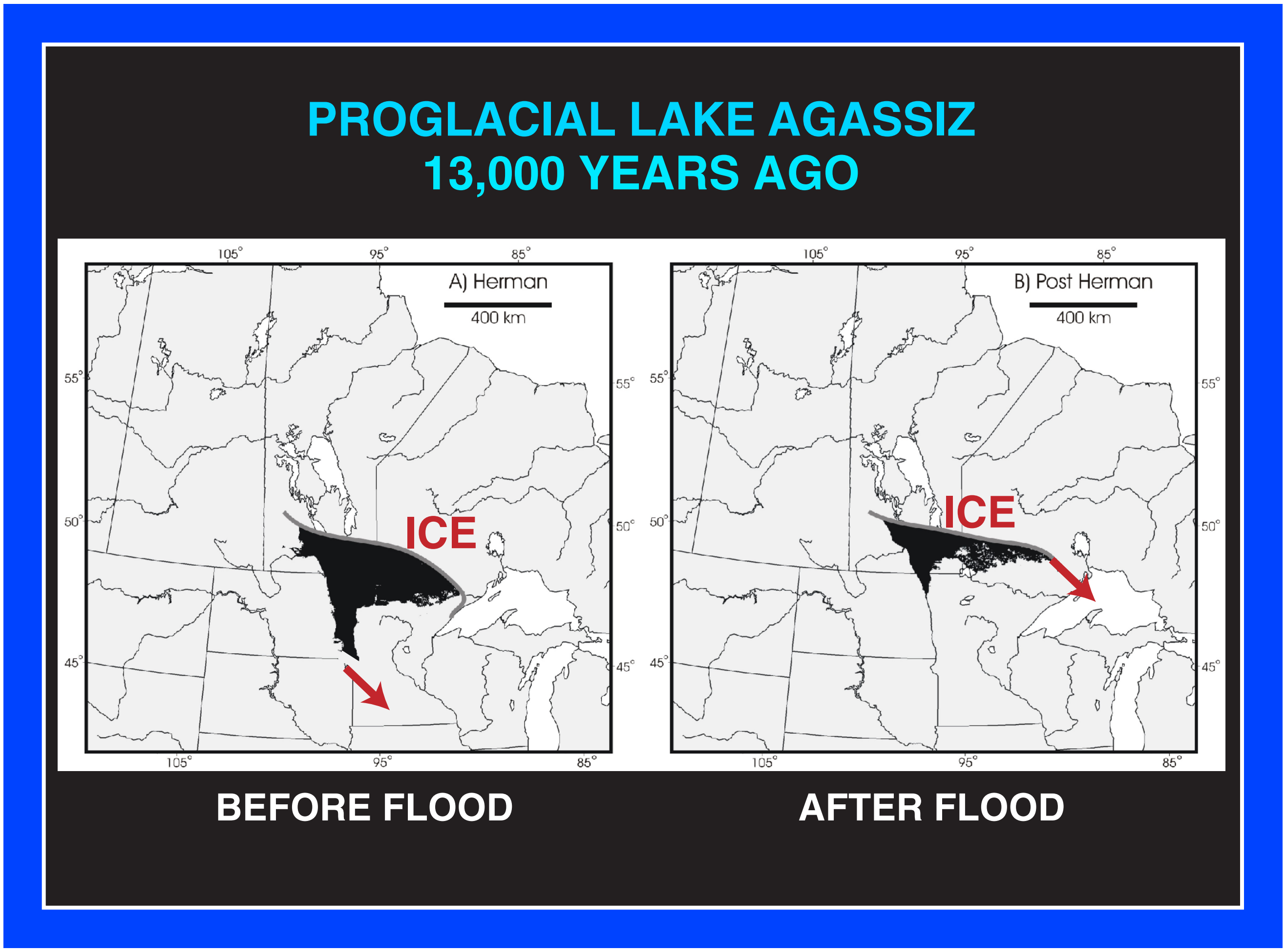


PROGLACIAL LAKE AGASSIZ
13,000 YEARS AGO

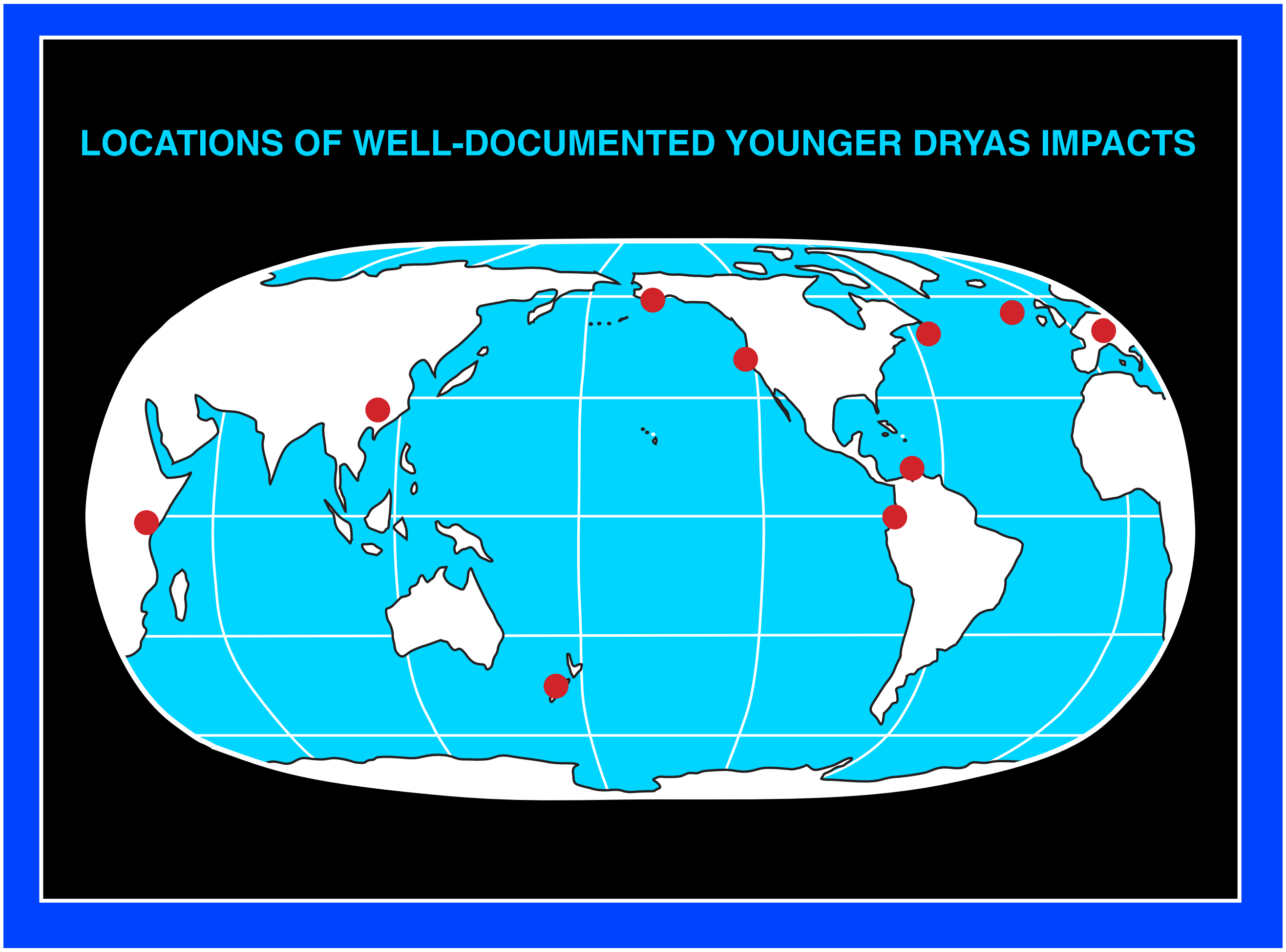
BEFORE FLOOD

AFTER FLOOD

Figure 40

The immediate impact was a shutdown of the vast amount of heat carried to the northern Atlantic by the upper limb of the Atlantic s conveyor. Although this provides a straight forward explanation for the pronounced YD cooling of Greenland and Scandinavia, paleoclimate records from ocean sediments, peat bogs and mountain moraines in far-flung places reveal that the YD had impacts far beyond what would be expected from the reduction in the supply of ocean heat to the northern Atlantic region (Figure 41). With one exception, in all of these places the change tended to recreate conditions which characterized glacial time. An example is the accumulation of $CaCO_3$ dust on the Greenland ice cap (see Figure 42). About 15,000 years ago the deposition $CaCO_3$-bearing dust dropped precipitously, heralding the demise of the frequent intense Asian wind storms of glacial time. Then just as suddenly 13,000 years ago at the onset of the YD, the dust storms resumed. It was not until the abrupt end of the YD that the dust rain was once again shut down. It has not resumed. Another example is the YD expansion of the mountain glaciers of New Zealand s South Island (see Figure 43). The one exception is Antarctica where records from ice cores show that the YD was a time of rapid warming. This finding was music to the ears of the proponents of the ocean trigger hypothesis. The reason is that if the supply of dense water to the deep sea is cut off at one place, it must soon be compensated by a supply from another place. We suspect that this alternate source was the margin of the Antarctic continent. A greater rate of deep water production in this region would supply extra ocean warmth and hence explain why, during the YD, climate shift on the Antarctic continent was opposite to that for the rest of the world.

What is not understood is how a reorganization in ocean circulation could impact the climate of the entire planet. Even harder to understand is how it could do so on the



LOCATIONS OF WELL-DOCUMENTED YOUNGER DRYAS IMPACTS

Figure 41

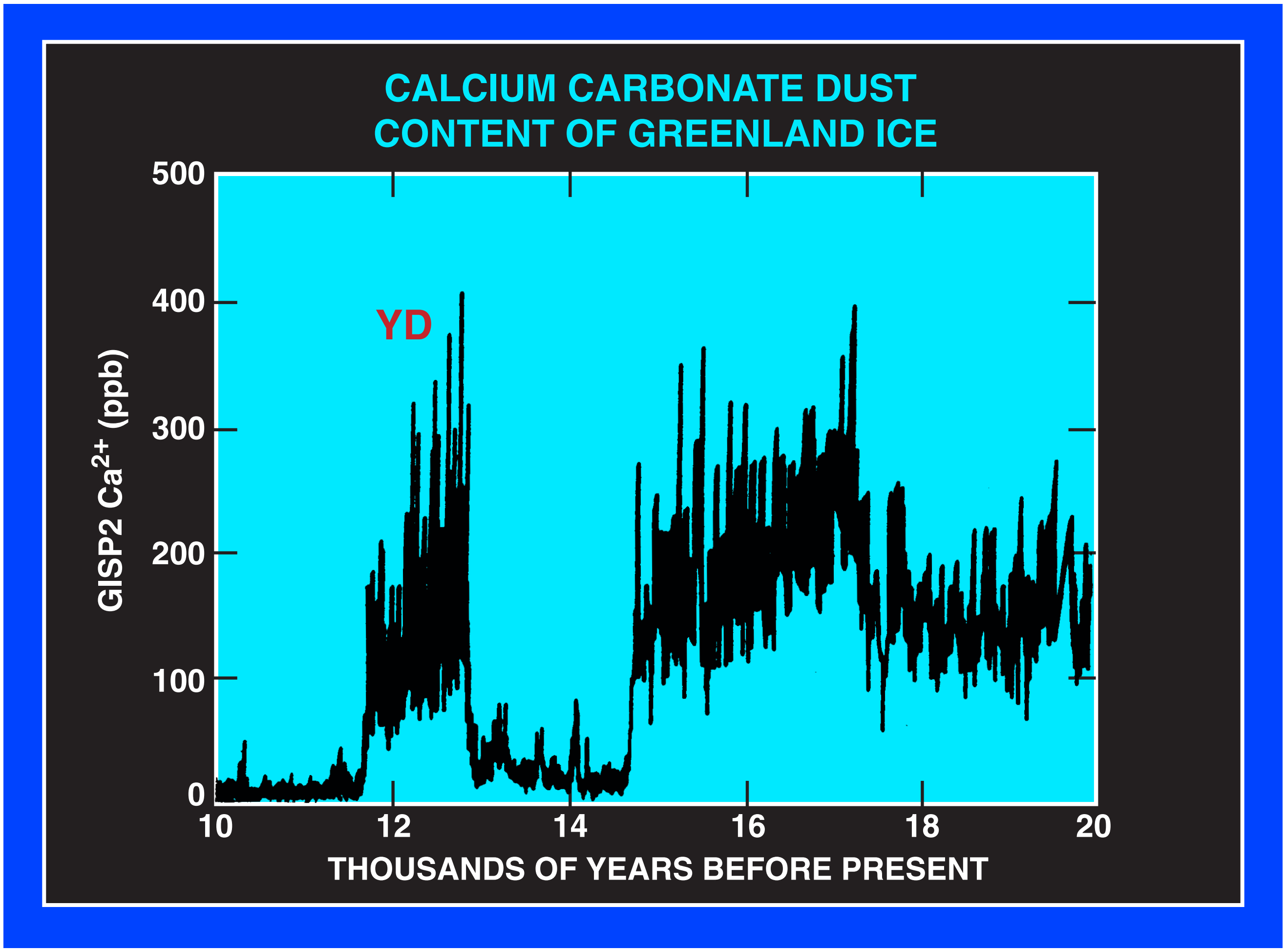
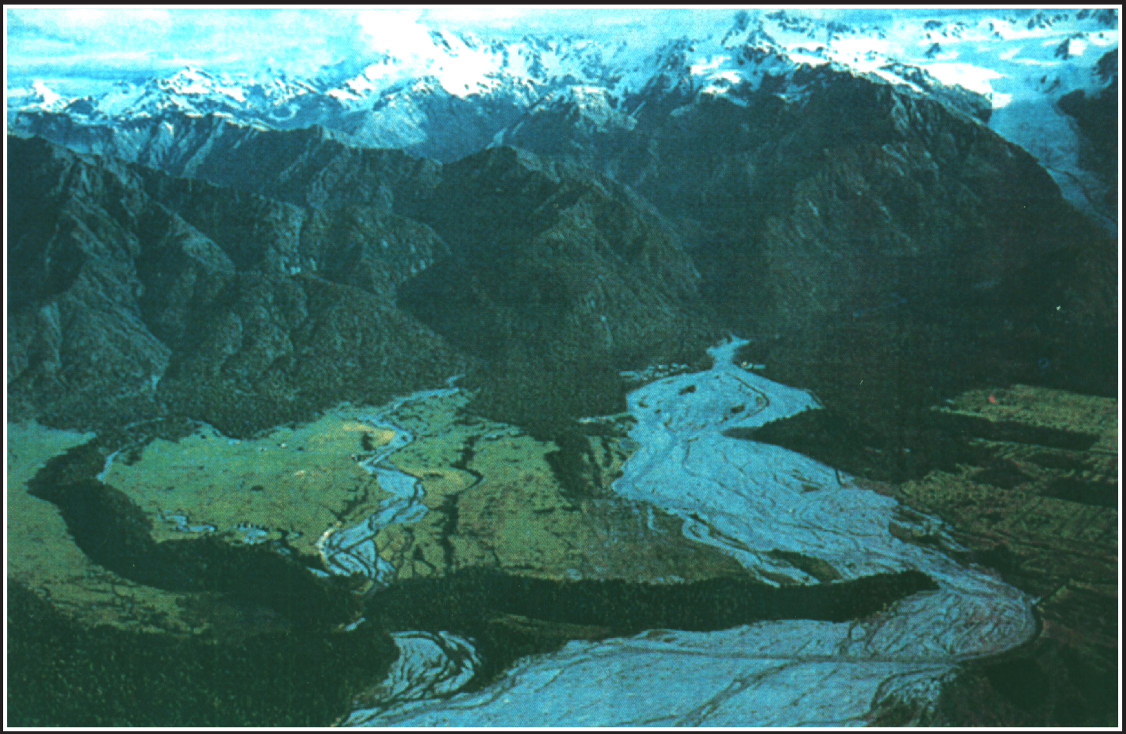

