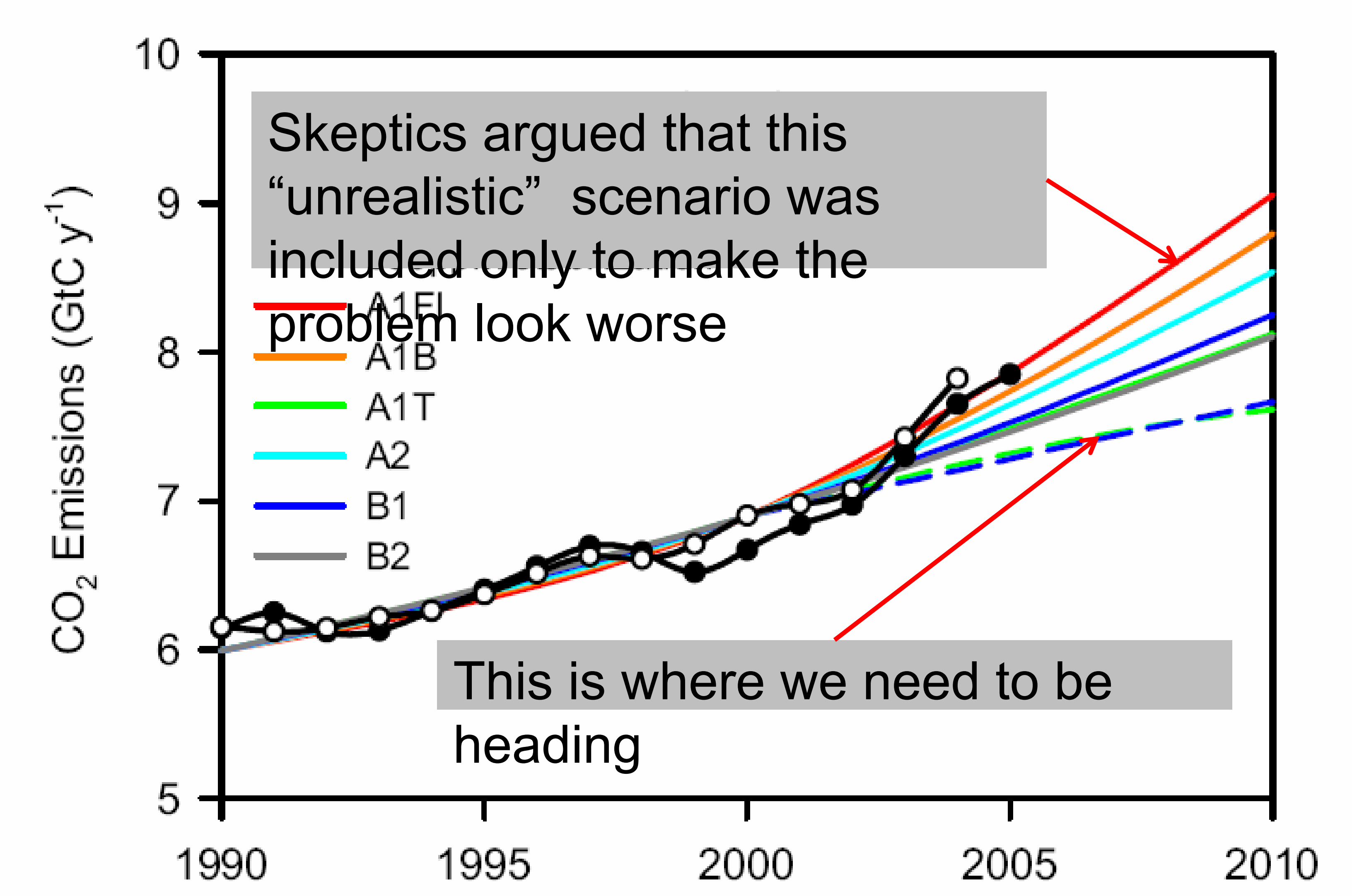
rents necessary for the onset of precipitation. This may mean less rainfall and cloud cover, so that still more sunlight can reach the earth's surface. Thus man tends to make his climate warmer and drier; should there be a decrease in carbon dioxide, a cooler and wetter climate would result.

Theory Applied to Glaciers

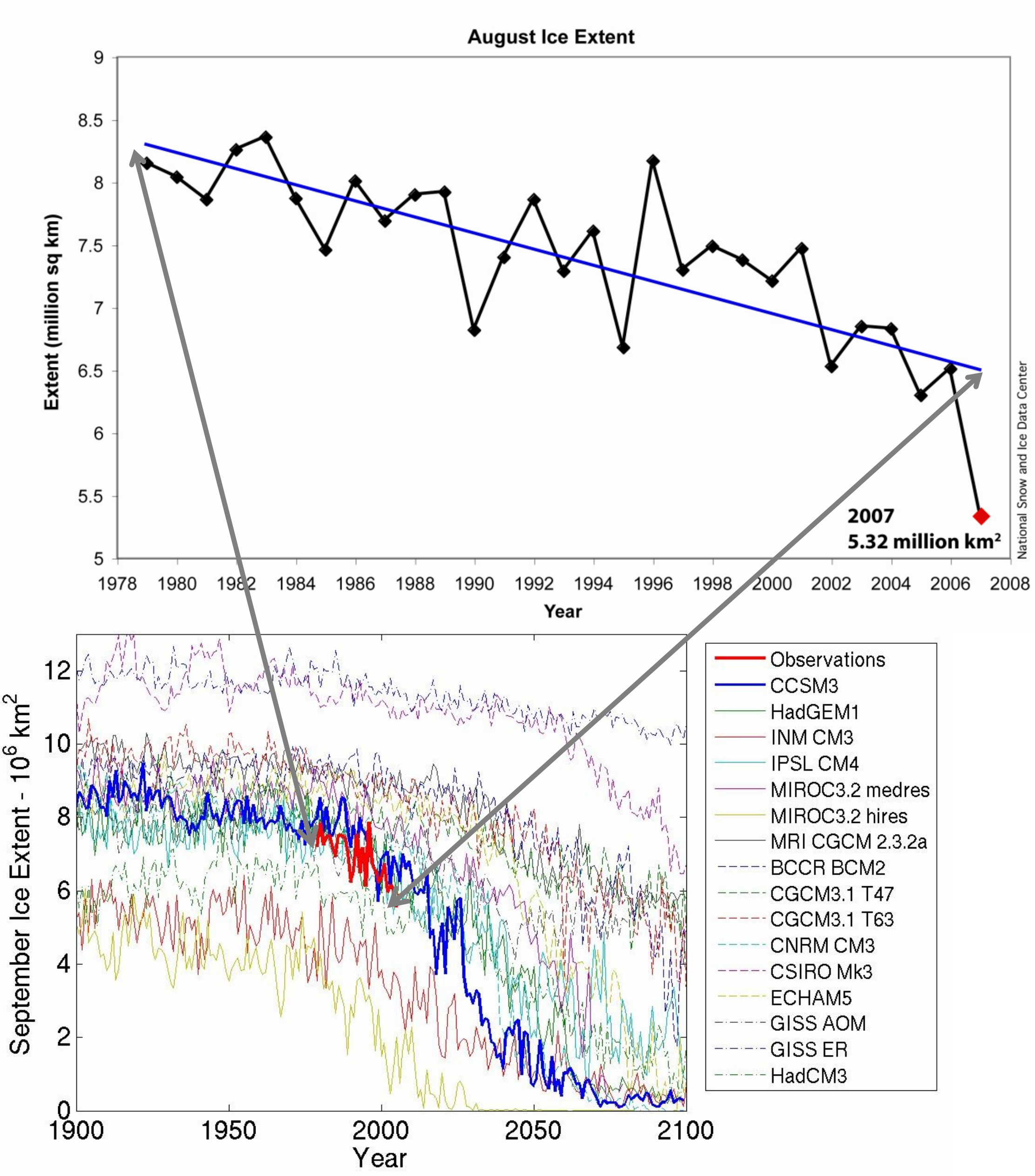
All this reinforces a theory advanced in 1861 that decreases in carbon dioxide explain the growth and advance of glaciers at various intervals in the