CALCIUM CARBONATE DUST
CONTENT OF GREENLAND ICE
GISP2 Ca^{2+} (ppb)
500
400
300
200
100
0
YD
10
12
14
16
18
20
THOUSANDS OF YEARS BEFORE PRESENT

Figure 42



Younger Dryas Moraine - South Island, New Zealand

Figure 43

time scale of just a few decades. Yet it happened. The take home message is that the Earth s climate system is not only highly responsive, but it also has built-in teleconnections which allow messages to be sent rapidly across the entire globe.

Heinrich s ice armadas as triggers for conveyor shutdown

In 1988, a young German scientist, Harmut Heinrich, reported that a study of a deep sea core in the eastern North Atlantic Ocean revealed six layers made up exclusively of debris dropped from melting icebergs. Punctuating the record for the last period of glaciation, these layers were spaced at intervals of about 8 thousand years. Heinrich envisioned that this debris was dropped as huge armadas of icebergs launched from eastern Canada melted. Subsequent studies verified Heinrich s discovery by showing that these layers formed a swath extending from Canada s Hudson Bay all the way across the Atlantic to the British Isles (see Figure 44). Apparently during the 8000-year periods separating these layers, the ice over Hudson Bay steadily thickened until earth heat diffusing up from beneath caused its base to melt. This lubrication triggered a massive surge of ice out into the Atlantic Ocean. These Heinrich (H) armadas gradually melted as they drifted across the Atlantic with the prevailing currents. The dilution of salt created by this melt water appears to have squelched the production of deep water in the northern Atlantic. Again, for reasons not yet understood, the consequences of these shutdowns were felt across much of the globe. Southern France experienced its coldest temperatures. The monsoon rainfall in China was greatly reduced. The dry lands of eastern Brazil and of central Florida were deluged with precipitation. In other words, enraged by the impact of these armadas, the angry climate beast struck back.

Geographic distribution of climate impacts

We have already seen that, with one exception, the YD cold snap appears to have caused a relapse toward glacial-like conditions everywhere on the globe. The exception

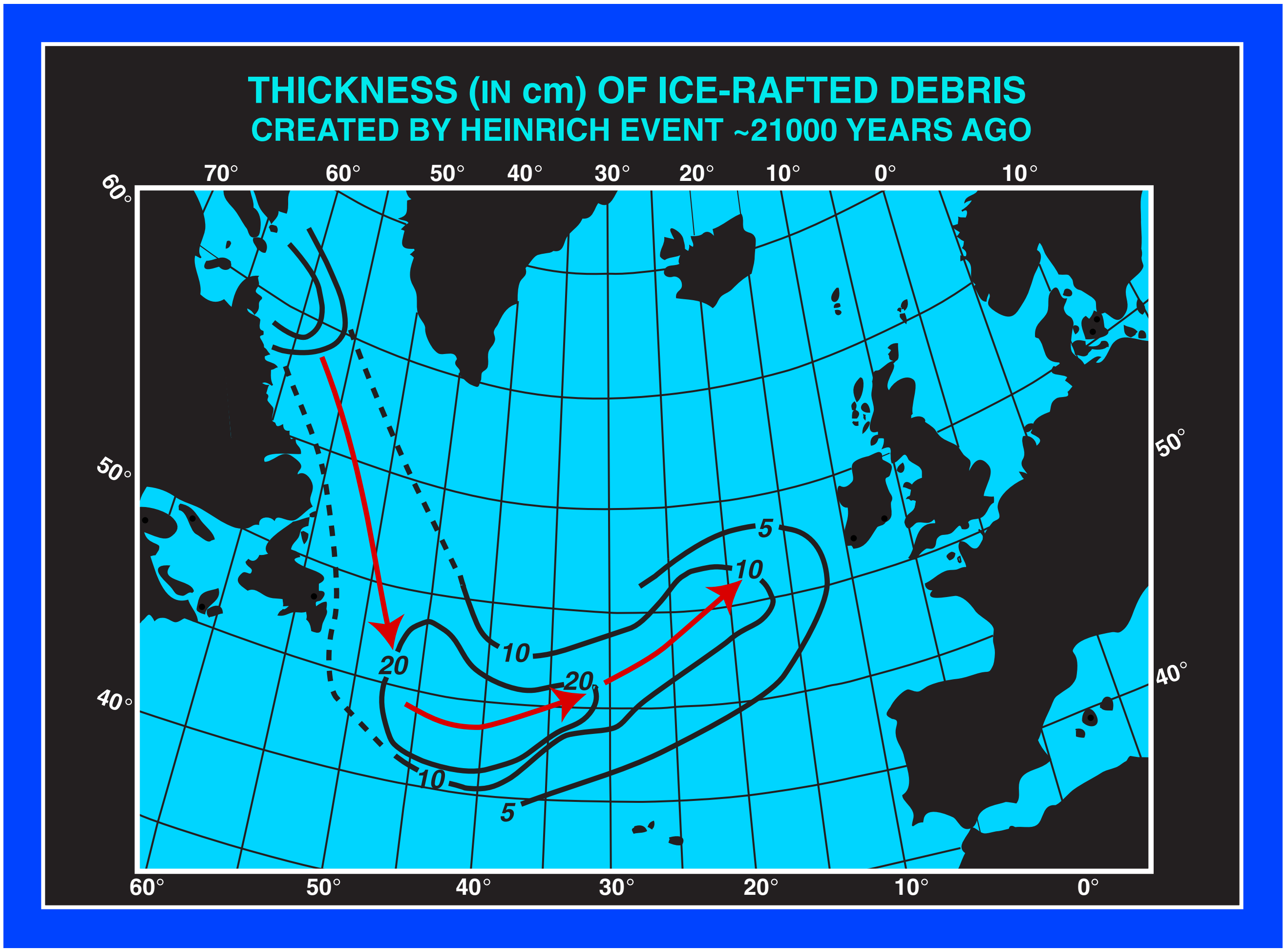

THICKNESS (IN cm) OF ICE-RAFTED DEBRIS
CREATED BY HEINRICH EVENT ~21000 YEARS AGO
70°
60°
50°
40°
30°
20°
10°
0°
10°
60°
50°
40°
50°
40°
5
10
10
20
20
10
5
60°
50°
40°
30°
20°
10°
0°

Figure 44

was the Antarctic continent where the climate warmed. Although the number of sites where D-O and H impacts have been identified is much smaller than for the YD, enough is known to say that the pattern and/or intensity of the impacts of D-O events differed from that of the H events (see Figure 45).

H impacts are not seen in the Greenland records of temperature, nor in those of soil and sea salt, nor in that of methane. In contrast, D-O events are not seen in the records from eastern Brazil or central Florida (see Figure 46). But in these latter two places, the times of H events stand out as episodes of intense rainfall. In records from the Iberian Peninsula and from southern China, both D-O and H impacts are seen. But in both places, the H impacts are stronger than the D-O impacts. For the Iberian Peninsula the times of coldest temperature correspond to H events. Both D-O and H events are prominently displayed in the record for a stalagmite from Hulu Cave in China. As is the case for Greenland ice, annual layers can be readily identified (see Figure 47). In addition, the calcite which makes up the stalagmite can be very precisely dated by measuring the ratio of ^{230}Th to ^{234}U.[3] The strength of the monsoon rains is recorded by the ratio of ^{18}O to ^{16}O in the calcite. Clearly, these geographic patterns hold clues crucial to deciphering the mysteries surrounding the abrupt climate changes which punctuated glacial time.

Implications to CO_2 warming

While the record for glacial time sends us a very clear message that our climate system can be likened to an angry beast, it also raises many questions. For example, does the absence of climate jumps during the last 12,000 years mean that the system misbehaves only during cold and icy times? If so, then one might conclude that by

---

[3] ^{234}U is radioactiive and decays to produce ^{230}Th. Because the element uranium is water soluble whereas the element thorium is water insoluble, cave waters are highly depleted in thorium relative to the uranium. Hence, cave deposits are much like hour glasses. When they form, all the sand (^{234}U) is in the upper half of the glass. With time, the lower half gradually fills with sand (^{230}Th). The ratio of ^{230}Th to ^{234}U constitutes a very precise clock (see Sidebar #4).

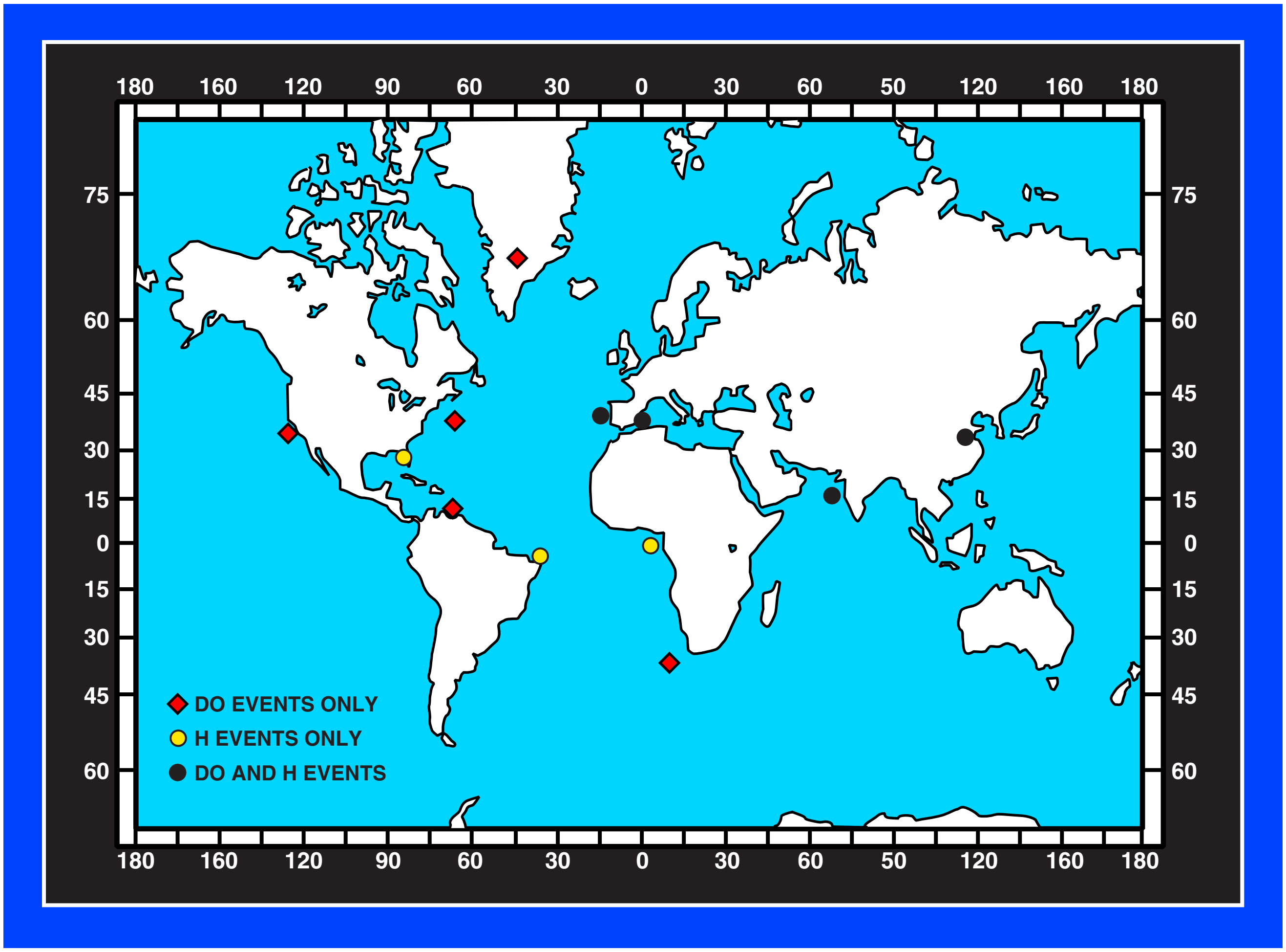

180
160
120
90
60
30
0
30
60
50
120
160
180
75
60
45
30
15
0
15
30
45
60
◆ DO EVENTS ONLY
○ H EVENTS ONLY
● DO AND H EVENTS