New York Times
May 24th **1953**

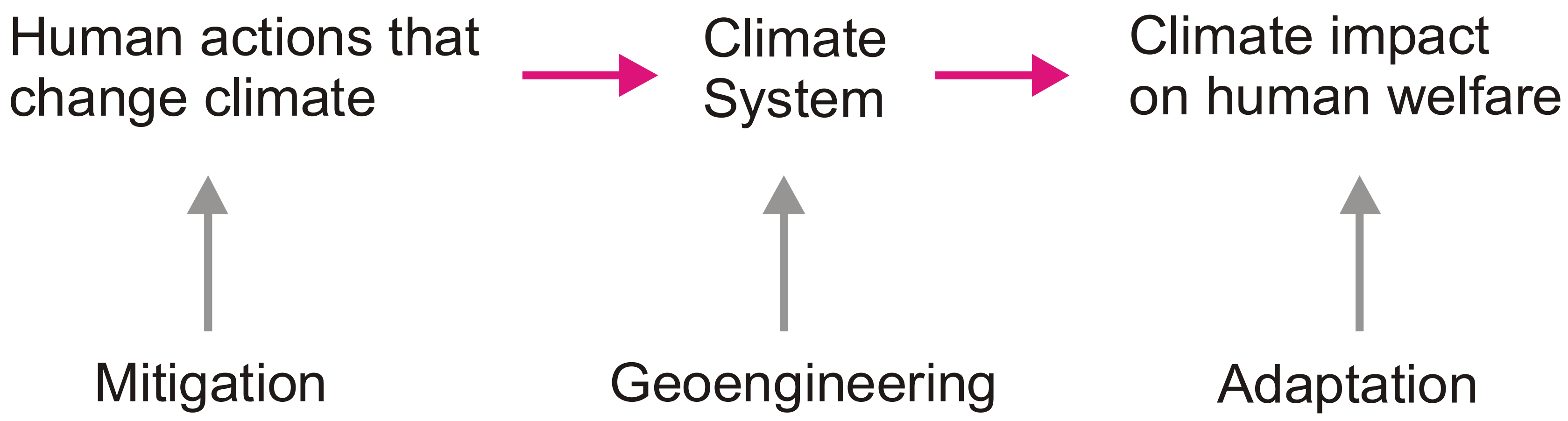
Emissions are rising faster than expected

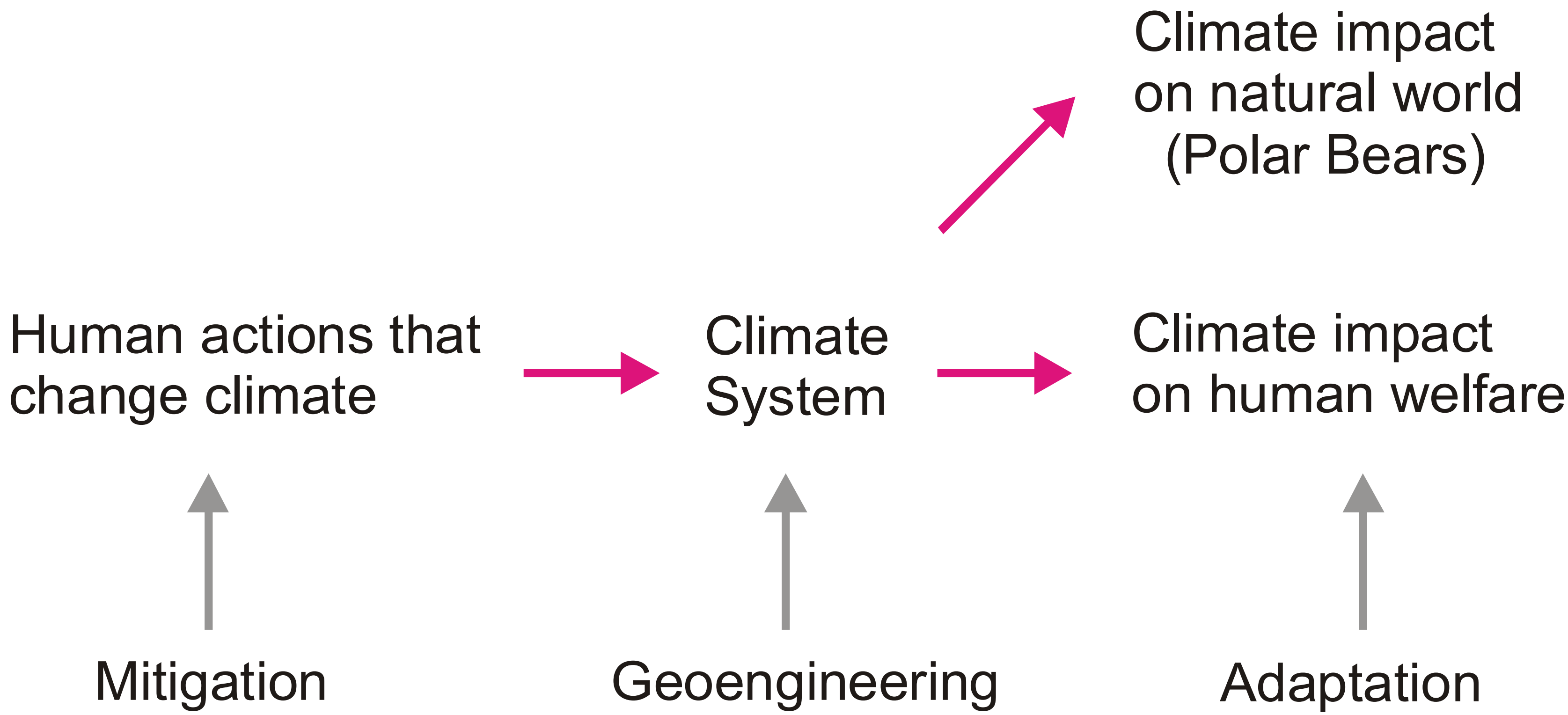


And, it's melting quicker than models predict



Human actions that change climate → Climate System → Climate impact on human welfare


Human actions that change climate
Climate System
Climate impact on human welfare
Mitigation
Geoengineering
Adaptation


Climate impact
on natural world
(Polar Bears)
Human actions that
change climate
Climate
System
Climate impact
on human welfare
Mitigation
Geoengineering
Adaptation

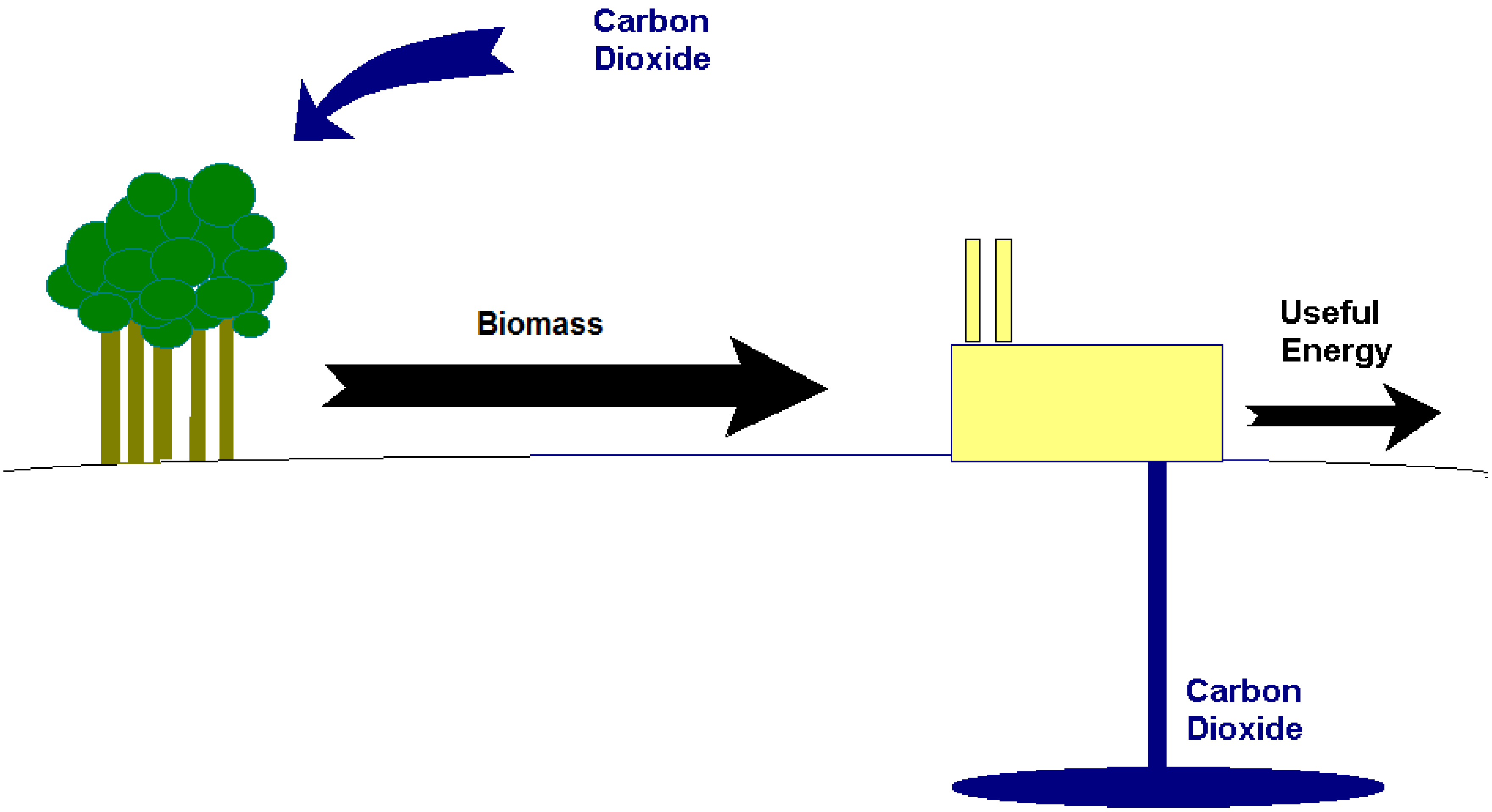
Carbon Management: Location *vs* Mechanism

Location

Mechanism	Land Surface	Ocean	Geosphere
Biological	Enhancing carbon content of soils Afforestation	Fertilization to accelerate biological pump	Use of anaerobic biological reactions to reduce CO_2 to CH4 in strongly reducing environments.
Chemical	Industrial production of stable carbonates	Acceleration of $CaCO_3$ dissolution Addition of alkalinity	Subsurface dissolution of carbonates or silicates by brines acidified by injected CO_2.
Physical		Formation of 'lakes' of liquid CO_2.	Physical confinement of gas phase CO_2 in underground formations.