Figure 45

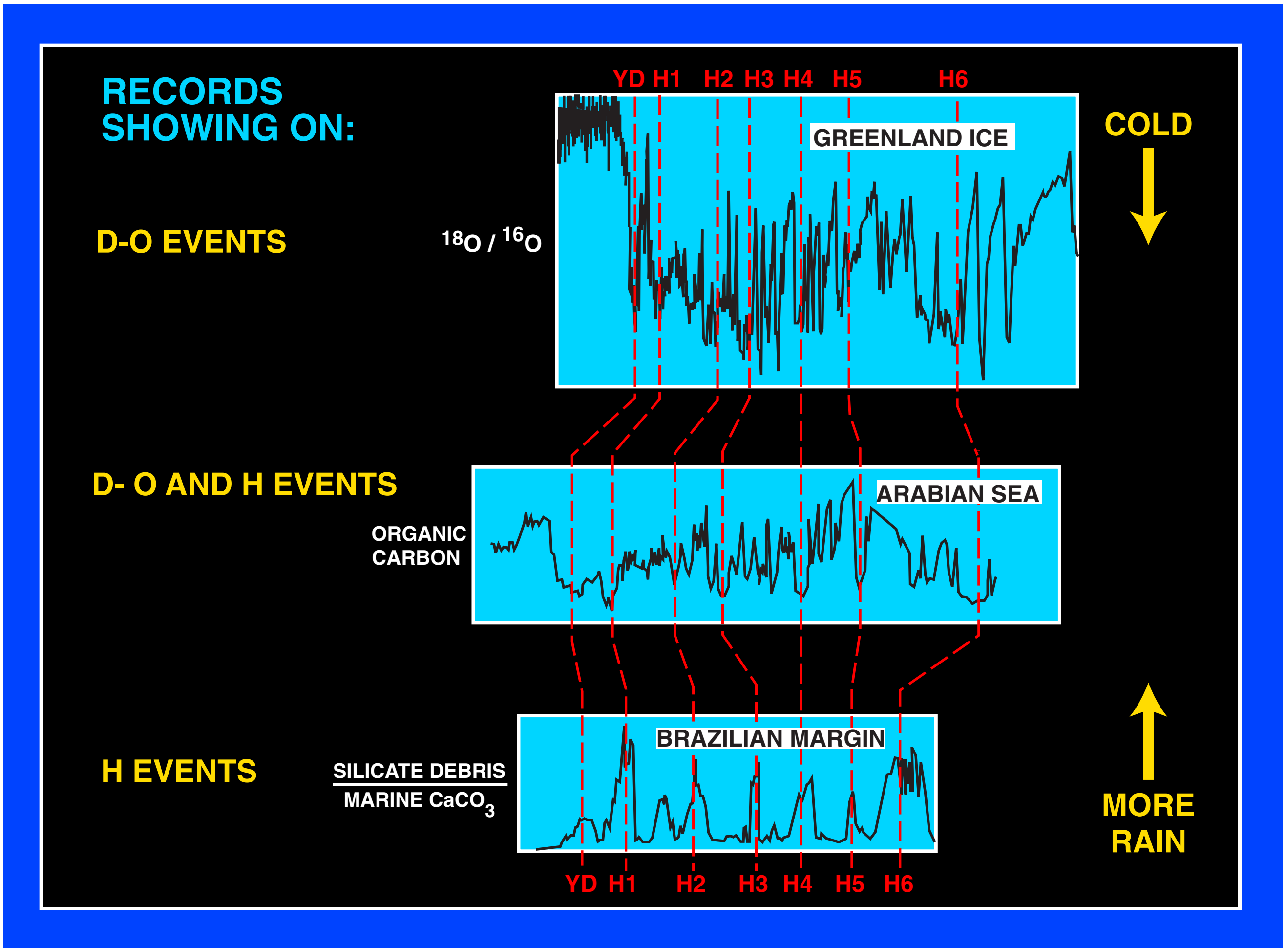
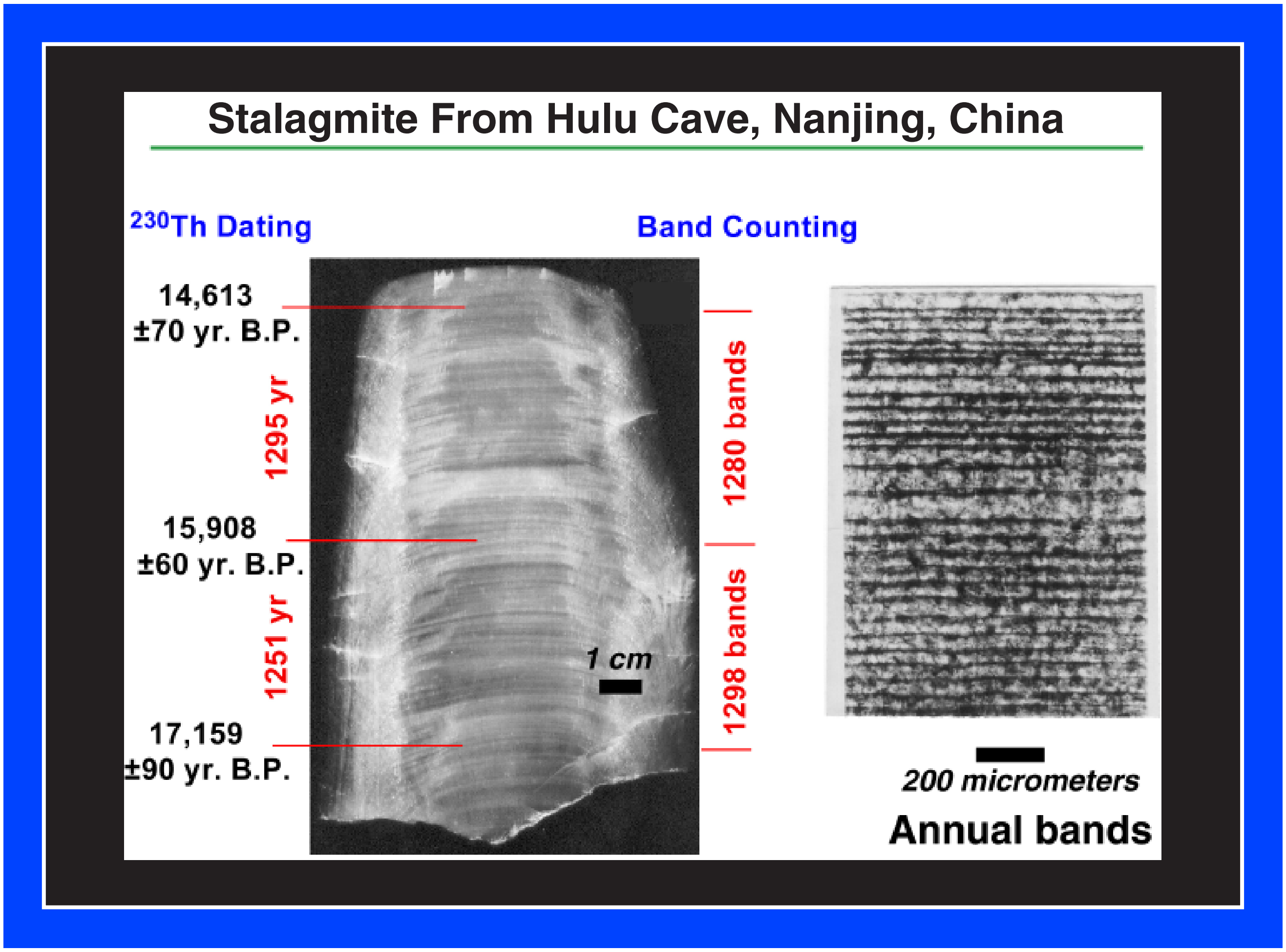

RECORDS SHOWING ON:
D-O EVENTS
^{18}O / ^{16}O
GREENLAND ICE
YD H1 H2 H3 H4 H5 H6
COLD
D- O AND H EVENTS
ORGANIC CARBON
ARABIAN SEA
H EVENTS
SILICATE DEBRIS / MARINE $CaCO_3$
BRAZILIAN MARGIN
YD H1 H2 H3 H4 H5 H6
MORE RAIN

Figure 46



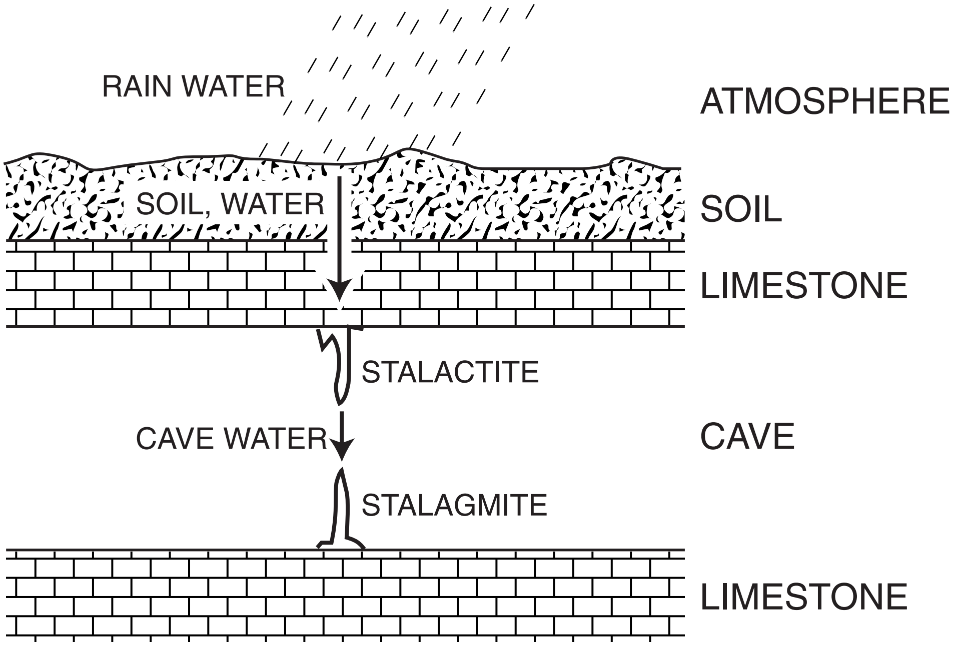
Stalagmite From Hulu Cave, Nanjing, China

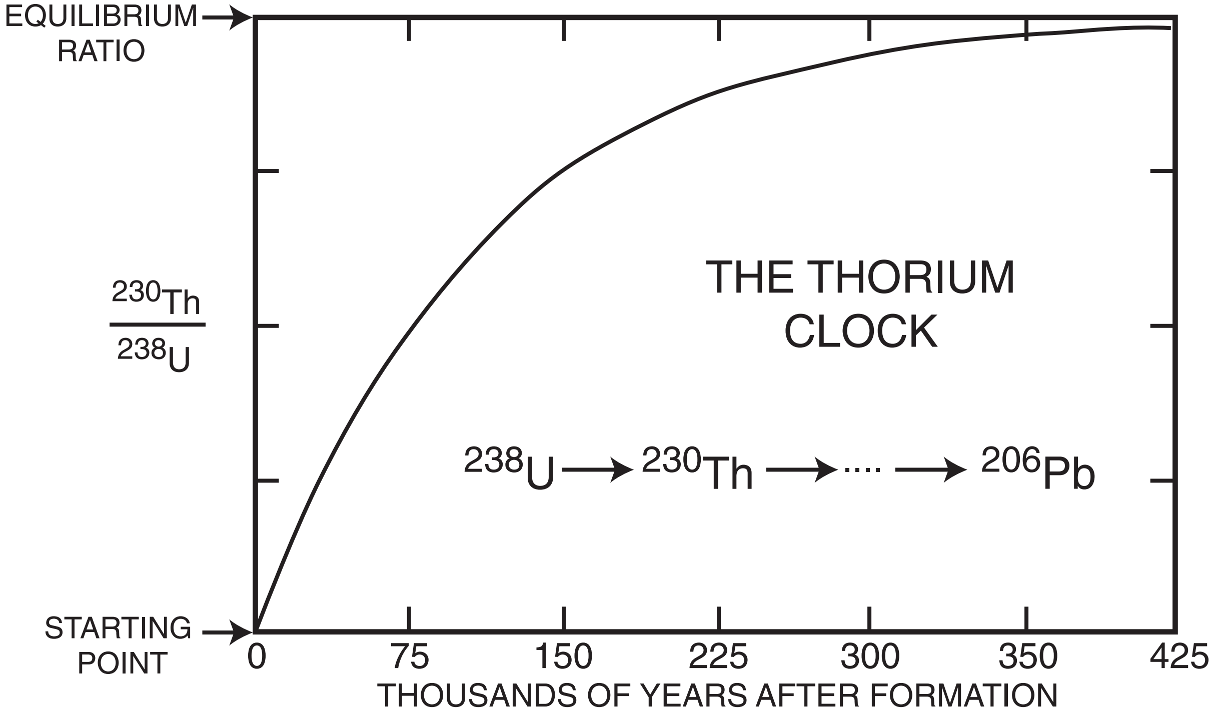
^{230}Th Dating

Band Counting

Figure 47

AGE DETERMINATION OF CAVE $CaCO_3$





Sidebar #4

warming the Earth with man-made greenhouse gases, we could fortify this stability. But the last interglacial sends us a message that we shouldn t bank on this. It was also a period of climate stability. But it came to an abrupt end. Hence, as happened in previous warm and stable periods of interglaciation, the current one is destined to come to an end whether by natural causes or by a nudge from fossil fuel CO_2. In the absence of floods from large amounts of fresh water released from ice-dammed lakes or put in place by the melting of huge armadas of icebergs, is there an alternate way to trigger an abrupt change? Perhaps. Computer simulations suggest that on a warmer planet, it would rain more and the extra precipitation reaching the northern Atlantic and its surrounding lands, would eventually cause a shutdown of conveyor circulation. But, even if this were to happen, would the consequences be as awesome as they were during glacial time? These are not questions we will soon be able to answer. So, it s as if we are blindfolded and walking toward a cliff. Unfortunately, we have only a vague idea how far away the cliff might be and we can t even be sure that it actually exists.

What should we do?

Even among those who have serious concerns about the possible consequences of global warming, there is no unanimity of opinion with regard to what should be done to stem the ongoing buildup of CO_2 (see Figure 48). To many, the Kyoto Accord was to be a healthy first step toward such a solution. The thrust of this international agreement is that the industrial nations would by 2015 cut their CO_2 emissions back to their 1990 levels. It was envisioned that this would be accomplished by a combination of more efficient use of energy and the substitution of non-fossil fuel energy sources (i.e., wind, nuclear, biomass). As an inducement to nations reluctant to sign on, the accord was amended to give credit for carbon storage as biomass (more trees, more soil organics). Even with this amendment, the U.S. refused to sign on.