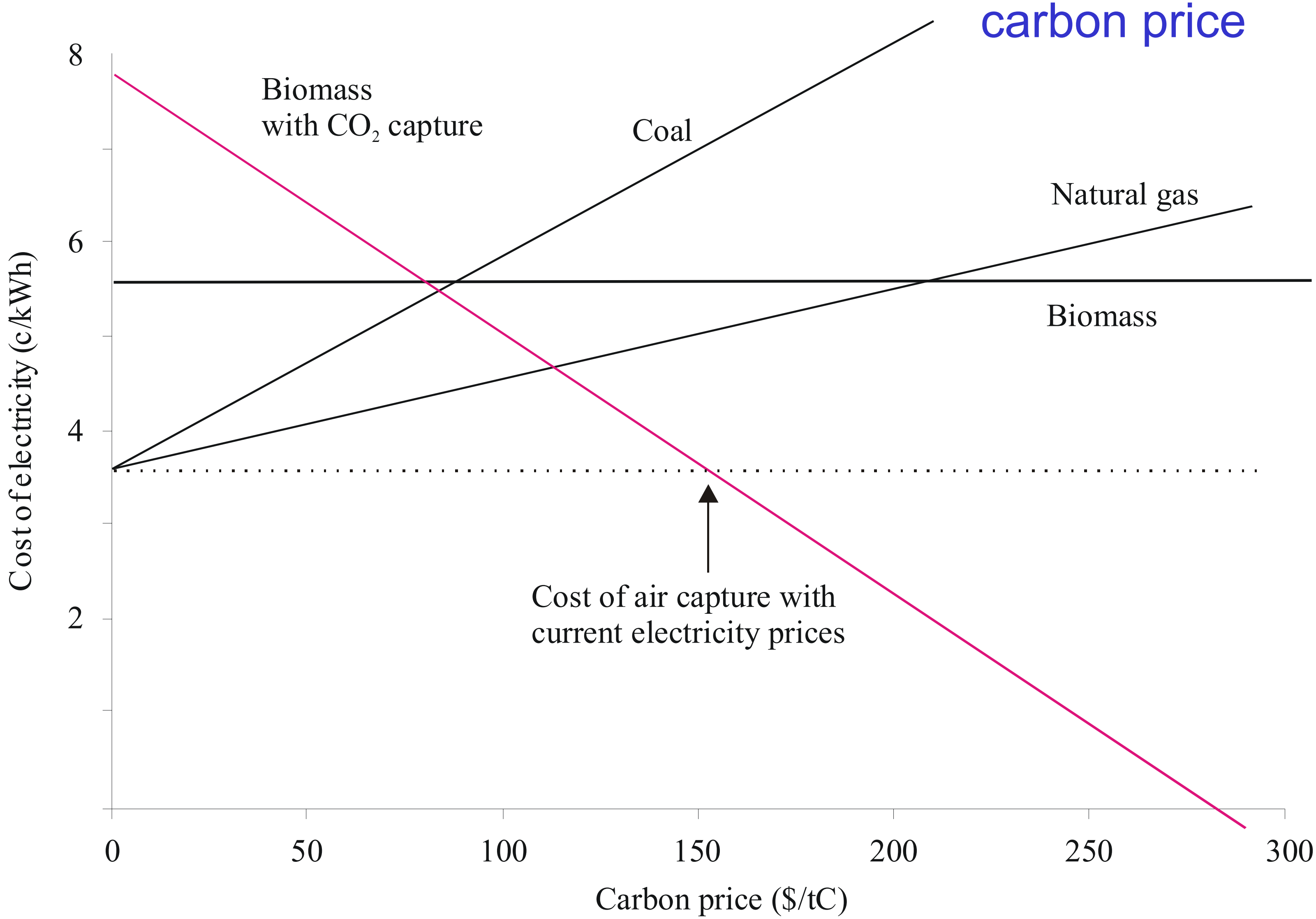
Biomass Energy with Capture

Biomass with Capture



Electricity for free…

… at a ~300 $/tC carbon price



Air Capture

Thermodynamics of CO_2 capture

Free energy of mixing:

$$kT \ln\left(p / p_0 \right)$$

To get 1 bar it takes:

~ 6 kJ/mol starting at 10% CO_2 in a power plant exhaust, and

~ 20 kJ/mol starting at the 380 ppm ambient atmospheric concentration

It takes ~13 kJ/mol to compress from 1 to 100 bar

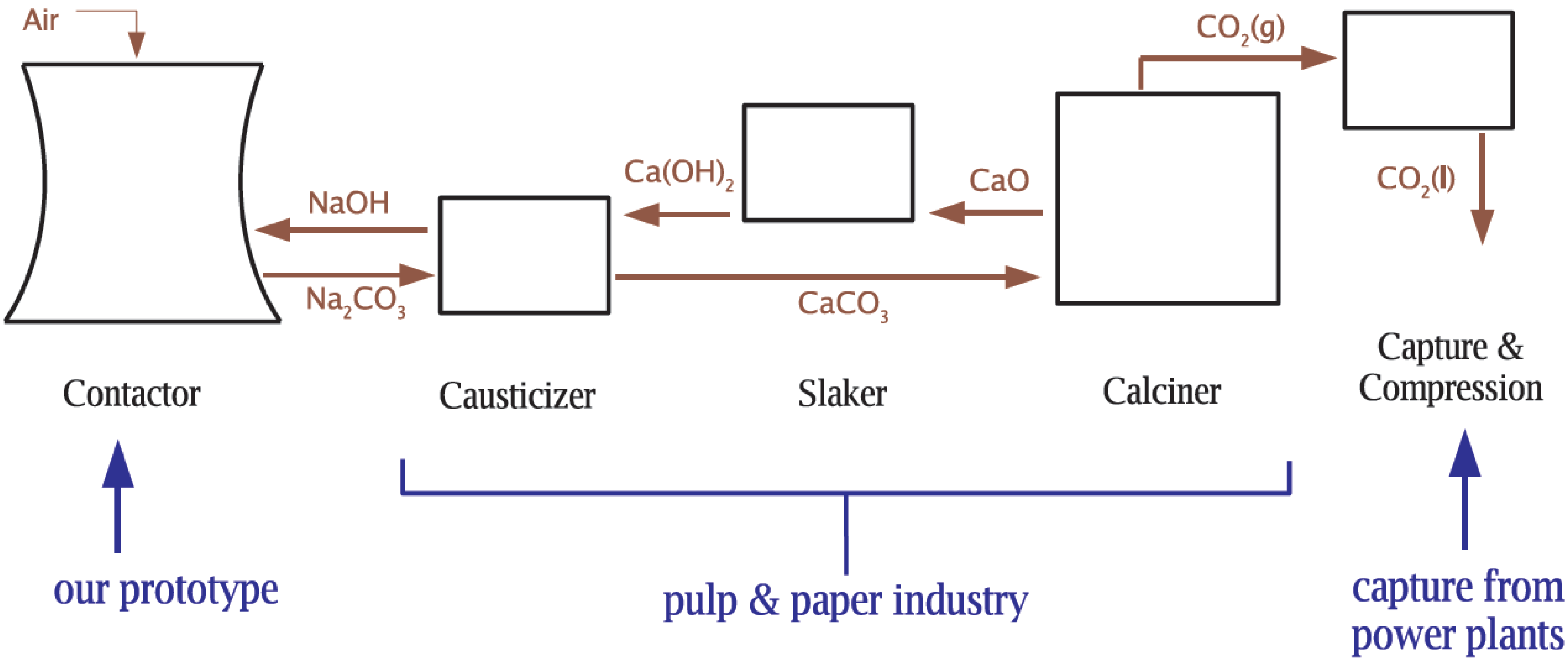
$C + 2\ O_2 \rightarrow CO_2$ 394 kJ/mol

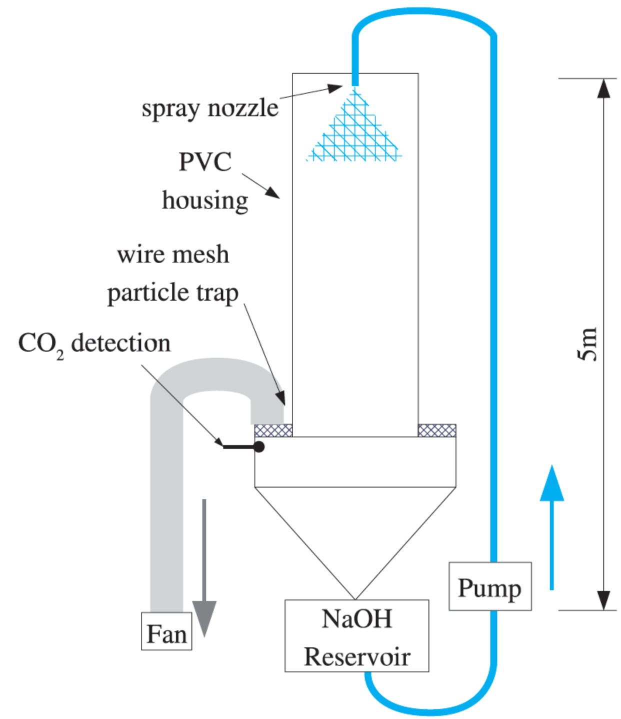
Power plants are ~35% efficient (~160 kJe/mol-C from coal)

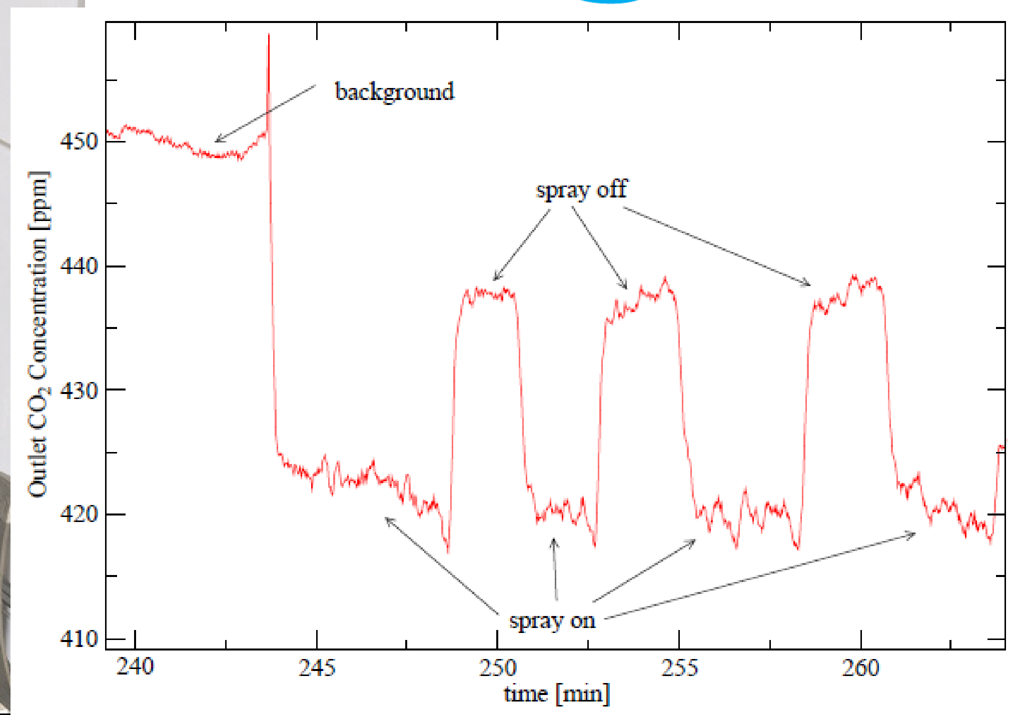
min loss of electric output should be ~12% ((6+13)/160).

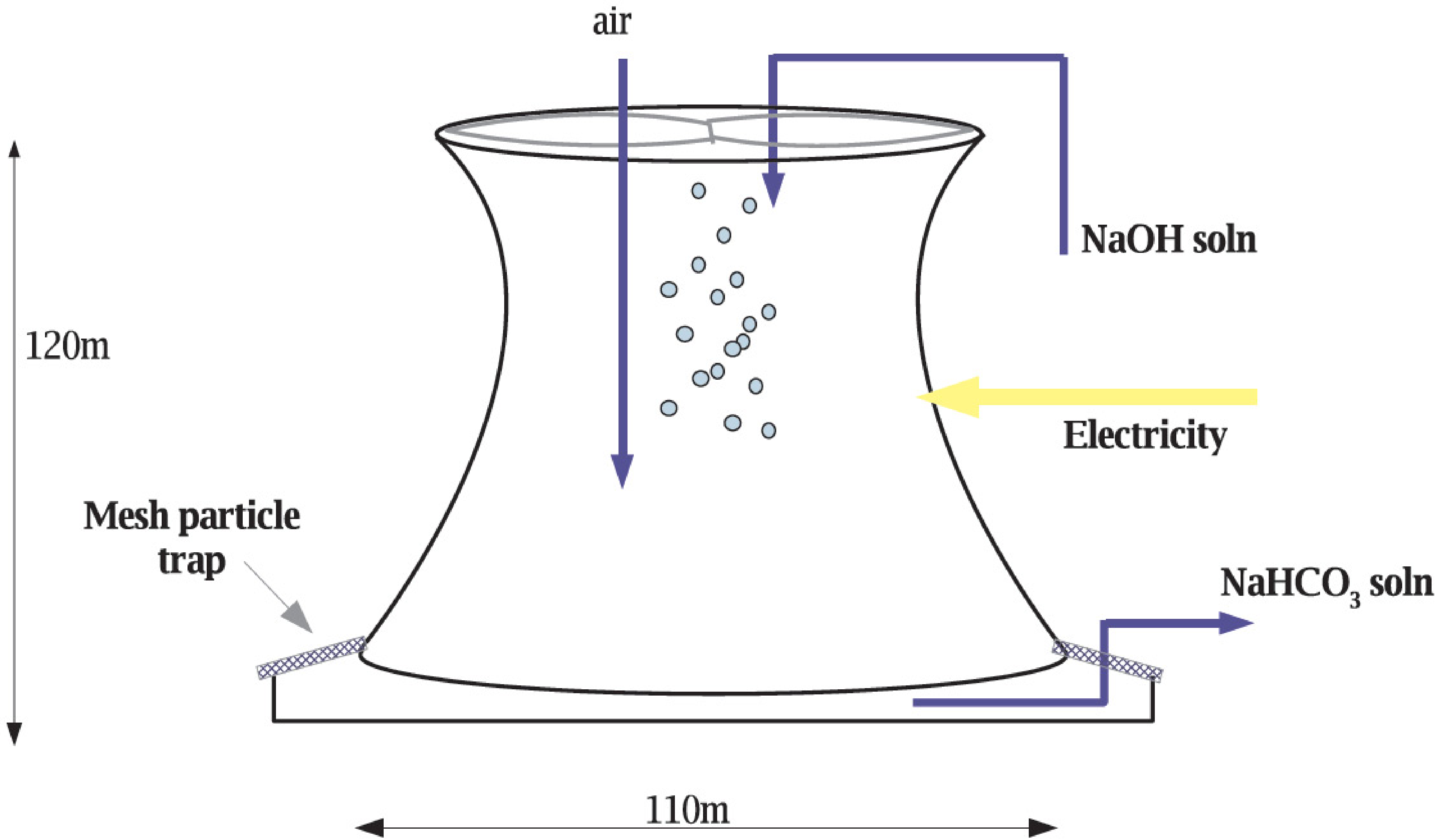
Current designs are at least twice as bad.