Although the Kyoto Accord constitutes a significant step toward limiting CO_2 emissions, it has some serious drawbacks. Clearly, the problem can t be solved by a

SO WHAT SHOULD WE DO ABOUT FOSSIL FUEL CO_2?

IT SURELY CONSTITUTES A BIG NUDGE!

PLENTY OF COAL, OIL, NATURAL GAS

WOULD TAKE AT LEAST 60 YEARS TO STOP CO_2 BUILDUP

WE MUST HAVE A SAFETY NET!!

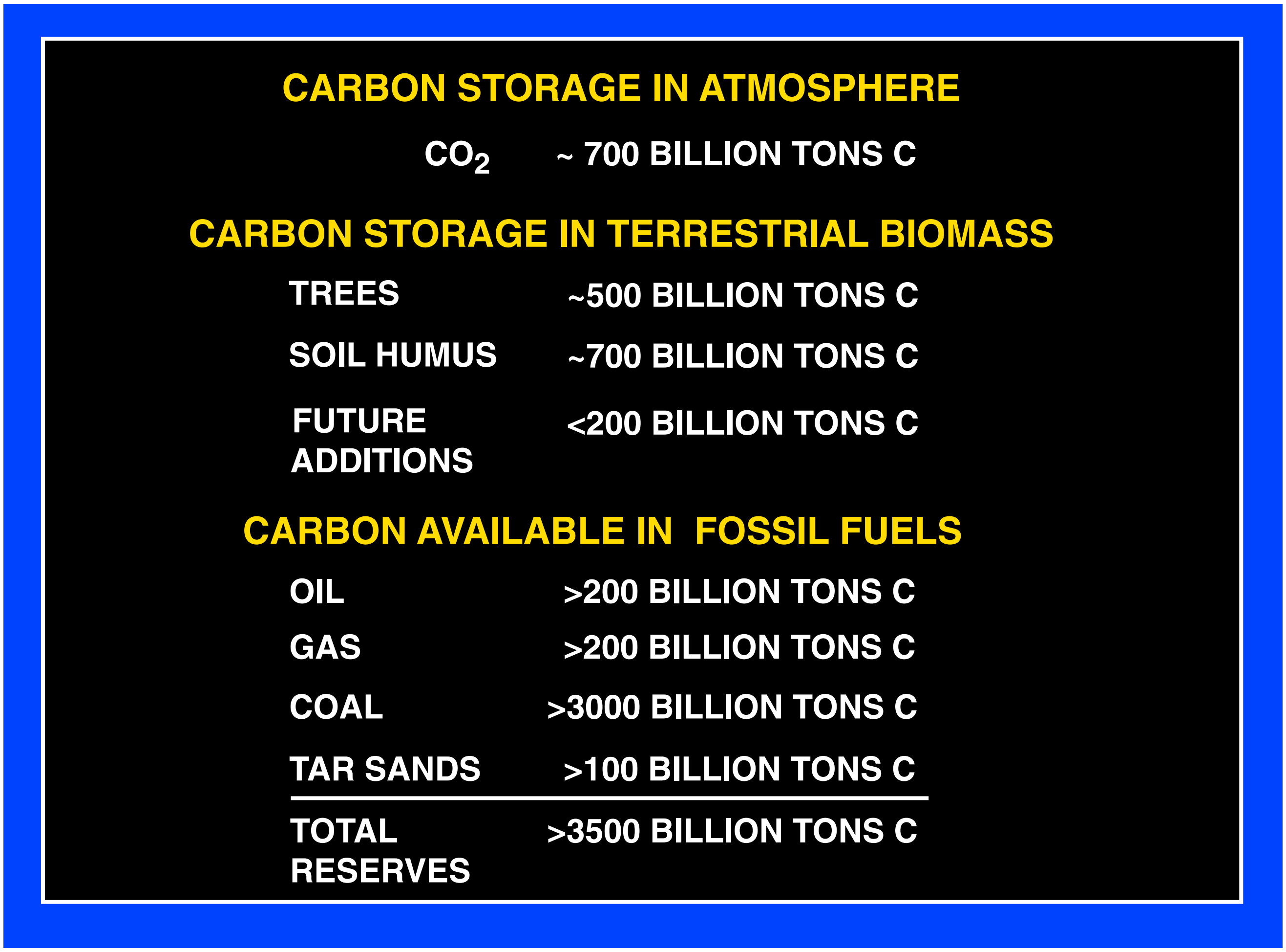
Figure 48

series of Kyoto-like steps. For example, if conservation were the main thrust of these steps, this would mean moving toward zero energy use. Clearly, if all the Earth s inhabitants are to achieve an acceptable life style, energy use will have to substantially increase. If substitution of non-fossil fuel sources were to be the main thrust, it would very likely require a shift to nuclear power. In a world where terrorism has become a major political instrument, this would surely be a dangerous path.

Storage of carbon as biomass is appealing. However, when the space available for new forests and capacity of soils to store humus are quantified, it turns out that the optimistic upper limit for such storage is about 200 billion tons of carbon (see Figure 49). Business-as-usual projections suggest that if fossil fuels continue to dominate the energy market, we are likely to consume 1000 to 2000 billion tons of fossil carbon over the next 100 or so years (see Figure 50). Hence, storage in biomass is destined to play a minor role.

Taken together, two of the three components of the Kyoto Accord, i.e., energy conservation and biomass storage, are capable of only a modest reduction in the buildup of CO_2 in our atmosphere. In order to prevent the CO_2 content of the atmosphere from reaching levels deemed undesirable, by the latter half of this century it will be necessary to entirely eliminate CO_2 emissions. This leaves only two options. Either we need to come up with an acceptable, safe and affordable alternate to fossil fuel energy or we must capture and store a major fraction of the CO_2 produced by fossil fuel burning.

Forty or so years ago, nuclear power appeared to be the panacea for energy production. Jane Fonda s performance in the movie China Syndrome alerted the public to the dangers associated with nuclear reactors. Then three weeks after the opening of this film, the Three Mile Island disaster occurred. Finally, these fears were solidified by the explosion of Russia s Chernobyl reactor. The emergence of terror as an international weapon has added yet another dimension to the problem. Most sobering is the possibility that plutonium produced as a byproduct of power generation would be



CARBON STORAGE IN ATMOSPHERE

CO_2	~ 700 BILLION TONS C

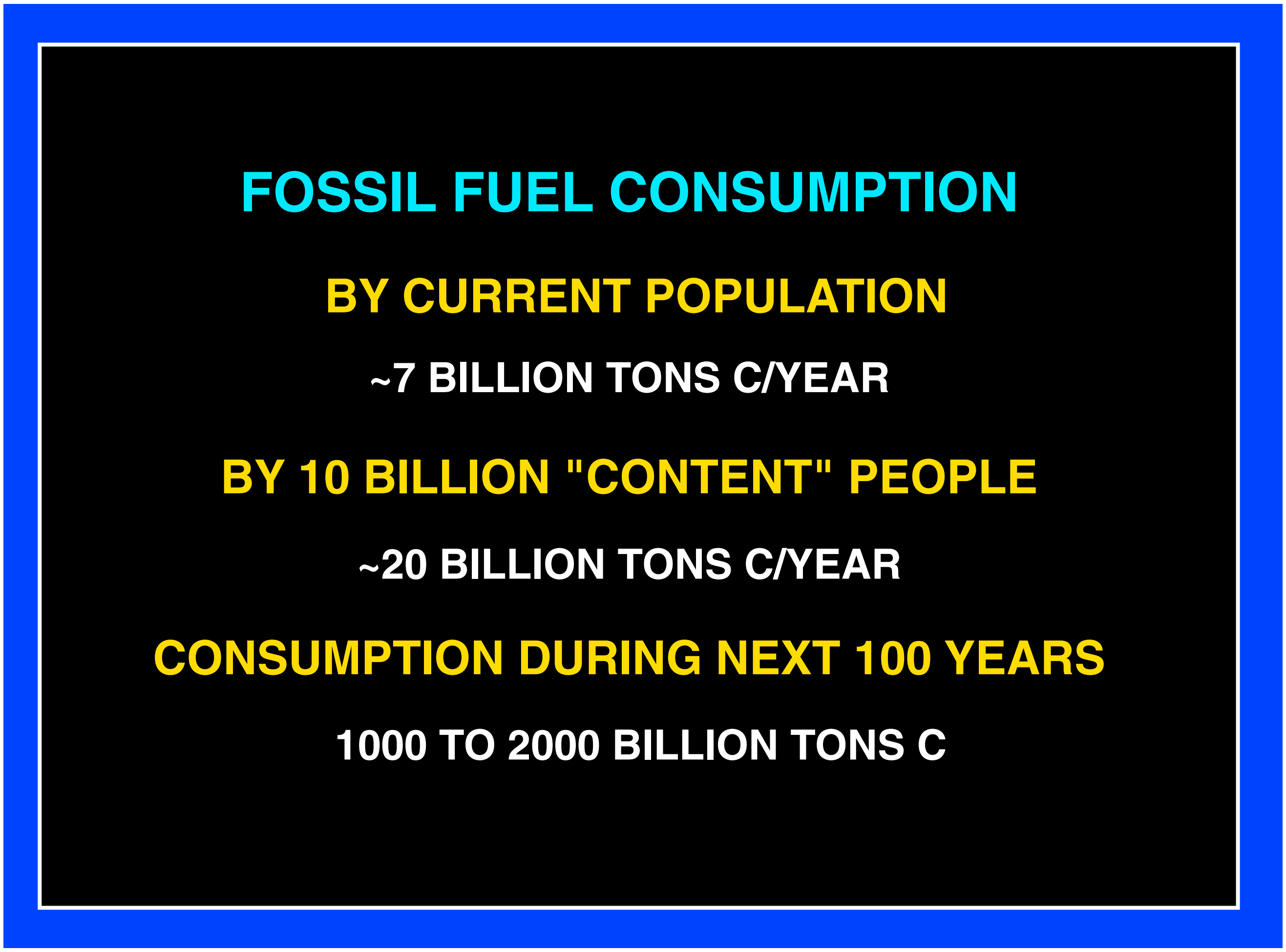
CARBON STORAGE IN TERRESTRIAL BIOMASS

TREES	~500 BILLION TONS C
SOIL HUMUS	~700 BILLION TONS C
FUTURE ADDITIONS	<200 BILLION TONS C

CARBON AVAILABLE IN FOSSIL FUELS

OIL	>200 BILLION TONS C
GAS	>200 BILLION TONS C
COAL	>3000 BILLION TONS C
TAR SANDS	>100 BILLION TONS C
TOTAL RESERVES	>3500 BILLION TONS C

Figure 49



FOSSIL FUEL CONSUMPTION

BY CURRENT POPULATION

~7 BILLION TONS C/YEAR

BY 10 BILLION "CONTENT" PEOPLE

~20 BILLION TONS C/YEAR

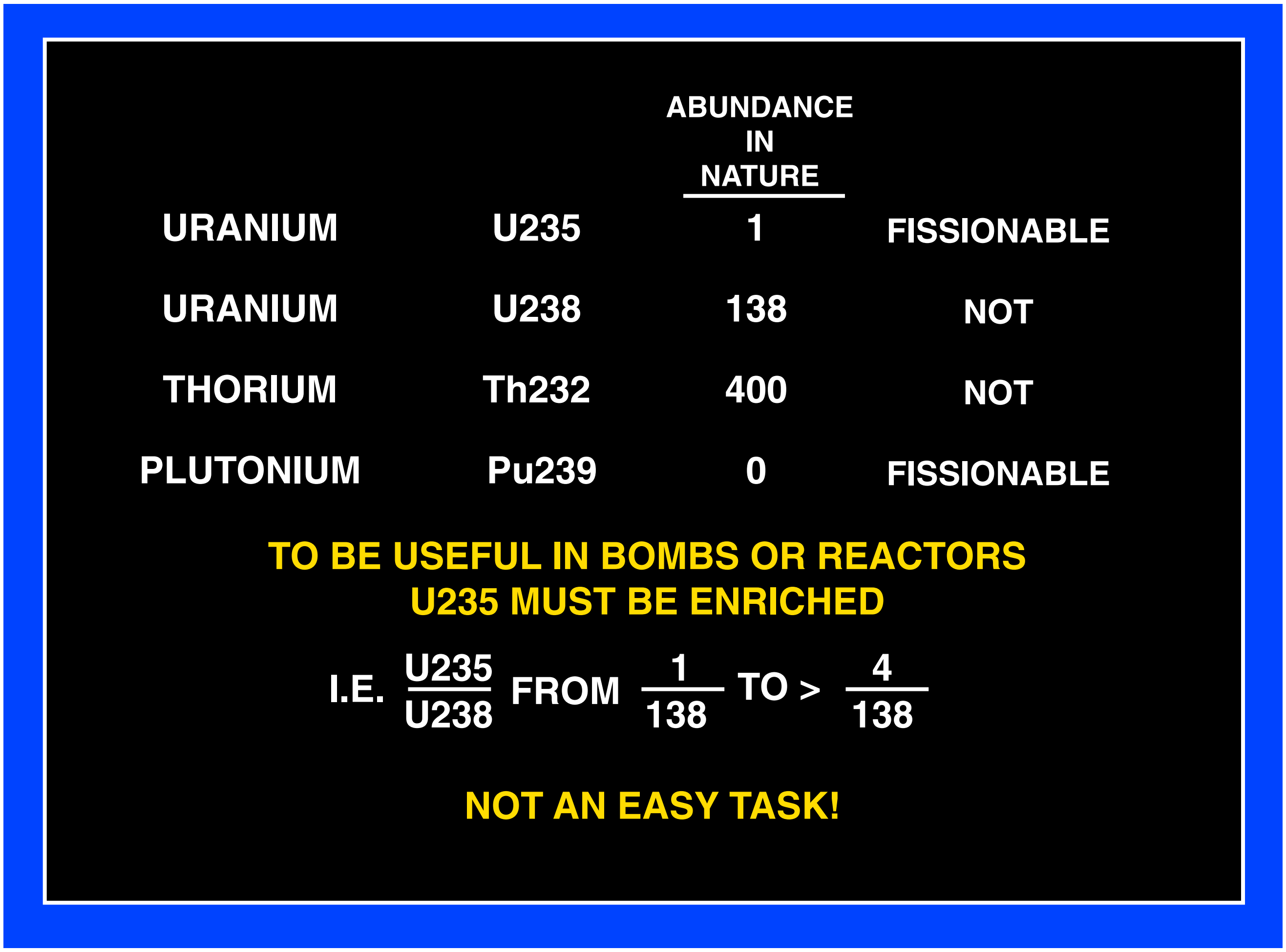
CONSUMPTION DURING NEXT 100 YEARS

1000 TO 2000 BILLION TONS C

Figure 50

converted to nuclear weapons by terrorist groups or rogue nations. The situation is made even more complicated by the fact that like crude oil, fissionable ^{235}U is a limited resource. Only one uranium atom in 138 is fissionable ^{235}U (see Figure 51). The rest are non-fissionable ^{238}U atoms. If nuclear power is to become the mainstay of our energy supply, then a new type of facility called the breeder reactor will have to be substituted for conventional nuclear reactors. In a breeder, a fraction of the neutrons released during fission are used to convert either non-fissionable ^{238}U or ^{232}Th to fissionable form. Hence such a reactor breeds at least as much nuclear fuel as it consumes (see Figure 52). As the supply of ^{238}U and ^{232}Th is 500 times larger than that of ^{235}U , such reactors could power the world for many centuries. However, the plutonium produced in breeder reactors could equally well be used to make atomic bombs. Finally, no breeder reactor for conventional electrical power generation has yet been brought on line.