Direct Air Capture

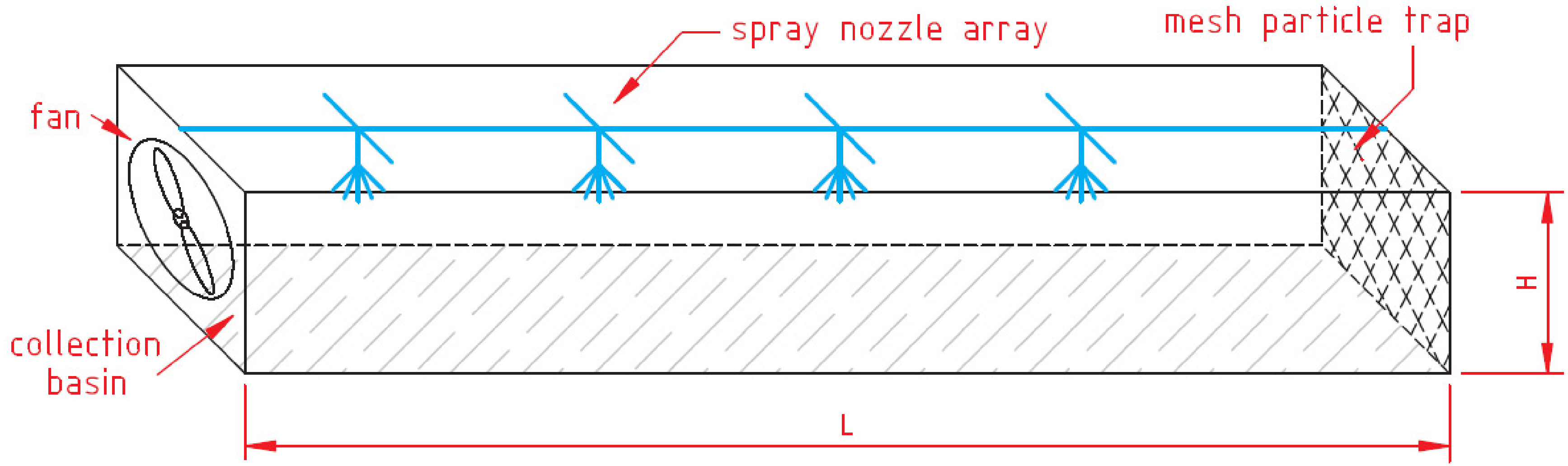


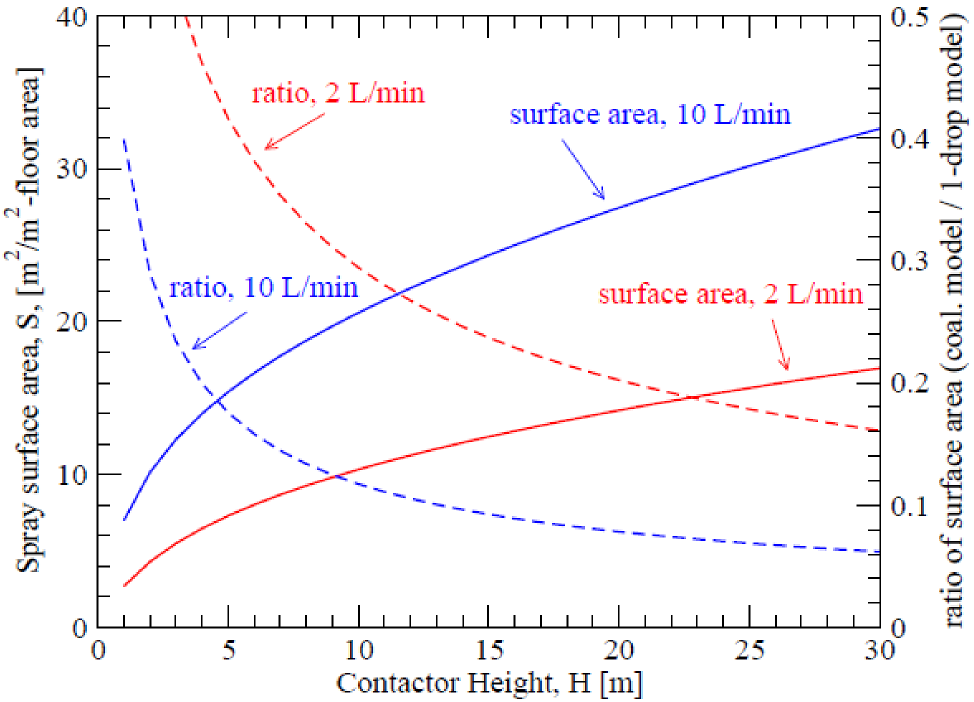

spray nozzle
PVC
housing
wire mesh
particle trap
CO_2 detection
5m
Pump
Fan
NaOH
Reservoir


background
spray off
spray on
Outlet CO_2 Concentration [ppm]
time [min]
410
420
430
440
450
240
245
250
255
260