Renewable energy sources certainly have allure. Solar panels, windmills, hydroelectric dams, geothermal heat, and biomass burning are viable substitutes for fossil fuels. However, each has serious limitations which make unlikely its adoption as the primary successor to fossil fuels. Electricity produced from solar cells remains far too expensive. Further, as electricity cannot be stored, solar power would have to be coupled with some means to take over during night hours and periods of heavy cloud cover. Windmills are currently economically competitive. However, were they to dominate the global energy market, they would sap 10 percent or so of the energy from the planetary wind system and thereby likely create major climate changes as well. And, of course, there would have to be tens of millions of windmills. Ugh! Hydroelectric power is severely limited by the availability of sites. Further, environmentalists are strongly opposed to additional construction of large dams and are even seeking to remove some of those already built. More worrisome is the fact that the reservoirs behind great dams like Aswan in Egypt, Tarbela in Pakistan and Three Gorges in China will eventually fill with silt rendering them inoperative. Despite extensive efforts, use of



		ABUNDANCE IN NATURE	
URANIUM	U235	1	FISSIONABLE
URANIUM	U238	138	NOT
THORIUM	Th232	400	NOT
PLUTONIUM	Pu239	0	FISSIONABLE

TO BE USEFUL IN BOMBS OR REACTORS
U235 MUST BE ENRICHED

I.E. $\frac{U235}{U238}$ FROM $\frac{1}{138}$ TO > $\frac{4}{138}$

NOT AN EASY TASK!

Figure 51

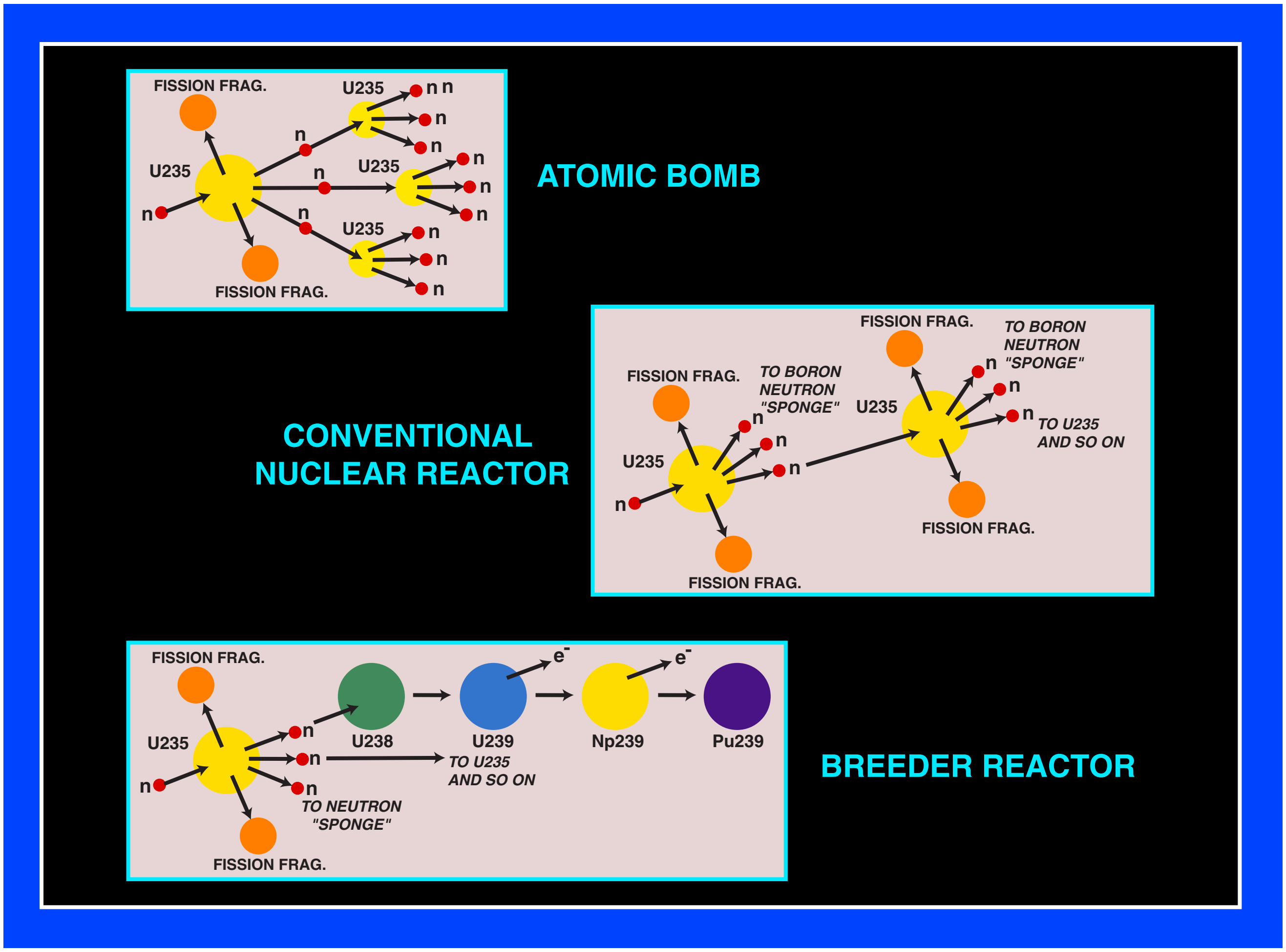

FISSION FRAG.
U235
n n
n
n
n
U235
n
n
U235
n
n
n
n
U235
n
n
n
FISSION FRAG.
ATOMIC BOMB
CONVENTIONAL NUCLEAR REACTOR
FISSION FRAG.
TO BORON NEUTRON "SPONGE"
n
n
FISSION FRAG.
TO BORON NEUTRON "SPONGE"
U235
n
n
n
TO U235 AND SO ON
U235
n
n
FISSION FRAG.
FISSION FRAG.
FISSION FRAG.
e-
e-
U235
n
U238
U239
Np239
Pu239
n
TO U235 AND SO ON
n
n
TO NEUTRON "SPONGE"
FISSION FRAG.
BREEDER REACTOR

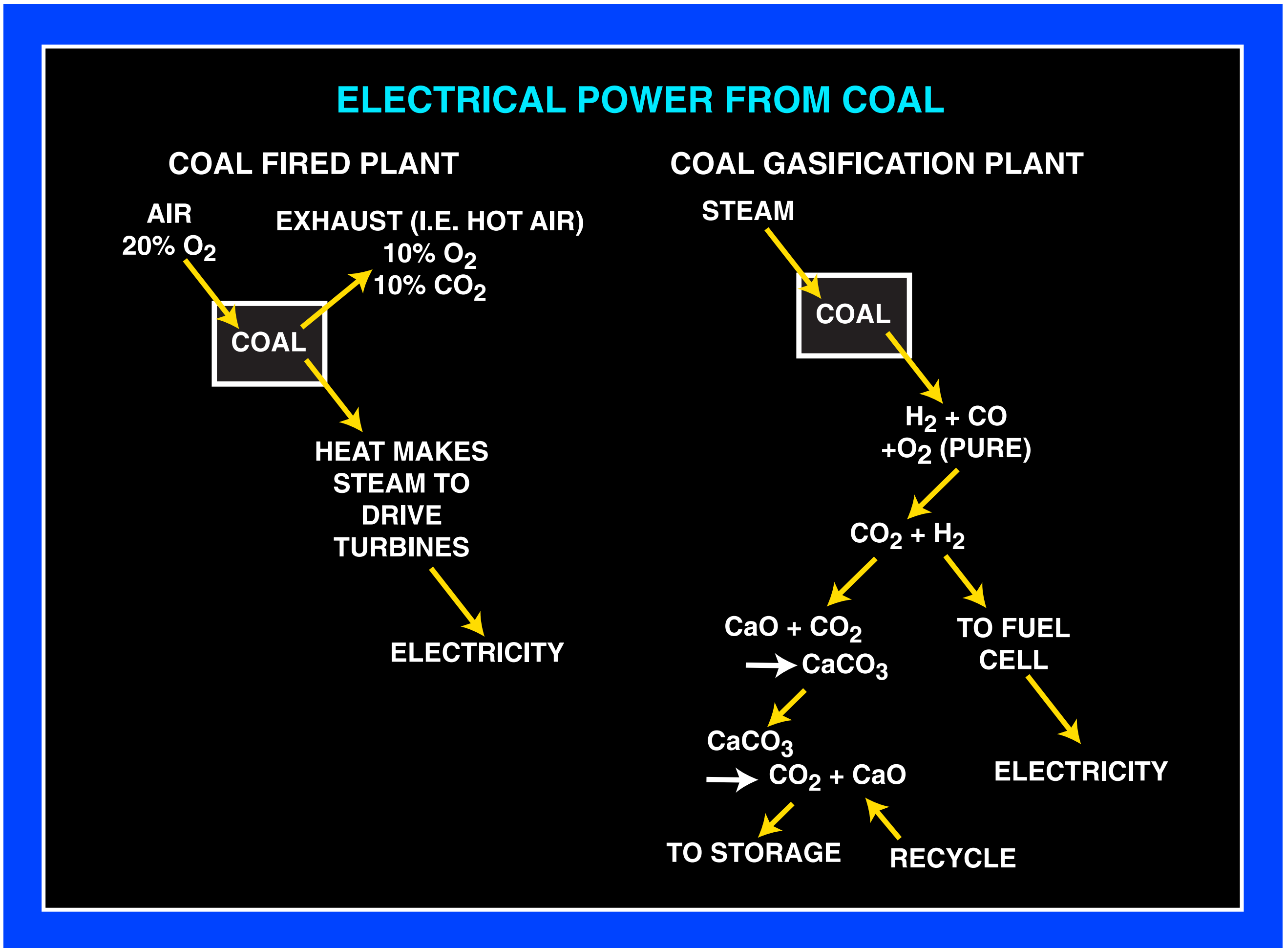
Figure 52

geothermal heat remains extremely limited. Biomass burning is a tantalizing option. Corn is already being used to produce an ethanol replacement for gasoline. Unfortunately there is not enough arable land available to both grow crops for human food as well as for industrial energy.

The hydrogen economy

More and more we encounter references to the so-called hydrogen economy. The idea behind all of this hype is that hydrogen could become a substitute for fossil fuels. It would be used in fuel cells to produce electricity and to power automobiles. Because water is its ultimate product (i.e., $2H_2 + O_2 \rightarrow 2H_2O$), the hydrogen economy would be largely non-polluting. Sounds great but a second look reveals some flies in the hydrogen ointment. First of all, no hydrogen wells exist for the natural abundance of this gas is extraordinarily low. Rather, hydrogen must be manufactured. One way to do this is to electrolyze water ($2H_2O \rightarrow 2H_2 + O_2$) which requires large energy inputs. Another is to treat coal in steam ($C + H_2O \rightarrow CO + H_2$) and to then oxidize the CO to CO_2 ($2CO + O_2 \rightarrow CO_2$). Were a cheap and unlimited source of energy available, then clearly electrolysis would be preferred. But as such a source remains a pipe dream, if hydrogen is to fuel the world, it will very likely be produced by steaming coal. The reason is that at current prices, H_2 derived by steaming coal is 10 times cheaper than that produced by the electrolysis of water. So what would be gained by the shift to a hydrogen economy? Just as in conventional coal-fired electrical power plants, in a coal-gasification plant (i.e., one that produces H_2) the coal would be converted to CO_2 (see Figure 53). But there is an advantage. The capture of CO_2 from a coal gasification plant can be done much more cheaply than from conventional coal-fired power plants. Further, if the hydrogen were used in a fuel cell, a greater fraction of the coal s chemical energy could be converted to electrical energy, thus raising the efficiency.

Those intrigued by the hydrogen economy dream of automobiles fueled by hydrogen rather than gasoline. Were this possible, then CO_2 production by the



ELECTRICAL POWER FROM COAL

COAL FIRED PLANT

AIR
20% O_2

COAL

EXHAUST (I.E. HOT AIR)
10% O_2
10% CO_2

HEAT MAKES
STEAM TO
DRIVE
TURBINES

ELECTRICITY

COAL GASIFICATION PLANT

STEAM

COAL

H_2 + CO
+O_2 (PURE)

$CO_2 + H_2$

CaO + CO_2
$\rightarrow CaCO_3$

TO FUEL
CELL

ELECTRICITY

$CaCO_3$
$\rightarrow CO_2$ + CaO

TO STORAGE

RECYCLE

Figure 53

transportation fleet would be eliminated. Instead, the CO_2 would be produced in large coal gasification plants where it could be readily captured. Indeed, General Motors has as one of its goals the hydrogen-powered automobile. The fuel cell which would replace the internal combustion engine is pretty much ready to go. However, a huge and perhaps insurmountable problem remains, namely, how to store the hydrogen onboard the vehicles. At one atmosphere pressure, hydrogen can be liquified but only at a temperature below -252°C (hence only 20°C above absolute zero temperature). An alternate would be to store the H_2 as a gas at thousands of atmosphere s pressure. No one has come up with an acceptably safe and inexpensive tank that could hold enough H_2 to operate an automobile for weeks at a time.

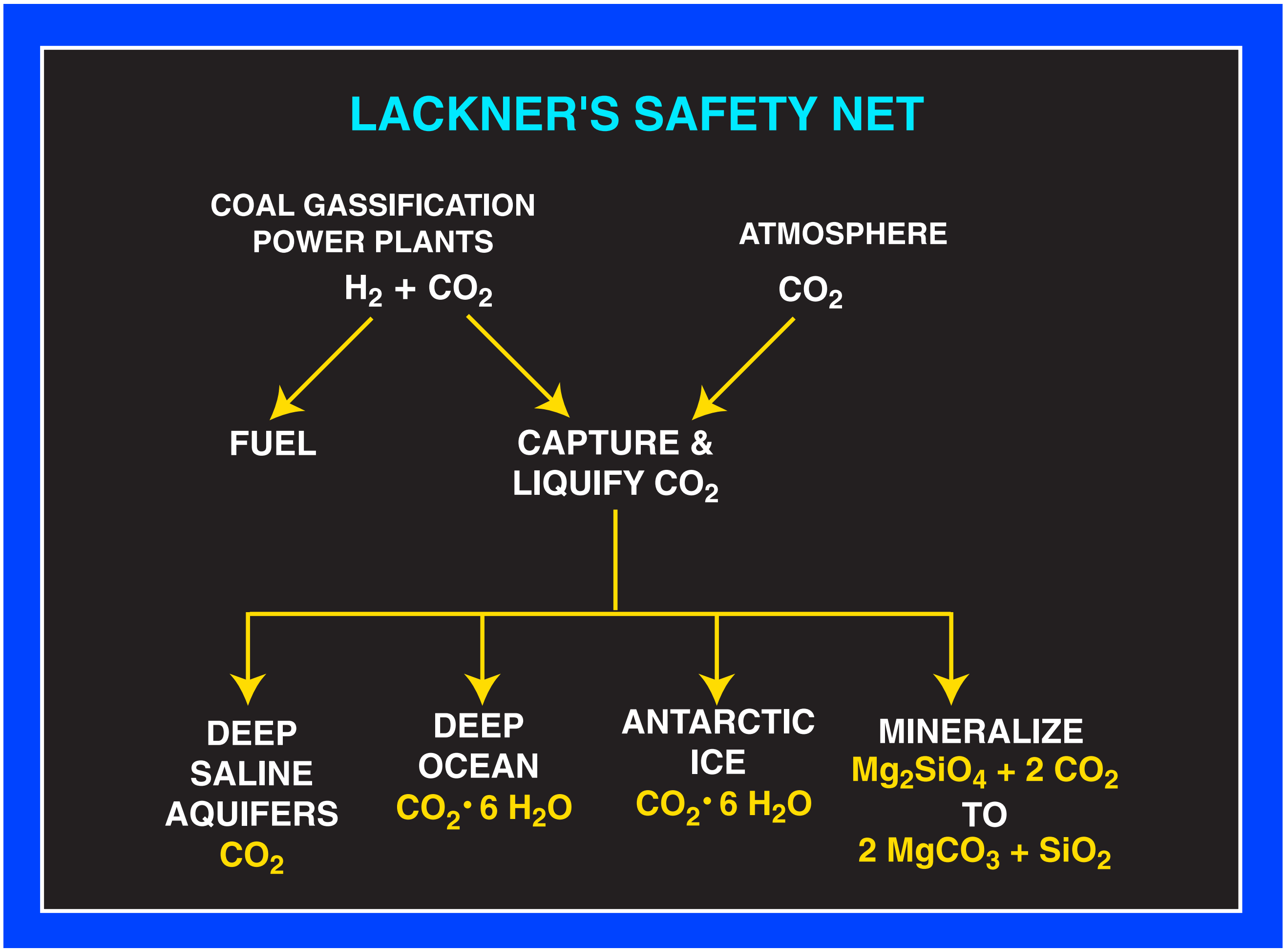
CO_2 sequestration

In my estimation there is currently only one sure route by which the buildup of CO_2 in the atmosphere can be brought to a halt. As championed by Columbia University s Klaus Lackner, it involves capture and storage of the CO_2 produced as a byproduct of fossil-fuel-based energy production (see Figure 54). The CO_2 generated in electrical power facilities would be captured on site, liquified (under pressure) and piped to a storage site. But as large power plants currently account for only about one third of the total amount of CO_2 generated, this route alone cannot solve the problem for we must head toward zero CO_2 emissions. However, as outlined below, it may be possible to remove CO_2 from the atmosphere. If so, vehicles could continue to be powered by gasoline.

CO_2 storage

Before discussing how CO_2 would be captured, it makes sense to first consider where it would be stored. A number of proposals have been put forward (see Figure 55).

1) *Deep sea storage*. Currently only about one sixth of the ocean s capacity for CO_2 uptake is being utilized. The reason is that subsurface waters are replaced only very slowly by waters which have been in contact with the atmosphere. The deeper the



LACKNER'S SAFETY NET

COAL GASSIFICATION
POWER PLANTS
$H_2 + CO_2$

ATMOSPHERE
CO_2

FUEL

CAPTURE &
LIQUIFY CO_2

DEEP
SALINE
AQUIFERS
CO_2

DEEP
OCEAN
$CO_2 \cdot 6\ H_2O$

ANTARCTIC
ICE
$CO_2 \cdot 6\ H_2O$

MINERALIZE
$Mg_2SiO_4 + 2\ CO_2$
TO
$2\ MgCO_3 + SiO_2$

Figure 54

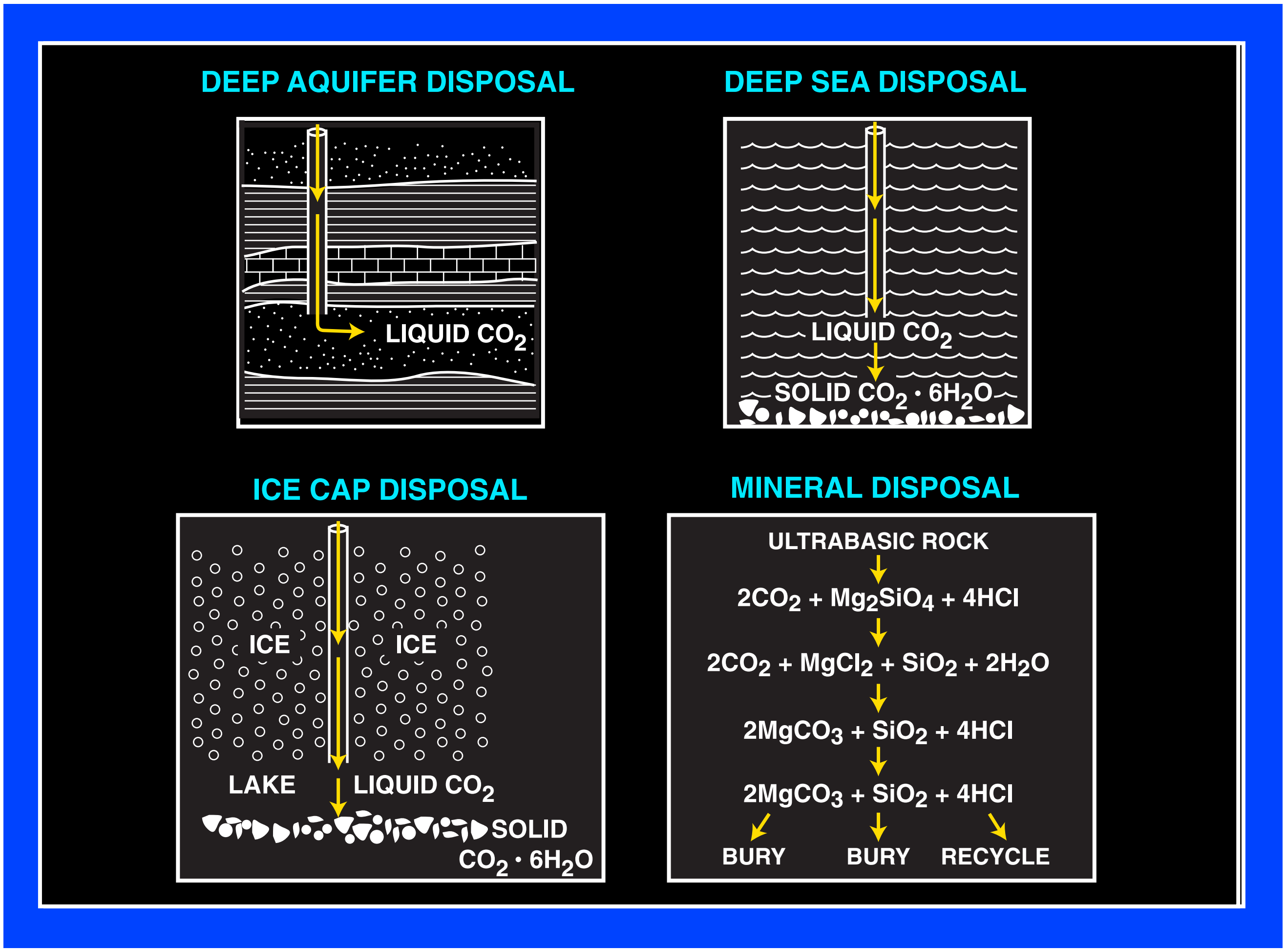

DEEP AQUIFER DISPOSAL
LIQUID CO_2
DEEP SEA DISPOSAL
LIQUID CO_2
SOLID $CO_2 \cdot 6H_2O$
ICE CAP DISPOSAL
ICE
ICE
LAKE
LIQUID CO_2
SOLID $CO_2 \cdot 6H_2O$
MINERAL DISPOSAL
ULTRABASIC ROCK
$2CO_2 + Mg_2SiO_4 + 4HCl$
$2CO_2 + MgCl_2 + SiO_2 + 2H_2O$
$2MgCO_3 + SiO_2 + 4HCl$
$2MgCO_3 + SiO_2 + 4HCl$
BURY
BURY
RECYCLE

Figure 55

water the slower its replacement. As the deeper parts of the ocean will not take up their share of the fossil fuel CO_2 for hundreds of years, the idea is to short-circuit the delivery by pumping liquid CO_2 directly into the deep sea. Although liquid CO_2 is less dense than surface ocean water, it is more compressible. At a depth of 3500 meters, the densities of sea water and liquid CO_2 become equal. Below this depth liquid CO_2 is more dense than sea water. Hence, if injected below a depth of 3500 meters, liquid CO_2 would sink to the sea floor. Further, it would not remain a liquid, for under the cold and high pressure conditions which prevail in the deep sea, the CO_2 would combine with H_2O to form a solid CO_2 x $6H_2O$. Chemists refer to this type of solid as a clathrate. As under these conditions the clathrate is more dense than either liquid CO_2 or sea water, it would pile up on the bottom. Of course, over time, the clathrate would dissolve and the CO_2 would be dispersed throughout the deep sea where it would react with the resident carbonate ions to form bicarbonate ions. In this way, delivery of CO_2 to the deep sea could be greatly accelerated.

2) *Storage in polar ice caps*. Antarctica s ice cap is underlain by hundreds of lakes. They form because Earth heat, diffusing up from beneath, warms and in some places melts the basal ice. The idea would be to pipe liquid CO_2 down through the ice into these lakes. Upon arrival, the CO_2 would react with the lake water and form a clathrate which would sink to the lake bottom. As it would be prohibitively expensive to pipe liquid CO_2 to Antarctica, it would have to be coupled with CO_2 extraction from the air over the ice cap. As the atmosphere mixes extremely rapidly, CO_2 removal could be carried out anywhere on the planet. Just as the air over regions like the New York metropolitan area does not experience a significant buildup in CO_2, neither would the air over Antarctica experience a significant depletion.

3) *Storage in saline aquifers*. The pores in the deep strata of sedimentary basins are invariably filled with very salty waters known as brines. As the brines have been

trapped in these reservoirs for millions of years, another option is to pump liquid CO_2 into these salty waters. Unlike the deep ocean and the lakes beneath Antarctica, these brines are too warm for CO_2 clathrates to be stable. Hence, the CO_2 would remain in liquid or gaseous form. This is fortunate because were clathrates to form, they would clog the sediment pores and prevent the liquid CO_2 from spreading out into the aquifer. Statoil, a Norwegian energy company, is already doing this. They recover methane from a reservoir beneath the North Sea. The 15 percent CO_2 this gas contains must be separated before the methane can be burned. Normally, this separated CO_2 would be released to the atmosphere. But, as Norway has an emission tax of 50 dollars per ton of CO_2, Statoil decided it would be cheaper to liquify the separated CO_2 and pump it back down into a water-filled stratum. This is now being done routinely. A tiny beginning!

4) *Conversion to $MgCO_3$*. With somewhat additional effort, it is possible to permanently immobilize CO_2. This option involves reacting CO_2 with MgO to form a tough and resistant magnesium carbonate mineral. The MgO would be obtained by grinding up and dissolving ultrabasic rock whose dominant mineral is olivine with a chemical formula Mg_2SiO_4. Hence, the reaction would be

$$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$$

Nearly all of the Earth s ultrabasic rock resides in its mantle far below the surface and hence is unavailable to us. However, surface outcrops do exist in many places. So, large electrical power plants and air extraction facilities could be constructed at the sites of these ultrabasic rock outcrops.

None of these storage options is without environmental impacts. Concern has been raised about the possible impacts of deep-sea storage on organisms inhabiting the ocean deeps. Green Peace has already taken a strong stand against this option. In order to implement Antarctic disposal, it would be necessary to modify an existing treaty which bans mining on the continent of Antarctica. Further, there would likely be a strong opposition to the construction of large commercial structures required for air-extraction on that pristine polar plateau. Before permitting large quantities of liquid CO_2 to be injected into saline aquifers beneath their homes, for example, people would want to be assured that this activity would not trigger damaging earthquakes or lead to catastrophic releases of CO_2. Finally, even the conversion of CO_2 to $MgCO_3$ is not free of environmental problems. Large quantities of rock would have to be mined. As the volume of the products would exceed that of the rock mined, large mounds of $MgCO_3$ and SiO_2 would have to be made at the sites of this activity. Further, if as is often the case, the ultrabasic rock has been partially altered to serpentine, then the release of asbestos to the atmosphere during the mining operation would be a concern.