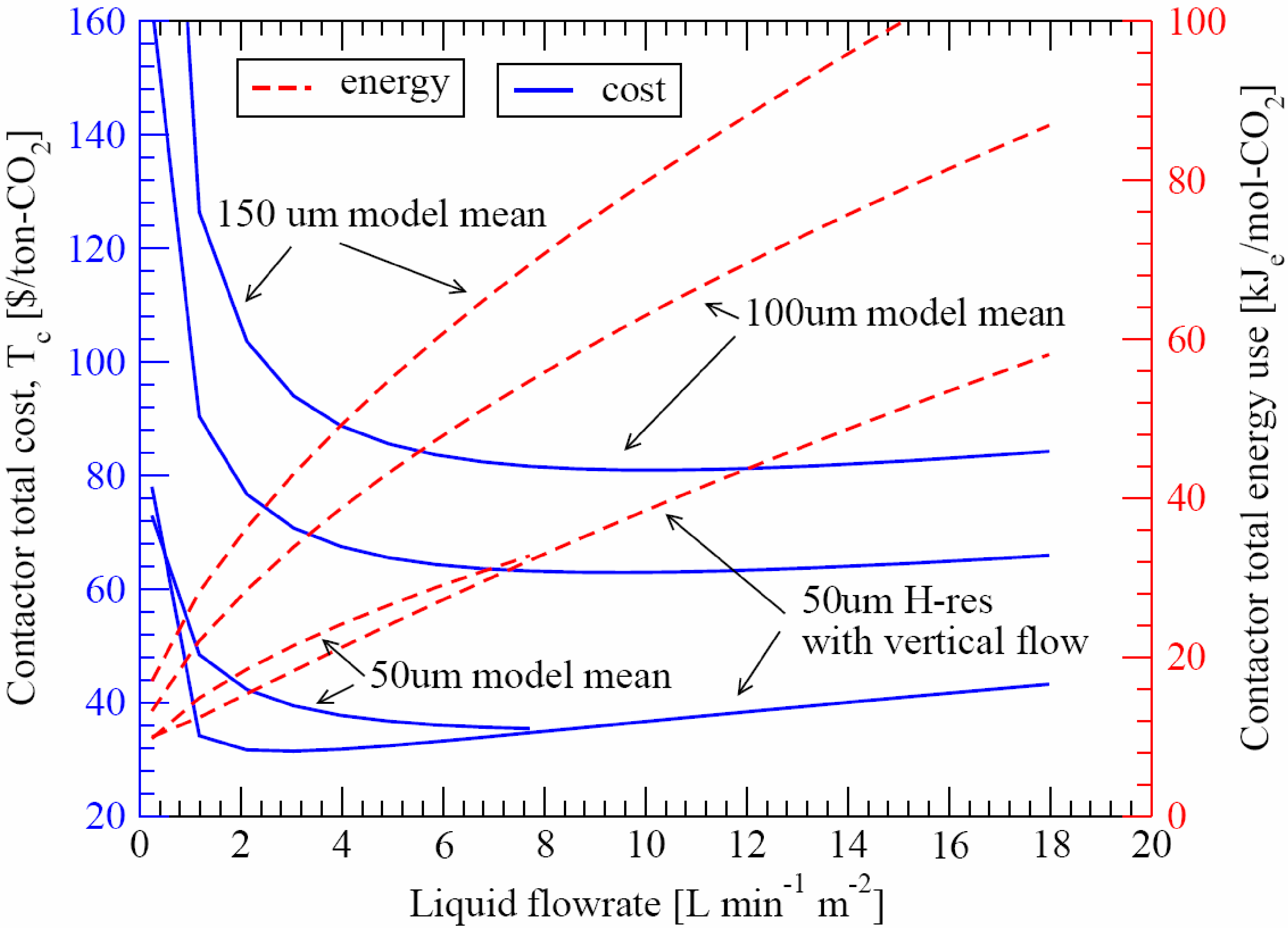

air
NaOH soln
120m
Electricity
Mesh particle
trap
NaHCO3 soln
110m


Global Research Technologies
will build a prototype
(100kg/day)
Art Courtesy Stonehaven CCS, Montreal

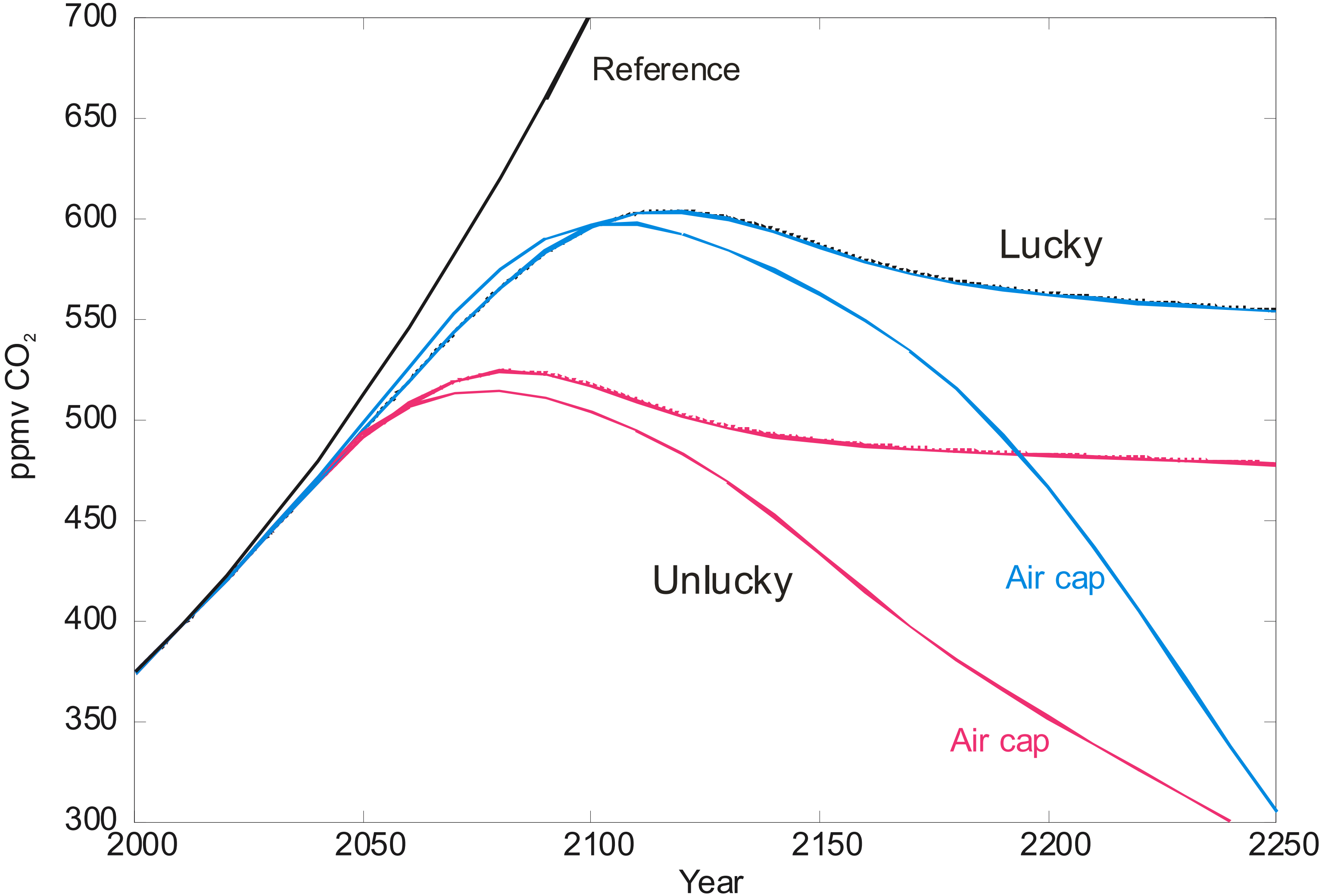

spray nozzle array
mesh particle trap
fan
collection
basin
H
L


ratio, 2 L/min
surface area, 10 L/min
ratio, 10 L/min
surface area, 2 L/min
Spray surface area, S, [m2/m2-floor area]
ratio of surface area (coal. model / 1-drop model)
Contactor Height, H [m]
0
5
10
15
20
25
30
0
10
20
30
40
0
0.1
0.2
0.3
0.4
0.5

Cost and energy use *vs* flow rate



Negative emissions change long-run climate policy



Keith, D. W., Ha-Duong, M. & Stolaroff, J. K. Climate strategy with CO_2 capture from the air. *Climatic Change* (2005).