Clearly, any solution to the CO_2 problem will have its own set of environmental concerns. As this is unavoidable, the goal would be that the environmental damage stemming from the solution be far, far smaller than that from the CO_2 itself.

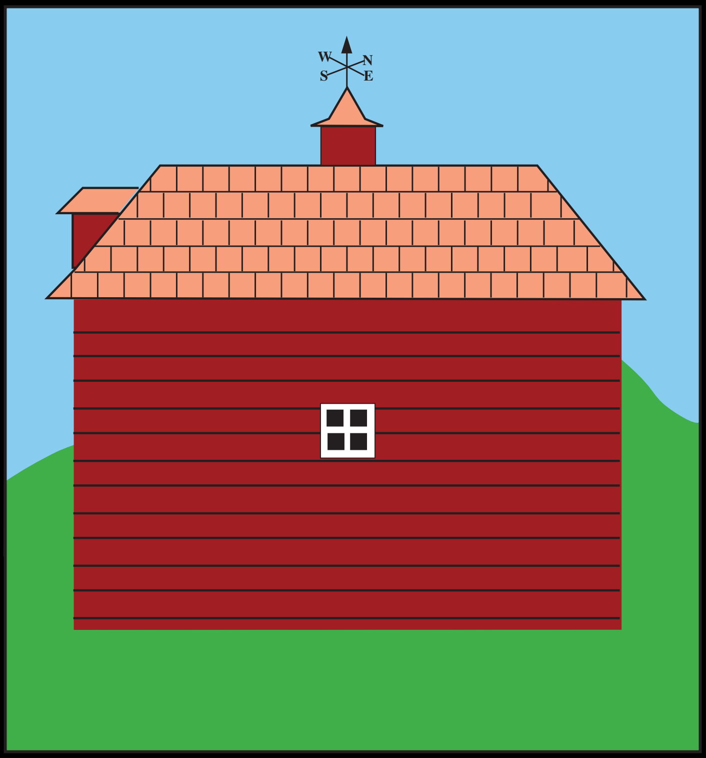
CO_2 capture from power plants

Although it is possible to capture CO_2 from the stacks of conventional coal-burning power plants, it would require very expensive retrofitting and the process would be cumbersome and expensive. A more economical option would be to move away from electrical power plants which combust coal in atmospheric O_2 (i.e., coal-fired plants). Instead facilities where coal is steamed to produce H_2 and CO_2 would be built (see Figure 53). The hydrogen would be used in fuel cells designed to generate electricity. Facilities of this type go by the name of coal gasification plants. It turns out that retrofitting this type of plant for CO_2 removal is far easier and their operation is less cumbersome and hence less expensive. So the idea is that as new electrical power plants are built or old ones replaced, it should be with coal gasification units instead of conventional coal-fired units. If this strategy were to be immediately put into place, the eventual implementation of CO_2 capture would be far more easily achieved.

Extraction of CO_2 from the atmosphere

Klaus Lackner, a scientist at Columbia University, stunned the energy world by demonstrating that CO_2 removal from the atmosphere is not only feasible but that it can likely be done at a cost equivalent to a 25 to 50 cent tax on a gallon of gasoline. His case is based on an analogy to wind power. In order to supply the energy utilized by the average USA resident, a rotor sweeping an area of about 80 square meters would be required and must be installed at sites characterized by brisk winds. In other words, brisk winds passing through an area the size of the side of a barn would have to be intercepted. Klaus points out that if, instead, the CO_2 produced by the burning of enough fossil fuel to supply the energy utilized by the average USA resident were to be extracted from the same wind stream, then only 0.2 square meters would have to be intercepted. In other words, the wind area intercepted would be equal to the size of a small window in the side of the barn (see Figure 56). Of course, there is no way that all the CO_2 could be removed from the passing air. But, even if only one half were to be captured, the size of the apparatus would be 80 times smaller than that required to generate an equivalent amount of wind energy.

Extraction of CO_2 from the air has two other advantages. First, China will probably not agree to sequester the CO_2 produced in its electrical power facilities until a means of balancing the international books on CO_2 emissions has been agreed upon. In other words, the world s rich nations would have to compensate for their past massive CO_2 production. A compromise might involve an agreement by the world s industrial nations to remove from the atmosphere some agreed upon amount of CO_2 in payment for their past excesses. A second consideration is that the ability to remove CO_2 from the atmosphere has this long-term advantage: if it is decided that the world was more habitable at some lower CO_2 content than that reached during the next hundred or so years, the means would exist to reestablish this desired level.



WIND POWER
80 m^2 / USA PERSON
(SIDE OF BARN)

CO_2 REMOVAL
0.2 m^2 / USA PERSON
(BARN WINDOW)

Figure 56

But how can air extraction be accomplished? In concept, it s quite simple (see Figure 57). If a tray containing liquid sodium hydroxide (NaOH) is exposed to air, it will absorb CO_2 ($2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$). The next step is to add calcium hydroxide to the sodium hydroxide, and calcium carbonate will promptly precipitate ($Ca(OH)_2 + Na_2CO_3 \rightarrow 2NaOH + CaCO_3$). This precipitate could be separated from the liquid sodium hydroxide and then heated to the point where it decomposed ($CaCO_3 \rightarrow CaO + CO_2$). The CO_2 could then be liquified for storage. The calcium oxide would then combine with water ($CaO + H_2O \rightarrow Ca(OH)_2$) and hence be readied for reuse.[4] Sounds simple but there are complications. First off, both sodium and calcium hydroxide are exceedingly caustic (in the sense that they readily dissolve the skin off your fingers!). Hence it would be necessary to prevent entrainment of the absorbent by the passing air and also to make sure the apparatus is constructed of materials immune to corrosion. Second, as calcium carbonate holds onto CO_2 with great tenacity, in order to force it to decompose, it must be heated to 900°C. The heating requires energy. Energy costs money and if produced from fossil fuels also generates additional CO_2.

Another option is to create an organic solvent which will combine with CO_2 at room temperature but release it when heated to a modest temperature. This solvent would not only have to be less chemically objectionable than NaOH but it would also have to require less energy input to implement CO_2 recovery than that required to decompose $CaCO_3$. Finally, this solvent would have to have a vapor pressure sufficiently low that its loss through evaporation would be acceptably small. To my knowledge, a solvent with all these properties has yet to be identified.

A third option involves a solid absorber. It would likely be a custom-designed artificial relative of the mineral, zeolite (see Figure 58). The focus is on zeolite because its structure contains an atomic scale cavity ideal for trapping a gas molecule. The idea

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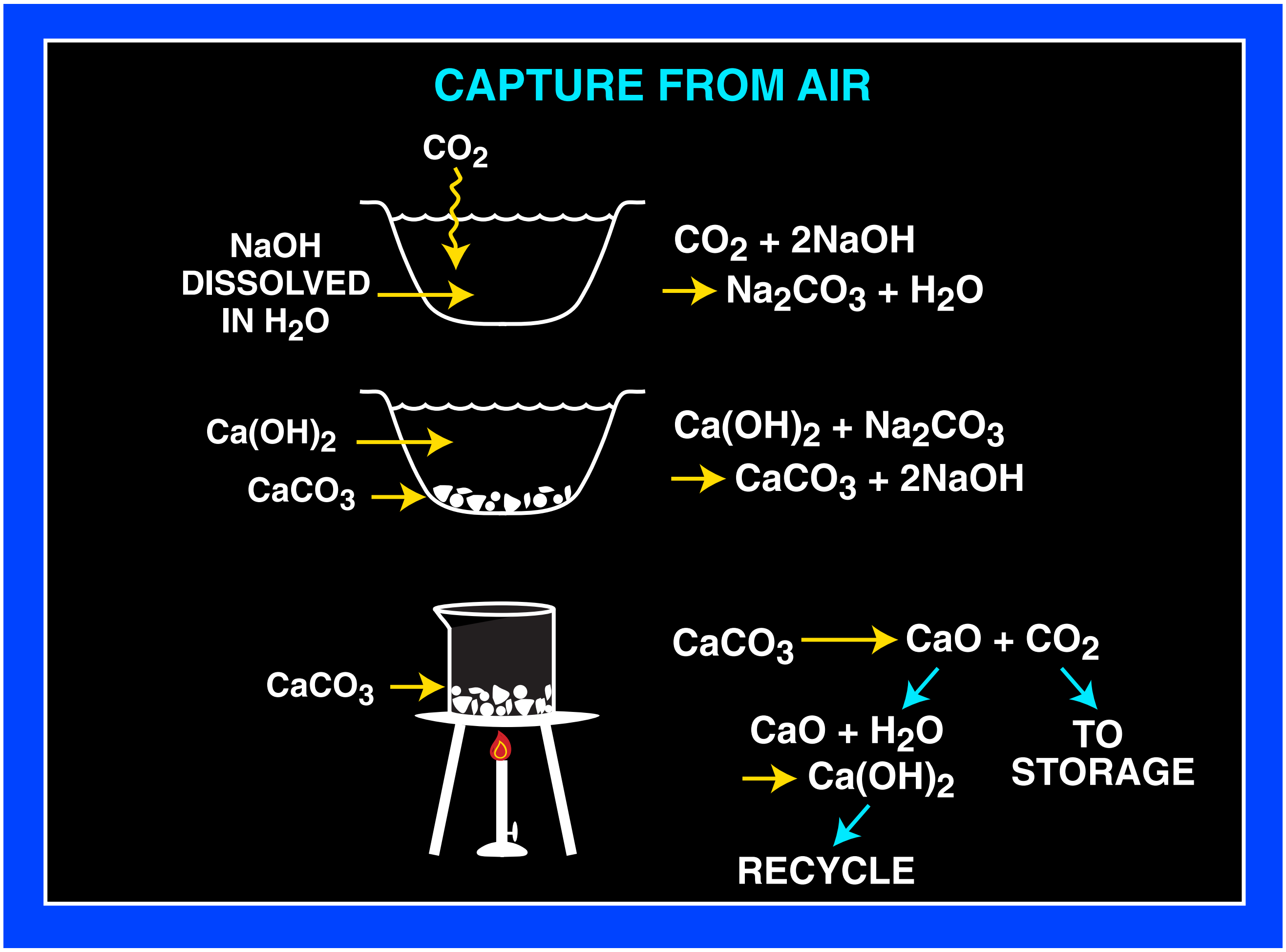
[4] As there are no natural deposits of CaO, it must be obtained by thermally decomposing the $CaCO_3$ which makes up limestone. This is equivalent to the process used to produce cement from limestone.



CAPTURE FROM AIR

CO_2

NaOH
DISSOLVED
IN H_2O

$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O$

$Ca(OH)_2$

$CaCO_3$

$Ca(OH)_2 + Na_2CO_3 \rightarrow CaCO_3 + 2NaOH$

$CaCO_3$

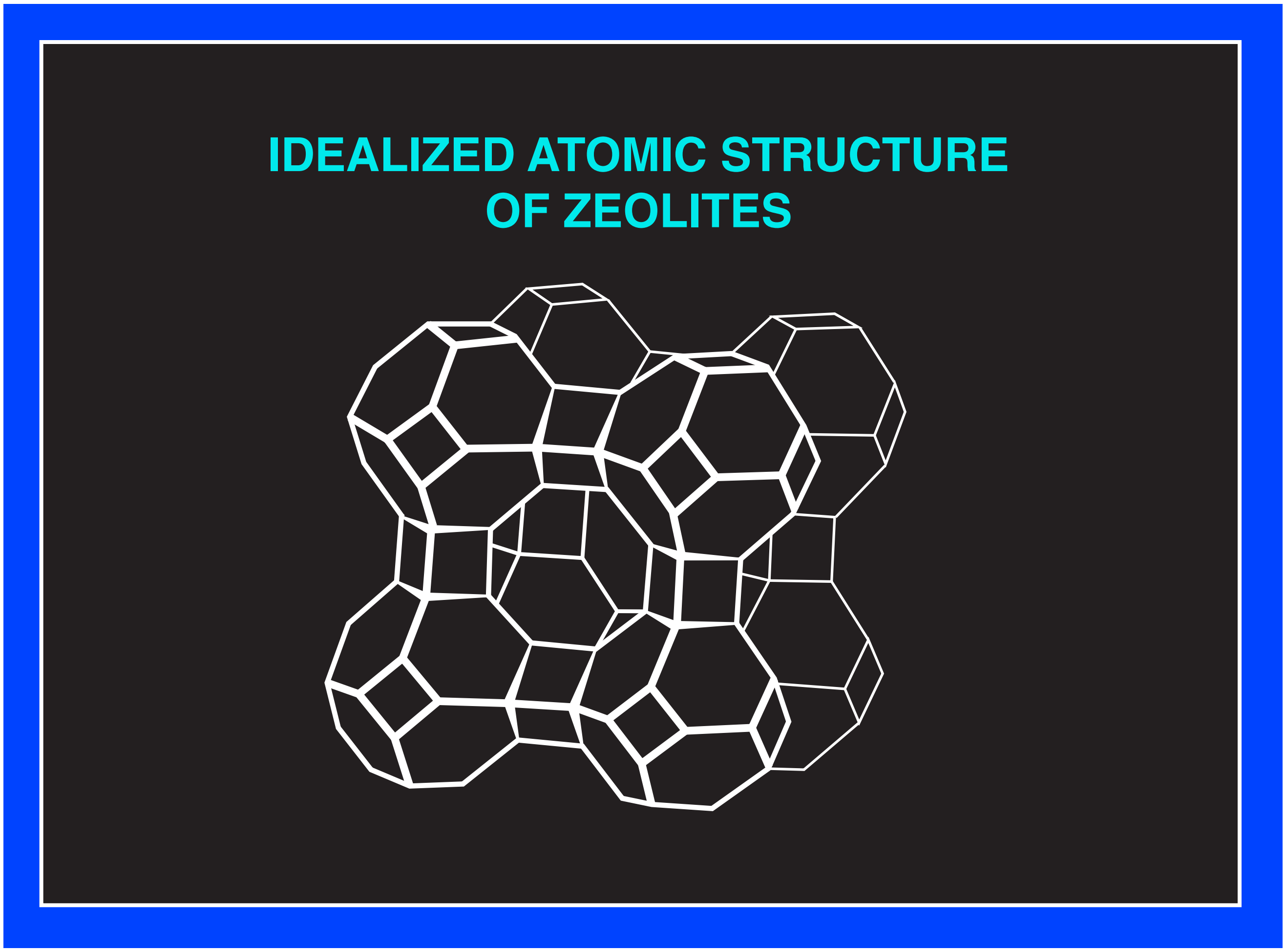
$CaCO_3 \longrightarrow CaO + CO_2$

$CaO + H_2O \rightarrow Ca(OH)_2$

TO
STORAGE

RECYCLE

Figure 57



IDEALIZED ATOMIC STRUCTURE OF ZEOLITES

Figure 58

would be to manufacture a zeolite cousin which would hold onto CO_2 molecules but not H_2O molecules. As the ratio of H_2O to CO_2 in air is very high, only such a zeolite would be able to pick up CO_2 without becoming clogged with water molecules.

Regardless of the CO_2 absorber selected, the required apparatus would be immense. Klaus Lackner envisions huge towers akin to the virtual one placed in New York s Central Park by Stonehaven Film (see Figure 59). If the absorber were zeolite balls, they would perhaps bounce down a series of baffles or slide down a mesh netting. The idea would be to design their descent through the tower so that when they reached its base, they would have picked up an optimum amount of CO_2 from the air stream. The balls would then be transferred to a chamber at the base of the tower. The chamber would be evacuated allowing a cooling coil placed within the chamber to pull the CO_2 off the zeolite converting it to dry ice (solid CO_2). Once freed of their CO_2, the zeolite balls would be sent back to the top of the tower for another pass. The dry ice would be converted to liquid CO_2 and piped to a storage site.

If the absorber were a liquid, it would likely trickle down a porous framework placed in the wind stream. Upon reaching the tower s base, it would be heated and passed down a similar but smaller framework and the CO_2 would be released from the heated solvent. It would be liquified and piped to the site of storage.

However, as no such apparatus has yet been built, the ultimate design could well be quite different. Whatever it turns out to be, several criteria will have to be met.

1) The framework on which the absorbent is held must present minimal resistance to the flow of the air.
2) As the absorbent must be recycled, its loss during each cycle must be kept small.
3) The amount of heat required to release the CO_2 from the absorbent must be kept to a minimum.

LACKNER CO_2 EXTRACTOR

Figure 59

Time constraints

No matter what course were taken to eliminate CO_2 emissions, it would be a huge enterprise. Were all the CO_2 currently created by fossil fuel burning to be liquified, about one cubic kilometer would be generated every two weeks. The technology required to capture and store CO_2 remains largely on the drawing boards. Only a small fraction of the people on the planet are convinced that such massive action is warranted. The unconvinced would probably argue; why should we pay to capture and store CO_2 when we can release to the atmosphere for free? The Bush Administration is hesitant to take any action, claiming more research is required. It is clear that proponents of action face a major uphill battle.

If the decision were made to create a backstop against an unfavorable greenhouse buildup involving capture and storage of CO_2, how might the schedule look? I see the next 20 years devoted to four tasks (see Figure 60).

1) Developing and testing the apparatus required for CO_2 capture and storage.
2) Working out a scheme for financing CO_2 capture and storage.
3) Making the complex set of political arrangements required to bring on board most of the world s 180 nations.
4) Monitoring the extent of climate change as a means of convincing the world s inhabitants of the necessity to cut off the flow of CO_2 to the atmosphere.

While 20 years sounds like a long time, it very likely is not nearly enough to complete these four tasks. To build and test a new type of power plant takes about 15 years. The Kyoto Accord was 15 years in the making. Almost nothing of consequence has been accomplished during the 30 years which have elapsed since scientists first raised a warning flag. So, if it s to be accomplished, we would have to move quickly into high gear on all four of these fronts.

In order to achieve the participation of dubious governments, it will likely be necessary to agree to hold off decisions regarding the rate of deployment of the

STRAWMAN 20 YEAR PLAN

1) DEVELOP AND TEST TECHNOLOGIES REQUIRED FOR CO_2 CAPTURE AND STORAGE

2) CREATE A WORKABLE PLAN FOR FINANCING CO_2 CAPTURE AND STORAGE

3) NEGOTIATE INTERNATIONAL AGREEMENTS REQUIRED TO BRING 180 NATIONS ON BOARD

4) MONITOR THE EXTENT OF CLIMATE CHANGE

Figure 63

sequestration apparatus until late in this 20-year period. This determination will likely be based on the rate at which global warming proceeds. If, as Lindzen predicts, little change occurs, then the technology would likely be shelved. On the other hand, if the extent of warming were to exceed that predicted by the models, then implementation would be pushed forward at the greatest economically permissible rate. Even if the preparation period can be kept as short as 20 years, when account is taken that the minimum time required to replace the existing energy infrastructure is roughly 40 years, the zero emission goal could not be achieved earlier than 2065 AD. The task is a huge one. If, for example, the CO_2 produced to support 10 billion people were all to be extracted from the atmosphere, roughly 300,000 Lackner units would be required (see Figures 61, 62). Hence, if we are to beat the clock, we must inject urgency into the preparation process.

Summary

Those who oppose serious action with regard to stemming CO_2 emissions base their case on the lack of solid evidence that climate change caused by this buildup will have serious consequences (see Figure 63). They would like to believe that we will be able to adjust to gradual warming. Some go further and, based on Lindzen s analysis, claim that no significant CO_2-induced warming will occur. Instead, they choose to attribute the warming which has occurred during the last 30 years to natural causes with the Sun being the favorite culprit. The finding that the Earth s temperature is currently no warmer than it was a millennium ago is taken as evidence in support of this conclusion.

Those who push for action base their case on computer simulations which suggest that the climate changes to be brought about by the rise in atmospheric CO_2 content will have highly adverse consequences to the world s remaining wildlife and will likely force major changes in how humans make their livelihood. Admitting that ongoing natural climate changes and the introduction to the atmosphere of man-made

A HUGE TASK

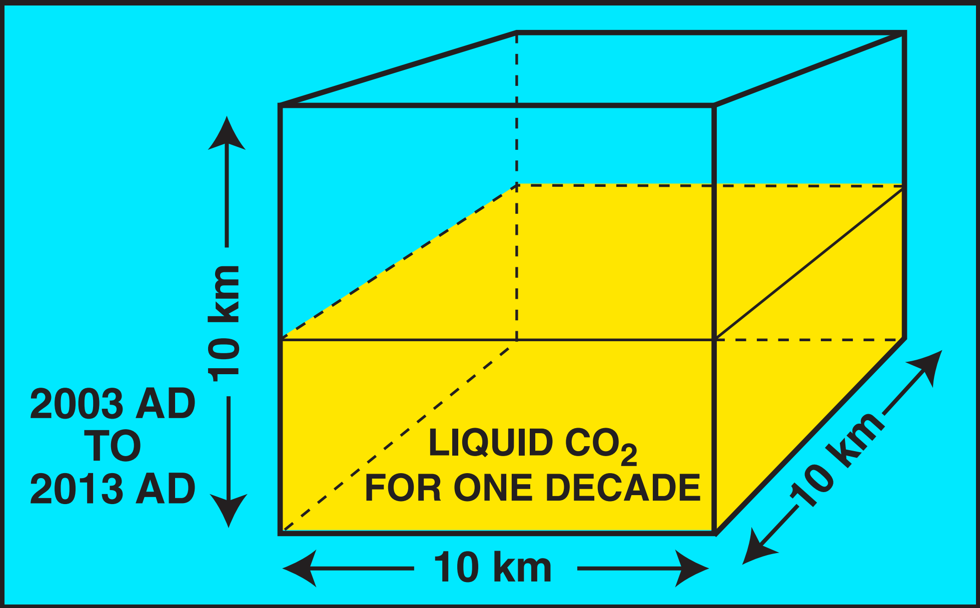
IF ONE UNIT WERE REQUIRED TO
REMOVE 1000 PEOPLE'S CO_2

THEN FOR
10 BILLION
PEOPLE

300 THOUSAND
EXTRACTORS
WOULD BE
NEEDED

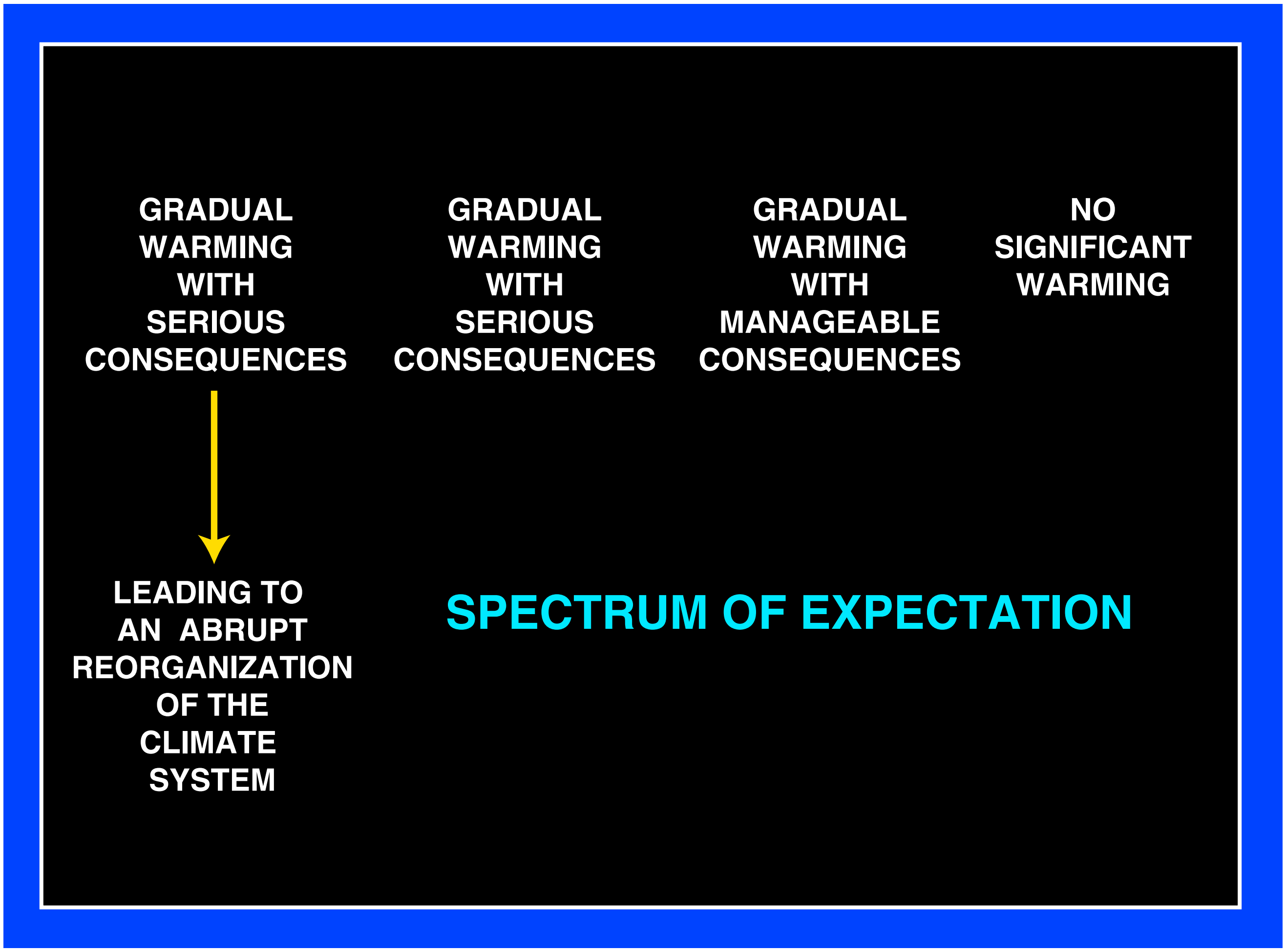
Figure 61

A HUGE TASK



AT CURRENT RATE OF FOSSIL FUEL USE
~2 km^3 LIQUID CO_2 PER MONTH
~500 km^3 LIQUID CO_2 PER DECADE

Figure 62



GRADUAL
WARMING
WITH
SERIOUS
CONSEQUENCES

GRADUAL
WARMING
WITH
SERIOUS
CONSEQUENCES

GRADUAL
WARMING
WITH
MANAGEABLE
CONSEQUENCES

NO
SIGNIFICANT
WARMING

LEADING TO
AN ABRUPT
REORGANIZATION
OF THE
CLIMATE
SYSTEM

SPECTRUM OF EXPECTATION

Figure 63

particulates complicate the situation, this group attributes the warming of the last 30 years primarily to increases in CO_2 and other greenhouse gases. Some go a step further and warn that a large buildup of CO_2 could trigger a reorganization of the global climate system. Based on the evidence from the records in polar ice and marine sediments, such reorganization would likely occur rapidly (decades) and during the transition period, climate would flicker much as do fluorescent lights when turned on. Their concern is that by adding large amounts of CO_2 to the atmosphere we are prodding the angry climate beast.

I stand with this latter group. It is my view that, as we have interfered with so many aspects of our planet s operation, we have inadvertently taken on the role as its steward. As such, we must carefully consider the long-term impacts of our activities on not only the welfare of our species but also that of all the other species with whom we share the planet. To me, it would be totally irresponsible not to pull out all the stops in an effort to develop a means to deal with rising CO_2. This task will require at least 20 years, and once completed, will require at least another 40 years to implement. We cannot afford to waste anymore time, for we are already well behind the curve.

The strategy of the Bush Administration to wait until research has produced more firm predictions is in my estimation deeply flawed. For despite the impressive ongoing efforts to depict how our climate system operates, the goal of making reliable predictions is not getting significantly closer. The more we learn, the broader the pallet of complexity. So, the answer will instead come from the Earth itself. During the 20-year preparation period proposed here, we should observe how much the tropics warm; where droughts become more severe; how much of the Arctic s ice melts; how much sea level rises. These observations will allow computer simulations to be correspondingly adjusted and hopefully lead to more reliable predictions.