Air Capture Summary

1. Three uses
   - Long run negative emissions (2100?).
   - Acting in a rush, AC along while we do Coal CCS (2030?)
   - Low Carbon Fuels and remote EOR (2015?)

2. NaOH contactor
   - ETH/Rome group using commercial data on packed towers.
   - Calgary/CMU using spray tower
   - Less than \$50/tCO_2

3. NaOH regen
   - Nuclear heat
   - Electrochemical
   - Borates/Titenates
   - No good end-to-end costing.

Other Methods

Increasing ocean alkalinity

Motivation: $2\times[CO_3^{-2}] + [HCO_3^{-}] \cong [A]$

- Mg-silicates
  - Olivine (Mg_2SiO_4) and serpentine ($Mg_3Si_2O_5(OH)_4$) are the most abundant Mg-silicates
- MgO
- $CaCO_3$
- CaO

Comparisons

Eos, Transactions, American Geophysical Union, Vol. 73, No. 27, July 7, 1992, Pages 289, and 292–293.

A Serious Look at Geoengineering

David W. Keith and Hadi Dowlatabadi

Possible responses to the problem of anthropogenic climate change fall into three broad categories: abatement of human impacts by reducing the climate forcings, adaptation to reduce the impact of altered climate on human systems, and deliberate intervention in the climate system to change the effects of anthropogenic forcing—geoengineering. Recent reports from the *National Academy of Sciences* [1991] and the *Office of Technology Assessment* [1991] aimed to provide a comprehensive look at possible responses to climate change. While they included geoengineering options, they failed to consider them systematically. We present the beginnings of a more systematic analysis and urge a balanced research program on geoengineering.

We define geoengineering as actions taken with the primary goal of engineering (controlling by application of science) the climate system. Geoengineering is the deliberate manipulation of climate forcings intended to keep the climate in a desired state, in contrast to abatement, which re-

on the worst case, thereby allowing more confidence in pursuing other policy options.

- It seems very unlikely that world greenhouse gas (GHG) emissions can be kept below ~40% of 1990 levels—a prerequisite for averting climate change in the long term [*Houghton et al.*, 1990].

Doubt about the prospects for cooperative abatement of global GHG emissions is a pragmatic reason to consider geoengineering, whose implementation requires fewer cooperating actors than abatement. Thus, geoengineering fills a unique niche because of its potential to mitigate catastrophic climate change.

To act as a fallback strategy, geoengineering must be more certain of effect, faster to implement, or provide unlimited mitigation at fixed marginal cost. Our definition of "fallback strategy" is an extension of the term "backstop technology" used in energy systems analysis for a technology providing unlimited energy at fixed (usually high) marginal cost.

The existence of a fallback is critically important, as it allows more confidence in choosing a moderate response strategy. Moderate responses are difficult to implement when catastrophic consequences are possible from weak anthropogenic climate forcing. Fallback strategies permit moderate responses to be adopted with the knowledge that should these prove inadequate, an alternative mitigation option is available. We examine a range of geoengineering techniques to gauge their suitability as fallback strategies.

Examples of Geoengineering Techniques

Geoengineering affects climate by altering global energy fluxes through one of two strategies, either by increasing the amount of outgoing infrared radiation through reduction of GHGs, or by decreasing the amount of absorbed solar radiation through an increase in albedo.

Three examples of the first strategy, which remove CO_2 from the atmosphere, are direct deep-ocean disposal, ocean-surface fertilization, or afforestation. For the second strategy, we discuss albedo modification by placing solar shields in Earth-orbit, or by increasing aerosol concentrations. Our five cases are chosen to survey geoengineering's wide range of risks and costs. With the exception of direct ocean disposal and afforestation, these schemes have the theoretical potential to mitigate the full effect of anthro-

Table 1. Summary Comparison of Geoengineering Options

Geoengineering Option	Mode of Action	Cost ($ per t CO_2 equivalent)	Risk: Side-Effects	Risk: Feasibility	Nontechnical Issues	References
Direct ocean disposal	CO_2 removal	15–30	Very low: damage to local benthic community.	High costs.	Equity: Like abatement all must bare costs.	*Golomb, NAS*
Ocean fertilization with phosphate	“ ”	1	Possible benefits: increased productivity higher up the food chain. Risk of eutrophication.	Very uncertain biology: can ecosystem shift off the current P:N ratio?	Equity and sovereignty: who pays and who gets the benefits (fish) if any?	*Broecker, Dyson*
Ocean fertilization with iron	“ ”	0.1–15	ditto	Very uncertain biology: is iron really limiting?	ditto	*NAS, OTA, NRC, Peng.*
Reforestation	Primary effect is CO_2 removal. Albedo decrease and increased atmospheric humidity may cause warming	3–10	Very low, but loss of key nutrients from soils and other effects could be significant in the long term.	Rate of C uptake by trees is still unclear.	Equity and sovereignty: who will provide the land for afforestation?	*NAS*
Solar shields	Albedo increase; equivalent to decrease of the solar constant.	0.25–2.5	Very low, but all albedo modifying options change climate.	Launch costs, space technology costs have very high uncertainty.	Security and equity: this may be weather control, who gets the rain?	*Sefritz, NAS*
Stratospheric SO_2	Albedo increase; will also cause stratospheric heating.	0.007	High: accelerated catalysis of CFC driven ozone depletion.	Residence times.	Equity: costs are so low that (who pays) is not an important issue Liability: ozone destruction.	*Broecker, NAS*
Stratospheric dust (inert)	“ ”	0.03–1	Risk of ozone depletion may be less than for SO_2.	Residence times, delivery system costs.	Ditto, except higher costs.	*NAS*
Tropospheric SO_2	Optical scattering *and* change in cloud	0.01–1	Low: we may already be	Uncertainties in transport	Equity	*NAS, Charlson*

Table 2. Costs Vs. Risks of Geoengineering Schemes

Risk of adverse effect	Cost		
	low	medium	high
low	—	reforestation	solar shields; direct ocean CO_2 injection
medium	SO_2 in troposphere; ocean fertilization-Fe	inert stratospheric aerosols; ocean fertilization-P	balloons in the stratosphere
high	SO_2 in stratosphere	—	—